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We dedicate this work to all four thousand million year-old bacteria who may once have lived in our Solar System, and to all life everywhere created, sustained, and sometimes destroyed by suns. With all our hopes for the future,

The Ra Team

Ra

Final Report

The Sun for Science and Humanity

International Space University | Summer Session 1996 | Vienna, Austria

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The 1996 Summer Session of the International Space University existed for ten weeks at the Technical University of Vienna, hosted by the Austrian Society for Aerospace Medicine.

The cover image of the Sun was taken by the Solar and Heliospheric Observatory Extreme Ultraviolet Telescope. The wavelength shown is 195 Angstroms, revealing highly ionised iron atoms in the lower corona at 1.5 million Kelvin. The North and South poles of the Sun clearly show coronal holes, a phenomenon not yet fully understood. The image was courtesy of the SOHO EIT Consortium (SOHO) is a joint endeavour by ESA and NASA.

Additional copies of the Design Project Executive Summary or the Full Report , *Ra: The Sun for Science and Humanity*, may be ordered through the ISU Headquarters in Strasbourg or the ISU North American Office .

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"I would say that man should live for loving, for understanding, and for creating. I think man should spend all his ability and all his strength on pursuing all these three aims, and he should sacrifice himself, if necessary, for the sake of achieving them. Anything worthwhile may demand self-sacrifice, and, if you think it worthwhile, you will be prepared to make the sacrifice."

Arnold Toynbee, Surviving the Future
Oxford University Press, 1971.

Over this summer at ISU, we spent most of our abilities and our strengths on appreciating each other and on understanding what "the Sun for Science and Humanity" could mean. Sacrifices have sometimes been necessary, and it was worthwhile. Here is what we have created...

The Ra Team.

Acknowledgements

To everyone who contributed their time, energy, and expertise to the Ra team, we wish to express a heartfelt: Danke, Thank you, Merci, Grazie, धन्यवाद, Gracias, Gracies, Spasibo, qJåpe©ΩwYc, Takk, Bedankt, Tack, Kiitas, 谢谢, Cam-on, Tak!

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Student Preface

The International Space University (ISU) was founded in April 1987 as a non-profit, non-governmental institution. It was created with the objective of becoming the world's leading centre for educating and training tomorrow's space professionals. The ISU Summer Session Program brings together international space experts from academia, industry, and government to educate students in multidisciplinary and advanced issues in space development in a ten week format. The design projects carried out by the students during the session have two purposes: first, to provide learning in international teamwork on problems requiring a multidisciplinary and multicultural approach, and second, to yield published results that can be influential in the world-wide space community.

This year's summer session was held in Vienna, Austria, and this report outlines the effort of one of its two groups of students. The team, composed of 53 professionals from 18 countries, brought to the project a variety of experiences, educations, and interests, from the societal through to the scientific, from the theoretical through to the applied. The members of our group used varied styles of problem solving, ranging from the ambitious and unconstrained to the more limited and immediately achievable.

Our mandate was to use an international perspective to examine present and planned activities in solar-terrestrial science and applications, critically review current goals, investigate new organisational schemes, develop innovative mission concepts and define a comprehensive baseline project that represented a realistic alternative or follow-on to the projects now being considered in space agencies.

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Faculty Preface

At each ISU summer session the students carry out one or more design projects. Their purpose is to give experience in intercultural and multidisciplinary teamwork and at the same time to generate results that can be influential in the world beyond ISU and useful to the students in their later careers. At ISU 96 the two projects were about remote medical activities and solar-terrestrial science and applications, named by the students DOCC and Ra respectively. Of the 104 members in the ISU class of 1996, fifty-three people from eighteen countries and all ISU academic disciplines chose to work on Ra. This document delivers their results.

The charge to the student team was for them to use an international perspective to examine present and planned activities in solar-terrestrial science and applications, critically review current goals, investigate new organisational schemes, develop innovative mission concepts and define a comprehensive baseline project representing a realistic alternative or follow-on to the projects now being considered in space agencies.

Recognising that the realm of Sun-Earth interactions is huge and diverse, the students had to make choices using their own judgement as to what they could achieve in a short project. They developed a Strategic Framework containing near, mid, and far term activities for both science and applications and analysed those that they believed most promising. They used information and advice from their faculty and teaching assistants plus that contributed by other members of the ISU community and visiting experts. They made effective use of the new information facility provided by the World Wide Web.

The students' decisions on what to analyse and report, what to treat by reference, and what to omit from the project were entirely their own. We, the faculty and teaching assistants for this project, are honoured and proud to have been associated with this energetic, disciplined and creative group of students and we commend their results to the reader.

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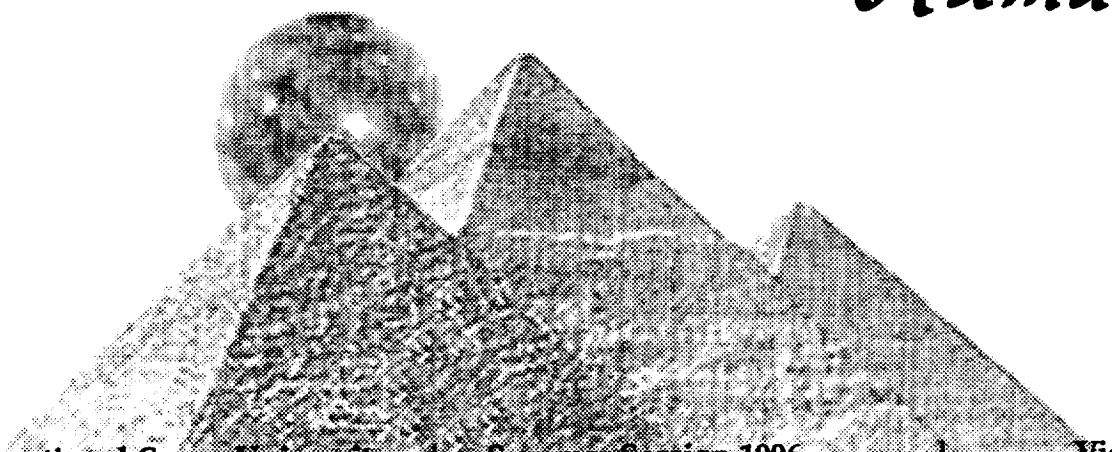
Ra

Executive Summary

The Sun for Science and Humanity



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Introduction

In this report, we set out a framework for pursuing solar science and applications. As a guiding charter, we have chosen the following mission statement:

> *Through an international perspective, we will explore and document strategies which will increase our understanding of the Sun and its effects, and help us apply solar knowledge for the benefit of humankind.*

Ra Team Mission Statement

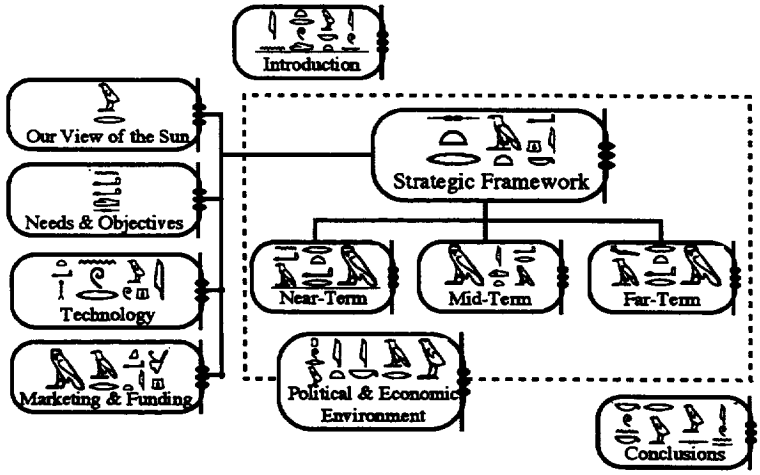
The timing is fortuitous.

The ESA Science Programme Committee (SPC) will be meeting in November 1996. After this meeting, the Call for Ideas for the M4 mission (part of the Horizon 2000 Plus programme) will most likely be released. The M4 has presently been reserved for a mission concentrating on the Solar System.

Also in the immediate future, the Inter-Agency Consultative Group for Space Science (IACG) will likely begin the process of choosing its next focal project. Currently, they have been co-ordinating the International Solar Terrestrial Physics Program (ISTP).

Furthermore, NASA is planning to bring its Sun-Earth Connections Roadmap to the American space science community for assessment. That meeting is set for the summer of 1997 at Woods Hole, Massachusetts.

We encourage the wider community to investigate the contents of our full report. Much of it has taken the form of recommendations for the future, and many ideas await your discovery within.



Report Overview Diagram: The hieroglyphs were found using the URL of Laurent Wacrenier, *Nom en hiéroglyphes*, http://yoko.ens-cachen.fr:8080/hiero, accessed August, 1996.

The International Situation

The global political environment within which space activities take place has been changed by a variety of economic, social, and technological factors. This altered paradigm has created both obstacles and opportunities for solar exploration and applications.

The end of the Cold War has had the most far-reaching implications for national space activities. Deep and integrated co-operation in space between the United States and Russia is no longer a political taboo, opening up a whole new array of international co-operative opportunities. Conversely, the loss of competitive Cold War rationales has been a primary driver of the decreasing national space budgets in both the United States and Russia. These same decreasing budgets stimulate increased national inter-agency co-operation and co-ordination. This trend toward greater collaboration presents an opportunity for a multilateral co-operative effort in solar exploration and applications.

The respective technological levels of spacefaring nations are no longer disparate. Although economic competition between spacefaring nations has partly supplanted the old political competition of the Cold War, less commercial sectors, such as space science, have experienced enhanced co-operation because of mutual payback opportunities and decreased concern about disproportionate or unilateral technology transfer.

The economic risks of insufficient global knowledge concerning dangerous solar phenomena have risen to new heights. The ever-increasing amount and level of complexity of the global space infrastructure, used by both developed and developing nations, points to an immediate need for improved solar warning and forecasting capabilities. The political environment recognises these economic needs, resulting in an enhanced opportunity for developments in solar warning and forecasting.

There has been an international trend toward greying the line between the basic and applied sciences. This greying has the potential to enhance the cohesion of the scientific community by diminishing traditional rivalries between speciality disciplines. The convergence is also notable for the movement toward interdisciplinary science missions, and the current climate is favourable toward joint science and applications endeavours.

The future of solar exploration and applications will be determined largely by how well the relatively low budgetary priority of solar and heliospheric physics and solar warning and forecasting services is overcome. The combination of diminishing national space budgets, increased opportunities for co-operation, and growing technological capabilities has led to a sustainable emphasis on smaller, modular, networked spacecraft with prioritised objectives. Disciplinary cohesion, inter-agency co-ordination, international co-operation, applications rationales, and smallsat technology offer a combination of effective means to sustain and even increase solar exploration and applications efforts.

A Strategic

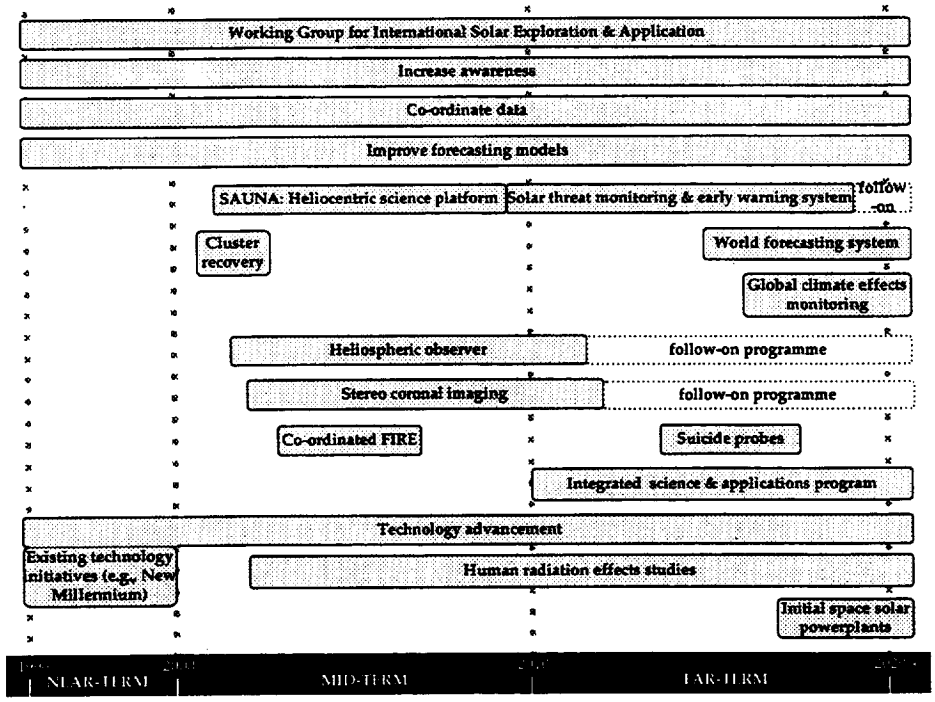
One of our goals in the report is to develop a Strategic Framework for solar science and applications, and from that programmes for the Near-Term, Mid-Term, and Far-Term. This Strategic Framework provides an integrated approach to solar exploration and application, as illustrated in the figure below. Three time frames are defined as follows:

- Near-Term: Focuses on programmes that are achievable within the next few years (1996 to 2000). Elements tap into current capabilities and programmes; they also seek to improve management and co-operative structures in preparation for the future.

- Mid-Term: Focuses on more ambitious programmes, some requiring technology development, with implementation times in the first decade of the next century (2001 to 2010).

- Far-Term: Focuses on the period from approximately 2011 to 2020 (and beyond) and is characterised by higher-risk, advanced technology, and/or integrated programmes.

The elements of the Near-Term programme are primarily political and managerial in their scope, in keeping with the Near-Term philosophy of building on existing capabilities. Central to this programme is the creation of a "Working Group for International Solar Exploration and Applications" (WG ISEA). We envision the WG ISEA as a forum for co-ordinating and planning the many solar missions that individual nations have proposed for the next decade, while preserving their independent sources of support. These missions tend now to be rather random. Other



parts of the programme may not be as ambitious but can have profound implications. The sharing of science data, for example, may produce synergistic results and lead to better solar environment forecasting models. Overall, the Near-Term programme lays a foundation for the projects of the later parts of the Strategic Framework.

We propose several mission flight opportunities in the Mid-Term period. A stereoscopic solar imaging system is envisioned to fulfil the high priority science objective of understanding the corona, as is a heliocentric near-Sun science platform (which we have named SAUNA). The corona is currently scheduled to be probed by the combined Russian-US FIRE mission. These missions will be supported by a new global heliospheric observation system (possibly one of the stereo observation platforms), since SOHO may have expired and not been replaced by the time it is needed to support FIRE and other missions. We envision a continuously operating solar threat monitoring and early warning system, perhaps one involving near-Sun platforms that build on the technology demonstrated by SAUNA. This system will mark the beginnings of a solar applications system, an idea central to Ra. Finally, we envision that humanity will be taking serious steps toward the establishment of human lunar outposts or Mars exploration; in which case, study of solar radiation's effects on tissue will be essential to the design of these missions. In summary, the Mid-Term programme elements represent a maturing of solar science and the beginnings of solar applications.

The elements of the Far-Term programme look toward the more distant future. Building on the foundations created earlier — better forecasting models, data co-ordination, increased solar awareness, and the WG ISEA (whose international activities will have continued and expanded in importance) — we envision an integrated programme for space science and applications. This integrated programme may have combined platforms, or it may share common resources (such as spacecraft bus designs, or a communication system to relay data from a new generation of solar spacecraft). The space threat monitoring and early warning system begun earlier should be mature enough by this time to create a global forecasting system, one that provides benefits to developing nations. Furthermore, applications will begin to focus on solar benefits, such as the beginnings of space solar power plants. Finally, as we look back on years of integrated data, we see these data, combined with new long-term missions, enabling scientists to study the relationship between the Sun and the Earth's climate.

We believe the Ra Strategic Framework is significant because it:

- is a coherent plan over time.
- relies on existing and planned programmes, and benefits from them.
- considers the political and economic environment, including future trends, and seeks to shape that environment for the advancement of solar science and applications.
- integrates solar science and applications, showing how one can complement the other.
- is an international framework.

Objectives

To guide the development of the Ra Strategic Framework, we defined scientific and applications objectives. For our primary areas of scientific interest, we chose the corona, the solar wind, the Sun's effect on the Earth, and solar theory and model development. For secondary areas of scientific interest, we selected sunspots, the solar constant, the Sun's gravitational field, helioseismology and the galactic cosmic rays. We stress the importance of stereoscopic imaging, observations at high spatial, spectral, and temporal resolutions, as well as of long duration measurements. Further exploration of the Sun's polar regions is also important, as shown already by the Ulysses mission.

From an applications perspective, we adopted three broad objectives that would derive complementary inputs for the Strategic Framework. These were to identify and investigate: possible application spin-offs from science missions, possible solar-terrestrial missions dedicated to a particular application, and possible future applications that require technology development. The Sun can be viewed as both a source of resources and of threats. Our principal applications focus was that of threat mitigation, by examining ways to improve solar threat monitoring and early warning systems.

We compared these objectives to the mission objectives of past, current, and planned international solar missions. Past missions (1962-1980) seem to have been focused on improvement of scientific knowledge, using multiple instrument spacecraft. A ten year gap followed this period, during which the results from previous missions were analysed and solar study programmes were prepared in international organisations. Current missions (1990-1996) focus on particular topics such as the corona, solar flares, and coronal mass ejections. In planned missions, Sun/Earth interactions and environmental effects of solar activity are becoming more important. The corona is the centre of interest of almost all planned missions. It seems that no international long-term strategy has yet been adopted. For these plans the number of necessary future missions can be reduced and the onboard instrumentation can be optimised by performing a comparative analysis.

The study of the corona must be done from different observing locations, orbits closer to the Sun, and by different means. The Cluster mission replacement is in progress; however, if the replacement is not implemented, the ISTP programme will fade after 1998. Furthermore, the physics of the Sun's interior should be emphasised more in the Mid- and Far-Term programmes. Finally, more emphasis should be placed on monitoring space weather and forecasting Sun/Earth interactions.

A Policy Proposal

The continued expansion of solar understanding will necessitate research rationales that include both basic and applied scientific objectives. To properly integrate these rationales, a single forum for solar exploration and applications co-ordination and planning is optimal. The Ra Strategic Framework calls this forum the Working Group on International Solar Exploration and Applications (WG ISEA). To take full advantage of current events in space science, the WG ISEA should be formed before the Summer 1997 NASA Woods Hole Sun-Earth Connections Roadmap meeting.

The programmatic means by which the WG ISEA achieves its international collaborative objectives should be flexible to maximise the political sustainability of the effort. The WG ISEA should include a Mission Co-ordination Group to synthesise co-ordination and data sharing between national solar science and applications missions outside, with, and beyond the International Solar Terrestrial Physics programme (ISTP). To supplement the inevitable gaps in solar observing capabilities that will still exist, the WG ISEA should also form a Mission Planning Group to recommend a strategic framework for solar exploration and applications that takes advantage of existing, cheap platforms, such as university mini-satellites, for quick response solar observation or solar instrument technology demonstration.

Discrete national hardware contributions to international efforts optimise the political environment for space activities. The use of standardised, common spacecraft systems, however, is also a key to reducing the cost of solar system exploration. To take advantage of this economic opportunity while realising its political realities, the WG ISEA should include an engineering group for the international design of reference models for solar spacecraft. This Reference Model Design Group provides a first step towards realising the benefits of international co-operation in space exploration beyond the co-ordination of scientific data acquisition and data dissemination.

Increased understanding of solar and heliospheric physics will generate advances in solar forecasting models, and current national plans to consolidate agency-level solar warning and forecasting resources will incorporate these advances. Existing international solar warning and forecast data distribution networks like the International Space Environment Service will feed data into these forecasts, but the advances needed to make solar warnings and forecasts relevant to potential users will require capital investment in hardware, especially in instruments placed between the Earth and Sun. National solar warning and forecasting plans should look abroad for opportunities to co-ordinate the deployment of dedicated but nationally discrete solar warning spacecraft. Meeting user needs will provide horizontally integrated commercial opportunities within the larger government space warning and forecast services. A solar warning spacecraft will also likely be the first operational deep space endeavour outside exploratory and technology demonstration missions, marking an important transition point in humanity's expansion into the universe.

Markets and Funding

There is a market transformation taking place from the public sector to a combination of the public and private sectors. Our vision is to support this transformation and to expand and fully use existing and potential markets. Our research has found three major markets for Ra:

- Space environment forecasting is an increasing market, and the next ten years will see it increase from $100 to $200 million U.S. annually. Potential markets are influenced by insurance companies and financial institutions. These markets are sensitive to failures of telecommunication satellites and energy suppliers.

- The science market will expand as Ra increases the benefits through augmenting scientific and technological knowledge. This increase will help develop and implement solar illumination and solar heating infrastructure systems. Including these in buildings and transportation systems has the potential to significantly influence the well-being of the global population.

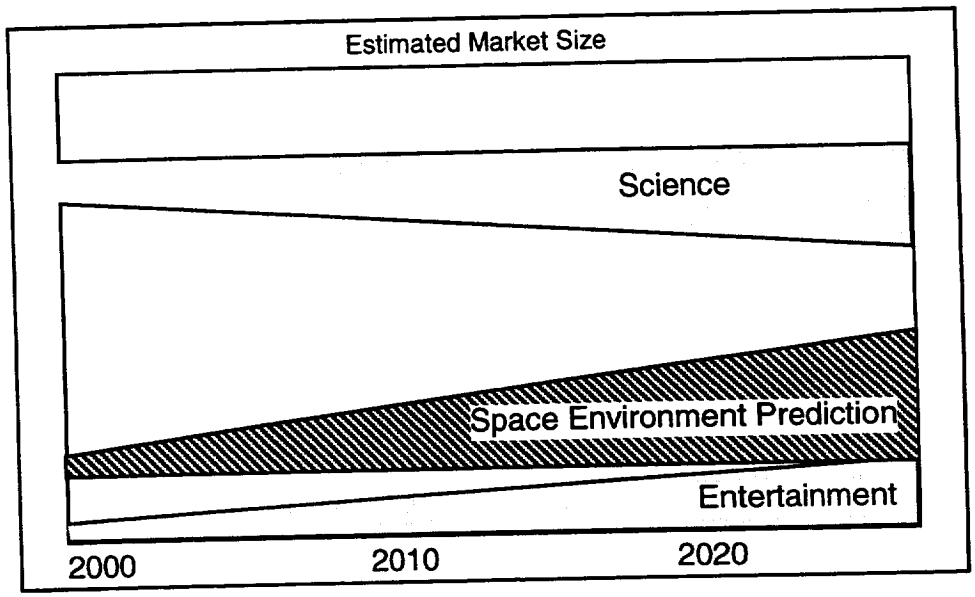
- Entertainment and education markets can be served by converting the Ra scientific results. This will increase the public awareness about the Sun and its effect on the Earth and human life.

We expect these markets to evolve as shown in the figure below.

Increasing public interest in the Ra programme will likely increase the availability of governmental funding. We recommend further studies.

Space agencies are interested in solar science and space environment forecasting. Improved measurements and models of the space environment will benefit both manned and unmanned space programmes and thereby constitute a ground for funding.

There is a trend toward joint ventures between universities and industry. The universities' research is relevant to industry, and industry funds part of it. We see a trend where Sun activities are moving from being research driven to product/service driven.



A Near-Term Programme

Each part of the Near-Term programme is relatively low in cost and either builds upon existing systems and infrastructure or incorporates modest developments. We believe that the recommendations are realistic and play an important role in realising important science and applications objectives. They also provide a foundation for the projects described in the Mid- and Far-Term programmes.

To build on existing solar observation instruments (namely SOHO) and to continue with a logical sequence of solar observation satellites, we recommend recovery of the Cluster programme. As we believe space environmental forecasting will become more important to the space community in the Mid- and Far-Term, we recommend immediate work on improving forecasting models. As the amount of archived data continues to grow and additional solar observation satellites are launched, we advise co-ordination of and accessibility to both the new data and those from the past. We call for the Working Group for International Solar Exploration & Application (WG ISEA) to be started in the Near-Term. To help advance the Mid- and Far-Term programmes through to fruition, we advocate increasing awareness of solar science and solar-terrestrial connections, thereby fostering support beyond the scientific community. Finally, in the Near-Term programme, we support actively incorporating existing technology initiatives.

Programme	Description
Cluster recovery	A replacement for the Cluster programme and direct new Cluster mission toward Ra's objective
Improve forecasting models	Perform correlation studies; innovative acquisition of new forecasting models
Co-ordinate science and other data	Continue ground-based observations; create an international data centre; research with and co-ordinate science data; co-ordinate future planning of independent groups
Working Group for International Solar Exploration and Application (WG ISEA)	Incorporates science and applications interests from government and private sectors; submits to government agencies specific recommendations for actions necessary for the fulfilment of the solar exploration and application strategic plan, while encouraging independent complementary efforts
Increase awareness of solar science and Sun-Earth interaction	Develop a "common language" for solar science and applications; work with planetariums and museums; educators via WWW; correlation study on satellite anomalies, ground power station anomalies and solar activity
Actively incorporate existing technology initiatives	Examples include: Japan Nereus, ESA TRP (esp. Theme 10) and GSTP, NASA New Millennium, University Small Sat, Clementine, DC-XA, Commercial bus

The most significant suggestions are two correlation studies: one to establish the relationship between solar activity and satellite anomalies, and a second to evaluate the accuracy of current solar activity forecasting models. These are interrelated and each serves, in the Near-Term, to get the applications objectives "off the ground".

The major components of the Near-Term programme are summarised in the above table.

A Mid-Term Programme

The Ra Mid-Term framework aims to:

- provide a solar science programme to address fundamental issues of solar physics.
- improve the capability for solar applications, and do so in co-ordination with the science programme.

The second objective is served by a transient phenomena monitoring and early warning system, and a small but important human dosimetry payload. The latter is clearly needed for the safety of manned interplanetary missions, and as such must fly before a crewed expedition to Mars or a lunar base become reality. The stereoscopic mission will open the third dimension for solar physics, flying moderately capable remote sensing instruments at 1 AU on small spacecraft buses, sharing heritage with existing small satellites. This will also serve as a precursor to an operational stereoscopic solar event prediction and early warning system. The SAUNA mission aims to send a medium-sized science payload to a moderately close heliocentric orbit inside that of Mercury, at about 0.2 AU. This mission will provide long-term high resolution monitoring of the solar disk in the extreme ultraviolet and of the corona in white light. Stereoscopy and contextual measurements will be possible when the data are combined with those from observations made on or near the Earth. SAUNA will also act as a technology demonstrator for subsequent long-term missions in closer orbits such as a heliosynchronous/polar constellation system. SOHO is showing the value of long-term heliospheric measurements from an orbit not significantly nearer the Sun than the Earth. Although it will probably remain operational until 2004, the planning of a replacement must start now if new and outstanding questions about the Sun are to be investigated effectively. The new platform should aim to reduce mission cost while improving capability, since SOHO itself is clearly a "monster mission" using large-scale 1980's technology. The currently proposed joint Russian-US FIRE mission, a simultaneous dual-spacecraft close flyby of the Sun to investigate the corona, is included in Ra's Strategic Framework. The dual mission is of far higher scientific value than if only a single spacecraft were flown.

The major components of the Mid-Term programme are summarised in the following table:

Programme	Description
SAUNA: a heliocentric, near-Sun science platform	Ion-propelled single spacecraft to 0.2 AU heliocentric orbit. 5 yr. mission duration
Solar threat monitoring and early warning system	Heliocentric orbiters; Other options included: L4/L5 tripwire and solar wind event imaging and tracking
Stereoscopic corona imaging system	Small remote sensing platforms at L1, L4 and L5
New heliospheric observing platform	Extended SOHO mission, then smaller follow-on
Co-ordinated FIRE Mission: Russian Plamya and U.S. Solar Probe	Dual spacecraft close flyby mission to 4 R_S and 10 R_S
Human radiation studies on host spacecraft	Tissue-equivalent dosimeter measuring direct radiation and secondary radiation from shielding

A Far-Term Program

The Far-Term programme of the Ra Strategic Framework is designed to build upon the experience gathered during the Mid-Term programme. We assume that more ambitious and higher-cost projects are possible in the Far-Term, providing that these are balanced by a proportionally increased economic viability in terms of commercial exploitation and direct benefits to society.

- Propulsion: further improvements in ion engine performance, development of prototype solar sailing vehicles for the inner solar system, further research into advanced concepts like mass drivers
- Power: high efficiency heat resistant solar arrays

Programme	Description
Integrated solar science and applications programme	Options: science "piggybacking" on applications; application prototype sensors on science platforms; use of common buses
Small suicide probes	Wide range of concepts available
World-wide space environment forecasting system	Characteristics include: distributed, provides information to developing nations, integrates military, civil, commercial data; independently maintained in participating nations
Preliminary space solar power applications	Prototype space-based solar power station for small-scale distributed use
Monitoring the Sun's effect on Earth's climate	Long-term space-based observation programme to monitor solar output and Earth's climate

Integrated solar science and applications programmes would succeed in reducing cost through co-operation in areas of common interest and through exploiting available opportunities. Small suicide probes would explore the acceleration and heating in the solar corona by means of *in situ* measurements. A world-wide space environment forecasting system would offer benefits to all humankind. Preliminary solar power applications would be instrumental in exploring ways to solve the imminent global energy crisis on Earth. Monitoring the solar constant and its effect on the Earth's climate would allow study of the impact of variations in the solar output on the Earth's climate.
In order to succeed in the Far-Term, the following technological developments will be required:

- Materials: high-temperature ceramics and alloys
- Electronics: radiation hardened high-temperature electronics, more powerful small lasers
- Communications: optical communication techniques
- Guidance, Navigation and Control: autonomous interplanetary navigation techniques (e.g. based on planetary ephemerides), increased on-board intelligence
- Launchers: low-cost access to orbit by means of fully reusable launch vehicles

The major components of the Far-Term programme are summarised in the above table.

Conclusion

The Ra report is a call to action. Knowledge of the Sun is vital to us as humans and to our planet. Our star deserves our attention and study.

The global political environment within which space activities take place is changing for a variety of economic, social, and technological reasons. The current international situation presents both obstacles and opportunities for solar exploration and applications. This situation is ideal for the introduction of Ra.

We present in our report a Strategic Framework for pursuing solar science and applications. From this Framework a programme emerges for the Near-Term, Mid-Term, and Far-Term. We believe the Ra Strategic Framework is significant because it:

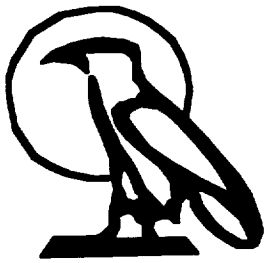
- offers coherency over time.
- utilises, benefits from, and adds to current programmes.
- harmonises with our political and economic environment.
- integrates solar science and applications.
- capitalises on global talents and resources.

By defining and analysing objectives, we give impetus and focus to the Strategic Framework. We have identified potential markets and sources of funding.

We recommend that a Working Group for International Solar Exploration and Applications (WG ISEA) be established immediately. The WG ISEA would:

- ensure that a Strategic Framework is put into action.
- synchronise independent efforts in different countries.
- facilitate the interaction between science and applications.
- help to combine the output into products useful on a global scale.

The time is opportune, ideal for the introduction of our ideas into the space science and applications community. Having in place a Strategic Framework dedicated to solar science and applications, and forming a small but broadly-based international WG ISEA would prove most beneficial. We hope that our report will help to make this happen.



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Acronyms

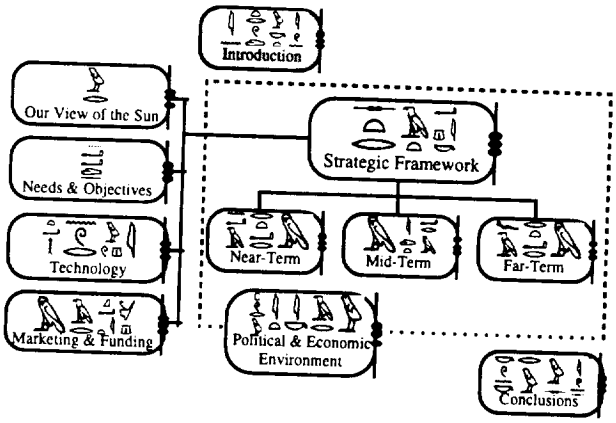
"Triple I"	Interagency/International Interface organizational model for solar warning and forecasting services
μ_{SUN}	Sun gravitational constant.
ACE	Advanced Composition Explorer
ACRIM	Active Cavity Radiometer Irradiance Monitor
ACS	Attitude Control System.
ADCS	Attitude Determination and Control System.
AOCS	Attitude and Orbit Control System
APS	Active Pixel System.
AU	Astronomical Unit (1 AU=1.5 10^8 km) Mean distance between the Sun and the Earth
CCD	Coupled Charge Device
CDF	Common Data Format
CDM	Code Division Multiplexing
CDR	Critical Design Review
CEOS	Committee for Earth Observing Satellites
CIS	Commonwealth of Independent States
CME	Coronal Mass Ejection
CMOS	Complementary Metal-Oxide-Semiconductor.
CNES	National Center for Space Studies (France)
Co-I	Co-Investigator
COSPAR	Committee on Space Research
CR	Commissioning Review
CSA	Canadian Space Agency
CSDS	Cluster Science Data System
CSEF	Committee for Space Environment Forecasting (U.S.)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSW	Committee for Space Weather (U.S.)
DARA	German Space Agency
DC	Direct Current
DIPS	Dangerous Interplanetary Plasma Structures
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt e. V.
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DSN	Deep Space Network
EDAC	Error Detection And Correction
ELDO	European Launcher Development Organisation
EOM	End Of Mission (Review)
ESA	European Space Agency
ESOC	European Space Operations Center
ESRIN	European Space Research Institute

EUMETSAT	European Meteorological Satellite Organisation
FAC	Field Aligned Current
FAST	Fast Auroral Snapshot Explorer
FDIR	Failure Detection, Isolation and Recovery
FDM	Frequency Division Multiplexing
FGF	Fluctuating Geomagnetic Field
FY	Fiscal Year
GCC	Gore-Chernomyrdin Conference
GCR	Galactic Cosmic Rays
GEO	Geostationary Earth Orbit
GGCM	Geospace General Circulation Model
GGS	Global Geospace Science
GIC	Geomagnetically Induced Current
GMS	Geostationary Meteorological Satellite (Japan)
GNC	Guidance, Navigation and Control.
GPS	Global Positioning System
GSOC	German Space Operating Centre
GSTP	General Support Technology Programme
HESI	High Energy Solar Imager
HGA	High Gain Antenna
HRG	Hemispherical Resonator Gyro
i	Inclination of the orbital plane.
IACG	Inter-Agency Consultative Group
IC	Integrated Circuit
IFOG	Interferometric Fibre-Optic Gyro.
IKI	Soviet Space Research Institute (now with Russia)
IMAGE	Imager for Magnetopause to Auroral Global Exploration
IMEWG	International Mars Exploration Working Group
IMF	Interplanetary Magnetic Field
IMP	Interplanetary Monitoring Platform
IMU	Inertial Measurement Unit.
INPE	National Institute for Space Research (Brazil)
IP	Inter Planetary
IPS	Interplanetary Plasma Structures
IRU	Inertial Reference Unit.
ISAS	Institute for Space and Astronautical Sciences (Japan)
ISEE	International Sun Earth Explorer
ISES	International Solar Energy Society
ISES	International Space Environment Service
ISL	Inter Satellite Link
ISPM	International Solar Polar Mission
ISRO	India Space Research Organization
ISS	International Space Station
ISTP	International Solar-Terrestrial Physics Programme
IZMEM	IZMIRAN Electro-Dynamic Model
IZMIRAN	Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation
JSOC	Joint Science Operations Center
L1, L4, L5	Lagrange Point 1/4/5, Libration Point 1/4/5
L4,L5	Stable Lagrangian points.
LAN	Local Area Network

LEO	Low Earth Orbit
LGA	Low Gain Antenna
MAMS	Modular and Multifunctional and Systems (one of NMP's Integrated Product Teams)
MEO	Medium Earth Orbit.
METEOSAT	European Meteorological Satellite Programme
MMH	Monomethyl Hydrazine
MMS	NASA Goddard Space Flight Center's Multimission Modular Spacecraft
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MSM	Magnetospheric Specification Model
MSM	Minimum Solar Mission.
MSTI	U.S. Air Force Miniature Sensor Technology Integration satellites and program
mv	Visual magnitude of the stars. It defines star sensor sensitivity.
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NMP	Jet Propulsion Laboratory's New Millennium Program
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NSF	National Science Foundation (U.S.)
NSSDC	National Space Science Data Center
NSWC	National Space Weather Council (U.S.)
NSWP	National Space Weather Program (U.S.)
NTO	Nitrogen Tetroxide
OFCM	Office of the Federal Coordinator for Meteorology (NSF)
OPAL	Stanford University's Orbiting Picosat Automatic Launcher
OSO	Orbiting Solar Observatory
OSS	Office of Space Science (part of NASA)
OSTP	Office of Science and Technology Policy (U.S.)
OTH	Over-The-Horizon radar
PDR	Preliminary Design Review
PE	Pluto Express.
PI	Principal Investigator
PRR	Preliminary Requirements Review
QMPP	Quantitative Magnetospheric Predictions Program
R&D	Research and Development
RAM	Random Access Memory
RCS	Reaction Control System
Re	Mean Earth Radius = 6371 km
RF	Radio Frequency
R_s	Solar Radius
RSA	Russian Space Agency
RTG	Radioisotope Thermal Generator
RW	Reaction Wheel.
RWC	Regional Warning Centers
SAC B	Satélite de Aplicaciones Cientifícas
SAMPEX	Solar Anomalous Magnetospheric Particle
SAPPHIRE	Stanford Audio Phonic Photographic Infrared Experiment
SAUNA	Solar Adjacency Using a New Approach
SCF	Smaller, Cheaper and Faster

SCM	Standardisation, Commonality and Modularity
SEC	Space Environment Center (NOAA, formerly SEL)
SEC	Sun-Earth Connection
SEE	Single-Event Effects
SEL	NOAA Space Environment Laboratory (NOAA now SEC)
SEP	Sun-Earth-Probe
SESC	Space Environment Services Center (U.S.)
SEU	Single Event Upset
SiC	Silicon Carbide
SMEI	Solar Mass Ejection Imager (Phillips Lab)
SOHO	Solar Heliospheric Observatory
SOI	Silicon On Insulator
SOLRAD	Solar Radiation
SOS	Silicon On Sapphire
SPC	Science Programme Committee (part of ESA) IACG Inter Agency Consultative Group
SPF	Sun Protection Factor
SPP	SAUNA Predevelopment Programme
SQUIRT	Stanford University's Satellite QUIck Research Testbed
SRR	System Requirements Review
SSC	Sudden Storm Commencements
SSR	Solid State Recorder
STA	Science and Technology Agency of Japan
STSC	Star Tracker Stellar Compass.
STSP	Solar-Terrestrial Science Programme
SWRI	Southwest Research Institute
TAOS	Technology for Autonomous Operational Survivability
TDM	Time Division Multiplexing
TEPC	Tissue Equivalent Particle Chamber
TID	Total Ionising Dose
TIMED	Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics
TRACE	Transition Region And Coronal Explorer
TRP	Technology Research Programme
TTC	Tracking, Telemetry and Command
U.S.	United States
UK	United Kingdom
USAF	United States Air Force
UV	Ultraviolet
WAN	Wide Area Network
WG	Working Group
WG ISEA	Working Group on International Solar Exploration and Applications
WWA	World Warning Agency (ISES)
WWW	World Wide Web
XTE	X-Ray Timing Explorer

Chapter 1



Introduction

Through an international perspective, we will explore and document strategies which will increase our understanding of the Sun and its effects, and help us apply solar knowledge for the benefit of humankind.

Ra Team Mission Statement

"One of the least understood objects in the solar system is our star the Sun." These words initiated one of the two Design Projects undertaken by the 1996 Summer Session Program of the International Space University (ISU). This particular project attracted 53 young professionals representing 18 countries. Together, we students brought to the project a variety of experiences, cultures, education, and interests: from the societal to the scientific, from the theoretical to the applied. Varied styles of problem solving were also present among us, ranging from the ambitious and unconstrained to the limited and immediately achievable. We called the project *Ra: The Sun for Science and Humanity* and chose the opening statement as our charter or, as we called it, our mission statement. Keeping in mind the mission statement, we produced a plan of action, our "Strategic Framework," an outline providing possible direction for the future of solar exploration.

Before charting this course, it is wise to pause and reflect upon the past. Questions often asked include:

"What reasons do we have for pursuing these investigations?"

"How did we arrive at our present situation?"

"What have we learned thus far?"

"Where have we failed before, and why?"

"What is our current situation?"

"What would we like to do next?"

"What are we able to do next?"

As men and as women, as individuals and as society, we humans have entered into and departed from many relationships. Some of these relationships were and are with nature. Among nature's elements, the Sun has always held a unique position in our psyche. Culture and daily life are shaped by the Sun, perhaps more than by any other natural body.

As special as our Sun is, we now see it also as a star. It has an anatomy. It has a structure, and it is far more dynamic than we first assumed. The Sun is the only star that resides in our immediate neighbourhood. As such, we hope to learn more about other stars by seeking to learn more about our own.

The inhabitants of any neighbourhood are intertwined, often in complex relationships. The Sun is by no means an exception. Our solar system is truly a system that is dominated by its star. Our Sun has its own unique way of communicating. It attracts. It emits. It broadcasts. It expels.

Our Earth responds. The planet on which we live takes all of this solar input and modifies it. In a sense, the Earth digests the food that the Sun offers. The Earth, too, has certain structures and dynamic attributes that allow it to participate in the life of our solar neighbourhood.

We ourselves, as members of this solar community, are also affected by all that goes on. Our surroundings and the tools we use are affected as well. It is our duty, then, to stay informed of our community's activities and interrelationships. In getting to better know our Sun and Earth and their interaction, we will be able to better discern our roles. For example, we can help minimise or perhaps avoid altogether solar-induced effects that in the past have proven to be harmful. Furthermore, may be able to take advantage of the new opportunities and partnerships that will arise. There is much to be gained by involving ourselves in our solar community. There is also much to be lost whenever we delay the next step in our involvement.

We have already begun to involve ourselves. Many projects have been implemented. We still benefit from their discoveries today. Some projects are currently underway. Others are attempting to establish themselves. These activities, their successes, and their struggles are better understood when societal factors are considered. The current social, political, and economic structures which we have created play a significant role in advancing or hindering our continued involvement, the latter being an essential ingredient which may influence the quality of life on our planet, Earth.

1.1 Mission Statement

Early in the project, the students of the Solar Probe Design Project Team agreed to adopt a mission statement. For a broadly stated problem like this, it is useful to provide some initial direction. A mission statement defines an overall goal for a group to work with. It should be credible and make sense, be simple, without being simplistic and be solution independent. Effectively, it gives a guideline such that, in case of a conflict, the mission statement refreshes your memory, focuses the objectives, and indicates the main priorities.

From our mission statement we derived the following goals and objectives:

- To explore and document the science and applications needs for the future;
- To develop a Strategic Framework for solar science and applications, and from that a program for near-term, mid-term, and far-term missions; and
- To explore and document the challenges in technology, policy and funding, related to solar science and applications.

Given the broad aim of this project and the intended audience for this project, we consider "mission success" in a broad framework as well. We have succeeded if this project sparks new discussion in the space community concerning solar science and solar application issues. Our efforts will have been worthwhile if we are able to influence the international community with new ideas and force the rethinking of old ones. We hope that this project will provide the background, environment, and stimuli to enable meaningful decision-making within the envelope of increasingly limited resources that are available world-wide and that these decisions will provide true benefits to all humankind.

1.2 Strategic Framework

From the mission statement, we focused our attention towards defining a strategy for future solar exploration: the Strategic Framework. Discussed in detail in chapter 2, the Strategic Framework outlines a plan for solar exploration based on missions that may be accomplished during three specific periods: in the near-term (present to 1999), in the mid-term (2000-2010), and in the far-term (2010 and beyond).

Our approach for developing this framework consisted of various steps. First, we researched possible objectives that would satisfy current scientific and application needs. We then compared these objectives to those of various solar missions that have flown in the past, that are currently flying or that are planned for the future. The resulting objectives formed the basis for new solar missions, which were then evaluated in light of the political, budgetary, and technological challenges that they may face in the near-, mid-, and far-term. The result is a comprehensive program for science and applications that could be used as the starting point for making decisions about future solar exploration missions.

1.3 Report Organisation

Our report reflects the importance of the Strategic Framework we present. The eleven chapters in this report could be grouped into three parts that support this framework: the political and economical environment that sets the stage for the framework; the issues that define the need for the framework and mould it; and a description of the missions that constitute the framework itself.

<u>Political and Economic Environment</u>

In this section, consisting mainly of chapter 3, we present a broad picture of the political and economical environment that affect most of the decisions currently made about solar exploration projects. We provide the reader with concrete examples illustrating the concepts presented and examine lessons learned from these case studies. We explore the rationale for achieving international co-operation through solar science and applications, study models for this co-operation and propose a new organisation, the Working Group

for International Space Exploration and Applications (WG ISEA) responsible for overseeing this co-operation and establishing a data dissemination structure.

Issues that Shape the Strategic Framework

The chapters in this section [chapters 4, 5, 6, and 7] provide a background, rationale and issues that mould the Strategic Framework. First, we present a description of solar science as we view it today. The Sun is presented not only in a scientific context but also in a historic and societal context that should provide a general view of the Sun to the reader. After the foundation has been set, we describe the scientific and applications objectives that drive the need for solar exploration. In this description we discuss past and present needs from a broad perspective. Applications objectives are presented not only in light of the threats posed by the Sun, but also in the opportunities that the Sun may present for potential technological advances. Once these science and applications objectives are identified, we present the technological and economic issues that constrain these objectives and that influenced our decisions on shaping the framework. We discuss challenges, and how these challenges may be overcome.

Strategic Framework Missions

Chapters 8, 9, and 10 of the report discuss the missions that make up the structure of our Strategic Framework. These missions are grouped based on chronological distribution: near-term missions, mid-term missions, and far-term missions. They are categorised based on the use of existing technology and capability, as well as on their availability. Assembled together, these missions constitute a complete plan for solar exploration that spans several decades of scientific investigation and opportunities for applications.

1.4 Organisational Diagram

The interaction between the three sections described above is represented in figure 1.1 and at the beginning of each subsequent chapter. The figure provides an overview of the entire report and helps to place each chapter within the context of the Strategic Framework. As we go through each chapter, that chapter will be highlighted in grey.

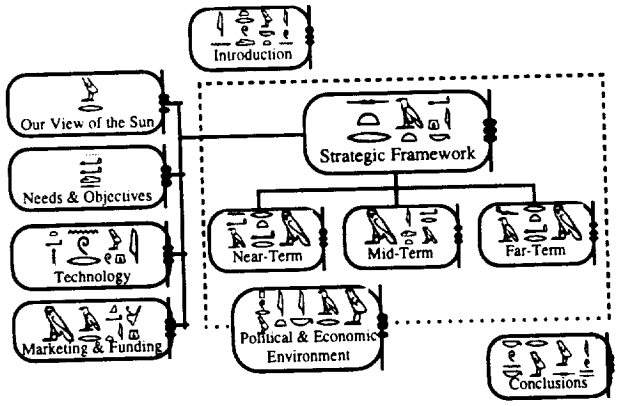
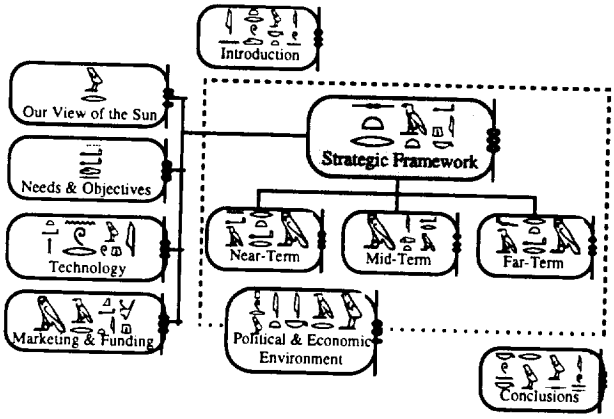


Fig. 1.1 **Report Overview Diagram: The Heiroglyphes were found using the URL of Laurent Wacrenier "Nom en hiÇroglyphes", http://yoko.ens-cachan.fr:8080/hiero, accessed August 1996**

Chapter 2



The Ra Strategic Framework

As mentioned in the Introduction, one of our goals in this report is to "develop a Strategic Framework for solar science and applications, and from that a programme for Near-Term, Mid-Term, Far-Term Missions". This Strategic Framework provides an integrated approach to solar exploration and application, as illustrated in figure 2.1. Three time frames are defined as:

1. Near-Term: Focuses on programmes that are achievable within the next few years (1996 to 2000). Elements tap into current capabilities and programmes; they also seek to improve management and co-operative structures in preparation for the future.
2. Mid-Term: Focuses on more ambitious programmes, some requiring technology development, with implementation times in the first decade of the next century (2001 to 2010).
3. Far-Term: Focuses on the period from approximately 2011 to 2020 and beyond, and is characterised by high-risk, advanced technology, and/or integrated programmes.

In this chapter, we present the Ra Strategic Framework: its programme elements, the logic behind its development, and special implications. We developed the Strategic Framework by consulting science and application experts; developing and assessing objectives; examining instruments and technical capability; considering policy and business concerns; and conceiving and assessing scenarios. Our approach is illustrated in figure 2.2. A similar analysis is being conducted by NASA's Office of Space Science: the Sun-Earth Connection (SEC) Roadmap [Sun-Earth Connection Roadmap, WWW]. Unlike the SEC Roadmap, the Ra Strategic Framework is international and less concerned with recommending specific programmes than with focusing the direction of exploration and

applications (the former is beyond the scope of the report). Also, we avoided investigating the Earth's magnetosphere—this area is too complex for an adequate investigation given our schedule.

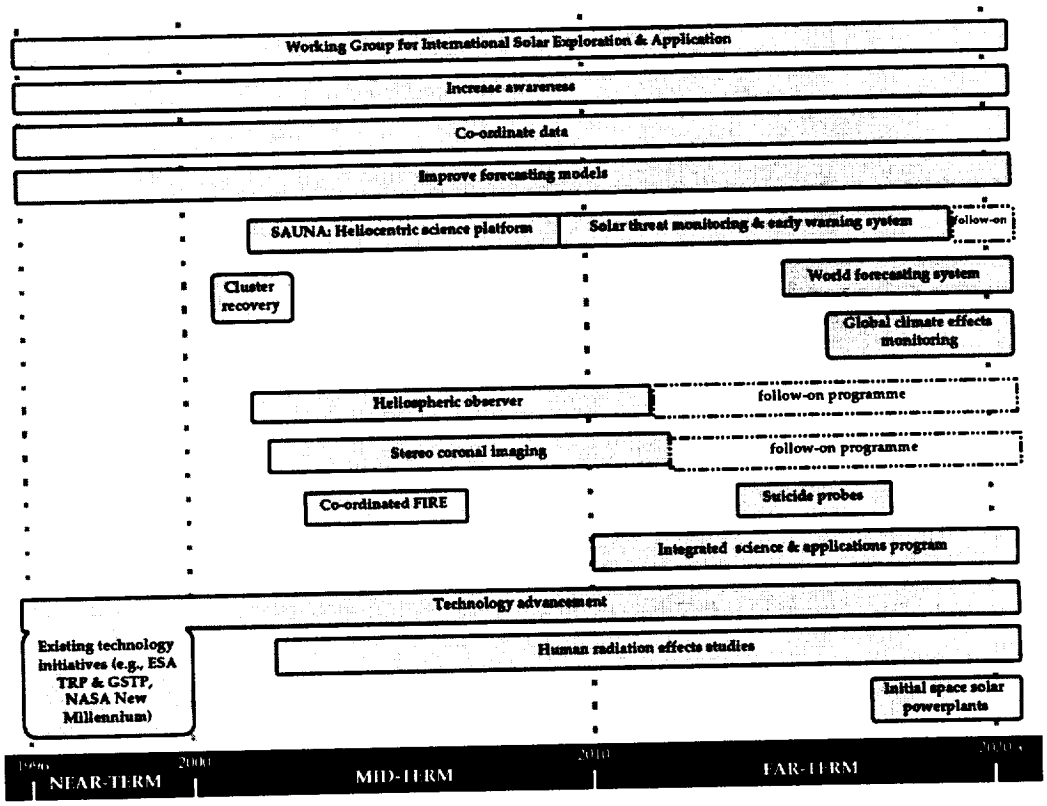


Fig. 2.1 **Strategic Framework Overview. Section 2-1 and tables 2.1, 2.2, and 2.3 provide more detailed descriptions of these programme elements, as do chapters 8, 9, and 10.**

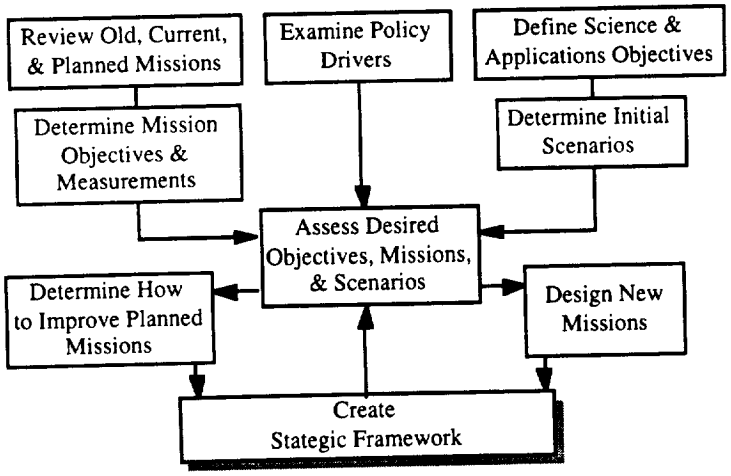


Fig. 2.2 **Strategic Framework development process.**

2.1 Overview of Programme Elements

In this section we present and discuss the programme elements of the Ra Strategic Framework. A more detailed description of the individual elements is found in chapters 8, 9, and 10.

Table 2.1 Near-Term Programme (1996 to 2000).

Programme	Objectives	Description	Rationale
Cluster recovery	Complement to SOHO and ground-based observations	A replacement for the Cluster programme and direct new Cluster mission toward Ra's objective	Utilise all of the existing work done for the original Cluster toward what Ra team believes to be the most pressing concerns
Improve forecasting models	Improve space environment forecasting	Perform correlation studies; innovative acquisition of new forecasting models	Current operational forecasting models are old and empirical; better models will save degradation and replacement cost
Co-ordinate science and other data	Make use of all past and current data	Continue ground-based observations; create an international data centre; research with and co-ordinate science data; co-ordinate future planning of independent groups	Other research communities may be interested in solar data, easier data access provides more time for actual research
Working Group for International Solar Exploration and Application (WG ISEA)	An international forum for the planning, co-ordination, and implementation of an international effort in solar exploration and applications	Incorporates science and applications interests from government and private sectors; submits to government agencies specific recommendations for actions necessary for the fulfilment of the solar exploration and application strategic plan, while encouraging independent complementary efforts	Changing global paradigm for space science and applications points to the advisability of combining resources across both national boundaries and science vs. applications disciplines. We believe WG ISEA is the most efficient and expedient organisational forum to enable this merger
Increase awareness of solar science and Sun-Earth interaction	Increase awareness among: general public, space community, power companies	Develop a "common language" for solar science and applications; work with planetariums and museums; educators via WWW; correlation study on satellite anomalies, ground power station anomalies and solar activity	Maintaining funding will require a basic public understanding; science, as a "public good", should be shared; establishing a correlation between space weather and satellite anomalies will motivate further investigation/ interest
Actively incorporate existing technology initiatives	Continue with efficient technology development	Examples include: Japan Nereus, ESA TRP (esp. Theme 10) and GSTP, NASA New Millennium, University Small Sat, Clementine, DC-XA, Commercial bus	Matches post Cold War era trends; logical progression into the future

2.1.1 Near-Term Programme

The elements of the Near-Term Programme, presented in table 2.1, are primarily political and managerial in scope, in keeping with the near-term philosophy of building on existing capabilities. Central to this programme is the creation of a "Working Group for International Solar Exploration and Application" (WG ISEA). We envision the WG ISEA as a forum for co-ordinating and planning the many solar missions that individual nations have proposed for the next decade while preserving their independent sources of support. As discussed in chapter 5, these missions currently tend to be rather random. Other parts of the programme may not be as ambitious but can have profound

implications: the sharing of science data, for example, may produce synergistic results and lead to better solar environment forecasting models. Overall, the Near-Term Programme lays a foundation for the projects of the later parts of the Strategic Framework.

Table 2.2. Mid-Term Programme (2001 to 2010).

Programme	Objectives	Description	Rationale
SAUNA: a heliocentric, near-Sun science platform	High resolution coronal and surface imaging; *in situ* solar wind measurements; technology demonstrator	Ion-propelled single spacecraft to 0.2 AU heliocentric orbit. 5 yr. mission duration	Affordable ($200M) science mission and demonstrator of survivability near Sun; precursor to heliocentric constellations
Solar threat monitoring and early warning system	Measure position, velocity of southward interplanetary magnetic fields	Heliocentric orbiters; Other options included: L4/L5 tripwire and solar wind event imaging and tracking	Initial dedicated space environment system; selected option most compliant with identified potential customers
Stereoscopic corona imaging system	Magneto-hydrodynamics of corona	Small remote sensing platforms at L1, L4 and L5	First stereoscopic mission-low cost but high return-opening the third dimension
New heliospheric observing platform	Helioseismology, solar atmospheric and coronal studies, solar wind monitoring	Extended SOHO mission, then smaller follow-on	Maintenance of long-term observation and monitoring
Co-ordinated FIRE Mission: Russian Plamya & U.S. Solar Probe	Heating of the corona and acceleration of solar wind	Dual spacecraft close flyby mission to 4 R_s and 10 R_s	Low-cost close flyby mission with finely targeted objectives
Human radiation studies on host spacecraft	Determine radiation risks for humans in interplanetary space and requirements for protection	Tissue-equivalent dosimeter measuring direct radiation and secondary radiation from shielding	Essential precursor for human Mars exploration or lunar base; could be a show-stopper

2.1.2 Mid-Term Programme

The elements of the Mid-Term Programme are presented in table 2.2. We propose several missions in this time period. A stereoscopic solar imaging system is envisioned to fulfil the high priority science objective of understanding the corona, as is a heliocentric near-Sun science platform (which we have named "SAUNA"). The corona will also be probed by a combined Russian-U.S. FIRE mission. These missions will be supported by a new global heliospheric observation system (possibly one of the stereo observation platforms), since SOHO may have expired by the time it is needed to support FIRE and other missions [Randolph, 1996]. More significantly, we envision a continuously-operating solar threat monitoring and early warning system, possibly involving near-Sun platforms that build on the technology demonstrated by SAUNA. This system will mark the beginnings of a solar application system, an idea central to Ra. Finally, we hope that humanity will be taking serious steps to the establishment of human lunar outposts or Mars exploration; in which case, study of solar radiation's effects on humans will be essential to the design of these missions. In summary, the Mid-Term Programme elements represent a maturing of solar science and the beginnings of solar applications.

Table 2.3 Far-Term Programme (2011 to 2020 and Beyond).

Programme	Objectives	Description	Rationale
Integrated solar science and applications programme	Reduce costs by co-operation in areas of common interest and by exploiting free opportunities	Options: science "piggybacking" on applications; application prototype sensors on science platforms; use of common buses	Solar science and applications have common elements; an integrated programme spreads risk and provides synergistic benefits
Small suicide probes	Explore acceleration and heating of corona by direct sensing	Wide range of concepts available	Understanding of coronal physics is of high scientific value
World-wide space environment forecasting system	Enhance the benefits of space environment forecasting for humankind	Characteristics include: distributed, provides information to developing nations, integrates military, civil, commercial data; independently maintained in participating nations	Political, social and commercial interests ultimately converge in the maximum availability of early warning systems
Preliminary space solar power applications	Explore ways to solve the imminent global energy crisis	Prototype space-based solar power station for small-scale distributed use	Solar power represents a "next generation" application
Monitoring the Sun's effect on Earth's climate	Understand the impact of variations in the solar output on the Earth's climate	Long-term space-based observation programme to monitor solar output and Earth's climate	Co-ordinated programme allows long-term data to be gathered so that potential correlations can be uncovered

2.1.3 Far-Term Programme

The elements of the Far-Term Programme look toward the more distant future. Building on the foundations created earlier — better forecasting models, data co-ordination, increased solar awareness, and the WG ISEA (whose international activities have continued and expanded in importance) — we envision an integrated programme for space science *and* applications. This programme may have combined platforms, or it may share common resources (such as spacecraft bus designs or a communication system to relay data from a new generation of solar probes). Also, the space threat monitoring and early warning system begun earlier should be mature enough by this time to create a global forecasting system, one that also provides benefit to developing nations. Furthermore, applications will begin to focus on solar benefits: the beginnings of space solar power plants. Finally, as we look back on years of integrated data, we see these data (combined with new long-term missions) enabling scientists to study the Sun's influence on Earth's climate.

2.2 Factors Considered in Developing the Strategic Framework

We considered several factors while formulating the Strategic Framework. Among those highlighted below are: policy drivers (political and economic); science objectives; applications objectives; past, current, and planned missions; technology; programme element inter-relationships; orbital vs. flyby missions; and our vision for the future.

2.2.1 Policy Drivers

The Strategic Framework is shaped by political and economic factors that transcend the scientific objectives, applications needs, and technological opportunities for solar observation. In this section we delineate these factors, including an overview of the impact these "policy drivers" have had on the Strategic Framework. Further information on the politico-economic environment can be found in chapter 3.

2.2.1.1 Post Cold War Environment

The principal policy driver for the Strategic Framework is the evolving Post Cold War environment for space activities. This environment possesses inherent benefits and drawbacks. For example, it provides opportunities for scientific co-ordination between former adversaries on solar missions like FIRE (see Mid-Term Strategic Framework) while depriving space activities of their former national security rationales and funding levels, which limits Strategic Framework recommendations in the near-term. Many of the policy drivers listed below will refer to the Post Cold War environment as their definitive paradigm.

2.2.1.2 Convergence of International Technology Levels

Less than two decades ago, the technological capabilities of the Soviet Union and the United States easily outstripped those of the other spacefaring nations. Today, the gap between the technology pools of the former superpowers and those of the other spacefaring nations has drastically narrowed. Although this shortening gap fosters national and commercial competition in space technology development, it also promotes success when international co-operation in solar observation missions is undertaken. On a level technological playing field, partners are able to offer more resources and benefits to each other, and the costs of international co-operation are reduced through the common technical literacy of the partners. International co-operation is also no longer primarily limited to scientific data co-ordination. Converging international technology levels make co-operation in spacecraft and mission engineering more likely, and the Strategic Framework takes advantage of this by emphasising the need to include engineers in an international solar working group. The Strategic Framework also takes advantage of converging technology by setting an objective for the engineers in this international solar working group: the production of common, spacecraft system designs to serve as world-wide baseline reference models to make solar observation missions more affordable.

2.2.1.3 Global Nature of Solar Threats

Dangerous solar phenomena and their interaction with the near Earth space environment and the Earth's upper atmosphere and magnetic fields transcend national boundaries. Although the damage to specific human resources may be nationally local, rarely is the damage from a solar incident limited to one nation's resources. The rising world-wide technology pool (described in section 2.2.1.2) and the increasing number of spacefaring nations (described in section 2.2.1.5) put more and larger human resources at the mercy of solar phenomena. Understanding these phenomena requires data from nations around the world. Though international scientific and solar forecasting organisations do exist to ensure that this data is exchanged and disseminated, the improvement of current solar forecasting models and solar warning systems would benefit more from international co-operation and co-ordination at the level of space hardware. The Strategic Framework favours organisational and technical solutions to space warning and forecasting that go beyond mere data sharing.

2.2.1.4 Flat or Declining Space Agency Budgets Among Developed Countries

Without Cold War rationales for space activities, space agencies throughout the developed world have found their budgets levelling out or declining with time. Solar research, already a low priority in many space agencies, will suffer if actions are not taken to counteract its budget priority and its available resources. Declining space agency funds require missions that fit within small budgets, require various solar science disciplines to prioritise their objectives with one voice, and require solar observers and forecasters to multiply their resources by going outside their agencies and nations. The

Strategic Framework highlights spacecraft with low budget ceilings, a means for organising solar science and applications disciplines internationally, and solar data acquisition and modelling resources outside national space agencies in the academic, commercial and military spheres.

2.2.1.5 Emerging Space Capabilities in Developing Countries

The developing world is becoming more reliant on space activity to create the communications infrastructure needed for prosperity and to monitor the externalities associated with economic growth. While these fragile capabilities are essential for continued development, developing countries may lack the resources, both material and technical, to effectively protect their nascent space and terrestrial technology systems from dangerous solar phenomena. Integration of the developing world's needs in solar warning and forecasting organisations necessitates international co-operation in the Strategic Framework.

2.2.1.6 Increasing Co-operation Between National Agencies

Co-operation in solar observation and forecasting among national space agencies, weather agencies, science and technology development agencies, and militaries is required by the flat or declining budgets each is being subjected to in the Post Cold War environment. Previous budgets allowed these national actors to duplicate early solar observation and forecasting capabilities. New budgets drive them to co-operate to preserve old capabilities and necessitate co-operation to create new ones. The Strategic Framework points out opportunities to share data, human resources, hardware, and costs at the national level to further solar science, warning and forecasting.

2.2.1.7 Interdependence of Solar Science and Space Warning and Forecasting Applications

Expanding basic knowledge about the Sun and its interaction with the Earth's magnetosphere and atmosphere will be crucial to refining solar forecasting models. Sensors used to perform basic solar research will also find applications in solar warning systems. The Strategic Framework has attempted to expand, rather than narrow, the links between solar science and solar warning and forecasting.

2.2.1.8 Trend Towards Interdisciplinary Science Missions

Because solar science is a low budget priority for most space agencies, the Strategic Framework has sought out opportunities for solar observation wherever they may be found. These opportunities include missions that piggyback solar sensors on other spacecraft and missions that use hardware developed for other uses to perform solar observation for science or forecasting.

2.2.1.9 Emergence of Smallsat Technology

Smaller, faster, cheaper concepts have driven missions in the Strategic Framework to consider current smallsats for new solar observation missions in the near- and mid-term and to design high technology, low mass, standardised smallsats for mid- and far-term missions. Constellations and commonality are two important concepts that drove Ra mission selection.

2.2.2 Science Objectives and Priorities

The Strategic Framework concentrates on the high priority science objectives identified in chapter 5 [section 5.1] and summarised in table 2.4 below. These objectives concentrate

on the corona, solar wind, and the Sun's influence on Earth's climate. Accomplishment of these objectives requires long duration observations from appropriate vantage points. Hence, our emphasis on stereoscopic observations, global solar observation, heliocentric orbital platforms, and occasional solar probes. These efforts must be co-ordinated to achieve maximum benefit: co-ordination of missions and of the resulting data.

Table 2.4 Primary Science Objectives.

Primary Objective	Investigation Areas
To understand the physical processes leading the Sun to emit plasma structures and high energy particles that are potential threats to humans and technology.	• Heating mechanism of the corona • Formation of coronal holes • Emergence of the slow solar wind • Relationship of fast solar wind to coronal holes • Causes of and underlying physical principles of solar flares • Causes of the acceleration of particles to very high energies • Release of coronal mass ejections (CME's) • Propagation of CME's in the interplanetary medium
To understand the physical processes which may lead the Sun to influence our climate.	• Cause of changes to the solar constant • Long-term variations in the solar constant • Influence of variations in the solar constant on Earth's climate

2.2.3 Applications Objectives and Priorities

Given the applications objectives discussed in chapter 5 [section 5.2], we focused our priorities on one application: solar threat monitoring and early warning. Such an application is in its infancy, and a mature market does not exist. Therefore, the creation of a viable market is a primary concern in developing the Strategic Framework. Since funding is also limited, existing resources must be maximised: as sources of data and as a means to improve forecasting models. By laying a solid foundation in the Near-Term Programme and by taking realistic steps in establishing initial capabilities, we believe a viable, self-sustaining system will follow.

2.2.4 Past, Current, and Planned Missions

In developing the Strategic Framework, we also examined past, current, and planned solar missions [see chapter 5, section 5.3]. Several conclusions resulted from this comparative analysis :

- There is no global co-ordinated plan for solar exploration, although there is some activity, such as the International Solar-Terrestrial Program (ISTP);
- A solar applications programme is lacking; and
- Study of the corona is a hot topic: it was studied by eleven out of twenty past and current missions (since 1962), and seven out of the eleven planned missions plan to collect more data. The high priority given to coronal study as a science objective means that continued observation from different spatial, spectral, and/or temporal perspectives is necessary.

2.2.5 Role of Technology

Solar missions benefit from advanced technology in three ways:

1. Spacecraft can be made smaller and more effective, thereby reducing costs ("Smallsats" were previously discussed in Section 2.2.1.9); and
2. Innovative thermal protection technology can help protect close-to-the-Sun missions (e.g., 0.4 AU) which face a harsh environment (e.g., temperatures, communication interference) ; and
3. Mission hardware requires high Δv's to get into their proper orbits.

Thus, the use of advanced, "leading edge" technology is advocated in the Strategic Framework and is reflected in the designs of individual programme elements. In the Near-Term, technologies from efforts such as ESA's Technology Research Programme (TRP) (in particular Theme 10) and General Support Technology Programme (GSTP), NASA's New Millennium, and the U.S. Clementine programme should be exploited. Projects requiring very advanced technologies, however, should be placed in the Far-Term Programme of the Strategic Framework, allowing time for these technologies to mature and risk to become reasonable. In short, we should expect only "one miracle at a time" [Worden, 1996]. Otherwise, delays and cost overruns will result, endangering not only that particular project but possibly other elements of the Strategic Framework.

2.2.6 Programme Element Inter-relationships

The Strategic Framework is programme in time. Not only did we divide it into three consecutive periods: near, mid, and far-term. We also desired that individual programme elements followed a logical progression (see figure 2.1 at the beginning of this chapter). The inter-relations between programme elements are further illustrated in figure 2.3 below. This figure also illustrates that some programmes are complementary: FIRE, for example, requires a heliospheric observer (like SOHO) for instrument calibration and a global solar reference [Randolph, 1996].

2.2.7 Orbital vs. Flyby Missions

Achieving our science objectives requires long-term observation. Hence, the Strategic Framework favours heliocentric orbital missions over short duration flybys. However, sometimes critical data cannot be gained without directly sensing the phenomenon of interest. Therefore, the Strategic Framework still needs to consider probes. In the Strategic Framework, the "suicide probes" following FIRE are placed in the Far-Term Programme — after we received the results from FIRE and heliocentric missions, when technology may better support near-Sun probes (e.g., thermal protection and communications improvements), and when a science/application heliocentric system may support these probes (e.g., acting as a communications relay or as a "piggy-back mother ship" to reduce costs).

2.2.8 A Vision for the Future

The Ra Strategic Framework is a focused path to the future. In developing that path, we asked ourselves where we wanted it to lead. Common responses included "integrated," "global," and "the next step." The Far-Term Programme allowed us to formalise these ideas which ranged from an integrated science and application programme and a programme that benefits all regions and aspects of the globe (e.g., developing countries and understanding global climatic change) to the beginnings of using the Sun as a resource (e.g., space solar power stations). Some of these elements are not very visionary;

policy trends discussed earlier do point to an integrated programme and more global awareness. Yet implementing these ideas requires a persistent international vision and will — one that may be realised through a step-wise, logical plan.

		Cluster recovery	Forecasting models	Co-ordinated data	WG ISEA	Increase awareness	Incorp. tech initiatives	SAUNA	Solar early warning sys.	Stereo coronal imaging	Heliosphereic observer	Co-ordinated FIRE	Human radiation effects	Integ. science & apps pgm	Suicide probes	World forecasting system	Prelim. space solar power	Global climate effects
Near-Term	Cluster recovery																	
	Forecasting models	F																
	Co-ordinated data	F	C															
	WG ISEA			C														
	Increase awareness				C													
	Incorporate tech inititaves	C																
Mid-Term	SAUNA				C		C											
	Solar early warning sys.		F	F	C		C	F										
	Stereo coronal imaging																	
	Heliosphereic observer							C										
	Co-ordinated FIRE				C						C							
	Human radiation effects		F	F	C			C	C	C	C							
Far-Term	Integ. science & apps pgm		F	F	C				F									
	Suicide probes				C							F						
	World forecasting system		F	F	C	F			F									
	Prelim. space solar power				C	F	C											
	Global climate effects		F	F		F			F	F	F			F	F	F		
		Near-Term						Mid-Term						Far-Term				

This is a...
F=Follow-on
C=Companion
...to

Fig. 2.3 **Strategic Framework Inter-relations Matrix. The matrix shows how a programme in a row is related to one in a corresponding column.**

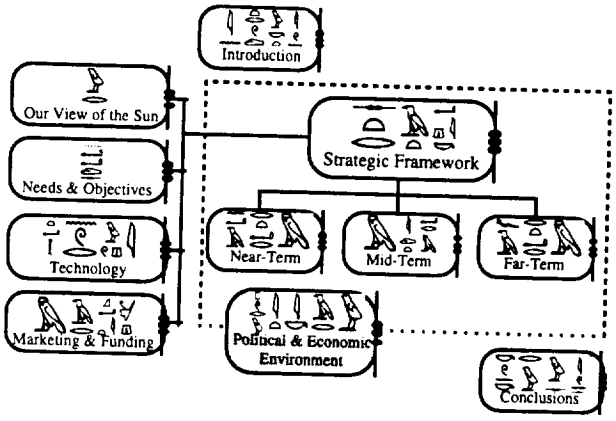
2.3 Implications

We believe the Ra Strategic Framework is significant because it:

- Is a coherent plan over time;
- Relies on existing and planned programmes and benefits from them;
- Considers the political and economic environment, including future trends, and seeks to shape that environment for the benefit of solar science and application;
- Integrates solar science and applications, showing how one benefits the other;
- Is an international framework that capitalises on global talents and resources; and
- Seeks to provide global benefits.

Additional study is required for specific programmatic decisions. We hope, however, that the Ra Strategic Framework will have a positive influence on increasing our understanding of the Sun and its effects, helping to apply that knowledge for the benefit of humanity.

[C1][C2]Chapter 3



Political & Economic Environment

The political and economic environment is a powerful force shaping the nature and form of space activities. In Chapter 2, we overviewed some primary policy considerations that drove the general direction and configuration of the Ra Strategic Framework. This chapter will explore these issues in more depth and add considerations of policy topics deemed important for the success of the Ra Strategic Framework. We begin the chapter by setting the stage for international cooperation with an analysis of past and existing examples of cooperation in space. We continue to build on that foundation with a recommendation for the structure of an international cooperative forum for solar and heliospheric science and applications, the Working Group on International Solar Exploration and Application. Particular issues concerning the successful implementation of international data dissemination structures are then assessed as they relate to the Ra Strategic Framework.

Through cooperative associations like the Working Group, knowledge about solar processes and their influence on the space environment is increased and this knowledge has practical applications in space environment forecasts, forecasts that can help governments and industries mitigate or even prevent damage to terrestrial and space resources from dangerous solar phenomena. Although an array of agency, national and international resources exists to aid the pursuit of a viable solar warning and forecast service, space "weather" forecasting exists at an infantile state of development, requiring the measured marshalling of information and hardware resources to improve the accuracy of solar warnings. We review and critique current and future organizational models for consolidating and increasing the capabilities of solar warning and forecast service resources. Drawing recommendations from this analysis, we then present a new organizational synthesis, the Inter-agency/International Interface ("Triple I") Model for future solar warning and forecasting organizations. Chapter 3 concludes with a consideration of Russian contributions and participation in international solar forecasting organisations and a review of international and national contracting arrangements.

The ideas and issues addressed in chapter 3 create a textual structure that enables the reader to more readily appreciate the environment that shaped the Ra Strategic Framework and this report's remaining chapters.

3.1 Setting the Stage for International Co-operation: Criteria and Modelling

In order to establish an effective international framework for solar and heliospheric science and applications, it is important to first define the environment within which the framework must function, and then describe some means by which the framework can maximise its chances of survival and success in such an environment. With these considerations in mind, the Ra team has evaluated six examples of international co-operation in space activities, and drawn upon these examples for lessons we can learn and apply to our formulations for Ra. The following criteria and project analyses, then, provide us with a foundation upon which the Ra team can build an international co-operative framework for solar exploration and applications.

3.1.1 Criteria for Solar Science Co-operative Frameworks

International co-operation in space has taken on many forms since the Soviet Union first launched Sputnik on October 4, 1957. It is difficult to speak of success in many cases, however, without first defining what success means. Success for a scientist is the return of useful data; for an engineer it is a fully operational spacecraft; and for politicians success is often defined less tangibly in terms such as technology transfer, political influence, and economic return. All definitions of success are both valid and vital, for their mutual achievement is essential to maintain overarching support for a project or programme. However, the varied faces of success are often problematic because in many cases conflict can occur if the goals of the partners (at all levels) are not at least compatible, if not complementary. The attainment of the overall "success" of an international project can very often be judged as a product (at least partially) of the political and managerial frameworks under which the endeavour functioned. The purpose of this section is to define both constraints which *must* be met if an international co-ordinating framework for Ra is to have *some* chance at fulfilling its mission, and some "optimisation means" that may give the framework a *better* chance of doing so.

3.1.1.1 Constraints

Political and managerial frameworks inherently function within a certain set of constraints. Most obviously, these constraints are restrictions imposed by the overall legal and political structure of the involved nations. For instance, when NASA engages in a co-operative venture, the Memorandum of Understanding signed between the parties (if there is any) always includes a clause similar to, "subject to the availability of funds". This is due to the political structure of the United States, which precludes NASA from obligating Congress to appropriate funds. However, structural constraints such as this are unavoidable, and the space activities of nations alone are not likely to precipitate fundamental alterations of the national political frameworks involved. The political and legal structures under which space activities take place transcend beyond individual sectors (such as space), and thus respond rather inflexibly to the needs of national space activities alone.

Taking this into consideration, it is helpful to have some working definitions of the most pressing constraints within which any international organisational framework for Ra must function.

Identifiable, Sustainable Rationale — Without an easily recognisable reason for co-operating to which the involved agencies can point, support for the effort will waver. This reason must be universally understandable, although it may consist of multiple factors, so long as they are believable and consistent. Successful co-operation allows all parties involved to meet their own set of objectives; many times these objectives are distinct yet compatible. Further, these rationales must be both clearly stated in relatively simple terms and well-communicated to the national communities involved.

Sufficient Domestic Political Will — Even when rationales are firmly defined, there is no guarantee that they will resonate well enough with the public and appropriations bodies to guarantee funding. Thus the rationale must fit within established national goals to maximise the compatibility of the co-operative effort with domestic political agendas.

Cohesive Scientific Community Support — Competition between scientists in relatively closely related specialities has proven to undermine the capability of those scientific communities to effectively influence the national funding mechanisms in their favour. Cohesion in the science community is essential, then, to build long-term domestic political will for particular space science projects such as those outlined in Ra.

Identifiable Funding Sources — The necessity of funding international co-operative projects seems obvious, but it is the issue of funding which threatens international efforts most often. Upon entering into a co-operative framework, minimum sources of funding from all parties need to be identified and marked as firmly as national political constraints allow. It is helpful if funds for co-operative projects can be identified under previously approved programmes in order to minimise their vulnerability in the funding process.

Economic Return — No matter how attractive Ra's scientific and application potential or friendly its international framework is, countries will only substantially contribute if it serves their national interest. With this in mind, science and application will probably not sell the programme on their own, but job provision and/or technology acquisition will be much better incentives to join Ra. Therefore it may be necessary in some cases to implement some "juste retour" policy to guarantee each participant of identified, tangible, short-term and politically sellable benefits.

This issue has already been addressed on national or continental scale. For example in Europe, governments allocate money to ESA, which redistributes it as contracts to private companies. Financially speaking, this makes a match between a country's contribution to ESA and the contracts it gets back, and is therefore referred to as "juste retour" policy. On the contrary, when the United States participates in an international programme, transfers of funds are avoided as much as possible (the International Space Station being a notable exception). An innovative economic return policy could thus harmonise the different attitudes currently adopted throughout the world, and try to maximise global political satisfaction.

Open Communications Infrastructure — Clear and established means of communication between the co-operating parties are essential. Such means need not be extremely formal (indeed, the models show us that the best communication is often informal), but they must be distinguishable and active. This mandate goes for all levels of co-operative projects, from the scientists through to the engineers, mission planners, and managers engaged in the effort.

3.1.1.2 Optimisation Means

Once these constraints have been fulfilled, thus enabling the viability of the project, there remain some parameters that will help maximise its likelihood of success. Being aware of some past programme difficulties due to inappropriate political environments [Section 3.1.2.1], we will take special care in the establishment of an international framework within which Ra is to be achieved.

Emphasis on an International Co-operative Nature — The benefits brought by international co-operation have several origins.

The first one has already been mentioned and is economic: given the limited and often decreasing financial resources available for space activities throughout the world, the only way we can meet Ra's ambitious scientific and application objectives is to share the resultant cost among several countries.

The second benefit is both technological and scientific: the more participants, the more equipment technologies, analyses capabilities, and knowledge in solar physics are available. This means that in the end there will be greater scientific progress, and tangible end products and benefits with all the associated risk sharing.

The third is political: if the prime rationale for Ra remains science and its applications, we consider that the political improvements in international relations it can bring is part of the success criteria. A successful co-operation within Ra would be beneficial, since it would strengthen relations among numerous countries, among which some hardly communicate with each other in a recent past, and hopefully colour these relations with friendship. In the era of globalisation, we want Ra to help efforts toward global peace. Also, Ra's political and managerial success would be beneficial in being an example and a model for further co-operation in other areas such as medical research, environment protection, or industrial development.

Appropriate Use of Existing Assets — In some crucial areas, the background level of expertise requisite for the success of Ra is still fragile. For instance, from the scientific stand-point, solar science is relatively young, and from the political and managerial one, this particular type of co-operative effort has never been attempted. Therefore, we need to use the assets available world-wide as much as possible.

The practical consequences of this are twofold. First, it means optimising all the national resources: scientific, technological, human, financial, legal, political, and geographic. We expect a lot of trade-offs among these different resources, for example technological, financial and political, and consider them unavoidable. Nevertheless, the overall optimisation is certainly one of the parameters that will determine Ra's success.

Secondly, it means building Ra's international framework preferably based on current models. International bodies require a long time before having enough proficiency and recognition to be effective, and the newly formed are sometimes received suspiciously. They can be represented as heavy objects moving in a viscous medium: momentum is their prime quality and we more easily change their direction than set them in motion. Therefore precedent can be a valuable tool when establishing Ra's international framework.

Minimum Complexity — The more complex a mechanism, the more likely the dysfunctional modes. This is well known for engineering designs, and it also holds true for management structures, where dysfunctioning means for instance making bad or no decisions, wasting time and money, and favouring inter-personal clashes. Therefore, we

first need to avoid any extra layer of bureaucracy in the decision making process, just as an architect hunts for sophisticated non-necessary devices, and secondly to keep sound overall success oriented priorities while allocating tasks.

Also in this domain, trade-offs — if not incompatibilities — among national expectations, optimisation of resources and global efficiency will be unavoidable; but here is also one of the challenges Ra is willing to address: building an efficient, yet mindful of all, international co-operative framework.

Minimum Vulnerability — The strength of a chain is no more than that of the weakest link, which means that vulnerability has to be assessed for each participating country, agency and even company, and at every level: political, financial, technological, scientific, human, etc. We will not address in detail each of the latter in this section, but rather emphasise that Ra's framework would be better chosen keeping the following questions in the background of considerations:

- Are the participants likely to have a long term local political and financial support?
- Is there a way to increase this likelihood (if necessary)?
- In case of withdrawal, what back-up solution can be implemented, how fast and at what cost?

A good example of the kind of decisions political vulnerability considerations can drive has been described in sections 2.2.9 "Emergence of Smallsat Technology" and 6.11.5 "Future Opportunities", which deals with the spacecraft configuration choice. We advise a fleet of small, almost identical spacecraft, each of them being entrusted to a country or agency as far as design and integration are concerned, with a possible constraint to use a commonly designed bus. We thus:

- facilitate national or agency approvals.
- facilitate the overall management.
- reduce unwanted technology transfer.
- make a "reasonable" use of inter-dependence.
- reduce the consequences of withdrawal.

We consider that these factors will contribute to a more favourable and stable political and managerial framework.

3.1.2 Developing a Model for International Solar Exploration and Applications

Co-operation in space is by no means a new phenomenon. Spacefaring nations have engaged in co-operative activity since the inception of spaceflight; indeed, the first satellites were launched as part of an international collaborative effort known as the International Geophysical Year. The purpose of this section is to provide an overview of some available examples of international co-operation in space, and to draw upon the lessons learned from these examples, both positive and problematic, in developing a model for international co-operation in solar exploration and applications. We have used the categorisation of positive and problematic here for the purpose of simplification and ease of reading. However, we do not intend to imply that it is a matter of taking past experiences all or nothing into consideration for Ra. No single model can be said to fully contain all the good or bad experiences from which we can draw. Later in this report, we

will recommend exactly how these lessons can provide the foundation upon which we can build an international co-operative framework to fully implement Ra's strategic plan.

3.1.2.1 Problematic Examples

Europa — The Europa launcher provides us with a good example of a programme that failed mostly for managerial and organisational reasons. It is good to keep it in mind while trying to set up an appropriate international framework for Ra, so that we do not repeat the same destructive mistakes [de Dalmau, 1996].

European co-operation in space dates back in 1960, when the United Kingdom was searching for international co-operation to support its "Blue Streak" endeavour. It was soon followed by the signature of the European Launcher Development Organisation (referred to as ELDO) convention by governments of UK, France, Germany, Italy, the Netherlands, Belgium and Australia, in 1962.

ELDO was to develop the three stage-launcher Europa, whose breakdown method consisted in chopping the rocket up into almost autonomous parts, then entrusted to the participating governments. UK would provide the first stage, France the second, Germany the third, Italy would take care of the payload, Belgium the tracking, the Netherlands the telemetry, and launches would take place from Australia (later from French Guiana).

The programme had to face three series of difficulties:

- Economic first, beginning in 1964, when the cost estimates doubled and later quadrupled.
- Political then, from 1966 to 1971, with the withdrawal of UK from the programme.
- Finally technical, as of 1967, with a number of failures.

Europa did not manage to survive them and the programme was cancelled in 1972, without any payload delivered into orbit.

The lessons learned from this sad story can be summarised in the main factors that led to the failure:

1. From the beginning, a political top-down approach was mostly carried out: there was no prime contractor, governments kept financial and decision power on what was done nationally, ELDO had very limited authority. For example, ministerial conferences had to be organised for every important decision.
2. No initial mission, clear responsibilities, rights and management method had been defined.
3. The political motivations were very different from one country to another: UK wanted to prove that it was a reliable partner to join the European Community, France was seeking access to British technology.
4. The levels of development of rocket technology were also quite different.
5. All lacked experience in such a multi-national project.

In conclusion, the whole project failed due to inappropriate initial institutional decisions and lack of experience. It is also worth noting that the lessons learned from it have helped in the success of the subsequent European launcher: Ariane.

International Solar Polar Mission (Ulysses) — The National Aeronautics and Space Administration and the European Space Agency signed a Memorandum of Understanding (MOU) in 1978 to co-operate on an International Solar Polar Mission (ISPM). The agreement was for each agency to build a single spacecraft for solar exploration. The European probe was to fly by the Sun's North pole, while the American craft was to fly over the Sun's South pole in a co-ordinated, simultaneous trajectory. Both spacecraft were to be launched on the same Shuttle flight, and the United States would provide the nuclear power source for the ESA spacecraft, as well as the spacecraft support in flight through the Deep Space Network (DSN). The intended launch was 1983 [Johnson-Freese, 1990].

The sequence of events that subsequently transpired with respect to the American contribution to the ISPM is now widely acknowledged as a painful, but valuable, learning experience for the European Space Agency.

The ISPM was one of five new start requests in NASA's budget for Fiscal Year (FY) 1979. The mind set was premised on an expanding NASA budget in the out years to accommodate the maturation of all programmes. However, President Ronald Reagan's Administration planned a series of domestic civilian spending cuts in its first term in office. These plans led to a domino effect that, when coupled with increasing Space Shuttle development costs, ultimately led NASA to cancel the construction of the American ISPM spacecraft. It was the manner in which the matter was handled, however, that places the ISPM here as a problematic example of international space science co-operation. [1]

NASA exhibited a surprising (to Europe, that is) ***lack of political will*** when it came to defending the ISPM. In 1981 European Space Agency (ESA) Director-General, Erik Quirstgaard, was notified of the NASA intention to cancel its ISPM spacecraft only a few hours prior to the Reagan Administration's announcement of budget cutbacks. The amended FY 1982 U.S. Federal Budget allowed for only US$584 million for space science, as opposed to the previously intended amount of $757 million. This large budget cutback was the impetus upon which NASA predicated the necessity of cutting the funds for an entire spacecraft outright. While NASA was admittedly beset by a variety of constraints which arguably made the spacecraft cancellation a necessity, the attitude which NASA relayed about the position that American actions put ESA in was not a very sincerely sympathetic one.[2] The fact that NASA's withdrawal jeopardised the European investment in ISPM went almost unacknowledged. The lack of consultation by NASA with ESA prior to the decision was the primary cause of ESA's tension. The decision taken was a ***unilateral*** one, without any real consideration given to alternatives raised by ESA. In short, while ESA thought it understood the precarious nature of the American budget process, it at least felt it could count on NASA to fight for what it had committed itself to in an MoU. When NASA failed to do so, ESA was left not only with a single ISPM spacecraft, but a bitter uncertainty about America's reliability as a partner in space efforts [Johnson-Freese, 1990].

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[1] NASA did intend to continue to support its contributions to the European spacecraft, including the radio-isotope thermal generator, the American experiments, the use of the DSN, and the launch aboard the Shuttle, although the last committment would have to be delayed until 1986.

[2] For a concise, but detailed political history of the cancellation of the U.S. ISPM spacecraft, see Johnson-Freese, 1990.

In summary, the ISPM is a problematic example of an international co-operative effort because it:

1. allowed the withdrawal of one partner to jeopardise the entire mission.
2. was premised on an incomplete understanding of obligations and interests.
3. lacked clear lines of communication.
4. had generated insubstantial domestic political support and will.
5. involved extremely substantial sums of money, and therefore consisted of large portions of the involved agencies' science budgets (related to 4).

International Space Station — As an ongoing project, the International Space Station (ISS) is a well known example of international co-operation. While ISS has been successful so far in co-ordinating the efforts of all partners involved (The United States, Russia, ESA, Japan, and Canada), its turbulent history has some valuable lessons of which Ra is taking note.

Begun in 1984 after U.S. President Ronald Reagan invited the American "friends and allies" to participate in the development and operations of an orbiting space station, what is now known as ISS has undergone numerous redesigns and adjustments for a variety of reasons. Several "descoping" redesigns due to American budget constraints were only the beginning of an extended space station history that always seemed to have an uncertain future and a delay in development. In addition, the space station project has repeated many of the same mistakes made during the ISPM. The high political visibility of the space station, however, has given it its own set of advantages and disadvantages as an international co-operative effort.

Space station has seen the same American propensity for unilateral decision making as experienced under the ISPM. When the Russians were brought into the collaborative effort, it was done so without consultation with the European, Japanese, and Canadian partners in the venture. The deal was presented fait accompli once NASA had issued the invitation to Russia.

While the invitation to Russia highlighted an undesirable American decision-making methodology, it did provide the U.S. political system with a more sustainable rationale for the ISS. Since Russia joined the project, domestic American political support for ISS has wavered little. When President Reagan called for a space station with allied participants in 1984, the initiative was an artefact of the Cold War between the East and West. Upon the dissolution of the Soviet Union, space station supporters attempted to transfer its justification to science. In a time of diminishing U.S. budgets for space, however, the American space science community fractured and support for space station was not forthcoming. Bringing the Russians in provided an overarching political rationale, stabilising station's political support. By engaging the Russian space community in station work, the U.S. had a powerful incentive with which to persuade Russia to comply with agreements such as the Missile Technology Control Regime, a political objective much more central to American domestic and foreign policy than an orbital station for science. Conversely, while the marriage between Space Station Freedom and Mir II (to form ISS) had the effect of bolstering political support in the United States for the project, in Europe it served to emphasise the unilateral mind set of the Americans toward the endeavour, effectively endangering European political will for the effort.

The decision-making mechanism of the American space complex notwithstanding, the sheer size of ISS (and associated costs), coupled with its origins, has made it exceptionally

vulnerable to domestic political considerations. One year before inviting the Russians in, the station survived a vote for cancellation in the U.S. House of Representatives by a single vote. One year later, after Russia joined the programme (and provided the aforementioned rationale), the station survived a similar motion by a margin nearing one hundred votes. In Europe, ESA's commitment to ISS was not finalised until the October, 1995 ESA Ministerial meeting, the outcome of which, just a couple of months earlier, had not been assured. Even more recently, budget constraints made Canada seriously consider withdrawing from the ISS; only after extensive consultations with NASA did Canada commit itself to building the ISS remote manipulator arm.[3] Only in Japan has the commitment to ISS never wavered, despite the budgetary and political fluctuations in the other partner nations.

What lessons can Ra learn from the experience of the International Space Station? The most pertinent can be summarised as follows:

1. Political attention to projects is proportional to their size. The higher the interest, the more likely that the project is subject to changing domestic political winds. Meanwhile, positive aspects of this attention can be high level political support, but changing domestic political environments can endanger this. Additionally, the higher the political interest, the more likely it becomes that "micro-management" by political figures and/or bodies hinders the project.
2. There must be a sustaining rationale for any space project.
3. International co-operation can be a sustaining rationale (especially concerning Russia at this point in time).
4. Internal, cohesive scientific community support is essential to domestic political will (if rationale is closely tied to scientific return).
5. Unilateral decision making harms partner trust and alters perceptions of reliability.

Additionally, ISS has re-emphasised the lessons learned from ISPM. There is considerable danger involved in projects where the withdrawal of one partner can jeopardise the entire effort and investment of the partner nations. Open communications is essential to good will between partners, and may help alleviate tensions, especially when dealing with the American budgetary process.

It should be noted that what has *not* remained the same between ISS and ISPM is the political will on the part of NASA as an agency with regards to the project. Contrary to ESA's experience with ISPM, at the highest levels of NASA ISS has always been top priority. Regardless of the internal reasons for this, it is a precedent for international co-operation that should be emulated.

3.1.2.2 Positive Examples

Committee for Earth Observing Satellites (CEOS) — Founded in 1984 on the recommendation of the Economic Summit of Industrialised Nations (G-7), CEOS is an inter-governmental, inter-agency committee intended to serve as the focus of international Earth observation co-ordination. The committee now has a small budget for a secretariat, but there is no permanent staff. In this manner the involved nations keep an informal structure, avoiding a more rigid and bureaucratic organisational form [U.S.

[3] Originally, Canada was to contribute the arm plus the "hand." Under the new arrangement, NASA will buy the "hand" and Canada will sustain its committment to provide the robotic arm.

Congress, Office of Technology Assessment, 1993].[4] Agency representatives meet to discuss current and future Earth observation systems and their related issues such as data dissemination and compatibility. Representatives then bring back to their home organisations information on world plans for Earth remote sensing.

While CEOS itself has no decision-making powers, the information exchange that it enables, coupled with its forum for policy and engineering issues, has resulted in effective world-wide Earth observation co-ordination. CEOS recommendations are taken seriously in the member agencies, and where possible (the most usual restriction being funds), follow-through has been clearly evident.

In summary, CEOS is a positive example of an international co-operative framework because it:

1. minimises complexity;
2. possesses high domestic political will (it sprung from high political levels — very good for sustainable support);
3. Is based on an internationally recognised immediate need;
4. has a clear, definable rationale;
5. has enabled nations to contribute to the international Earth observation programme in a flexible, independent manner;
6. maintains an informal organisational structure that empowers national agencies instead of divesting them of power, thereby generating bureaucratic incentive for the agencies to follow CEOS recommendations.

Inter-Agency Consultative Group for Space Science (IACG) — The Inter-Agency Consultative Group has been, arguably, the most successful example of international space science co-operation of the space era. Begun in 1981 on the primary initiatives of Roald Sagdeev, Director of the Soviet Space Research Institute, and E.A. Trendelenburg, ESA Director of Scientific Programmes, the IACG membership consisted of NASA, ESA, ISAS, and IKI (USSR) [Johnson-Freese, 1990]. Its purpose was to co-ordinate the numerous Halley's comet flyby missions in 1986. NASA was the only agency involved that did not have a dedicated Halley's comet spacecraft, but it did contribute substantially by tracking the crafts with the DSN. The co-ordination consisted of arranging complementary trajectories, instrumentation, and rapid data evaluation and turn around. The organisational structure proved so successful that the ad-hoc IACG became a permanent organisation in 1985 with the purpose to,

> "maximise opportunities for multi-lateral scientific co-ordination among approved space science missions in areas of mutual interest. The IACG is a multi-agency international forum in which space science activities are discussed on an informal basis among representatives of member agencies" [Johnson Freese, 1990].

In the terms of reference it is specifically stated that the IACG does not have a formal planning role for future missions, nor is it intended to supplant bilateral co-operative efforts. In fact, many of the IACG's "Core Missions" are bilateral efforts that operate as well within the IACG framework [IACG, WWW].

The IACG's second project has been the co-ordination of the International Solar Terrestrial Physics Programme (ISTP). Begun in 1986, the Cluster satellite constellation

[4] Member agencies are: CNES (France), CSA (Canada), CSIRO (Australia), DARA (Germany), ESA and Eumetsat (Europe), INPE (Brazil), ISRO (India), STA (Japan), NASA and NOAA (U.S.A.), and the Swedish National Space Board (Sweden) [U.S. Congress, Office of Technology Assessment 1993].

was to mark the final ISTP core mission launch. Currently, the IACG is working on choosing its third project, the first steps for which will most likely be taken in the December, 1996 meeting [Huber, 1996].

The IACG has three ongoing working groups:

- Science working group (WG 1): Approximately three scientists from each member agency participate. This group works to define co-ordinated science objectives;
- Data exchange working group (WG 2): Co-ordinates the data needs of WG 1 and has established an IACG Science Information System. Membership consists of involved agency and community scientists;
- Mission design and planning working group (WG 3): The planning that this group does is co-ordinating trajectory changes, etc. to maximise the science return for WG 1., *not* any *future* mission planning [IACG, WWW].

Additionally, the IACG forms ad-hoc panels to study areas of space science that would be suitable for future multi-lateral co-ordination efforts. Currently, there are three panels:

- Very Long Base Interferometry (Panel 1)
- Planetary and Primitive Bodies (Panel 2)
- High Energy Astrophysics (Panel 3) [IACG, WWW].

It is interesting to note that although the IACG does not have mission planning powers, its current and prior projects have benefited from a degree of international joint planning. The first project, Halley's comet, was a unique event that generated widespread scientific interest, and because of its relatively long-period, the 1986 flyby was viewed as a unique opportunity to study a comet. The second project, ISTP, was predated by a significant amount of joint space science planning on the parts of NASA and ESA [Johnson-Freese, 1992]. This joint planning led to other partners being pulled in through bilateral agreements (such as ISAS and IKI). Thus the existence of complementary missions on the agendas of national space agencies was not coincidence. While the IACG does not have a future mission planning function, its projects have been shaped by joint planning prior to the engagement of the IACG co-ordination role.

The IACG has survived and successfully co-ordinated international space science return because it:

1. has limited itself to a single project at a time;
2. keeps itself small at the decision-making level. Around 1990, when the involved ISTP missions began to number more than twenty, the IACG began to exhibit the bureaucratic inefficiency typical of a large multi-lateral organisation. There was co-ordinated movement among the longer-standing IACG scientists to get the group back to the small, informal structure that it had under the Halley's comet phase. The move has consolidated internal IACG support and helped it to more clearly define its ISTP objectives;
3. does not have a functional allocation role, and is therefore not a threatening body to the organisational existence of the member agencies;
4. is a grass roots organisation with cohesive support among the space science community.

International Mars Exploration Working Group (IMEWG) — Put together in 1993, the International Mars Exploration Working Group has the mandate to:

- "Produce an international strategy for the exploration of Mars *beyond the currently approved missions* (emphasis added)."
- Provide a forum for the co-ordination of future Mars exploration missions.
- Examine the possibilities for an International Mars Network Mission as the next step beyond the 1996 launch opportunity ["Together", 1994].[5]

Agency representatives meet every six months to discuss co-ordination issues of planned missions. In 1994 the working group submitted to the Committee on Space Research (COSPAR) a strategic plan for Mars Exploration with international participants. At the same time they also published their findings as to an International Mars Network Mission. The former findings have resonated more fully with national space agency objectives than the network mission. The network might involve ceding some decision making power to a central body (such as a multi-national scientific committee), something that the national space agencies are not yet prepared to do.

The IMEWG seems to have a mixed record of success. While it has fulfilled its mandate, its relative programmatic influence is debatable; the network mission has received little serious mission consideration. On the other hand, the working group is a useful forum for the exchange of Mars plans, allowing interested parties to come together in more discrete co-operative ventures. Furthermore, it does form a venue for the co-ordination of current and planned missions, allowing agencies to both avoid unnecessary duplication and increase their relative scientific return from individual missions.

The IMEWG was caught in an unfortunate situation; its submission of findings came during a period of decreasing national space budgets (with the notable exception of Japan). Accordingly, agencies with diminishing budgets approach new mission proposals warily, and if the mission involves the concession of decision making power (something that the shrinking budget is already draining) then the organisational incentive to pursue that option is minimal. Conversely, during times of increasing funds, the concession of decision making power over a portion of the budget (that grows smaller, not larger, with time) is less threatening to the agency as an institution.

The limited success of the IMEWG can be attributed to:

1. a clear, definable rationale. While "Mars exploration" is vague in scientific terms, it points definitively to spacecraft on and around Mars and is something to which the public can easily relate;
2. its versatility. The continued existence of the IMEWG is not tied to a specific mission, but to a long term goal. Therefore setbacks, such as mission cancellations or payload descopings, do not lead to the dissolution of the working group, allowing its advocacy of Mars exploration to continue;
2. its established communications infrastructure;
3. an informal, grass-roots nature.

[5] Member agencies of the IMEWG are: ASA (Austria), ASI (Italy), BNSC (U.K.), CNES (France), CSA (Canada), DARA (Germany), ESA (Europe), IKI (Russia), ISAS (Japan), NASA (U.S.A.) ["Together 1994"].

Conversely, the international space exploration community was not ready to concede decision making power in order to make an International Mars Network Mission a reality. It is reasonable to assume, then, that in the intervening two years, as funds have become even more restricted for national space endeavours, that the situation remains the same. Any international framework for solar exploration and applications must keep this lesson in mind.

3.1.2.3 Summary of Lessons Learned

The lessons learned from past and current examples of international collaboration in space activities served the Ra team as valuable guides in the creation of an international co-operative framework for solar exploration and applications. While the presentation of individual examples above summarised the lessons extracted from each project, it is useful to reiterate here the most important conclusions the Ra team has drawn from this analysis.

- Political, scientific, and technological objectives of the partners need not be identical, but they must be compatible.
- Partners must possess a mutual understanding of all parties' obligations and interests.
- Clear and open communications structures are essential.
- An identifiable, sustainable rationale is integral to generating the requisite domestic political will for international co-operation.
- Internal, cohesive scientific community support is a prerequisite to generating domestic political will if the sustaining rationale for the project rests heavily on scientific objectives.
- Flexible and versatile contribution structures enhance the viability of international co-operative efforts by minimising their vulnerability to programmatic alterations and political whims.
- The withdrawal of a single partner from the effort should not structurally cripple the entire effort.
- Low-cost missions/spacecraft increase a projects chances of acceptance at both the national and international level.
- Unilateral decision making is to be avoided as a barrier to building trust between partner nations.
- Advisory international bodies are more acceptable to national bodies than those with functional allocation roles.
- An internationally recognised, immediate need is a good basis for international collaboration.

3.2 The Working Group on International Solar Exploration and Applications (WG ISEA)

A successful international framework should allow that the programmatic means by which the objectives are achieved be *flexible*. We have seen the benefits of this within both the IACG and the IMEWG. Particular mission cancellations/failures do not jeopardise the entire return of the venture. This philosophy coincides very well with today's move toward smaller spacecraft and more focused mission by mission objectives. The flexible framework permits large, multi-lateral collaboration efforts while allowing nations to autonomously build their individual spacecraft (or form their own bi-lateral agreements for crafts). This is a particular concern when we consider the domestic political

implications of transferring industrial opportunities outside the nation because of international co-operation; it is a politically volatile issue at best. Small, discrete craft bring less attention from domestic economic interests and are more easily defended against charges of "job exportation." In turn, small craft lead us naturally to multi-lateral, flexible co-ordination and planning mechanisms, such as that proposed here under the name, the "Working Group on International Solar Exploration and Applications," or WG ISEA.

This section will overview the WG ISEA purpose, representation, and structure. In conclusion, we will evaluate how the WG ISEA meets the constraints on international frameworks as outlined in Section 3.1.1.1 and the optimisation means of Section 3.1.1.2. Implicit in our formation of the WG ISEA and its structural evaluation is an awareness of the lessons learned from our review of international space co-operation models.

3.2.1 Purpose

The WG ISEA should serve as a forum for economical and innovative solar and heliospheric mission planning, co-ordination, and implementation. In this endeavour, the WG ISEA should take into full consideration the specific information needs of both the space science and space applications communities [Section 5.1 and 5.2]. To do this, the WG ISEA should have three functions:

- Strategic Framework planning for national and international solar and heliospheric science and applications initiatives (the findings for which should be submitted to the agencies involved)[6],
- Current and planned mission co-ordination,
- Reference model design for standardised spacecraft bus configuration (cost driver).

3.2.2 Representation

To best fulfil its purpose, membership in the WG ISEA should not be limited to the exploration agencies alone. Here we have detailed a three-tier representation system which includes Members, Adjunct Members, and Advisors. Full membership should include any national or multi-national agency which contributes either:

- a primary spacecraft for the programmes we involved in the Strategic Framework,
- a significant portion of a primary spacecraft, defined here as forty percent,
- an equivalent capability such as deep space tracking.

The space science community has seen these criteria successfully used to designate full membership in the IACG. However, the WG ISEA goes beyond the IACG in that it is open to any organisation that contributes, not just space science and exploration agencies. Some potential applications-oriented members include NASDA, NOAA, and USAF. Chairs and other important offices would rotate between these first-tier members.

[6] Applications initiatives fall within the venue of the WG ISEA insofar as they are information-gathering and/or developmental in nature. Once a system goes operational, then responsibility for its coordination, etc. would naturally be moved beyond the WG ISEA framework. See section 3.4 on models for solar warning and forecasting organizations.

The second tier of members (adjunct members) include those bodies which contribute either hardware for mission spacecraft, principal and co-investigators, or adjunct ground support or observations. Potential members here are national space science and applications agencies, solar observatories, and universities.

In addition, advisory status should also extend to:

- national space applications advisory and implementation bodies (CSW, NSWC),
- international space applications working groups and services (ISES),
- spacecraft manufacturers (including university small satellite programmes),
- current and potential private users of space environment warning and forecasting systems,
- potential industrial interests in financing an eventual private space environment warning/forecasting system.

With respect to the international and national advisory bodies and services, there is likely to be significant overlap in membership, since international representatives are usually persons involved in national efforts.

Obviously, there is a danger of having too many participants creating disparate objectives and conflicting methodologies, thereby failing to minimise complexity. In order to better manage this risk, we have proposed a three tier membership (Members, Adjunct Members, and Advisors) to better delineate the structure. The Ra team believes, however, that the integration of basic and applied science (seeking knowledge for knowledge's sake vs. seeking knowledge for a pre-designated end) requires the active involvement of the applications community in the planning process. Thus, membership must extend beyond the traditional national space research and development agencies.

Members are distinguished from adjunct members in the WG ISEA by both their contribution and by the allocation of decision-making powers within the group. Advisors are those groups whose expertise and input to the process are valuable, both to the working group and to the advisors themselves; they participate on the invitation of the majority of Members. More detail will be given on this structure in the following section.

3.2.3 Structure

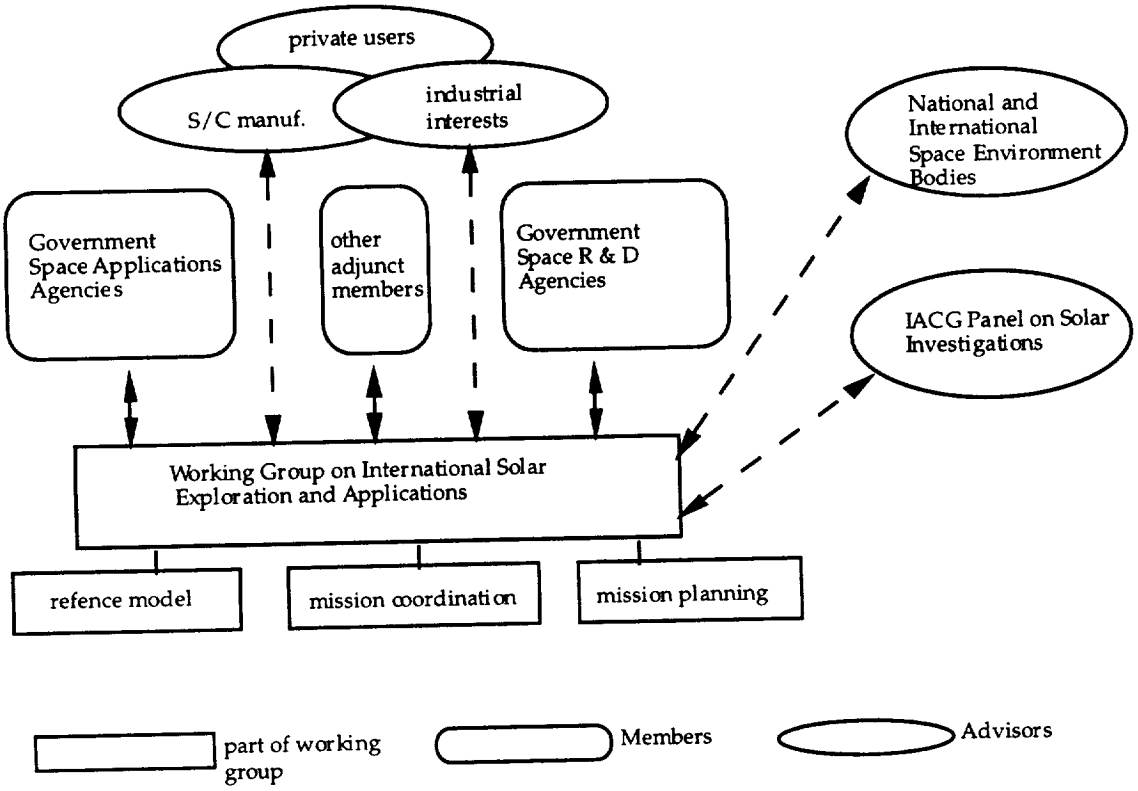


Fig. 3.1 **Organigram of the Working Group on International Solar Exploration and Applications.**

In figure 3.1 solid lines represent direct or adjunct membership status in the working group. Dashed lines represent advisory and consultative relationships. Dr. Martin Huber of ESA will ask the IACG to form a Panel on solar investigations this December at the 1996 IACG Plenary session [Huber, 1996]. If this is approved, interaction between the Panel and the WG ISEA should help delineate scientific objectives and areas of consensus. This relationship is likely to be informal, as the same scientific community involved on the IACG Panel will also be key to the WG ISEA. However, it is important to note the advisory relationship because the responsibilities of the WG ISEA extend beyond basic science, and thus decisions will incorporate views that transcend IACG considerations.

We would like to note here that the IACG is *not* an appropriate vehicle to co-ordinate solar exploration and applications for a variety of reasons.

- Advance planning of future missions is necessary. Currently, agencies do not have solar missions budgeted.
- Integration with the applications community is advisable; therefore membership should include applications agencies to best incorporate their needs.
- Work on a standard reference model spacecraft bus could not take place within the current IACG framework.
- The nature of the IACG, a very successful organisation as it is, would be permanently altered by an expansion to include the above groups.

Instead, the Ra team has decided to model the WG ISEA as what could be described as a synthesis of what we needed from the structures of both the IACG and the International Mars Exploration Working Group. Additionally, the WG ISEA has some innovative features such as applications-oriented memberships and the reference model sub-working group that should enhance its capability to fulfil its objectives. By keeping the planning and co-ordination at the working group level, bureaucratic inefficiencies are minimised as much as possible. Additionally, the working group structure provides a flexible mechanism through which outside expertise can more easily be accessed, a particularly necessary capability when considering private sector participation.

3.2.3.1 Standardisation Design & Consultation Group

This support working group is the forum for the creation of a standard international reference model spacecraft bus for inner solar system exploration. A considerable cost driver in small, discrete missions is the design of the spacecraft. Like robotic planetary missions, solar exploration and observation lends itself well to international co-ordination because the effort can be accomplished with many small, relatively low-cost platforms [U.S. Crest, 1993]. In an international solar and heliospheric exploration initiative, nations can save money while still building their own, discrete craft because the objectives of each craft are limited and the basic bus design standardised. This support group will bring the most direct involvement of the private sector spacecraft manufacturers in the WG ISEA. The interaction of science, applications, and the private sector will ensure the appropriateness of the design to the purpose of the WG ISEA, as well as its economic feasibility. This support working group should take into full consideration the recommendations and opportunities outlined in Section 6.11 of Ra on spacecraft modularity and standardisation.

3.2.3.2 Implementation and Co-ordination

This support working group is responsible for mission co-ordination, data dissemination issues, and operational considerations. Its role is to support the solar and heliospheric missions that have been approved in the member agencies, maximising the complementary data return to the fullest possible extent. This group should also co-ordinate mission data with Earth-based complementary data sets and historical observations of interest to the science and applications communities.

3.2.3.3 Strategic Framework Mission Planning Group

The Strategic Framework and Mission Planning Group evaluates and recommends the Strategic Framework and its constituent missions to the member agencies. This goes beyond what a panel on the IACG may do. This group is responsible for developing the Strategic Framework (which we recommend closely mirrors the framework outlined in Ra) that both integrates and looks beyond currently planned and/or studied missions in the member agencies. This includes both science and applications missions of the member agencies, as well as integrated efforts (science and applications instrumentation on the same craft where it is technically feasible and scientifically appropriate). Additionally, the planning group has the task to incorporate the scientific priorities of the applications sector into the overall mission planning process. That is, the applications community has demonstrated particular information needs concerning basic solar science. Therefore, the prioritisation process for scientific missions should incorporate these information needs. It is in this manner that science and applications can most efficiently come together.

3.2.3.4 Funding Support

Although the WG ISEA does not develop or operate solar exploration and application missions directly, costs are associated with the meetings that the WG ISEA will hold and with the reference design projects the WG ISEA undertakes. It is suggested that funds for WG ISEA overhead and reference design projects come from first-tier members, perhaps with membership contingent on contributions to cover these minor costs.

3.2.4 Evaluation of the WG ISEA According to Our Constraints and Optimisation Means

The Ra team has attempted to fully incorporate the lessons learned from past co-operative experiences in order to build an organisation that best meets our criteria for a successful international framework, the WG ISEA. In this section we assess the WG ISEA against our original criteria in order to assure that the working group may function successfully within the current environment and resources for international co-operation in solar exploration and applications.

3.2.4.1 Constraints

Identifiable, Sustainable Rationale — The rationale of the WG ISEA, to "serve as a forum for economical and innovative solar and heliospheric mission planning and co-ordination," can be argued to be both clearly identifiable and yet imprecise. A rationale such as, "to land a man on the Moon before the turn of the decade," is much more definitive. However, the difference lies in whether the same rationale is *sustainable.* There may need to be a trade off between precision on the level of the working group's stated purpose, and sustainability. If the WG ISEA's goal were to implement "a" then "b" then "c" — in that order — then the project (and therefore the WG ISEA) would be unsustainable if funding for "a" was not available. The issue comes back to the ability of people outside the community to identify with the rationale of the working group and its efforts. In this respect, the WG ISEA is the facilitator of national interests, and the national interests of the involved parties will transmit their own, individual, yet *complementary* rationales to their publics.

Sufficient Domestic Political Will — To argue for science and long-term economic payback as the basis of domestic political will is tenuous at best. Rather, it is the economical and innovative nature of the WG ISEA's efforts that will form the backbone of domestic political support. Today's space participants have general domestic support for space programmes. The difficulty often comes when justifying the enormous expenditure of single projects. The WG ISEA and its efforts can generate domestic political will in two ways. First, the individual mission profiles should be kept relatively small such that they are not targets for budget cutters. Secondly, their economical and innovative approach to space activities should draw positive attention as a means to continue national efforts in space without the exorbitant price tag.

Cohesive Scientific Community Support — The WG ISEA should take into consideration both the solar and heliospheric scientific communities. Both specialities supply valuable knowledge for potential explanations and predictions of occurrences such as coronal mass ejections and solar flares. In doing this, the WG ISEA avoids the pitfall of splitting scientific community support when there is no substantive reason for doing so.

Identifiable Funding Sources — Some of the missions outlined in Ra have the potential to be included in currently funded space agency programmes. The NASA Discovery programme, for instance, could potentially include some of the small spacecraft missions included in Ra. In ESA, the Horizons 2000+ indicates its M4 mission simply as "Solar

System exploration." Additionally, the C5 Mercury mission has the potential to serve as a platform for some simple solar observation instruments [Scoon, 1996]. Overall, the programmatic scenario proposed by Ra starts small and builds in the long term. The key is to build international awareness, something that organising on an multi-lateral scale does very well. Moreover, the Ra report has intentionally limited mission scenario recommendations to generally small craft programmes. This enables the individual components of Ra to be included in agency budgets as either individual spacecraft missions or as a mission "group," such as ESA's Solar Terrestrial Science Programme.

Economic Return — This constraint is more difficult to deal with in the confines of the WG ISEA. Because the working group co-ordinates multi-laterally, and expends no money itself, any economic return is a nebulous concept. However, the involvement of the applications community has indirect economic implications. Reliable space environment forecasting is being pursued for a variety of rationales, a significant one of which is the cost to satellite operators and users every year due to solar event disturbances (some ground segments are also significantly affected by solar events [Section 4.5.3.2 and 4.5.3.3]). The potential economic return is very real, then.

Open Communications Infrastructure — The structure of the WG ISEA is conducive to good communications. With established meeting intervals, a horizontal organisation, and a grass-roots nature, the WG ISEA hopefully will mirror the communications success of the IACG and IMEWG.

3.2.4.2 Optimisation Means

Emphasise International Co-operation — While international co-operation is not *the* reason for the WG ISEA (the reason being the maximisation of return on global solar science and applications resources), the international co-operative nature, as we learned from the International Space Station model, is a political positive. However, the WG ISEA is programmatically flexible, unlike the ISS, and thus improves on the concept (similar to the IACG and the IMEWG).

Appropriate Use of Existing Assets — While the WG ISEA is a new organisation, it draws on the expertise that currently exists. The consultative functions of the potential IACG Panel, as well as the advisory roles of the national and international space environment bodies (such as the CSW and ISES) allow the WG ISEA to maximise its available body of knowledge while minimising the extension of its own resources. The primary reason that the WG ISEA intends to bring together both basic and applied scientists with spacecraft manufacturers, industrial interests, and private users is because the lessons learned from their respective experiences have yet to be maximised by bringing them all together in a single forum for solar and heliospheric investigations. The combination of perspectives has the potential to be a powerful tool for economical and innovative space activities.

Minimum Complexity — The flip side of bringing all these different experiences together is that the complexity level of the working group is increased. Admittedly, the WG ISEA is more complex than both the IACG and the IMEWG. CEOS, however, operates at a complexity level more consistent with the level that the WG ISEA will experience. As mentioned previously, we have attempted to minimise the impact of this complexity on the working group's efforts by creating a two-tiered membership system and avoiding hierarchical decision-making. Avoiding the pitfalls of bureaucratic inefficiency is a chief challenge faced by all multi-lateral frameworks. The structure we have given the WG ISEA here should aid them in this labour.

Minimum Vulnerability — In one way or another, all the above constraints and optimisation means all have a single goal in mind: to minimise vulnerability. Among

other things, the structure of the WG ISEA is not organisationally threatening to its participant agencies; it should create bureaucratic incentive for active involvement through its generation of domestic political will; it is programmatically flexible; individual investment risk is minimised with the discrete spacecraft approach; complexity has been minimised as much as possible; clear and open communications exist; and it makes appropriate use of existing resources and expertise. In all, the Ra team has attempted to insure the WG ISEA as fully as possible against domestic politics, individual mission difficulties, internal inefficiencies, and national funding constraints, to simply name a few.

3.2.5 Final Recommendations for the WG ISEA

In conclusion, the Ra team believes that the WG ISEA format is the most innovative and efficient mechanism to pursue international space efforts in solar exploration and applications.

The Ra report is uniquely timed to take advantage of current space science trends. While the IACG will most likely form a Panel on solar investigations in the coming year, NASA is planning to bring its Sun-Earth Connections Roadmap to the American space science community for assessment. That meeting is set for August, 1997 at Woods Hole [Sun-Earth Connections, WWW]. It would be very expedient if an international mechanism such as the WG ISEA could be in place before then. With such a vehicle established, the NASA Space Science strategic plan could more fully incorporate international opportunities and capabilities into its programmatic recommendations. Furthermore, for planning to be effective it must take place before the budgetary cycles for the target years are locked in. Therefore the medium-term scenarios that require an advance planning element need to be planned in the near future if they are to fly before the year 2010.

Additionally, the culmination of the International Solar Terrestrial Physics Programme provides a natural foundation upon which to build Ra's Strategic Framework. The near Sun and heliosphere environment is a natural extension of solar-terrestrial interactions. It is important, then, to have a timely formation of the WG ISEA to take full advantage of the current period in space science.

3.3 Data Dissemination Principles for the Ra Project

An efficient and workable scientific data sharing system is one of the most important issues for the successful operation of the Working Group on International Solar Exploration and Applications (WG ISEA), as described in Section 3.2. Within this group, a special support group is considered for data dissemination, mission co-ordination, and operational tasks [Section 3.2.3.2].

A data collection and dissemination system is characterised by a large amount of complex data from different missions and the various geographical locations of the data users.

In previous years, each solar system exploration mission had its own information distribution policy and structures. In 1981 the Inter-Agency Consultative Group for Space Science (IACG) was created to co-ordinate scientific research of the four space agencies to study Comet Halley [Section 3.1.2.2]. This Group now "provides the means for the optimally co-ordinated operations and a mechanism for data sharing and joint data analysis"[IACG, WWW].

For the newly developed WG ISEA, special information structures are needed as well as development of data acquisition, archiving, distribution and exchange principles. Four

models are examined for the WG ISEA. The principles of data dissemination for the Cluster project is an example of data organisation at the mission level. The International Solar Terrestrial Physics Programme (ISTP) and the IACG Science Information System building principles are compared as examples of data co-ordination of multiple missions. Despite the fact that the organisational structure of the IACG is not completely appropriate for the WG ISEA working scheme, its "Rules of the Road" for data exchange seem to be well developed and are also reviewed.

Data distribution issues have three aspects: economic, political and technical. Before establishing rules for data exchange it is necessary to create hardware structure and software for data receiving, processing and exchange.

3.3.1 Cluster Data Technical Details and Infrastructure

Forty four instruments from the four Cluster satellites were planned for data collection. The Cluster Science Data System (CSDS) was established for data management. This system has the following components:

- National Data Centres (six national centres were directly involved in the CSDS - Austrian, French, German, Scandinavian, UK, Hungarian, and two centres in the USA and China were registered via directly involved centres).
- Operations Control Centre
- Joint Science Operations Centre (JSOC)
- Ground-based programmes
- network infrastructure within the CSDS
- Cluster user interfaces

Each Data Centre processed the raw data from a specific set of experiments and makes it available via the network for the other Centres. The European Space Operations Centre (ESOC) (Darmstadt, Germany) was responsible for mission planning, data disposition and bulk distribution of the raw data. ESA provided infrastructure for data and information exchange within the CSDS and also for data ingestion by National Data Centres and data manipulation by scientific users.

The CSDS net interconnected the CSDS National DATA Centres, the JSOC and various ESA establishments. The principal CSDS net is based on the existing ESA infrastructure implemented as a self-contained logical system from an addressing, routing and security point of view. The net has been designed to provide a logical interconnection between local area networks (LAN) across a wide area network (WAN) infrastructure.

The CSDS user interface was developed on the base of the software available at the European Space Research Institute (ESRIN), ESA's establishment in Frascati, Italy. Under the overall responsibilities of the Cluster project, ESRIN has tailored the existing software to the specific Cluster requirements.

A Cluster-specific standard for data exchange based on the Common Data Format (CDF) was established.

A large community of users with varying levels of familiarity with data manipulation caused the need to have both a convenient user interface and a solid and reliable network infrastructure. Given the different configurations, existing at the various national Data Centres, two versions of the CSDS user interface were developed, one running on Solaris and the other Open Visual Machine System [Drigani, 1995].

3.3.2 Data Dissemination Policy Issues (Cluster, ISTP, IACG)

Policy issues at either mission level or intra-agency level should define common components: categories of the users, their rights to access the information, types of data, rules of distribution, periodicity of exchange, types of missions from which data are going to be analysed simultaneously, services suggested by national data centres, and time period after which whole data is released to the general public.

Categories of users:

Cluster — principal investigators (PI) and co-investigators (Co-I), general public.

ISTP — principal investigators, co-investigators, associates, students, guest investigators and general public.

IACG-IACG Community members — principal investigators and co-investigators; non-IACG scientists who received general approval from IACG; general public.

Established classification of the users defines their different rights to access the information. Usually the PI and Co-I have raw data or high resolution data access and can share information from the instruments for which they are responsible with anyone they choose but are not allowed to distribute another investigators data [Green, 1996].

ISTP and NASA have following data policy rules: NASA-funded missions and instruments have an open data policy; key parameter digital data will be non-proprietary and publicly available to identify possible scientifically interesting events or intervals (the key parameters are not intended for journal publication unless certified by the PI); all teams will contribute relevant digital process data for any special events or intervals that are selected for study by the Global Geospace Science (GGS) Team and for the IACG Campaigns in a timely and responsive fashion; during a validation period of up to three months after data acquisition, all use of data for scientific investigations must be approved by the PI whose data are being used; and higher level process instruments and theory data products, along with their associated documentation and all relevance software, will be publicly available immediately after validation [Data Policy for ISTP/NASA Funded Missions and Instruments homepage, ISTP, WWW].

The Cluster data distribution policy is as follows: data such as a summary of the parameter database and summary data plots have unrestricted access, however the prime parameter database has restricted access limited to the Cluster community only. The high resolution data will be handled by the Principal Investigators. The PIs will also respond to requests for the data from the user community. The CSDS infrastructure will probably be used to route the requests from the high resolution data.

The raw data would be distributed on a set of CD-ROMs to each participating institute (about 80 world wide) on a weekly basis to reduce network loading; the network will contain quick-look data. Data Centres are responsible for the registration of scientific users, assignment of data access rights and checking of these rights when they access the data. Not all the Data Centres will offer the same services on-line.

Specific IACG Information System Policy Issues:

During the 1990s, the IACG plans three scientific campaigns, each of which addresses a set of specific questions related to the solar-terrestrial environment. The scientific aim of the first IACG campaign is a multi-mission (Geotail, Interball, Wind) collaboration which greatly extends the interchange of data within the international research community. For

the first IACG campaign, special "Rules of the Road" were developed for different operations with data exchange from the spacecraft and ground-base facilities for identification of the obligations of researchers about data provided by other science research investigators. "Rules of the Road" consider mission rules, key parameter distribution, campaign rules, IACG membership, membership for the non-IACG mission scientists, sharing of data issues, data set preparations, authorship and public release of data. "Rules of Road" of the first IACG campaign are adopted now as rules for all campaigns. However, each campaign can develop its "special rules" that apply only at agreed upon campaign times [Green, 1996].

Mission rules — Key parameter data are generated by the IACG core missions and other ancillary data sources in a common format. During a campaign the key parameter data from "core missions" are freely exchanged and accessible to all principal investigators (PI) and co-investigators (Co-I). Key parameter data will be used for the multispacecraft event identification and are not publishable unless explicit certification is given by the appropriate instrument PI.

Campaign rules — "Rules of the road" govern access to and use of data contributed to the IACG first campaign database and data analysis. During campaigns, any data base can be created and included into the information system. "Rules of the road" are mandatory for all participants and those applying to participate. Even if the member withdraws from the IACG the campaign is obligated to continue to respect the rules established.

Sharing of key parameter data — Data are routinely exchanged between campaign members and used to support the identification of events. Members share high level campaign data products with members of their research team, but are not entitled to further distribute the campaign data provided by other investigators. Distribution of detailed instrument data is the responsibility of the instrument principal investigator.

Data set preparations — Location of databases is preferably in the centres such as NASA and ISAS. Access to the database and support software will be provided by individual members of the campaign.

Authorship — When an investigator's data is used in the analysis of an event, the investigator who provided these data should be kept informed of what they are being used for, should be invited at an early and appropriate time to participate in the correlative analysis and would normally have the option of being a co-author of any resulting publication or presentation, including abstracts.

Public release of data — Unrestricted access to a database will be granted at the conclusion of the campaign; usually the period between proprietary data and open data is typically 2 years. It is important to note the effect of NASA's new open data policy on the IACG "Rules of the Road." [Green, 1996] NASA no longer temporarily restricts data access to mission scientists whereas other space agencies still maintain restrictions for a certain time period to incentivize researcher involvement. Provisions in the IACG "Rules of the Road" were necessary for non-NASA IACG investigators to be given the opportunity to withdraw their data from the IACG first campaign database before NASA public release. [IACG homepage, IACG WWW].

The idea of restricted access has two side effects. From one side it allows the owners of the instruments to generate new scientific ideas. From another it makes the number of scientists who work with these data much smaller.

3.3.3 Principles of the Development for the Ra Data Systems

Data dissemination principles within the WG ISEA will take guide-lines from the data policy of the IACG Science Information system development.

One of the driving ideas behind the WG ISEA is to close the gap between pure science and applications. Classification of users is suggested to be more specific: basic scientists such as principal investigators and co-investigators, applied scientists, associates, students, guest investigators and private operators. Private operators are those who own, for example, satellite constellations and will be aware of the space weather. Private users are important for financial reasons. However, consideration of restricted access to the raw and high resolution data over a two year period is important.

In order to minimise costs, the Ra team suggests utilising for data purposes, system structures that have already been developed by different national agencies for solar science missions (structures for SOHO, Cluster, Interball, Geotail). Data processing application needs and distribution to the private users must be added to the main national data centres.

It is important to develop the following: formats for data exchange between different space agencies, types of data dissemination, categories of users, periodicity of data distribution, and a list of services provided by different centres.

In summary, the main significant features of the Ra user interface and infrastructure should be:

- minimum training needed to use it (user friendly)
- participation of interdisciplinary and various federal agencies
- international participation and data exchange
- free and open access for the general public to secondary data [Scoon, 1996].

3.4 Organising for Solar Warning and Forecasting

Increased understanding of solar processes and improved technologies for solar observation present the opportunity to mitigate or prevent damage to human activities and assets from dangerous solar phenomena, both in the space environment and on Earth. The creation of solar warning and forecasting services, however, relies on more than scientific and technical knowledge. It requires an efficient organisation that is appropriate to the service's resources, tasks, users and political environment. This section reviews and proposes criteria by which models for solar warning and forecasting organisations can be judged and introduces current and future models for these organisations. This sets the stage for the construction of a specific organisational model, the Inter-agency/International Interface ("Triple I") Model for modern solar warning and forecast services.

3.4.1 Basic Criteria for Examining Solar Warning and Forecasting Organisational Models

Sections 3.4.2 and 3.4.3 discuss current and future models for solar warning and forecasting organisations. Before examining these models in detail, it is important to set criteria to compare and contrast them. This section presents ten general criteria by which the nine models in sections 3.4.2 and 3.4.3 will be judged for solar warning and forecasting organisational recommendations in Section 3.5.

3.4.1.1 Adequate Development Funding and Stable Operations Funding

Arguably the single most important criterion for any solar warning and forecasting organisation is its ability to garner the initial funds needed to erect the infrastructure (satellites, ground instruments, tracking stations, data archives, data dissemination networks, etc.) for its solar warning and forecasting service. Some organisations, such as the U.S. Air Force, already have many of these elements in place and would need less in the way of infrastructure development than, say, a commercial solar warning and forecasting service. Likewise, some organisations may have more ready access to development funds than other organisations. This requisite may prove to be the most important criterion in coming decades for solar warning and forecasting organisations as improved services will be dependent on investment in technology, hardware and knowledge, especially the deployment of *in situ* instruments between the Earth and Sun and refinement of various operational space physics models.

After the erection of the service's infrastructure, any solar warning and forecasting organisation will require a long-term and stable source of funds for operations to ensure the continued existence of the service. Continued funding will also be important for infrastructure upgrades and replacements. Long-term funding will thus need to be flexible enough to accommodate cyclical highs and lows in equipment acquisition. Certain organisations, like NASA by its own admission with the Space Shuttle, may be unsuited to operations and reluctant to undertake such funding.

The source of these development and operations funds is also a major consideration for a solar warning and forecasting organisation because it determines to whom the organisation is primarily responsible. Civil government, military, commercial and international solar warning services all have different potential sources of funding that determine their prime users and political masters and thus the makeup of their services.

3.4.1.2 Take Advantage of Current Solar Warning and Forecasting Capabilities

Future solar warning and forecasting services, if rationally constructed, will take advantage of current solar warning and forecasting capabilities rather than rebuilding the necessary infrastructure and reconstructing the necessary knowledge base from the ground up. This criterion drives intra-governmental (agency level) solar warning organisations to co-operate with other solar warning organisations within the same government. It drives governments with solar warning capabilities to co-operate with each other as well.

The advantage of existing capabilities is an especially important criterion for commercial solar warning organisations. Without the withdrawal or metering of current government solar warning services, commercial organisations will find it extremely hard or even impossible to compete with what are "free" public solar warning services (although taxes obviously do support such services). Commercial solar warning organisations are more likely to find market niches or horizontal interfaces within the more comprehensive solar warning services that governments provide.

3.4.1.3 Simple Structure With Clear Functional Allocation

Because several different organisations currently provide solar warning services, future services may well be provided by conglomerates of today's organisations. It will be vitally important to these future services to clearly delineate different functions between their constituent organisations to avoid confusion, duplication and plays for power. This does not necessarily require a standing, overarching manager for the whole service but simply requires thoughtful planning in its organisation. The correct organisational

structure will be simple, clearly outline the functions of each element and grant each element autonomy in achieving its functions while co-ordinating with the other elements.

One important functional allocation decision will be the division of development (design, fabrication and launch of the space segment, for example) from operations (spacecraft monitoring and data acquisition). Another rational organisational division might also be set at the boundary between raw data acquisition versus data interpretation, phenomenon modelling, and warning and forecast dissemination. However, if *in situ* instruments are placed between the Earth and Sun for solar warning, traditional functional allocations based on government agency domain over the terrestrial versus space environment systems may be blurred. NASA and other national space agencies will likely no longer be the sole operators of spacecraft in the deep space environment.

3.4.1.4 Identified Users

Any solar warning and forecasting organisation will need to clearly identify the users of its services so it can adequately and reliably meet their needs. These users can be classified into user communities based on their common backgrounds (civil, military or commercial) and into user groups based on the commonality between their resources (satellites versus power grids). The following paragraphs list the possible user groups for a solar warning and forecasting service and briefly delineate their unique needs (user groups derived from Space Weather Prediction homepage, American Geophysical Union [WWW]; Lund Space Weather and AI Centre homepage, Lund University [WWW] and Spacecraft Anomalies Due to the Radiation Environment in Space homepage, NASA [WWW]).

Commercial, Civilian and Military Satellite Operators — Solar phenomena can affect satellites in four ways: heavy energetic particles can penetrate electronic components and create errors in instrument data or false spacecraft commands, energetic electrons can shorten component lifetime through dielectric charging, less energetic particles can cause surface charging problems, and geomagnetic storms can heat and expand the Earth's upper atmosphere which creates drag on satellite orbits. Satellite operators require advance warnings of large energetic particle emissions from the Sun (such as flares) from *in situ* plasma devices. Additionally, monitoring or modelling of the magnetopause during a geomagnetic storm is required for geosynchronous satellites to predict when these spacecraft may pass through the magnetopause boundary and be subjected to quickly reversed magnetic fields. These quick field reversals can cause dangerous electric discharges and disorient satellites that rely on magnetic torquing for attitude control.

Humans in Space (Astronauts, Future Employees and Tourists) — Energetic protons from intense solar flares and large CMEs (Coronal Mass Ejections) can increase the radiation dosage for humans in space by magnitudes of order in a very short time frame (tens of minutes from a solar event). Although present systems do provide adequate solar flare warnings for short stays or small numbers of persons in low LEO orbits, better CME tracking is needed to ensure safety levels for long duration spaceflight and the predicted large numbers of future space workers and tourists. Future manned missions to the Moon, the asteroids or Mars will also require the expansion of current CME tracking capabilities to new regions of the solar system and better long term predictions of solar activity (over periods of years) for mission planning purposes.

Civilian and Military Radio Communications Users — High frequency terrestrial radio waves that rely on ionospheric reflection for propagation near and across the Earth's polar regions can be interrupted by solar induced ionospheric disturbances. Satellite radio waves that must penetrate the ionosphere are also altered by these disturbances. Although television and commercial radio signals can be affected, critical rescue and

military communications are the most vulnerable users. Better accuracy in solar warnings through *in situ* magnetometer and better forecasting models, especially the interaction of the ionosphere with geomagnetic storms, will allow the users of these critical systems to better predict when they need to seek other means of communication.

Civilian and Military Navigation System Operators — Ionospheric disturbances induced by solar phenomena in the magnetosphere can alter the path of navigation signals that transverse the ionosphere (through refraction) or propagate via ionospheric reflection (by changing the altitude of the ionosphere). Like radio communications users, better upper atmospheric models that interface with current ionospheric and magnetospheric imaging instruments and magnetometers are needed to enable navigation system operators to predict these signal path deviations and correct for them.

Commercial Electric Power Companies — Geomagnetic storms can create disturbances in the Earth's magnetic field which induce currents (Geomagnetically Induced Currents or GICs) in long power lines. These currents can destroy transformers, cause generator heating, and create rapidly and widely varying power levels in transmission lines. Although power network damage from geomagnetic storms can be measured in the millions of dollars and is well recorded, techniques to mitigate this damage are poorly understood and underemployed. Additional accuracy in geomagnetic storm warnings and forecasts will give power companies the confidence they need to develop, deploy and utilise adequate GIC countermeasures [Bolduc to Sillen, 1996].

Pipeline Managers — To prevent corrosion in today's buried pipelines, managers pass small currents through their pipelines to eliminate anode junctions with moist soil. GICs in pipelines can temporarily negate or even reverse the benefits of pipeline currents. Pipeline manager requirements are similar to those of electric companies; additional solar forecasting accuracy is needed to enable countermeasure development.

Industries Using Extremely High Quality Control Manufacturing Processes — Peaks in the number of control problems in extremely high quality manufacturing processes (those that limit defective sub-units to a few parts per million such as semiconductor manufacturing) have been statistically linked to geomagnetic storms, but the physical connection between storms and the lowered quality in various manufacturing processes has not been determined. Industrial manufacturers require research on this connection before they become future users of solar warning and forecasting systems.

Geodetic Surveyors — Surveyors that use the Earth's magnetic field to make measurements have been long-time users of solar forecasting data. Solar warnings and forecasts enable surveyors to know when their data is inaccurate due to solar phenomena. Although their needs can be better met through continued refining of current solar warning systems and forecasting models, geodetic surveying imposes no remarkable requirements on future solar warning and forecast services.

3.4.1.5 Capability of Users to Protect Their Resources from Dangerous Solar Phenomena

Although the previous section identified eight potential user groups and three user communities for a solar warning and forecast service, the services that such an organisation provides will be relatively useless unless most of the noted user groups can protect their resources from dangerous solar phenomena. For example, a solar warning will not actually protect terrestrial electric power distribution grids from a geomagnetic storm unless the companies that operate those grids have procedures and equipment in place beforehand to protect their resources from the storm. Likewise, satellites that rely on a solar warning and forecasting service must be designed with various active and

passive countermeasures in mind to prevent damage to the satellites from dangerous solar phenomena, regardless of any solar warning or forecast. Current user capabilities in these countermeasure areas are very limited, and the potential countermeasures themselves are often system specific. Thus the link between a solar warning and forecasting organisation and its users must also include the technical analysis of user countermeasures to dangerous solar phenomena. This will require yet another specific functional allocation within the solar warning and forecasting organisation or require a third party to perform the analysis needed to erect the physical and procedural solar countermeasures.

3.4.1.6 Ability to Satisfy User Data Needs

Section 3.4.1.4 classified solar warning and forecast users based on their common resources (user groups) and on their common backgrounds (user communities). These differences must be taken into consideration when considering the data needs of specific users. Some possible differences in data needs between various user groups and user communities include:

Relevance of Solar Data Supplied to the User (Which Solar Phenomena Are Being Observed?) — Any solar warning and forecasting organisation will need to concentrate its observations on those solar phenomena which affect its users. Differences in the solar phenomena that various users are interested in falls along user group lines because of the similarities of user group resources. For example, civil, military and commercial satellite operators will all be interested in the interaction of geomagnetic storms with the ionosphere while power companies will be interested in interactions between geomagnetic storms and the Earth's magnetic field. Although the details are technical, some solar warning and forecasting organisations are better suited to satisfying certain user groups data needs because they concentrate their observations on certain phenomena.

Timeliness of Solar Data Supplied to the User (How Often are Solar Forecasts Updated?) — Different organisations provide different update rates for solar forecasts, and these differences lend themselves to various user communities which require a shorter or longer duration between updates. The military user community may require very rapid updates during times of conflict, whereas the commercial user community's forecasts can be updated at more regular intervals.

Lead Time of Solar Data Over Phenomena (Does the User Have Enough Time to Protect His Resources After a Solar Warning?) — Different user groups may require more or less lead time in order to enact countermeasures to protect their resources. For example, powering down an electric grid may take less time that reorienting a satellite before a geomagnetic storm. This criterion will be especially important in the near future as forecasts and countermeasures are tested and refined through experiential contact with dangerous solar phenomena.

Comprehensibility of the Solar Data (Can the User Understand the Significance of a Solar Warning or Forecast?) — Different user groups and communities will possess different levels of technical knowledge regarding the interpretation of the implications of a solar warning or forecast for their resources. For example, power companies are unlikely to have ready access to solar physicists whereas satellite operators may have implicit knowledge about the effect of solar phenomena on their systems from designing those systems. Warnings and forecasts will need to be tailored to the technical sophistication of the user either through the primary solar warning and forecast organisation or through secondary organisations who take raw data from the primary organisation and interpret it for different users.

3.4.1.7 Warning Versus Forecasting

Until this section, solar warning and solar forecasting have been discussed as a single organisational service and function. Solar warnings, however, require a level of technical understanding that falls below that required for solar forecasting. Solar forecasting requires an interface with human expertise that solar warning does not necessarily require except in its development phases. Certain organisations, because they already possess this technical expertise, will thus be better suited to solar forecasting in addition to solar warning than other organisations.

3.4.1.8 Reliability and Accuracy of Solar Warnings and Forecasts

Although an obvious point of concern, the reliability and accuracy of solar warnings and forecasts will be important criterion in choosing between different organisational models for a solar warning and forecasting service. For example, military users may have solar warning accuracy requirements that are too costly for a commercial service to provide. Likewise, a military service may lack the expertise needed to generate a long-term forecast for a commercial user. It will be easier to match the right service provider to the right user, rather than forcing the provider to change or improve its data gathering and interpretation methods or forcing the user to cope with less than ideal data.

3.4.1.9 Stability of Solar Warnings and Forecasts Over Time

Although this criterion is partially addressed in section 3.4.1.1 by continued operations funding, it is also an especially important criterion when considering a military solar warning and forecast service. National emergencies may require a military service to temporarily halt the dissemination of solar data to commercial or civil users. Similarly, civil or commercial services that serve military users in addition to other users may also be required to limit their data dissemination in times of emergency. Clear internal policies that conform to national laws must be in place to anticipate these contingencies if the line between military and civil/commercial solar warning and forecasting is crossed by either users or providers.

3.4.1.10 Capacity to Incorporate New Solar Knowledge and Technology

Despite the fact that solar warning and forecasting are relatively undeveloped fields, both scientifically and technologically, any enduring solar warning and forecasting organisation will find it vital to possess the capability to integrate new solar models and new solar observing technologies into its warning and forecasting services. Some organisations are well suited to perform this continuous development in house whereas others will need to co-operate with external organisations to transfer this knowledge because they lack the necessary technical expertise and infrastructure.

3.4.2 Current Models for Solar Warning and Forecasting Organisations

With these ten criteria in mind, four contemporary models for solar warning and forecasting can be introduced. These models are drawn from existing organisations that deal with some aspect of solar warning and forecasting.

3.4.2.1 Single Civilian Agency (NOAA — SEC)

Perhaps the simplest organisational model for a solar warning and forecasting service is that of the single civilian government functionary. The U.S. National Oceanic and Atmospheric Administration (NOAA) undertakes solar warning and forecasting duties in addition to its other terrestrial weather services through its Space Environment Centre (SEC) located in Boulder, Colorado. The SEC, formerly the Space Environment

Laboratory (SEL), is one of NOAA's seven National Centers for Environmental Prediction. NOAA obtains solar warning and forecasting data from its Geostationary Operational Environmental Satellites (GOES) and its Polar-orbiting Operational Environmental Satellites (POES). NOAA is responsible for processing this data, analysing it to create forecasts, and real time "nowcast" warnings oriented to meet the needs of civilian government and some commercial users [Space Environment Center homepage, WWW].

A single civilian agency like NOAA has several advantages over other organisations including stable operations funding, a base of warning and forecasting capabilities on which to draw, a relatively simple organisational structure, defined user groups, and the ability to continue warnings and forecasts uninterrupted. NOAA, however, cannot develop new solar observation technology independently, may lack the ability to create forecasting models, may not provide data services appropriate to military (and possibly some commercial) users, and does not currently integrate user countermeasures with its warnings and forecasts.

3.4.2.2 Single Military Functionary (USAF — AFSFC)

The United States Air Force (USAF) undertakes the development of new models for solar forecasting through its Air Force Space Forecast Center (AFSFC) at Colorado Springs, Colorado. These models concentrate on near-Earth space and include the Parameterised Real-time Ionospheric Specification Model (PRISM), the Ionospheric Forecast Model (IFM), the Magnetospheric Specification and Forecast Model (MSFM), the Solar Wind Transport code (SWT) and the Interplanetary Shock Propagation Model (ISPM). Except for PRISM, all these models are still under development and current 24 hour AFSFC geomagnetic forecasts provide, at best, 44% accuracy [Space Weather Prediction Home Page, WWW]. The AFSFC also obtains a variety of *in situ* space environment measurements through the U.S. Defense Meteorological Satellite Programme (DMSP).

Although a solar warning and forecasting service in a military department is organisationally as simple as a civilian government functionary and derives many of the same benefits described in Section 3.4.2.1, it is questionable whether a purely military organisation could promise to provide uninterrupted solar warnings and forecasts in times of national emergency or whether military user community requirements match the requirements of civilian or commercial user communities. It is also interesting to note the emphasis DoD places on solar forecast model development, which complements the wider solar and space environment instrument arrays deployed on NOAA's weather satellites.

3.4.2.3 Inter-agency Functionary (SESC)

The United States has resolved the tension between its military and civilian users by consolidating NOAA SEC resources and USAF AFSFC resources in the U.S. Space Environment Services Center in Boulder, Colorado. The SESC is staffed by NOAA civilians, uniformed NOAA Corps, and USAF personnel. It provides forecasts of solar and solar induced geomagnetic activity through optical and radio indicators and geomagnetic indices. These indicators and indices are obtained through ground based observations of solar flares and solar activity, through particle, X-ray and magnetometer data from NOAA's GOES satellites, from particle data from NOAA's POES satellite, and from various data from DoD's DMSP satellite. The SESC provides a single, national point for space warning and forecast organisation in the United States by drawing on the resources of government agencies whose individual requirements necessitate a certain level of resource independence [Space Weather Prediction Homepage, WWW].

The advantages of an inter-agency functionary like the SESC are obvious, especially for commercial users who can look to one public service for their solar warning and forecast needs. It is important to realise that the SESC does not programmatically co-ordinate NOAA and USAF resources and thus does not prevent the duplication of agency capabilities within the U.S. government.

3.4.2.4 International Data Collection and Dissemination Service (ISES)

Formerly known as the International Ursigram and World Days Service (IUWDS), the International Space Environment Service (ISES) provides an international data network for the acquisition and distribution of solar warning and forecasting data. Supported by various scientific societies, the ISES collects data from ten Regional Warning Centers (RWCs) throughout the world [International Space Environment Service homepage, WWW]. RWCs are nationally supported organisations and primarily serve the needs of their national users. The data contributions from RWCs to ISES can vary greatly and include data from such disparate sources as Japan's Geostationary Meteorological Satellite (GMS) [Space Weather Nowcast abstract homepage, WWW] and Australia's Radio and Space Services [IPS Radio and Space Services homepage, WWW]. The SESC in Boulder, Colorado acts as the clearing-house for RWC data and serves as the ISES's World Warning Agency (WWA).

ISES is a valuable glue between the world's various solar warning and forecasting services, although obviously dominated by SESC's contributions. Its purview, like that of the SESC, is limited to data co-ordination, and it cannot prevent the duplication of national resources internationally and is extremely dependent on national resources for service continuity and improvement. ISES clearly defines the functional boundaries between development, operations and raw data acquisition at the national level and data collection and distribution at the international level. ISES may suffer from a clearly defined set of users but is also considering initiatives to improve forecasts from the point of view of user end requirements.

3.4.3 Future Models for Solar Warning and Forecasting Organisations

Five possible future models for solar warning and forecast services also exist as national plans, in current meteorological organisations or as theoretical ideals.

3.4.3.1 True National Functionary (NSWP)

Attempts are underway in the United States to consolidate NOAA, USAF and SESC resources with other agency resources to create a National Space Weather Programme (NSWP). In 1993, the U.S. National Science Foundation (NSF) was prompted by the science community to undertake the improvement of solar forecasting capabilities. The NSF formed three working groups (Sun / Solar Wind, Magnetosphere, and Ionosphere / Thermosphere) to address the technical and organisational issues involved. Through the actions of these working groups and the NSF Office of the Federal Coordinator for Meterology (OFCM), a Committee for Space Environmental Forecasting (CSEF) was formed. The CSEF wrote the first drafts of the NWSP Implementation Plan and directed the formation of a National Space Weather Council (NSWC) and a Committee for Space Weather (CSW which replaced the CSEF) in late 1994. The NWSP Implementation Plan is now a living, changing document that is continually refined by the NSWC. The NSWC is a multi-agency oversight and direction group consisting of representatives from DoD, the U.S. Department of Commerce (DoC — NOAA's parent department), the U.S. Department of the Interior (DoI), the U.S. Department of Energy (DoE), NASA and NSF. These representatives act as spokespersons for their agencies and departments in the NSWC and address issues of individual agency scope, requirements and resource

commitments. The NSWC ensures that common agency needs are met while securing the planning, programming and budgeting interests of the agencies involved. By its own admission, the NSWP does not co-ordinate the engineering aspects of the technical systems of its constituent agencies and relies upon its users to tailor its solar warning and forecast products to their needs. The NSWC is overseen by the CSW. An important element of the interaction between the NSWP Implementation Plan, the NSWC and the CSW is the use of defined metrics to measure the progress of U.S. solar forecasting capabilities evolution [National Space Weather Implementation Plan homepage, WWW].

The "overarching goal" of the NSWP "is to achieve an active, synergistic, inter-agency system to provide timely, accurate, and reliable space weather warnings, observations, specifications and forecasts within the next ten years." Technical objectives to achieve this goal include the development of accurate 72 hour solar event forecasting models and 48 hour near Earth space weather forecasting models [National Space Weather Implementation Plan homepage, WWW].

Each agency involved in the NSWP contributes unique hardware and human resources to the programme. The USAF, in addition to its current observational and modelling capabilities as described in section 3.4.2.2, has proposed through its Air Force Phillips Laboratory a Solar Mass Ejection Imager (SMEI) for 48 hour CME warnings. The SMEI would fly on a Sun-synchronous polar orbiting satellite [Space Weather Prediction homepage, WWW]. The USAF might also contribute daily CME warnings through its Over-The-Horizon (OTH) radar to a future NSWP [OTH Space Weather Forecasts homepage, WWW].

NASA also promises to contribute critical observation and modelling capabilities to the NSWP. Real time solar wind data from NASA's WIND spacecraft currently provides a testing ground for potentially very accurate two hour space environment forecasts from a spacecraft placed at L1. However, even with adjustments WIND cannot constantly monitor the solar wind, and NOAA is providing resources to modify NASA's Advanced Composition Explorer (ACE, to be launched in 1997) for the provision of longer term, real time solar wind data. NASA is also developing the Quantitative Magnetospheric Predictions Programme (QMPP) in its Space Physics Division which will relate different regions of solar induced phenomena through WIND and ACE measurements.

The last contributor to the NSWP is the U.S. National Science Foundation (NSF). Through its Geospace Environment Modelling (GEM) programme, NSF is developing the Geospace General Circulation Model (GGCM) which is a modular programme adaptable to the forecasting needs of various users. GGCM complements NASA's QMPP.

Perhaps the most important aspect of the NSWP Implementation Plan is its recognition of the eventual need to replace the temporary WIND and ACE spacecraft with dedicated *in situ* solar warning spacecraft at Lagrange points or in solar orbit. The ability of the NSWP to co-ordinate hardware contributions makes it a potential vehicle for the deployment of these spacecraft. However, the NSWP has yet to seek additional contributions to such an effort outside the United States.

Although the NSWP organisation is not a simple structure and de-emphasises user end requirements, it is flexible, maximises the use of current national solar warning and forecast capabilities, rests solidly on the budgets of its constituent agencies, and has the capability to improve U.S. solar forecasts and sustain forecasting services over time.

3.4.3.2 National Inter-agency Functionary with Foreign Contributions (NPOESS)

A hybrid of the NSWP model and the ISES model is a national inter-agency functionary that incorporates hardware contributions from foreign countries. The U.S. National Polar-Orbiting Operational Environmental Satellite System (NPOESS) is a developing meteorological system that may demonstrate the theoretical operational feasibility of foreign contributions to a national interagency solar warning and forecasting service. NPOESS developed out of studies of the convergence of NOAA and DoD polar orbiting weather satellite capabilities dating as far back as 1972. Increased Congressional interest in 1993 led the Vice President to recommend convergence, and a Tri-agency Study Group under the U.S. Office of Science and Technology Policy (OSTP) was formed in 1994. The OSTP recommended convergence to the U.S. Congress and the President in 1994. A tri-agency ad hoc conversion transition team was established, and in October 1994 the team established the Integrated Programme Office for NPOESS. In May 1995, a tri-agency Memorandum of Agreement (MOA) between NOAA, DoD and NASA was signed. In the MOA, NOAA and DoD agreed to provide a total of $1.4 billion for NPOESS acquisition through 2001, NOAA became the lead agency for NPOESS execution and operations, DoD became the lead agency for NPOESS acquisition, NASA became the lead agency for technology transition, and the involvement of the international community was recognised.

The NPOESS Integrated Programme Office consists of an Associate Director for Acquisition from DoD, an Associate Director for Operations from NOAA and an Associate Director for Technology Transition from NASA who all report to an NPOESS System Programme Director. A Joint Agency Requirements Group feeds input to the Associate Directors while a Senior Users Advisory Group confers directly with the System Programme Director. Above the System Programme Director, an Executive Committee consisting of the DoD Under Secretary for Acquisition and Technology, the DoC Under Secretary for Oceans and Atmosphere and the Deputy Administrator of NASA holds power and is advised by a Joint Agency Requirements Council [Williamson, 1996].

In terms of physical hardware, the U.S. portion of NPOESS consists of two common, Sun-synchronous, polar orbiting weather satellites; one procured with DoD funds and one procured with NOAA funds. At this level, the NPOESS organisation resembles the solar warning and forecast capabilities currently shared between NOAA and DoD in the SESC with additional hardware co-ordination. However, NPOESS also includes a third satellite contributed by ESA and Eumetsat that carries both European and U.S. instruments. European participation grew out of NOAA budget overruns, which forced NOAA to look for partners to take over this responsibility. NOAA and Eumetsat drew up a plan to have ESA and Eumetsat assume half of NOAA's civilian morning-crossing operational meteorological data responsibility through Eumetsat's METOP polar satellites. NOAA found a partner to be responsible for hardware in Europe before political pressure forced NOAA and DoD to co-operate domestically, and this European partnership was folded into NOAA and DoD agreements. Further co-operation with the Russian polar orbiting meteorological satellite, Meteor-3, is also being considered as a serious possibility [U.S. Congress, 1993].

The direct integration of discrete foreign hardware in a national, interagency co-operative structure makes NPOESS a unique model for a future solar warning and forecast organisations beyond the current SESC, NSWP and ISES structures. The NPOESS model also clearly separates functional responsibilities based on the unique advantages of each participant. The NPOESS model may be especially applicable when solar warning and forecast services decide to deploy dedicated solar and space environment observation satellites at Lagrange points or in solar orbit. The high development cost of such systems

may require burden sharing beyond that which any national, interagency organisation can provide.

3.4.3.3 Regional Convention Organisation (EUMETSAT)

Although a solar warning and forecasting service is unlikely to be based on a regional organisation because of the global impact of solar phenomena, the European Meteorological Satellite Organisation (EUMETSAT) does provide a possible model for international co-operation in solar warning and forecasting. The convention creating the EUMETSAT organisation was ratified in June of 1986 for the exploitation of ESA's Meteorological Satellite Programme or METEOSAT (the first European geostationary weather satellite had been operational since 1977). EUMETSAT is a classical international organisation, governed by a Council with representatives from all member states for issue arbitration and resolution. The day to day functioning of EUMETSAT is undertaken by a small Director's secretariat. Although ESA is still charged with the development and launching of new METEOSATs and the European Satellite Operations Center (ESOC) handled the data acquisition and daily operation of the METEOSATs until 1995 (both of these functions are arranged in a separate agreement between ESA and EUMETSAT), EUMETSAT is responsible for METEOSAT administration and financing. METEOSAT financing is accomplished through mandatory contributions from signatories to the EUMETSAT Convention. If contributions are withheld, EUMETSAT data is not provided to the signatory in question. It is important to note that EUMETSAT, ESA and ESOC do not analyse METEOSAT data. That function is instead carried out by national meteorological agencies which are signatories of the Convention and by the European Centre for Midterm Weather Forecasting [van Traa-Engelman, 1993].

Future international solar warning and forecasting services might wish to utilise aspects of the EUMETSAT organisation, namely the consolidation of administrative and financial functions under an international management. This international management overlay stabilises funding, allows for national processing of the international data stream, clearly delineates functional boundaries and provides a vehicle for data and hardware co-ordination. The two inappropriate aspects of the EUMETSAT organisation for an interagency or international solar warning and forecast service are (1) the integration of resources on single spacecraft designs and (2) the nature of EUMETSAT data release, which is dependent on participant contribution. These aspects of the EUMETSAT organisation are made possible by the increasing interdependence and unification of European states but would probably not be possible in a rival interagency setting or a global international setting.

3.4.3.4 True International Functionary

Given enough time, an international agency under the aegis of the United Nations or a service funded through similar national contributions might possibly emerge as the world provider of solar warning and forecasting data. However, the need for solar warning and forecast data is not yet great enough to warrant the expenditure of limited international resources on such a service and an international agency would likely still be extremely dependent on national solar warning and forecasting resources, limiting its independent yet international character. International data collection and dissemination services like ISES are more likely to continue as the primary means of international co-operation in solar warning and forecasting. If international co-operation in solar warning and forecasting does extend beyond mere data co-ordination into hardware contributions, then the Eumetsat model (with services dependent on treaty membership and payments supporting the hardware) or the NPOESS model (independent but co-ordinated hardware contributions) will probably emerge well before any true international solar warning and forecast agency.

3.4.3.5 Commercial Service

It is theoretically possible that a commercial entity could undertake all the functions necessary to provide a solar warning and forecasting service. Competition with government services available to the public makes that possibility unlikely, however, unless government users are willing to rely upon a commercial provider and unless governments are willing to eliminate, meter or transfer their solar warning and forecast services to a commercial entity. Bureaucratic inertia in the case of civilian government services and security requirement rationales for military services makes both of these contingencies distant propositions, however. There is also the question of just how commercial such a service would be since its primary customers would continue to be government users and because it would likely be a monopoly once established, preventing the market entry of equal competitors. There may be a market for a commercial solar warning and forecasting service, but that market can probably accommodate only one major provider.

In the foreseeable future, the commercial world is more likely to fill horizontal gaps in government solar warning and forecasting services by adding value to those services rather than by creating its own vertically integrated service. Some potential gaps for commercial entities to fill include: the development of countermeasure routines for specific satellites, power grids and other systems threatened by dangerous solar phenomena, the real time interpretation of government warnings and forecasts for less technically literate users, and consulting regarding the impact of solar phenomena on user resources. An example of value added commercial activity in solar warning and forecasting is ARINC Incorporated of Colorado Springs, Colorado, which developed a Space Weather Training Programme for the USAF Space Command and 50th Weather Squadron and a solar effects flowchart under DoD contract [Davenport, G.R., WWW].

3.5 Recommended Organisational Structure for Future Solar Warning and Forecast Service Services: The Interagency/International Interface ("Triple I") Model

Based on the ten criteria for an ideal solar warning and forecast organisation in section 3.4.1, none of the nine current and future solar warning and forecast organisations in sections 3.4.2 or 3.4.3 address all the possible shortcomings of such organisations. It is necessary to derive a unique model to approach the ideal match between solar warning and forecast services and the current political and economic environment in which they exist.

3.5.1 Themes for the Construction of a Modern Solar Warning and Forecast Organisational Model

Several themes can be drawn from the critical review of the nine current and future solar warning and forecasting organisations in sections 3.4.2 and 3.4.3:

1. The United States is by far the predominant actor in solar warning and forecasting services throughout the world. Actions undertaken by the United States will critically affect any international solar warning forecast efforts and must take the international context into consideration.
2. The United States is taking sufficient measures to sustain and enhance interagency co-operation to reduce the costs of solar warnings and forecasts and to synergise advances in its total capabilities without endangering the independence of these individual agency services. The SESC and NSWP are central to achieving these objectives.

3. The international solar warning and forecasting community possesses an adequate vehicle for data collection and dissemination in the form of the ISES.
4. The international solar warning and forecasting community lacks an organisational means to collectively improve solar forecasting models and solar warning systems. This is partly because these advances require national political, military and budgetary commitments and partly because of the dominant role of the United States.
5. Future advances in solar warning and forecasting will require investments in two key areas: the refining of forecast models and the deployment of dedicated *in situ* solar and space environment instruments outside Earth orbit. The former is realisable within certain agency or national resources, but the latter will be highly dependent on resource contributions, risk sharing and cost sharing between agencies or governments without threatening the independence and ability of those organisations to meet their own user needs.
6. Public government organisations are likely to remain the primary providers of solar warning and forecast services for the foreseeable future. Commercial services can, however, assume secondary roles left unattended by government services.
7. Even with greatly improved solar forecasting models and solar warning systems, a gap may exist between very accurate solar forecasts and the ability of users to take advantage of a forecast's warnings.
8. Advances in solar warning and forecasting will be highly dependent on the application of basic research into the Sun and its effect on the space environment.

3.5.2 Requirements and Structure: Constructing the Interagency/International Interface ("Triple I") Organisational Model for Modern Solar Warning and Forecast Services

Taking these eight themes into consideration, it is possible to recommend an organisational model for future solar warning and forecasting organisations. The requirements of this model should include:

1. Sustain intra-governmental efforts like SESC and NSWP to co-ordinate, consolidate and improve national solar warning and forecasting capabilities, especially space environment modelling.
2. Continue international solar warning and forecasting data collection and dissemination (ISES).
3. Expand international solar warning and forecasting service co-ordination to the level of hardware contributions. The NWSP can facilitate this effort by identifying and involving potential international partners according to the NPOESS model.
4. Share risks and distribute cost burdens among the number and type of participants needed to achieve 3.
5. Clearly delineate functions according to the strengths of national and international participants as in the EUMETSAT and NPOESS models.
6. Maintain an open dialogue with basic solar and heliospheric research organisations.

7. Provide a focus for user end requirements. Commercial solar warning and forecast services are appropriate for this role.

These requirements lead to the organisational structure shown in figure 3.2.

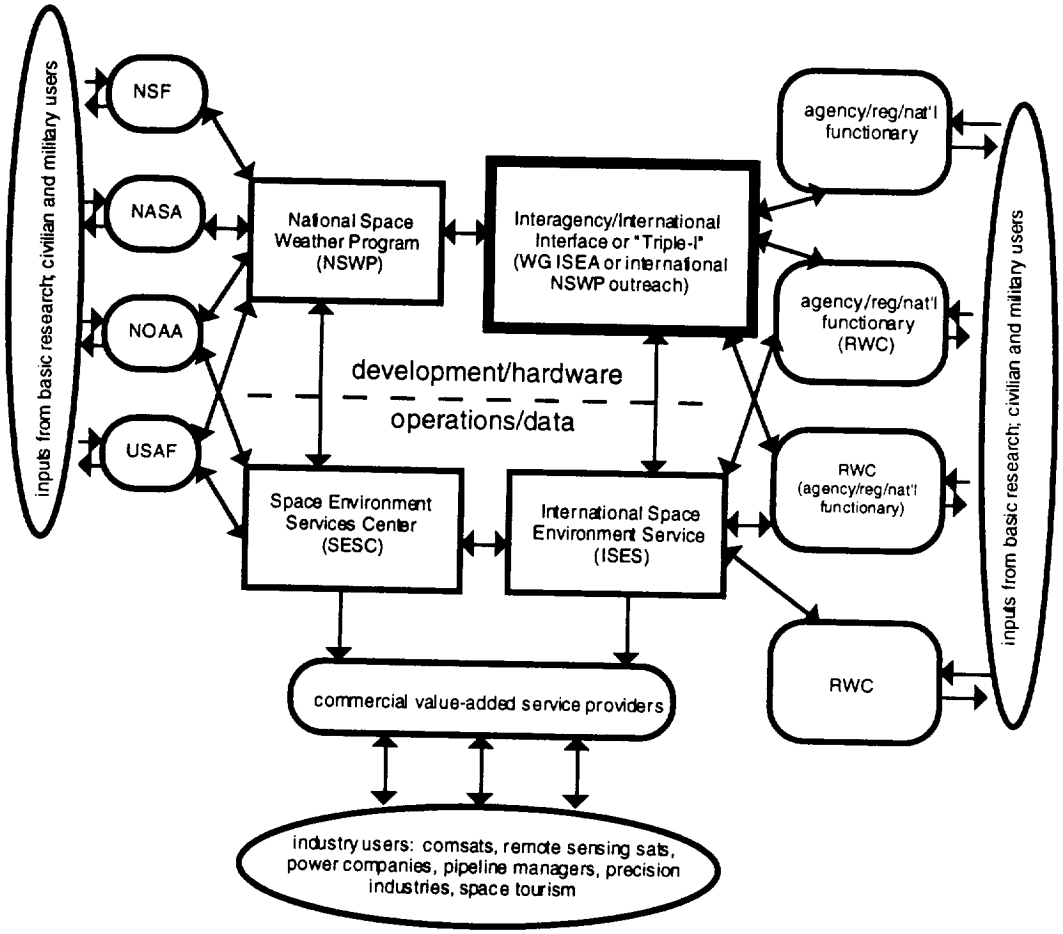


Fig. 3.2 **The "Triple I" Model: An organigram of evolving solar warning and forecast organisational relationships emphasising the critical role played by the interagency and international interface. Note the dashed line separating development and hardware roles from operations and data roles.**

The critical, currently non-existent junction in this structure is the Interagency/International Interface, and this organisational model is appropriately named the "Triple-I" Model for Solar Warning and Forecasting Service Organisation to emphasise that interface. It is possible that the role of the "Triple-I" box in this organigram could be filled informally through international NSWP outreach. Given the recommendations in Section 3.2, however, the "Triple-I" function could also be more formally instituted through the applications side of the proposed Working Group on International Solar Exploration and Application (WG ISEA).

3.5.3 The "Triple I" Model and Its Relationship to a Proposed Solar Warning and Forecast Spacecraft Constellation

In chapter 9, a minimal, mid-term, *in situ*, solar orbiting constellation of ten to twenty small spacecraft in the ecliptic, each carrying a magnetometer and a plasma instrument, for space warning and forecast applications is introduced. It is suggested that the "Triple I" model presented here is an ideal model for the development and deployment of such a

solar warning and forecasting constellation. The mission definition, standards and reference designs for spacecraft contributions to the constellation proposed in chapter 9 would be developed jointly through the "Triple I" model, but each participant would be responsible for the actual acquisition, launch and operation of its own spacecraft. Data sharing would occur through existing channels like ISES in the "Triple I" model.

3.5.4 A Thought for the Future: Will Solar Warning Spacecraft Become the First Operational Deep Space System?

If a solar warning and forecast organisation, regardless of its makeup, does deploy solar monitoring spacecraft beyond Earth orbit to protect terrestrial and space based resources, it will likely mark an important transition in human space activities. Although national space agencies and even military functionaries have undertaken scientific, exploratory and technology demonstration missions beyond Earth orbit, no organisation has yet deployed spacecraft beyond Earth orbit for an immediate, "practical," operational rationale. Many have predicted that the first human robotic activities in deep space beyond science, exploration and technology demonstration would involve resource gathering or even colonisation on other celestial bodies. This section predicts, based on the history of human space activities in Earth orbit which was initiated and dominated by communications and remote sensing satellites, that the first operational human activities in deep space will be solar and space environment monitoring spacecraft in solar orbits or at various Lagrange points. The significance of solar warning and forecasting organisations will lie not only in the economic benefits that may be derived from their services, but also in the important historical footnote they will provide as humanity expands its presence in the universe.

3.6 Solar Research and Forecasting in the Context of Russian Space Policy

Current Russian space policy was initiated in February 1992 with the foundation of the Russian Space Agency by a Decree of the President of the Russian Federation.

The Soviet space industry began its development in the late 1950s in the Ministry of Defence ('Sputnik" was designed as extension of the development of intercontinental ballistic missiles). During the Soviet era, there were multiple ministries and committees (such as the Ministry of General Machine Building "Minobshemash", Academy of Sciences etc.) which were involved in the space industry, but there was no single agency responsible for space development in general. During the Cold War period, space policy was aimed at preserving the strategic military balance and political leadership between USSR, the USA and their partners. Changes which occurred in Central and East European countries in the late 1990s shifted national governments space policy goals towards broader international co-operation in space exploration, as well as in global security and environmental problems.

3.6.1 Current Situation

Russia inherited the major part of the Soviet space industrial complex. Since 1991, newly independent states have started the transition to a free market economy. The transition period is characterised by an unstable political and economic situation, undefined time boundaries and an unclear programme of further development (nobody can predict now what type of society will exist in Russia after the transition period). In such tenuous times, planning becomes even more difficult but must nevertheless continue.

Russia is aware of the potential developments in the national space industry and has made the following steps to support national space activities: a) the foundation of the Russian Space Agency in 1992, b) the resolution in 1992 of the Government for the development of the Federal Space Programme, c) adoption of the Russian Federation Space Activity Law in 1993 (now under revision in Parliament) and d) the government resolution on Space Activity support in 1994 [Mironjuk and Pieson, 1996].

The Russian Space Agency serves both as state customer and the major space technology manufacturer, providing operation co-ordination for the enterprises and organisations involved in space activities. The Russian Space Agency is responsible for space policy in the Russian Federation:

- development of the Russian Federal Space Programme
- development of scientific and applied space technology
- co-ordination of scientific and applied commercial space projects
- further development of research and testing facilities in the Russian space industry
- international co-operation as well as co-operation with CIS states.

The Russian Federal Space Programme, together with the resolutions of the Government of the Russian Federation, define the development of the space activity. The main goals of the Russian space policy were formulated by the Russian Federal Space Programme as follows:

- fundamental and applied space exploration and Earth monitoring;
- use of space industry benefits for the national economy, scientific, technical and social progress;
- ensuring the Russian Federation defence needs and control of the fulfilment of the arms control agreements
- international co-operation in the interests of world scientific, technical and social progress, global environmental monitoring, world space market participation.

The Russian space industry suffers today from the general tendencies of the current economic situation in Russia as well as from the specific issues of the legacies of USSR space policy. Negative issues of the current economic situation in the country include: an economic crisis and a decrease in industrial production; absence of the well developed private sector; absence of customers with sufficient funds for the space services inside the country [Moscow Aviation Institute Space Economics Department, 1995]. An unwillingness of the newly created financial structures to invest money into the state industry together with high level of militarisation of the space industry; absence of competition space projects and absence of the independent expertise, make life of the space industrial enterprises more difficult and complex [Hozin, 1995].

However the Russian space industry, despite all the problems mentioned above, has very high scientific and technological potential, especially in such fields such as booster design, telecommunications, navigation, remote sensing, biotechnology, microgravity materials processing, manned spaceflight and dual use of military technologies.

Commercialisation of the space industry in Russia became one of the important issues in Russia after 1991. International co-operation and establishment of the new world space markets are the primary challenge for future development of the Russian space industry.

The Russian Space Agency is aware of the developing domestic space market, as well as need for participation in international space markets.

Today space commercial activity is controlled by state through licensing of various activities by the Russian Space Agency. Therefore, search and rescue operations, natural disaster and emergency warning as well as weather forecasting are excluded from commercial space activity. The state has exclusive rights to own cosmodomes with all launching facilities. Foreign investors are allowed now to have not more than 49% in the property of the joint companies dealing with space activities [Moscow Aviation Institute Space Economics Department, 1995].

Commercialisation of the Russian space industry is going slowly because of inflexible structure of the management, decision-making marketing strategies and developed user infrastructures.

3.6.2 International Co-operation Within the Ra Strategic Framework

The International Co-operation Department of the Russian Space Agency is responsible for co-operation with other space agencies and organisations. In the later stages of negotiations, the Office of the Federal Space Programme Planning can be involved to include future missions into the Federal Space Programme. Usually the institutes of the Russian Academy of Sciences, such as the Institute of Space Studies ("IKI"), Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation ("IZMIRAN") are the principal investigators from the Russian side in solar and interplanetary missions.

Due to its unstable domestic economic situation, Russian participation in current international space projects have been limited but can take place through the following channels:

- contributing intellectual property
- provision of a spacecraft bus for a research programme with an international set of experiments and instruments
- conversion of military technologies or dual use of military technologies
- building space equipment through direct financing by foreign organisations.

3.6.3 Possible Russian Space Programme Contributions for the Near-Term RA Strategic Framework

The Russian space programme can suggest for the Near-Term Ra Strategic Framework the current mission "Interball" as well as different meteorological and military satellites under conversion which have instruments for measuring geophysical parameters in a near-Earth orbit which are already functioning or planned to be launched in the framework of the Space Segment of the Unified State System for Eco-monitoring [Scoon, 1996; Johnson-Freese, 1996]. For example, the meteorological geostationary satellite "Electron" is part of the Russian meteorological system "Planeta-C." It was launched in November 1994 and has special instruments for helio-geophysical monitoring on board. It provides measurements of protons at 0.2-500.0 keV, electrons at 0.2-2.5 MeV, particles at 2.0-12.0 MeV, UV emission at 10-130 nm and gamma rays at 0.2-1.0 nm. It also measures variations in the direction of the Earth magnetic field [Zhdanovich, 1994].

The development of the Unified State System for eco-monitoring needs special consideration. The concept of the Space Segment of that system is based on the unification and further development of existing Russian remote sensing systems as well

as systems for space weather monitoring into one global informational system with common control centres, various data analysis centres, and user terminals at different levels [Bondur, 1995]. The Space Monitoring System is based on the multi-level hierarchical principle with the various spacecraft flying in different orbits, with a wide range of instruments on board and a network of ground stations. In the framework of this space segment a few declassified systems are suggested to be utilised:

Space system for ocean control: "Legenda" — Space system "Legenda" (circular orbit, H = 300 km, i = 65°) with radar which gives images 100x100 km^2 or strip with the width 100x100 km with resolution 300-1500 m and satellite spacecraft with circular orbit H = 400 km and i = 65 "Legenda" includes "Diagnosis" instruments for the mapping of the Earth's magnetic field, "Pole" instruments for the forecasting of Earth eruptions, and "Predvestnik" instruments for the monitoring of the ionosphere and magnetosphere and ground stations for the measurement of the electromagnetic fields on the ground.

System for global monitoring: "Oko-1" and "Oko-2" — These spacecraft monitor Earth in real time. They use two types of orbits: geostationary and half-day elliptical. They can be utilised for understanding the helio-geophysical situation and diagnosing the complex phenomena of the space environment. Oko includes "Reis" spectrometers for hot and cold plasma detection; differential proton spectrometers; electron, proton and alpha particle spectrometers; plasma sondes for the measurement of the velocity and density of the solar wind [Bondur, 1995].

System for space weather monitoring: "Prognoz" and "Orion" — The system for direct monitoring of space weather is based on the "Prognoz" satellite. Two satellites of "Prognoz-M" (first apogee 20,000 km, second apogee 200,000 km) have two ion and electron spectrometers and "Reis" instrument complexes. Two more space weather monitoring spacecraft are also planned: "Orion-C," for the measurements of the parameters of the near-Earth space different from the direction to the Earth heliocentric angles and Orion-Sl, planned to be put into a libration point orbit at 1.5 million km.

3.6.4 Russian Space Programme Contributions for the Mid- and Far-Term Ra Strategic Framework

For the mid-term and far-term, it is possible to use space science experience and research heritage in mission strategic planning, as well as solar missions which were included in the Federal Space Programme up to 2000 but are not able to be fulfilled because of the difficult economic situation in Russia. One of these projects is "Solar Zond" - to study the Sun as a star from the distance 5 solar radii. The Russian space industry can provide the following platforms for future solar missions: space buses and sub-systems for the joint designs [Pieson, 1996]; launchers such as "Energia", and "Proton" etc.; special heat protection materials; and robust engineering. An example of the resources Russia has to offer is a needle-shaped space probe with a cone looking towards the Sun which reflects 70% of the incident photons, allowing only 30% of the them affect the space probe, which reduces thermal system protection requirement by a factor of three [Marov, 1996].

3.7 International Agreements and Contracts in the Ra Strategic Framework

In order for the Ra programme to advance, co-operation between government bodies and contracting private companies is required. Section 3.7 reviews the types and forms of international contracts, involved when co-operation among and between government bodies and private companies occur.

The inter-governmental agreement would also refer to applicable state obligations and responsibilities found in the United Nations treaties dealing with space law, the Outer Space Treaty of 1967, the Liability Convention of 1972, and the Registration convention of 1975.

3.7.1 Co-operative Agreements Between Governments

The Ra project involves co-operation between government bodies. This co-operation can render the following benefits:

- reduction of cost to individual participant countries,
- maximising the potential of achieving programme objectives,
- risk sharing,
- limiting the ceiling of liability,
- increased support base across the national/international spectrum.

There are also disadvantages to involving government bodies in a programme such as Ra, which must be considered. These include:

- potential funding uncertainties
- lack of coherency and continuity in decision-making processes
- susceptibility to political processes

Although international co-operation has some potential risks, as discussed above, there are also substantial benefits to be gained. These benefits far outweigh the risks.

3.7.1.1 How to Co-operate

In a co-operative programme of the type proposed, an inter-governmental agreement is required. An inter-governmental agreement will include discussions on major items such as:

- how expenses will be shared
- designations of responsibility for facilities and decision-making
- intellectual property rights
- registration, jurisdiction and control
- ownership of elements and equipment
- proposed design and development timetable

3.7.1.2 Plans for Utilisation

From past examples, however, it is recognised that agreements of this type need to be flexible. Differing legal requirements among countries dictate the desirability of building a legal framework which allows individual countries to fulfil their own bureaucratic and political requirements, and permit the structure to evolve along functional lines that will best maximise the potential for programme success. A successful example of such an arrangement is the Tamamushi agreement concluded between ISAS and NASA in 1986 [Johnson-Freese, 1993]. The agreement allowed both agencies to fulfil their bureaucratic needs while flexibly allowing the programme for which it was created, Solar-A, to proceed.

3.7.2 International Industrial Contracting

Each country in the world has different domestic laws. Therefore when the government is contracting with another country's private company, or between other country's private companies, a detailed, written contract is necessary.

Contracts are routinely concluded between governments and private companies. Some types of contracts include a fixed cost contract and an upper limit cost contract.

3.7.2.1 Fixed Cost Contracts

Fixed cost contracts decide costs at the beginning of a project. If the conditions of the contract have not changed, the cost has not changed. But if the conditions of a contract have changed, the cost changes. When the objects of a contract have a market price or have been made before, a fixed cost contract is the most economical and simple contract form. Fixed cost contracts are awarded using a bidding system.

3.7.2.2 Upper Limit Cost Contract

Upper limit cost contracts decide the cost of a project with a rough estimate in the beginning of the contracting process. After finishing the work, the government bodies check the actual money spent to fulfil the contract, and the government bodies and private companies decide the final cost. When the objects of the contract are developing something new, upper limit cost contracts are the most common contract form. It is impossible to correctly estimate the development cost of new objects. However, it is important to set some limits on the cost because the budgets of government bodies are limited. Additionally, the upper cost limit is a warning against wasting money to private companies. However, upper limit cost contracts make a lot of work for the government bodies, limiting the number of upper limit cost contracts used.

3.7.2.3 Intra-Industry Contracts

This type of contract is useful in the case of very big projects, for example, in the case of developing and making a new satellite in Japan. Company A is the prime contractor, company B makes antennas, company C makes batteries, and company D makes sensors. The prime contractor takes the responsibility to fulfil the contract, assuming responsibility for the work of the subcontractors. This arrangement is easier for the government bodies because they need to oversee the prime contractor only.

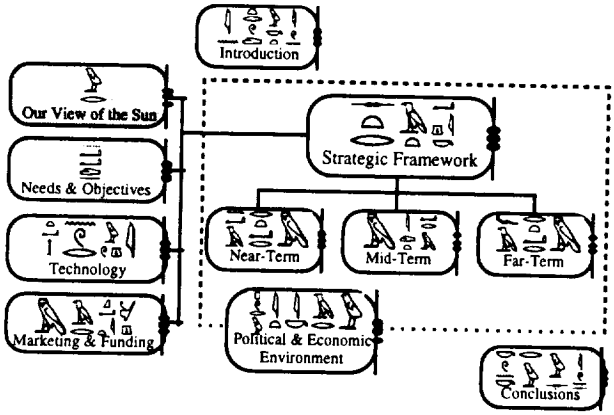
The Ra Strategic Framework includes new, internationally interconnected projects and brings new factors into consideration. It is important to use different contract types as designated by the environment and objective of the contract.

3.8 Concluding Remarks

Chapter 3 outlined the political environment in which solar exploration and applications must take place by examining previous examples of international cooperation in space science and various organizational models for solar warning and forecast services. Criteria were introduced and important lessons learned by critically examining the history of international cooperation in space science and the organizational schemes for solar warning and forecasting services. Out of these lessons, two critical recommendations are made. First, those national and international bodies involved in either solar research or solar warning should form an international Working Group on International Solar Exploration and Application before August 1997. The second is that international solar warning and forecasting cooperation should be improved by stressing

coordination at the Interagency/International Interface, either through the WG ISEA or through international outreach by the U.S. National Space Weather Program. If these steps are taken, solar exploration can look forward to a more coherent and sustainable future, and solar warning services can begin to mount the modelling and spacecraft infrastructure needed to improve their forecasts.

Chapter 4



Our View of the Sun

Since the earliest day of humankind we have observed the Sun crossing the sky every day in an apparently never ending cycle. From the worship of ancient cultures to our current scientific study of the Sun, there has been a great change in the way humans see the Sun as well as a steady development in knowledge.

The intention of this chapter is to provide the background information for why we study the Sun, how this study has been attempted throughout history and how solar science is performed today. Furthermore, it should stress the questions about the Sun that lead to the objectives given in chapter 5.

The chapter is divided into six sections. The first gives an overview of how ancient cultures have seen the Sun and leads to the sections where our discovery of the Sun is described in a modern scientific way. Section 4.2 introduces the Sun as a star and section 4.3 presents the phenomena in interplanetary space. Section 4.4 describes the basic Sun-Earth interrelations and section 4.5 the effects of the Sun on humans and technologies. Section 4.6 closes this chapter by suggesting how the Sun may be used as a resource.

4.1 Studying our Sun

Our earliest observations of the Sun are reflected in the myths and artefacts of various cultures, which demonstrate the various levels of sophistication humans have had in their understanding of the Sun. Modern solar science, however, will touch the mysteries of the Sun in ways that our ancestors could never have dreamed. But in many ways our motivation for this exploration remains mythic in nature. We are the first generation that can undertake this journey through spacecraft-based science. What we discover will likely change the way we view our solar system, the universe and, ultimately, ourselves.

4.1.1 The Sun in Myth and Legend

To early humans, the Sun was surely one of the most awesome forces in their daily lives and perhaps the most celebrated. Its power warms the air, grows food and materials for fuel and shelter, and drives the cycles of wind and rain.

Myths about the Sun are found throughout most cultures. Although these stories vary greatly, they give a glimpse into the importance of the Sun within various societies. As Indo-European peoples spread throughout Europe, India, Iran and Asia Minor, they spread the concept of a high sky god. This sky deity quite often faded in importance leaving the universe to his offspring, usually the Sun god.

In Africa, it is common for the Supreme Being to be expressed as a Sun god. For example the San believed that the Sun was once a mortal being who emanated light from his armpit. Children of the village wanted to make the light brighter so they threw him up into the sky where he still shines now as a round disk for all mankind.

Evidence demonstrates that some primitive cultures had sophisticated knowledge about the astronomical and solar phenomena. Stonehenge in England is a Celtic monument that marks the solar solstices and the changes of the seasons. Likewise, the ancient meso-American cultures were deeply connected to the Sun in their calendar as well as their religions.

Meso-American Sun Worship

The early cultures of meso-America were perhaps the most elaborate Sun-oriented cultures. The Mayans had a sophisticated society although much still remains unknown. The supreme being was a sky god depicted as an old man. He also became the Sun god and was believed to be married to the Moon. The Toltecs borrowed from the Mayans and developed the myth that the Sun god died every evening and had to be resuscitated every morning with human blood. Ancient mosaics show the offering of a human heart to the Sun.

Aztecs drove the Toltecs out from their Mexican homeland but took on many of their customs such as their calendar and their practice of sacrificing humans to the Sun. However, the Aztecs took this sacrifice to new levels of morbidity. On occasion, sacrifices of up to twenty thousand people would be performed. Tonatiu, the Aztec Sun god pictured on the great stone calendar, was surrounded by fire serpents which defended the Sun from his enemies at night. The battle between life and death, light and darkness, was the entire foundation of the Aztec religion.

The Incas of Peru were much less bloodthirsty than the Aztecs, but they also had an autocratic Sun god as a paternalistic deity. The Sun was the symbol of royal power and the emperor was believed to be the son of the Sun. The Inca built their Sun temples so that the sunrise fell on a golden disk which illuminated the shrine with a numinous light.

Chinese Legend

In China, there is a legend which tells of the plight of too many Suns and of the hero who returns the world to balance.

A long time ago, there were nine Suns in space. Rivers dried gradually. Trees and plants died as well. Everything was going to die. People did their best trying to save the things in the world but could not. Just at that time a brave and kind young man came out whose name was HOU YI. HOU YI wanted to save mankind and everything still alive no

matter how difficult it was and how big the sacrifice. He would give even his life. Everyone was moved. Some people gave their ideas which would be helpful. Some went back home to devote themselves to things they had just left behind and some youngsters went ahead to join the activity.

HOU YI refused anything but food and water, brought his bow and arrows, and went straight to the East where people believed Suns were born and grew. He wanted to meet the one who could manage the things related to the Sun, in order to ask him to cancel some Suns so everything would be OK again. He went on and on, through many, many lands, mountains, and dried up rivers; overcame lots of difficulties not even imaginable today. At last, all he had was finished, no food, no water, nothing. He was exhausted.

When he was almost dead, he encouraged himself to stand up, stared up at the suns, shouted to them "Why do you do things in this way? We don't even touch you or disturb you?" Then he laid down. He used his final energy to pull the bow, aimed an arrow at one of the suns, and shot. One after the other he fired his arrows-0. Finally, eight suns were shot down, only one was left. The universe restored its order. Everything became alive. But HOU YI died without any regret. He had done his all for the whole universe within which we still live .

Native American Legend

Arrow to the Sun--an Acoma Pueblo story.

A young woman in a pueblo is visited by a ray of Father Sun and bears a child, a young boy. As the boy grows up he is ostracised by his playmates because he has no father. So he goes to his mother and tells her he must find his father. He goes off and asks a farmer who doesn't know, a potter who also doesn't know. Finally he comes to an arrow maker who does know, and forms the boy into an arrow and shoots him on the long journey to the Sun.

The boy lands on the Sun but is told by his father, the Sun, that he must endure four trials before he can be acknowledged as the son of the Sun. The trials are of endurance in kivas of lions, snakes, bees, and finally lightning. With the last trial the boy is transformed and can take his place alongside his father, filled by the power of the Sun.

The father and son rejoice but the Father tells the son that he must return to the Earth and bring his spirit to the world of people. The Father makes the son into an arrow again and shoots him off to Earth. When he returns he marries the Corn Maiden and, with all the pueblo, dances the Dance of Life.

Japanese Sun Goddess

In Japan the Sun goddess, Amaterasu Omikami, is the centre of Shinto worship. She is intended to bind the world together and maintain harmony among the gods, mankind, and nature. The prominence of Amaterasu as the greatest reality visible in the heavens symbolises the greatest reality known and revered on Earth.

An old Japanese myth about Amaterasu explains why the Sun is so important for life. It also explains why many Japanese Shinto households have a rice-straw rope across the top of their doors.

Many years ago Amaterasu, the goddess of the Sun, was abused relentlessly by her brother and so she hid in a cave. In her absence, the world became consumed by darkness. Other gods and goddesses knew that life would perish without the Sun so they

danced and played music to try and coax her from the cavern. Amaterasu was curious when she heard the music playing. She proceeded to the entrance of the cave to see from where the music was coming. When she came upon the musicians, a powerful god pulled her from the cave while another god stretched a rope made of rice straw across the entrance to prevent her from going back. The gods beseeched Amaterasu Omikami to stay in the sky so that the world would remain light and never be consumed by darkness again.

Ra: The Egyptian Sun God

Ra was the Egyptian Sun god during dynastic Egypt. The name "Ra" was thought to mean "Creator" and took the form of a hawk or falcon-headed man. Ra travelled through the waters of the sky during the day and through the underworld at night on a barque or Egyptian river boat.

Some accounts of Ra's daily journey through the sky describe how he was born anew each morning, grew through the stages of childhood, adulthood and old age only to die at sunset. Other symbols associated with Ra are the scarab or dung beetle which recreated itself by rolling its eggs in a ball of dung. The scarab was believed to roll the solar disk across the sky.

Ra was believed to be the father and king of the gods. Tears fell from the eye of Ra. These tears grew into humans and all living creatures. Ra presided during a golden age period when men and gods lived together on Earth.

In Egyptian mythological structure, Ra was father of Shu and Tefnut, grandfather of Nut and Geb, great-grandfather of Osiris, Set, Isis, and Nephthys and the great-great-grandfather of Horus.

Ancient Greece

Ancient Greece is perhaps the doorway between the human mythological relationship to the Sun and a more logical one. According to Homer, Helios "rides in his chariot, shines upon all men and deathless gods, and piercingly gazes with his eyes from his golden helmet. He rests upon the highest point of heaven until he marvellously drives down again from heaven to the Ocean." The image of the Sun in his chariot is seen over and over again in Greek art and continues into Roman times.

The Sun in the Bible

In the Bible the Sun is an important symbol of God's illuminations as exemplified in Genesis. "God made the two great lights, the greater light to rule the day, and the lesser light to rule the night. . . And God set them in the firmament of the heavens to give light upon the Earth, to rule over the day and over the night, and to separate the light from the darkness" [Genesis 1:16-18].

4.1.2 Looking Back in Order to Move Forward

Why explore solar mythology in the context of a scientific project? One must remember that in order "to understand where you are going, you must truly comprehend from where you have come". Understanding what the Sun has meant to the human psyche throughout the millennia is important for guiding scientific exploration into the future. The exploration of the Sun will be as much a quest of mythological significance as it is an objective scientific investigation into the Sun's physical properties.

Like the young Pueblo boy who seeks to know his father the Sun, the Ra solar project will journey like an arrow to our Sun exploring the mysteries of its nature. There will be trials to endure like the lions and snakes of technical challenges, economic difficulties, and international co-operation. But in the end the mysteries that are revealed will be shared with all peoples for the good of the world.

For this mission to succeed, we must draw on the mythic motivation that still drives our quest for knowledge and adventure. For we are as much creatures of story and mythology as were our ancient grandparents gathered around the camp-fire. Only now the myths we live by are "economic development" and "scientific investigation" and our camp-fires are computers and televisions. Consciously drawing on these mythic powers can help motivate our generation to be "heroes" who provide good for all the people through the exploration of space. Such psychic inspiration can propel this mission to successfully realise our dreams of unravelling the mystery of our own star.

4.1.3 Heliobiology: The Influence of Solar Activity on Society

Not only has the Sun had important mythological significance, some philosophers have investigated solar influences on social activity. In the 1920's a Russian philosopher named Alexander V. Chizhevsky (1874-1964) began to develop theories about the influence of solar activity on humans and their social behaviour. He belonged to the Russian school of space philosophers and one of the main statements of this school is that the Universe, Earth, and humans are constituents of one system which can be characterised by life cycles and rhythms. He stated that "mass human behaviour is the function of the Sun energy activity". Sun flow particles (or "z-flow particles," a name given by Chizhevsky) have impact on the blood, nervous and hormone-endocrine systems of different individuals.

Chizhevsky hypothesised that increases in the amount of the Sun flow particles within peaks of Sun cycles caused an increase of excitability and aggressiveness of different social groups on the Earth. The famous revolutions and wars of 1789, 1830, 1848, 1905, 1917, 1941 happened during the highest Sun activity, (period with the biggest number of spots on the Sun's surface). During minimal Sun activity the social activity in society is minimal, about 5% and during Sun maximums social activity achieves 60%. Sun particles bombarding the Earth transform potential nervous energy of human groups into kinetic energy that demands an outlet which results in revolutions and different mass movements. According to Chizhevsky these social disasters change the velocity and rhythm of the life period of different societies [Chizhevsky, 1937].

The ideas of Chizhevsky are under development now in Russia. His theory is being applied for the prognosis of the further development of society, economy and environment [Zhdanovich, 1994]. Special research has been made and correlation was found between Sun activity and cardiovascular diseases [Atkov, 1996], Sun activity and numbers of accidents and technological disasters, Kondrat'ev's economic cycles and Sun cycles.

4.1.4 History of Solar Science and Observation

The history of more scientific observation starts with the Greeks who, six hundred years B.C., made attempts to understand the Sun, the Universe, and their relationship to Earth, both through physical studies and philosophical ideas. The astronomer Aristarchus of Samos measured the distance to the Sun through measuring the angle between the Sun, the Moon and the Earth at a specific time. Though being underestimated to only 19 times the distance to the Moon, a similar distance was adopted by Claudius Ptolemy of Alexandria, and this distance was accepted for the next 1500 years.

In 450 B.C., Empedocles discovered that solar eclipses were caused by the Moon covering the Sun, and in 350 B.C. Helicon actually predicted a solar eclipse for the first time.

In 1543, Nicolaus Copernicus proposed the Sun as the centre of the planetary system in his famous book 'De Revolutionibus Orbium Coelestius', still using the underestimated distance to the Sun from Aristarchus and Hipparchus. Only when Kepler stated his three laws about the Solar System in the seventeenth century, did this underestimate give way to a more correct idea. Kepler also stated that the planets do not have circular orbits around the Sun, but elliptical orbits.

Sunspots were first referenced by Aristotle's pupil Theoprastus in the mid-fourth century B.C., who also sighted the aurora. The first sunspot sighting happened in China in 165 B.C. As many as 157 records of sunspots seen by the naked eye were known and scientists were well aware of their existence when the first telescope was discovered in 1608, allowing further and more accurate studies of the Sun. In Europe, records of sunspot observations through the centuries seem to be lacking, due to the Aristotelian view of the Solar System being strongly supported by the Church. Galileo observed sunspots in 1610, using the telescope. Cristoph Scheiner, a Jesuit priest, observed the Sun from 1611 to 1627, and both he and Galileo noticed that the paths of sunspots are not in straight lines as the Sun rotates, but are curved, and they showed that sunspots are confined to a band extending to latitudes of 30 degrees north and south. Heinrich Swabe in 1843 announced the "eleven-year sunspot cycle" and also introduced the term sunspot groups.

The aurora was given its full name, aurora borealis (northern lights), by the French astronomer Pierre Gassendi in 1621, but many previous descriptions of the aurora exists. Already in ancient Greece and Rome, as well as in early Chinese, Japanese and Korean writings, auroral sightings are mentioned.

More detailed information about solar observation history can be found in Phillips [1992], on which this chapter is based.

4.2 The Sun as a Star

In spite of the scientific means that have been developed since mankind first became aware of the Sun's significance, the Sun is still full of mysteries.

It is amazing how little we actually know about our live-giving force. The standard model of the Sun is threatened by the neutrino-problem, the origin of the magnetic field is not well understood and the physics behind the eleven-years long sunspot-cycle remains more or less unexplained. It is not clear on what time-scale and how much the energy output of the Sun varies, the heating mechanism of the corona has not been identified, and the physics of flares is a riddle to scientists.

In this section we introduce the Sun as it is seen by the scientists today. We begin with how the Sun evolved and how it compares to other stars in section 4.2.1. Based on figure 4.1 we then explain the interior, photosphere, chromosphere and corona in the following sections. Finally we describe solar activity in section 4.2.6.

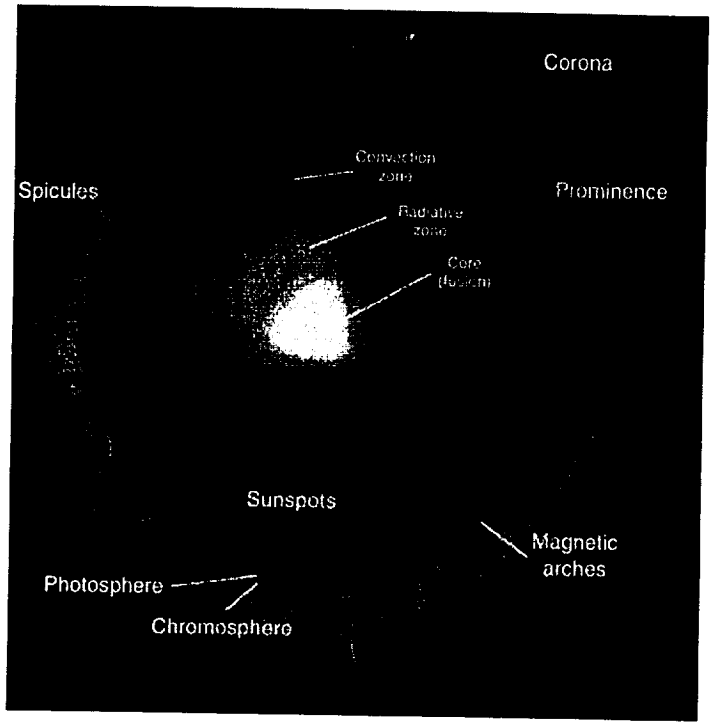


Fig. 4.1 **The interior of the Sun [Beatty and Chaikin, 1990].**

4.2.1 The Sun among Other Stars

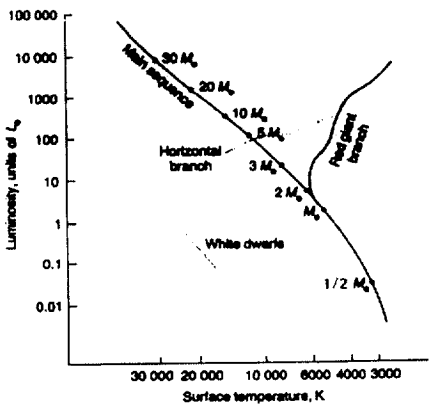
In theoretical models of stellar structure and evolution, a star is taken to be a spherical mass of gas (mostly hydrogen with some helium) compressed by its own gravity. Each layer inside the star is squeezed by the weight of layers above it. The heat from compression in the interior is transferred to the surface where it radiates into space. Under these conditions of hydrostatic equilibrium, the radius of the star shrinks and its interior heats up until thermonuclear reactions become possible at the centre. Initially, the single most important nuclear reaction converts hydrogen into helium. Once nuclear burning starts, the radiation becomes so intense that it can support the outer layers, and the shrinkage slows considerably as long as there is fuel for nuclear reactions.

The luminosity of a star is proportional to the product of its surface and the energy radiated per unit surface area. A star at a given temperature could be of any luminosity, merely by being of the appropriate size. Nature however, does not make stars randomly as was first demonstrated by Henry Norris Russell and Einar Hertzsprung in the 1920s, described by **the Hertzsprung-Russell (H-R) diagram** [see figure 4.2].

If one accumulates information on the luminosity and temperature of as many stars as possible, and represents each star by a dot in a graph of temperature (horizontal axis, increasing to the left) versus luminosity (vertical axis, increasing upward), 90% of stars lie along a band called the main sequence in the H-R diagram. Hotter main sequence stars are more luminous, and also larger, as one can see from the lines of constant size in the diagram. The 10% of stars that are not on the main sequence mostly fall in the lower-left corner of the diagram--a region of very high temperature but very low luminosity--and thus of very small stars. These are the white dwarfs. A very small percentage of the total fall in the upper right of the diagram, corresponding to low temperature but very high luminosity--a circumstance which could only come about with very large stars--hence their name "red giants".

As stars age, their luminosity and temperature change in a well-defined way. When the luminosity and temperature of stars are plotted on a diagram, we see the points lying along a path we call the main sequence. Eventually, stars exhaust their nuclear fuel and shrink to become white dwarfs, neutron stars, or black holes, depending on their mass.

The Sun appears to have been active for 4.6 billion years which means it lies on the main sequence [Noyes, 1982], about half-way along and has enough fuel to go on for another five billion years or so [figure 4.3]. At the end of its life, the Sun will start to fuse helium into heavier elements and begin to swell up as a red giant, ultimately growing so large that it will swallow the Earth. After a billion years as a red giant, it will suddenly collapse into a white dwarf--the final end product of a star like ours. It may take a trillion years to cool off completely.



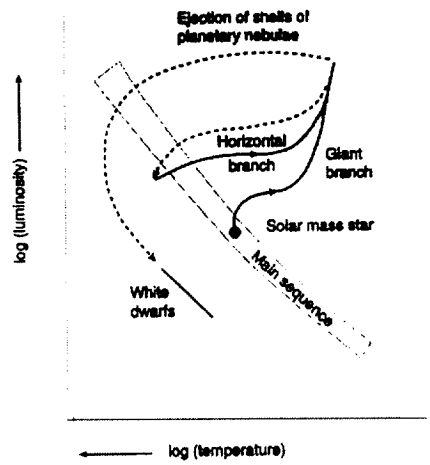


Fig. 4.2 The H-R diagram [Noyes, 1982]. Fig. 4.3 The path and position of our Sun [Noyes, 1982].

4.2.2 The Interior of the Sun

The Sun core can not be directly observed, as no radiation directly emerges. However, it is possible to put together a picture of the Sun's interior with the use of the theoretical solar core model. The theoretical model is a mathematical description of the way the pressure and temperature vary with the distance from the core of the Sun to its surface.

The Sun's energy is released from the core by the fusion of four protons to form a helium nucleus. At the centre of the Sun, where the temperature is calculated to be 15.6 million Kelvin, the first stage of the nuclear fusion chain is the combination of two protons to a deuteron. The second stage of the chain is the fusion of a deuteron with another proton to form the nucleus of an isotope of helium, consisting of two protons and one neutron. The final stage is the fusion of two such helium nuclei to form a nucleus of helium consisting of two protons and two neutrons [Wentzel, 1989].

Most of the energy is produced in a comparatively small region near the Sun centre. Heat is **transferred** by radiation in the deep interior to about two-thirds of the way out, then **convection** becomes the dominant mode of transfer near the surface. The main zones of the interior of the Sun are indicated schematically in figure 4.4.

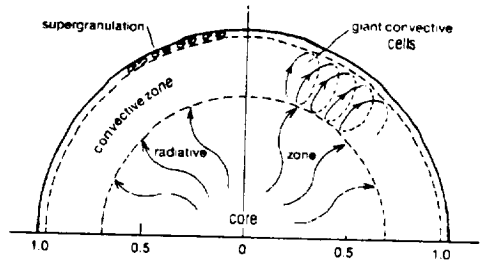


Fig. 4.4 **Principal zones in the solar interior (based on standard model of J. N. Bahcall, 1989) [Phillips, 1992].**

Solar neutrinos are small packets of energy, invisible and with no electric charge. Whether they have mass or not is a question discussed by scientists. The word neutrino comes from little neutral ones, relating to the specifics of these small subatomic particles that are part of conserving the energy of the Sun. Their existence was postulated more than half a century ago by Wolfgang Pauli, based on the fundamental principle of conservation of energy within a system, and were first detected in the early 1950s. Neutrinos pass right through matter, and are not easily observable, and only in the 1970s did physicists develop the first capabilities to detect neutrinos emitted directly from the Sun fusion reactions.

Fusion reactions in the Sun can only be observed through the neutrino emission from the main proton-proton chain reaction in the core. Thus, to obtain more information and knowledge about these fusion reactions, and also to understand the before mentioned energy conservation in the Sun, it is important to study the neutrinos and understand their formation and existence.

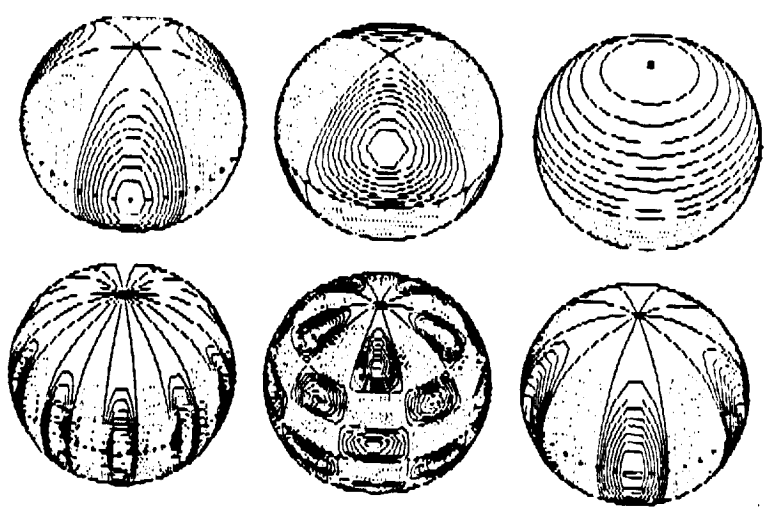


Fig. 4.5 **Modes of oscillation in the Sun [Friedman, 1986].**

Helioseismology is the study of solar oscillation. Modern helioseismology dates back to 1975 only, when new technology and methods made it possible to further study the spatial and temporal properties of the solar oscillations. This gives us the necessary tools to measure the depth of the solar convection zone, the internal rotation profile, the sound speed throughout the Sun, the equation of state of partially ionised plasmas and the solar helium abundance in the solar convection zone, by analysing the three different types of small-amplitude oscillations of the solar body about its equilibrium state:

- pressure-modes (p-modes), the pressure is the dominant restoring force, the wave propagates by compression and rarefaction at the speed of sound [Friedman, 1986]
- gravity-modes (g-modes), the gravity or buoyancy is the dominant restoring force on a displaced mass of solar matter
- surface-modes (f-modes), nearly compressionless surface waves, also called interface modes [American Association for the Advancement of Science, 1996].

Helioseismology uses all available pulsation data, including growth rates, phases, different modes--and not just observed frequencies--to search the internal structure and evolution of the Sun.

In figure 4.5, contour plots of selected modes of oscillation of the Sun are shown. Solid lines represent expansion, dotted lines contraction. The longer the period of these pulsation, the deeper within the Sun is the origin of the vibration. Though impressive accomplishments have been made, there are problems related to background noise when extracting information about the Sun's oscillation from measurements and observations. These limitations are however well understood [ESA, 1995]. As the science of helioseismology improves, solar oscillations will give valuable information about the interior of our Sun and about the processes happening within the Sun.

4.2.3 The Solar Photosphere

The photosphere is the first layer of the atmosphere of the Sun, and the main part of the visible and infrared light is coming from it. It has a very small depth of only 200 to 500 kilometres.

A *typical* **granule**, a convection cell in the photosphere, measures 110 km across, though it is not clear whether there is a defined size scale for granules since they seem to be steadily more numerous the smaller they are. The larger granules are bright, polygonal areas separated by darker channels, called intergranular lanes. A typical distance between two granules is about 1400 km. The smaller ones appear less regularly shaped. It has been claimed that granules are on average smaller at sunspot maximum than at minimum. The brightest part of a granule is generally about 30% brighter than the intergranular lanes. This means the temperature in centre is about 400 K greater than in the outer region of the granule. Their appearance is altered near sunspots, and they become lengthened when they are in contact with the penumbral boundaries of spots. Granule lifetimes average about 18 minutes, with the largest granules lasting the longest. It seems likely that granules are rising convection cells of hotter gas and intergranular lanes descending currents of cooler gas. There are strong horizontal flows from the centres of granules towards the intergranular lanes.

Another convection is observed in the Doppler-shift of lines which indicates horizontal flows occurring over tens of thousands of kilometres. These cell structures are about 30,000 km across and last a day, revealed by an outward, almost horizontal flow of material from the centre of the cell to its sides, with velocities of 0.4 km/s. This phenomenon is called **supergranulation**. The improved resolution of solar photographs in recent years has resulted in the identification of a very fine bright structure in the spectroheliograms taken in the light of weak Fraunhofer lines. This consist of tiny bright points, **filigree**, strung along the dark lanes between granules, frequently clustering to form linear structures, called **crinkles**. The smallest elements are perhaps 150 km in size and last for about 20 minutes. They are a few hundred Kelvin hotter than the surrounding photosphere, and are associated with high magnetic fields. Connected with

these are **faculae**, the most conspicuous seen in the neighbourhood of sunspots. Others occur at high latitudes and are therefore known as polar faculae. Both are associated with high magnetic fields and both vary in number over the course of the solar cycle.

A comparison of the solar spectrum with the ideal case of a black body in thermal physics shows a crude similarity with the radiation curve of a black body at about 6000 K. This is very roughly the temperature of the photosphere. Over the height range of the photosphere, the temperature decreases from about 6400 K at the base to 4400 K at the top. Beyond this level, temperature increases again, so that there is a temperature minimum region. In visible light a point at the limb is at a level just beneath the temperature minimum, so you see a less hot part of the atmosphere than at the Sun centre, being less intense and somewhat redder. This decrease of solar intensity towards the limb is called **limb darkening**, it is very noticeable in whole-Sun photographs.

There are several possible line broadening mechanisms. The first is that resulting from the motion of emitting atoms. The atoms move in all possible directions and any line will have its profile broadened. This broadening is called **thermal Doppler broadening**. The second mechanism is connected with the amount of time an atom spends in its upper energy state. An atom making a transition from this state to the lower state emits a photon with a small energy range. The spectral line formed is said to have **natural broadening**. For certain lines, **collision broadening** is important. Charged particles do not collide in a billiard-ball sense, but pass near enough to come under the influence of the electric field. The orbiting electron will gain a momentary perturbation. As these collisions are random, the perturbations are random and so any emission line is broadened.

The photospheric magnetic field is measured by the Zeeman splitting of certain photospherically formed Fraunhofer lines. The largest field strengths occur in sunspots (0.4 T). Fields exist elsewhere, and indeed it is likely that the entire solar surface is pervaded by at least a very weak field.

A **sunspot group** generally appears on a magnetogram as a bipolar magnetic area, with the leading spot having the largest field strength of one polarity and the following spots slightly weaker fields of the opposite polarity. In addition to the active regions, there are many very small bipolar magnetic areas without spots. They even appear when the sunspot cycle is near minimum and they have lifetimes of even less than a day. The small-scale magnetic field is also associated with the **filigree**, which occurs where the field is particularly strong (about 0.1 T). There are also small clumps of field concentration distributed round the boundaries of supergranules. They are coincident with structures observed in the chromosphere forming a **chromospheric network**.

4.2.4 The Solar Chromosphere

The photospheric Fraunhofer spectrum is, at the moment when a total solar eclipse begins, suddenly replaced by an emission line or **flash spectrum**. The strongest emission lines are the Hα line and the H and K lines produced by Ca^{+}. Therefore spectroheliograms made in the light of these lines are used to study the chromosphere. In addition to that, observations in the UV light can be made by spacecraft.

The outer edge of the chromosphere is very irregular. The edge is found to be made up of numerous fine jet-like structures, the so called **spicules**. An individual spicule is revealed to be a narrow column, a few hundred kilometres in diameter, ascending almost radially into the corona with velocities of about 30 km/s. It is attaining an altitude of about 9000 km and last approximately 15 minutes. Spicules are very numerous, but they can only be seen in the solar limb. On the disk of the Sun there are small dark regions

(about 1000 km) visible, which are associated with an upward motion in the chromosphere. Therefore these so called **fine mottles** are assumed to be the spicules seen on the disk. They are located on the boundaries of the supergranulation of the photosphere and have an average lifetime of 10 minutes.

An average lifetime of some hours and a size of 2000 to 8000 km have got the **coarse mottles**. These dark areas form the "chromospheric network". The individual network cells are about 30,000 km in diameter and last for some days if the chromosphere is quiet. These patches in the vicinity of sunspots or other active regions are the most conspicuous features of the spectroheliograms, particularly in the K-line images.

Sunspots, faculae and filaments are not directly connected to each other. They are different responses to a perturbation of the magnetic field. The chromospheric features and photospheric magnetic field are related on both small and large scales.

The most striking instance of solar activity is the solar **flare,** sudden release of energy appearing as electromagnetic radiation over an extremely wide range and as mass, particle, wave and shock-wave emittance. Flares invariably occur in active regions, being most common and largest when the region is in a rapidly developing state. They can last only for some minutes or for some days.

Although much information about the chromosphere can be obtained from images made at the wavelength of lines in the visible spectrum, there is no indication of the connection between the chromosphere and the overlying, much hotter corona. This connection can be studied by observing the Sun in the ultraviolet part of the spectrum and in short wavelength radio waves. The UV lines of the chromosphere, corona and transition region tell us a great deal about the structure of the solar atmosphere.

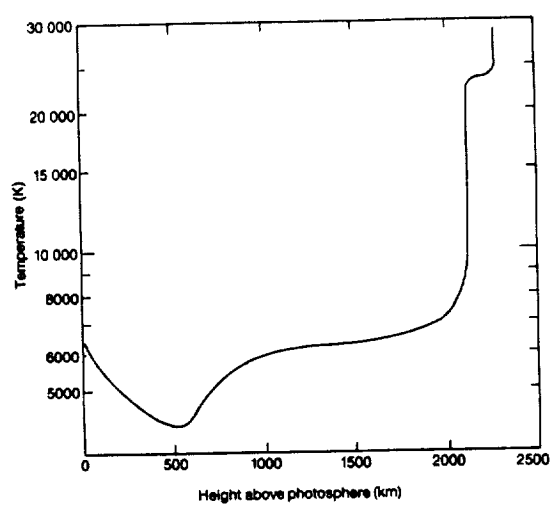


Fig. 4.6 **The variation of temperature with height in the solar atmosphere [Phillips, 1992].**

From the base to the top of the photosphere, there is a decrease of temperature owing to a decrease in the density of H^+ ions, reducing the ability of the photospheric gas to absorb energy and maintain its temperature. However, as seen in figure 4.6, above 500 km altitude the transport of non-radiative energy, whatever form it takes, leads to a rise of temperature. This results in an increase in the ionisation of hydrogen, so there is a greater number of free electrons and protons. The electrons are available for collisional

excitation of certain atoms and ions, which de-excite by emitting line radiation. These emission lines include Hα and the H- and K-line of Ca^+. Although energy is still delivered to the middle regions of the chromosphere in some form, the temperature hardly rises at all because that energy is being radiated away. The radiating atoms and ions act as a "thermostat", and a broad temperature plateau is thereby formed.

There is a limit to these effects, as the supply of neutral hydrogen atoms becomes depleted and further input of energy does not produce such a large number of free electrons. The amount of energy radiated away cannot any longer compete with the energy that continues to pass into the chromosphere so that the temperature rises sharply. This is the **transition region**.

In the corona, there is a number of very highly ionised atoms that radiate a lot of energy, much more than the neutral or singly ionised atoms. This would be expected to result in a flattering out of the temperature rise, as in fact happens, with the temperature of about 2,000,000 K. Much effort has been taken into what forms the rise of temperature for the chromosphere. Wave motions generated in the photosphere are a promising candidate for heating the chromosphere. Sound waves by themselves do not heat the gas they pass through, but merely cause the gas particles to oscillate. But a sound wave travelling outwards from the photosphere soon encounters gas with much lower density and because of this is altered. So the form of the wave is more and more distorted until a *shock front* is formed. The passage of such a front through the atmosphere does give rise to heating. This mechanism is assumed to be responsible for the heating of the lower chromosphere.

Above the lower chromosphere, the role of the magnetic field is thought to be important. Magnetic field lines in a plasma or ionised gas are subject to wave motions called magnetohydrodynamic (MHD) waves. One can imagine the field lines behaving like tensed elastic bands. The wave would give up some of its energy if the plasma were not perfectly conducting, i.e., were slightly resistive, and this energy could be available for heating the the gas through which it passes.

4.2.5 The Solar Corona

Above the transition region the solar corona extends outward into the Solar System. It is an extremely hot and very tenuous plasma with a density of about 10^{-15} g/cm^3. The mechanism that pumps energy into the corona and heats it up to about 2 million Kelvin still remains one of the most fundamental unresolved question in solar physics. It is believed that the main cause for the heating of the corona is different than the one responsible for heating the chromosphere.

About one in a million photons emitted from the photosphere is scattered by the corona. This **white-light corona** has a brightness equivalent to that of the full Moon and thus can only be observed during total eclipses. The spectrum of this radiation up to heights of about 2 solar radii is continuous (*K corona*), reflecting the fact that the light is scattered by electrons. Even further away dust-scattered **absorption lines** become dominant (*F corona*), but at those distances the brightness is already 2 orders of magnitude lower. In addition, there are many **strong emission lines** that could not be identified for a long time until they were recognised as forbidden transitions between highly ionised atoms such as Fe X and Fe XIV. This was the first hint for the extreme thermal conditions and the low density of the corona. Another hint are the **radio bursts** from decimetres upward emitted by the corona; they give an upper limit for the plasma frequency and thus for the density. Finally, the corona's **X-ray and Ultraviolet emission** in the form of both emission lines and a continuum, provides the most accurate means to determine the temperature.

In the 1960's we only had a very simple *model of a spherically symmetric corona.* It was believed that the dissipation of sound waves superheats the corona [McWhirter *et al.*, 1975], which in turn leads to the solar wind [Kivelson and Russel, 1995]. However, with the advent of high-resolution X-ray telescopes it became apparent that the corona is in fact highly inhomogeneous with complex structures theoretically treated as *magnetic loops* [Rosner *et al.*, 1978, Vesecky *et al.*, 1979, Withbroe, 1981]. In the view of the 1990's, the **fast solar wind** only arises away from the loops in the **coronal-hole** regions. There the plasma is much hotter than in average, and also less dense, since it is drained by the wind. It is still not clear where the **slow solar wind** originates from. It might arise between narrow open-field channels between coronal loops, or "evaporate" from large, old loops.

The connection between magnetic fields and loop structure led to a proposed connection between magnetic fields and coronal heating in place of the old notion of acoustic heating, which would have been far too uniform to account for active regions. However, there has not been an agreement yet on the actual mechanism. *Heating by electrical currents*, that are naturally associated with twisted magnetic field lines, has been suggested, through the use of *nanoflares* [Emslie, 1996], or the dissipation of *Alvfén-waves*.

The observation of **stellar coronae** [Haisch and Schmitt, 1996], as evidenced by their X-ray emission, suggests that coronal emission mostly depends on the existence of a convective zone and the presence of stellar rotation. This gives also a clue that the magnetic dynamo is the underlying cause. For example, in the Hyades cluster stars that look just like our Sun, except for the fact that they rotate 5 times as fast, emit 50 to 100 times brighter in X-rays [Stern, 1996].

4.2.6 Solar Activity

An **active region** [Tsuneta, 1996] is an area on the Sun with a lot of magnetic field activity in the form of sunspots, pores, and plage. **Sunspots** are regions where the very strong magnetic field rises up from below the surface of the Sun [Azariadis and Guesnerie, 1986]. Sunspots appear darker than their surroundings because they are a few thousand degrees cooler than their surroundings. Sunspots range in diameter between about 2500 km and more than 50,000 km. A sunspot is roughly circular in shape, though some are have a very irregular shape. Because the closed nature of magnetic field, sunspots usually come in pairs or groups. Sunspots have two distinct parts: the umbra and the penumbra. The umbra is the central, darkest part of a sunspot. The penumbra is an annulus around the umbra of a sunspot. Several sunspots can be seen in the full-disk continuum image.

The amount of magnetic flux that rises in the Sun varies with time in a cycle called the **sunspot cycle**. This principal cycle lasts 11 years on average. **Pores** are like small sunspots but without a penumbra. Pores get up to about 2500 km in diameter and are less dark than sunspot umbrae. The **plage** is an area on the solar surface that looks brighter than its surroundings when observed in the centre of a spectral line. An active region is essentially a collection of intense magnetic loops; they together from a magnetic bubble, or magnetic sphere of influence, in which the strong magnetism dominates the motion of charged particles in its vicinity. Energised material is also concentrated and enhanced within solar active regions where magnetic loops shape, mould and constrain the material and give rise to intense radiation at both visible and invisible wavelengths. Active regions contain relatively cool loops, such as those found in prominences, as well as very hot ones. Active regions are never permanent, but instead continually alter their magnetic shape. They are the seat of change and unrest on the Sun. The interacting magnetic forces can, for example, trigger the catastrophic release of magnetic energy stored within active regions, resulting in energetic eruptions, called solar flares. Indeed,

the continually evolving magnetic structure and intense radiation, as well as the eruptive solar flares, give active regions their name. The whole range of activity varies with the 11-year solar cycle. Big active regions may grow to 160,000 km in diameter and remain for two months or more, but small ones may appear and disappear within a matter of days.

Prominences are clouds of solar material that float up to about 50,000 km above the solar surface [Bothmer and Schwenn, 1994; Lang, 1995]. They can be observed in the centre of strong spectral lines but not in the continuum. When seen beyond the limb of the Sun, these clouds appear bright. When seen against the solar disk, the clouds appear relatively dark and are called filaments. **Filaments** can be seen only in the centres of strong spectral lines, such as Ca, K or H-alpha. We can see several filaments in the full-disk H-alpha image. Filaments and prominences can remain for up to about two months, though some of them disappear much faster. Some seem to appear as a result of solar flares. The electrically-charged gas that makes up a prominence or filament can hover above the Sun for weeks or months at a time, supported against the downward pull of gravity by the magnetic fields that arch above bipolar regions in the underlying photosphere. The long, thin filaments lie at the tops of magnetic loops, along the magnetic neutral line centred between regions of opposite magnetic polarity. Apparently the gas is held up by numerous magnetic arches, extending in a line, each sagging at the top into a hammock-like shape. Despite its flamelike appearance when viewed at the solar limb, a prominence is about 100 times cooler and denser than the surrounding material. The magnetic fields that support a prominence or filament also act as a shield and insulate it against hotter surrounding material.

Solar flares are enormous "explosions" in the solar atmosphere, involving sudden bursts of particle acceleration, plasma heating, and bulk mass motion [Feynman and Hundhausen, 1989, 1994, Lang, 1995]. Solar flares are believed to result from the sudden release of energy stored in the magnetic fields that thread the solar corona in active regions around sunspots. Usually solar flares are observed inside active magnetic regions between the upper chromosphere and the lower corona. Solar flares may last from seconds up to hours. In the largest flares, 10^{27} J or more can be released in a few minutes. Such large flares only occur a few times within a year or two of the solar activity maximum. Many smaller flares occur down to the limits of detectability of modern instruments at about 10^{20} J. These smaller events generally last for shorter times down to a few seconds; their occurrence rate also follows the 11-year cycle, peaking at several tens of flares per day. The detailed mechanism of flare generation is still unknown. Interesting features of the region include a long twisted X-ray structure, which formes shortly before the flare and disappears after it, being replaced by a system of unsheared post-flare loops. Neither the X-ray nor H-alpha morphology nor the photospheric magnetic field show any indication of gradual build-up of nonpotential energy prior to the flare. Rather, the long structure appears to result from the **reconnection** of two shorter ones just tens of minutes before the filament eruption and flare.

Coronal mass ejections (CMEs) are considered the key causal link with solar activity [Feynman and Hundhausen, 1994]. CMEs are spectacular manifestations of solar activity and also the most energetic events in the Solar System. The magnetic loops become unstable, carrying out billions of tons of coronal material as they lift off into space. The outward-moving CMEs stretch the magnetic field until it snaps, leaving behind only bright rays rooted in the Sun. They can expand to become larger than the Sun itself, streaming outward past the planets and dwarfing everything in their path. Such events work only in one direction, always moving away from the Sun into interplanetary space and never falling back in the reverse direction. CMEs are vast bubbles of plasma and magnetic fields expelled from the Sun into the heliosphere [figure 4.7]. They often exhibit

a three part structure: a bright loop, followed by a depleted region, or cavity, that rises above an erupted prominence. The leading bright loop, or CME, may be formed by a rapidly expanding, bubble-like shell that opens up and lifts-off like a huge umbrella in the solar wind, piling the corona up and shoving it out like a snowplough. When the global magnetic fields become unstable, the CMEs erupt, carrying significant amounts of energy and matter into large volumes of interplanetary space. Five billions tons, or five million billion grams, of solar material are thrown outward during an average ejection with typical speeds of a few hundred kilometres per second. Some of them are ejected so forcefully that they move with speeds of up to 2000 kilometres per second. In the larger CMEs, up to 10^{13} kg of coronal material may be ejected outward at speeds as high as 1000 kilometres per second. The energy of this mass motion is comparable to the net radiated energy of a large solar flare.

The theoretical explanation of these activities are as follows. According to one scenario, large-scale, oppositely-directed magnetic fields come together and merge to energise solar eruptions. Such a magnetic configuration is suggested by the bulb-shaped base and elongated stem of a helmet streamer; they respectively consist of low-lying closed magnetic fields and magnetism that opens up to the interplanetary medium. A theoretical model that invokes large-scale magnetic connection has been dubbed the **CSHKP model** [figure 4.8; Lang, 1995].

Some flares detected in Yohkoh's soft X-ray images exhibit a helmet-shaped geometry when detected at the Sun's apparent edge or limb. In this X-ray structure, opposing magnetic fields stretch out and are brought together at the top of a coronal loop. This lends support to the CSHKP flare model in which the magnetic structures open and close like a sea anemone. The initially closed coronal loops open up-allowing the catastrophic release of energy and material stored within the coronal loops and then close again as the magnetic fields come back together. The closed magnetic loops become buoyed up and inflated, and a CME results. The mass ejection, with its accompanying erupting prominence, blows open the previously closed magnetic structure, like a hot-air balloon that breaks its tether. The associated flare is the result of the energy released by magnetic coupling of the open field lines as they pinch below the rising prominence.

Non-thermal electrons accelerated at the site of magnetic connection produce the radio and hard X-ray radiation of a solar flare. Flare loops are subsequently detected at soft X-ray and H-alpha wavelengths, shining from the newly closed magnetic loops in the flare's thermal afterglow. A loss of equilibrium in the large-scale magnetic field configuration apparently drives a CME outward. The corona may not be altogether surprised by this development, and may be expecting it. Mass ejections occur in pre-existing coronal streamers that bulge and brighten for one to several days before erupting. The helmet streamer is then blown away by the ejection and disappears.

Therefore, it looks as if CMEs could be magnetically controlled and driven as the theoretical model suggests. Yet, while we believe magnetism to be the ultimate source of energy involved in both solar flares and CMEs, no one has ever measured the predicted depletion of magnetic energy that supposedly spawns eruptive outbursts on the Sun. Perhaps the instruments are not sensitive enough, or maybe all the magnetic action occurs in the unseen corona. The available magnetic energy might greatly exceed the amount released during a solar eruption, so little overall change in the magnetism would be observed, but if this is the case why aren't the eruptions more powerful and why don't they occur more frequently?

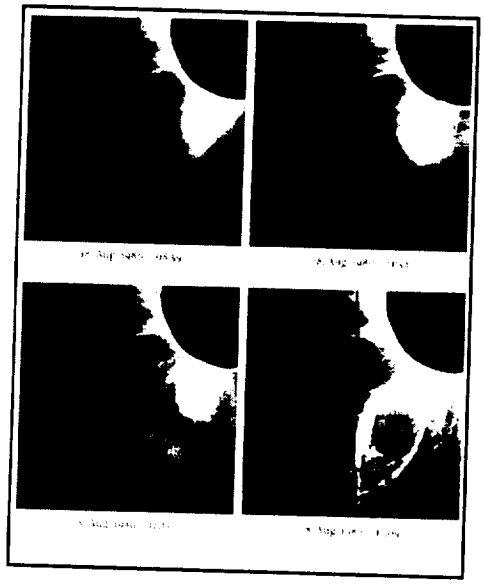


Fig. 4.7 **Coronal mass ejections [Lang, 1995].**

Whatever the explanation, we have no direct observational evidence that stored magnetic energy powers eruptions on the Sun. Moreover, even if current-carrying magnetism does supply the energy, the exact mechanism of releasing that energy and converting it into heating the gas and the acceleration of particles remains unknown. It has been supposed that the energy required for eruptions is stored in stressed magnetic structures, and that the magnetic fields rearrange themselves into a simple configuration after the event. Solar flares do, in fact, occur in regions of strong magnetic shear in the photosphere. However, many sheared regions never erupt, so contorted magnetism seems to be a necessary but not sufficient condition for solar eruption.

Debates continue to rage over exactly what strikes the match that ignites explosions on the Sun. Magnetic fields coiled up in the interior could bob into the corona and interact with pre-existing ones, or existing coronal loops may be brought into contact by the shearing and twisting motion of their photospheric footprints. The eruptions might even be triggered by the disappearance of coronal loops when they cancel out and return back inside the Sun. It could be the emergence , interaction or submergence of coronal loops, but no one knows for sure.

Thus, the Sun's sudden and unexpected outbursts remain as unpredictable as most human passions. They just keep on happening, and even seem to be necessary to purge the Sun of pent-up frustration and to relieve it of twisted, contorted magnetism.

Billion-ton bubbles of hot gas grow larger than the Sun in just a few hours. This time-sequence of coronagraph images, covering just over 4 hours, illustrates some of the principal features of many CMEs the presence of a bright, outer loop of material, followed by a dark cavity, under which is visible a bright loop-like structure identified with erupting prominence material. According to a version of the CSHKP model proposed by Peter Sturrock in 1968, the magnetic reconnection results in high-energy particle acceleration of two bright ribbons in the chromosphere.

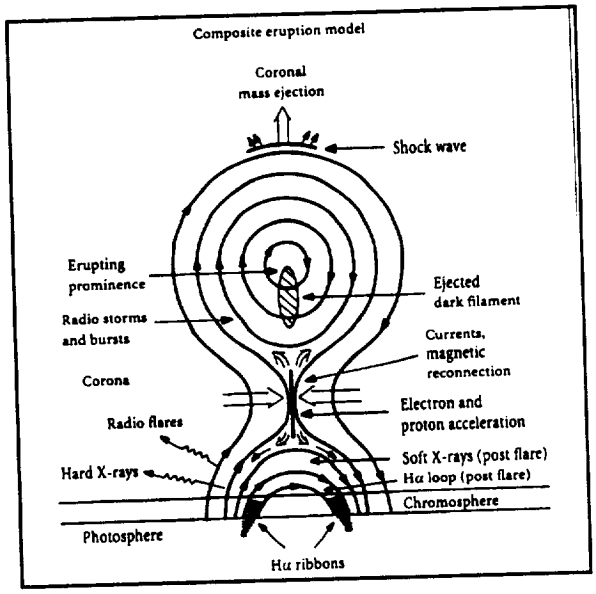


Fig. 4.8 **Composite eruption model [Lang, 1995].**

In this cross-sectional view, a CME, and the erupting prominence that follows it, blast an open pathway into previously closed magnetic fields. Energetic electrons accelerated at the reconnection site give rise to intense, impulsive radio and hard X-ray radiation. When the reconnected magnetism regroups to form closed structures, post-flare loops shine at soft X-ray and H-alpha wavelengths.

4.3 Interplanetary Space

This section introduces in the basic physics that is known about the solar wind, the interplanetary magnetic field and several dynamic features like magnetic clouds and the propagation of CMEs. Furthermore a brief description of galactic cosmic rays is given.

4.3.1 Solar Wind and Interplanetary Magnetic Field

Solar wind is an invisible flow of superheated, charged coronal gas flowing continuously out of the Sun. The particles traverse outwards into interplanetary space, eventually hitting bodies. Solar wind consists not only of particles from the Sun, that is plasma consisting of protons and electrons, but also of particles from the interplanetary medium, including comets, asteroids, and atmospheres of planets and satellites.

Solar wind composition can be determined in great detail by observations. If the composition of the corona--where the solar wind originates--is known, assumptions can be made also about the composition of the interplanetary medium. Generally, solar wind consists of 95% protons (H^+), 4% alpha particles (He^{++}) and 1% minor ions: carbon, nitrogen, oxygen, neon, magnesium, silicon and iron. The energy of the ions range between 0.5 and 2.0 keV/nucleon, at a density of 1 to 10 particles per cubic centimetre.

There are two types of solar wind, slow and fast. These are affected by the solar magnetic field, and as the slow and the fast solar wind leaves the Sun surface, the two interact because of the rotation of the Sun and create compression and rarefaction, forming the so called *corotating interaction regions*. The fast plasma in the stream overtakes the slower plasma and collides with it. The plasma and the magnetic field are compressed, the plasma is heated up and pressure waves are produced. These pressure waves enhance

the accelerating of the slow plasma ahead and the decelerating of the fast plasma behind. *Shock waves* are formed if the speed of the faster plasma is higher than the speed of sound in the surrounding plasma. On the front edge of the pressure waves a front shock with enhanced pressure, density, and plasma velocity is formed whereas on the back edge a back shock with decreased pressure, density and plasma velocity is created [Marsden, 1986, p.191].

The solar wind velocity in the ecliptic plane is generally between 300 and 600 km/s, although in seldom cases velocities in the range of 200 to 1000 km/s can be reached. According to the frozen-in theorem, the expanding solar wind drags the solar magnetic field outward, forming what is called the *interplanetary magnetic field* (IMF). The region of space in which this solar magnetic field is dominant is called the *heliosphere* with it's boundary, the *heliopause*, separating the IMF from the stellar magnetic field. Although the solar wind moves out almost radially from the Sun, the rotation of the Sun gives the magnetic field a spiral form (garden hose effect) as indicated in figure 4.9. At the orbit of the Earth the angle between the field lines and the Earth-Sun line is about 45 degrees.

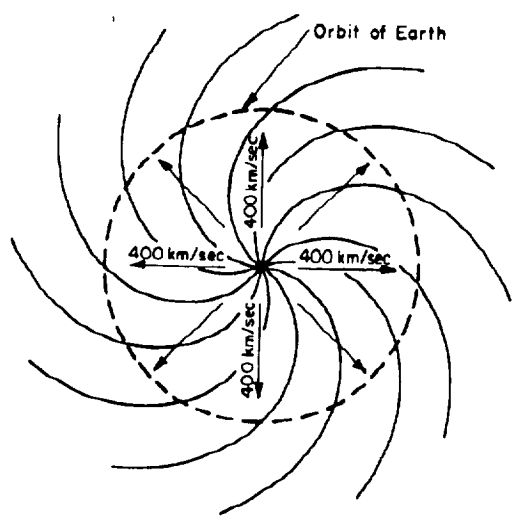


Fig. 4.9 **Spiral IMF lines frozen into a radial solar wind expansion at an average speed of 400 km/s. [Kivelson and Russel, 1995].**

The heliospheric neutral sheet or current sheet separates the oppositely directed magnetic field-lines nearly in the Sun's equatorial plane. This sheet is bent like the skirt of a ballerina and, as a consequence of the rotation of the Sun, the Earth is either above or below the neutral sheet. Therefore, sectors (typically four) with alternating inward and outward directed magnetic fields can be identified. This model is often called the sector or ballerina model of the IMF. Even though the energy density of the magnetic field is small in comparison with that of the solar wind plasma, the IMF seems to play an essential role in space physics.

As solar wind spreads into space and reaches different bodies, it spreads around them in different ways, according to their size, and whether they have a magnetic field or not. Figure 4.10 shows the four principal types of solar wind interaction with planetary bodies: the Moon, an unmagnetised body without an atmosphere; the Earth, a magnetised body; a comet, an unmagnetised body with negligible gravity; and an unmagnetised body with an atmosphere (e.g., Venus).

4.3.2 High Energy Particles and CMEs

Very high energetic electrons and protons are sometimes ejected from the Sun. These bursts of particles are accelerated probably in two stages in solar flares. These particles are forced to follow magnetic field lines in the interplanetary space. This means that they are different from the solar wind. Energies can reach typically from 10 keV to a few MeV for electrons and from 10 MeV to 100 MeV for protons. Because of their high speed they encounter the Earth in twelve to twenty minutes.

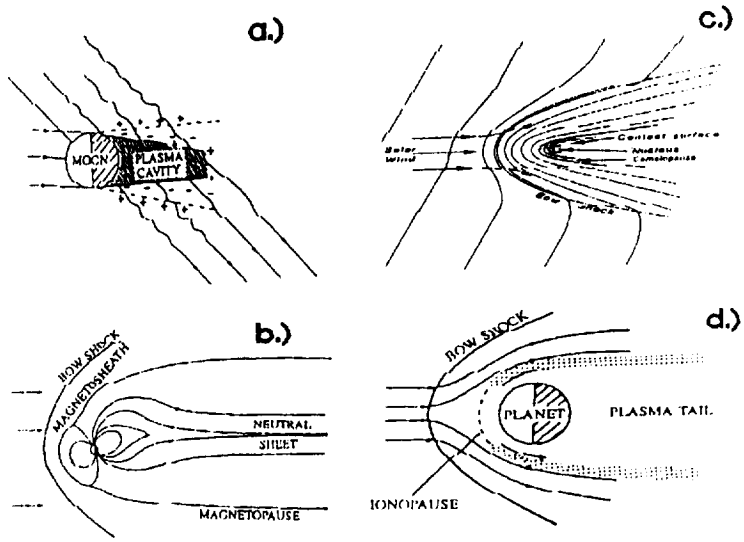


Fig. 4.10 Interaction with bodies in the Solar System [Biernat *et al.*, 1994].

The field lines the energetic particles follow must originate on the visible side of the Sun. However, it is possible for particles to move across the field lines in the inhomogenous magnetic field area near the Sun [Buttighoffer, 1996]. Thus they can move parallel to the surface of the Sun before final acceleration along the field line. As a result of that it may happen that particles encountering the Earth's environment are coming originally from a flare occurring on the backside of the Sun [Svestka, 1976].

Origin of CMEs at the Sun is considered in section 4.2.6. CMEs represent a great concentration of mass and energy transferred from the corona of the Sun to the IMF. They can be taken as bubbles in the solar wind. These bubbles are reservoirs of plasma trapped by closed field lines to cloud-like formations (also rope-like forms occur). A formation moves with velocities up to 2000 km/s. If the velocity is higher than the speed of sound a shock wave forms ahead of the CME. CMEs are characterised by strongly enhanced helium abundance and bi-directional streaming of supra-thermal electrons and energetic particles.

Magnetic field lines in the leading edge of the CME and of the IMF are compressed and draped. If, in addition, the strong field in the leading edge of the CME is southward, this may result in a severe storm on Earth. CMEs drive all large geomagnetic storms [section 4.4.3] and their attendant effects, such as auroral displays [section 4.4.5]. Fast CMEs produce transient inter-planetary (IP) shocks which cause sudden storms on the Earth. The CME-related shocks also accelerate the solar energetic particle events associated with major IP disturbances and with radiation hazards at Earth. The geomagnetic index used to quantify the magnitude of geomagnetic storms [section 4.4.3] is highly correlated with

the solar wind speed and the strength of the southward component of the IMF. These parameters are in general enhanced during the passage of IP CMEs [Marsden, 1986].

Approximately one-third of the CMEs are *magnetic clouds*. A magnetic cloud is defined by relatively strong magnetic fields, a smooth rotation of the magnetic field direction over approximately 0.25 AU at 1 AU, and a low electron and proton temperature. Magnetic clouds have a loop-like structure and are connected to the Sun [Burlaga and Lepping, 1990] as illustrated in figure 4.11. Magnetic clouds are expected to propagate with constant speed which depends on the surrounding solar wind velocity [Umar and Rust, 1996], but the direction of propagation is deflected by a few degrees from the radial direction [Smith *et al.*, 1996, Vandas *et al.*, 1995, 1996]. Magnetic clouds are ideal objects for solar-terrestrial studies, first because of their simplicity and their longevity of passage. Secondly, their extended intervals of southward and northward magnetic fields combined to smooth the variation of the field (as well as bulk flow velocity) makes effects to the magnetosphere very slow compared to its characteristic time-scale [Biernat *et al.*, 1994].

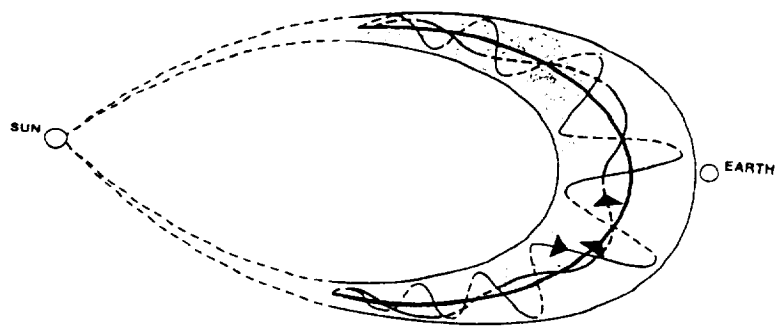


Fig. 4.11 **A schematic showing a magnetic cloud modelled as a toroidal magnetic flux rope** [Biernat, H. K. *et al.*, 1994].

4.3.3 Galactic Cosmic Rays

Galactic cosmic rays (GCR) are extremely energetic (~10^9 eV) charged particles, consisting mostly of protons, that enter the heliosphere from the interstellar medium.

In the measurements made on Earth, and in outer-space, it has been found that the intensity of the GCRs in the Solar System is regulated to a large extent by solar activity: the maximum intensity of GCR occurs during the minimum solar activity, and the minimum intensity during the maximum solar activity.

One of the main present day challenges has been to study the GCR in their unchanged form. As the GCR coming from the interstellar space are changed considerably by the magnetic field lines in the solar wind, the best location to find relatively unchanged GCR is near the poles of the Sun, where the solar magnetic field is not as strong as near the equator.

4.4 The Sun-Earth Interactions

This section introduces the basic physical properties of a region often referred as *Geospace*. This term includes the magnetosphere, the ionosphere, the atmosphere and the

interaction in between. Furthermore their dynamics will be described including magnetospheric storms and auroral lightning.

4.4.1 The Earth as a Magnet

For the space physicist, the most important aspect of the Earth is that it has a magnetic field. The English physician and natural philosopher William Gilbert was the first to demonstrate this [Gilbert, 1600], although the effects of terrestrial magnetism had been utilised much earlier by the Chinese in primitive compasses.

In first order the magnetic field is that of a dipole whose axis is tilted with respect to the spin axis by about 11 degrees. The south magnetic pole is presently located off the western coast of Bathurst Island, in the Canadian Northwest Territories, almost 1290 km north-west of Hudson Bay. The north magnetic pole is presently situated at the edge of the Antarctic continent in Adélie Land about 1930 km north-east of Little America. The magnetic field points down towards the surface of the Earth in the northern hemisphere, and away from it in the southern hemisphere.

The magnetic field can be divided into two parts: the main field and the variation field. The first has the origin in the Earth's outer core which is supposed to be liquid and to have a high amount of iron. The electric currents there are due to thermal convection and are the source for the main field. It changes very slowly in time and space and these changes are called *secular changes*. The latter is due to currents in the ionosphere. The variations there are very fast (compared to the secular changes) but are also very weak. However, they are strong enough to influence the transmission of radio and television signals and are the source of geomagnetic activity on the ground.

4.4.2 The Magnetosphere

The area around the Earth governed by the Earth's magnetic field is called the *magnetosphere*, and its boundary the *magnetopause*. Short definitions of some of the most important magnetospheric regions, currents and fields are shown in figure 4.12. This figure as well as the following information are taken from Kivelson and Russel [1995] and the Space Physics Group of Oulu [1996].

The existence of the magnetosphere is very important, since it shelters the surface of the planet from the high energy particles of the solar wind. However, the pressure of the solar wind and the magnetic field it carries along, the IMF [see section 4.3.1], modify the form of the magnetosphere radically, by pushing it in the dayside and creating a long tail (*magnetotail*) in the nightside. As a consequence, the distance of the magnetopause from the Earth is only about 10 Earth radii (Re = 6371 km) in the dayside, while the tail is about 10 times longer (it was registered by Pioneer 7 in the nightside at more than 1000 Re). In front of the dayside magnetopause another boundary, called the *bow shock*, is formed because the solar wind is supersonic with an average flow speed of about 400 km/s at 1 AU, whereas a typical value for the speed of sound waves in the solar wind plasma is 60 km/s.

The magnetosphere is filled with plasma that originates both from the ionosphere and the solar wind. Because of the magnetosphere-solar wind interaction, the plasma in the closed tail field lines is forced into a large scale sunward motion called the magnetospheric convection. The exact way how the solar wind drives this convection is still under some debate, but it is usually assumed that the Earth's magnetosphere is opened as the interplanetary and geomagnetic fields merge at the dayside magnetopause. In the open magnetosphere model initially suggested by Dungey [1961], merging of the interplanetary and geomagnetic field lines partially opens the Earth's magnetic field to

the solar wind. For this merging to occur, the field lines must be oppositely directed: a southward IMF is thus needed to open the Earth's closed dayside magnetic fields. The antisunward magnetospheric convection is produced when the connected, open field lines are swept over the polar cap at the solar wind speed. The strong correlation between increased geomagnetic activity and a southward directed interplanetary magnetic field supports this hypothesis.

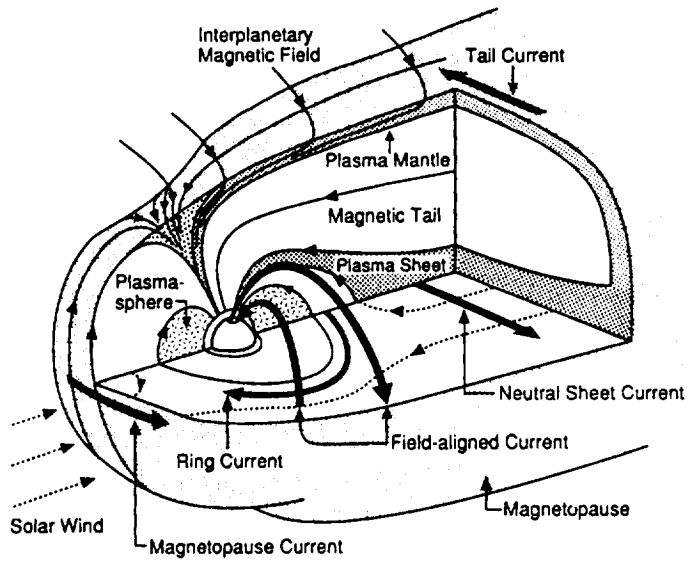


Fig. 4.12 **Three-dimensional cutaway view of the magnetosphere showing currents, fields and plasma regions [Kivelson and Russel, 1995, chapter 1].**

In addition, some models for magnetospheric substorms are based on reconnection models. Substorms are part of a magnetic storm and occur several times therein [see section 4.4.3]. This is quite natural, since the magnetic field lines above and below the *neutral sheet* (*current sheet*) are oppositely directed, and the plasma sheet is typically thinning during the substorm growth phase.

All this is very important for the electrodynamics of the ionosphere- magnetosphere-solar wind system. The coupling between the magnetosphere and the ionosphere is due to *field-aligned currents* (FAC) flowing between these regions and are further described in Section 4.4.4.

The *ring current* flows around the Earth in a circle at distances of about 4 to 6 Earth radii [see figure 4.12]. It is created by hot (tens of keV) plasma with opposite drift directions for electrons (towards dawn) and ions (towards dusk), originally flowing from the tail towards the Earth. It can be measured by ground-based magnetometers at middle or equatorial latitudes because of its diamagnetic effect that means that it decreases the intensity of the Earth's magnetic field.

The plasma in the inner magnetosphere co-rotates with the Earth. As a consequence, the ionospheric plasma at mid-latitudes can expand upward along the magnetic field lines and fill them until the plasma gas pressure is equal along the entire field line. The plasma region above the ionosphere on such closed magnetic field lines is called the *plasmasphere*. The plasmasphere can be considered as an extension of the ionosphere because there is no clear distinction between them. The plasma density inside the plasmasphere is significantly higher than outside, because field lines at higher latitudes are convected to

the magnetopause and are thus open to the interplanetary medium (where the ionospheric-supplied plasma is lost).

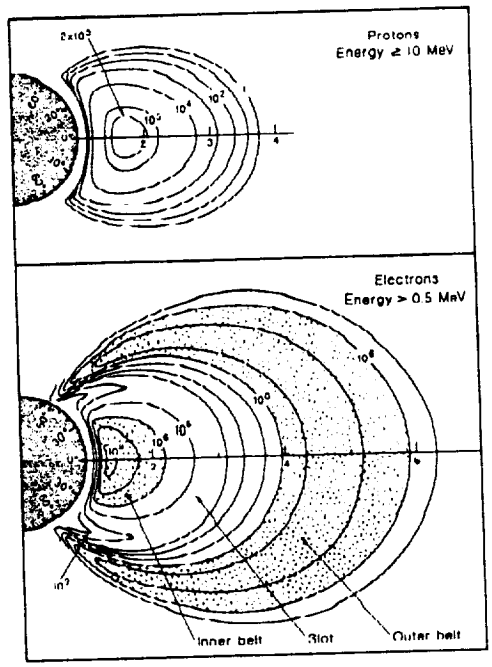


Fig. 4.13 **The Earth radiation belts. The top panel shows the contours of the omnidirectional flux of protons with energies greater than 10 MeV. The bottom panel shows the contours of the omnidirectional flux of electrons with energies greater than 0.5 MeV [Kivelson and Russel, 1995, chapter 1].**

The trapping regions of high-energy charged particles surrounding the Earth are called *radiation* or *van Allen belts* and they are indicated in figure 4.13. The inner one, located between 1.1 and 3.3 Re in the equatorial plane, contains primarily protons with energies exceeding 10 MeV, but also electrons with energies higher than 0.5 MeV. This is a fairly stable population but it is subject to occasional perturbations due to geomagnetic storms, and it varies with the 11-year solar cycle. The source of protons in this region is the decay of cosmic ray induced albedo particles from the atmosphere. The outer belt contains mainly electrons with energies up to 0.5 MeV. It is produced by injection and energisation events following geomagnetic storms, which makes it much more dynamic than the inner belt (it is also subject to day-night variations). It has an equatorial distance of about 4 to 6 Re. The radiation belts are of importance primarily because of the harmful effects of high energy particle radiation for humans and electronics as described in section 4.5.

This was only a brief introduction to the magnetosphere. For more information and further reading see Kivelson and Russel [1995].

4.4.3 Magnetic Storms

Geomagnetic storms are initiated when enhanced energy is transferred from the solar wind/IMF into the magnetosphere, via magnetic field merging [see section 4.4.2], which leads to intensification of the ring current. The ring current, can be measured with the

Dst index [Sugiura, 1964]. The Dst index is obtained from magnetometer stations near the equator. At such latitudes the H (northward) component of the magnetic perturbation is dominated by the intensity of the magnetospheric ring current. Large negative perturbations are indicative of an increase in the intensity of the ring current and typically appear on time scales of about an hour. The decrease in intensity may take much longer, on the order of several hours. The entire period is called a magnetic storm .

The ring current is enhanced via energisation and injection of particles from the tail towards the inner magnetosphere during substorms, which are typical for storm times (note that they can occur also during non-storm times, and that the relationship between storms and substorms may not be understood very well yet). The following storm definition has been proposed by Gonzales :

> Storm is an interval of time when a sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial energisation in the magnetosphere-ionosphere system, to an intensified ring current strong enough to exceed some key threshold of the quantifying storm time Dst index.. [Gonzales *et al.*, 1994]

This notwithstanding, geomagnetic storms, especially the largest ones, often begin with major enhancement of the solar wind velocity accompanied by southward IMF direction referred to as Sudden Storm Commencements (SSC). During a storm, auroral ovals become greatly disturbed, broadening and expanding towards the equator, particularly on the nightside. This brings the aurora to the skies of middle and low latitudes [see section 4.4.5].

Storms are typically divided into three distinct phases according to the signatures in Dst:

<u>Initial phase</u>

- Lasts from minutes to hours. Dst increases to positive values up to tens of nT.
- Dayside magnetopause is compressed inward (perhaps by several Re).

<u>Main phase</u>

- Lasts from half an hour to several hours. Dst can reach negative values of hundreds of nT.
- Ring current is built up by multiple intense substorms.

<u>Recovery phase</u>

- Lasts from tens of hours to a week. Dst gradually returns to the normal level.
- Ring current ions are gradually lost.

Geomagnetic activity as a whole has a seasonal variability with maxima at the equinoxes. This is especially true for intense storms. Furthermore, intense storms show two peaks within the solar cycle, one somewhat ahead or at solar maximum and the other 2 or 3 years after solar maximum. This effect can even be seen in the yearly number of SSCs but the reason for this relationship is not very well understood yet.

Some of the effects of practical importance produced by the magnetic storms are described in section 4.5.

4.4.4 The Ionosphere

The ionosphere is the ionised upper part of the atmosphere at altitudes above about 100 km. It is composed of ionised gas (plasma). Plasma contains mainly neutral particles, but in ionospheric phenomena charged particles have the main role. Charged particles

are affected by electric and magnetic fields. They also carry electric currents and hence cause magnetic fields themselves. Effects of these fields are discussed in section 4.5.

The origin of ionisation is the radiation and particles coming from the Sun. While the magnetosphere shields the Earth from energetic charged particles, the ionosphere shields it from energetic radiation. The atmosphere is a filter which stops all short wavelength radiation from coming to the surface of the Earth.

This filtering effect means energy transfer from the Sun to the Earth and its atmosphere. As a result temperature increases upwards in the upper atmosphere. This region is called the *thermosphere* and the main reason for its formation is solar ultraviolet radiation [Akasofu and Kamide, 1987].

Ionisation rate is at a maximum at altitudes between 100 to 200 km. Up from there ionisation rate falls due to decreasing gas density. Below 100 km the main part of radiation has already been absorbed. Different radiation types penetrate to different depths of the atmosphere depending on their energy and interactions with atmospheric particles. Vertical profile of electron density shows a special layered structure of the ionosphere [see figure 4.14]. Maximum of electron density varies typically between 200 and 300 km, but below that there often appear several "bumps".

All ionisation in ionosphere is caused by outside origins. If this source stops, the plasma will recombine becoming neutral gas. Variation of Sun radiation (day and night) causes clear variation in electron density profile. Also seasonal variations occur, as well as disturbances due to Sun activity, magnetic storms and auroras. At night time the presence of charged particles depends mostly on energetic particle flows (currents) penetrating the ionosphere and causing ionisation, because of the absence of ionising Sun light.

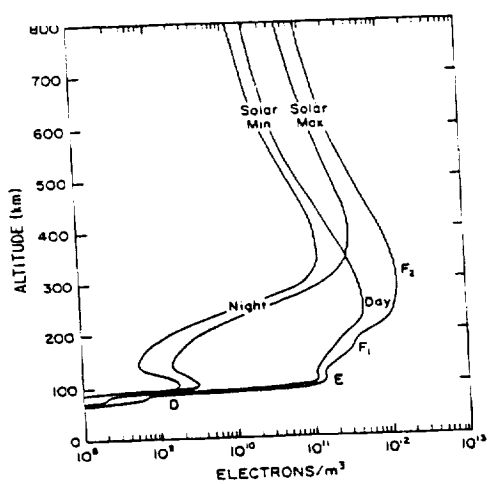


Fig. 4.14 **Typical ionospheric electron density profiles. Different altitude regions of the ionosphere are labelled D, E, F1, and F2 [Akasofu and Kamide 1987].**

The ionosphere and magnetosphere are not separate parts of the Earth's near space. They are coupled with each other by electric currents which transfer energy between them. Currents exist at all times but during magnetic storms and auroral substorms they are strongly intensified. These currents are the result of particle streams which lose their energy due to collisions with atmospheric particles. Collisions cause energy transfer from the current to upper atmosphere and ionosphere due to heating at heights around

100 km. Part of the energy is first stored as excitation energy of atoms and molecules, and is then released as electromagnetic radiation. These currents are based on charged particle reservoirs in the plasma sheet. Magnetic field lines of plasma sheet sets the boundaries of the *auroral oval.* This is the main region of particle streams in the ionosphere.

Currents flowing between magnetosphere and ionosphere are called field aligned currents (FAC or Birkeland currents) illustrating that they flow along the magnetic field lines. Downward and upward field aligned currents are connected in the lower ionosphere by Pedersen currents flowing parallel with the Earth's surface and magnetic meridian. They are closed in the magnetosphere. In the lower part of this loop the electric field is perpendicular to the magnetic field causing drift of currents carrying particles in east-west direction (Hall currents). These currents flowing along the auroral oval are called *auroral electrojets* [Meng *et al.*, 1991].

A weaker current system lies in low latitudes of the Earth. The equatorial electrojet current flows above the equator (at 100 km altitude) to the east. In the evening side this current turns to the south, and it is connected via magnetic field lines to current system in northern side of equator. Currents in the night side are small due to lack of charges [Akasofu and Kamide, 1987].

4.4.5 The Aurora

The aurora is the only visible sign of solar wind-magnetosphere-ionosphere interaction. They can be associated to oscilloscope describing changes in electric and magnetic fields around the Earth.

During magnetic storms energy originating from the solar wind and interplanetary magnetic field, is stored in the magnetic field of the Earth and then released to the atmosphere carried by accelerated charged particles (mainly electrons). During so called quiet conditions electrons don't have typically high energies. However when accelerated in magnetic storms they can gain very high energies. The result is luminosity called auroras when those excited states release emitting electromagnetic radiation (light). This is called *auroral substorm.*

Auroral forms are usually thin curtain-like sheets illustrating the shape of current sheets. Auroral luminosity actually consists of numerous separated emission lines and emission bands. Green 557.7 nm line is dominant in higher heights, except some high altitude red aurora, and in lowest altitudes red lines become dominant due to increasing nitrogen concentration.

Auroral substorms intensify and disturb the current system between the magnetosphere and ionosphere. This intensification can be observed in changing magnetic field on the ground. Luminous effects show currents along the auroral oval. Other auroral phenomena are polar auroras. They are caused by particles coming directly from the solar wind along field lines reconnected to the IMF [Meng, *et al.*, 1991].

Auroral phenomena have many effects on the Earth, its atmosphere and human activities. Heating caused by currents flowing in the ionosphere cause temperature gradients and hence winds. Currents also cause momentum exchange from current carriers to neutral particles resulting in the same effect. One main example of that is neutral particle flow following current from dayside of the Earth to the nightside. Auroral currents cause magnetic fields which can cause effects on the ground and near space as described in section 4.5.

4.5 Effects of the Sun on Earth, Humans and Technology

The Sun is the primary source of energy for the Earth's climate and Biosphere functioning. As solar irradiance changes as a result of solar activity, it is reasonable to think that these variations can affect our climate. A possible climate change could imply, according a variety of predictive models, environmental disturbances such as the shift of terrestrial and marine ecosystems, regional agricultural production change and their related social impact.

Radiation effects on humans mainly provoke different types of cancer, the probability of fatal cancer increases as doses and time exposure increase. On Earth, solar activity can cause many serious medical problems. There are also more direct and less controversial effects on technology, especially outside the magnetosphere's protective barrier and when solar flares occurs. The Sun's influence on the space environment can present hazards to spacecraft and Earth-bound instrumentation, and communication interference in space and on Earth as well. These effects are therefore extremely important to take into account in space missions.

These are the main reasons why we should understand better the Sun-Earth system, solar activity mechanisms, and their effects on Earth, humans and technology by obtaining new data from space and solar probes missions.

4.5.1 Effects of the Sun on Earth's Climate and Biosphere

Since the Sun provides the energy which drives the climate system, variations in solar output are obviously a potential mechanism for driving climate changes. At present, there is already statistical proofs of a correlation between the Earth's temperature and variations in the solar cycle. However, climate change is thought to be mainly influenced by atmospheric concentrations of greenhouse gases, therefore, first we need to know the climate dynamics and the main critical parameters to its change in order to analyse objectively the effects of solar activity on the variation of Earth's climate.

Environmental and social implications as a result of climate change have been widely discussed for several decades. The unpredictable and maybe catastrophic consequences are extremely important to our society. The possibility to determine the greenhouse warming signal and predict long-term climate changes by appropriate modelling of the Sun's dynamics could be a critical issue to save uncountable human lives, avoid hunger starvation and loss of biodiversity.

Global Climate Change

It is thought that real warming of the globe of 0.3 °C to 0.6 °C has taken place over the last century. Is this increase human-induced or is it a natural process? To answer the question we must first take into account that the climate varies naturally on all time scales from hundreds of millions of years to a few years. Prominent in recent Earth's history have been the 100,000 year Pleistocene glacial-interglacial cycles when the climate was mostly cooler than at present [Imbrie and Imbrie 1979]. Global surface temperatures have typically varied by 5 °C to 7 °C through the Pleistocene ice ages cycles, with large changes in ice volume and sea level, and temperature variations as great as 10-15 °C in some middle and high latitude regions of the Northern Hemisphere.

In an unperturbated state, the solar radiation absorbed by the Earth's surface and atmosphere is balanced at the top of the atmosphere by outgoing radiation at infrared wavelengths. About a third of incoming solar radiation is reflected back to space. Of the remainder, some is absorbed by the atmosphere, but most is absorbed by the land, ocean,

and ice surfaces. Some of the outgoing infrared radiation is trapped by the naturally occurring greenhouse gases (principally water vapour, but also carbon dioxide (CO_2), ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and clouds. This is the natural greenhouse effect. A change in average net radiation at the top of the troposphere, because of a change in either solar or infrared radiation, is defined as a **Radiative Forcing**. The incoming solar radiation is not considered a radiative forcing, but a change in the amount of incoming solar radiation that would be a radiative forcing.

Anthropogenically emitted gases such as CO_2, CH_4, N_2O and CFCs contribute to an enhanced **greenhouse effect** by reducing in outgoing infrared radiation and a positive radiative forcing. Human activity has also led to an increase in the abundance of **aerosols** in the troposphere, mainly produced by oxidation of sulphur dioxide and from biomass burning, which causes a direct radiative forcing through their reflection and absorption of solar radiation. An indirect radiative forcing effect is believed to result from the influence of aerosol particles the size of cloud droplets, and hence cloud reflectivity. The radiative effects of aerosols are mainly negative and tend to cool the surface.

Effects of the Sun on Earth's Climate

Observations of changes in solar output on longer time-scale using indicators have been recorded since the 17th century. There are an increasing number of studies which have shown significant correlation between indicators of solar variability and changes in climate. The reality of any connection is often controversial, especially when there is no physical mechanism that can provide a quantitative explanation. However, if these correlation come from a real physical association, the predictions of a possible climate change in the future will be very different from the greenhouse gas effects.

The Sun is the primary source of energy for the Earth's climate system. Variations in the amount of solar radiation received by the Earth can affect our climate. There are two distinct sources of this variability: **(1)** Variations in the Earth's orbital parameters are believed to initiate variations in climate on time-scales ranging from 10,000 to 100,000 years. These orbital changes influence latitudinal and seasonal variations of solar energy received by the Earth, so-called the *Milankovitch Effect*. **(2)** Variability due to changes in total solar irradiance or the **solar constant**. In terms of direct effects on climate, of greater potential importance are changes integrated over all wavelengths, the solar constant. Over the period from 1980 to 1986, there was a decline in irradiance of about 1 Wm^{-2} corresponding to a globally-averaged forcing change at the top of the atmosphere of a little less than 0.2 Wm^{-2}. Since then irradiance has increased due to the Sunspot cycle [Climate Change 1994].

Correlation between Climate and Solar Activity

Since the late 1970s, the variations of both integrated and spectrally resolved solar irradiance have been precisely measured from a number of different space-borne instruments. On the other hand, the ZÅrich observatory reconstructed the Sunspot number back to 1700; epochs of maxima, minima and solar cycle length could be estimated and tables of such information have been prepared by Schove [1955].

The comparison between the temperature record and solar activity indicates a good association between the long-term variations in the temperature and in the solar cycle record, although the coincidence may be less obvious during the pre-instrumental period than for the modern instrumental record. In 1991 Lassen and Friis-Christensen showed this relationship correlating the temperature deviation in the Northern Hemisphere and solar cycle length, they obtained a statistically significant correlation coefficient of 0.83. Other correlations were obtained by many other authors [Labitzke and Van Loon 1993,

Reid 1991, Tinsley and Heelis 1993]. In these studies they examined the correlation between solar indices such as sunspots, solar cycle length, and observed characteristics of the atmosphere (e.g., temperature at particular locations, global average sea surface temperature, etc.).

Some authors have questioned the usefulness of solar cycle correlation studies, noting that undersampling other periodic atmospheric phenomena could lead to spurious results. A combination of, for example, biannual and quasi biennial oscillations could induce 10- to 12-year periodicities and hence lead to correlations similar to those observed, but unrelated to solar forcing [Dunkerston and Baldwin, 1992].

In order to establish credibility to the large number of correlations between various solar and climate parameters there is a need to identify a physical mechanism that can account for the hypothesised solar activity effects on climate. That is the reason why we should better understand Sun-Earth system, climate and solar activity mechanisms by obtaining new data from Earth, space, and solar probe observations.

Implications of Climate Change to the Biosphere

The importance of the hypothetical temperature increase of 0.3 to 0.6 °C is the effect on regional climate distribution over the world and the expected increase of variability in temperatures and precipitation. Despite that we do not know how exactly will be the new pattern of regional climate, there is a certainty that a little increase of average global temperature will cause a new spatial distribution associated with extreme weather.

A new climate distribution implies the redistribution of biomes (terrestrial regions inhabited by certain types of life) associated with loss of biodiversity, the change in agriculture to optimise or at least maintain plant crop production, new ocean currents implying new pattern of phytoplankton production, and therefore different areas of fishery activities. On the other hand, an hypothetical increase of temperature would also cause the rise of sea level.

Temperature changes in the Earth's history have been associated *with shifts in the geographic distribution of terrestrial biota*. For example, the boreal forests of Canada extended well north of the current timber line during Medieval Warm Epoch (800 to 1200 A.D.); a time when temperature in that region was about 1 °C warmer than today.

A shift in the geographic distribution of biomes is a long-term (decades to centuries) response to climate change. Temperature and moisture are considered major controllers of plant and ecosystem processes. They exert a strong influence on birth, growth, and death rates of plants. They also act as primary controllers of the biogeochemistry of ecosystems.

Photosynthesis and respiration have different optimum ranges for temperature and moisture. The combination of these variables, together with nutrient sources, establish an optimum range which is specific to each plant species and enables each one to be selectively favoured in one environment. Direct climate changes to individual plants is followed by slower changes in plant communities; complex interactions of ecosystems must readjust to new conditions as a result of changes in competitiveness of species. The greater the physical change, the stronger the ecosystem is affected. However, the most complex ecosystems such as tropical forest and coral reefs, are well adapted to constant weather conditions; little changes in the climate could dramatically impact these fragile ecosystems with consequences of loss of biodiversity.

On the other hand, in order to predict climate variations, the effects of terrestrial ecosystems changes on the climate change must be taken into account. Some induced changes of ecosystem structure and function are expected to feed back to the climate system. For instance, the warming of high latitude wetlands will almost certainly increase the production of CH_4 and as it is released into the atmosphere it will accelerate warming.

One of the more generally accepted conclusions of the general circulation climate models is that as average global temperatures increase, the hydrologic cycle will speed up, increasing global precipitation. As temperature and precipitation patterns change, so will soil moisture and the timing and magnitude of runoff, with possibly adverse effects for many of the world's important agricultural areas. One likely consequence of these changes would be that the demand of water, especially for irrigation, would increase in some regions. As pointed out in the last part, the combination of temperature, moisture and water supply optimise plant production. Therefore, these variables will drive the new distribution of agricultural production, how crop yield will change, and also forestry resources.

It is highly likely that the global-mean sea level has been rising over the last 100 years. The estimates of different studies ranges from about 0.5 mm/yr to 3.0 mm/yr. There are two major climate-related factors that could possibly explain *the rise in global mean sea level* on the 100-year time scale: **(1)** The thermal expansions of the oceans. Density is inversely related to temperature, thus, as the oceans warm, density decreases and the oceans expand and the sea level rises. **(2)** A possible increase of global temperature will cause a direct effect on retreating glaciers, small ice caps and polar ice sheets which will cause the rising of sea level.

Based on the record of the past, there is a little doubt that global warming will result in different *distributions of marine planktonic organisms* than those of today. Changes in temperature and precipitation will have an influence on the circulation of surface waters and on mixing of deep waters with surface matter. Changes in circulation and/or a restriction of the mixing could reduce ocean productivity. As in terrestrial ecosystems, a global warming will redistribute production as a consequence of different spatial patterns of physical conditions. Since fish concentrate in rich plankton production areas, fishery activities would have to change their common areas of activity with possible consequences of social and state conflicts.

The adaptation of our society to these changes will depend on the degree, the sign of regional change, and the capacity of the particular culture, that is the technological development.

4.5.2 The Effects of the Sun on Humans

The Sun affects both people living on Earth and astronauts in space. These effects will be discussed below.

4.5.2.1 The Sun's Effects on Astronauts

The issue of radiation may be the "big show stopper" in respect to long duration manned space flight. The trapping of ionised particles by the Earth's magnetic field in the Van Allen belts provides a shield against deep space radiation. Such ionising radiation exists in many forms--high energy protons, heavy ions, and electrons--and may originate from solar flare (solar energetic particles), the particles trapped in the Van Allen belts, and galactic cosmic radiation.

The effects of this deep space radiation on the human body are not well known because all the past human space flights, with the exception of certain Apollo missions, have been in LEO, which is well below the van Allen belts (except for the South Atlantic Anomaly). The Apollo missions minimised the dangers involved with radiation, by avoiding periods of solar flares. Some scientists believe it is unethical to send humans beyond LEO, as the consequences will range from an unacceptable increase in tumours to possible death. It is not known what type, if any, of shielding will successfully protect humans in this environment. Ironically, the more shielding you use the greater the danger from "secondary" radiation becomes. Impinging particles impart their energy to molecules in the shielding material, rendering them, in turn, ionised.

Exposure to space radiation is painless. On a long duration mission to Mars, cosmic-ray particles will pass through every cell in the body; however no immediate ill-effects among the crew are likely. The risk of getting cancer in the years to follow, increases. Radiation effects on humans are generally placed in two categories:

1. Acute, early effects of radiation exposure occur within a few days or less. These are usually associated with exposure to a high dose of radiation over a short period. Indicated by symptoms of radiation sickness.
2. Delayed, late effects may occur many years after prolonged exposure to radiation at a low dose rate. These effects include cancer of the lung, breast, digestive system and leukaemia.

Doses in the range of 100 rem to 200 rem (rem is a common unit of dose equivalent, 1 rem = 1 rad = 100 ergs/gram = 0.01 Si) generally cause nausea and vomiting within a few hours, which may be accompanied by discomfort, loss of appetite and fatigue [Churchill]. These symptoms disappear after a day or two, but may recur after a latent period of about two weeks. There is little chance of death from exposure at this level.

Doses in the range of 200 rem to 1000 rem are very serious and require medical attention. The initial response to radiation in this range is similar to radiation at a lower dose exposure, and diarrhoea may occur. After a latent period of two weeks other symptoms may occur including haemorrhaging and hair loss. The dose has caused serious damage to the blood-forming organs, limiting the body's ability to fight infection. Doses above 600 rem are generally lethal, but recovery is possible with adequate medical care.

In space, doses of 1000 rem are possible in cases of large solar mass ejections. Provisions for a "storm shelter" or other safe havens are essential for extended missions in space.

An astronaut's chance of fatal cancer is increased approximately 2% to 5% for each 50 rem exposure during his/her career. In concrete terms if 100 Space Station astronauts are exposed to 100 rem during a one year career in space, then between 4 and 10 of those astronauts would be expected to die of cancer resulting from that occupational exposure.

4.5.2.2 The Sun's Effects on Humans Living on Earth

The Sun can have many negative effects on humans. Most commonly known are the fact that looking straight into the Sun can cause blindness and that UV radiation causes skin cancer. There are also a number of medical effects for which the correlation with solar events can not be explained. Effects like these are studied by a branch of science called biometeorology. Examples of these effects include:

- Sudden, unexpected death in epileptics following sudden intense increase in geomagnetic activity [Pycha *et al.*, 1992]
- A drop in human immunoglobulin levels at the end of the 11-year sunspot cycle [Tisdale, 1995]
- A rise in intraocular pressure in healthy people during periods of increased geomagnetic activity [Tisdale, 1995]
- Correlation between increased solar activity and heart attacks, epileptic seizures and growth in hormone levels

There is a correlation between periods of geomagnetic storms and an increased number of angina heart attacks in patients with high blood pressure [Atkov, 1996]. Geomagnetic storms occur on average once every two months and are the result of solar activity. The connection between angina heart attacks and geomagnetic storms was discovered while trying to determine a correlation between medical conditions and weather patterns. It was found that geomagnetic fluctuations can cause heart attacks in certain high risk groups, such as elderly patients with high blood pressure. The full extent of this relationship is not well understood, but it has been discovered that angina attacks are most likely while entering or leaving periods of geomagnetic storms.

If sufficient warning of such storms could be given then doctors could prepare their patients who are most at risk, by giving them the appropriate drugs. If an early warning system like this made the information available to the medical community in real time, then deaths resulting from angina attacks would be reduced.

It has also been shown that UV light from the Sun can activate the human immunodeficiency virus (HIV) [Sun Exposure and HIV Activation web page]. These findings were the result of tests on laboratory mice which were introduced to the HIV virus, and subjected to UVA and UVB. While awaiting results of further test it was recommended that people with HIV should avoid excessive exposure to sunlight and wear a SPF 15 or higher Sun block.

4.5.3 Technology

At first glance, the Sun's effects on technology do not seem too obvious or too severe. However, the Sun's influence on the space environment can present tremendous hazards to spacecraft, Earth-bound instrumentation and communications in space and on Earth as well.

4.5.3.1 Effects on Spacecraft

Great pains are taken by engineers to overcome the changes that the Sun effects on the space environment. Even so, the Sun can cause problems that degrade or even prematurely end a spacecraft's lifetime.

Atmospheric Drag

Solar emitted X-rays, extreme ultraviolet radiation and charged particles that intersect the Earth, deposit their energy in our upper atmosphere. During intense geomagnetic storming or periods of increased solar activity, this deposited energy forces the atmosphere to heat up and rise. Satellites and orbital debris orbiting through this heated atmosphere experience varying atmospheric densities which result in a loss of orbital altitude along with pointing perturbations. This atmospheric drag will make the object's position somewhat lower and ahead of where it was expected to be. These effects may even cause early and unplanned re-entry of orbiting objects into the Earth's atmosphere,

just as Skylab did in 1979 [Worden, 1996]. Atmospheric drag will delay acquisition of LEO satellites, expending valuable antenna contact time. It also can necessitate additional manoeuvres to raise the altitude of the spacecraft before atmospheric re-entry. Atmospheric drag also complicates orbit debris tracking necessary for collision avoidance missions. Since an estimated 25,000 pieces of orbital debris are created in Earth orbit monthly [Wilson, 1995, p. 158], collision avoidance is more and more important for new payloads and piloted missions.

Surface Charging

Low-energy electrons deposit their charges on the spacecraft surfaces and over time, these charges build up. Eventually they will produce a discharge that can cause erroneous signals to be read by sensors and can permanently damage electronic components and photovoltaic cells. These effects are observed to prevail in high equatorial orbits along with low polar orbits [Lemke and Mendell, 1996]. More information on surface charging for interplanetary missions can be found in section 6.1.4.

Single Event Upsets

Heavy ions and high energy protons emitted from large solar flares occasionally will impact spacecraft. These particles have sufficient energy to actually pass through the spacecraft's structure and change the spacecraft's chemical bonds [Lemke and Mendell, 1996]. If these particles happen to come into contact with sensitive electronic components, single event upsets (SEU) may be experienced. An SEU can re-write on-board computer memory by replacing 1's and 0's or may actually cause erroneous commands to be executed by the vehicle with unpredictable and perhaps catastrophic effects. An SEU is suspected to have caused the Magellan satellite to act erratically in its orbit around Venus [Sellers, 1994].

Spacecraft Disorientation

Many spacecraft use star sensors to provide accurate pointing. Particles emitted by the Sun, along with those of cosmic origin, can impact star sensors and provide false readings. This can lead to degraded pointing or a loss of attitude control. Extreme cases of a loss of attitude control may lead to a loss of the mission life since batteries may discharge beyond their designed specifications and sensitive equipment may be exposed directly to the Sun or to cold space for too long [Worden, 1996]. Other satellites that use geomagnetically stabilised attitude pointing routines can experience pointing problems during intense geomagnetic storming and magnetic reconnection events.

Surface Degradation

The space environment produced by the Sun can also have significant effects on surface coatings of some spacecraft. In the Earth's upper atmosphere, the Sun causes oxygen molecules to breakdown into oxygen atoms. Impact of these atoms on spacecraft surfaces causes an effective oxidising reaction that is similar to rusting [Sellers, 1994, p. 68]. Another phenomenon is experienced by spacecraft which fly through the auroral regions. The increased flux of high speed particles can cause a "sand blasting effect" on spacecraft coatings and external sensors [Sellers, 1994, p.74]. Finally, extreme doses of ultraviolet radiation are experienced during a satellite's lifetime which result in degradation of the spacecraft's surface coatings and solar photovoltaic cells [Sellers, 1994, p. 71].

Magnetopause Crossings

Nominally, the Earth's magnetosphere provides a protective barrier from interplanetary space. The Earth's magnetopause is the equilibrium barrier between the Earth's magnetosphere and the Sun's solar wind [see section 4.4.2]. Between the Sun and the Earth, the magnetopause usually provides shielding from the solar wind out to approximately 10 Earth radii. However, the magnetopause can be compressed. Occasionally, satellites at geosynchronous altitudes (6.6 Earth radii) will cross the compressed magnetopause and be exposed directly to the solar wind. This increased flux of particles, protons and high-energy electromagnetic radiation can create problems within spacecraft since most are not engineered to withstand direct solar wind [Worden, 1996].

4.5.3.2 Effects on Terrestrial Technology

The Sun can disrupt many terrestrial technological systems, especially the ones with electromagnetic components. Some of the most prevalent phenomena directly linked to the Sun that have effects on terrestrial technology are discussed below:

Geomagnetically Induced Current (GIC)

The occurrences of solar flares, and prominences on the Sun changes the magnetic field lines in the solar wind emanating from the Sun. When this solar wind hits the Earth, it distorts the natural geomagnetic field lines of the Earth by greatly compressing the field lines.

As any change in the magnetic field induces current in a conductor, the changes in the geomagnetic field lines, commonly referred to as geomagnetic storm, also induce current in conducting materials on the Earth. This type of induced current is known as the GIC.

The GIC is most prevalent in high latitude countries like Canada and Sweden, because significant geomagnetic storms take place mostly near the North Pole, or the South Pole; and usually, in these places, the long power lines take the place of conductors carrying the GIC. The effects of the GIC can range from small irregularities in voltage output to large saturation of current in transformers, saturation to such an extent that sometimes the transformers have been known to burn up.

An example of technology affected by the GIC is electrical power transmission line. On March 13, 1989, in Montreal, Canada, due to the GIC some six million people were left without electrical power for 9 hours, and quite a few elsewhere were left without power for a few days. The financial loss to the power company was estimated to be over ten million U.S. dollars. During this time of geomagnetic storm, some cities in the northern part of the U.S., and Sweden were also left without power [Campbell, 1995].

Another example of technology affected is the transnational petroleum pipelines made of conducting materials. The geomagnetically induced current in the pipelines can lead to erroneous readings in the flow meters of the pipes, which usually results in high corrosion rates in the pipelines.

In addition to its effects on power transmission lines, and petroleum pipelines, the GIC also affects telecommunications cables, precision instruments, manufacturing equipment, and computers [ARINC, 1996].

Fluctuating Geomagnetic Field (FGF)

Like geomagnetically induced currents, fluctuating geomagnetic field is also caused by changes in the solar wind. An example of affected technology is the scientific equipment used for geological explorations. Geological surveyors use magnetometers to detect minute changes in the Earth's magnetic field to locate oil, gas, and other mineral deposits. This type of exploration can be impossible during periods of high solar activity due to fluctuating geomagnetic field. Another example of affected technology is magnetic compass used for air and sea navigation. In addition to its effect on equipment used for geological exploration and the magnetic compass, fluctuating geomagnetic field also affects precision instruments, manufacturing equipment, and computers [ARINC, 1996].

4.5.3.3 Effects of the Sun on Radio Links and Propagation

The Sun can also have severe effects on radio propagation. Problems have been documented with satellite and ground communications as well as radar propagation and the GPS navigation signal.

Satellite Communications

Satellite communications experience radio frequency interference when a radio energy burst from a solar flare occurs at the right frequency and when the receiver is in the field of view of the Sun. The knowledge of such radio bursts enables the operator to determine the source of interference [Worden, 1996]. The IPS Culgoora Solar Observatory uses instruments to monitor solar radio bursts in the frequency range of 18-1800 MHz. Radio bursts are often emitted during solar activity in addition to other elements which cause the disturbances. Hence, their monitoring enables the prediction of other following emissions and the disturbances that may result [Culgoora Solar Radiospectrograph, IPS Radio & Space Services, WWW].

A similar geometry related effect called solar conjunction occurs when the Sun is aligned with the spacecraft as seen from the Earth station. This problem does not require a solar flare to be in progress but is much more pronounced at solar maxima when the Sun is a strong background radio emitter. The spacecraft's orbit will determine the number and duration of solar conjunctions. The level of interference depends upon a number of factors including the antenna radiation pattern, the receiver bandwidth, the acceptable signal to noise ratio and the Sun's temperature that is a function of the frequency used and the solar activity [Solar Interference to Satellite Communications, IPS Radio & Space Services, WWW]. For geostationary satellites, solar conjunctions will occur around the March and September equinox due to simple geometrical considerations [Maral and Bousquet, 1993] and calculations of antenna noise temperature increase can also be found in this reference. Similarly, solar conjunction in the case of aircraft can cause jamming of air-control radio frequencies.

Plasma density instabilities at the F2-region altitude of the ionosphere lead to the ionospheric scintillation effect. Through rapid, random variation in signal amplitude, phase and/or polarisation this will cause strong amplitude fading and phase fluctuation to most frequencies currently used by satellites, namely UHF (0.3-3 Ghz) up to C-Band at the high frequency end [Kivelson and Russel, 1995]. Different mechanisms will cause scintillation at high latitude and equatorial regions and resulting in some frequencies being more affected in a region [Secan, 1996].

Ground Communications

HF or short-wave (3 to 30 MHz) radio communications systems traditionally use the ionosphere to "bounce off" and get extended transmission ranges. However, increased X-rays emission during solar flares increase the D-region's electron density which in turn can absorb HF signals. This leads to what is referred to as short-wave fade events. Moreover, the variation of the solar ultra-violet flux during the solar cycle results in changes in the range of frequencies available to HF communications [The Diverse Effects of Solar Events, IPS Radio & Space Services, WWW]. LF and VLF communications are ducted by the ionosphere, thus sudden changes to the ionosphere can produce phase anomalies in these communications and range errors on navigation systems using these frequencies.

Radar Systems

The enhanced, irregular ionospheric ionisation can produce a phenomenon called "Radar Aurora" which is an abnormal radar signal back-scatter on polar-looking radars. The impacts include increased clutter and target masking, inaccurate target locations, and even false target or missile launch detection [Worden, 1996]. RFI also affects missile detection or spacetrack radar.

Another effect of the ionosphere is the refraction and delay of UHF/SHF radio waves from missile detection and spacetrack radars. This leads to target bearing and range errors that can be compensated for based on the expected ionospheric Total Electron Content (TEC). TEC values, however, can be invalidated by individual solar and geophysical events.

NAVSTAR Global Positioning System (GPS)

The severe plasma density instabilities described above can also cause errors in individual GPS navigation signals. The scintillating effect of these plasma patches produces transmission path delays between satellites and receivers. Because the system measures signal time delays, any phase variation will cause a time delay and will introduce an error in the navigation solution. As of now, no conclusive studies have been completed that characterise potential error sizes in GPS due to ionospheric scintillation [Bainum, 1996]. Another potential problem with the GPS system is signal fade. Each GPS receiver is designed with a TEC gradient threshold. The edges of plasma patches are characterised with sharp TEC gradients. Sustained gradients will cause users to lose lock on the GPS signal [Bainum, 1996]. Ionospheric scintillation of GPS is a regional phenomenon and seems to only be observable at the poles [Bainum, 1996] and at the Earth's magnetic equator [National Space Weather Program, 1995].

4.6 The Sun as a Resource

A way to look at the Sun is to view it as a resource. From an applications point of view this enables one to recognise a wide variety of applications related to that Sun. Four different types of resources are identified and described.

4.6.1 The Sun as an Energy Resource

The Sun has been the main source of energy for our planet since the beginnings of time. Plants depend on sunlight to produce oxygen without which we could not survive. Humans have devised ways to increase the benefits of sunlight, ranging from its use in

the production of salt from sea water to solar cells for domestic and industrial use. In space, the Sun is the main energy provider for spacecraft.

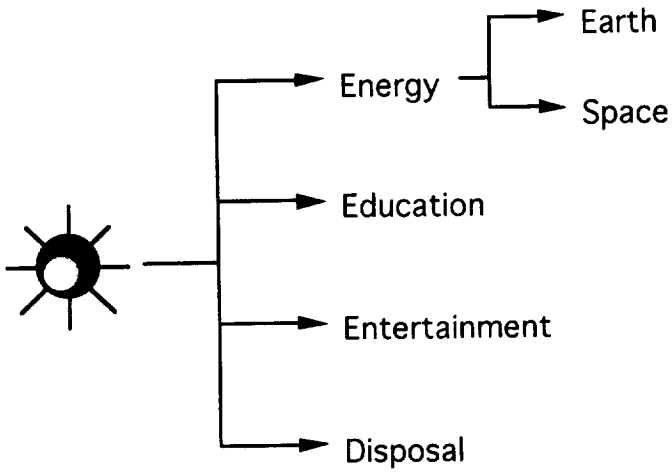


Fig. 4.15 **The Sun viewed as a resource.**

Solar energy on Earth

As traditional energy resources like coal, oil and gas are becoming scarce and have major environmental impacts, alternative sources of energy are becoming more and more important. Solar energy is one of the most promising sources of energy. Energy can be generated using solar cells or heat-exchangers. Focused solar energy can be used for high temperature manufacturing uses. Significant potential energy savings could evolve from efficient heat/light technological infrastructures implemented in buildings and transportation media.

Solar energy in space

In space the Sun provides the main source of energy for spacecraft through the use of solar cells that provide the electric power. A major problem with solar cells is degeneration due to radiation. Besides that efficiencies are relatively low. New developments in solar cells technology focus on increasing efficiency, decreasing degeneration and methods for regeneration of solar cells. For propulsion purposes solar sails offer a new way to utilise the Sun's energy [see section 6.4.3].

More futuristic plans involve collecting solar energy in space and sending it down for use on Earth. The basic technology to perform such a task is available, however the market for this kind of energy still does not exist [ISU, 1992].

4.6.2 The Sun as an Education Resource

The Sun is an education resource in the way that it has a large influence on our daily life. Being the closest star, the Sun provides us with an excellent study object for research into the mechanisms that make it work. See section 8.6.1 for further discussion.

4.6.3 The Sun as an Entertainment Resource

With the auroral lights, the Sun provides us with one of the most impressive features of nature. Given the attractiveness of auroras a business opportunity might exists for their

accurate prediction. Assuming that an aurora could be predicted with an accuracy of 90% or better, tours could be organised to places where the aurora is visible, either on Earth or in the sky.

Helioseismological oscillations (i.e., sunquakes), when transformed to the sound spectrum might provide entertainment to those who want to be closer to nature. Listening to the sounds of the Sun might very well fit in with current New Age trends. Remember, people are already listening to whales and forests.

4.6.4 The Sun as a Disposal Resource

Due to its high temperature, the Sun is able to permanently dispose of anything by breaking it down to protons and electrons. During solar storms, the increased solar wind disposes of some of the space debris in low earth orbit.

The safe disposal of nuclear waste is one of the most important waste problems humanity is facing. Nuclear waste takes thousands of years to degrade to benign matter. Nuclear waste could be permanently disposed of by shooting it into the Sun. The obvious problem with this solution is that the nuclear waste will have to be launched in orbit. A launch failure of a launcher carrying nuclear waste would have severe local environmental impacts. Because of this the political willingness to even consider the possibility is very low.

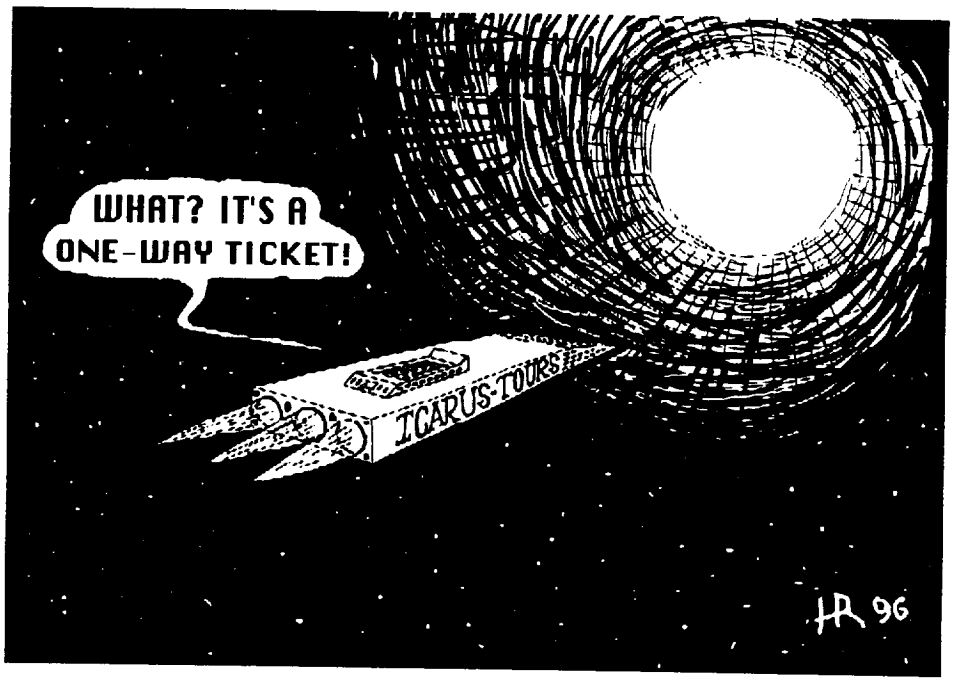


Fig. 4.16 **Space tourism, the next step (Courtesy of H. M. Rehorst).**

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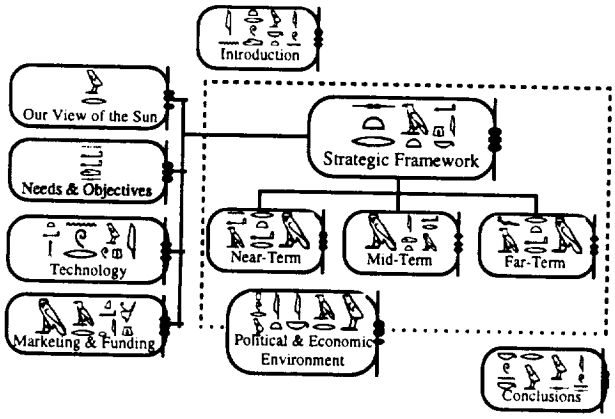


Objectives & Requirements

In this chapter we put forward the objectives deemed to be most important to the Strategic Framework. The first section discusses the scientific objectives, and the second section discusses objectives related to applications. Next these objectives are compared to the objectives of past, current, and planned solar missions and are linked to the Strategic Framework. Finally we offer recommendations for Near-, Mid-, and Far-Term mission requirements.

5.1 Science Objectives and Priorities in the Ra Strategic Framework

To guide the development of the Ra Strategic Framework, it is essential that the scientific objectives for such a programme be clearly defined. Several related lists have been published, either in scientific literature or by agencies. Most of these refer to single campaigns (e.g. FIRE) or a programme of missions (e.g. Solar Connections). Of course many published scientific objectives have already been met, either fully by a completed mission, or partially by current missions such as SOHO. We compiled our own list of objectives based on our view of the situation in August 1996 and advice from a number of visiting lecturers at ISU. Their input helped revise our original set of objectives and focus them more precisely.

In particular the importance of stereoscopic imaging was stressed, as well as observations at high spatial, spectral, and temporal resolutions, and long duration to provide information on physical processes such as magnetic reconnection.

The objectives listed in section 5.1 apply to the whole Ra Strategic Framework, and as such can not apply to (or be achieved by) a single mission. They are to be used in conjunction with other objectives (such as applications and policy objectives) to guide the development of actual missions.

Science priorities are always challenging subjects because scientists' opinions differ. For the Ra project we have chosen our own priorities and we defend them by references to scientific literature. The listing of the objectives does not imply the order or priorities of importance.

5.1.1 Primary Objectives:

Many, if not most of the processes happening in, on and around the Sun are poorly understood, such as the neutrino problem, the origin of the Sun's magnetic field and its connection to differential rotation, and the solar cycle.

However, for determining how important a specific scientific objective is, we chose as a criterion its relevance to Earth. This goes partly hand-in-hand with the application-type and Earth-relevant objectives. To come up with better space environment predictions, we need to understand the physics behind the *phenomena that trigger magnetic storms*. Seen from a longer-term perspective we are even more worried about *the Sun's influence on potential climate changes*. Thus we divided our primary objectives into exactly these two categories.

<u>To understand the physical processes leading the Sun to emit plasma structures and high energy particles that are potential threats to humans and technology.</u>

This automatically leads to the following issues to be addressed:

- What is the heating mechanism of the corona?
  - What leads to the formation of coronal holes?
  - From where does the slow solar wind emerge?
  - How intimately is the fast solar wind related to coronal holes?
  - What are the causes for and underlying physical principles of solar flares?
  - What are the causes of the acceleration of particles to very high energies?
  - What leads the corona to release coronal mass ejections?
  - How do the different types of coronal mass ejections propagate in the interplanetary medium?

To answer these questions it is essential both to develop new observational techniques, such as stereoscopic imaging of the corona, and to improve theoretical models.

<u>To understand the physical processes which may lead the Sun to influence our climate.</u>

This automatically leads to the following questions:

- What causes the solar "constant" to change?
- What are the long-term variations in the solar constant?
- To what extent do variations in the solar constant influence the Earth's climate?

5.1.2 Secondary Objectives:

We determined the following objectives (not directly related to the Sun's influence on Earth) to be secondary:

- To determine the cause of the solar cycle.
- To determine what causes the solar constant to change.
- To investigate the origin of the Sun's magnetic field and its connection to differential rotation.
- To determine the internal state of the Sun by measuring the higher harmonics of its gravitational field.
- To determine the internal state of the Sun by means of helioseismology.
- To test general relativity by using the Sun's gravitational field.
- To measure the abundance of galactic cosmic rays in the Sun's vicinity.
- To solve the neutrino problem.

The first three secondary objectives are very closely connected to the primary objectives; however, we chose to make the distinction as above. On the one hand we placed emphasis on the effects that a changing solar constant might have on Earth, as opposed to its cause, which is a phenomenon related to the interior of the Sun. Similarly, we did not ask for the origin of the magnetic field, instead placing emphasis on its effects.

5.2 Applications Objectives and Priorities in the Ra Strategic Framework

To keep the mission objectives input to the Ra Strategic Framework as comprehensive as possible, a broad view of the possible nature of missions to the Sun was taken. This view went beyond the traditional science-only missions view and included the possibility of applications-focused missions. From an applications perspective the following three goals were adopted to derive inputs for the Strategic Framework:

- identify and investigate solar-terrestrial missions dedicated to a particular application,
- identify and investigate application spin-offs from science missions, and
- identify and investigate future applications that require technology development,

all for the benefit of humanity and commerce.

5.2.1 Applications Needs and Opportunities

To assess the needs and opportunities for solar-terrestrial related applications it is helpful to consider the Sun as either a threat [see detailed description of section 4.5] or as a resource [see overview of section 4.6]. Since utilising the Sun as a resource was the focus of a previous ISU report [ISU, 1992] it was decided to focus on responding to the Sun as a threat. Two different categories of a response to a threat are possible:

- either, *eliminate* the threat by preventing it from occurring, by deflecting it, or by continuously protecting your system from the threat,
- or, *mitigate* the threat by predicting its impact and taking appropriate safeguard actions.

Based on our current state of knowledge concerning the threats outlined in section 4.5, threat elimination was not considered feasible although opportunities for protection technology development are numerous (e.g. thermal shielding, radiation hardening, discharging techniques, etc.). These technology oriented issues are explored in chapter 6.

5.2.2 Applications Focus

The chosen applications focus was therefore on mitigating the harmful effects of the Sun by predicting their occurrence and making it possible to temporarily safeguard systems, i.e. Solar Threat Monitoring and Early Warning. In the Near-Term this would include increasing the awareness of solar event impacts and improving the use of current resources [sections 8.6 and 8.4], in the Mid-Term this would possibly include applications oriented science mission enhancements and/or the implementation of a dedicated early warning system [section 9.2], and in the Far-Term this would include future applications requiring technology development [section 10.1.2] plus a permanent, world wide prediction and warning system.

To justify this focus we made a survey of the existing solar threat monitoring and early warning systems and we found that no dedicated system currently exists [see Appendix E: Existing and Proposed Early Warning Systems]. The current state of the art is opportunistic in terms of its acquired measurements and the result is probabilistic, not unlike Earth weather forecasting in the past! This need not be the case given advances in our understanding of the triggering mechanisms of magnetic storms and advances in sensor technology. The goal of section 9.2 which explores different options for a dedicated early warning system is to define a system that will make solar threat monitoring and early warning more deterministic and far less probabilistic.

5.3 Mission-Objectives Analysis

The aim of this paragraph is to analyse the current scientific and application objectives discussed in sections 5.1 and 5.2 and perform a comparative analysis among the objectives that have been defined for the past, current, and planned international solar missions. Space research can provide us with more comprehensive information needed for understanding, predicting and monitoring solar activities for the benefits of humankind. The measurements performed by each mission to fulfil its scientific and application objectives are categorised as depicted in Figure 5.1.

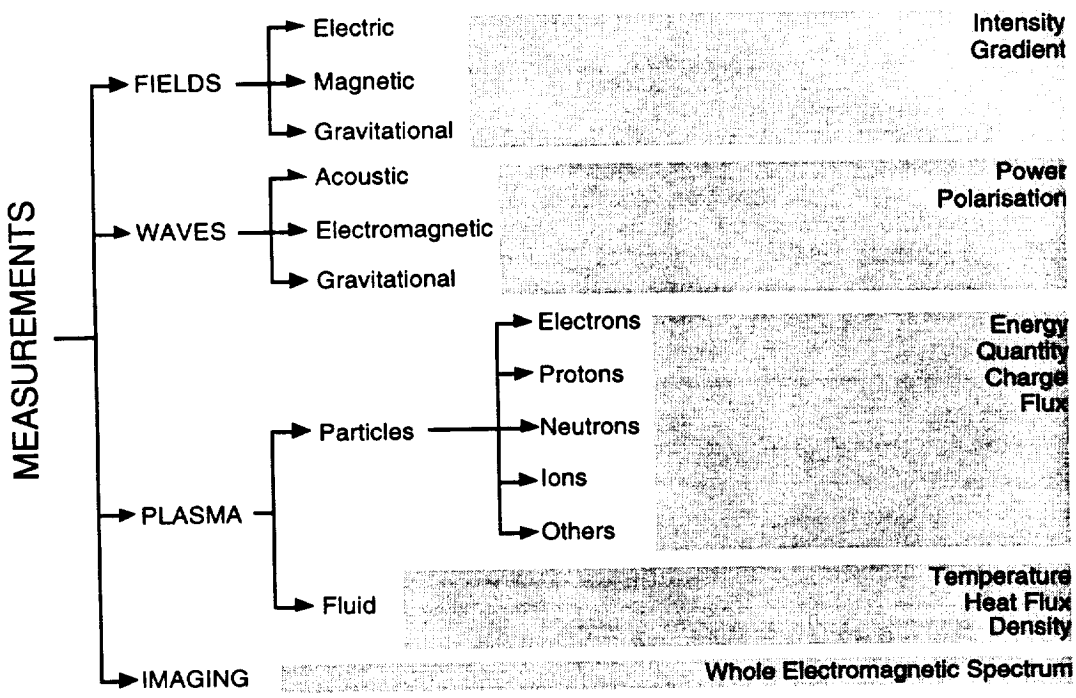


Fig. 5.1 Categorisation of measurements.

5.3.1 International Missions Objectives Background

This paragraph will describe and analyse the specific objectives of the past, current and planned solar missions (see Tables 5.1, 5.3. and 5.5). In the measurements tables [see Tables 5.2, 5.4 and 5.6], the regions in space where the spacecraft have been collecting data are divided in three [see Figure 5.2]:

Region 1: Close to the Earth, up to 30 R_E;

Region 2: Intermediate region, from 30 R_E to 30 R_S to the Sun;

Region 3: Near the Sun, closer than 30 R_S from the Sun.

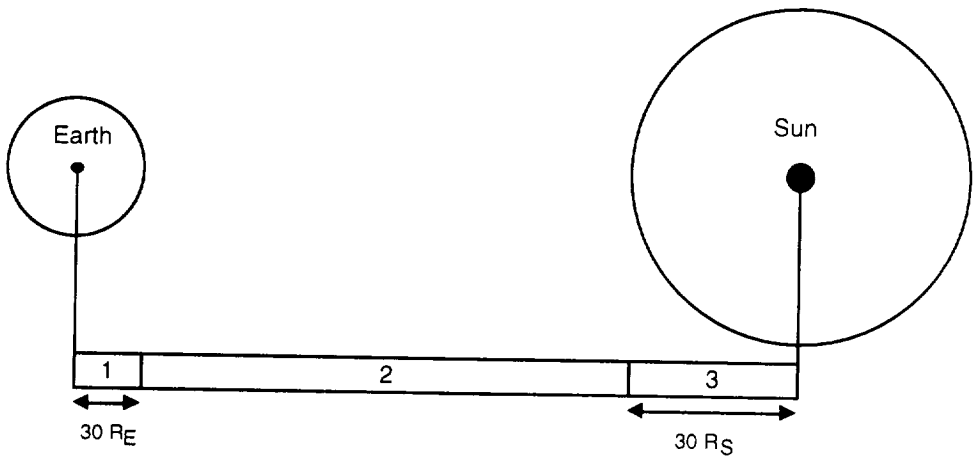


Fig. 5.2 Space Region Classification.

5.3.1.1 Past Missions

The period 1962-1980 has been arbitrarily chosen, even if some spacecraft launched at that time are still in operation today. The missions during this 18 year period have covered various objectives, have been launched on a variety of trajectories and have been implemented through a number of significantly different collaborative agreements. The scientific objectives of these spacecraft seem to have been global, no mission was specially designed to one specific objective. On the contrary, every mission carried experiments and instruments covering multiple scientific objectives. In the survey and assessment of past missions, there is no evidence of any substantial or direct interest in applications based either on the availability of solar related environmental information or Sun-Earth interaction. The main emphasis has clearly been on improvement of our knowledge of the Sun and interplanetary medium and solar system/Sun related environmental information, to prepare manned space missions and to cope with disturbances to Earth-orbiting artificial satellites. The national programs (US and USSR) are more numerous than the international ones. However, there were some bilateral partnerships between countries (USA / Germany, USSR / France) or between agencies (NASA / ESA). The trajectories of the spacecraft were very different. Some were in low Earth orbits, others were in intermediate Earth orbits. It is in this period that the mission to date closest to the Sun (Helios) was successfully conducted. Several interplanetary spacecraft were carrying instruments to study the Sun even from high latitude (Ulysses).

5.3.1.2 Current Missions

There is a 10-year gap between current missions and past missions. Solar Max was launched in 1980 and Ulysses was launched in 1990. In the intermediate period only a few Prognoz spacecraft were launched. Why this gap? We assume the scientific community has been analysing the data gathered by the previous missions while at the same time preparing combined, continuous and co-ordinated Sun's study programs, within the ISTP or IACG organisations. Objectives covered the whole range of scientific fields of interest at this time. More missions focused on particular fields, some of the most important being the corona, solar flares and the CMEs. The interest for Sun/Earth interaction increased during this period and some missions are more focused on these objectives. The majority of the trajectories and final orbits were near Earth, at low or intermediate altitudes, with only Ulysses orbiting over the solar poles and no spacecraft at an approach distance closer than 64 R_S.

5.3.1.3 Planned Missions

The planned missions appear in two different types: the ones that are already scheduled with a definite launch window and very precise characteristics, and the ones that are still in the approval cycle. Among the last ones we find the missions designed to complete measurements of previous missions, in particular those co-ordinated through the ISTP. Sun/Earth interaction studies have an important role in the forthcoming period and environmental effects of solar activity are more precisely assessed. The corona is the centre of interest in almost all planned missions and for the first time plans have been established to send spacecraft closer to the Sun to make measurements from very small distances in high temperature environments. Important programs launched in the beginning of the 90's are about to reach their completion, and in the present schedule there are no foreseen replacements. At the same time the Cluster constellation was lost in a launch vehicle failure representing a significant set back in the program. Are we going to have another empty decade such like in 1980? From the co-operation point of view, we do not find the same strategy adopted as in the previous period; no ambitious joint program such as SOHO, CLUSTER or ULYSSES exists; only some bilateral or trilateral project is being considered. However, CLUSTER recovery options are being studied and evaluated by ESA and the science community.

Table 5.1 Past Missions: General Objectives.

	1962	1971	1972	1972	1973	1974	1977	1977	1978	1980
Missions	OSO (8 s/c)	SOLRAD (3 s/c)	Pioneer (11 s/c)	PROG-NOZ (9 s/c)	IMP8 (3 s/c)	HELIOS (2 s/c)	Voyager (2 s/c)	SIGNE 3 (1 s/c)	ISEE (3 s/c)	Solar Max (1 s/c)
Primary Sci objs										
- Solar Corona										
- Solar wind										
- Earth/Sun										
Secondary Sci objs										
- Inner Sun's Physics										
- Gravitation										
- Cosmic rays										
Others Sci objs										
- Transition region										
Application Objs										
- Threat apps										
- Resource apps										

Table 5.2 Past Missions: Measurements.

Missions	1962 OSO (8 s/c)	1971 SOL-RAD (3 s/c)	1972 Pioneer (11 s/c)	1972 PROG-NOZ (9 s/c)	1973 IMP8 (3 s/c)	1974 HELIOS (2 s/c)	1977 Voyager (2 s/c)	1977 SIGNE3 (1 s/c)	1978 ISEE (3 s/c)	1980 Solar Max (1 s/c)
Space Region [5.3.1]	1	1	2	1	2	2	2	1	2	1
Fields										
- Magnetic										
- Electric										
- Gravitational										
Plasma & Solar wind										
- Particles										
- Electrons										
- Protons										
- Neutrons										
- Ions										
- Others										
- Fluid										
Waves										
- E mag										
- Radio										
- IR										
- Visible										
- UV										
- X-rays										
- γ rays										
- Acoustic										
- Gravitational										
Images										
- Radio										
- IR										
- Visible										
- UV										
- X-rays										
- γ rays										

Table 5.3 Current Missions: General Objectives.

Missions	1990 Ulysses (1 s/c)	1990 Gamma (1 s/c)	1991 Yohkoh (1 s/c)	1992 Geotail (1 s/c)	1992 SAMPEX (1 s/c)	1993 SPAR-TAN (1 s/c)	1994 WIND (1 s/c)	1995 INTER-BALL (2 s/c)	1995 SOHO (1 s/c)	1996 POLAR (1 s/c)
Primary Sci objectives										
- Solar Corona										
- Solar wind										
- Earth/Sun										
Secondary Sci objectives										
- Inner Sun's Physics										
- Gravitation										
- Cosmic rays										
Other Sci objs										
- Transition region										
Application objectives										
- Threat apps										
- Resource apps										

Table 5.4 Current Missions: Measurements.

	1990	1990	1991	1992	1992	1993	1994	1995	1995	1996
Missions	Ulysses (1 s/c)	Gamma (1 s/c)	Yohkoh (1 s/c)	Geotail (1 s/c)	SAM-PEX (1 s/c)	SPAR-TAN (1 s/c)	WIND (1 s/c)	INTER-BALL (2 s/c)	SOHO (1 s/c)	POLAR (1 s/c)
Space Region [5.3.1]	2	1	1	2	1	1	2	1,2	2	1
Fields										
- Magnetic										
- Electric										
- Gravitational										
Plasma & Solar wind										
- Particles										
- Electrons										
- Protons										
- Neutrons										
- Ions										
- Others										
- Fluid										
Waves										
- E-mag.										
- Radio										
- IR										
- Visible										
- UV										
- X-rays										
- γ rays										
- Acoustic										
- Gravitational										
Images										
- Radio										
- IR										
- Visible										
- UV										
- X-rays										
- γ rays										

Table 5.5 Planned Missions: General Objectives.

	1996	1996	1996	1997	1997	1998	2000	2000?	2003	2003	2003
Missions	SAC B (1 s/c)	Cluster (4 s/c)	FAST (1 s/c)	ACE (1 s/c)	TRACE (1 s/c)	TIMED (1 s/c)	HESI (1 s/c)	IMAGE (1 s/c)	SOLAR B (1 s/c)	Plamya (1 s/c)	Solar Probe (1 s/c)
Primary Sci objectives											
- Solar Corona											
- Solar wind											
- Earth/Sun											
Secondary Sci objectives											
- Inner Sun's Physics											
- Gravitation											
- Cosmic rays											
Others Sci objs											
- Transition region											
Application objectives											
- Threat apps											
- Resource apps											

Table 5.6 Planned Missions: Measurements.

Missions:	1996 SAC B (1 s/c)	1996 Cluster (4 s/c)	1996 FAST (1 s/c)	1997 ACE (1 s/c)	1997 TRACE (1 s/c)	1998 TIMED (1 s/c)	2000 HESI (1 s/c)	2000? IMAGE (1 s/c)	2003 Solar-B (1 s/c)	2003 Plamya (1 s/c)	2003 Solar Probe (1 s/c)
Space Region [5.3.1]	1	1	1	2	1	1	1	1	1	2, 3	2, 3
Fields											
- Magnetic											
- Electric											
- Gravitational											
Plasma & Solar wind											
- Particles											
- Electrons											
- Protons											
- Neutrons											
- Ions											
- Others											
- Fluid											
Waves											
- E-mag.											
- Radio											
- IR											
- Visible											
- UV											
- X-rays											
- γ rays											
- Acoustic											
- Gravitational											
Images											
- Radio											
- IR											
- Visible											
- UV											
- X-rays											
- γ rays											

5.3.2 Comparative Analysis

The first conclusion of the analysis is that no long-term strategy has been adopted to define the solar missions that have been flown or developed so far. International co-operation has been promoted only recently so that many similar missions have been conceived by different countries without there being any correlation. The number of necessary missions can eventually be reduced and the on-board instrumentation can be optimised if a comparative analysis is performed on the measurements.

Four other main observations can be made by analysing the past, current and planned missions:

1. The corona has been studied from 1962 up to now by 11 out of 20 past and current missions; while 7 out of the 11 planned missions plan to collect more data. Despite this fact the corona remains to be one of the most mysterious regions of the Sun. From a scientific point of view we conclude that we need measurements different from those made up to now, from different observation locations (L4), from closer orbits to the Sun (maybe suicide probes) and by different means (3D imaging, stereo imaging).
2. ISTP programs are today giving us very good data on the influence of the Sun on terrestrial environment. However GEOTAIL will end its mission in 1996, Wind and SOHO in 1997 and Polar and INTERBALL in 1998. Even if their lifetime will be extended, no additional missions are scheduled to replace them during the next decade using a similar international co-operation. Cluster was an important part of the ISTP and its launch has

failed so valuable data are missing today to achieve the goals of co-ordinated observation for the ISTP.

3. Up to now only a few spacecraft have been dedicated to study inner Sun physics and none are planned up to 2004. We assume it is because a lot of data on this subject can be gathered from Earth or from non-dedicated spacecraft making remote measurements of gravitational or acoustic waves. However, even if inner Sun physics is a secondary objective for scientists maybe it should be emphasised more in the Mid- or Far-Term programs.
4. Applications are quite absent of all past, current and planned missions, even though indirectly data are being gathered by existing spacecraft (WIND, SOHO) and are used for monitoring the space environment and forecasting Sun / Earth interaction. Today the need for such forecasts is increasing. Private space companies, governmental agencies and even human every day life are more and more concerned about it. Such an objective would likely get a large approval consensus among decisional entities.

5.4 Scenarios

This section provides a technical link between the analysis presented in the previous section and the Strategic Framework. It depicts the multiple dimensions of a Sun exploration mission, and lists the options available today or in the Near-, Mid- or Far-Term, if any change is foreseen. This allows to match the means to the needs.

5.4.1 Needs and Measurements.

A conservative, step-by-step approach, without new missions is necessary in the Near-Term. Mid-Term is concerned with low-risk applications offering a material benefit to the community. Far-Term addresses more ambitious questions about the corona and inner solar physics, taking advantage of new technologies. Viewed today as 'enabling', these technologies should become mature in the 15-25 year Far-Term time frame.

5.4.2 Spacecraft Fleet and Trajectory

Increasing the number of spacecraft in a mission allows stereoscopic and/or time-spread measurements, helping the analysis of Sun processes. Miniaturisation could help to conserve total mission mass, avoiding launcher penalty. This will depend on the improvement in mass and volume of instruments, electronics and thermal shielding, and likely is a Far-Term opportunity. In the Mid-Term, 'a few' spacecraft per mission seem preferable, helping to master intercommunication and control questions for later constellation missions. Size is affected by propellant mass, i.e. trajectory, mission duration and propulsion technology. Chemical propulsion gives too low speed levels. This imposes to use gravity assists, a long process that suffers from the low solar energy available for on-board power (Jupiter) and suffers from long link distances.

Getting 'closer to the Sun', and 'more often', are two scientific repeated requests, that are expensive and long to achieve with chemical propulsion. However two alternatives look promising: first electric propulsion and then solar sails. Electric propulsion is currently planned for demonstration in the US New Millennium program and offers much greater jet velocities allowing closer access to the Sun. Because of its relative novelty, it is a Mid-Term to Far-Term option. Solar sails offer similar advantages to electric propulsion but are considered as more unconventional. Deployment and survivability close to the Sun appear as challenges, although the capability of changing orbit inclination is attractive for

high latitude measurements and mapping. This makes solar sails attractive for Far-Term constellations.

Table 5.7 Needs and Measurements.

Field	Options	Trade-Off
Solar Science	**Corona:** cause of heating, cause of CME, dust at <0.3 AU, holes, cause of flares, EM field. **Solar Wind:** origin and process, polar wind. **Sun-Earth Interaction:** Earth weather, effect of Sun on Earth magnetosphere, magneto-iono-atmospherics. **Secondary items:** sunspots and their EM field, solar 'constant', Sun gravity field, seismology, cosmic rays near Sun.	*In situ* vs. remote sensing. Ecliptic vs. inclined trajectories. Field or particle instruments.
Applications	GIC prevention, power line and sat protection, EVA protection, public and leisure, power generation, energy-efficient technologies.	
Instruments	**Philosophy:** **in-situ,** **remote sensing**: EM spectrum through solar layers. single measure vs. imager. **Particle:** plasma analyser, energetic particles detector, dust detector. **Field:** magnetometer, gravity gradiometer. **Waves:** visible, IR, microwave, X, K-band. White light coronograph, EUV telescope	In-situ is more dangerous to spacecraft. Power, atmospheric attenuation Data quantity and transfer rate. EUV and microwave allow to relate corona with photosphere.
Recommended Requirements	**Near Term:** - continue existing missions, - use other observation means (observatories, mil sats), - improve data management and distribution. **Medium Term:** - develop applications related to Earth protection. - develop scientific missions on Sun/Earth interaction. - improve international co-operation. - set up long duration observation programmes. - optimise Instruments suites per s/c. - develop constellations for multiple measurements. **Far Term** - address solar physics. - develop in-situ missions and 3D measurements - explore space collection of solar energy.	

Table 5.8 Spacecraft Fleet and Trajectory

Field	Options	Trade-Off
Spacecraft Number	**Single,** **a few,** **constellation.** **suicide probe**	3D and multiple measurements, series production effects, risk spreading, launcher size. Shorter total duration. Deeper exploration.
Trajectories	**Orbit:** around Earth: LEO, synchronous. around Sun: circular: at 1 AU, 30 R_S... elliptic: at 30 R_S or more, 4 R_S... **Direct** **Gravity Assist at Jupiter:** out of ecliptic or for ecliptic circularisation. **Resonant Venus GA** perihelion at 0.25 AU, inclined at 20°. **Helicoidal**: see ion thrust or solar sail.	Remote sensing. In-situ sensing. High velocity. Duration, comm., heat. Shortly close to Sun. Too costly, especially out of ecliptic long.
Propulsion	**Solid Chemical** has the lowest jet speed and can not be switched. **Liquid Chemical** is limited to 5 km/s jet velocity. **Electric** offers very high exit velocity but very low thrust. **Solar Sails.**	Can not propel fast enough for solar orbit. Needs demonstration. Flying in New Millennium. Needs robustness to survive.

5.4.3 Environment and Subsystems

The environmental constraints mainly concern the extremely wide variations of parameters to be coped with by the spacecraft. Jupiter assists imply low solar energy for on-board power, low temperature and long flight time and communication distances. Proximity of the Sun involves thermal shielding and signal/noise separation issues. Earth-Sun celestial mechanics imposes very high spacecraft speeds, exceeding current capabilities.

Some subsystems technologies should alleviate these issues. Carbon/carbon is the shielding material of choice, up to about 4 R_S. Cost issues might however restrict Mid-Term mission to trajectories further from the Sun. In the Far-Term however, high temperature electronics and optical communications should make more affordable the closer solar orbits desired for in situ observation.

Table 5.9 Environment and Subsystems

Environment	**Transmissions:** Sun-Earth line noise. **Heat:** current heat shield up to 4 R_S. **Outgassing:** from s/c, might corrupt measurements. **Particles:** solar flare first result in protons that are dangerous for electronics, and then in heavy ions causing electronics upsets. High speed particles might be catastrophic. **Radiation** is significant in planetary magnetospheres. **Electrostatic charging** is induced by solar plasma. Discharging might damage subsystems. **Magnetic induction** might cause perturbation torques and blur measurements.	
Heat Protection	**Carbon/Carbon,**	Convenient, emissivity/absorptivity.
	Ceramics,	Brittle, UV sensitive.
	Refractory Alloys	Mass loss.
	High Temp Composites	Relatively low temperature.
Communications	**Outer Corona** will affect transmission amplitude and phase. **Data Storage** can relieve transmission issues close to the Sun. **Distance** affects communication sizing (Jupiter). **Sun-S/C Separation** is negligible below 4 R_S.	Depends on storage duration
	Data rates lead to consider SHF/EHF and X, Ka-bands.	Need to develop high frequency transponders, Ka-band stations.
	Microwave transmission relies on frequency windows in the ionosphere.	
	Optical links offer greater data rates due to greater frequency. They avoid scintillation from corona and solar wind.	Allows coherent light detection, discarding Sun noise, but is attenuated by atmosphere.
	Electronics Temperature: **current electronics** operates up to 65°C. **SOI**, silicon on insulator, operates up to 300°C, **SiC** electronics operates up to 600°C.	Needs new receiving telescopes, better in orbit (Earth or libration point).
Power		Large variations temperatures and in solar flux (3% of Earth level at Jupiter).
	Solar Arrays: classical or with concentrator.	Concentrator is 1/2 present cost, better hardened and uses higher voltage.
	Fuel cells, electrolysing water	Any power, but heavy and delicate.
	Nuclear Generator	More compact and lighter than solar arrays, but difficult to launch and less efficient. Policy restriction.
	RTG, radioisotope thermoelectric generator.	Expensive, creates high radiation and heat.
	Electrodynamic Tethers	Wire needs deployment and insulation.
	Solar Heat Converters	Bimetallics are 5-7% efficient, thermionics are 20 % efficient.

5.5 Recommendations on Requirements

Based on the analysis in sections 5.3 and 5.4 these are the recommendations for Near-, Mid-, and Far-Term mission requirements.

5.5.1 Near-Term Missions Recommendations

In the Near-Term, in order to get, in the most cost-effective way, the data necessary to fulfil the current scientific and application objectives defined in sections 5.1 and 5.2 we recommend:

- to focus on the solar missions under development at the moment that do not require any particular technology development and co-ordinate them,
- to look for any other potential sources of data about the Sun/Earth interaction to be used for the benefit of the Earth environment (military satellites, and observatories world wide),
- to improve international data availability and management.

5.5.2 Mid-Term Missions Recommendations

For the Mid-Term missions the solar science benefits should be the main goal to be achieved. Therefore we recommend:

- to focus mainly on the fulfilment of the application objectives related to the Sun as a threat (solar weather monitoring and early warning), as this would minimise economic damage to industrial equipment,
- to focus on the primary scientific objectives related to the effects of the Sun on the Earth,
- to promote world wide international organisation co-operation, paying particularly attention to developing countries,
- to assure continuity of observations on a long-term basis,
- to focus on missions related to region 1 and 2 (Distance from the Sun greater than 30 R_S to the Sun).

No particular time correlation in measurements being required for these missions, each spacecraft should be oriented to a specific measurement category (fields, waves, plasma, images) and the number of objectives to be fulfilled should be optimised on a measurements based criteria. Following this approach the spacecraft structure can be optimised in relation to the type of measurements to be performed, resulting in a reduced weight, reduced interference among instruments, increased overall performance, and lower costs. Small spacecraft constellations, using possibly a common bus are suggested. Daily monitoring would generate information useful for scientific analysis and solar model improvements. No technological leap would be required, but several improvements could 'spin-off' for later missions: pilot use of electric propulsion, spacecraft to spacecraft communication, smaller scale electronics and self-healing software.

5.5.3 Far-Term Missions Recommendations

For the Far-Term missions requirements we recommend:

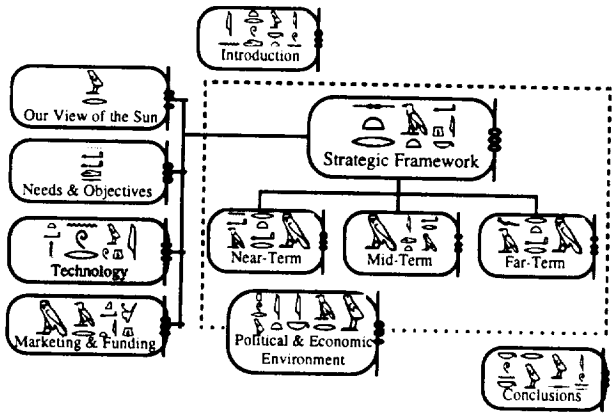
- to focus on the fulfilment of the application objectives related to the Sun as both a source and a threat,

- to focus on the fulfilment of the scientific objectives related to solar physics and theory.

The fulfilment of the scientific objectives requires specific in situ measurements. Time correlation measurements being the key for most of those observations, a mission design should be based on the use of multiple spacecraft in the same spatial region taking simultaneous measurements. Each spacecraft should be optimised for a particular measurement category taking advantage of the related optimisation design experience gained in the Mid-Term. Technological improvements should make deep exploration and in-situ multiple-latitude mapping missions, able to gather data on macro and micro solar processes, affordable thus allowing revision of current solar physics understanding. This extensive collection of information should help to discover solar physical principles that remain unknown today. This should help to advance the sciences of matter and their applications such as electronics and computing.

The enabling technologies would be a combination of electric propulsion and or solar sails, robust solar arrays or solar heat converters, high temperature electronics, optical communication with Earth-orbiting relay spacecraft. The development of constellations should benefit from spacecraft 'series' production, modularity of sensors, and from image fusion with improved database management. The smaller more numerous spacecraft would be better suited for incremental improvement and make the system more failure-tolerant.

Chapter 6



Technology Challenges and Issues

A mission to the Sun presents many technological challenges due to the harsh and extreme environments that a spacecraft will encounter. The purpose of this chapter is to document the anticipated technological challenges to the Ra missions and to provide a menu of available technologies, including their advantages and disadvantages.

6.1 Solar Environment

The space environment is a key challenge in the design of spacecraft. For solar missions all the different conditions experienced from the geocentric parking orbit, eventually gravity assist near a planet, and heliocentric orbit must be addressed. This section gives a brief introduction to the specific issues under concern for interplanetary missions, specifically with focus on close solar approach. The interplanetary environment is in many cases different from the Earth's atmosphere, as described in section 4.5.3.1.

6.1.1 Electromagnetic Disturbance

Communication between ground station and the spacecraft can be problematic as the Sun emits electromagnetic noise in all radio frequency bands. The most severe case is when the spacecraft is close to the Earth-Sun line as periodically will be the case for the heliocentric orbits. High gain antennas are required and very narrow beam receivers need to be used on ground.

6.1.2 Solar Infrared and Visible Radiation

The solar radiation becomes increasingly more severe when going close to the Sun. The thermal energy must be dissipated to provide a proper operating temperature range for

the payload. Heat shields and thermal control can be designed to go as close as four solar radii (see the Solar Probe mission [Randolph, 1995]). In our case, the heliocentric missions with orbits down to 30 solar radii are different in the sense that the spacecraft have less radiation, but must be designed to live for several years. Outgassing of material from the shield must be minimised to avoid contamination of the scientific instruments.

The trajectory selection is central in the design of solar arrays, as the available power depends on the distances to the Sun. Far away from the Sun the flux is approaching zero. This fact is part of the reason for avoiding Jupiter gravity assist in the design of the Ra missions. Close to Sun, the solar arrays are heated causing degraded performance.

6.1.3 Particle Radiation

High energy particle radiation can have hazardous effects on electronics. Microstructural damage leads to degradation and possible failure. Proton radiation with energies above 30 MeV, which increases in density with solar flares, can be extremely dangerous. Single Event Upsets are caused by heavy ions from the galactic cosmic radiation and increase in solar wind energetic particles following solar flares. Particle radiation is a problem anywhere in space, but more energetic particles are trapped in the magnetic fields of the planets. The problem is therefore particularly important for periods when the spacecraft is close to Earth, and even more serious if the spacecraft goes by Jupiter, which has extreme radiation belts [Petrukovich *et al.*, 1995], [Tascione, 1994].

6.1.4 Surface Charging

The electrostatic surface charging of a spacecraft when it penetrates the solar wind plasma must be considered. A voltage potential of the spacecraft, due to photoelectric effects, disturbs measurements of charged particles. Furthermore, discharging can cause spurious electronic switching, breakdown of thermal coatings, and degradation of solar cells, amplifiers, and optical sensors [Tascione, 1994]. The main contributions to charging come from the plasma electron current, photoemission current, and thermal emission. The current balance is very different for the environment of the Earth, other planets, and heliospace, and must be considered individually. The most severe is the Jovian radiation belt, where a spacecraft can charge up to tens of kV [Petrukovich *et al.*, 1995].

6.1.5 Deep Dielectric Charging

Deep dielectric charging is different from surface charging because it originates from 2-10 MeV electrons that penetrate deeper into the surface. This can create voltage potentials in the internal circuitry and cause malfunction of computers, electronics, and instruments [Tascione, 1994].

6.1.6 Dust Particles

Solid particles in the solar system originate from decaying comets, asteroid debris, and interstellar grains penetrating the solar system [Morfill *et al.*, 1986]. The impacts on spacecraft are not very well known, but relative speeds above 100 km/s could be catastrophic [Tsurutani *et al.*, 1995]. When trajectories and orbits are determined, the possible presence of dense dust regions should be taken into account. Dust rings may exist around the Sun with densities 5-10 times larger than the overall dust density [Mann,1995]. Details on the interplanetary dust cloud can be found in [Giese *et al.*,1986].

6.1.7 Magnetic Induction

When a spacecraft flies through a magnetic field, eddy currents can be generated in structural parts that are not properly electrically bonded or insulated. This causes a magnetic residual that can disturb magnetic measurements and generate disturbance torques affecting the attitude.

6.1.8 Summary

The most significant environmental effects with impacts on interplanetary spacecraft have been briefly introduced. Detailed descriptions are covered in the specific sections where the technological solutions are considered.

6.2 Payload Instrumentation

In this section we give a short description of the instrumentation developed for various missions dealing with studies of the Sun as well as main problems and challenges which may be encountered during the development of new instruments to meet our objectives.

6.2.1 Classification of Instruments

Two basic types of space instrumentation exist for use in interplanetary spacecraft.

- Remote sensing instruments measure the properties of photons or particles arriving at the spacecraft from a distant point of origin.
    - *In situ* instruments measure the properties of fields around the spacecraft and associated waves and particles coupled to the environment surrounding the spacecraft.

The boundary between these two definitions is somewhat blurred. For instance, in the electromagnetic spectrum there is no clear boundary between radio waves arriving from a distant source and electromagnetic waves coupled to the surrounding plasma. Wave-particle duality blurs the boundary even more.

Instruments may be further classified into active and passive measurement methods, though for interplanetary missions most measurements are passive (exceptions include radar imaging of planetary surfaces).

For space-based solar physics the main tools of investigation are plasma instruments and remote sensing of various layers of the solar atmosphere with the electromagnetic spectrum. A basic plasma package consists of an electrostatic analyser for detection of electrons, protons and ions, together with a magnetometer to establish the strength and direction of the magnetic field to which the plasma flow is coupled. Extra information is gained by also including sensors for electric field. Useful observations of the Sun may be made in virtually every part of the electromagnetic spectrum. Some wavelengths may be observed from the ground, but for the UV, X-ray and gamma ray parts of the spectrum it is essential to go beyond Earth's atmosphere. Techniques associated with remote sensing in the electromagnetic spectrum include the use of the Doppler and Zeeman effects as well as polarisation. Spatial, spectral and temporal resolution are key parameters together with field of view and aperture.

Tables 6.1 and 6.2 summarise the basic measurable phenomena and their associated requirements for detection. The *in situ* phenomena in table 6.1 include basic plasma

properties as well as particles such as neutrons and cosmic rays. Gravitational fields can only be sensed by tracking the spacecraft's motion.

Table 6.1 *In Situ* Measurement Types.

Subject of Measurement		Instrumentation required	Science obtained
Fields & Waves	Magnetic (B)	Fluxgate magnetometer on boom	Basic plasma properties
	Electric (E)	E-field probes on booms	Basic plasma properties
	Gravitational (g)	Low perihelion, accurate clocks, drag-free motion, accurate tracking	Heliodesy, General Relativity
Dust		Dust analyser (various designs)	Interplanetary dust environment & composition, interaction with Sun
Particles	Electrons (e-)	Plasma analyser	Basic plasma properties
	Ions (p+, He^{2+},...)	Plasma analyser	Basic plasma properties
	Neutrons (n)	Scintillation	Detection of solar neutrons before decay (T1/2=11 min)
Cosmic Rays (CRs)	Galactic CRs	Energetic particle telescope	Variation with 11 year solar cycle
	Energetic Solar Particles (ESPs)	Energetic particle telescope	Origin & acceleration of ESPs

Table 6.2 shows the basic categories of available remote sensing measurements. In addition to the electromagnetic spectrum there are other means of remotely sensing the Sun, including the new technology of neutral particle imaging, as demonstrated for Earth's magnetosphere on the Astrid satellite and due to fly on IMAGE [The IMAGE Mission, NASA GSFC WWW]. Neutrinos are only practicably measured with many tonnes of detection material down in mines on the Earth. This due to their small interaction cross-section and the shielding necessary to exclude high energy cosmic rays. During the Ra project we found no information to suggest that measurements of other remotely-detectable phenomena (examples include gravitational waves or subatomic particles other than those already mentioned) were of use in investigations of the Sun.

Table 6.2 Remote Sensing Measurements.

Subject of Measurement	Instrumentation required	Science obtained
Neutral Atom Imaging (NAI)	Plasma analyser with filter & ioniser at aperture	Charge exchange processes, context for *in situ* observations, early warning
Neutrinos	V. large scintillation chamber or solid state detector with CR shielding or discrimination	Fusion processes in solar core
Radio	Radio wave propagation (attenuation, refractive index, Faraday rotation)	Plasma density, magnetic field
Microwave	No immediately obvious observations	
Infrared	IR imaging and spectrometry [IAU, 1994]	Imaging solar disk and interplanetary dust distribution
Visible	White light coronograph, desirably stereoscopic	Coronal structure, context for *in situ* observations, early warning
Ultraviolet	Spectroscopic imaging of solar atmosphere	Temperature variations with depth, location & time
X-Ray	X-ray telescope X-Ray spectrometer	Coronal structure, context for *in situ* observations, early warning
Gamma Ray	Collimated scintillator & photomultiplier tube	High energy processes, e.g. solar flares, e-e+ recombination

Phenomena not originating from the Sun itself but worthy of investigation include galactic cosmic rays and the dust environment near the Sun. Galactic cosmic rays (in fact high energy charged particles) are modulated in correlation with the Sun's 11-year cycle. High solar activity reduces the influx of cosmic rays into the inner solar system. Interplanetary dust has only been studied at distances greater than 0.3 AU from the Sun. The "dust community" has identified the dust environment in this unexplored region close to the Sun as worthy of investigation [Mann, 1995].

6.2.2 *In Situ* Instruments

6.2.2.1 Introduction

The past 25 years of studies demonstrated that a continuous flux of charged particles streams from the Sun past the planets and into interstellar space. An understanding of the dynamics and solar sources of a continuous plasma outflow has been much more recently acquired. Spacecraft whose trajectories take them beyond the Earth's magnetospheric cavity are able to directly sample the charged particles flowing out from the Sun. Such *in situ* measurements account for most of our understanding of the solar wind near the plane of the Earth's orbit.

6.2.2.2 *In Situ* Instruments from the Solar Probe

With modern spacecraft technology, the last frontier for in situ exploration of our solar system is the solar corona. Among the current solar probe missions, the Solar Probe mission of USA has the most advanced in situ instruments. So we would like to adopt its instruments to the Ra missions as a result of having made comparisons with those of previous solar missions [see appendix C.1].

Solar Wind Plasma Particle Analysers

The basic requirements for the solar wind plasma particle analyser are that the ion instrument must be able to distinguish alpha particles from protons under all conditions and measure complete three-dimensional velocity distributions. The basic moments of the distributions, density, velocity and temperature, should be obtained fast enough and accurately enough to enable AlfvÇn fluctuations and MHD turbulence to be analysed.

3 - D Ion Velocity Spectrometer

This proposed design scheme is based on sensors (table 6.3) currently being built or completed for flight programmes. *The Proton Alpha Sensor* is designed to define both the geometric factor and the angular response. *The Thomson Parabola Ion Analyser* can define the sensitivity and angular response, a magnetic deflection system, and an electric deflection system with the electric field parallel to the magnetic field.

Table 6.3 Characteristics of the Sensors.

Instrument	Mass (g)	Power (W)
Proton Alpha Sensor	250	0.6
Thomson Parabola Analyser	300	2.0
Electronics box & connectors	525	
Tilt table & electronics	1000	2.7

Ion Analyser

This instrument intended for specific studies of the ion population should measure energy and mass/charge with time resolution of 10 s. Determination of charges is the major objective of this instrument in order to unambiguously resolve key ion species like oxygen and iron and their charge distributions, which through their freezing-in temperatures may serve as plasma thermometers for the solar wind particles' source regions in the inaccessible lower corona. Of the existing designs, such as the ones used on Ulysses and SOHO, the latter one is to serve best on the non-spinning solar probe, because it employs quadrupole lenses for FOV enlargements to a cone of 50 degrees opening.

3 - D Element Velocity Spectrometer

The electron spectrometer will provide the electron velocity distribution within energy ranges from 1 eV to 4 keV and from 2 keV to 20 keV and density range from 10 to 10^6 cm^{-3}. The detector accuracy must be high enough to ensure the precise determination of the density, velocity vector, pressure tensor and heat flux vector of the electrons. The proposed energy resolution is 15 % and angular resolution is 22.5°.

Magnetometer

The magnetometer must be able to measure coronal magnetic fields over a broad dynamic range to study solar corona heating mechanisms, especially the mechanism for solar wind acceleration. Hence a combination of sensors should be used. First there must be fluxgate sensors with the possibility to switch between regimes of relatively weak magnetic fields. In case of stronger magnetic fields the saturating fluxgate sensors should be used instead. A combination of the DC magnetometer with a current probe would

allow a more complete *in situ* determination of local magnetic fields and current properties. The range /resolutions of the instrument are: 1 mT/32 nT for magnetoresistive channel and 64000 nT/2 nT, 3200 nT/0.1 nT, 256 nt/8 pT for fluxgate channel.

However, since the magnetometer of *Russian Fire Mission* has better mass and power characteristics, we would like to suggest using the Russian's to save its consumption of energy and reduce cost.

Plasma Wave Experiment Package

The role of the Plasma Wave Experiment Package is to identify the various wave modes that comprise the turbulence spectrum existing within the extended coronal envelope and to measure their intensities within the frequency range from 0 to 10's of MHz.

Suprathermal Particle Sensor

This instrument is designed to study the low energy end of the solar energetic particle population, particles accelerated at shock waves in the corona, and pick-up ions from particles outgassing or being sputtered from interplanetary dust. It has two energy regimes: 20 keV and 1000 keV/charge

Solar Energetic Particle Analyser

The set of sensors included in this instrument has to be able to measure protons from 50 keV up to 50 MeV and electrons from 4 keV to 10 keV. The system must be flexible to work in different regimes, since any SEP information while approaching the Sun to distances closer than 0.3 AU is essentially new. It is necessary to use different sensors to cover the broad range of energies for protons and electrons.

Detectors for Interplanetary Dust Particles

The aims of the dust experiment are to detect IDPs with masses between 10^{-16} g and 10^{-6} g determination of IDPs spatial distribution, and determination of IDPs size distribution and its spatial variation.

6.2.2.3 Model Payload for a Future Mission

The table below shows the model payload with a ten-percent margin from our present knowledge about the instruments.

Table 6.4 The Model Payload for a Future Mission.

Instrument	Mass (kg)	Power (W)	Telemetry (kbits/s)	Typical Time Resolution (s)
Magnetometer	4.0 (4.6)	3.0 (6.2)	4 (4)	0.01
Plasma Waves	6.5 (6.7)	5.0 (5.1)	12 (12)	0.001
3 - D Ions	2.0 (3.1)	2.0 (2.7)	6 (2)	0.1 - 1
3 - D Electrons	2.0 (3.0)	2.0 (2.0)	4 (4)	1
Heavy Ions	3.0 (3.5)	3.0 (3.5)	0.9 (0.1)	10
Superthermal Particles	2.0 (4.0)	2.5 (2.5)	2.0 (0.7)	1
Energetic Particles	2.0 (3.5)	2.5 (4.0)	3.0 (2.0)	1 - 10
Dust	1.0 (1.2)	1.0 (1.0)	0.1 (0.1)	—
Total	22.5 (29.6)	21.0 (27.0)	32 (24.9)	—

6.2.3 Remote Sensing Instruments

6.2.3.1 Introduction

Optical imaging is a major tool for remotely studying the solar corona both from the ground and from space and indeed coronographs have extensively contributed to its understanding.

UV solar physics also has always been the centrepiece of solar research from space since a) UV solar radiation smaller than 300 nm is absorbed by the Earth's atmosphere and therefore can only be explored from space; b) the solar UV is the dominant energy source of the upper Earth atmosphere; c) the outer solar atmosphere from the transition region in to the corona emits most of its radiation in the UV [Brueckner, 1993].

An ideal solar remote sensing instrument set has to combine:

- High angular resolution combined with the pointing stability.
- High spectral resolution.
- Good time resolution compatible with the angular resolution.
- Wide and simultaneous spectral coverage required to follow structures and phenomena in velocity, density and temperature from chromosphere to corona.

To meet all the scientific requirements involved in understanding the corona, a set of instruments that complement each other and observe the same area or even the same fine structure during co-ordinated programmes is needed. Their co-alignment will be more and more difficult with the increasing angular resolution. Most of the instruments also require high spacecraft attitude stability: upper limit of angular velocity for many of them is of the order of 1″/sec.

Although it is not easy to combine high angular, spectral and time resolutions within the physical constraints placed on space instruments, progress in this direction continues. The most important trends in development of optical and UV devices are slow increase of angular and spectral resolution along with steady decrease of mass and dimensions. The latter parameters can not decrease as fast as those for electronic devices because they are limited by optics, but there is a tendency to integrate several devices having different bands (and even instruments from other spacecraft systems such as attitude determination sensors).

To improve the quality of remote sensing measurements, it is necessary to improve a) image quality and stability limited by quality of the optical surfaces and effects of structural deformations; b) spectral resolution and stigmatism. Sufficient precautions are to be taken to ensure that the image quality is optimised not only for ground tests, but also for in-orbit constraints, by selecting the proper mechanical structure and mounts for the optics and taking the spacecraft characteristics into account.

One more restriction is caused by negative effects of the solar environment on the instruments and, especially, the optical surfaces. These effects can be reduced either by placing the instruments behind tiny holes in the heat shield or by using retractable mirrors which can be extended out of the umbra only for short measurement periods.

In this chapter only the instruments being designed for future solar probes, i.e. spacecraft visiting the solar corona, are considered. Such an approach is caused by unique

requirements on such instruments and, hence, their significant difference from payloads of spacecraft designed for 1 AU environment such as SOHO, Mir or Space Shuttle.

6.2.3.2 Remote Sensing Instruments from Russian Probe Plamya

Among the planned solar probe missions the Russian Plamya spacecraft has the most advanced remote sensing instrument complex [Oraevsky, Kuznetsov, 1994]. That is the reason for considering all of them.

The purpose of the proposed Plamya "Solar Coronograph" experiment is to construct a global 3-D white light image (spectral range 5500...6000 A) as well as a global 3-D model of the solar corona within 1.3...5 solar radii. The FOV of the instrument is 18°; angular resolution is 2.1′ per pixel. A series of white light coronal images recorded in various projections during the Plamya passage between the two poles will be used to extract the 3-D structure of the entire solar corona. Using techniques similar to computer tomography a quantitative model of the solar corona can be derived from the Plamya imaging data.

According to [Vaisberg, 1996] Russian scientists and engineers managed to reduce the mass of the instrument from 3 to 1.5 kg (without reducing capability).

The "Solar Vector Magnetograph" experiment is designed to study solar magnetic fields and radial velocities with spatial resolution of about 100 km within FOV of 100 000x100 000 km at a distance of 20 solar radii. On-board storage having 10 Mbits will permit to obtain temporal resolution of 2-4 hours.

EUV Telescope with FOV 12° is modified version of the EUV channel (190-205 A) of RES-C (solar X-ray spectrometer) operating on board of the CORONAS-I.

Plasma Analyser is to be mounted on a boom and has almost spherical field-of-view ($2x2\pi$).

6.2.3.3 Other Remote Sensing Instruments for Solar Probes

For future solar probes the Jet Propulsion Laboratory offers an instrument consisting of a high resolution visible light telescope, a high resolution EUV telescope and two EUV pinhole imagers combined in an integrated configuration [see table 6.5]. The estimated total cost of the instrument is 6.5 million US$.

Table 6.5 Characteristics of the JPL EUV/VIS Remote Sensing Instrument.

Band	Wave-length (A)	Spectral resolution (A)	FOV at 4 R_s (km)	Spatial resolution at 4 R_s (km)
EUV	304	few A	100 000	390
	304	few A	5 000	20
	171	few A	100 000	390
Visible	4308	+10/-2	2 560	18

The Coronal Optical Imager is designed by Laboratorire d 'Astronomie Spatiale and Institut d'Astrophysique, France [Lamy, Koutchmy, 1994]. The instrument combines the capability of EUV, UV and visible imaging with spatial resolution of 100 km as well as visible polarimetry. The authors proposed two versions adapted to spinning and 3-axis stabilised probes respectively. A Coronal Optical Imager (COI) can detect the faintest plasma and magnetic structures, analyse the He/H ratio and the cool plasma component

and observe possible sources of dust near the Sun. The instrument will have on-board storage of 1.5 Gbits

The Solar Pioneer is a mission concept developed by Johns Hopkins University Applied Physics Laboratory (JHU/APL) [McNutt *et al*, 1994]. Although the "core" set of instruments for this mission includes only *in situ* measurements, there are also two "strongly desired" remote sensing instruments.

Table 6.6 lists physical instrument characteristics for various programmes.

Table 6.6 Summary of Physical Characteristics of Remote Sensing Instruments.

Instrument	Mass (kg)	Power (W)	Data rate (kbit/s)
Solar Pioneer Coronal Photometer	0.7	0.5	0.1
Solar Pioneer Coronal Disk Imager	3.3	5.5	0.4
Plamya White Light Solar Coronograph	3→1.5	5	5
JPL integrated instrument (Vis. + UV)	4	1	0.35
Coronal Optical Imager (Vis. + UV)	15	15	5
Plamya EUV Telescope	7	5	5
Plamya Vector-Magnetograph	7	8	5
Plamya Plasma Analyser	6	6	

6.3 Orbit and Trajectory Definition

The objective of the orbit and trajectory analysis is to determine the flight profiles of spacecraft subject to various constraints such as scientific orbital requirements, launch time frames and minimisation of propellant expenditure. The Δv budget (the sum of the velocity changes required throughout the space mission life) is traditionally used to account for the trajectory energy required throughout the whole mission. Various trajectories will be discussed, and some elementary calculations will be made of the velocities required for missions approaching the Sun. Due to the very high velocity requirements, it will become apparent why until now, gravity assist trajectories have been primarily selected. However, we will also explore the merits of low thrust trajectories where propulsion is provided by electrically powered thrusters, solar sails, or a combination. In addition, the possibilities of trajectory alteration due to aerodynamic forces induced by planetary upper-atmospheric flight will be mentioned. This section will provide a broad overview of solar-oriented trajectories, and will give some possible trajectory options for the Ra missions.

6.3.1 Summary of Recommended Trajectories and Orbits for Ra

Alternative trajectory solutions were examined and the following conclusions and recommendations were made. Further details are provided in the sections following this summary. The emphasis of the analysis was on innovative solutions that did not rely upon time extensive gravity assist and chemical propulsion manoeuvres that appear to be the norm today.

Low thrust trajectories powered by solar sails or electric propulsion were examined as well as the various combinations of gravity assist coupled with chemical or electrical propulsion. Various orbits ranging from heliosynchronous to highly elliptical orbits out of the ecliptic were considered.

The following is a list of conclusions drawn from the reviews of the literature and of our own judgements and calculations.

- Solar sails can provide a significant reduction in time of flight. Solar sail trajectories have been analysed and should be considered as optimal solutions for the long term plans, given the fact that many technological issues still need to be addressed relating to the deployment and attitude control of extremely large area and lightweight structures. Based on some of the studies conducted by JPL [Wright and Warmke, 1976], [Friedman *et al*, 1978] on solar sail trajectories, it is feasible to reach highly inclined circular orbits at distances within 0.3 AU of the Sun in time periods that are sometimes half of the required time to make it through a Jupiter Gravity Assist (JGA). In addition, coplanar (non-optimal) orbital transfers were examined with software we developed. The key advantage of the solar sail lies in the fact that little or no propellant mass nor power is required (compared to electrical and chemical propulsion) to provide the necessary thrust. It is a fact, though, that attitude control of a spacecraft equipped with large solar sails will require more attention and will be much more complex.
- *Interesting applications for Ra are presented in section 6.3.6.9 [Circular Orbit] and in section 6.3.6.10 [Polar Eccentric Orbit].*
- Electrical Propulsion (EP) provides low thrusts at very high specific impulses and hence over a long period of time can deliver high velocity increments (high Δv). This technology is currently being applied to upcoming interplanetary missions such as the New Millennium spacecraft developed by NASA and for the Japanese Muses-C for its rendezvous with an asteroid. The electrical propulsion should be seriously considered for the Mid-Term Programme. Some solutions using electrical propulsion are proposed in the following section of the report for the SAUNA mission [see chapter 9], since EP transfers are efficient means to inject into high velocity circular orbits. EP provides a reduced time of flight compared to gravity assist scenarios and a reduced propellant mass compared to chemical propulsion. Depending upon the thruster type and mission characteristics, the power requirements for thrust production may be quite large. Solar array-powered EP thrusters are most efficient when not too close to nor too far from the Sun and this has an impact on the potential orbit selection.
- *Interesting applications for Ra are given in section 6.3.6.6 [Electric Propulsion Trajectories] and section 6.3.6.7 [Combinations of Direct Insertions].*
- Gravity Assist (GA) flybys are conventional and low risk manoeuvres with a proven historical heritage and therefore represent a viable solution for missions in the short term. Given suitable planetary bodies, GA flyby manoeuvres can provide a huge Δv saving for the injection to elliptic heliocentric orbits. However, very large or unfeasible Δv's are required for the eventual orbit circularisation. Compared to direct injection, solar sails or low thrust, GA flybys introduce launch date constraints imposed by the required phasing of the planetary bodies. Jupiter GA is the most effective flyby because any change of inclination is attainable and very low perihelia can be achieved. However, such trajectories imply a longer transfer time and can expose the spacecraft to intense radiation environments. Venus and Mercury GA flybys, although less effective due to the relatively lower mass of the planets, can provide sufficient impulse to reach orbital inclinations up to 20 degrees. Nevertheless, perihelia lower than the altitude of a Sun-synchronous orbit seem to be difficult to achieve.

- *An interesting example for Ra is given in section 6.3.6.4 [Highly Eccentric Orbit], showing a resonant Venus flyby for a transfer to a 20ß inclined orbit with a 0.25 AU perihelion. GA transfers could possibly be integrated with electrical propulsion or solar sail for the final orbit circularisation.*

Preliminary Background and Information

The potential planetary bodies for gravity assist and their relative size and mass are given in appendix C.5, table C.5.1. Table C.5.2 in appendix C.5 lists some of the distance units that we will make extensive use of during this section of the report.

6.3.2 Orbit Review and Definition

Note that all the orbits evaluated in this chapter have the Sun as the principal focus of the orbit. The most interesting possibilities for heliocentric orbits are studied and some of the advantages of the various options are raised in this chapter.

6.3.2.1 Circular Sun Orbit in the Ecliptic (Eccentricity < 0.1)

These orbits are contained within the ecliptic and therefore can allow a study of the Sun from low latitudes of the solar environment.

Sun-Synchronous Orbit (0.18 AU orbit, ~28 days period)

These orbits are a subset of the circular Sun orbits, and allow the spacecraft to have a period equal to the Sun's rotation (approximately 28 days, around the Equator and increasing towards the Sun poles). This is achieved by sending the spacecraft into a heliocentric orbit with a semi-major axis of approximately 0.18 AU from the Sun and a relatively low eccentricity. Although this orbit appears to be quite close to the Sun throughout the whole duration of its orbital path, it allows very interesting studies of the solar environment, since the spacecraft can investigate the same point on the Sun by turning around it with the same period and around itself once during one orbit.

Lagrangian Points (L1 -> L5) and Halo Orbits

The Lagrangian points, or Libration points, for two celestial bodies in mutual revolution are the five points such that an object placed at one of them will remain in essentially the same position relative to the bodies. They are in the orbital plane of the two body system. The motion about one of the stable Lagrangian point may be dominated by the perturbation due to a third-body interactions. For the Sun-Earth system, L1, L2, L3 are unstable points; that means if we place a body in one of these points, small correction manoeuvres must be applied to prevent excessive departure from the nominal orbit. L4 and L5 are stable points.

L2 and L3 are of no interest for the Solar Probe mission since they are located in positions where they either can not see the Sun or they cannot see the Earth (respectively).

Spacecraft (i.e. ISEE/ICE and SOHO) have been launched to orbit around L1, which is located between the Sun and Earth at one hundredth of an AU from the Earth. Refer to the various sections in this document and appendix C.5 to learn more about the trajectory and orbit of SOHO. The spacecraft is actually orbiting around the L1 point in a path that we call a halo orbit.

L4 and L5 are very interesting points since they would eventually allow multiple view points of the Sun and would provide images for building a fully integrated three-dimensional (or at least fully two-dimensional) model of the Sun's environment.

6.3.2.2 Eccentric Sun Orbit (eccentricity > 0.1)

The main advantage of these orbits that are highly eccentric is that there is mainly no need to circularise the orbit once the spacecraft has reached the desired location with respect to the Sun and once that it has been injected in the proper course. This implies of course a much lower Δv (in the order of 5-10 km/s instead of 25-35 km/s).

The main disadvantages lie in the fact that the period of the orbit is much longer, on the order of 5 to 6 years depending on the aphelion, thus allowing close studies of the Sun only during short periods when close to the perihelion.

6.3.2.3 Polar Orbit Around the Sun

This orbit has already been used by previous spacecraft and Ulysses is orbiting in a path that takes it around the poles of the Sun in an eccentric orbit that brings it back to the orbit of Jupiter where it had its trajectory modified through gravity assist. The main interest of having a probe in a polar orbit around the Sun is that the polar environment of the Sun is still quite unknown and would surely reveal a lot if we were to study the presence and structure of solar magnetic fields and other solar events in the vicinity of the solar poles.

6.3.2.4 Heliocentric Geosynchronous (HGS) Orbit

This orbit is an heliocentric orbit with the orbital plane precessing at 1 deg/day to maintain a fixed angle between the orbit plane and the Earth direction. The feasibility of such orbits was initially investigated because of the obvious advantages that they would offer for a prolonged mission. Earth Sun-synchronous orbits exploit the Earth oblateness (term J_2) providing such an orbit plane precession for a given altitude and inclination. However, HGS orbits are found not to be feasible because of the high sphericity of the Sun ($J_2=5\times10^{-8}$).

6.3.3 Achievable Orbits (Trajectory, Time, Energy)

The purpose of this section is to examine a broad range of trajectories to provide an overview of how costly solar missions can be in terms of velocities required.

We will consider the possible following trajectories (a subset of which will be analysed in higher detail in the following section): 1) direct injection; 2) gravity assisted (with or without aerobraking); 3) low thrust with electric propulsion; 4) solar sail; and 5) a combination of the mentioned orbits/techniques is also possible, e.g. gravity assist plus low thrust or solar sail ; solar sail plus low thrust etc.)

For more information on the various propulsion systems, please refer to section 6.4.

6.3.3.1 Gravity Assist and Aerobraking

An important consequence of a spacecraft entering a sphere of influence of a planet is the possibility of gaining or losing energy with respect to the Sun (the vast majority of the solar system's angular momentum is retained within the planets). It is this same momentum that is used to accelerate spacecraft on so-called "gravity-assist" trajectories. The gain or loss of energy is caused by the turning of the spacecraft velocity vector under the influence of the gravitational field of the planet around which we perform the flyby.

The spacecraft's arrival date for the flyby needs to be carefully timed so that it would pass close to the planet in its orbit around the Sun (optimisation software used for trajectory definition are covered in a following sub-section). Gravity assists can be also used to decelerate a spacecraft, by flying in front of a body in its orbit, transferring some of the spacecraft's angular momentum to the body (negligible amount for the planet). When the Galileo spacecraft arrived at Jupiter passing close in front of Io in its orbit, Galileo experienced deceleration, helping it achieve Jupiter orbit insertion.

6.3.3.2 Chemical Propulsion (or Direct Injection)

Analytical formulas can be used for this purpose. The analysis is quite straightforward and shows that with present technologies the huge Δv's required for direct injection into a Sun orbit (e.g. a highly elliptical Sun orbit or, more difficult, a circular Sun-stationary orbit) is so costly to make this option not feasible (SOHO had only to be launched into the Lagrangian point L1 relatively close to the Earth rotating around the Sun with the same period as the Earth). If a change of inclination is required (to go out of the ecliptic plane to take high latitude measurements of the Sun), the situation is even worse. This situation could however change in the future (though probably not in the short plan) if new and more powerful launchers and upper stages are developed; therefore, this option was not discarded during a first analysis and some results will be given in this report.

6.3.3.3 Ion Propulsion

Characteristics and advantages of ion propulsion are discussed in section 6.4.3.1.

6.3.3.4 Solar Sails

Space sails use solar or other radiation directly as a method of propulsion. They are large, lightweight mirrors which reflect either photons or electromagnetic radiation. The advantage of using solar sails is that a power generator and converter are not necessary onboard, thus saving mass and costs. The biggest disadvantage is the necessity of large sails [refer to section 6.4.4.4].

The trajectory course is determined by the departure and destination points, the characteristic acceleration, the orientation of the sail, and by the thermal requirements of the sail and the spacecraft.

Usually, the optimisation of interplanetary trajectories is based upon the minimisation of the transfer time between the departure point and the final destination. This means the sail angle must be optimised as a function of time. Orbital transfer optimisation with solar sails has been studied at JPL, see for example [Sauer, 1976].

The initial conditions at the departure point depend on the speed and direction of motion that the ship can have as it departs from planetary space into interplanetary space, crossing the sphere of influence of the planet.

6.3.4 Orbits and Trajectories of Previous Solar Missions

For a review of the trajectories of the missions directed to the Sun that have been accomplished, or are being conducted at the moment and that may even be planned for the near future, refer to appendix C.5.

6.3.5 Orbit Optimisation and Software Review

6.3.5.1 MIDAS

Please refer to the appendix C.3 on the MIDAS Software.

6.3.5.2 SKYNAV

Please refer to the appendix C.4 on the SKYNAV Software.

6.3.5.3 Solar Sailing Optimisation Software

Please refer to the appendix C.2 on the Solar Sailing Software (called Sailing) to get the complete code in FORTRAN generated during the Summer Session Program in Vienna 1996. Take note that the code was based on a previous program written during the ISU session of 1994 in Barcelona for the study of Mars Aerobraking and that it does not perform any optimisation.

6.3.6 Ra: Appropriate Orbits and Trajectories

In this section of the report, the examples that were analysed using the available tools mentioned above are presented. Depending on the technology available (solar sails, low thrusters etc.) some of these sample trajectories could be considered for the mid-term or for the long-term missions.

6.3.6.1 Circular Orbits in the Ecliptic Plane using Direct Injection Trajectories

The first type of trajectories to be studied were the direct injection trajectories. To get the orders of magnitude for these types of trajectories, a study of the different velocity increments for various ecliptic heliocentric orbits was made. Varying the radius of the orbit, we computed the first Δv required first to reach the required orbit, and then the second Δv to circularise the trajectory to the final orbit.

Table 6.7 Velocity Increments for Various Ecliptic Heliocentric Orbits.

r_p (Solar radii)	Δv_1 (km/s)	Δv_2 (km/s)
5	23.6	77.7
10	21.1	52.8
39	13.4	21.1
50	11.6	16.9
100	6.1	7.4

Using MIDAS software (by Carl Sauer and Stacy Weinstein of JPL) for trajectory optimisation, some single and multiple planetary swing-bys were analysed. In computations in sections 6.3.6.2 through 6.3.6.5, we assumed always to start from a circular LEO parking orbit at about 200 km altitude.

6.3.6.2 Polar Highly Eccentric Orbit using Jupiter Gravity Assist (JGA)

Jupiter is often used for gravity assists when going to the Sun and cranking the orbit in a polar and highly eccentric orbit (like the American Solar Probe) or in order to stay in the ecliptic plane and further circularising. Using MIDAS, optimal Jupiter Gravity Assist

(JGA) trajectories were studied to go to a highly eccentric orbit with a very low perihelion (about 4 solar radii R_s).

A polar (90 deg inclined) orbit with a perihelion of 0.018 AU (4 solar radii, like Solar Probe) was studied: taking 13/12/2004 as a launch date, a transfer time of about 4 years was found to be necessary, and the launcher has to provide a C_3 =103 (km/sec)^2 (for a Δv=7.2km/sec). The distance at flyby from Jupiter is 16 Jupiter radii, which should not be a too harmful radiation environment. This is represented in figure 6.1.

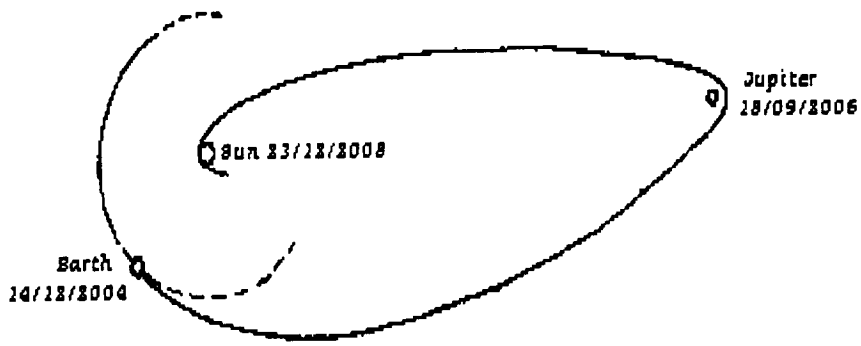


Figure 6.1 Jupiter Swing-by with 90ßInclination Change.

If the constraint on the perihelion of the target orbit is relaxed to be 0.18 AU (about 30 solar radii, similar to a polar version of the SAUNA option), the C_3 required decreases to 91 (for a Δv of 6.8 km/sec).

6.3.6.3 Highly Eccentric Orbit in the Ecliptic Plane using JGA

Similar cases as in the previous section (final perihelion of 0.019 AU and 0.18 AU) were analysed, while staying in the ecliptic plane. The required transfer time remained the same (4 years approximately), as well as the C_3 requirements. The JGA to a final perihelion of 0.18 AU in the ecliptic plane could in principle be used as a transfer orbit for the SAUNA mission [see chapter 9] but the Δv required for the final circularization is very large (29 Km/sec). An alternative method with finite thrust starting from Jupiter was not considered here because of the difficulty of providing the required electrical power (from solar panels) at such high distances from the Sun [see below for circularization with low thrusts].

6.3.6.4 Orbit Slightly Inclined (20°) using Resonant Flybys around Venus

This case considered is a resonant Venus Gravity Assist (RVGA) to go from the Earth orbit to a solar orbit with a perihelion of 0.25 AU, 20 deg inclined with respect to the ecliptic plane. This represents a rather cheap option and we found that using a resonant gravity assist of this type, starting from a LEO, a C_3 =15.3 (km/sec)^2 is required from the launcher (providing a Δv of about 3.8 Km/sec). The onboard propulsion must provide an additional Δv of 4 Km/sec at the time of the second Venus flyby. As expected, a further circularization would need a very high impulsive Δv at perhelion (13 Km/sec). Finite thrust options could be studied for this latter purpose, since it is shown below that circularization in a spiral low thrust trajectory starting from a Venus orbit (though with different conditions) can be effective.

This case is illustrated in the following figure 6.2.

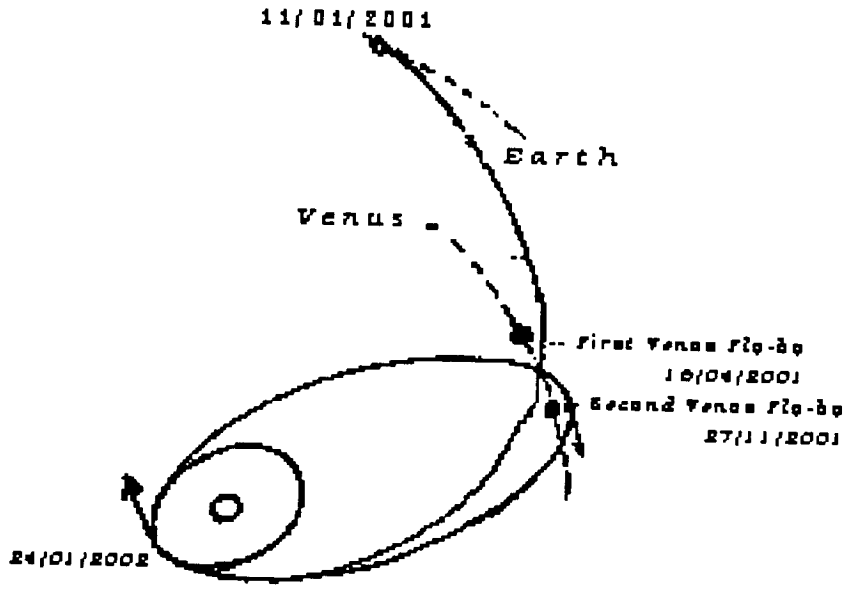


Figure 6.2 **Resonant Venus Flyby.**

6.3.6.5 Circular and Elliptical Orbits using Multiple Mercury and Venus Flybys

Such a technique was analysed in order to get to a Sun-synchronous orbit (defined as a circular orbit at about 38 Solar Radii or 0.18 AU from the Sun, in the ecliptic plane). This option allows a relatively fast transfer, but imposes very costly requirements both on launcher and onboard propulsion. Selecting the launch date on 29 December 2000 the launcher has to provide a C_3 =113 (km/sec)^2 from a LEO (meaning a Δv =7.5 Km/sec), Mercury and Venus orbits will then be encountered respectively after 68 and 115 days (both flybys being unpowered), and two additional manoeuvres of 2.5 and 19 Km/sec are needed after the Mercury flyby in order to respectively get to the desired perhelion and then circularise. The launcher requirements would make the launch very expensive, requiring possibly a PROTON launcher with upper stage). The final orbit is reached after about 8 months from launch. The use of low thrust for circularization after the Mercury flyby was also considered and optimised (using the software SKYNAV) but did not give an interesting result (probably due to the eccentricity of the spacecraft orbit after the Mercury flyby and to the vicinity of the Sun, see figure 6.3). About three more months are needed after the last Mercury flyby, a thrust level of 1.3 N for a total Δv of about 40 Km/sec. Even using 4 Plasma Xenon thrusters (providing 0.3 N each) with a relatively high specific impulse (2000 sec), the mass and power requirements (60 kW for propulsion) make this option not recommendable. This example is illustrated in the following figure.

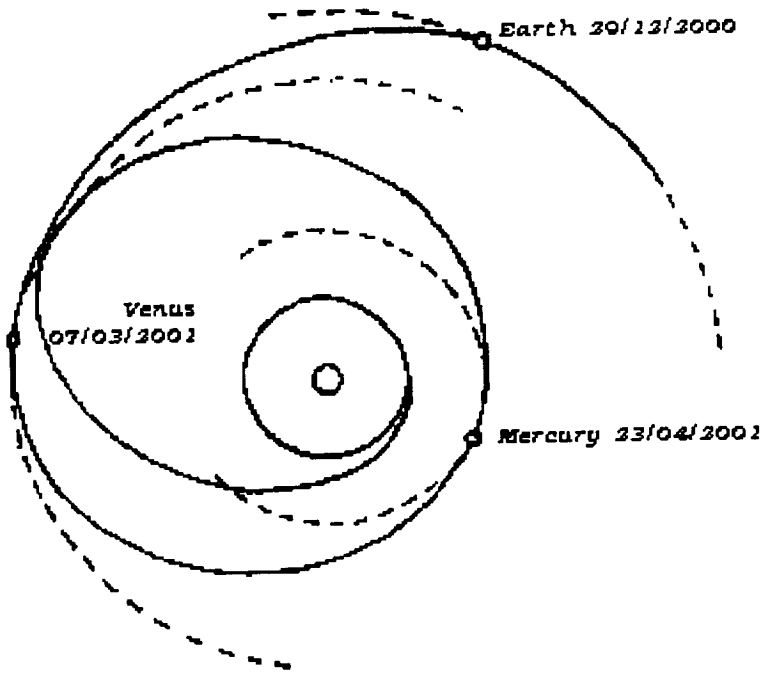


Figure 6.3 Venus-Mercury Flyby followed by Electrical Propulsion.

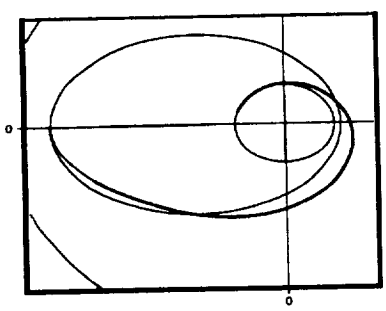


Figure 6.4 Top View (Ref. Radius).

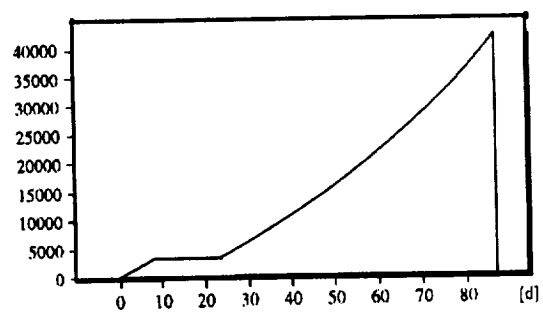


Figure 6.5 Δv Requirement (m/s).

We used the same technique to go to a distance of 30 R_s (solar radii) or 0.14 AU from the Sun (circular or not), changing the inclination to about 20 deg. The launch date was set to 29 December 2000. Starting as usual from a LEO, the launcher has to provide a C_3 =113 $(km/sec)^2$ and the two planetary flybys are unpowered. An additional Δv of 5.6 Km/sec lowers the perhelion to 30 R_s and modifies the inclination, whereas a huge final Δv = 24 Km/sec would be required for the final circularisation. The total transfer time is 8 months.

6.3.6.6 Electric Propulsion Trajectories

Using a special software (SKYNAV) available at ISU some low thrust trajectories were considered. This technique can also be considered in conjunction with GA flybys or with direct injection, since in these cases the eventual circularization with impulsive manoeuvres is very expensive.

The trajectories studied in this section and in the following one assumed an initial spacecraft mass of 300 kg. The final orbit for both trajectories was the same: Sun-synchronous orbit (0.18 AU) in the ecliptic plane. This orbit is similar to that proposed by for the SAUNA mission [see chapter 9].

Direct injection into the orbit. The low thrust propulsion system was chosen to consist of xenon ion thrusters with a combined thrust level of 0.28 N. The transfer time was about 380 days. The total Δv is 37 km/s and the required Isp is 6000 resulting with a vehicle final mass fraction of 0.54.

This trajectory is illustrated in figures 6.4 and 6.5.

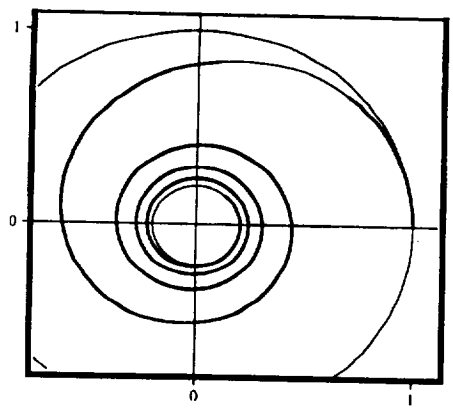


Figure 6.6 Top View (Ref. Radius).

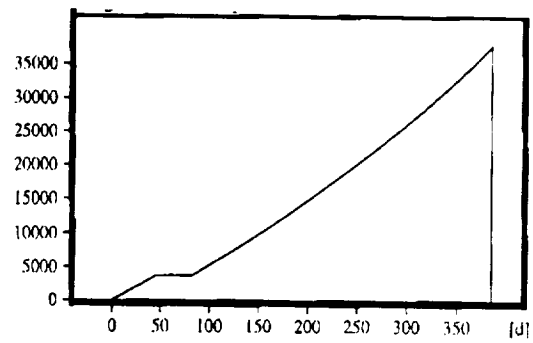


Figure 6.7 Δv Requirement (m/s).

6.3.6.7 Combinations of Direct Injections and Electric Propulsion

The second low thrust trajectory uses an initial velocity increment to Venus' orbital distance from the Sun provided by a launcher and upper stage. Upon arrival at this orbit, low thrust is activated. A thrust level of 0.27 N and an Isp of 4500 s is assumed. The total Δv is the same as in the previous case, but the total transfer time is one year. This could be possibly improved by incorporating a simple or a resonant gravity assist at Venus [as in section 6.3.6.4].

This trajectory is illustrated in figures 6.8 and 6.9.

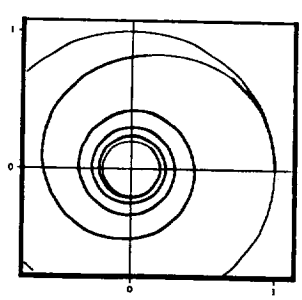


Figure 6.8 Top View (Ref. Radius).

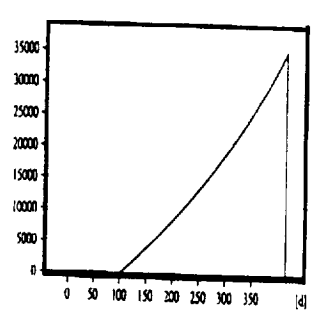


Figure 6.9 Δv Requirement (m/s).

6.3.6.8 Lagrangian Point L4 and L5 using Conventional Direct Injection

The easiest way to make it to L4 using a conventional direct injection trajectory, would be achieved by allowing the spacecraft to go from a parking LEO orbit to a heliocentric orbit that would have a lower period than the Earth for some time and to then re-inject it back to a 1 AU orbit. This would take 5/6 of a year (0.833 year) and would require approximately 3.885 km/s of Δv through a transfer to an orbit with a semi-major axis of 1.32x108 km. Please refer to figure 6.10 for more information and visualisation of the scenario.

The same conceptual approach to reach the L5 would lead to allowing the spacecraft to go to a higher orbit than the Earth until it actually reaches the desired location (by taking some delay on the Earth during their orbit) and would then be re-injected to a 1 AU orbit. The process would then take 7/6 years (1.167 years) and would require approximately 2.843 km/s of Δv through a transfer to orbit with a semi-major axis of 1.65x108 km.

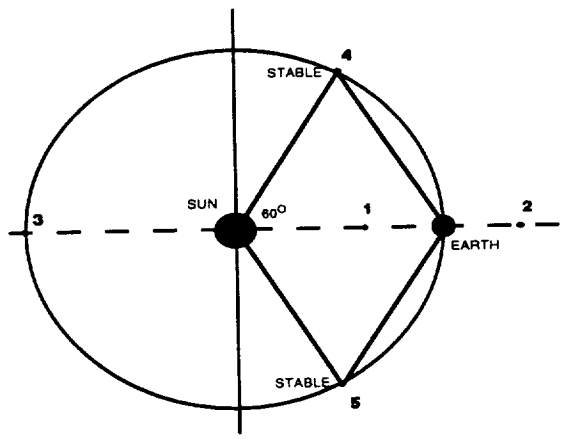


Figure 6.10 The Five Lagrangian Points.

6.3.6.9 Circular Orbit at 0.18 AU using Solar Sailing

Using the Solar Sailing Software (written at ISU), we have tried to model the nature of a trajectory for a spacecraft leaving the Earth and spiralling towards the Sun using only solar sailing as the main propulsion. We have assumed that the sails maintain a constant angle of attack with respect to the incoming solar pressure and that the trajectory could be contained in a two-dimensional plane.

To provide the report with an order of magnitude, we have computed the trajectory for a spacecraft leaving a parking orbit, with a mass of 250 kg, and solar sails of 9000 meter square (that represents 30 meters x150 meters sails on both sides of the spacecraft). The results of the calculations show that the spacecraft would require approximately 928 to 937 days (or approximately 2.55 years) to make it to a 0.18 AU orbit around the Sun if the sails are maintained at a 45 degree angle of attack throughout the complete spiral. We have also noticed that the inclination of the sail has a great impact on the nature of the orbit. If the sail was to be inclined with a 60 degree angle, than the spacecraft would never manage to reach the 0.18 AU in 950 days, but if the sail was oriented with a 30 degree inclination, then the 0.18 AU orbit would be reached in less than 546 days (approximately 1.49 years). Please refer to appendix C.2 for more information on the computations and on the mathematical equations used.

We also repeated the orbit propagation with solar sail when starting from Venus circular orbit and ending with the Sun-synchronous orbit: a total transfer time of 540 days is found, considerably longer than with low thrusters [section 6.3.6.6].

6.3.6.10 Polar Eccentric Orbit 0.2-1.4 AU using Solar Sailing

The trajectory to make it to a heliocentric orbit with a semi-major axis of 0.3 AU has been studied using square solar sails of 250 m^2. The spacecraft would first spiral all the way through 0.3 AU, then crank the orbit to a 90° inclined orbit to the ecliptic. The orbit's aphelion would be raised to 1.4 AU and the perihelion would be lowered to 0.2 AU, therefore providing a final period of 2.7 years for the orbit. The example was provided by the Jet Propulsion Laboratory (JPL) and is illustrated in figure 6.11.

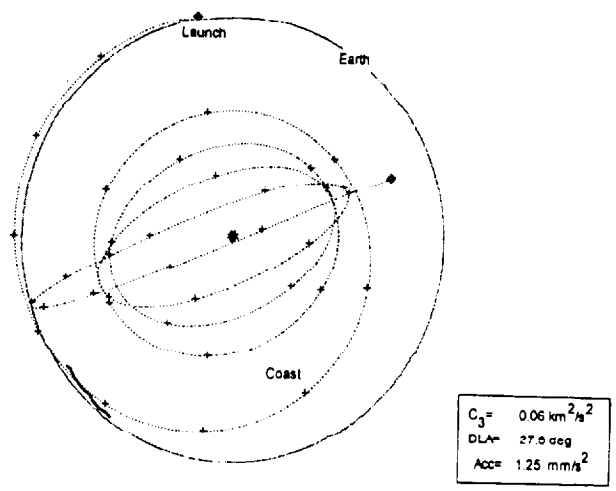


Figure 6.11 Polar Eccentric Orbit 0.2-1.4 AU using Solar Sailing.

6.4 Propulsion

An important subsystem of spacecraft is the propulsion system whose function may be to provide any or all of the following: orbit insertion, orbit correction, attitude control, or even as in the case of electric propulsion or solar sails, to provide low thrust over an extended period of time to achieve large velocity increments. As was discussed in section 6.3, the velocity increments required for orbits close to the Sun are very high. The purpose of this section is to discuss briefly the various propulsion technologies that are or will be available for use on proposed Ra missions in the various time frames and to make recommendations concerning the most suitable propulsion systems.

6.4.1 Summary of Recommended Propulsion Systems for Ra

Chemical propulsion is extensively used in main and attitude control propulsion for upperstages and spacecraft. What makes chemical propulsion attractive is its relatively low amount of development testing and cost. However, chemical propulsion performance is not as good as many advanced propulsion systems. If very high Δv is required and a planetary assist manoeuvre is not a viable option, then the use of chemical systems for main propulsion could be prohibitive from a volume and mass stand-point. However, chemical propulsion, with its extensive flight heritage is the best option for the attitude control system.

Although electric propulsion (EP) does not have an established flight heritage, especially for scientific missions, it is an attractive choice for missions that require large velocity increments due to the low propellant consumption rates. Indeed, EP is an enabling technology to reach inner solar orbits without the use of gravity assist manoeuvres. The most viable current EP system that is available for lower power applications is an ion thruster, and both U.S. (New Millennium) and Japanese (Muses-C) missions are planning on using such systems in the intermediate future. In the intermediate and far term time frames, it is strongly urged that ion thrusters be used as primary propulsion on trajectories such as direct injection into circular heliocentric orbits < 1 AU.

Photonic propulsion is a very efficient and cost effective way for solar exploration because 1) its performance increases with decreasing distance to the Sun; 2) it can easily change the orbital plane when it is close to the Sun; 3) it needs no onboard power plants to obtain propulsion effects; and 4) it does not consume propellant. However, solar sails still require much development work, especially in the field of the ultra-light structural design and deployment techniques. Therefore, this propulsion technology will be available only for the far term program. As this program is supposed to go close to the Sun, including suicide probes, it will able to exploit the advantages of photonic propulsion. Together with nanotechnology which reduces the mass of the spacecraft and also the area of the solar sail significantly, solar sails will represent a substantial leap in technology for propulsion for future solar explorations. Below, the various propulsion technologies are discussed in greater detail.

6.4.2 Chemical Propulsion

When selecting a propulsion system for a spacecraft, one option often considered is chemical propulsion. This is especially true in today's environment where space budgets are decreasing, and the use of existing technologies, such as chemical propulsion, is encouraged and often required. Chemical propulsion has been the dominant propulsion technology since the beginning of the space program. This extensive heritage and the possibility of minimal development testing and cost, will continue to make chemical propulsion an attractive choice. However, the heritage of a propulsion technology is not enough to justify its selection, if its performance is not adequate to fulfil mission requirements, or poor performance results in a heavy, large volume spacecraft and hence large development costs. This chapter will provide information on various chemical propulsion technologies including their advantages and disadvantages. A summary of typical performance data for various chemical propulsion technologies is included [see table 6.8]. A summary of advantages and disadvantages of various chemical propulsion technologies is included in table 6.9. For a more detailed description of each propulsion system, the reader is encouraged to refer to [Sutton, 1992] and [Wiley and Wertz, 1992].

Table 6.8 Typical Performance Data for Various Chemical Propulsion Technologies [Larson and Wertz, 1992], [Price, 1996].

Propellant	Thrust Range (N)	Average Bulk Density (g/cm^3)	Vacuum I_{sp} (sec)
LO_2/LH_2	$5 - 5 \times 10^6$	1.14/0.07	450
GO_2/GH_2	110 - 890	1.14/0.07**	440
NTO/MMH	$5 - 5 \times 10^6$	1.43/0.086	300-340
N_2H_4	0.05 - 0.5	1.0	150-225
Cold Gas (GN_2)	0.05 - 200	0.28*	50 - 75

* At 24 MPa and 0°C. ** Stored as a liquid

Table 6.9 Advantages and Disadvantages of Various Chemical Propulsion Technologies [Price, 1996].

Propellant	Advantages	Disadvantages
LO_2/LH_2	• Extensive Heritage • Best Performance of Chemical Options	• Complex Engines • Thermal Challenge of Keeping Propellants at Liquid Phase • Large Propellant Storage Volumes (Especially LH_2)
GO_2/GH_2	• Good Performance • Potential For Integration With a LO_2/LH_2 System	• No Flight Heritage-Potentially High Development Cost • Challenge of How to Best Get GO_2/GH_2 From LO_2/LH_2
NTO/MMH:	• Extensive Heritage • Best Performance of the Storable Technologies • No Ignition System	• Corrosive Propellants • Risk of Upstream Ignition of MMH and NTO Propellant Vapours • Compatible With a Limited Range of Materials
N_2H_4	• Extensive Heritage • No Ignition System • One Propellant-No Risk of Upstream Ignition • Positive Expulsion Propellant Acquisition	• Corrosive Propellant • Ammonia Dissociation Removes Energy From Exhaust Gas • Compatible With a Limited Range of Materials
Cold Gas (GN_2)	• Good Heritage • Lowest Performance of the Chemical Propulsion Technologies	• Non-toxic • Simple, No Combustion • Large Volume Required For Propellant Storage • Performance Degrades With Time For Blow Down Systems.

6.4.3 Electric Propulsion Systems

Electric propulsion (EP) is increasingly being considered for a variety of applications ranging from technology demonstrators to science missions and commercial applications such as station-keeping on geostationary communications satellites. EP is attractive because the advantage of the high exhaust velocities is significant on reducing propellant mass.

However, in addition to increased propulsion system performance, spacecraft designers and integrators must also consider the unique and important issues of spacecraft contamination by EP thruster plume backflow, and how EP thrusters modify the environment surrounding the spacecraft. This aspect is particularly important for scientific spacecraft that must take sensitive measurements. If these issues prove problematic, it will be possible to cycle thruster operation and scientific measurements.

EP thrusters have traditionally been divided into electrostatic (ion and Hall), electromagnetic (magnetoplasmadynamic), and electrothermal (arcjet and resistojet) types. Based upon evaluations considering the specific impulses, efficiencies and power levels required, ion and Hall thrusters are the preferred thrusters for high velocity increment missions. They also are relatively advanced in their state of technology readiness and have been selected for future missions (NASA New Millennium and Japan's Muses-C).

6.4.3.1 Ion Thrusters

In ion thrusters, ions are formed in a chamber either by electron bombardment, radio frequency excitation, or surface contact ionisation. These ions are then extracted and accelerated as a beam to very high velocities (>10 km/s) by a system of highly charged

grids. To maintain charge neutrality (and current balance for the spacecraft), electrons are injected into the beam.

An example of a current ion thruster is the 30 cm diameter NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) ion thruster that utilises xenon propellant. The thruster is throttleable, and operating conditions can range from power levels of 0.7-4.9 kW, with thrusts from 28 to 178 mN, and exhaust velocities ranging from 28-45 km/s. This thruster is currently planned for use on upcoming NASA New Millennium missions, with the performance constrained to a peak power of 2.3 kW (throttle range 0.49-2.3 kW), a thrust level of 20-92 mN, and a specific impulse of 2000-3300 s. The NSTAR thruster has a mass of 8 kg (power processing unit is an additional 13 kg), an efficiency of 92% at full power, and a lifetime of 8000 hours at full power.

NASA has also developed a 14 cm diameter, 1 kg (power processing unit is an additional 8.5 kg) ultra-light NSTAR derivative that operates at a peak power of 1 kW (throttle range 0.25-1 kW), a thrust level of 30 mN, and a specific impulse of 3300 s. At full power, the efficiency is 85-90%, and the lifetime is 15,000 hours. In addition, the UK has developed a number of ion thrusters which are described in other mission sections.

6.4.3.2 Hall Thrusters

Hall or Stationary Plasma Thrusters (SPT) are also attractive propulsive systems for lower power, high specific impulse missions. SPT's are essentially gridless ion thrusters that make use of the j$\times$**B** force. Propellant, typically xenon, is fed between two concentric cylinders in which a gas discharge takes place. Magnetic coils create a nearly radial magnetic field on the order of 150-200 G. An axial electric field is applied, on the order of 100-700 V, which generates an azimuthal Hall current in the E$\times$**B** direction. This current interacts with the magnetic field, producing a volumetric j$\times$**B** accelerating force on the plasma. Since the magnetic field is sufficiently weak that the ion gyroradius is much larger than the dimensions of the thruster, the ions are accelerated to nearly the full applied potential. The absence of grids, and a quasi-neutral plasma means that the current-limited condition of conventional ion thrusters is not experienced. Similar to ion thrusters, the plumes of SPT's contain fast beam ions, neutral propellant, slow CEX ions, and sputtered electrode material. Xenon is the most common propellant, and between 50-100 SPT's have been used onboard Russian spacecraft over the last twenty years for attitude control [Wetch *et al*, 1991].

Currently, the U.S. Ballistic Missile Defence Organisation (BMDO) and NASA are proposing a mission for a solar electric powered spacecraft that will test a Russian Hall Thruster with a specific impulse of 1600 s, and an efficiency of 50%. Other versions of this thruster, sometimes referred to as a thruster with anode layer (TAL) have a peak power of 10 kW (throttle range 2-10 kW), a thrust level of 0.25 N with a specific impulse of 2500-3000 s. Thruster mass is 8 kg, with a lifetime of 5000 hours.

6.4.4 Solar Sails (Photonic Propulsion)

Besides chemical and electric propulsion, photonic propulsion using solar sails is a major challenge for propulsion techniques used in solar missions. Photonic propulsion is a unique technique because it uses the Sun as the major energy source which, unlike rocket fuel, is free and unlimited. The use of solar sails is most effective for missions in the inner solar system due to the increase of solar flux with an decreasing distance from the Sun. Therefore, it represents one of the most attractive propulsion systems for solar missions close to the Sun.

Fundamentally, the concept behind the solar sail [Wright, 1992] is to use large reflective surfaces to provide propulsion for the spacecraft through the use of Sunlight pressure (solar photon flux) for the motive force. This force F is generated by the process of collision and reflectance of photons with the reflecting surface of the sail, see figure 6.12, and can be roughly approximated by using the equation

$$F = AQ_{sun}(1+q)\frac{\cos(\phi)}{c} \tag{6.1}$$

where A is the total area of the sail, Q_{Sun} is the solar photon flux [see section 6.7], q is the reflectance of the sail, ϕ is the angle of incidence of the solar sail [see figure 6.12], and c is the velocity of light.

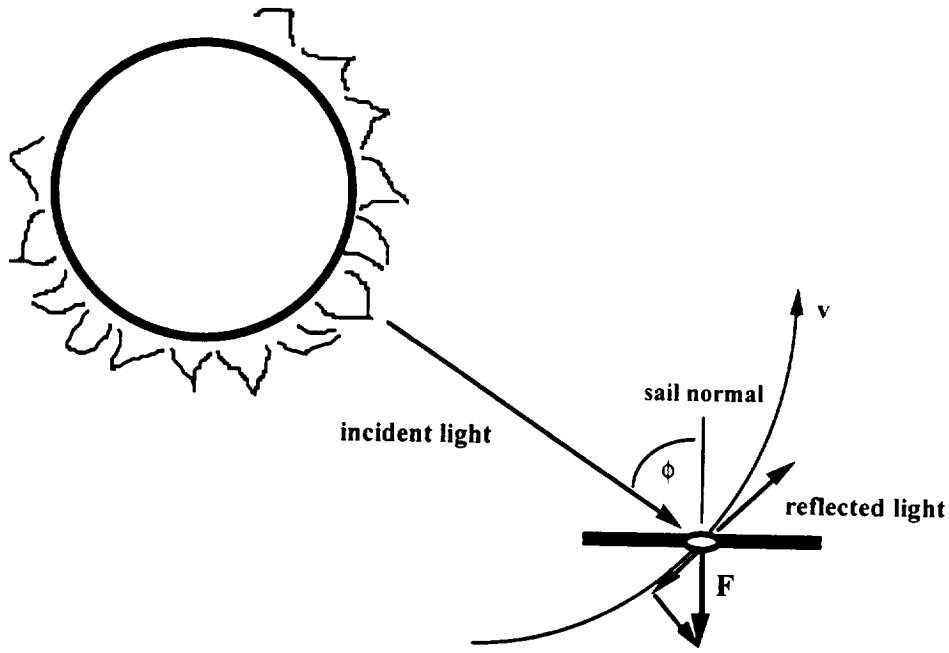


Figure 6.12 Schematic Representation of a Solar Sail with a Tilting Angle for Decreasing the Velocity of the Spacecraft.

In order to reach locations in the vicinity of the Sun, sunlight must be reflected ahead of the sail along its orbital path. This creates a negative force component along the sail's path which pushes the spacecraft back and reduces its velocity [Diedrich, 1996]. In addition to manoeuvring in the ecliptic plane, solar sails can also change the orbital plane around the Sun easily by turning the sail so that the lateral acceleration is out of the orbital plane. This orbit changing capability allows the investigation of the polar regions of the Sun.

The major advantage of solar sails used as a propulsion system in solar missions is that mass and cost of the spacecraft can be reduced significantly due to the absence of an onboard generated power system which provides the propulsive effect [Friedman, 1988]. However with solar sailing the change in velocity is applied very slowly but constantly which leads to long mission times for achieving large values of Δv. For a reasonable acceleration by using photonic propulsion for solar missions, large solar sails must be considered which span over an area of several square kilometres depending on the spacecraft's mass. This leads to technology challenges [Boisard, 1995] in many other technical disciplines besides propulsion, *e.g.*

- Ultra-light structural design and analysis of large scale structures
- Material engineering and manufacturing for the sail and the supporting structure
- Packaging and unfolding techniques for launch and deployment of the sail
- Reducing the payloads mass by using nanotechnology.

With today's technologies the use of solar sails is efficient in a temperature range roughly (because it depends on the material) between -270°C and 400°C and the minimum approach distance to the Sun is about 0.06 AU [Wright, 1992]. However, solar sails still require much development work, especially in the field of the ultra-light structural design and deployment techniques. Together with nanotechnology which reduces the mass of the spacecraft and also the area of the solar sail significantly, solar sails will represent a promising new propulsion technology that should be considered in far term Ra programs.

6.4.5 Other Advanced Propulsion Concepts

An interesting propulsion technology that is being explored currently is solar thermal propulsion, where solar energy is used to heat a working fluid that is expanded out in a nozzle [Frye and Law, 1996]. Typical specific impulses range from 700-800 s. The term "bimodal" systems is also commonly used to denote the use of a system that both provides propulsion, and power via thermoelectric converters. Research on solar thermal propulsion is being conducted at the U.S. Air Force's Phillips Laboratory at Edwards Air Force Base. Development of a technology base for unconventional rocket thrusters using intensely concentrated solar energy is currently in the exploratory development phase.

6.5 Power Systems

This section provides a brief discussion on power systems [section 6.5.1] and energy storage [section 6.5.2] with respect to possible solar missions. Critical parameters to consider for power system selection include the planned **trajectory,** the **average electrical power requirement**, the **peak electrical power requirement** and the planned **mission life**.

6.5.1 Power Sources

6.5.1.1 Photovoltaic Solar Arrays

A solar array is a very convenient method of converting energy and generating power. It uses sunlight to convert energy directly into electricity. Important factors when selecting solar arrays are temperature and degradation. Solar arrays are designed to work in *specific* temperature ranges. The bonding between the arrays and the structure is also temperature dependent and potentially critical. Solar array degradation is caused by thermal cycling, micrometeoroid strikes, plume impingement from thrusters and material outgassing. This depends heavily on radiation and is an important consideration near the Sun. The fact that the solar flux varies with the distance from the Sun must be also considered.

<u>Efficiency</u>

The efficiency is limited due to losses produced by sunlight reflection, conversion of absorbed energy into heat and photon absorption. A comparison of the efficiencies of the common solar array materials can be seen in table 6.10.

Table 6.10 Solar Array Parameters [SMAD, 1992].

Cell Type	Achieved Efficiency	Degradation caused by radiation	Problems
Silicon	14%	High	Low resistance to high temperatures
Ga-As	18%	Medium	More mass, costs
Indium-Phosphate	19%	Low	Very high costs

There are basic methods to increase the efficiency to include, increasing the solar flux by use of a concentrator [Scarlet Program, WWW] or by using a multi-layer or matrix design.

6.5.1.2 Radioisotope Thermoelectric Generator (RTG)

A radioisotope (e.g. plutonium element) is used as a heat source [RTG Program, 1991]. Electricity is produced by a temperature gradient conversion method. **Thermoelectric coupling** is a method of producing temperature gradients across materials of different thermoelectric potentials in order to produce current flow [see section 6.5.1.5]. **Thermionic energy conversion** is a means of producing electricity by forcing an ionised gas to evaporate and condense through an electrical load. Typically efficiency is between 10 and 20%. Table 6.11 shows a few of the advantages and disadvantages inherent in RTGs.

Table 6.11 RTG Advantages and Disadvantages.

Advantages	Disadvantages
Do not depend on environmental or orbital parameters	Politically very hard to handle High specific costs Radiation (requirements and constraints about instruments)

6.5.1.3 Solar Thermal Dynamic Power Generation

Never before has the thermal control of a spacecraft been combined with turbine power generation in practice [French, 1996]. Here the technological possibilities and challenges are discussed.

A closed steam cycle is used where a part of the excess heat is transformed into electrical power [figure 6.13]. The heat from the instrument or spacecraft system that needs to be cooled is transferred to a fluid in evaporator tubes. (The tubes do not pass by the heat shield or the multi-layer insulation because the small vessels would not support a temperature higher than about 400 K and the correspondingly high pressure.) By the fluid tubes, the steam is transported to a turbine which expands the steam. No steam should condense in the turbine because this would cause blade damage. Condensation takes place in a radiator afterwards. The turbine does not only drive a generator but also a pump that transports the liquid back to the heat source. The turbine will be switched on only at a certain distance from the Sun, when there is the coincidence of the requirements for excess heat to deal with and instruments needing electricity to do measurements.

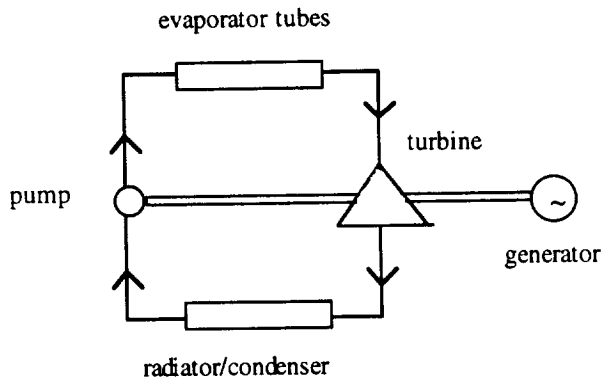


Figure 6.13 Closed Steam Cycle.

We estimate that a single-stage, single-valve turbine, for instance, though it has a lower efficiency (about η=0.3) than multistage turbines could generate 15 kW of power with a mass flow of 0.5 kg/s. So, the turbine could provide the power for the small set of instruments for a spacecraft. Some investigations about a turbine cycle were done in the Solar System Exploration [ISU, 1994]. The turbine/generation system described consisted of copper straps and aluminium heat exchangers and tubes. The system was reliable for one year and had a 20 - 30 kg mass.

6.5.1.4 Stirling Engine

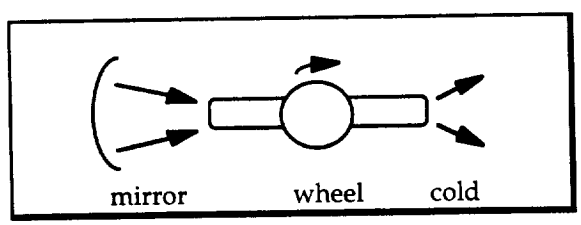


Figure 6.14 Stirling Engine Principle.

The Stirling engine fulfils power and thermal protection needs. It can be applied as a heat engine cycle, in which heat is accepted at a high temperature, rejected at a lower temperature, and work or power is produced. A mirror collects the heat and transfers it to the Stirling cycle. The Stirling cycle engine has proved to be the most promising candidate of various solar thermodynamic cycles [Egushi, 1990] because its efficiency (around 27%) is much higher compared to for example Peltier elements (5%). Figure 6.15 shows the Stirling cycle, the useful work produced by the cycle is represented by the areas inside the P-V and T-S diagrams.

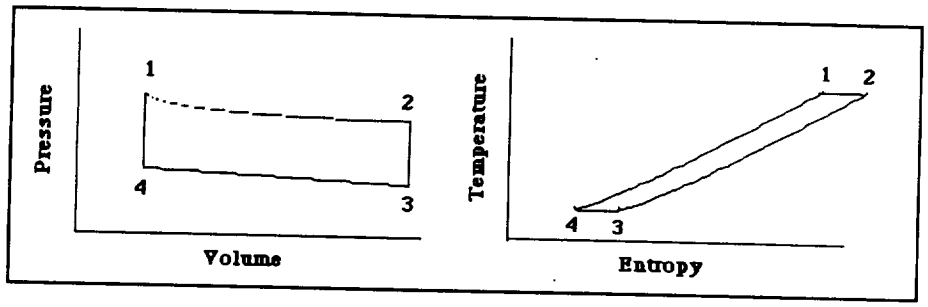


Figure 6.15 P-V- and T-S Diagram of the Ideal Stirling Cycle.

Two space applications of Stirling engines have been proposed [Scarlet Program, WWW]. One are the Small Radioisotope Stirling Engines, as the Stirling engine can be combined with isotope power systems. The Stirling converter is able to achieve higher efficiencies at these lower power levels, so a lower amount of isotope is required. The second application are the Large Free-Piston Stirling Engines. Their power output is about 25 kWe at 25% overall efficiency. Heater temperatures of 1050 K and cooler temperatures of 525 K have been tested. Lifetime was 60000 hours, specific mass 6 kg/kWe.

So, the Stirling engine would be an effective power and thermal control device for a solar mission. The power output is higher than our first estimate of the fluid turbine's. Heater and cooler temperature are not limited like in the turbine cycle (400 K temperature limit of the fluid tubes). The heat-collecting mirror can be mounted just behind the heat shield, a high temperature gradient can be reached. But the fluid turbine's specific mass (1.3-2 kg/kWe) is much lower than the surveyed Stirling engine's (6 kg/kWe).

6.5.1.5 Peltier Elements Power Generation

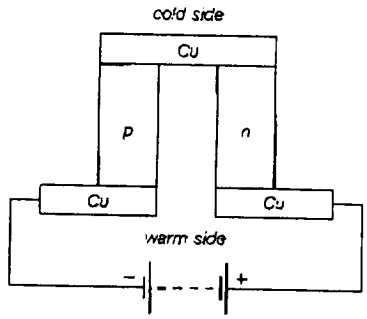


Figure 6.16 Peltier Element.

Peltier elements are a means of thermoelectric coupling [see figure 6.16]. Advantages are the very rapid heating and cooling and the precise temperature control, as well as simplicity and reliability. No moving parts and refrigerants are required, which means there is no mechanical wear out, no danger of mechanical damage and less mass compared to the Stirling engine or the fluid turbine. But, the temperature range would also be different. While the Stirling engine is applicable everywhere behind the heat shield and the turbine between 400 K and the instrument temperature, Peltier elements operate at room temperature to -100°C. That qualifies them as a follow-up device for precise instrument cooling, maybe for infrared and gamma ray detectors. More widespread use of Peltier elements is limited by their very low efficiency.

6.5.1.6 Electrodynamic Tethers

This method uses the magnetic field of planets or the Sun [figure 6.17] to produce electricity. The spacecraft has to provide a large, thin and isolated wire which crosses the magnetic field. This induces a current in the wire and therefore power. Additionally to the isolated wire an electron gun must be used to make the current constantly flow. Limitations include: high voltage (20kV-40kV) isolation at the tether and the spacecraft; high power, high-to-low voltage converter; plasma-electrodynamic interactions affecting return current losses; the current produces a small thrust which must be added to the trajectory calculations; and all past attempts including those of recent missions have failed due to defects in the deployment mechanism and/or deployment.

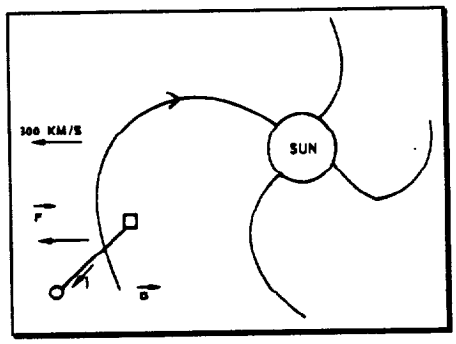


Figure 6.17 Electrodynamic Tether [Tethers in Space, 1983].

6.5.1.7 Comparison

Table 6.12 shows a comparison of the discussed power systems. Figures 6.18 and 6.19 relate specific power and specific cost, respectively.

Table 6.12 Power Source Comparison.

Power Source	Efficiency	Max. Temp.	Boundary Conditions	Qualification Status
Solar Arrays				Spaceflight approved
Silicon	14%	700 K		
Ga-As	18%	780 K		
In-Phosphate	19%	680 K		
RTG	7%	heat shield		Spaceflight approved
Fluid Turbine	30%	400 K	Fluid Tubes	Not yet qualified
Stirling	25%	1050 K	Mirror	Not spaceflight approved
Peltier Elements	7%	300 K	High Temperature Gradient	Spaceflight approved
Electrodynamic Tethers	99%	1000 K	Needs strong magnetic field	Not successfully spaceflight approved

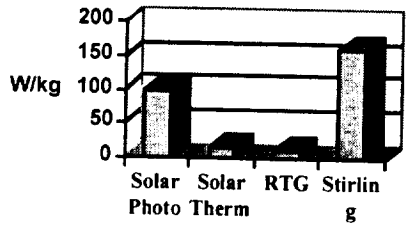


Figure 6.18 Specific Power [SMAD, 1992].

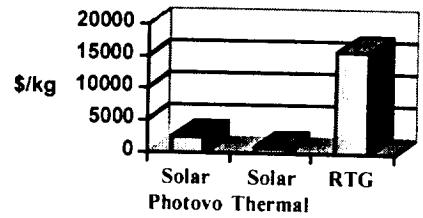


Figure 6.19 Specific Costs.

6.5.2 Energy Storage

Energy storage is an integral part of the spacecraft's electrical-power subsystem. Any spacecraft that uses photovoltaics as a power source requires a system to store energy for peak-power demands and eclipse periods. Primary batteries [table 6.13] are mainly used for memory backup systems, which use very little power. They convert chemical energy into electrical energy but cannot reverse this conversion, so they cannot be recharged. Secondary batteries [table 6.14] convert chemical energy into electrical energy during discharge and electrical energy into chemical energy during charge. An important factor is the depth-of-discharge (DOD). It is the percent of total battery capacity removed during a discharge period. Higher percentages imply shorter cycle life. Finally, fuel cells store energy by water electrolysis. Fuel cells combine the two gases again and produce electricity. The main advantage is, that it is not significantly influenced by the power flux. One the other hand it has much more mass and is more difficult to operate.

Table 6.13 Primary Battery [SMAD, 1992].

Primary Battery Couple	Specific Energy Density (W hr/kg)	Typical Application
Silver zinc	60-130	High rate, short life
Lithium thionyl chloride	175-440	Medium rate, moderate life
Lithium sulphur dioxide	130-350	Low/medium rate, long life
Lithium monoflouride	130-350	Low rate, long life
Thermal	90-200	High rate, very short life

Table 6.14 Secondary Battery [Technology for Small Spacecraft, 1994].

Secondary Battery Type	Specific Energy Density [W hr/kg]	Lifetime Cycles (at 50% DOD)	Qualification Status
Nickel-Hydrogen	29	5000	Spaceflight approved
Lithium-Carbon	60	1200	Spaceflight qualified
Lithium-Ion	90	1000	Not Spaceflight approved

6.6 Structures and Materials

During the solar mission the spacecraft will meet very powerful multiform influence of solar environment like huge heat, gases flows and radiation. In such conditions one of the main questions is how to protect delicate instruments and at the same time give them full ability to provide all necessary measurements. To reach these goals we have to pay great attention to the new advanced materials with unique properties and to the structure

which have to provide stable conditions inside the spacecraft during the entire solar mission.

6.6.1 Structures

The goal of this chapter is to show all the requirements on the structure and to describe two main varieties of structures that can be used in this case, including their advantages and disadvantages.

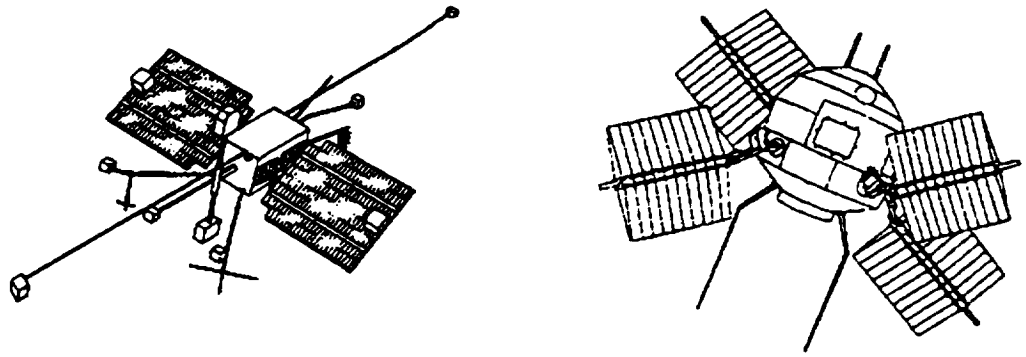
6.6.1.1 Requirements

The structures used for our solar missions must meet many requirements. The requirements vary with the proposed missions. These requirements are stringent because the solar environment is very harsh and because there is very sensitive equipment on the spacecraft. We can distribute the requirements into several groups as shown in following table:

Table 6.15 General Requirements.

Caused by	Requirement	Description
Environment	Heat protection	Both equipment and structure must be protected. The deformations due to extreme heat can be very complicated and unpredictable. To avoid high stress concentrations, the temperature should be distributed equally among all the elements of the structure.
	Gases protection	Physical properties of the structure can be changed under action of hot gases and possible chemical reactions. If we cannot ensure that changes are not dangerous the only way is providing necessary protection
	Radiation protection	The action of radiation on the structure is similar to gases action but it's more predictable and depends on working time.
Equipment	Certain stiffness	The particle's flows of different density can cause dangerous oscillations and disturb work of systems. To avoid that we have to use right materials and also provide necessary geometry of the construction able to damper the vibrations.
	Certain strength	We are not able to avoid absolutely temperature gradient and internal forces in the structure. So this requirement serves to minimise deformations.
	Certain stability	We have to remember about long elements of the structure and provide the necessary cross section area because under action of deformations they can lose their form
	Ability to provide accurate measurements	The structure has to have additional mechanisms to provide especial conditions during the short periods of time for extremely accurate devices
	Certain alignments of devices and distances between them	Close location of different devices can cause a conflict among them. Their needs are very special and the structure is to provide necessary conditions for each system
Launch vehicle	Minimum mass	Apart from using advanced light materials we can compute the optimum geometry of the structure to make whole mass as less as possible
	Accessible geometry	Under the payload fairing we'll locate special damper system to avoid strong actions during the launch. So sizes of the payload are very limited
	Ability to stand overloads	Because of complicated trajectory we have to turn on the engines several times. So the structure has to stand all shifts of external forces.
Technology	Possibility to produce	Implementation of new materials and engineering solutions will force to find new technologies and check their reliability
Managers	Cost	The work on solar mission supposes to provide a lot of researches and tests those can be expensive

6.6.1.2 Two Possible Types of Structures



Frame **Unified Volume**

Figure 6.20 Frame and Unified Volume Spacecraft Structure.

Two quite different structure's types are examined: Frame and Unified Volume. Both types are illustrated in figure 6.20. In case of Frame all instruments are independent enough and the only connection the other ones is the frame construction itself. Using the Unified Volume we have everything in one protected box. These types have their advantages and disadvantages represented in tables 6.16 and 6.17:

Table 6.16 Frame.

Advantages	Disadvantages
• Provides necessary distances We can relatively avoid useless and harmful interactions among the sensitive devices and so simulate only natural environment surrounding the sensor • All necessary protection is individual Each device may require its own level of protection and access to the environment. In this case we also can reach minimal mass of the whole spacecraft. • Small mass Usually frame type of the structure provides minimal weight	• Extremely high frames stiffness Under action of gases flow the structure is getting disturbances. To avoid vibrations we must use a lot of additional bars increasing the number of connections among the main frames. It makes the construction heavier. • No general protection Many elements of the structure may require similar kind of protection but it is unique for each element and can be sometimes implemented with difficulties because of complicated shapes and big summary surface area of the elements.

Table 6.17 Unified Volume.

Advantages	Disadvantages
• Small inertia moment To provide orientation control in conditions of strong solar influence is very important task. If onboard power amount is limited the SC has to spend as less as possible for control purposes. So inertia moment will determine the minimal expenditure of energy for orientation and stabilisation • Easy production Unified volume means also unified standard protection covering the whole surface and having maybe several complicated openings for systems' tasks. • Low cost Production of such SC type for solar mission is more traditional and can use wide experience.	• Harmful influences on the instruments Reflection of external radiation inside the box, not perfect sealing from heat gases, interactions among the devices and systems located too closely because of limited volume can cause errors in their work • Temperature deformations In solar environment strong heat at the one side and no heat at the other one causes large temperature gradients which cannot be absolutely reduced by thermoregulation system. So hot surfaces of relatively big sizes can lead the structure to significant deformations which could be avoided by additional heavy elements.

6.6.2. Materials

For the survival and proper function of a spacecraft used for a solar mission applied materials and structure must meet extreme requirements for adequate resistance to the harsh space environment. This chapter will provide a description of this environment as well as the requirements. In addition an evaluation of materials which are suitable for different kinds of solar missions is included in this section.

6.6.2.1. Environmental Conditions

The effect of the mission environment on structures must be considered in terms of both the role of the structure and its operational life requirements. The environments to be considered when selecting the appropriate materials are:

- manufacturing, transport, and storage
- launch
- in orbit space environment

We will only focus on the orbital environment of a solar mission, as the first two items do not differ from others. However, they will be included for the material evaluation. The material selection must consider the following:

- vacuum: primary concerns are the sublimation of metals, outgassing, offgassing, and surface contamination in deep space
- radiation: particle and ultraviolet radiation, which becomes more severe closer to the Sun
- temperature excursions, thermal cycling effects: the temperatures in a solar mission can vary from -100 °C for some detectors to 2000 °C for a heat shield at 4 R_S. Changes in temperature influence both the mechanical and physical properties of materials.
- space debris: assumed density of 2.8 g/cm^3. It must only be considered in the very early phase of a solar mission.
- micrometeoroids: average density of 0.5 g/cm^3 at altitudes higher than 1000 km. Increased dust densities close to the Sun. Although the average density is much lower than that of space debris, impacts of micrometeoroids must be considered during the whole solar mission.

These effects act together, their intensity varying over the spacecraft surface. Their negative effects on the materials' performance must be evaluated and counter measured, especially for long term missions. Moreover, the scientific measurements of a solar spacecraft can also be disturbed by:

- electromagnetic disturbances
- surface charging
- deep dielectric charging
- magnetic induction

6.6.2.2 Material Requirements for Spacecraft:

The selection of materials is basically governed by functions to be performed, environmental factors and costs. Besides general requirements, in a solar mission, the following requirements must be met:

- high specific strength
- high specific stiffness
- high stability (resistance to buckling, cracking, corrosion, thermal loads)
- low thermal expansion
- appropriate thermal and electrical conductivity
- low outgassing
- high resistance against the space environment close to the Sun

For scientific spacecraft the selected materials must meet additional requirements to ensure minimal disturbances of the measurements:

- magnetic cleanliness
- electromagnetic cleanliness
- control of contaminants

6.6.2.3. Material Evaluation for Solar Missions

For solar scientific missions, which tend to utilise applied materials in a way which is at the "limit of the state of the art", the material selection and the development of new materials is a major challenge. Materials with high specific properties (*e.g.* ratio of strength or stiffness versus density) are attractive for creating mass efficient structures. The primary choice of materials for present and future space structures is between light metal alloy and polymer fibre composite materials. In high temperature or other hostile environments, other metallic, ceramic or specialised composite materials are appropriate. Figure 6.21 shows a comparison between the specific properties of typical aerospace materials. Steels are included for comparative purposes.

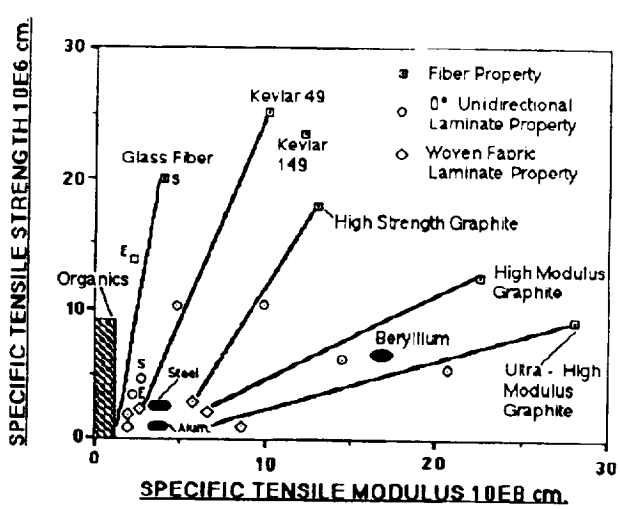


Figure 6.21: Specific Properties of Typical Aerospace Materials [Stonier, 1991].

Alloys

Aluminium is relatively light in weight, strong, easily available, easy to machine and low in raw material costs. In spite of their higher specific strength and stiffness, magnesium and beryllium are difficult to machine. If harder structural materials are required, steel

and titanium are selected. A major problem of light metal alloys is stress corrosion cracking. Light metal alloys are applicable between 0 K and 1000 K. In this temperature range, the sublimation of metals is not a major problem. So light metal alloys are a good choice for secondary structure in any solar mission. Table 6.18 shows some material characteristics of metal alloys.

Table 6.18: Material Characteristics of Light Metal Alloys [Turner, 1990].

Material	Density	Specific Stiffness	Specific Ultimate Strength	Young's Modulus	Coefficient of Thermal Expansion
	(kg/m^3)	106(N•m/kg)	103 (N•m/kg)	(N/mm^2)	(10-6/K)
Aluminium	2800	25	98.6	68000	22.5
Beryllium	1854	152	103.5	304000	11.5
Magnesium	1770	26	129.4	45000	25.2
Titanium	4428	25	187.5	110000	9

Composite Materials

Composite materials are a good choice for the primary structure of solar spacecraft because of their unique combination of high specific strength and stiffness, good dimensional stability and damping capacity, and low weight. Moreover, due to their coefficient of thermal expansion which is close to zero they are best suited for high precision structures. The general advantage of these materials is that the designer can tailor and optimise the structure with respect to lightweight, strength, stiffness, and temperature range by specifying 1.) the combination of the fibre and the matrix material 2.) the fibre volume fraction 3.) the number of plies and 4.) the fibre orientation angle of the plies which constitute the laminate.

Fibre materials mainly used for spacecraft are carbon and Kevlar fibres. Carbon, boron, silicon carbide, aluminium oxide, ceramics discontinuous fibres, whiskers, and particles are used in metal matrix composites. Typical matrix materials are epoxy resins, thermoplastics and metals.

Thermal Coatings

Spacecraft temperatures are strongly influenced by surface absorptivity and emissivity values. To reach the desired values in the solar environment, several types of surface finishes can be used: Black paint coatings have a high absorptivity (≈0.95) and emissivity (≈0.88) and are used to maximise the heat exchange between a surface and its environment by radiation. White paints, in contrast, have a lower absorptivity (≈0.25) and high emissivity (≈0.90). There are also other paints, film and tape coatings and metal conversion coatings with very different properties available. Vapour deposited coatings can reach very low absorptivities (≈0.04) and emissivities (≈0.03).

6.6.2.4. Hot Structures

For the SAUNA mission, which is expected to go to 0.2 AU distance from the Sun, and the Suicide Probe which will go as close to the Sun as possible, until it is destroyed, hot structural materials must be used. The development of these kinds of materials is a major technological challenge.

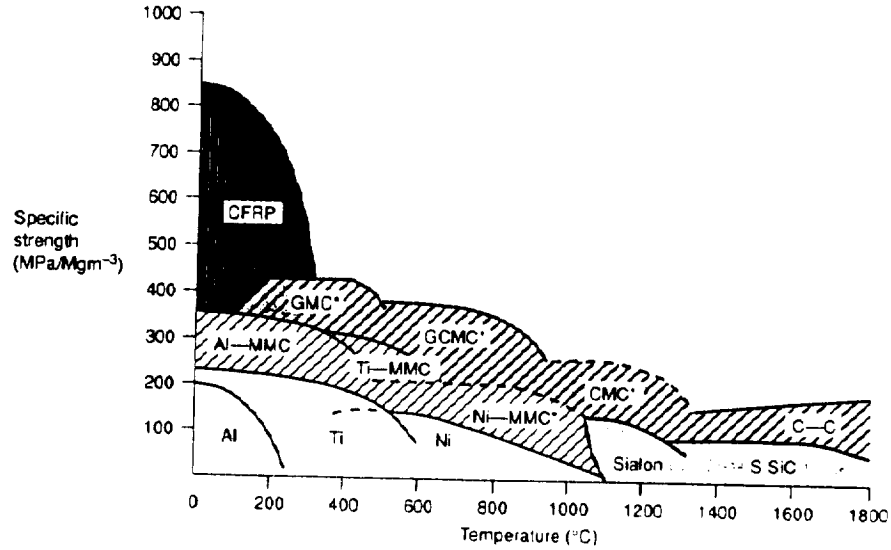


Figure 6.22 **Specific Strength Versus Temperature for Metal- and Ceramic-Matrix Composites. CFRP, carbon fibre reinforced polymers; GMC, glass-matrix composites; GCMC, glass-ceramic matrix composites; CMC, ceramic-matrix composites; MMC, metal-matrix composites; C-C, carbon-carbon composites. GMC, GCMC, CMC, and MMC are research materials [Koczak *et al.*, 1993].**

The materials used for a solar mission's heat shield or other hot structures should combine a high temperature resistance and light weight. figure 6.22 illustrates the relationship between specific strength and temperature for various materials. A more detailed description of heat shield requirements and materials can be found in chapter 6.7. Here we concentrate on high and elevated temperature materials in general. Currently, material candidates are:

- carbon/carbon (C/C), mostly the chosen material for very high temperature applications
- carbon/silicon (C/Si) for thermal protection
- carbon/silicon-carbon (C/SiC), most suitable lightweight material for hot structures at >1200 °C
- tungsten
- refractory metals (low mass loss, high mass, brittle shells)
- ceramics (low mass loss, brittle shells, UV degradation)
- refractory composites (low mass loss, low mass, strong shells)

New materials are being developed [Bensimhon, 1996] [Randolph, 1996], *e.g.*:

- titanium aluminides to cover the temperature range from 650 °C to 850 °C (beyond titanium capability)
- metal matrix composites: silicon carbide fibres in a metal matrix
- carbon fibre felts for thermal insulation

Carbon-Carbon Composites

Carbon-carbon composites are the state-of-the-art material for very high temperature structures like heat shields, and they have been chosen for the heat shield of the SAUNA spacecraft and the Suicide Probe. Typical material characteristics are [Ngai, 1991]:

- light weight and low density
- high strength and stiffness, which increase when temperature increases in the range from 20 °C to 2000 °C
- low thermal expansion
- high thermal conductivity, decreasing with increase in temperature
- high thermal shock resistance
- high fracture toughness
- pseudo-plastic behaviour
- good fatigue and creep resistance
- controllable and predictable ablation, erosion, and recession characteristics
- excellent wear rate, applicable when a high coefficient of friction is required

Different types of carbon fibres are available. When structural properties are important, high strength, high modulus fibres are selected. High modulus fibres provide a high thermal conductivity and low thermal expansion. If low thermal conductivity is necessary, low modulus fibres are preferred.

Ceramic Matrix Composites (CMCs)

CMCs can be divided into non-oxide ceramic systems, which are silicon carbides (SiC) and silicon nitrides. The oxide ceramic matrix system in use is alumina. The tensile and flexural strength of SiC/SiC show a maintenance of properties up to 1500 °C. The coefficient of thermal expansion of SiC/SiC increases for temperatures higher than 100 °C, which is critical for joints. CMC-materials can have long lifetimes.

Long manufacturing times and expensive raw materials lead to very high prices for the finished CMC components, which restricts their application in space. To overcome these restrictions, DLR in Germany is currently pursuing a low-cost technology [Krenkel *et al.*, 1995]. If one day CMCs can more commonly be used in space, there might be new conclusions. Currently, we see no advantage over carbon-carbon composites for a solar mission.

Metal Matrix Composites (MMCs)

Typical metal-matrix materials are aluminium, magnesium, copper and titanium. MMCs are used in jet and car engines where they provide high power to weight ratios. They have the properties necessary for elevated temperature applications. These properties are low density, high specific strength and stiffness, high thermal conductivity, good fatigue response, control of thermal expansion, and high wear resistance. But degradation of the properties of MMCs still starts at about 300 °C. Still, we recommend the investigation of MMCs for the propulsion system of solar spacecraft.

6.7 Thermal Control Technology Challenges

In this section, the technological challenges, for the thermal control of a spacecraft which travels toward the Sun, are discussed. Examples of such spacecraft are a flyby probe or a suicide spacecraft.

The objective of a thermal control system is to control the temperature of the instruments within the required range. The thermal control can be subdivided into two parts, the heat shield to obtain a shadow for the spacecraft and the thermal control of the instruments. For a spacecraft near to the Sun (2 -20 R_S) the use of solar arrays is difficult due to the high thermal radiation flux. Therefore the possibility of using the heat for generation of electric power is discussed.

6.7.1 Thermal Environment

The environment of a spacecraft, when it travels to the Sun, can be subdivided into:

- Radiation of the visible and the short-wavelength (50 - 140 nm) electromagnetic radiation
- Solar wind, the flux of particles ejected by the Sun
- Outgassing due to evaporation and desorption of the spacecraft materials, a plasma is created around the probe

The radiative heat flux from the Sun (Qsun) received at a distance equal to the Earth's mean orbital distance is known to be 1353 W/m^2. Assuming that the Sun is a perfect sphere and its radiance varies with spherical symmetry, the normal heat flux at distance R (measured from the centre of the Sun) becomes,

$$Qsun = 6242.5 \bullet 10^4 \bullet \left(\frac{Rs}{R}\right)^2 (W/m^2) \qquad (6.2)$$

where R_S is the Sun's radius being $6.96 \bullet 10^5$ km [Park *et al.*, 1981]. The solar electromagnetic radiation has a very wide spectral range. The long-wavelength component contributes only a very small amount of heat and is therefore negligible. However, they can significantly degrade the optical properties of the heat shield. In the short-wavelength range (50 - 140 nm), the most prominent is the radiation at 121.6 nm caused by the lyman-alpha line of the hydrogen atom. This radiation can ionise surface atoms when it reaches a hot surface or gas and therefore can cause interference with the scientific measurements onboard the spacecraft.

The solar wind consists of particles ejected from the Sun. At a distance less than 10 R_S, the behaviour of the solar wind is unknown. Hence, determination of the solar wind in this near-Sun region is one of the scientific objectives. The particles can interact with the heat shield material, changing the optical properties of the heat shield surface. The optical properties determine the temperature of the heat shield. Therefore, the studying of the effects of the solar wind on the optical properties of the heat shield material is important [Park *et al.*, 1981].

When a spacecraft approaches the Sun, the temperature of the heat shield will increase. Therefore mass loss will occur due to:

- Sublimation of heat shield material generating a plasma of heat shield material around the solar probe

- Outgassing of air molecules adsorbed while the spacecraft was in the Earth's atmosphere

The outgassing species can generate a self-induced plasma cloud around the spacecraft at a time when the instruments were attempting to measure natural plasmas around the Sun. Thus, the principal requirement on the heat shield design is to minimise the mass loss [Randolph *et al.*, 1996].

6.7.2 Description of a Heat Shield

When a spacecraft travels towards the Sun the heat flux will increase dramatically [equation 6.3]. This requires the spacecraft to be protected within the shadow envelope of a protective shield. The temperature of a shield (Tshield) between the spacecraft and the Sun is about:

$$Tshield = \sqrt[4]{\frac{Qsun}{\sigma}\frac{\alpha}{\varepsilon}\frac{\sin(\theta)}{(F+1)}} \qquad (6.3)$$

where: Qsun = heat flux from the Sun

Â = Stefan-Boltzmann constant ($5.728 \bullet 10^{-8}$ $W/m^2 \bullet K$)

‡ = solar absorptivity of heat shield material (typically 0.91)

Ó = emissivity of heat shield material (typically 0.82)

θ = angle of incidence (approximately 30 °)

F = backside view factor to space (typically approximately 0.7)

Using the typical values for a carbon-carbon heat shield the temperature for a distance of 0.2 AU is 600 K [figure 6.23]. This temperature can be decreased by decrease of the ‡/Ó ratio and/or decrease of the angle of incidence.

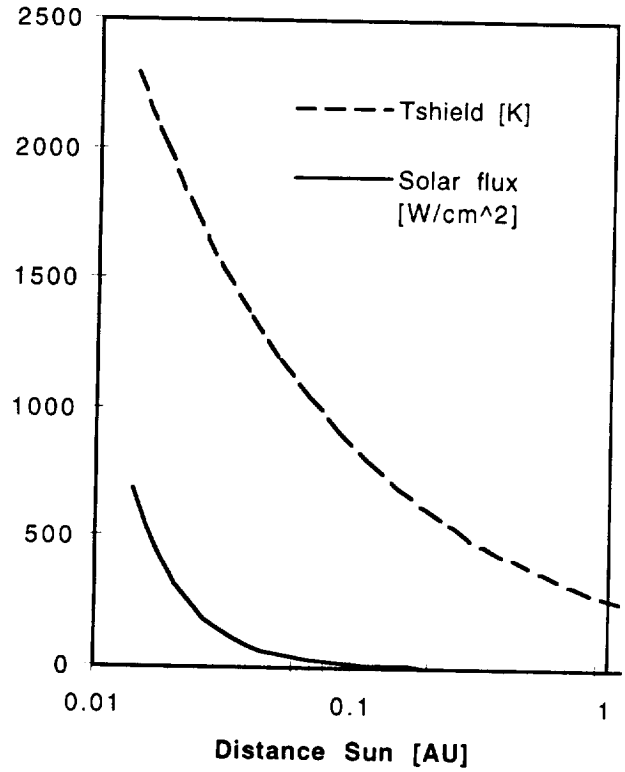


Figure 6.23 **Temperature of a typical heat shield and the heat flux as a function of the distance from the Sun (steady state).**

So the main properties of the heat shield necessary to decrease the temperature of the heat shield and the heat flux to the spacecraft are:

- Low solar absorptivity, low ‡/Ó ratio, which are optical material surface properties.
- High angle of incidence, which is restricted by dimensions of the launcher and structural constrains.

In addition, the mass loss rate (dm/dt) of the shield at elevated temperatures must not interfere the measurements of the plasma, other requirements are:

- No change in optical properties during the spacecraft lifetime, as these determine the temperature of the shield.
- Minimal mass of the heat shield construction.
- Dimensions compatible with the launcher.
- No change in mechanical properties during spacecraft lifetime.
- The heat shield must be resistant against vibration during launch.

Previous studies evaluated the candidate materials, refractory metals (tungsten, rhenium, tantalum, and their alloys), ceramics and refractory graphitics (graphite, carbon-carbon). It was concluded that carbon-carbon is the most appropriate material [Randolph *et al.*, 1996] for the heat shield due to:

- Low density and high elasticity modulis, therefore a low heat shield mass.

- Low vapour pressure, which results in a low mass loss rate.
- Stability of properties in charged particle and high ultraviolet flux environments.
- Experience with the manufacture and characterisation of this class of materials.
- Relatively stable ratio of solar absorptivity to emissivity (‡/Ó).

The major reason to reject the refractory metals is the high density, brittleness and the so called "darkening" due to charged-particle flux. This "darkening" decreases the ratio (‡/Ó) and therefore increases the temperature of the heat shield. The major concern of ceramics is the degradation of the material due to UV-radiation and not nearly as mature in technology development as carbon-carbon.

The absorptivity of carbon-carbon is about 0.9 which is high, and at first consideration, it would seem that a reflective surface (absorptivity small) would be an advantageous material selection to minimise the absorbed radiant solar energy. Up to now this approach is rejected because of the unknowns associated with the response of reflective surfaces to the charged-particle, ultraviolet radiation and micrometeoroid fluxes that the spacecraft is exposed to during the long flight time. Determination of the material response to these environmental conditions is very difficult to simulate with ground tests.

In a previous solar probe study the requirement for the mass loss rate is less than 2.5 mg/s [Millard, 1992]. The requirement of 2.5 mg/s is bases on a flyby of the Sun which takes only a few hours. However for a spacecraft which is in orbit around the Sun the value of 2.5 mg/s results in a total mass loss of 10 kg (of a 10 kg heat shield) within 1.5 months. Therefore the requirement of 2.5 mg/s is not sufficient, decrease by a factor 100 up to 10^4 may be needed.

The mass loss rate may be predicted by the Langmuir-Knudsen equation, which shows that dm/dt, for a certain material, can be decreased, by decreasing the temperature of the heat shield. For carbon-carbon the dm/dt increases a order of magnitude for every 100 K [Randolph *et al.*, 1996] increase of temperature. Possibilities to decrease the temperature of the heat shield are:

- A coating with industrial diamond powder.
- Surface treatments, chemical vapour deposition of pyrolytic graphite coating [Randolph *et al.*, 1996].
- Thin sheet of tungsten, which is protected against darkening during the flight to the Sun by a thin protective layer. If the protective layer will become too hot it will evaporate and the low absorption tungsten sheet will decrease the temperature of the heat shield.
- Making the angle of incidence smaller, by using a larger heat shield. To accommodate the shield in the launcher, a deployable shield can be used.

6.8 Guidance, Navigation and Control

In this section all the issues related to the functions to be performed by the spacecraft system as a whole to know its position, velocity and attitude are included. The Guidance, Navigation and Control (GNC) subsystem is responsible during the whole spacecraft lifetime to maintain the required position and orientation during every phase of the mission. The analysis and selection of the trajectories to be followed by the spacecraft is performed in the section 6.3.

Both concepts, position and attitude determination and control, will be dealt separately in this chapter in the sections 6.8.1 and 6.8.2, respectively.

With a focus on describing challenges and possibilities for GNC advances in relation to solar missions, this section will take into account possible enhancements in the following fields of interest:

- Increase the knowledge of the environment faced by spacecraft in an interplanetary mission, in particular near the Sun and near other planets (if fly or swing-by operations are required). Better modelling of this environment will improve the operation of the spacecraft (from the point of view of the GNC and ACS subsystems) because of better design of the control system.
- Increase the performances of the existing sensors or development of new measurement techniques.
- Increase the computer performances to allow more complex spacecraft operations. In this area, the growth has been exponential during the last years leading to a remarkable increase of the functions that the satellite can perform in an autonomous way.
- Increase the performances of the existing actuators or development of new actuator systems.

The current state of the art in this technological area will be briefly reviewed to use the most advanced techniques available in the near future to solve the technological problems derived from these missions with the Sun as objective.

6.8.1 Orbit Determination and Control

Orbit determination and control commands are usually provided from the ground for interplanetary missions and it is based on the tracking of the spacecraft by radio signals. Triangulation techniques using on-board instrumentation are available but they have a reduced accuracy in the position determination when compared with the ground-based technique. These triangulation techniques may be based on measuring star or planets directions or the time of occultation of some stars behind close planets or satellites (it could be useful during flybys) [Battin, 1989]. The actions to be taken by the spacecraft to correct the position are also commanded from ground, by using a propulsion system (based on hydrazine, cold gas, etc.).

Ground control for orbit determination has been extensively used for interplanetary missions and it has also been used for near Earth satellites until Global Positioning System (GPS) became operational on 1989. Nowadays, on-board orbit determination systems based on GPS signals are being analysed and planned for the next future.

The birth of the GPS system has had a strong impact in the current way to navigate in LEO and MEO and it provides very exact position estimates. Perhaps, an equivalent system to GPS but extrapolated to interplanetary navigation would represent the future frame in this area if a system providing suitable performances is developed.

The development of such a system is out of the scope of this project with the Sun exploration as the major objective, but some ideas about this concept can be highlighted here.

- The immediate and obvious extrapolation of the GPS concept to a Solar System point of view would lead to a constellation of satellites orbiting around the Sun

providing a signal leading to a navigation solution in the area covered by these satellites. This concept has strong problems due to the high number of satellites required to provide a suitable coverage feature in a so huge area and to locate all those spacecraft in orbits in different planes around the Sun to provide a suitable 3-D measurement. GPS system is designed to provide four satellites in the field of view of an antenna on the Earth surface during the 95 % of the time. The location of the spacecraft in different planes around the Sun could require the use of new propulsion technologies like ion propulsion, solar sailing, etc.

- Beacon spacecraft located in the L4 and L5 Lagrangian points of each Sun/planet system. It would be a feasible solution for the mid-term future but it would require a detailed analysis of the obtainable performances. A problem will be that all the beacons will then be located in a near-ecliptic plane and only a 2-D navigation solution will be available, being necessary an additional source of information from out the ecliptic plane. Anyway, it could be a system to aid future interplanetary navigation but it will not be autonomous by itself.
- Beacon spacecraft around each planet (or asteroids) of the Solar System or beacon stations on planetary ground could be located to aid the navigation in the vicinity of each planet.

Anyway, the development of such a system will only be interesting if an extensive use of interplanetary flights will be done in the future when any ground control would be overpassed by the high number of spacecraft. It is not justified at the current state of spaceflight but in the future, the system could look similar to the current way used by aeroplanes to fly, where the approach operations (flights around a planet) are controlled by ground but the flight along the airways (interplanetary flight) is autonomously performed by the plane itself. In this direction, the paper from Reidel may be interesting to highlight the future autonomous navigation systems based on optical systems [Reidel, 1996].

As a summary, the orbit determination and control functions will be provided by ground stations in the near-future. For the mid- and far-future, the system would be autonomous using optical measurements navigation (mid-term) or by an interplanetary navigation system (far-term).

6.8.2 Attitude Determination and Control

The ACS is the responsible to maintain the required orientation of the spacecraft due to the need of pointing the solar arrays, the antennas, thermal control elements, the instruments, the GNC propulsion system,...

A wide set of sensors and actuators are currently used providing a high number of possible operational configurations in a near Earth operation.

The available sensors used by near-Earth missions are typically: Sun sensors, Earth sensors, star sensors, inertial measurement units, GPS receivers and magnetometers. The available actuators used in near-Earth missions are: magneto-torquers, reaction/momentum wheels, thrusters and solar sailing.

Most of the commercially available sensors and actuators (for near-Earth orbits) have not application to interplanetary missions. Therefore, only star sensors, gyrometers and, maybe, Sun sensors could be used for interplanetary missions. Actuators which do not require propellant consumption will be favoured because they will not limit the lifetime of the spacecraft.

6.8.2.1 Environmental Issues

The definition of the environment to be faced by the spacecraft is a major task in order to define the equipment selected for the on-board operations. A global view of the problem provides the following set of environments:

- Launch (common to every space mission and introducing requirements to the structural characteristics of the sensors and actuators)
- Near-Earth environment (at least in the first stage of the mission)
- Interplanetary environment
- Environment of other planets (if fly-by operations are required and it could include the planet atmosphere when aerobraking is used). Jupiter can provide a very aggressive environment from the point of view of the radiation due to its strong magnetic field (it is an issue to be taken into account for all on-board electronic equipment).
- Near-Sun environment

Most of the environmental aspects are identified in the section 6.1. The attention will be focused here in the environmental issues which lead to disturbances in the rotational dynamic behaviour of the spacecraft. The usual elements which can introduce disturbance torques to the system are typically planet atmospheres, gravity gradients, magnetic interactions and solar radiation pressure.

Obviously, atmospheric disturbances are only taken into account when a fly-by at a low altitude over a planet with an atmosphere is performed and during Earth orbit operations. However, these operations are only developed during a short period of time with respect to the total mission duration to take it into account as a major issue in the ADCS design.

Gravity gradient disturbance is a torque produced by the no coincidence of the centre of mass of the spacecraft and the centre of application of the gravitational forces acting on each particle of it. These effects are not relevant during interplanetary flight phases and they are not taken into account during fly-by operations or operation around L4 or L5 points, but it may be relevant for spacecraft orbiting the Sun if the distance is relatively small and if it is going to operate at that distance for a long time. The values for SAUNA has been estimated and are negligible when compared with solar radiation pressure disturbance.

Magnetic disturbance torques may appear due to the residual magnetic field of the spacecraft itself. The value of this field is difficult to predict but can be measured after the spacecraft integration. It would be desirable to reduce it to a minimum because the magnetic fields that the spacecraft will find are not well-known and it could increase the operational problems of the spacecraft. Anyway, if we are going to have magnetic measurements, the value of this residual field should be small.

Solar radiation pressure disturbance will have a major effect on the spacecraft dynamics being actually the dominant effect. This disturbance appears due to the non-coincidence of both the centre of mass of the spacecraft and the centre of the solar pressure force over the spacecraft surface. This will produce an external torque on the spacecraft changing its angular momentum.

When operation at L4 or L5 is considered, solar radiation pressure is still the dominant perturbation but with a considerable reduced intensity because they are at the same

distance from the Sun as the Earth but a spacecraft operating on them will not have disturbances from Earth atmosphere, gravity or magnetic fields.

6.8.2.2 Other Missions ADCS Review

To start the definition of this subsystem it is necessary as a preceding step to review the past missions, in order to identify the technological problems that have already been solved. The review should not be intended as an exhaustive recompilation of every mission but the compilation of most relevant configurations that could guide our design.

For missions with the objective to operate as close to the Sun as possible, the paradigm to take into account at the current state of the art is the Solar Probe mission, planned to operate at a distance of 4 R_s over the Sun with a three-axis stabilised configuration.

The Solar Probe attitude determination system [Randolph, 1995] is based on star trackers and an HRG (Hemispherical Resonator Gyro), which will be used alone during the perihelion pass in order to avoid possible malfunction of the star tracker. The HRG drift is periodically calibrated by using the measurement from the star trackers. The Cassini HRG is still considered to be the only existing design capable of meeting the drift requirements of the mission (the drift is 0.006 °/h, 3-sigma) with an internally redundant capability and radiation hardness needed for the mission. The largest impact was the realisation that the steady state power usage of the Cassini HRG is now estimated at 24.6 W, and it will be worse during calibration periods with the star trackers operating at 12 W.

HRG technology advances that would allow for comparable accuracies at lower power usage and less mass are under continuous assessment.. At this time there are no available qualified designs with superior performance and lower power and mass characteristics. It is anticipated that within two to three years an IFOG technology (Interferometric Fibre-Optic Gyro) may challenge the HRG performance and have lower mass and power levels. IFOG is planned to fly on Clementine [Eliason, 1994].

The Hughes Danbury HD-1003 unit is the star sensor used in the Solar Probe mission. The accuracy of this instrument is about 50 μrad.

The actuator system has evolved from the early versions of the Solar Probe to the last one called Minimum Solar Mission (MSM) to become a single actuator system based on hydrazine to perform both the orbital and the attitude corrections. The former version based on a dual engine configuration with a cold gas system to perform the attitude corrections has not been selected at last.

PLAMYA mission attitude determination [Randolph, 1995] is based on an IRU calibrated by optical sensors for Sun and star measurements. The IRU contains four angular velocity sensors, each capable of measuring rates up to 10 °/s. The angular velocity measurement error will be less than 0.05% with a drift rate of less than 4.5 arcmin/min. The lifetime is expected to be 50000 hours.

The optical instruments are provided by the firm NPO "Geofizika" [Randolph, 1995] and the characteristics of them are summarised below:

- Sun sensors: 40 ° x 186 ° Field Of View (FOV) with measurement error not exceeding 2 arcmin in the FOV. Redundant units are provided with total mass of 6.7 kg and 8 W power consumption. These allow for drift measurement to better than 0.003 °/hr and determination of the axes

orthogonal to the Sun to within 2 arcmin and roll error about the Sun line to no more than 1.5 arcmin.

- Star sensors: bright star sensors to measure references from Sirius, Canopus and Vega exhibit a measurement error of no more than 3 arcmin, within a FOV of 2.6 ° x 2.6 °. The instrument has a mechanical device which can move the FOV around one axis with an error not greater than 2 arcmin, within a range of ± 37 °. With redundant instruments, the mass is 29.5 kg and power consumption is 21 W.

Another potential set of star sensors is the "stellar occultation instruments" (POZ) [Randolph, 1995], which utilise certain parts of the stellar sky along the flight path. The firm NPO "ELAS" has an instrument with an 8 ° x 8 ° FOV. This device delivers angular co-ordinates of up to 8 point objects located in the FOV with a brightness range of 0 to +6 stellar magnitude. The limiting total error of the instrument is less than one arcmin. A solar protection cover is automatically closed when the Sun is near the FOV of the instrument. Two sets of instruments have a mass of 11 kg, while the electric power consumption of one instrument is 22 W. This device has not yet been flight tested.

The actuator system is based on thrusters and it is commanding by a reaction devices control system. An amplifier/converter have a mass of 3 kg and consume 10 W of power.

The Magellan mission to Venus [Young, 1990] attitude determination system is based on an IRU calibrated periodically by a star scanner, entering into a calibration mode with a required inertial pointing. The gyroscopes are required due to the high number of manoeuvres to be performed by the spacecraft. The control of all these operations is performed by reaction wheels, reducing the amount of fuel needed for the manoeuvres. As a complement to the attitude control hardware, there is a set of Sun sensors and solar-array drive motors which keep the solar panels pointed toward the Sun.

6.8.2.3 Review of Available Instrumentation

As it has been seen in the previous section, most of the designs are based on star trackers and IMUs for attitude determination and reaction wheels and thrusters (cold gas and hydrazine) for attitude control. They are the baseline instrumentation for this mission. The following table lists accuracy, FOV, and sensitivity data for some star sensors.

Table 6.19 Accuracy, FOV, and Sensitivity (mv) of Some Star Sensors.

	Accuracy	FOV	mv
Star Tracker Stellar Compass (STSC) - LNLL [LLNL, 1996]	150 µrad (p&y) 450 µrad (r)	28.9°x 43.4°	< 4.5
OCA'S WFOV LLNL [LLNL, 1996]	---	28°x 44°	4.5
CT - 601/602 Ball [Ball, 1996]	3 arcsec	8°x 8°	+ 1 / + 6
CT - 611 Ball [Ball, 1996]	15 arcsec	10°x 10°	- 7 / + 3.9
CT - 621 Ball [Ball, 1996]	11 arcsec	20° x 20°	+ 0.1 / + 4.5
CT - 631 / 632 / 633 Ball [Ball, 1996]	20 arcsec	20°x 20°	+ 0.1 / + 4.5
Mini Star Tracker Clark Technologies [Clark, 1996]	6 arcsec (p&y) 20 arcsec (r)	---	---
NPO "Geofizika" Star Sensor (PLAMYA) [Randolph, 1995]	< 3 arcsec	2.6°x 2.6°	Bright stars
NPO "ELAS" Stellar Occultation instrument [Randolph, 1995]	< 1 arcmin	8°x 8°	0/+6
Astro 1M [Elstner *et al.*, 1991]	1 - 2 arcsec	5.3°x 8°	< 8

The performances of star sensors will increase when the new concepts based on APS (Active Pixel System) will be developed. Some information about this system based on the use of CMOS technology can be found in [JPL, 1996].

The technology of gyrometers has evolved from the past gyros with moving mechanical parts to the current designs based on HRG. The performances of HRGs are the best ones at present time with a drift of 0.006 °/h. However, its main problem is its high power consumption, but it is expected to reduce in the next future. New systems based on IFOG are planned for the future with enhanced performances (Clementine, [Eliason, 1994]).

For missions located on L4 or L5, commercially available Sun sensors could be used, because the Sun is seen in the same way than from Earth. For spacecraft orbiting the Sun, it could be interesting to have Sun sensors. They should be based on a different concept than the currently available ones to withstand the high temperatures and the high relative size of the Sun. Maybe, this concept would not be possible for SAUNA mission because it is too close the Sun.

In tables 6.20 and 6.21, the performances of some reaction wheels which can be used for these missions are summarised.

Table 6.20 Performances of Some Reaction Wheels.

Performance Characteristics	Speed (r/min)	Ithaco Type A *	Ithaco Type B *
Angular Momentum [N•m•s]	1000	0.75	3.25
	3000	2.25	9.75
	5000	3.75	16.25
	6000	N/A	19.50
Torque [mN•m]	-------	20.0	40.00
Steady-State Power (W)	1000	3.0	3.0
	3000	5.0	5.0
	5000	7.0	7.0
	6000	N/A	8.0

* [Ithaco, 1996]

Table 6.21 Performances of Some Reaction Wheels (Cont.).

Performance	Momentum Wheel Ithaco *	Reaction Wheel Ithaco *	Clark Technologies **
Momentum Storage	80 N•m•s @ 6200 r/min	50 N•m•s @ 3850 r/min	---
Max. Reaction Torque	> 0.15 N•m	> 0.3 N•m	0.025
Minimum Life	8 years	8 years	---
Mass	11.7 kg	14.1 kg	---
Power: Steady State Peak	30 W @ 5000 r/min 110 W @ 5000 r/min	35 W @ 3850 r/min 200 W @ 3850 r/min	---

* [Ithaco, 1996] ** [Clark, 1996]

No detailed information is provided about thrusters. They typically can be based on hydrazine, cold gas or ion propulsion and the performances can be suited for the concrete mission with the corresponding constraints.

6.8.2.4 Proposed ADCS Configurations

One important task leading the overall configuration of the spacecraft is the selection of the type of stabilisation. Most of the reviewed missions are based on a three-axis stabilisation in order to satisfy different requirements from thermal control, communications, instruments pointing, etc. Some spinning configurations have been explored for the Solar Probe mission but none of them was selected. Three-axis stabilisation has some benefits from the point of view of some subsystems when compared with spinning options and the obtainable accuracy is potentially smaller. Dual-spin allows better performances than pure spin spacecraft but the problem then appears in the lubricant to be used at high temperatures. Star sensors can only operate in a suitable way when the angular velocity is under a relatively small value (~0.5 °/s). Therefore, the spacecraft ADCS configuration would be based on a three axis configuration unless spin options could be used depending on the mission.

Different equipment for attitude determination can be used. Star sensors provide an attitude measurement independent of the position in the Solar System. If the mission requires to perform some manoeuvres or if it includes a pass near the Sun, then an IRU would be needed because the star sensor could not operate in a correct way in those conditions. However, star sensors are needed to calibrate the drift of the IRU during slow rate phases of the mission not close the Sun. For missions operating at L4-L5, one star sensor head could be substituted by a Sun (it is a star too) sensor in order to reduce cost.. Suicide probes would require an IRU to operate in their flight towards the Sun and star sensors for calibration.

The actuator system could be based on reaction wheels (not limiting the spacecraft lifetime) which need to be periodically desaturated using typically thrusters (solar sailing could be an option). It could be advantageous to use the same propellant for attitude control that the used for orbit control (this conclusion is true for Solar Probe mission [Randolph, 1995]). Therefore, the selection of the attitude control could be guided by the propulsion subsystem if it can be used for attitude control. For one-shot missions (suicide probes), the control system could be based on thrusters alone because the disturbance level is higher and the lifetime is not a constraint. This solution was selected for Solar Probe because the estimated propellant mass to perform attitude control was less than that required for the reaction wheel system.

6.9 Communications

This section is concerned with the design of the communications system for spacecraft in interplanetary cruise phase and near-Sun environment. After a description of the different issues related to communications, we have reviewed proposed technological communication challenges to overcome these issues. The last part describes the recommended approach for the implementation of the communications links for the Ra missions in the near, mid- and long-term.

A lot of proposed or actual missions have either addressed or evaluated classical problems, which have not been discussed here.

6.9.1 Communications Issues

The constraints on the data communication links in the context of the Ra project are discussed hereafter. The discussion will be divided into problems related to special conditions prevailing in the Sun's environment and those arising from mission requirements.

6.9.1.1 Environmental Issues

Thermal noise

Thermal noise is a major concern in the vicinity of the Sun as the star appears as a noise source producing interference at all frequency bands. This results in an increase of the system noise temperature that has to be carefully taken into account when designing the communications link.

The Sun's noise temperature depends on the frequency and the level of solar activity. Several models are available for different bands [Maral *et al.*, 1993] and yield values varying from 200,000 K to 300,000 K at 1 GHz to 20,000 K at 10 GHz. The increase of system noise temperature due to the Sun's contribution has to be weighted by the receiving antenna pattern. The design should ensure that there is enough separation between the Sun's direction and the antenna's main lobe, first and secondary side-lobes.

According to recent JPL measurements from a DSN station with a spacecraft close to the Sun, at about 1.12 R_S (where the angle between the spacecraft and the Sun as viewed from the receiving Earth station, or SEP angle is about 0.3 °), the system noise temperature in X-band (8.4 GHz) ranged from 1417 K to 2300 K, depending upon the direction. In Ka-band (32 Ghz) it was in the range of 456 K to 614 K. For antennas with a reasonably high gain, *e.g.* 30 m at X-band (65 dB gain), thermal noise increase due to the Sun is no longer a major problem.

Scintillation

As the spacecraft moves through or behind the solar corona, the relative geometry between the transmitter, propagation media and receiver changes, and the received signal will fluctuate like the twinkling of the stars. Similar to the ionospheric scintillation that has been discussed in section 4.5, the plasma irregularities, or "blobs", will randomly modulate both the phase and amplitude of the signal leading to significant degradation of the link. This effect which is critical mostly around the solar corona is a major concern for communications, but scientific information can be extracted.

Theoretically, the frequency dependency is $f^{-1.5}$ at 1 GHz and above. For example, if scintillation at 2.2 GHz is 6 dB peak-to-peak, then the scintillation at 7.25 GHz is 1.0 dB peak-to-peak. Therefore the link degradation due to scintillation can be limited through the use of higher frequencies.

A further understanding of the effects of scintillation will be gained through interesting measurement opportunities offered by the NEAR mission. As the spacecraft will cross the ecliptic plane, it will encounter a "blob" region and suffer from signal strength degradation due to scintillation that can be monitored on Earth [Randolph, 1996].

6.9.1.2 Mission Related Issues

Spacecraft Configuration

The selection of a spacecraft configuration and of the communication scheme affect each other mutually. Thus, in the case of a 3-axis stabilised spacecraft orbiting around the Sun, the antenna needs to be continuously steered to be kept pointed towards the Earth. In case the antenna is mechanically steered the reliability is significantly degraded due to the use of moving parts. Therefore, alternatives need to be considered for cases where the lifetime needs to be long or where no risks can be taken.

Orbital Considerations

The problem of solar conjunction can be avoided by careful choices of trajectory and/or planned use of on-board storage of data while in conjunction. Some Ra missions (*e.g.* SAUNA) will have repeated solar conjunctions with a requirement for continuous high data rate transmission throughout that time. When the spacecraft is behind the solar disk, transmission is deemed impossible unless relay satellites are used or the spacecraft have inter-satellite links. These will be discussed below.

For missions closer than 4 R_s (*e.g.* Suicide Probe), there is a 1.5 ° arc field of view from Earth for the Sun within which it is extremely difficult to use RF in a conventional manner. Some missions will get so close that the phenomena observed will have a direct effect on the communication medium, *e.g.* coronal phenomena will prevent any kind of radio emission. Other techniques will have to be investigated.

Interplanetary Travel

The link will have to be engineered to cope with the restrictions imposed by interplanetary travel, *e.g.* trade-off between data rate and long distance/low power related to Jupiter gravity assist.

Ground Segment

An early warning mission would require a constant coverage while a scientific mission could do with on-board storage. If a network is considered, connectivity and accessibility issues must be addressed.

6.9.2 Technological Communications Challenges

The different technological challenges that can overcome the issues presented above are described here.

6.9.2.1 Radio Frequencies

RF communications have been used extensively - almost exclusively - in deep space applications. It is a known and mature technology and as such, is a prime candidate for low-risk missions, assuming the environment allows for transmission or the distance/interference does not result in impossible power, antenna size and /or overall mass requirement.

Figure 6.24 presents the advantages/disadvantages of the Ka band over the X band that are the two frequency bands that we have considered for Ra.

Advantages		Disadvantages
high data rate	Ka Band	atmospheric sensitive
impervious to scintillation		not technically proven
low power requirements		
reduced hardware size		poor ground segment availability

Figure 6.24 Advantages and Disadvantages of Ka Band Over X Band.

Due to scintillation the X band is not a favoured candidate in the vicinity of the Sun (< 4 R_S) except for particular geometrical configurations (*e.g.* the Solar Probe [Randolph, 1996]). Therefore, we propose to limit the use of this band for up and downlink communications while the Ka band is more suited for inter-satellite links.

6.9.2.2 On-Board Hardware

The typical block diagram of a deep space X band transponder is given in figure 6.25.

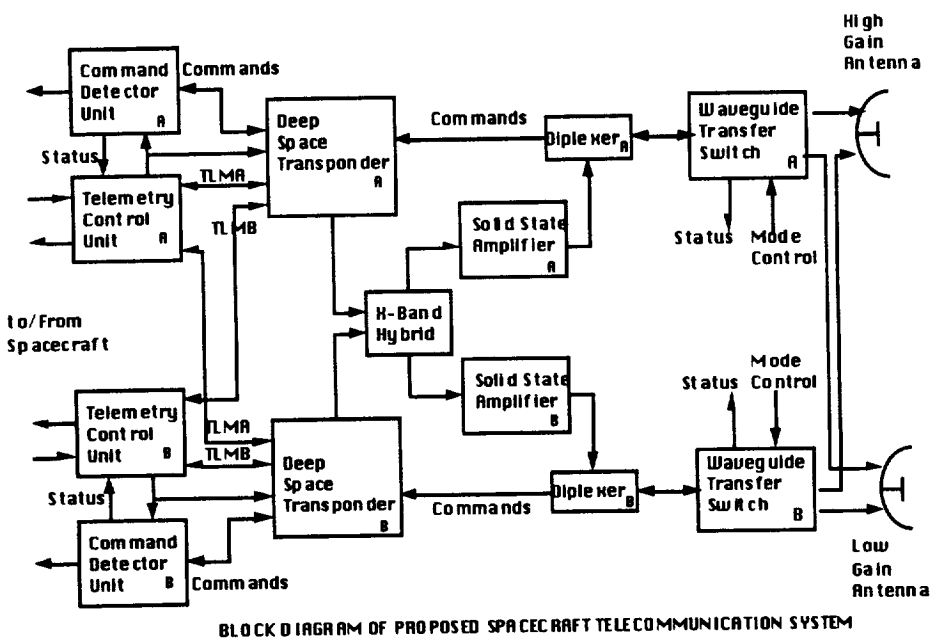


Figure 6.25 Typical Block Diagram of a Deep Space X Band Transponder.

6.9.2.3 RF Ground Segment

The design of the ground segment is a trade-off between the ground station and spacecraft complexity. A typical block diagram of a ground station is available in the appendix C.7. So far, most deep space missions have required full time coverage by high gain antennas. Thus the Deep Space Network was a prime candidate, if not the only one, to support such missions, leading to problems of availability of the network facilities. Instead, the use of smaller stations should be considered and possibly make use of the

availability of several US Department of Defence decommissioned antennas and/or Russian facilities. Other possibilities include the use of antennas belonging to small space agencies or organisations (*e.g.* GSOC of DLR), or the ESATRACK network of ESA. The Villafranca station, currently used for the Infrared Space Observatory (ISO) mission, has the right characteristics for Ra [Maldari *et al.*,1996].

Continuous coverage should not be a driving factor in the ground station design but instead should be the result of a trade-off between on-board storage, data volume, link capacity, and ground station costs.

6.9.2.4 Optical Links

The use of optical frequencies allows for a dramatic increase (> 90 dB) in power concentration of the beam onto the target receiver compared to RF systems. Thus, optical links can trade off some of that gain towards smaller aperture terminals, reductions in power, size and mass, and increased link capacity. For a properly selected wavelength, and with accurate filtering and pointing, reduction in background noise or direct illumination from the Sun can be countered.

Direct detection might simply not be efficient enough to overcome the background noise, even though the transmit frequency is carefully selected. The amount of signal energy that would have to be transmitted from the spacecraft would be unmanageable at such distances from the Sun. Coherent detection seems more promising since light from the Sun is inherently non-coherent. Thus the effect of background noise is acceptably reduced. Heterodyning reception has the disadvantage of being more complex to implement.

In order to achieve the total power required, an array of diodes is necessary. Some diode-pumped lasers are currently in use which produce power in the order of a few watts, yet it is still a state-of-the-art technology. However, the power and reliability of laser sources has been doubling every year and this trend does not seem to be stopping. Consequently it is reasonable to assume that the necessary technology in terms of power rating and lifetime will be there for some of our far-term missions (*e.g.* Suicide Probe) and we recommend that this should be a focus for technology development.

Since spatial phase coherence has to be preserved, detectors should be ideally put in space or the effects of the atmosphere would have to be taken into account. It is envisioned that spaceborne reception will eventually be used [Lesh, 1992]. First it gets the receiver above the cloud cover, as well as the phase front disturbances caused by atmospheric turbulence. Second, by being outside this same atmosphere, background light associated with daytime scattering will be eliminated.

Spaceborne reception could become a reality in low Earth orbit, perhaps aboard or near the Space station, by the turn of this century. However this still leaves Earth blockage to a deep space probe, approximately half of the 90 minutes station orbit period if not more due to Sun blockage when orbiting around it. In addition, it makes telescope pointing more complex. Thus one would like to have such a station located on a much higher orbit, perhaps geosynchronous, or at one of the stable libration points [Lesh, 1992]. Once received by the orbital terminal, the data would subsequently be relayed to the ground via conventional RF techniques. The use of the Hubble Space Telescope has even been proposed [Ashford, 1996]. A space-based interferometer could be constructed on either side of the Earth, in Lagrangian points Earth-Moon, or using the south pole of the Moon.

If the receiving detectors are placed on the Earth then atmospheric effects must be considered. Absorption of light from the atmosphere in the UV, optical and IR spectra

varies and is a very serious consideration since the total amount of energy received is limited. Atmospheric turbulence is another effect to include in the optical link budget.

6.9.2.5 Inter-Satellite Links

Depending on the configuration and requirements of the mission/constellation (SAUNA, Early Warning) inter-satellite links (ISL) will be required. As discussed earlier, the Ka band is a suitable candidate for ISL if RF technology is considered. However, in the vicinity of the Sun the use of laser for ISL is recommended. Solar interference, in terms of beam disturbance and/or background noise, can be reduced with high pointing accuracy. Depending on the data rate requirement (*e.g.* > 1 Mb/s), optical links may be the only cost-effective and technical solution available.

6.9.2.6 Advanced Antennas

Due to the extreme conditions of the near-Sun environment, a high gain mechanically steered antenna is subject to thermal conditions that will limit the lifetime of the reflector, joints, lubricants etc., on top of normal wear and tear. This reduces the system reliability by introducing critical elements subject to single-point failure.

Other alternatives to the pointing mechanism are:

- reflectors with multiple feeds
- electronically steered phased arrays

The use of parabolic reflectors with multiple off-axis feeds is interesting to compensate the motion in the orbital plane with respect to the ecliptic. These antennas have, however, high mass and volume. In addition, antennas scanned off-axis have high losses, even though for small displacements (in the case of SAUNA ±7 °) a shaped secondary reflector can be used to compensate for these losses.

A better approach would be to use a phased-array antenna. Phased arrays steers electronically the antenna by means of varying the phase or amplitude of each radiating element. This would reduce the mechanical and structural requirements on the spacecraft, allow for higher gain and possibly adaptive nulling of nearby interference sources, like the Sun.

For the SAUNA mission, the physical shape of the array would have to allow for a near-circular shaping of the beam, as the spacecraft will be orbiting the Sun and will have to stay in permanent communication with Earth. Since all elements of the array are active, the power required increases but, for SAUNA, this impact on the power budget would not be significant.

6.9.3 Recommended Approach

This part presents the recommended technical approach concerning the communication system for the variety of Ra missions and for the time frames considered.

6.9.3.1 Near-Term Programme

Technology development: Ka band transponder and ground stations, high power laser sources, advanced antennas for deep space/Sun environment.

Missions: Concentrate on the existing technology, both in the space- and ground-segment. Thus, the use of X band is recommended.

6.9.3.2 Mid-Term Programme

Technology development: phased array antennas to avoid the use of 2 degrees of freedom mechanisms, space-qualified high power lasers and coherent detection techniques, spaceborne detectors.

SAUNA: Use of Ka band in missions near to the Sun. This will yield an increase in capacity, decrease in power, mass and size of the on-board hardware and antenna

SOLAR EARLY WARNING: The use of X band is foreseen for this mission as the constellation is to be sited at 0.5 AU from the Sun. However the implementation of a global network of ground stations is necessary, as the current capacity of the conventional networks (*e.g.* DSN) is limited and would not be suitable for continuous monitoring of the spacecraft.

6.9.3.3 Far-Term Programme

Technology development: Implementation of spaceborne optical receivers network, leading to spaceborne interferometry.

SUICIDE: Communications for the proposed Suicide Probe will have to be implemented using optical links. The mass and power constraints of the probe prevent any practical use of RF. Moreover, the scintillation effects as the probe nears the Sun would simply overwhelm the RF signal. It is hoped that an optical coherent-detected link, at a carefully chosen wavelength, will be possible however, specific technologies will have to be further developed.

6.10 Command and Data Handling

This section discusses various aspects of electronics, command and data handling for solar missions. We focus on the following selected themes:

- On-board electronics: Thermal and radiation environment.
- Telemetry Processing: Standard telemetry formats, multiplexing
- Autonomy: Vehicle management, fault detection, isolation and recovery (FDIR), payload data (pre)processing, collision avoidance, etc.

6.10.1 On-Board Electronics

The environment in the vicinity of the Sun is very harsh and extreme, especially in terms of temperature and radiation. This means that the electronic equipment on-board the spacecraft have to use a technology suitable to withstand and to survive this environment. This is especially important when missions of relative long duration in orbit and at a short distance to the Sun are considered.

In the Ra framework, missions of several years in orbit around the Sun at a distance of around 30 R_S are proposed. This forces one to consider issues as reliability and protection against degradation due to temperature and radiation. In addition, mission where suicide probes are sent into the Sun corona are proposed. For this kind of missions, a maximum survival time is desired, which poses additional requirements on the technology.

The high demands in terms of propulsion associated with getting close to the Sun importantly constrain the mass available. This means that all the different elements on-board the spacecraft are highly constrained in mass.

In order to reduce mass associated to the electronic equipment, it is desirable first of all to apply miniaturisation in order to reduce the mass and bulk of electronic components. In addition, to reduce the mass required for shielding the equipment against temperature and space radiation, it is very desirable to develop electronic technologies able to withstand the high-temperature and high-radiation environment. Developments are under way in space and other fields, which probably will provide sufficient demand for the technologies to be mature enough for its use in space in the mid- or the long-term.

6.10.1.1 Miniaturisation

It is very desirable to reduce the mass and volume associated to the electronic equipment. This leads directly to a significant reduction of cost or enables the integration of more equipment within the same configuration. An example of the gain achievable with miniaturisation is the unfortunate Cluster spacecraft, which development started in 1986. In the 10 years gone by since then a substantial change in technology has been produced. Thus, using technologies available today, the on-board data handling equipment would have a mass at least one order of magnitude smaller. The application of micro- and nanotechnologies to space applications for future space system goes far beyond and predicts 40 cm microlanders with a mass of 550 g and 5 cm free-flying magnetometers [Martinez de Aragon, 1995]

In the case of the electronic components this points out to the use of high-density processes and advanced packaging technologies (e.g. high-density 3-D packaging) in order to minimise the mass of electronic components. This advances in electronic component miniaturisation will shift the critical point in electronic equipment dimensioning towards the interfacing accessories (connectors and cabling) and mechanical fixation to the spacecraft structure. Development in these areas will need to be carried out in the far term in order to make use of the advances achieved and foreseen in the near and mid-term.

6.10.1.2 Temperature Considerations

Even though there are possible missions in the Ra framework that would be exposed to extremely low temperatures, the important concern is regarding the high temperature environment near the Sun.

The approach followed in the missions carried out or proposed to date consists of using conventional electronic technology in combination with important thermal shields to keep the electronics and sensitive material at a reasonable temperature. This, however, constrains the mission budgets, mass, volume, and hence cost, and imposes limits to the spacecraft resources and configuration. Thus, for example, the NASA Solar Probe provides a thermal shielding that assures that the electronic equipment don't exceed a temperature of 40 °C during the perihelion pass (4 R_S), where the maximal temperature is reached [Randolph, 1996].

In the near term and even in some cases in the mid-term, where budgetary or risk constraints are imposed, mission planners will very likely have to use this approach for missions in the vicinity of the Sun.

However, research is being carried out in different areas (automobile, aircraft, communications and radar, power, and also spacecraft) on the development of new

materials for advanced semiconductor electronic devices capable to withstand hostile environments, and especially high temperature, high power, and high radiation. Particularly, the NASA Lewis High Temperature Integrated Electronics and Sensors (HTIES) Team is working is developing silicon carbide (SiC) as a material for these demanding applications [HTIES Team, 1996]. Even though the technology at this point is immature, requiring improvements in crystal growth and device fabrication processes, the enabling technology is available for it to evolve to meet the system demands for hostile-environment electronics [Neudeck, 1996].

Silicon carbide electronics can operate at much higher temperatures (up to 600 °C) than silicon (up to 125 °C) or gallium arsenide (limited to 350 °C). Therefore, the size and mass of radiators and thermal shields on a spacecraft could be greatly reduced. This would enable substantial mass savings on the spacecraft, or at least allow greater functionality by utilising the volume and mass formerly occupied by the thermal management system. Furthermore, SiC electronic devices have also been shown to be less susceptible to radiation damage than correspondingly rated silicon devices.

A more mature and today more cost-effective alternative to SiC is silicon on insulator (SOI), even though its lower limit temperature makes the technology less attractive for its use in extremely high-temperature environments. SOI devices withstand temperatures up to 225 °C for an operating lifetime of 5 years, and up to 300 °C with reduced operation lifetime [Swenson, 1996].

The use of these high-temperature materials is very important for missions targeted to the inner planets, where high temperatures will be encountered. So far, only very limited use has been made of SiC for space applications. There are discussions in NASA about the use SiC for Venus missions. However, the reduced number of missions planned in the near future to the inner planets would not probably justify the investment required for such a technology development. Nevertheless, the other applications, and especially the automotive, aircraft and power industries will probably provide the pull required for this new technology to develop and mature to an extent sufficient for its use in space applications. Thus, even though it is unlikely that this technology will be available for space applications in the near- or mid-term, it is expected that far-term missions aimed at the inner planets or the Sun vicinity will possibly use SiC electronic technology.

6.10.1.3 Radiation Considerations

From the point of view of radiation, it is expected that the radiation fluxes in the Sun vicinity will be very important. In addition, the long duration of some of the possible missions proposed lead to very important cumulated radiation doses. Thus, the electronic equipment in mission scenarios with high exposure to radiation need to be protected against the effects of this extreme environment.

<u>Space Radiation Effects On Electronics</u>

In space, high-energy particles can penetrate devices and cause temporary upsets and permanent damage. Particle sources in space, and in the vicinity of the Sun in particular, are the cosmic-ray background, solar flare events and the solar wind. In planets with a strong magnetic field, there are important number of trapped particles. Interactions with spacecraft components cause secondary particle emissions as well. Finally, components on the spacecraft itself, such as radioactive heaters, radioisotope thermoelectric generators, and nuclear reactors, can emit particles.

In space, radiation effects on semiconductor devices are classified into two major types: total ionising dose (TID) and single-event effects (SEE). TID is the accumulated effect of

ionising radiation over the lifetime of a space mission and depends not only upon total trapped charge, but also upon the rate of incoming particles. SEEs are transient upsets (soft errors, or single-event upsets, SEUs) or permanent damage (hard errors or latchups) due to single particles. A third type, displacement damage, is less important [Messenger *et al.*, 1986] [Rasmussen, 1988] [Stassinopoulos *et al.*, 1988].

Soft errors (single-event upsets in storage elements and multiple-bit upsets in some types of memory devices) are temporary since they merely cause a logical error, they do not damage the chip. Once any affected registers are reset, the chip will resume correct operation. But that error has the potential to propagate and effect critical functions, causing any number of permanent problems on board the spacecraft. As an example, a soft error in a register of the critical control electronic elements for deployment or attitude control may initiate potential catastrophic failures.

Finally, the high number of particles and highly energetic environment could cause interference and charging problems. In order to avoid such problems a well planned grounding scheme together with interference mitigation measures must be engineered.

Table 6.22 summarises the components of the natural space radiation environment and its primary effects in CMOS devices, by far the most used electronics technology.

Table 6.22 Summary of Space Radiation Environment and Their Effects on CMOS Electronic Devices.

Radiation Source	Particle Types	Primary Effects
Solar wind	Electrons	Ionisation damage
Trapped radiation belts	Protons	Ionisation damage; SEE in sensitive devices
Galactic cosmic rays	High-energy charged particles	SEE
Solar flares	Electrons	Ionisation damage
	Protons	Ionisation damage; SEE in sensitive devices
	Lower energy heavy-charged particles	SEE

Protection Strategies Within the Radiation Environment

Radiation shielding is an integral part of any spacecraft design. The best shields have low atomic number, such as carbon and aluminium. Shielding can significantly reduce TID, but it can rarely affect SEEs since particles energetic enough to cause SEEs typically require shields several inches thick to be adequately attenuated. Unfortunately, shielding may also enhance TID and SEEs by slowing fast particles into energy ranges of SEE or TID sensitivity.

Given that flight path considerations and shielding cannot completely shelter electronics from radiation, designers must use radiation hardened (rad-hard) or radiation tolerant electronics, depending upon the radiation total dose and flux and fault tolerant subsystems as the final recourse [Kerns *et al.*, 1988]. Radiation tolerant electronic components normally can withstand up to a few tens of krad(Si), while rad-hard components withstand hundreds of krad(Si) or up to Mrad(Si). Rad-hard electronic components are normally manufactured in CMOS-SOS technology, even though some

other hardening technologies exist that have been used occasionally, such as epitaxial or silicon-on-insulator (SOI) substrates or bulk CMOS.

Fault tolerance includes built-in self tests, redundancy, and other methods. Built-in self tests constantly check faults so that the system can implement backup procedures immediately. Redundancy can be implemented in different manners, depending upon the requirements on reliability and the amount of risk acceptable,

- **Hot redundancy**, which consists of several elements operating in parallel, with additional components devoted to deciding on correct results, such as majority voting schemes.
- **Cold redundancy**, where the redundant equipment are switched off until a supervisory circuitry detects a failure in the nominal equipment. Then the function is taken over by the redundant equipment.

One frequently used approach to harden a system against SEU effects is to apply error detection and correction (EDAC). EDAC can be implemented in a number of ways, and can be a very effective way to accommodate SEU-induced errors in memory, microprocessor, or interface blocks.

The problems associated with the use of rad-hard electronic components are a comparably lower density of integration and substantially higher power consumption. This results in significantly higher mass and power budgets. This fact has an important impact for missions where large amounts of electronic components are required. A clear example is in solid state recorders (SSR), where large quantities of memory are required (in the order of hundreds of Mbits or even Gbits). The bulk and power consumption associated to the use of rad-hard technology in this case, very likely rules out the possibility of rad-hard SSRs. Instead, the combined use of shielding, redundancy, failure detection and recovery (FDIR) and EDAC together with high-density memory devices and advanced packaging is foreseen for such recorders, even in harsh environments [Seidleck *et al.*, 1996].

6.10.1.4 Recommended Approach

Given the extremely harsh environment in the vicinity of the Sun, and considering the state-of-the-art and the foreseen technology development in electronics for high-temperature and high-radiation environments, we suggest the following approach for on-board electronics:

<u>Near-Term Programme</u>

- Standard CMOS technology for non-critical electronics with adequate thermal and radiation shielding, FDIR and EDAC
- CMOS-SOS technology for critical electronic components with adequate thermal shielding, FDIR (redundancy)

<u>Mid-Term Programme</u>

- SOI or CMOS technology for non-critical electronics with adequate (reduced) thermal and radiation shielding, FDIR and EDAC
- CMOS-SOS technology for critical electronic components with adequate thermal shielding, FDIR (redundancy)
- SiC technology depending on technology maturity at the time

Far-Term Programme

- SiC technology for most electronics with adequate (highly reduced) thermal and radiation shielding, FDIR and EDAC (if at all needed)
- Standard CMOS technology for non-critical electronics requiring high density or high performance, with adequate thermal and radiation shielding, FDIR and EDAC.

6.10.2 Telemetry Processing

The following section will discuss telemetry processing. Two topics that will be discussed are standard telemetry formats and multiplexing techniques.

6.10.2.1 Standard Telemetry Formats

The use of a standardised telemetry format such as the CCSDS format can contribute to reductions in ground efforts, e.g. in mission control centre software and in the world-wide utilisation and processing of the spacecraft data. Such standardised formats are advisable for science missions [SAUNA, chapter 9.1] to allow total format compatibility and easy access to the data.

A standard telemetry format is absolutely *required* for larger constellations of spacecraft such as the solar environment monitoring networks discussed in the far-term time frame of the Ra Strategic Framework; without it, each spacecraft would require its own software at the operations centre, and this would make ground support very expensive for such networks.

6.10.2.2 Multiplexing Techniques

Multiplexing is the process where multiple channels are combined for transmission over a common transmission path. There are three predominant ways to multiplex (hybrids of these techniques also exist):

Frequency Division Multiplexing (FDM)

In FDM, multiple channels are combined onto a single aggregate signal for transmission. The channels are separated in the aggregate by their frequency. Signals occupying non-overlapping frequency bands are added and any one of these can be recovered by filtering.

Time Division Multiplexing (TDM)

In Time Division Multiplexing, channels "share" the common aggregate based upon time! Signals are compressed into high speed bursts which are placed in non-overlapping time slots within a time frame. Recovery of the original burst is accomplished by selection of the specific time slot in which the burst is positioned. Clearly this procedure requires timing references.

Code Division Multiplexing (CDM)

With code division multiplexing all users simultaneously operate within the same frequency band and each user occupies all the time the entire transponder bandwidth. Each user combines the signal to be transmitted with a signature sequence which displays two main correlation properties: (1) each sequence can easily be distinguished from a time shifted version of itself; (2.) each sequence can be easily be distinguished

from every other one in the set. Using these properties the receiver is able to separate the received signals even though they occupy the same bandwidth at the same time.

There are many solutions to the problem of multiplexing to a repeater by a group of network stations. The choice of access type depends above all on economic considerations: there are the global cost in terms of investment and operating cost and the benefits in terms of revenues [Maral *et al.*].

Multiplexing may be pushed to the limit of current performance capabilities by the advent of large satellite constellations (as proposed in the Strategic Framework) providing early warning data through a lesser number of Earth relay satellites.

6.10.3 Spacecraft Autonomy

The Ra missions require significant advances in technology as the programmes outlined in the Strategic Framework [chapter 2] become more and more ambitious with time. The increased complexity makes the spacecraft difficult to operate and also very dependent on the correct operation of all involved instrumentation. More on-board systems shall be integrated on the same computer and utilise the same instrument. This integration is demanding for the design process and the on-board autonomy. This section suggests improvements on different operational aspects related to on-board autonomy, which is feasible with increased computational power of future spacecraft.

6.10.3.1 Rationale for Autonomy

The two main objectives for on-board autonomy are to decrease the cost and to improve the performance of the spacecraft without increasing the risk. Several aspects related to these factors are displayed in figure 6.26 and described in the sequel. Some guidelines are specific to the individual Ra missions, but all shall be applied in some degree. A large variety of techniques can be used to increase a spacecraft's level of autonomy. More on-board automation requires more processing, but several advantages are possible.

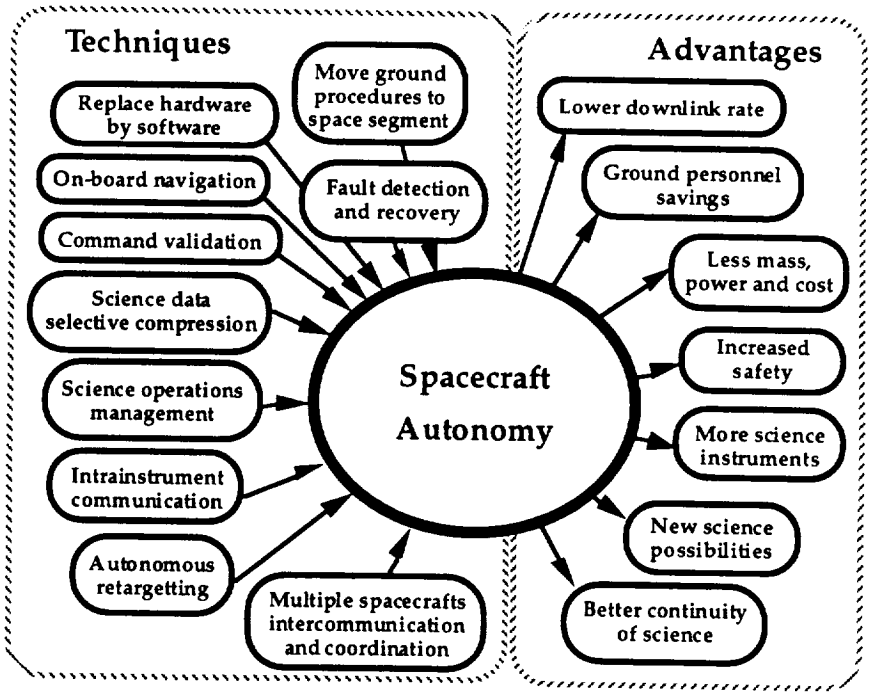


Figure 6.26 Factors Relating to Spacecraft Autonomy.

The ground operational expenses can be reduced by moving some of the functions traditionally performed on the ground to the spacecraft and also by reducing the requirement for a network of tracking stations. One example is to have on-board orbit/trajectory calculation, so periodic upload of parameters is avoided. An approach for interplanetary navigation has been proposed by [Bhaskaran, 1996] based on optical navigation using asteroids as beacons. This is, of course, only applicable in regions with asteroids that have known ephemeris data. The Ra missions operate inside the Earth's orbit with almost no asteroids, so the principle is not applicable. Instead, we propose to develop the concept to operate on planets. The principle is to measure the angle between a near object (a planet) and an inertially fixed object (a star). Applying multiple constellations, three axes position determination should be possible in the inner solar system. The SAUNA mission [section 9.1] needs on-board orbit information to control the pointable antenna. An on-board orbit model can provide this, but automatic navigation is desirable because a model has drift errors and needs updates from ground. If the antenna pointing is wrong, the spacecraft life depends solely on the low gain antennas. Anyhow, it may not be possible to develop the technique within the SAUNA programme, because the budget assumes mostly well known technologies.

The Ra mission satellites are designed to automatically reconfigure in case of anomalies, because there will be periods without ground contact and when contact is possible, the communication round-trip is up to the order of an hour (8 minutes for 1 AU). The Suicide Probe [section 10.2] goes as far as 5 AU from Earth, so real-time decisions must be taken on-board. Fault detection, isolation and recovery (FDIR) has the objective to provide a graceful degradation in case of minor anomalies, so the maximum performance of the spacecraft is utilised so as to keep the payload in operation as long as possible and enter a safe mode if the spacecraft health is in danger. Modern methods using analytical redundancy (exploiting the relationship between the input and the output of a dynamic system) in combination with advanced statistical methods will be applied in the Ra missions and thereby reduce the level of sensor redundancy.

On-board command validation is considered for all Ra missions, but it is specifically important in the multiple spacecraft missions [Suicide Probe, section 10.2; Early Warning System, section 9.2]. Commands and information transmitted from one spacecraft to another can be erroneous, but wrong commands can also be sent from ground, because international network operations have people employed from different nationalities and ground personnel may be renewed. Ground validation shall also be performed to the extent possible, but with increased spacecraft autonomy, the ground station may not comprise all required information.

The communication system in all the Ra missions is critical because of limited transmission power and mass. Therefore, science telemetry data rate will be reduced by data compression and by science operation management control. Modern methods for compression can be implemented in either hardware or software and make a significant reduction with none or very little loss of information. On-board selection between different compression methods (or bypass) can be installed to match specific data sequence characteristics. Science operation management comprises the triggering of special modes of the science instruments, like high speed data acquisition, activation of measurements, attitude manoeuvres for targeting, and eventually ejection of the Suicide Probe from the mother spacecraft. The ability for communication close to Sun is uncertain in the present design (SAUNA will probably not be able to have high data rate in 2/3 of the time), so it is very important to implement an intelligent manipulation of science data in case of reduced downlink capabilities, including prioritisation of science categories.

The Early Warning System proposed in section 9.2 with 20 small spacecraft floating around the Sun provides some interesting possibilities for increased autonomy between the individual satellites. Intercommunication can provide synchronisation of actions or even remote diagnostic of spacecraft behaviours with respect to anomaly detection. It is also possible to implement the measurement analysis on-board, so only a detected alarm is sent to ground.

6.10.3.2 Previous and Planned Missions with Focus on Autonomy

Autonomy is not a new concept. Some of the spacecraft flown to develop different aspects of automation are Ulysses, Clementine, TAOS, and XTE. Future missions include ESA's PROBA satellite, NASA's New Millennium Programme, and the Japanese MUSES-C satellite proposed by the Institute of Space and Astronomical Science. These do not constitute a complete collection of spacecraft designed with the attribute of autonomy, mainly because the concept of autonomy has different interpretations. In this context, autonomy is considered as decision making, a higher level of automation than signal processing and feedback control loops. Further information can be found in the following references, listed in order of appearance: [Ulysses Spacecraft Home Page, WWW; Clementine Information Home Page, WWW; TAOS, 1996; Technology for Autonomous Operational Survivability (TAOS) Satellite Home Page, WWW; Day *et al.*, 1996; Francesco, 1996; Lisman, 1996; and Nakatani, 1996].

6.10.3.3 Design and Implementation Issues

The implementation of more autonomy suffers from the paradox that increased complexity also raises the inherent probability of failures. Therefore, generic methods shall be developed and used to ensure completeness and correctness of on-board decisions. Tools have been developed by the Artificial Intelligence community that can assist to organise the inter-relationship between a large number of on-board functions. It is very important that the end-product has improved reliability, so the operator does *not* just disable the autonomous functions if something goes wrong or a critical operation is carried out. In any case, it is recommendable to let one team design the basic system and another team design the supervisory system to protect against making the same mistakes twice. In this way it is more likely that all situations will be covered.

6.11 Opportunities for Spacecraft Commonality, Modularity and Standardisation in Future Solar Science and Applications Missions

During a luncheon speech, at ISU 96, on the international implications of smaller, cheaper, faster (SCF) spacecraft, Dr. Gregg Maryniak of the Space Studies Institute hypothesised what SCF spacecraft might mean for the science fiction film industry, in particular, for the script of the tenth or so *Star Trek* film [Maryniak, 1996]:

Chekhov: Captain! Sensors indicate three Starfleet Class M matched handbags!

And Kirk will be cool...

Kirk: Steady Chekhov! Many bags look alike.

Although Maryniak was having fun at the expense of future "luggage" sized spacecraft, the fact that his joke included more than one spacecraft (or handbag) and these spacecraft (or handbags) looked alike, points in the direction of several important, but rarely

discussed, concepts behind SCF spacecraft. These three concepts are commonality, modularity and standardisation, and they have practical benefits and potentially large implications for future solar science and solar warning spacecraft missions.

Solar science spacecraft missions suffer from a lack of political, institutional and space science community support which makes these missions a relatively low priority in some space agency budgets. Chapter 6 has discussed several technological alternatives that may make future solar missions less costly and more budgetarily viable. Chapter 3 discusses organisational solutions to gathering support for solar science research and solar warning and forecasting applications. This section attempts to link the technological solutions in chapter 6 to the organisational solutions in chapter 3 through the system engineering concepts of commonality, modularity and standardisation. A tentative plan will be introduced on how these three concepts can be used to foster cost reductions in solar science and solar warning spacecraft through international co-operation.

6.11.1 Defining Commonality, Modularity and Standardisation

Before proceeding with a discussion of how the concepts of commonality, modularity and standardisation can be applied to a high technology, international solar observation framework, it is important to define these concepts. These three concepts will be collectively referred to as SCM (not to be confused with SCF) throughout the rest of this section.

6.11.1.1 Commonality

Commonality refers to the repeated use of the same component or system on more than one spacecraft and is a measure of the versatility inherent in a single component or system. Commonality is important in realising the economic and temporal benefits of utilising SCM concepts in spacecraft design and relies heavily on standardised requirements.

6.11.1.2 Modularity

Modularity defines the ability of a spacecraft design to integrate different components or systems for different missions. Modularity can be thought of as the measure of the universality of a spacecraft's interfaces and overall design. Modularity is enabled by standardised interfaces, common components and systems, and clear reference designs.

6.11.1.3 Standardisation

Standardisation is simply the organisational task of setting and agreeing to abide by defined component, system or spacecraft specifications for certain mission requirements. Standardisation in the context of this section is especially critical for setting design requirements, for building interfaces and for creating reference designs [section 6.11.1.4].

6.11.1.4 Reference Design

Another important term also used in this section is "reference design." A reference design is a "blueprint" for a system or spacecraft that can be utilised as a generic and adaptable baseline for further engineering to create a system or spacecraft design that meets specific mission requirements. In the terms of this section, a good reference design is a design that meets the needs of multiple users with minimal adaptation.

6.11.2 Rationales for Commonality, Modularity and Standardisation

SCM concepts, if successfully implemented, can create significant advantages in terms of resources spent on spacecraft design and production and can thus decrease the cost of solar observation. Additionally, several technological and political themes also serve as rationales for SCM in future solar observation spacecraft design.

6.11.2.1 Technological Opportunities

Many currently emerging spacecraft technologies can leverage the operational flexibility needed to create true SCM capabilities in solar probe and satellite designs. Pushing technological limits too far can have detrimental effects on the ability of certain users to afford, build and exploit an SCM reference design, but if properly combined and applied, emerging technologies promise to make a single system or spacecraft design viable for a wider, rather than narrower, group of users. The promising candidate technologies include:

Non-chemical Propulsion Systems

Electric propulsion (solar and nuclear) and solar sail propulsion can endow a single solar probe or satellite design with the capability to reach a variety of solar orbits or Lagrange points.

High Density Power Systems

New power system technologies like lithium polymer batteries, gallium arsenide, indium phosphide and multi-layer solar cells, and solar thermodynamic generators can increase the total available power per unit mass of power system on a spacecraft over standard batteries and silicon solar cells. Radioisotope generators (RTGs) also offer this capability using proven technology. By incorporating larger power capabilities at less mass cost, a single power system or spacecraft design can accommodate a greater variety of solar instrument payloads and operational lifetime requirements.

Lightweight Alloy and Composite Structural Materials

If certain production challenges are overcome, lightweight alloys and composites can contribute to solar probe or satellite structure mass reduction, which can contribute, in turn, to the ability of a common spacecraft design to reach different orbits and Lagrange points and use different launch systems.

Smart Structures

Adaptive systems and materials capable of reacting to external input rapidly, repeatedly and autonomously through material properties or active electromotor input can allow a spacecraft to adapt to different environments and vibration regimes.

Inflatable Structures

Externally and internally rigidized inflatable structures offer low mass and low cost options for various deployable spacecraft components such as instrument booms and reflector dishes.

Variable Thermal Systems

Microlouver, variable emissivity radiators are a promising technology capable of enabling a single spacecraft design to operate in different temperature regimes.

Small, Lightweight Sensors

Military derived sensors can decrease the mass of the tracking system and instrument payload for solar spacecraft while maintaining or increasing previous observational capabilities.

Fibre Optic and Wireless On-Board Communication

Wire cables, cable harnesses and connectors occupy a noticeable mass fraction of any spacecraft. The use of fibre optic cables or wireless communication (infrared beams, radio signals or low power laser beams) on board a spacecraft can reduce the total mass of a spacecraft introduce flexibility in data transmission.

Converging International Information Processing Standards

The increasing international standardisation and compatibility of computer hardware, software and interfaces can contribute to the commonality of spacecraft information systems.

6.11.2.2 Decreased Unit Development Costs and Time Frames

Once available technologies are correctly incorporated, an SCM reference design can lower the development costs and time frame for the a new spacecraft. Instead of "reinventing the wheel" for all of a given spacecraft's systems, those systems that are non-specific or non-critical to the spacecraft's mission requirements can be lifted from the reference design and applied to the new spacecraft.

6.11.2.3 Cost Reduction Through Economic Scales of Production

Utilising the same system or spacecraft for multiple missions will also reduce the production costs of the system or spacecraft. Production costs are lowered because the tools and knowledge needed to create one system or spacecraft do not have to be modified to create an additional system or spacecraft. The learning curve that is advanced by producing more than one system or spacecraft also contributes to lowered costs.

6.11.2.4 Increased Scientific Return Per Unit Cost

With lowered development and production costs, the costs of scientific exploration are also lower because more data can be obtained for the same investment.

6.11.2.5 Convergence of Science and Applications in Solar Observation

Proposed solar science observation missions hold many instrument and spacecraft requirements in common with proposed solar warning and forecasting spacecraft. Solar observation at various Lagrange points, solar stereoscopic observation, and instruments for ionospheric and magnetospheric observation have the potential to satisfy scientific curiosity and to provide data for improved solar forecasting models at the same time. Project managers and engineers for solar science and solar warning spacecraft can cooperate to design common instrument systems, support systems and spacecraft to lower development and production costs.

6.11.2.6 Potential Synergistic Interaction of Cost Reduction and International Co-operation

International co-operation in space science projects and missions usually implies a higher total cost for a particular project or mission because of the higher managerial costs associated with complexity of international co-operation. In the past, international co-operation in space science has also been limited primarily to scientific data co-ordination of independent agency projects and missions. However, by expanding space science co-ordination into the engineering of international projects and taking advantage of the international demand for solar observation spacecraft, it may be possible to actually reduce the costs of international co-operation in space science by designing and utilising SCM spacecraft on an international scale.

6.11.3 Trade-offs and Drawbacks to Spacecraft Commonality, Modularisation and Standardisation

Designing for SCM in a system or spacecraft holds certain risks, and this section outlines the risks that must be balanced against the benefits of SCM concepts described in section 6.11.2.

6.11.3.1 Large Initial Development Costs and Time Frames

Although the development costs and time frames for future spacecraft that use common systems are lowered, the cost and time frame needed to develop a common system that can meet more than one set of mission requirements can be greater than designing the equivalent system for one spacecraft.

6.11.3.2 Design Non-optimization

Even a very flexible SCM spacecraft design will not meet the requirements of every potential user. Unique but critical requirements must be addressed by a separate spacecraft or by a modular system that can interface with the basic SCM reference design. Although an SCM design may meet the requirements of a variety of users, it may not meet them all in an efficient manner. A minimum of overdesign in certain system capabilities will be needed to make a design suited to the mission requirements of more than one user.

6.11.3.3 Potentially Limited User Demand

Care must be taken when defining potential users for an SCM spacecraft and obtaining development funding from them. Commitments from multiple groups to utilise an SCM spacecraft may be needed before the additional funding and development necessary for SCM can be undertaken. If an SCM design does not meet the needs of more than one of its intended users, the additional funds needed to design for SCM are wasted. If multiple user demand is not viewed as likely early in the design process, SCM concepts should not drive that process. If enough users are found to warrant SCM, it is critical to build to those user needs (possibly with some negotiation between different user needs) throughout the design process.

6.11.4 A Short Synopsis of Spacecraft Commonality, Modularisation and Standardisation in Space Science: The Tale of Two SCM Programmes

SCM has long been a goal of spacecraft designers since the earliest satellites were launched. Communication satellite families achieved SCM early in their development, and some commercial, military and civil government remote sensing satellites are currently converging on SCM designs. Science satellites and probes, however, experienced a less successful advance towards SCM over the same time period. This is partly because of the unique requirements that science missions impose on spacecraft payloads and buses through their different observation objectives and their varied operating environments. These requirements simply made SCM impossible or very costly using past, mission specific technologies. Many of the emerging technologies described in section 6.11.2.1, however, are not specific to any particular mission; rather, they increase the flexibility of a spacecraft or system by increasing its support and performance capabilities. The lack of SCM concepts in science spacecraft design is also attributable to the dual goal orientation of most space agencies throughout the world which teams scientific exploration with technology development in the same programmes. NASA has taken steps to remedy this situation through the separation of scientific missions in its Discovery programme from technology development missions in

its New Millennium programme. This new technological and programmatic environment provides an opportunity for SCM to be achieved and applied in various spacecraft missions, including solar observation. Before describing how SCM might specifically benefit solar observation in a stepwise progression, it is important to contrast two purposeful efforts, one past and one present, towards SCM in science spacecraft design.

6.11.4.1 Goddard Space Flight Center's Multimission Modular Spacecraft (MMS)

In the early 1970s, NASA's Goddard Space Flight Center recognised the need to develop a large, adaptable spacecraft bus to support future orbital observatories. To capture the most astrophysics and Earth sensing missions in one spacecraft, the MMS focused on four missions: solar, Earth and stellar observation from LEO, and Earth observation from GEO. The MMS bus incorporated only power, attitude and control, command and data handling and thermal systems on a triangular, prism-shaped support structure. Instrument payload, additional solar power and propulsion were all mission specific and integrated on the top and bottom of the support structure via transition adapters. MMS was compatible with the Delta, Atlas, Titan and Space Shuttle launch. [Falkenhayn, 1987]

MMS followed several design rules to obtain its CMS capabilities: one thermal design for all missions, maximise the use of qualified and standard NASA components, minimise electrical and mechanical connections at interfaces, and no thermal break at interfaces. Testing and competitive procurement was placed at the system level to guarantee modularity. The MMS created cost advantages in total spacecraft design by reducing spacecraft integration and test time. MMS held interfaces standard but permitted modular system upgrades to improve performance and create design flexibility. [Falkenhayn, 1987]

In summary, MMS achieved limited SCM advantages with proven technology by designing a common service bus with modular components that could interface with different propulsion systems and instruments payloads to accommodate different mission requirements in a common environment. MMS reduced costs and development time frames by applying SCM concepts to users with common support system requirements.

6.11.4.2 Jet Propulsion Laboratory's New Millennium Programme

In contrast to MMS, the Jet Propulsion Laboratory's approach to SCM in its New Millennium Programme (NMP) is driven more by technologies that enable SCM than by meeting the common needs of several users. One of NMP's Integrated Product Development Teams is dedicated to Modular and Multifunctional Systems (MAMS). Instead of designing a standard service bus with modular systems and common interfaces, MAMS is concentrating on exploiting technologies to combine multiple functions (propulsion, power, structures, mechanisms, thermal systems) into single systems. One of the best examples of the MAMS approach is an inflatable reflecting dish that can be adapted for long baseline interferometry, in subsurface planetary sounding, in remote sensing radar, in soil moisture radiometry, for a submillimeter space telescope and as a space power antenna. Another example of a MAMS concept is a micropropulsion unit for miniprobe propulsion or precision station-keeping in larger spacecraft. MAMS drives SCF through multifunctional SCM systems that significantly reduce overall spacecraft mass and enable open spacecraft architectures. [NMP Events Theme 10 Homepage, WWW]

6.11.5 Future Opportunities to Incorporate and Exploit SCM Concepts in Solar Observation Spacecraft Design

Future solar observation spacecraft for solar science and solar warning systems have opportunities available to them to take advantage of both the MMS and MAMS approaches to achieving SCM benefits. These opportunities stretch across the near-term, mid-term and far-term Ra Strategic Framework.

6.11.5.1 Cluster Phoenix: A Near-Term Opportunity for International Commonality and Standardisation in Solar Science

The loss of the Cluster constellation presents ESA and possibly other space agencies involved in the International Solar Terrestrial Physics Programme (ISTP) with the opportunity to apply SCM concepts immediately and at low investment to replace Cluster's capabilities. Although ESA management is currently leaning towards launching the Cluster spare satellite as soon as possible to complement ISTP data in the magnetospheric cusp region, ESA should also consider not wasting its Cluster development investment and procure three more common Cluster satellites for a future launch. Alternatively, if Cluster procurement funds are not available, ESA should look outside its programme for a small satellite design that can carry the most important Cluster instruments to complement the Cluster spare satellite. Possible candidates might include university minisatellites [section 6.11.5.2] or a proposed NASA second generation space physics and particles microspacecraft [Second Generation Microspacecraft Homepage, WWW]. The Cluster loss could provide an international driver for ESA, NASA and other space agencies to advance independent, but coherently related, development of small, common, standardised solar observation spacecraft in co-operating countries.

6.11.5.2 University Microsatellites, Military Minisatellites and Commercial Buses: Mid-Term Opportunities to Exploit SCM Concepts for Solar Science and Solar Warning Spacecraft

In the mid-term, space agencies involved in the ISTP programme should take advantage of existing and developing modular university microsatellites. For example, Surrey Satellite Technology Limited, a company formed by the University of Surrey in Great Britain in 1985, currently offers the Micro-Bus, a modular microsatellite platform that houses systems and payloads in customisable tray modules [Micro-Bus--SSTL Modular Microsatellite Platform Homepage, WWW]. A Micro-Bus satellite can be developed in as quickly as 9 months and offers university and agency researchers involved in ISTP the opportunity to quickly and inexpensively obtain additional data about a particular phenomenon when the current ISTP constellation and instruments prove to be inadequate. University minisatellites can also be utilised for technology demonstration, especially the flight validation of new, lightweight sensor technologies for future solar missions. Stanford University in the United States has developed two SQUIRT (Satellite QUIck Research Testbed) microsatellites, one of which is known as SAPPHIRE (Stanford Audio Phonic Photographic Infrared Experiment). SAPPHIRE is flight testing a micromachined infrared sensor for NASA's Jet Propulsion Laboratory [SQUIRT SAPPHIRE Homepage, WWW].

Some SCM technologies and platforms previously developed by the U.S. Department of Defence for its Strategic Defence Initiative and by its Ballistic Missile Defence Organisation may also be applicable to solar science or solar warning spacecraft. The U.S. military is currently developing Clementine II, a miniprobe bus nearly identical to the now famous Clementine I spacecraft, which is capable of launching, monitoring and controlling three identical, high thrust, daughter spacecraft designed for asteroid interception [Worden, 1996]. The Clementine bus and daughter spacecraft might be

easily adapted to the deployment of a solar sensor constellation in a libration orbit around a Lagrange point. Stanford University is also pursuing a mother microsatellite capable of launching four identical daughter picosatellites through its second SQUIRT programme, OPAL (Orbiting Picosat Automatic Launcher) [SQUIRT OPAL Homepage, WWW]. The U.S. military has also developed a modular minisatellite structure design for its own sensor demonstration needs. Known as MSTI (Miniature Sensor Technology Integration), the third spacecraft in this series has been adapted to track warm objects in space but its ability to gather background clutter data has the ability to derive data on the solar interaction with the Earth's atmospheric limb, solar scattering effects and solar specular intensities [Barnhart, *et al.*, 1995]. Future MSTI spacecraft might be guided towards more direct solar phenomena observation missions.

Modular commercial satellite buses may also prove to be adaptable to certain solar observation missions. Lockheed Martin recently offered its LM700 bus which can accommodate distributed payload components or more modular payloads up to 500 lbm. The LM700 uses a graphite epoxy structure to reduce weight, features gallium arsenide solar cells and can launch on Proton, Delta, Long March and LMLV-1 vehicles [LM700 Homepage, WWW]. Although designed for remote sensing and surveillance missions, the LM700 can attain two nadir orientations and has two-axis gimbals for its solar arrays which could permit certain solar observations. Although not ideally suited to solar science, the LM700 might prove to be a cheap means of creating a dedicated solar warning and forecast satellite. Alternatively, the modular university or military micro- and minisatellites described above could be used to create small solar warning observation networks.

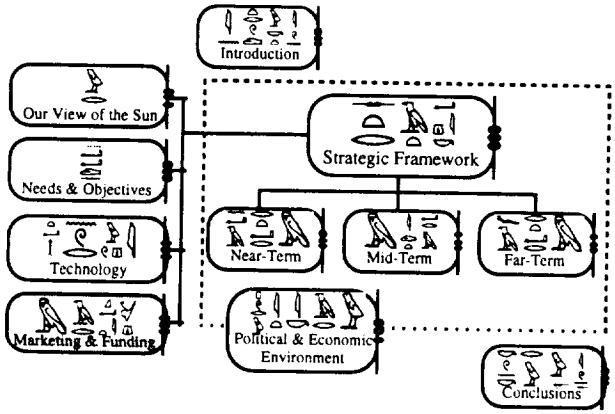
By exploiting existing SCM and SCF spacecraft in academia, industry and the military, cheap, quick response solar observation missions could be mounted in the mid-term to support current and planned solar science efforts (ISTP and FIRE). These existing spacecraft might also provide the first dedicated platforms for space-based solar warning and forecasting instruments in Earth orbit or at various Lagrange points. Use of these spacecraft will also be crucial in flight testing instruments and gaining experience in SCM design concepts for a new generation of *in situ* solar observation spacecraft.

6.11.5.3 An International Reference Bus Design for Solar Observation: A Far-Term Opportunity to Pursue SCM Concepts to Sustain Multiple, Long Duration, *In Situ* Solar Missions

The Ra Strategic Framework realises the scientific need for dedicated constellations or networks of solar observation platforms beyond the Earth orbit and Langrange point spacecraft discussed thus far. Such spacecraft may also prove crucial to extending solar warning lead times and improving the accuracy of solar forecasting beyond the capabilities envisioned even with dedicated, Lagrange point spacecraft. Although the Framework predicts that these spacecraft will occupy different solar orbits (polar, synchronous, etc., see section 10.1) and will carry different instruments (stereoscopic, neutral atom imagers, etc.), the environments in which these spacecraft will fly and their possible payloads do not impose radically different or impossible design requirements, especially when the technologies of section 6.11.2.1 are taken into consideration. In light of their common, baseline requirements, it is recommended that the international community pursue the design of a standard, common bus for *in situ* solar observation constellations and networks. This bus should be a reference design only, adaptable to the needs of several solar observation missions, but not contingent on planned national space agency or solar warning and forecasting missions. The bus design, its requirements, its standards, and its interfaces would be hashed out through an international forum similar to various international scientific working groups but endowed with an engineering emphasis. Section 3.2 presents the organisation of a proposed international solar working

group, which includes an engineering section dedicated to the creation of a solar observation service bus reference design. Once the reference design is available, national space agencies can utilise it as a baseline to save development costs and time frames by adapting it to their specific solar observation mission needs through their own modular payloads. The commonality of the service bus reference design would allow space agencies and solar warning and forecasting organisations to pursue independent projects while co-ordinating to engineering costs and time frames. By involving the international community, the demand needed to justify an SCM reference design for solar observation spacecraft networks and constellations is met, and its benefits distributed to the maximum number of solar observers.

Chapter 7



Market and Funding Issues

In this chapter the market issues and the possibilities of funding for the Ra Far-Term programme are discussed. When we say market, we refer to the interaction between the parties in a given business situation. The involved parties are the scientific community, the public and private sector, private industry, education and entertainment. In the first section, we will discuss the market and its related issues, in the second the funding sources, means and methods and in the third the marketing.

7.1 Markets for Ra

In the search for potential and existing markets for Ra, the following ideas have been put forward. Up to now, the results from missions performing solar measurements and acquisition of relevant data, are mainly used by the scientific community and the space environment prediction services. It is important to differentiate between profitable markets and non-profitable markets. The non-profitable market in the case of space environment prediction is made up of elements in the public sector that exists more or less as a public good. They distribute the current space environment predictions at no cost. Does this mean that there is no profitable market for space environment prediction? Absolutely not! You can always charge money, if your product is of value to the customer. We have found an example where power companies pay for research and customer adapted space environment predictions [Lundstedt, 1996]. And this is done even though the power companies can get predictions at zero cost. There is an added value for the product! Another reason for not relying on the institutes giving predictions is that they do not have a responsibility to provide predictions during crisis such as wars. You add value to the service/product by providing more reliable predictions, longer alert time etc. The conclusion is that there is a profitable market for space environment prediction. You can even create a market through the development and provision of customer tailored products, in this case customer adapted prediction.

7.1.1 Space Environment Prediction

As part of the market survey and evaluation, the current end to end chain of users of solar data for space environment prediction was examined in terms of interest, opportunities, opportunity costs and market growth potential.

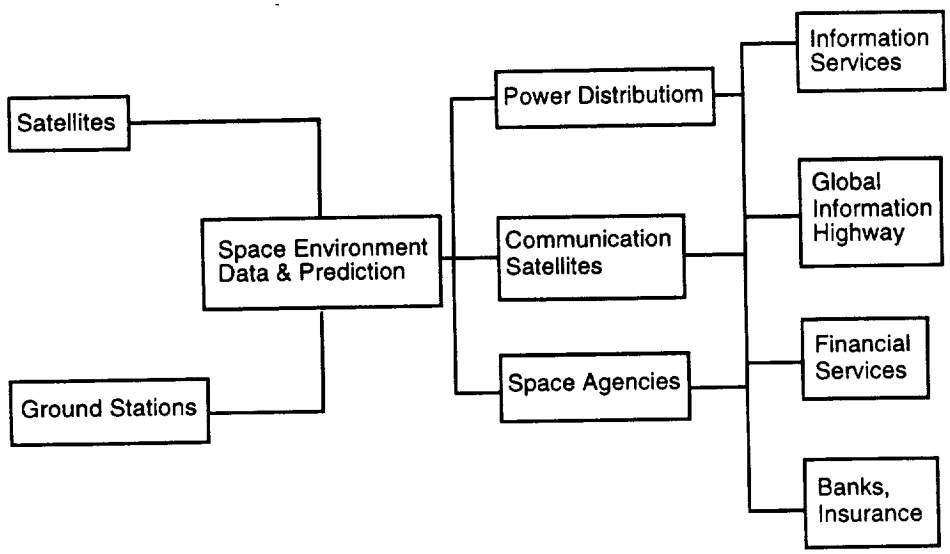


Fig. 7.1 **End-to-end chain of users of space environment prediction.**

Space environment prediction services get input data for their models either from institutes or space agencies. The prediction is done and then delivered to the customer as schematised in figure 7.1. The customer might be a space agency, a power company, a satellite operator or insurer. The big questions are : "Is there an end user willing to pay for the service?", "How big is the market?", "How do you estimate the size of the market?" and "What is its growth potential?"

One way of estimating the size of the market is to ask industry how interested they are in paying -for the specific service. This proves to be quite difficult, because the companies cannot estimate the value of a service until they see the direct benefit of the service/product. However, we have obtained from an electric power company the cost of a lightning locating system as being $20,000 U.S. annually [Andersson, 1996]. If a commercially available space environment prediction system would exist, this cost could be seen as a maximum [Andersson, 1996].

Another approach would be to see how much it costs for companies not to use the service/product. How much does it cost when a telecommunications satellite is destroyed by magnetic storms or high energy particles? A lot of research has to be done on this point. How much does it cost when an electric power net goes down in Canada as a cause of magnetic storms? The costs of the power breakdown of the Hydro Quebec is estimated to be more than $10 million U.S., but much higher costs have been estimated for consequences of the breakdown. This is also a reason for insurance companies to look into this matter. Good space environment prediction could prevent many expenses for the insurance companies.

The real issue is the pressure that a customer exerts, for example on a power company. If it is vital to have power continuously, the customers simply say they are prepared to pay for the extra service. The service in this case is in the form of space environment prediction used by the power company to deliver a more continuous service to the

customer. So the push towards the use of space environment prediction starts at the customer. The customer could be a bank or financial institution that needs 24 hours continuous information services or a hospital that needs continuous power.

How much is the cost of a lost life in a remote part of Australia (the country highly relies on radio links) as a cause of bad radio communications during a magnetic storm [Thompson, 1996]?

The total annual space environment prediction market is about $100 million U.S. at the moment [Worden, 1996]. It is expected to increase up to $200 million U.S., within the next ten years.

There is a clear demand for continuous space environment prediction which is more precise (at the moment 30-50%) and has a longer warning time [Worden, 1996].

There are indications that changes of the space environment have an influence on the Earth weather, and even, in some circumstance, possibly our human health [Atkov, 1996] [Campbell, 1996].

Let's have a look at the market of end users for prediction. Two interesting future end users are the electric power industry and the planned satellite constellations for mobile communication. The satellite constellations are made up of large numbers of satellites, some in low Earth orbit and some in medium Earth orbit. The estimated total budget of these nets is somewhere between $10 and $25 billion U.S. How much are they prepared to pay for space environment prediction? The answer depends upon other things, such as the quality of the prediction and what countermeasures can be applied during high solar activity. It is mostly the upper constellations that are interested in space environment prediction.

The efficiency of the commercialisation decreases as the technology matures. Space environment prediction is still an immature product and therefore interesting. Do not miss the window of opportunity. Space environment prediction has its window now! Use it!

7.1.2 Entertainment and Education Market

By converting the scientific results, partly and appropriately, into entertainment, two results can be obtained:

1. Increased public awareness and increased interest for solar science;
2. From the entertainment market the Ra scientific missions can be partly funded, if Ra shows the market potential for entertainment.

The entertainment market is big and even a small part of the market can generate large sums of money. However, the market is very sensitive to market pressures [section 7.3].

The prediction of auroras is an example of a combination of entertainment and education. The recording and telecasting of such solar generated phenomena can be a core element of televised documentaries. Taking spectators up in a helicopter to view the aurora at the right moment provides another business opportunity.

Another example of a potential entertainment market is the "Las Vegas mission", referred to as the suicide probe in section 10.2. This spacecraft is launched, toward the Sun, from a mother spacecraft. It will obtain valuable scientific knowledge about the Sun. Moreover, it is very special that a human built spacecraft will reach the Sun at such a close distance.

The "Las Vegas mission" can be a source of a lot of entertainment. Like, big gambling events. How long will it survive? Is it still alive? The name Las Vegas is strongly connected to gambling through the town in U.S. A suicide probe to the Sun will be consumed by the Sun. The big question is when? No matter how good all the calculations and estimations of the lifetime of the probe are, no one will know for sure how long the probe will survive until it actually is consumed by the Sun and its environment. This gives an excellent opportunity for gambling. Can you see the headlines "How long will Vegas make it?" or "Latest update from Vegas, temperature has now reached 600K and is rapidly increasing" in combination with pictures of coronal mass ejections.

7.1.4 Science Market

More and more contracts between universities and industry are being made. This is a way of getting funding for science. Some of the scientific questions are [section 5.1] :

What are the causes of coronal heating and coronal holes?

What are the causes of CMEs?

What is the origin and acceleration processes of the solar wind?

How different is the polar solar wind from the equatorial?

Does any change in the Sun also effect change in Earth weather/climate?

What causes the solar constant to change?

The universities or institutes perform research that is relevant to the industry and thereby receive fees, funds and/or grants. In this lies a big potential. In the case of space environment prediction this could be very interesting to power companies for example. Why not leave the leading role to industry as part of their Research and Development.

7.1.5 Expected Time Evolution of the Markets

To predict the evolution of the described markets is highly speculative. However we envisage a combination of the following factors [figure 7.2]:

- Science is more and more related to direct application of industry, therefore, it is expected that the space environment prediction market will increase [Worden, 1996] and the science market will be stable.
- To increase the funding for science, the public awareness concerning science has to be increased. A possible way to do this, is to increase the entertainment related to science or to increase benefits from scientific and efficient technological knowledge to develop and implement light and heating infrastructures for buildings and transportation. This results in potentially high and significant reductions in energy costs and significant influence on the health of the global population [section 10.4].

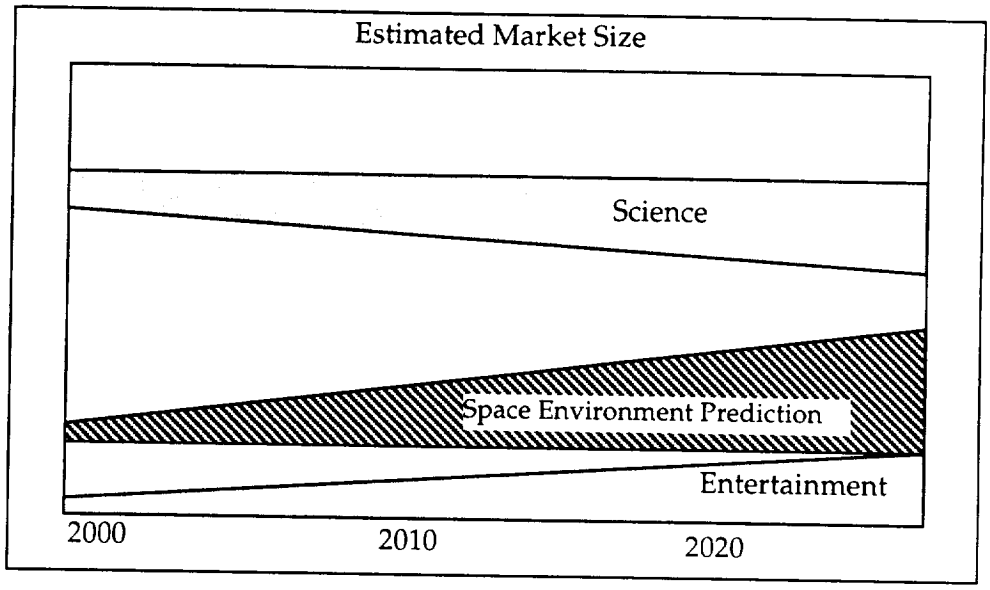


Fig. 7.2 **Estimation of market evolution over time.**

7.2 Project Funding

The sources of funding for Ra may be divided into three major parts. The first one is governmental funding, the second is private funding and the last is a combination of them both. The funding can also be spread along a time-scale.

7.2.1 Governmental Funding

Governmental funding can be civil, military, agency, institutional funding etc. It can be from a single source or from a combination depending on the specific project, its characteristics and national and/or industrial interests [section 3.2]. Funding decisions for Ra can also be made by organisations led by national politics.

The borderline between military and civil funding is not always clear. This is a case for dual use technologies, where a project might be of use for both civil and military purposes. In some space agencies the difference is clear. ESA only funds non-military projects.

In some places on Earth, radio communications that are influenced by the space environment can mean the difference between life and death. In other places the space environment affects public power networks. There is also military interest in the space environment. The list could be long and the intention is just to show that there is governmental interest in predicting the space environment.

Governments tend to have a shorter and shorter perspective in the sense that they have a higher priority in the near-term. They want to see a quick return on the investment for a public service in order to enhance their political strength.

Getting public interest in the Ra programme is likely to increase the availability of governmental funding sources [chapter 3]. We think that further studies on this should be done.

One of the big fund-raisers is the scientific community, irrespective of national boundaries. For science there is a governmental interest since science can create of benefits to the society. Scientists tend to be good in raising money from governments, funds, institutes and industry. But why not increase modest amounts of their funding effort. Let the scientists think and act commercial. Let scientists put on a fancy dress and talk to people! Do research that is relevant to industry and make contracts with them. Power companies could, and some already do, pay for science on space environment prediction [Lundstedt, 1996]. Go over the blocks in the funding? The Sun is the biggest plasma laboratory we know of. Why don't space physicists and nuclear physicists co-operate more? There is co-operation between , but it could definitely increase. There might be a problem with the two separated budgets (e.g. that is the case in U.S.), but with a bit of goodwill and enthusiasm they should be able to overcome such problems and thereby increase the total funding for Ra.

Another supra-national global funding source is the United Nations (U.N.). Lives of people all over the world can be saved and the life quality can be increased by using space environment prediction [section 3.4]. This is in the interest of U.N. and of all humanity.

Space agencies are interested in solar science and space environment prediction. This is extremely important for the manned programmes. Improved measurements and models should benefit the manned space programmes and thereby constitute a ground for funding.

7.2.2 Private Funding

Private industry is an alternative funding source for some elements of the Ra project. It is easier to see the direct benefits of applications for industry rather than the benefits of science on the Sun and its effects on Earth (even though there are benefits from science). Typical applications for industry could be space environment prediction. Potentially interested private parties in this domain are communication satellite operators and electric power companies in some countries. These two industries are big and they sometimes need better predictions than a "general" space environment prediction institute offers. Electric power distribution companies are large infrastructure companies. Satellite communications are increasing rapidly. A number of different satellite constellations are planned for mobile communications. Some of them will use satellites in low Earth orbit and some of them will use satellites in higher orbits. The average budget for each constellation is some 3 billion US dollars [Pelton, 1996]. The launching of the satellites in these constellations starts 1998/1999 and the volume is well over one hundred satellites. Space utilisation is very expensive and it will be affected by the Sun and its environment, therefore funding for Ra should take a prominent place in their priorities. Is there enough flexibility in their business plan to pay for the service?

There seems to be a lack of awareness in private industry about the Sun and its influences on Earth. If this situation could be improved it would surely be easier to find funding for Ra. Another problem is that private industry still knows that space is risky (high insurance premiums). This makes private funding more difficult. There is a big need of finding ways to show private industry that with proper insurance and technical measures space business does not have to be any riskier than any other industry.

One way to get funding money or risk money is to use small companies outside of the space field who wish to enhance their image through space work. You could argue that it introduces more risk, but that remains to be proven.

7.2.3 Combination of Private and Governmental Funding

If you can show technical and financial feasibility and if a market can be determined, private money funding could be invested together with governmental funding. "In today's environment shared funding is a prerequisite to get things going" [Cohendet, 1996]. One way of having combined funding is to let private industry build, finance, operate and transfer the project to the government. This is called concession funding. One of the difficulties here is who takes the risk. An alternative to this is to do it the other way around. This is motivated by the fact that private industry tends to be a more efficient operator.

To make this type of funding possible industry must show some interest in the Ra. Any will to invest, even if it is a small investment, is enough to show the space agency that the industry is interested. Space agencies on the other hand, should encourage non-aerospace companies to invest in Ra.

There seems to be a lack of interaction between potential users and sellers of solar data and applications. Improving the interactions between government and private industry would facilitate and improve the funding opportunities among industry. We think that there is a lot to improve in these areas and further studies on this should be done.

In some situations clusters of companies are very competitive. Could a cluster consist of electric power companies and space environment prediction institutes/companies? The answer is, yes it could, it already exists in Sweden [Lundstedt, 1996]. And this can expand to a global scale. In the U.S., similar suggestions have been made to let power companies invest together in geomagnetic storm prediction, but so far nothing has been done on that point [Worden, 1996]. You have to have a strong force or personality acting on the decision makers. In Canada the power companies use several different space environment prediction resources. The mere fact that the power companies have shown an interest in our investigations is significant. There are other clusters that could be interesting, e.g. communication satellite operators and space environment prediction services. The interesting thing is that clusters often have a competitive advantage. Are they willing to fund Ra? It depends on the market situation. Furthermore the clusters serve as development centres with strengthened competence and feedback. You get a situation where end users are innovators.

There is a trend toward letting contracts between universities and industry. The universities do research relevant to industry and the industry funds part of it. This is also a way of getting combined funding. We also see a trend where solar activities are moving from research driven to product/service driven.

7.3 Marketing

Space businesses have a lot to learn from private industry concerning marketing diversification and the creation of new markets. In general the market demand is a function of the marketing effort as seen in figure 7.3. By increasing the marketing effort, the market for solar data can be increased.

Among relevant aspects for Ra, are the importance of positioning the product on the market, in the correct market segment and in the customers requirements' domain, to convince the future customers why they need the use of space environment prediction.

For the space environment prediction, a way to increase the market is:

- show that a lot of satellite losses are due to magnetic storms/high energy particles;
- show power companies that they have increased power consumption in the transmission lines because of the magnetic storms;
- quantify the losses, to obtain a profit-loss calculation.

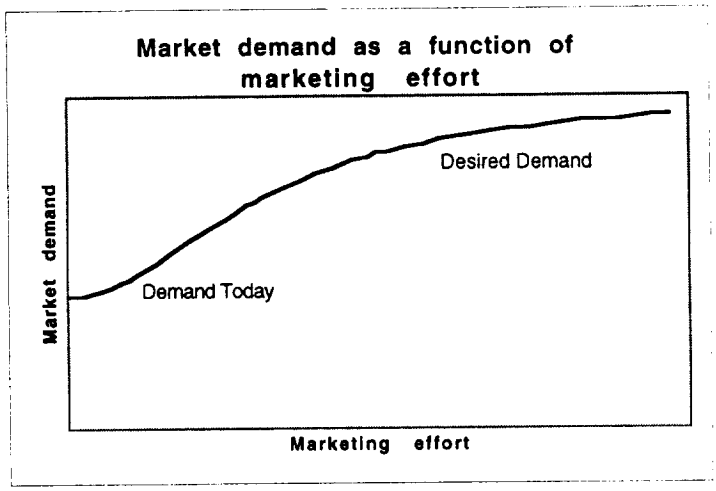
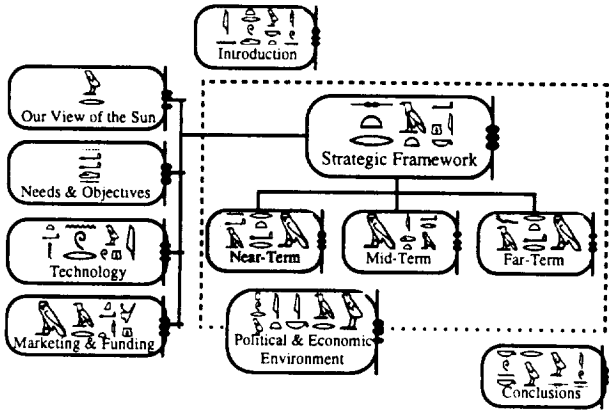


Fig. 7.3 Market demand as a function of marketing effort.

The marketing of the entertainment is based on perception and less based on rational thinking. Some examples of marketing are:

- Use famous persons to talk about solar physics and the space environment. Television personalities are examples of people that attract other people to listen. And why not? You do not have to follow the traditional way of doing things;
- Use solar relevant entertainment. Virtual reality trips to the Sun or a stereoscopic view of the corona;
- Use solar science in the public education. This gives a broader interest understanding for solar science;
- Make television programmes and contests related to the Sun for children. Contests have a multiplying effect [Willekens, 1996]. You only have one prize but a lot of people in the contest and a lot of viewers. As an example: ESA had a "space theme" at Disneyland Paris.

Chapter 8



Near-Term Programme

8.1 Overview

This chapter will provide the details of the Ra Near-Term Programme as introduced in chapter 2. As described in that chapter, "near-term" is from now until the year 2000.

Each part of the programme described in the following eight sections is relatively low in cost and either builds on existing systems and infrastructure or requires only modest developments. We believe the recommendations are realistic and play an important role in realising the objectives described in chapter 5. They also provide a foundation for the programmes described in the mid- and Far-Term Programmes. To build on existing solar observation instruments (namely SOHO) and to continue with a logical sequence of solar observation satellites, we discuss the Cluster replacement programme [section 8.2]. As we believe space environmental forecasting will become more important to the space community in the mid- and far-term, we recommend immediate work on improving forecasting models [section 8.3]. As the amount of archived data continues to grow and additional solar observation satellites are launched it becomes ever more crucial to ensure the co-ordination and accessibility of both the new data and those from the past [section 8.4]. Then, in section 8.5, we describe the near-term implications of the Working Group for International Solar Exploration & Application (WG ISEA) [chapter 3]. To help advance the mid- and Far-Term Programmes through to fruition, we envisage increasing awareness of solar science and solar terrestrial connection, thereby fostering support beyond the scientific community [section 8.6]. The Near-Term Programme is concluded with reasons to support the "faster, cheaper, and better" concept into future technology development.

8.2 Replace Cluster

The four original Cluster satellites were lost on June 4th, 1996 with Ariane 5's maiden flight failure. They, together with the Solar Heliospheric Observatory (SOHO), were to

be part of ESA's Solar-Terrestrial Science Programme (STSP), and part of the International Solar-Terrestrial Physics (ISTP) programme. The timeline of a Cluster recovery is governed by the desire to achieve simultaneous observations with other ISTP Spacecraft [Cluster within STSP]. ISTP includes STSP and spacecraft from the United States, Japan, and Russia, and aims to investigate solar-terrestrial physics and the Earth's magnetosphere.

Hence the loss of Cluster has not only destroyed that mission but also deprived both programmes of extensive valuable data, making the issue of replacement a critical one among the international scientific community. For example, NASA Office of Space Science (OSS) "roadmap", which develops a strategic plan for future space science missions, relies partially on Cluster in its near-term plan [NASA's roadmap, WWW].

8.2.1 ESA Science Programme Committee's Work on Cluster replacement

The replacement of Cluster is currently being studied at ESA, and its implementation has indeed already begun. "Everybody agrees with the principle that we should at least partially recover the Cluster mission" quoted from Balsiger in Space News [de Sedling, 1996]. At the 3 July 1996 meeting in London, the Science Programme Committee approved the funding of ECU 30 million to build the flight spare spacecraft of the first Cluster mission, called Phoenix, and have it ready to launch by spring 1997. A decision on a comprehensive replacement strategy is planned for November 1996, and four options are being considered so far :

1. Fly Phoenix as soon as possible, which means maybe on 502 or 503 Ariane 5 launch, and build nothing else.
2. Fly Phoenix as soon as possible, and build 3 new Cluster spacecraft to go up later for an estimated additional cost of ECU 350 million. 3 to 4 years are required for the construction, which enable a launch by 2000/2001. At that time, SOHO and the ISTP fleet will probably still be operational. Note that, along with the 3 new Clusters, ESA will have to build another flight spare.
3. Hold Phoenix, build 3 new Cluster spacecraft and launch them together.
4. Hold Phoenix, build 3 national mini-satellites to accompany it, and launch them together.

As of today, the second option has gained the most political support, for the following reasons :

- We need to get the unique Cluster instruments, even just one set, into the unique magnetospheric-cusp-region orbit, and contribute to the ISTP fleet as soon as possible. There are 10 ISTP spacecraft in orbit, and Cluster contributes a lot to the synergy.
- The cost of building three new spacecraft is easily identifiable and quite low, because no R&D is necessary, but who knows the cost and politics of building 3 small new satellites? What instruments would be jettisoned for example?
- We really need four spacecraft to do the subtle 3-dimensional gradient measurements needed in the solar wind.
- The flight spare as well as the new ones will be built by Dornier, basically the same people will do exactly the same things as before to keep costs down.

8.2.2 Ra's Recommendations

The Ra Strategic Framework strongly supports a Cluster recovery mission. The question is what form the replacement spacecraft should take. ESA should certainly explore the possibility of using new technologies to reduce cost while still retaining capability. As well as helping Cluster, this would also improve technology development for future space physics missions such as applications-oriented solar-terrestrial monitoring constellations.

Assuming an early launch of the original flight spare, a second important point is that by the time the replacement spacecraft are launched (maybe 2001), the old flight spare may well have ceased operating. Hence, provided adequate science instrumentation is flown, the building of **four** Cluster replacements would seem prudent to guarantee the scientific viability of the recovery mission.

Fig. 8.1 A low-cost alternative for Cluster recovery?

8.3 Improve Forecasting Models

The current state of affairs of the space environmental forecasting community has been compared with the state of terrestrial weather forecasting over fifty years ago [National Space Weather Program, 1995]. While there is a definite need for more measurements to provide better forecasting capabilities, spacecraft sensors alone will not perfect the forecasting job [Zwickl, 1996]. New measurements will need better forecasting models to exploit the new data.

8.3.1 Observations of Today's Space Environmental Modelling

The U.S. National Space Weather Program Strategic Plan, completed in August 1995, outlined specific recommendations for space environmental forecasting. The authors' recommendations for modelling included replacing the existing models with physics-based quantitative models, transferring research models into tailored operational ones,

integrating models, evaluating them and making future models easy to upgrade [National Space Weather Program, 1995]. We wholeheartedly agree, but we go beyond those American recommendations to extend the concept internationally.

Current systems used in space environmental forecasting organisations are mainly climatological and parameter-driven and many are quite old. For instance, many of the forecasting models that the United States Department of Defense's 50th Weather Squadron uses to predict ionospheric radio wave and solar event propagation were developed between 1976 and 1982 [Lindsey, 1996]. Recent efforts have, however, been made to acquire new specification models such as the Magnetospheric Specification Model (MSM) developed at Rice University. These specification models are now in the process of being converted to forecasting models.

Research efforts to predict and characterise the space environment have been on-going for several years. A quick search of the Internet will yield many space environmental models developed from a variety of places. Some research efforts have been made to characterise solar flare propagation and model the interplanetary magnetic field [IZMEM : IZMIRAN Electro-Dynamic Model, University of Michigan, WWW]. However, the 50th Weather Squadron, for instance does not have any forecasting models for either of these [Scro, 1996]. Other research projects show great potential for transition into the space forecasting community to replace current systems such as the Lund Space Weather Model which makes use of a neural network to predict a geomagnetic storm index [The Lund Space Weather Programme, Lund University, WWW]. Operational benefits from this and other research efforts, however, have not yet been realised [National Space Weather Program, 1995].

Another problem today with space forecasting models is a lack of co-ordination between the models. Currently, models are run independently of each other and do not provide a cohesive picture. Future forecasting and specification models must include feedback loops to "couple" the models. Coupled models are necessary to provide a clear picture from the Sun to the Earth for the space forecaster [Scro, 1996].

8.3.2 Acquisition of New Models

Clearly, some work needs to be done with operational space environment forecasting models. First, we recommend that a comprehensive international study be performed to compare the effectiveness of current space environmental forecasting and specification models. While the NSWP calls for verification of new models, there is no independent agency today tasked with validating even the existing ones [Lindsey, 1996]. This study would provide a baseline determination of which space environmental forecasts are good and which ones need more work and will provide a mechanism for validating proposed models.

Currently, very little money is budgeted for acquisition of new models. The Space Environmental Centre, for instance, has personnel that develop new models and try to keep apprised of research models that may be of use to the operational community [Detman, 1996]. We recommend a new approach for model acquisition.

<u>A New Approach to Model Acquisition</u>

We envision a suite of co-ordinated industrial contracts be competed in the appropriate countries with consortia of universities for acquiring new space environment forecasting models.

The models competed for should provide data from the Sun to the Earth and be coupled. This will mean, for instance, that an electric current predicted in the magnetospheric model will be used as an input into the ionospheric model. The models should also employ first-order analytical methods as much as possible. Empirical modelling should be used where the physics is not well understood. The system should be easy to upgrade for incorporating new knowledge and using new measurements. Finally, some sort of neural network or other form of artificial intelligence will be needed to fuse the models into a cohesive unit that will provide meaningful forecasting information.

The consortium should consist of universities that represent the fields of study in the space environment. Universities that specialise in solar phenomena, magnetic fields, plasma propagation, the ionosphere, the magnetosphere along with modelling specialists should work together to develop the new models. We believe that models developed at the university level as opposed to commercially derived models will be the most cost-effective.

The industrial contracts should be independently planned but placed on an internationally co-ordinated milestone schedule and modestly funded initially by agencies that will want to use the models. These users would include the space forecasting and scientific communities. Future versions of the models will of course be more expensive and will provide increased accuracy. Requirements for the models should be established by the users, and in the case of space forecasting users, the customers of the users. Future models must provide the precise forecasting information that the affected customer needs.

8.3.3 Summary of Modelling Recommendations

- Perform a correlation study to determine the reliability of current forecasting and specification models so as to determine areas for improvement.
- Acquire new coupled, physics-based models that are easy to update by use of internationally independent but, co-ordinated university consortium industrial contracts.
- Derive requirements of new operational models through interaction with proposed users and affected customers.

8.4 Co-ordinate and Apply Science Data

From section 2.2.4 "Past, Current, and Planned Missions" we know there already exists a large amount of data related to solar activity. From chapter 5 "Objectives and Requirements" we know there is a wide range of science and application objectives. Any future direction in solar data observations should consider not only what data have been collected but also how those data have been analysed, for what purposes, and how they may be usefully integrated into future work in various fields. In this section we will describe the impetus for co-ordinating solar data and then discuss some possible means to achieve co-ordination.

8.4.1 Need and Opportunities for Co-ordinating Solar Data

It is interesting to note a conclusion made in 1970 (!) that

> the detail now being achieved in measurements of electron and proton distribution functions is remarkable, and indeed is beginning to strain our ability to absorb and comprehend the data [Manno and Page, 1970].

This quote highlights the old idea that information and data are not enough but that meaningful work requires comprehension. Also, consider the following :

> The SOHO observations, in conjunction with co-temporal observations from other space- and ground-based observations, would create a dataset of extensive coverage and variety. These data could then be used as constraints on theoretical models quantifying the physics of the large scale global corona. One such analysis has been proposed by Biesecker and Gibson in SOHO JOP 44 (for a full description see JOP044: Structure of the Solar Minimum Corona, WWW), which would provide a quantitative description of the global magnetic field - something that observations alone cannot establish. By combining theory and data we will gain a picture of the solar corona from the solar surface to the interplanetary medium. [JOP 044-199608.txt, WWW]

This reference goes on to describe the magnitude of such a proposal. The main point concerns the combination of information -- theory and data, space- and ground-based observations -- to achieve better understanding. The fields of solar physics, solar wind physics, magnetospheric physics and ionospheric physics have developed substantially using space-based observations. However, until recently, there has not been a concerted effort to integrate these fields [Akasofu, 1996]. One recent effort is the "Solar Information Center" at Stanford University [Solar Information Center home page, Stanford University, WWW] which itself claims to be "under prototype development and only exists in very rudimentary form." There is also the International Solar Energy Society (ISES) which co-ordinates data collection from 10 Regional Warning Centres (RWCs) throughout the world. Each RWC is funded by its host government for its own solar warning purposes but the data are also sent to the U.S. RWC in Boulder, Colorado which then collates them and issues world-wide warnings. Co-ordination of solar science data measurements, at a certain level, is also already achieved through the Inter Agency Consultative Group (IACG) [Johnson-Freese, 1992]. Also, "Solar physics data occupy a sizeable portion of NSSDC's archives" [Solar Physics at the NSSDC, WWW]. So, there appears to be decent co-ordination of *current* solar data *within* the solar-terrestrial science community. However, due to the wide range of global effects [section 4.5] there is the need to make solar data more easily accessible beyond the traditional solar related fields into the areas of climatology [section 4.5.1], sociology and medical research [section 4.5.2] and technology fields [section 4.5.3]. The co-ordination of solar data should also include those data from the past. It is obvious from the list of past and current missions [section 2.2.4] that careful organisation of the existing and incoming data is essential if we want to exploit these data to extract as much information as possible.

Much solar data are remotely-sensed observations of electromagnetic radiation, and therefore co-ordination opportunities are the classic ones faced by Earth remote-sensing observers :

- it is more efficient to avoid similar observation and acquire data from different temporal, spatial, and/or spectral areas,
- different temporal, spatial, and spectral observations can be combined to produce much more information than the sum of the three individually,
- existing and/or historical data sources may prove to be complementary to new data sources, and
- *in-situ* observations complement remotely sensed data.

Based on the above, the framework which has been set up through Earth observation networks can serve as a model for solar observations.

8.4.2 Means of Achieving Co-ordination

Perhaps the easiest suggestion and maybe most important, is to continue with ground based observations and ensure that these observations are accessible and, indeed integrated into the analysis of space-based observations. These data are already being collected and, through their longer history, provide solid foundational data [Hoffman *et al.*, 1996]. Any efforts to maintain co-ordination and accessibility of ground-based data should be encouraged. This will help support both science and applications objectives by providing Ground based observations which are virtually continuous and provide the low spatial resolution "big picture".

For a second suggestion, borrowing from Earth Observation, we suggest the publishing of a "Sun Observation Directory" similar to the "1995/96 Earth Observation Spacecraft Directory" [Matra Marconi, 1995] which is a pocket sized directory updated semi-annually. (We have left out the word "spacecraft" for the Sun observations booklet because we believe ground based observations should be included.) As markets increase for solar activity forecasting [chapter 7] and the scientific disciplines become more related [Akasofu, 1996] it will be helpful to have an up-to-date directory of solar observers. This inexpensive and relatively simple suggestion could prove very helpful in organising solar data sources, especially for those not from the traditional solar-terrestrial fields. This suggestion is most helpful for meeting those application objectives.

A third suggestion is to work to establish an "International Solar Data Centre" for both solar science and solar applications as well as other fields which may be interested in exploring solar data. From an international perspective we see the most efficient use of solar data is to have the data available to as many users as possible. Our suggestion is not that these data be provided free, but that there be an international data co-ordination effort -- not a data archive or storage facility but a catalogue-type facility that could connect the data users with data providers, the buyers with the sellers. We believe that this co-ordination would lead to better scientific studies as well as improved modelling for solar warning [section 8.3].

As an example from Earth Observation, a WWW Search for "Earth Observation Data Center" yielded eight possible URLs, one of which, as an example is Netherlands Earth Observation NETwork's Earth Observation Data Center, United Kingdom, which allows the user to browse on keyword and location [Earth Observation Data Centre home page, WWW]. However, a search for "Solar Observation Data" found no sites. It would be helpful to create a browse-able international network for past and current solar data. (This is similar to what Stanford University [Solar Information Center, Stanford university, WWW] has started to do.)

A fourth suggestion is to encourage researchers to investigate all possible data sources, including those from the past, and have those data sources be relatively easily accessible to the scientific communities (which, of course, would result from the realisation of the previous suggestion). We recommend agencies consider using grants and fellowships to initiate research which integrates various solar data, current and from previous missions, to provide new insight for existing questions - similar to the research discussed by [Akasofu, 1996]. This research would help maintain our ability to absorb and comprehend all of the existing and proposed solar-terrestrial data. We recommend this to be an international programme where the amount of funding in research grants and fellowships given in a participating country would be proportional to the amount of that country's contribution to the programme. This would increase international co-ordination as well as provide efficiency by having a common administrative unit.

Another example from Earth Observation is the North American Land Characterisation Program which has organised "triplicates" of remotely sensed imagery for the same area : one from the early 1970s, one from the early 1980s, and one from the early 1990s [North American Landscape Characterisation, WWW]. This type of "value added" data package allows the user to focus on the content and not the gathering of data. We believe that a "Solar Observation Data Center" could facilitate some initial data processing to produce enhanced data products.

A final suggestion for this section is to assume co-ordinated data access for future mission planning. While there is some risk in such an assumption, we trust that co-ordinated effort will always be most efficient. *Assuming* co-ordination in all future missions will more or less force co-ordination - because there will be no other choice! For solar-system space science, international collaboration "has been outstanding" and "is a given"[Rahe, 1996]. Solar science and solar-terrestrial science would be wise to follow this example. Working toward, and then assuming, international co-ordination will help achieve observations from as many temporal, spatial, and spectral areas as possible.

8.4.3 Summary of Recommendations on Co-ordination

The near-term recommendation for data co-ordination can be summarised as :

- continue with ground based observations,
- publish a "Sun Observation Directory"(pocket-sized),
- develop an international data centre,
- provide support for research which co-ordinates scientific data, and
- assume data co-ordination in future planning.

8.5 The Near-Term Role of the Working Group for International Solar Exploration & Application (WG ISEA)

The WG ISEA is a recommended framework to act as an international forum for the planning, co-ordination, and implementation of an international effort in solar exploration and applications. To do this, the WG ISEA is structured to incorporate representation from both government and private sector space science and applications interests as they pertain to the Ra Strategic Framework [section 3.2]. The changing global paradigm for space science and applications points to the advisability of combining resources across both national boundaries and science vs. applications disciplines. The Ra team believes that the WG ISEA represents the most efficient and expedient organisational form to enable this merger for the benefit of international solar study efforts. Specific recommendations for action from the WG ISEA to its member agencies should form the basis for an international collaborative effort in solar exploration and applications.

The Ra report follows a phased approach in which each subsequent period builds on the one before it. It is important, then, that the multi-lateral planning, co-ordination, and implementation effort *begins immediately*. While in the near-term Ra recommends no new flights (save for Cluster recovery) the *need for the WG ISEA is immediate* for a variety of factors :

- Multi-lateral co-ordination of data sets from current spacecraft and projects such as they pertain to Ra is needed (such as appropriate military satellite data sets as Ra recommends)

- Mid-Term Mission Scenarios require advance planning and budgetary designations in space agency funding cycles. It is necessary for the WG ISEA to submit its findings and programmatic recommendations to agencies before the budgetary cycles for the target years are "locked in."
- The culmination of the ISTP, combined with NASA's Sun-Earth Connections Roadmap planning make the present a unique period in space science for solar and Heliospheric physics and applications--a uniqueness of which Ra and the WG ISEA should take advantage. In order to maximise its influence on this period, the WG ISEA should be formed and active before NASA's planned Woods Hole meeting in the summer of 1997 [SECAS Roadmap Planning, WWW].

8.6 Increasing Awareness

Clearly the Sun is the most obvious celestial body. In any society, developed or developing, people can identify the Sun. Many people enjoy the peaceful and wonderful experience of watching a sunrise or sunset. Yet the dynamics of the Sun are not very apparent when one sits on a beach. Most people have the opinion that the Sun is a relatively stable fiery ball far away from the Earth. While it is generally obvious that Earth receives heat and light from the Sun, solar physics beyond the photosphere (for example, CMEs and the intermixed Sun and Earth electromagnetic fields) are not yet part of what we could call "common knowledge," even in more developed societies. Perhaps more interesting is that the dramatic effects of the Sun and their interactions with each other and with satellites are not well understood *even within the space community* [Worden, 1996]. In this section we will discuss why it is essential to increase understanding of solar dynamics. We continue by offering some suggestions on how to increase this understanding.

8.6.1 Need for Increased Awareness of Solar Physics

The Sun makes an excellent case for the complexity of nature and the nature of science; different observations provide new clues to help our understanding and the phenomenon is certainly more involved than what is apparent from what we see every day. What could be a more effective and interesting way to explain the range of the electromagnetic spectrum as well as the complexity of solar activity than to display X-ray and ultraviolet images of the Sun? [See most any of the solar-related WWW sites; Lang and Kenneth, 1995; or Beatty and Chaikin, 1990, p.25]. Indeed this is why we, the Ra team, chose to use on the cover of this report an image of the Sun taken by an eye never before possessed by humans, the SOHO Extreme Ultraviolet Imaging Telescope. As the solar-related fields continue to grow with new observations and new theory, humanity too can grow by sharing in the complex and amazing knowledge of our Sun.

8.6.1.1 Need for Increasing General Public Awareness

Most space exploration and science is publicly funded. The public tends not to want to pay for something it knows nothing about. Space programmes must now realise that "good science" is not enough to keep a programme funded [Randolph, 1996]. Currently budget constraints require space agencies to pick and choose programmes carefully. Any programme needs to justify its spending, not just to scientists in the field but also to politicians and to the general public. This implies a need for communicating the importance and relevance of space programmes in common language.

Not only do space programmes need to justify their budgets but also they should spark the interest of the public as well as share the importance of their findings. Science,

technology, and space exploration affect all humanity : they help set our course for the future and reflect the general human endeavour to explore. So, whether it is to work together to plan the future, to share in the excitement of new findings, or to understand how tax money is being spent, as much of society as possible should be aware of advances in space exploration, science, and technology.

8.6.1.2 Opportunities in Education

We consider educational opportunities a strong component for increasing public awareness and involvement with space exploration. Space is an inspirational tool for science and mathematics education [ESA SP-384, 1995]. Also, as discussed in section 4.1, we know there is a social component to our explorations, and from chapter 3 there are related policy issues. It is the many facets of space exploration which make it an excellent resource to motivate students of all ages. This need has been well recognised and incorporated into the outreach programme accompanying the IMAGE spacecraft, approved in 1996, which states :

> The IMAGE Mission Team will be involved in a program of Public Outreach, Education, Teaching, and Reaching Youth : a program we call POETRY. IMAGE will produce spectacular images representing the plasma environment of the Earth. These images will not only allow the IMAGE investigators to understand the physics of the magnetosphere, but will entice the public, students, and teachers into learning more about the fascinating and complex processes that surround the Earth. [The IMAGE Mission : Imager for Magnetopause-to-Aurora Global Exploration, WWW]

8.6.1.4 Opportunities for Sun - Earth Interaction Awareness

Everyone connected to space exploration should, at the very least, be aware of the effects of solar activity on spacecraft [section 5.2]. One-half to three-fourths of anomalies in satellite behaviour are correlated with space environmental disturbances [Worden, 1996]. It is impossible to say whether the space environment has caused these anomalies because, at present, there has not been substantial research in the literature which established a correlation between solar activity and spacecraft malfunction. There is little connection between the government solar warning services and their users. So what if my satellite or power line or pipeline is hit by a geomagnetic storm? Does anyone know what I should do about it? At the present time, not really. There are some attempts to develop operational models for various users to instruct them on what to do when certain dangerous phenomena occur but they are far from complete. Satellites are certainly not designed with these phenomena in mind. There exists a weak link that must be improved between warning services and users.

8.6.2 Means of Increasing Awareness

Reflecting some of the different opportunities described in the previous section, we now offer some recommendations to increase awareness.

(See [ESA SP-384, 1995] for a general approach to communicate space agency activity to society.)

8.6.2.1 Awareness for the General Public

Scientists should be either encouraged or required to make at least the essence of their findings available and accessible to the general public. A "requirement" would probably be met with reluctance or even strong resistance. The best direction to take is probably a "strong encouragement". As an example, funding agencies could suggest that each technical proposal and research report derived from work sponsored by that agency be

accompanied by a *simplified* document (of the size of one to two pages), written in common language, which relays the interesting and/or fundamental elements of the research. This is similar to a press release, but at a micro scale for any research activity and research report. It should be possible to describe even complex scientific issues in common language. Having scientists do so will give space agencies baseline information to share with educators, museums, the media, and to publish on the WWW. It would also address the need for standardisation on certain scientific terms referring to different solar and space weather phenomena and regions of interaction.

To fully emphasise the importance of public outreach, funding agencies (national space agencies, in addition to granting organisations such as the National Science Foundation in the United States) should tie promotion opportunities, grant requirements, etc., into a scientist's (and other space activities participants') public outreach performance and plans. The key word here is *performance*, versus mere effort. It should be a responsibility of scientists in space activities to pro-actively address public outreach and education, and this means improving their public communications. We are not proposing that this become an ultimate determinant of funding availability and/or promotion opportunity, but one of the considerations taken in account in the decision-making process. The objective is to make space activity participants aware of the importance of public outreach in their field.

8.6.2.2 Awareness through Educational Programmes

The WWW is perhaps the best way for space agencies to communicate with the education world. We believe child orientated web sites (with accompanying information and training packages for instructors) offer an effective way to communicate the ever-growing body of scientific knowledge. There are several exemplary Internet-based programmes within NASA, namely the "Observatorium" [NASA Remote Sensing Public Access Center - NASA Observatorium, WWW], the "Solar Connections" educational page (Solar Connections, WWW), and "SpaceLink" [NASA Spacelink - An electronic information system for educators, WWW]. However, web sites alone are not enough to motivate school children. We believe that space agencies, as well as commercial educational materials programmes, should continue to play a role in educational programmes. We would encourage not only the production of various educational materials but also working with teachers through the WWW, video productions, and teacher workshops. Planetaria are a useful location for outreach and educational programmes. Of course, any of these could go beyond solar science and address space exploration in general.

A possibility, although perhaps more appropriate for the Mid- or Far-Term Programmes, is a relatively cheap satellite bus for solar research. The bus could be purchased by universities and research institutions and be used to enable students to do their own solar experiments.

We applaud the plans like that described for the IMAGINE programme and encourage educational programmes to be included in all space science mission plans -- near-, mid-, and far-term.

8.6.2.3 Awareness of Sun - Earth Interactions

It seems that the best opportunity to educate the space community and power companies is through a correlation study which aims to relate satellite malfunction with solar activity. If, indeed, these are found to be related it would become clear to those involved that it is in their interest to learn more about the effect of solar activity on their space

vehicles and, then, work to develop both operational procedure and future engineering developments which could reduce or avoid damage.

We propose a joint international research initiative between space/government agencies, military organisations, satellite producers, satellite communications industry, and power companies. Using this mix of public and private organisations, each could independently contribute small amounts of money, people, and other resources. By utilizing resources from those directly involved is positive in that they have a vested interest in the study. However, there is also the chance for each to have its own bias created by self interest. With this, it would be wise to invite outside consultants. The space agencies can play the role of organising the study and disseminating the results. The space/government agencies and military organisations can provide data (primarily on solar activity) and expertise. The satellite producers, communications industry, and power companies would also contribute data (primarily on anomalies) and expertise as well as direct the study, through consensus, to address their needs. Outside consultants would be comprised of a team which, collectively, had knowledge of solar-terrestrial physics, possible effects on satellites and power sources, and sufficient statistical background to conduct a time-series correlation study [Detman and Vassiliadis, *in press*]. It would be informative to look at the anomalies with respect to the damage (if there was any) in terms of cost. Any significant relationship should prove interesting and educational.

8.6.3 Summary of Recommendations on Awareness

The near-term recommendation for increasing awareness can be summarised as

- requesting and organising "common language" summaries for science reports, and making public outreach performance and plans an evaluation tool in funding and promotion determinations,
- space agencies, and possibly commercial educational resources, working with educators through the WWW, video productions, and workshops,
- a correlation study on satellite anomalies and solar activity.

8.7 Actively Incorporate Existing Technology Initiatives

We believe that in the near-term, and through the far-term, technology development should follow the "faster, cheaper, better" approach because doing things "slower, more expensive, and worse" would be wrong. (But seriously...)

A growing international trend that has emerged during the recent years, is a push for "faster, cheaper, better" (or some other permutation of that order) space programmes - both civilian and military. The forces driving this change are mainly the pressures of declining budgets in the post-Cold War environment, the emphasis on reduced programme risks, the emergence of advanced lightweight technologies, and the development of low-cost, small launch vehicles.

We believe that the Ra programme, from the start, should incorporate this technological philosophy. Smaller satellites mean simpler design, smaller launchers, smaller management organisations, shorter development time, and hence cheaper and ultimately more missions. With faster missions, there is greater opportunity for the incorporation of state-of-the-art technologies, and there can be an improvement in technology based on the flight results. In addition, if the mission development time is short (i.e. not a decade like previous spacecraft development times), participants can be involved in all phases of the mission, and personnel morale can be maintained.

The "faster, cheaper, better" paradigm has proven to be a successful one in securing government funding, and is espoused by NASA, ESA, and elements of the U.S. military space programme. Recent and current examples such as the Clementine and DC-X programmes demonstrate the utility of this approach in achieving results, and NASA is basing its New Millennium missions on this approach.

Of course, there are arguments that "small" may not necessarily be synonymous with "cheap". There are two categories of "small" :

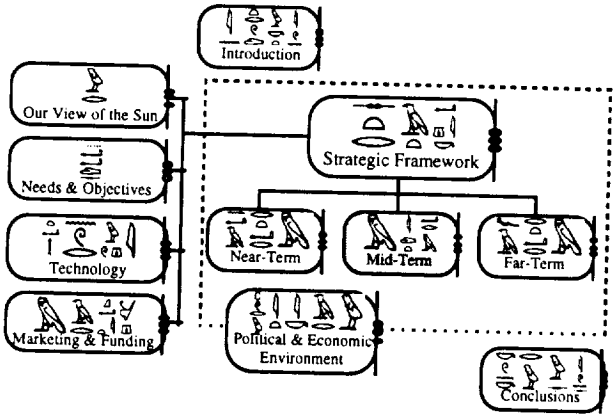
1. simple spacecraft with fewer functions based on a standardised bus and off-the-shelf components with minimum performance,
2. the miniaturisation of conventional components using new technology with high performance in mind.

The latter approach is more costly, but there is increasing interaction between the military sector that tends to favour approach second within the civilian sector. Hence, technology transfer is something that must be encouraged to continue, so that the civilian sector can take advantage of more performance oriented technologies. In summary, the advantages of the "faster, cheaper, better" approach are numerous, and given that this current paradigm has been and is successful, the Ra programme must foster, encourage, and incorporate this philosophy from the very beginning.

8.8 Conclusions

We believe the recommendations are realistic and play an important role in realising important science and applications objectives. They also provide a foundation for the programmes described in the Mid- and Far-Term components of the Ra Strategic Framework.

Chapter 9



Mid-Term Programme

The Mid-Term part of the Ra Strategic Framework comprises a number of suggestions, including a solar monitoring and early warning system, a pure applications mission, as well as a dedicated science mission to study the Sun from 0.2 AU.

9.1 The SAUNA Mission

The SAUNA (*Solar Adjacency Using a New Approach*) Mission is a new system to perform solar science in a low solar orbit over a time span of several years. Unlike e.g. the FIRE mission, SAUNA does not attempt a single flyby inside of the corona. Instead, the SAUNA spacecraft will go as close as requirements for a multi-year lifetime allow.

The SAUNA mission thereby also serves as a demonstrator for the constellation of spacecraft to monitor the solar environment in this region, as described in chapter 10 (Far-Term).

We have endeavoured to make this mission politically acceptable by designing to a US$ 200 million Life Cycle Cost and by applying no controversial technologies like Radioisotope Thermoelectric Generators (RTGs).

9.1.1 Design Procedure

The SAUNA design has evolved through the following process:

- Mission requirements definition
  - Mission feasibility: Trajectory and propulsion studies
  - Establishment of preliminary budgets
  - Spacecraft configuration trade-offs
  - Subsystem design and sizing

The work was fast-paced, of a parallel and interactive nature.

9.1.2 System Architecture

This section describes the system architecture of the SAUNA mission.

9.1.2.1 Mission Objectives

The SAUNA mission will perform *in situ* scientific measurements from a near Sun orbit. The scientific measurements will focus primarily on studying the solar wind and the Sun's corona and secondarily on studying interplanetary dust. Finally the mission will prove the survivability of a spacecraft in a near Sun orbit. This last objective is regarded as primary.

The study of the solar wind will be focused on analysing the solar plasma and measuring the Sun's magnetic field. For studying the Sun's corona the Sun's photosphere and chromosphere will be studied in extreme ultraviolet, energetic particles will be detected, and solar eruptions and coronal structures will be imaged. Interplanetary dust will be studied during the transfer from Earth orbit to Sun orbit. These objectives will be further discussed in 9.1.4.

Survivability in a near Sun orbit will be considered proven if the spacecraft provides protection against the solar environment to the extent that the payload remains operational during the required mission lifetime. Protection against the solar environment in this context includes maintaining a proper orbit and attitude, a thermal environment in which the spacecraft systems can operate, a communications link to Earth that enables a specified data volume and flow, etc. If for instance an instrument is destroyed by an impacting meteorite (a generic threat in space and an unavoidable risk for exposed instruments), this would not mean that the survivability objective is not met.

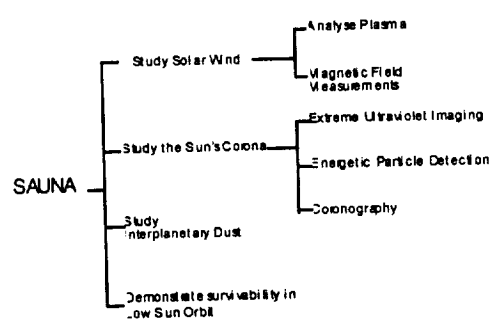


Fig. 9.1 Overview of SAUNA Mission Objectives

9.1.2.2 Mission Constraints

While being in Sun orbit, the SAUNA spacecraft will be operational for a minimum of three years. Furthermore the study of interplanetary dust, which is a secondary mission objective, may not interfere with any of the primary mission objectives. Finally the total mission life cycle cost shall not exceed US$ 200 million. For the total mission life cycle cost scientific analysis of the data is not taken into account.

9.1.2.3 Functional Analysis

Figure 9.2 shows the top level functions for the SAUNA mission as depicted in a Functional Flow Block Diagram.

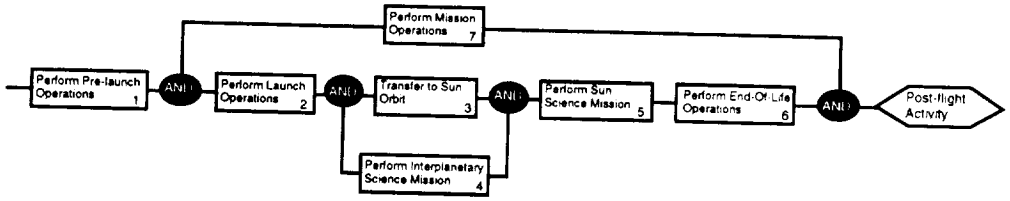


Fig. 9.2: Functional Flow Block Diagram for the SAUNA Mission

In this figure 'Perform Sun Science Mission' refers to the study of the solar wind and the Sun's corona whereas 'Perform Interplanetary Science Mission' refers to the study of interplanetary dust.

For the SAUNA mission the following top-level functional requirements were identified:

- The SAUNA spacecraft shall be accelerated beyond Earth escape velocity
- The SAUNA spacecraft shall be transferred to a near Sun orbit
- The SAUNA spacecraft shall study interplanetary dust during the transfer to a near Sun orbit
- The SAUNA spacecraft shall establish an orbit around the Sun
- The SAUNA spacecraft shall study the solar wind during its stay in Sun orbit
- The SAUNA spacecraft shall study the Sun's corona during its stay in Sun orbit
- The SAUNA spacecraft shall provide an operational environment during the mission lifetime

9.1.3 Mission Design and Spacecraft Configuration

In the following we shall discuss mission design, spacecraft configuration studies and their outcomes.

9.1.3.1 Mission Design

The focus of the mission design work was to define a low solar orbit and a transfer trajectory to that orbit able to fulfil the mission objectives. As an input to these problems the following factors were considered:

<u>Target Orbit:</u>

- The mean distance from the Sun would have to be small enough to be interesting from a scientific standpoint, yet large enough to sustain an extended life (thermal and radiation environment)
- The orbit would have to be attainable for a small spacecraft using presently or near-term available propulsion technology
- The cost of getting there and staying there must be balanced against the cost constraints of the mission.

Transfer Trajectory:

- The transit time should not exceed the time spent in final orbit
- The selected trajectory should not put extreme constraints on the deliverable dry mass
- The propulsion technology and performance required should be available in the near future.
- The injection conditions required should not lead to extremely high launch costs or assume the use of currently unavailable launch systems.

Initial trajectory studies quickly led to the dismissal of chemical propulsion for the transfer orbit due to the low I_{sp}, leading to a very small mass fraction. The circularisation of an orbit near the Sun requires a significant Δv which proved to be a very difficult condition to meet. Solar sailing was excluded as an option due to the immature status of this technology.

We selected ion propulsion, as this technology best covered our mission needs. The high I_{sp} and low thrust leads to a high mass fraction and (relatively) long trip times. Using an ion engine with 0.2 N thrust and an I_{sp} of 4700 s [section 9.1.5], we assumed an initial wet mass of our spacecraft of 300 kg and arrived at a feasible trajectory to a 0.2 AU circular orbit [figure 9.3], by using the SKYNAV optimisation software [Appendix C].

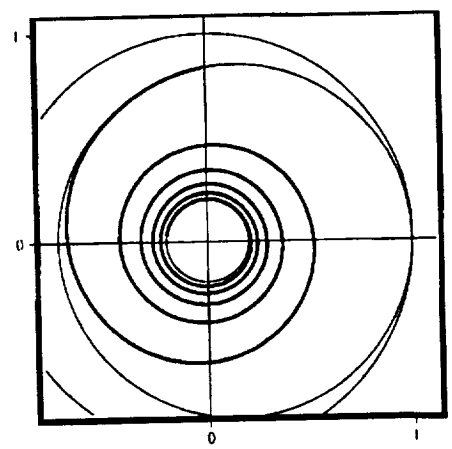


Fig. 9.3: Low Thrust Trajectory from 1.0 AU to 0.2 AU Circular Orbit: In Bold Lines is the Thrusting Phase of the Trajectory.

The total transfer duration is 507 days of which the first 90 days are spent coasting on a Venus transfer trajectory (this requires a launch energy of at least $C_3 = 15\ km^2/s^2$). The rest of the transfer is a continuously thrusting manoeuvre. The transfer time, although long, does not exceed the minimum survival time expected of the spacecraft in orbit. Furthermore, we have not included the effects of a Venus gravity assist in the above result.

We do not pretend to have an optimal solution to the selection criteria described above, but this trajectory does meet all the requirements.

9.1.3.2 Spacecraft Configuration

The ion engine considered consumes 6.3 kW of power at nominal thrust; we decided that solar arrays would be the most suitable source to provide this power [sections 9.1.6 and 6.5].

Having established a mission scenario, a propulsion system and associated power system, we set out to design a spacecraft to go with it. The configuration selection proved a difficult problem due to the following conflicting requirements:

- The spacecraft must be provided with a heat shield to protect against the thermal and radiation environment close to the Sun.
- The solar arrays must be sized to provide the required power throughout the transfer trajectory and when in orbit, while the solar energy flux density increases by a factor 25 from 1 AU to 0.2 AU.
- When near the Sun, the solar array must be protected from the heat to prevent an excessive rate of degradation and to ensure that the bonding of the solar cells is not compromised.
- The ion engine must be located on the forward part of the spacecraft to provide the retrograde (braking) Δv.
- The high gain antenna must be pointed towards the Earth for high data rate transmission.

Note that no payload requirements were included in the considerations above (e.g. FOV or pointing of the instruments) as it was determined that workaround solutions for instruments could be found in most cases. This harmonises with the idea that SAUNA is to be a general purpose solar orbiter with no strong optimisation towards the payload requirements.

Choice of Stabilisation

Three types of stabilisation principles were evaluated for SAUNA: Three-axis stabilisation, spin stabilisation and solar pressure stabilisation. Whereas the two first principles are well-known, the latter is an untried idea [Sirinian, 1974] and was deselected due to the technical and programmatic risks involved. For 3-axis stabilisation versus spin, table 9.1 was used for evaluation:

Table 9.1 Evaluating 3-Axis vs. Spin Stabilisation.

Type of Stabilisation	Propul	Power	Thermal	GNC	Comm	Instrum	System
Three-axis	0	+	0	0	+	0	+
Spin	0	-	0	+	-	0	0

The choice fell on 3-axis stabilisation mainly due to a consensus that the disadvantages could be more easily overcome than those of spin stabilisation, especially with regards to the pointing requirements described above.

Selected Configuration

After having considered various concepts, we decided that the design shown in figure 9.4 would best meet all requirements for pointing with a minimum of moving parts. A

central enclosure accommodates the propellant tank, batteries, avionics, instrument support electronics and the computer systems. This structure supports on its sunward side a "dislocated wedge" consisting of a tilted flat solar array (upper side) and a tilted flat heat shield (lower side). An articulated high-gain antenna is mounted on the side pointing away from the Sun. The ion engine is mounted on the forward (velocity vector) side of the spacecraft.

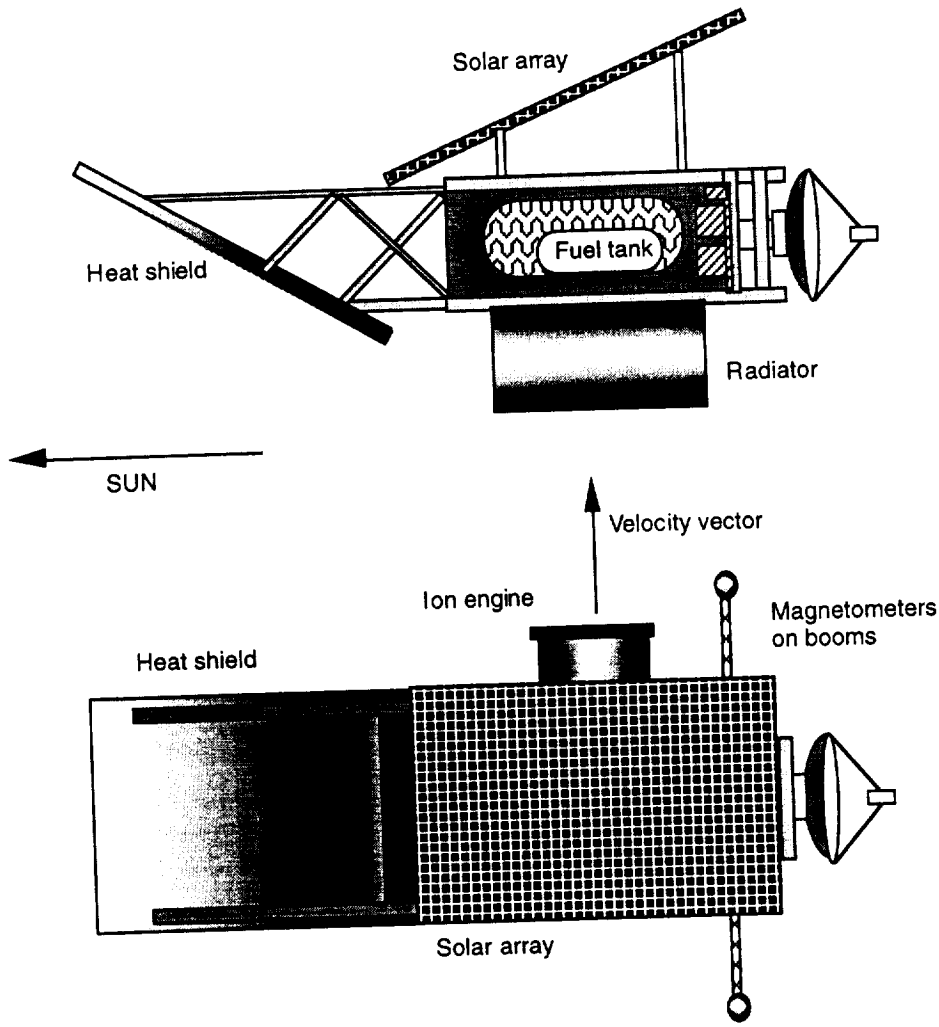


Fig. 9.4 SAUNA Spacecraft - Selected Configuration

Instruments can be accommodated on booms or on the main structure depending on their purpose. Imaging instruments may use a pinhole in the heat shield to peek at the Sun.

The functional concept of this spacecraft is very simple: When far away from the Sun, optimal pointing of the solar array is necessary to provide the full power to the ion engine. This can be achieved by rolling over so that the array is perpendicular to the incoming radiation. As the spacecraft approaches the Sun, the solar energy flux increases inversely proportional to the radial distance squared. This has two effects: (1) The temperature increases, and (2) the electric power generated by the solar array increases (until degradation of the cells due to high temperature sets in). By gradually slewing back to zero degree roll angle, the spacecraft simultaneously increases its thermal protection from the heat shield and ensures a bounded power output from the solar array. Figure 9.5 illustrates this concept:

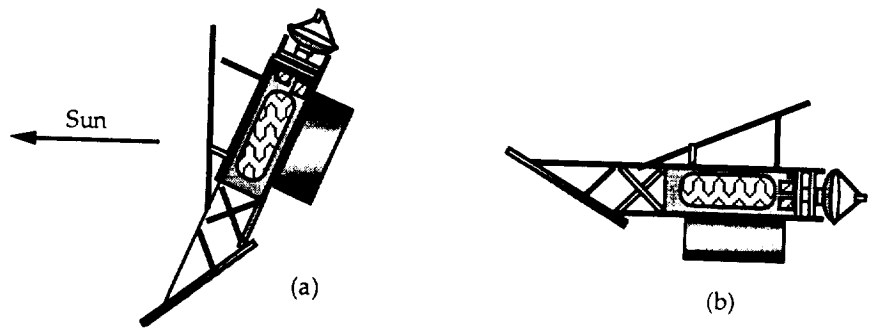


Fig. 9.5 Spacecraft Orientation (a) Far From the Sun, (b) Close to the Sun

The ion engine's thrust axis intersects the spacecraft centre of mass, somewhere in the middle of the propellant tank. The spacecraft can be pitched (i.e. around the radial vector of the Sun) without changing the articulation of solar array and heat shield. This feature allows the thrust to be directed in a number of ways, enabling e.g. orbit inclination changes. This principle is illustrated in figure 9.6:

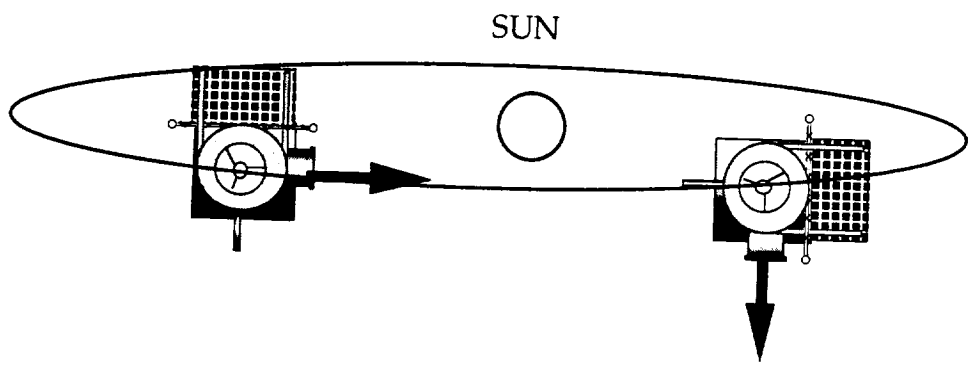


Fig. 9.6 The Thrust Axis Can Be Pitched To Provide Out-of-Plane Δv.

Launcher Considerations

Assuming a wet mass of 300 kg allows a launch to a high-energy Venus transfer orbit on e.g. a Delta II (7925) or a Zenit-3 type vehicle. The solar array, the high gain antenna and various instrument booms will have to be deployable in order to stow the spacecraft into the launch vehicle fairing.

9.1.4 Science and Payload

This section describes the science background and instrumentation payload of SAUNA.

9.1.4.1 SAUNA Science Background

The SAUNA mission aims to study the Sun using both *in situ* and remote sensing measurements, from a moderately close equatorial heliocentric orbit, at about 0.2 AU. The remote sensing payload, comprising a coronograph and an EUV spectroscope, will provide long-term observations of the Sun at high spatial, temporal and spectral resolution. The improvement in resolution will be achieved through a combination of the proximity to the Sun and improvements in instrument technology over previous

missions. *In situ* measurements will provide information on the behaviour of the solar wind in a region not previously studied over such a long period. The mission will improve our understanding of the physical processes at the surface of the Sun (especially magnetohydrodynamics), and act as a pathfinder for subsequent, more ambitious missions. Transient events will be studied as well as the "quiet" Sun. Measurements from SAUNA will be combined with those from spacecraft in the vicinity of the Earth to obtain stereoscopic and contextual information.

This data set will be extremely useful for solar physicists. Increased understanding of complex magnetohydrodynamics is a requirement for applications on Earth such as nuclear fusion reactors, as well as the modelling and prediction of solar processes which affect the Earth.

9.1.4.2 SAUNA Instrument Package

The payload of a Sun monitoring spacecraft placed on 0.2 AU orbit should include, at least, a white light coronograph and a EUV imaging spectrometer. From the review of these instruments in chapter 6.2 we can conclude that none of the existing instruments are relevant for SAUNA spacecraft. Russian Plamya instruments are separate and hence weigh too much. French COI is also too heavy (partly because it uses obsolete linear CCD instead of matrix CCD). The JPL instrument is designed in accordance with minimal requirements and hence has low performance. Probably, a new integrated instrument will have to be created. Based on the general ideas of the JPL instrument, its design must be improved to increase angular resolution and general reliability to provide longer life time (it will cause increase of weight).

To monitor off-nadir regions of the Sun, it would be very desirable to have a pointing sub-system to aim the high resolution equipment to areas of particular interest (may be based on measurements from a low resolution channel of the instrument). It might be possible to implement this idea by a rotatable mirror on a retractable boom, peeking around the heat shield.

The estimated characteristics of the considered instrument are based on the enumerated instruments as well as peculiarities of the SAUNA orbit:

- Visible light coronograph: 10° FOV
- Ultraviolet:
  1) 4° FOV - to monitor the solar limb
  2) $\leq$ 0.5° FOV - to monitor specific areas on the solar surface with high resolution benefiting from close proximity to the Sun.

Such an instrument would consume 5-10 W of power, weigh 6-7 kg, produce an average data rate of 5-10 kbps and cost roughly US$ 10 million.

A plasma analyser and vector magnetograph can be also very useful for the SAUNA mission. Unfortunately, conventional versions of these instruments presently have relatively high mass and can not fit into the stringent mass budget of SAUNA. A miniature plasma package, as proposed in response to current NASA and ESA study requests, could meet SAUNA requirements [NASA Research Announcement, 1995]

We conclude that the SAUNA mission will carry an optical/EUV imaging package and a miniature plasma package for its Sun-orbiting phase plus a dust detector for measurements during the transfer trajectory phase. The total weight and power of the instruments will be of the order 15 kg / 40 W.

9.1.5 The Propulsion System

In the following we describe the propulsion system, with emphasis on the main engine and the attitude control engines.

9.1.5.1 Main Engine

As mentioned in the mission design section, we selected a high thrust ion propulsion engine. This engine has a real-life counterpart: The UK-25E thruster [Latham *et al.*, 1995], which exists as an engineering model but has yet to be flight qualified. Its high specific impulse provides a good mass ratio and saves propellant.

Table 9.2 UK-25E thruster [Latham *et al.*, 1995]

Nominal Thrust	Total Power	Electrical Efficiency	Propellant	Operating temperature	Specific Impulse
206 mN	6300 W	89%	Xenon	350 K	4680 s

The thruster has a design lifetime of 10,000 hours (converting by coincidence to the exact time of thrusting for our selected transfer trajectory). It has a mass of 20.6 kg and will cost approximately US$ 200,000 [Martin, 1996].

Problems

- The engine has to be qualified for at least 10,000 hours continuous thrust
- The frontal engine mounting leads to plasma backflow during thrusting phases (potentially damaging to solar array and instruments)

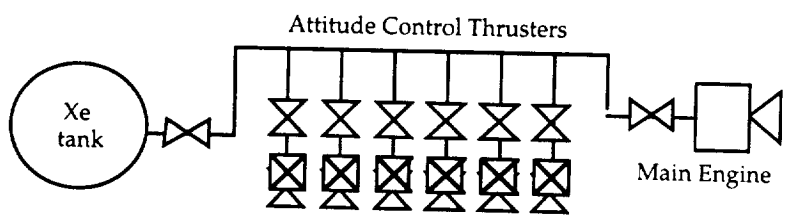


Fig. 9.7 Propulsion System Layout

9.1.5.2 Attitude Control Engines

For this purpose we need 6 small thrusters (required for 3-axis stabilisation) [Larson & Wertz, 1992]. They will also be ion engines which use the same main tank for their fuel. This saves mass as compared to separate systems for attitude control and main propulsion [figure 9.7].

9.1.6 Power Systems

Table 9.3 Solar Arrays [Larson and Wertz, 1992]

Source	Efficiency	Required power	Array size	Problems	Counter-measures
GaAs Solar arrays	19 %	7 kW (incl. 10% margin and all sub-systems)	14 m^2	Temperature at the Sun - bonding of the arrays	Tilt arrays
				Degradation	Balance losses and increased solar flux

The solar array consists of a single fixed tilted solar array which can be oriented towards the Sun by rotating the spacecraft. We did not make a choice of batteries and power regulation system.

Suitable high temperature bonding agents will be used in the development of the solar array.

9.1.7 Spacecraft Structure

The precise geometry, size, materials and mass of the SAUNA spacecraft structure have not been defined. The primary structure might be made mostly of Titanium alloy; ceramics would be used for those elements most exposed to heating (e.g. heat shield support structure).

Critical problems include the moving parts such as deployment mechanisms for the solar array and the antenna. Very high reliability will be required, and this increases development costs substantially. Continuously moving parts and rotating joints such as the antenna pointing mechanism will require special lubrication and tribological measures to avoid cold welding and potential malfunctions.

The spacecraft structure as a whole must withstand the loads and vibrations induced by the launch vehicle. Corrosion induced by the ion engine plasma may have to be counteracted by special measures.

9.1.8 Thermal Control System

In this section the thermal control of the SAUNA spacecraft is discussed. Special attention is given to the heat shield and the thermal control of the instruments and ion thruster.

9.1.8.1 Thermal Environment and Requirements

When the SAUNA spacecraft is in its target orbit, the distance between the Sun and the spacecraft will be 0.2 AU. The heat flux of the Sun is therefore $(1/0.2)^2$=25 times higher than at Earth. Moreover, due to the solar wind (the flux of particles ejected by the Sun) the frontal surface, which is always pointing at the Sun, is continuously subjected to particles.

We consider only the heat input by the Sun and by the spacecraft systems (a really close encounter with Mercury is not likely). The thermal production of the spacecraft consists of two main contributors:

- The instruments, communications system and the on-board computer, which dissipate in total approximately 100 W.
- The ion thruster system of 6.3 kW, which dissipates (Worst Case) 1.8 kW of heat (with special requirements for propellant tanks and batteries).

The temperature requirements for the spacecraft components are listed in table 9.4:

Table 9.4 Thermal Requirements for the Components

Component	Temperature Range (°C)
Electronics and Science Instruments	-20...60
Batteries	5...20
Ion Propulsion	300...400
Xenon Propellant	>20 at >125 bar
Structures	-45...65

Comparing the temperature requirements and the dissipation, it is clear that the thermal control system must be divided into two systems., one which takes care of the low dissipation sensitive instruments and electronics and one which takes care of the 1.8 kW heat dissipated by the ion thruster system.

9.1.8.2 Thermal configuration

The solar radiation (at 0.2 AU) is a flux of about 34 kWm^{-2} [section 6.7]; using a heat shield reduces the impact of this radiation on the spacecraft. Moreover, it can protect the spacecraft from the solar wind. Various materials can be used for the heat shield. However, Carbon-Carbon is up to now the most promising candidate [section 6.7]. It is a well known material (for temperatures below 2000 K) and it has a solar absorption and emission coefficient which is, comparing with other candidate materials, insensitive to the impact of UV-radiation and solar wind. It is expected that the outgassing of a carbon-carbon heat shield is not a problem because:

- The solar wind will interact with the outgassing atoms and therefore cleans the surroundings of the spacecraft. This reduces the danger of accumulating gases surrounding the spacecraft.
- The outgassing rate reduces with an order of magnitude for every 100 K and the outgassing rate is about 2 mgs^{-1} [Millard, 1992] for a temperature of 2000 K. Thus it is expected that for a temperature of 600 K the outgassing rate is worst case 2×10^{-10} mgs^{-1}. Taking in consideration that the total time near the Sun for SAUNA (3 year) is about 2000 times longer than for the Solar Probe [Randolph, 1996], at first hand, it is expected that the outgassing phenomena will not have an influence on the plasma measurements.

To reduce the heat flux from the Sun further, a standard multilayer insulation (MLI) (ε_{eff} = 0.015) is located between the heat shield and the instruments. The dissipated heat of the ion thruster is transported to radiators which radiate the heat into deep space. By using a two-phase heat transport system, the temperature difference between the ion thruster and the radiator is kept small. Therefore, the radiators can work at high temperatures, which reduces the needed surface and mass compared to other methods (conduction, fluid cooling loop).

9.1.8.3 Heat Balance

In this section, a simple heat balance (steady state), for an orbiting spacecraft, is used to determine the properties of the thermal control system. It is assumed that:

- The heat shield is always pointed at the Sun providing shade for the whole spacecraft.
- The thermal controls of the ion propulsion system and the instruments are separate and independent.

The heat balance equation [eqn. 9.1] does not directly include solar radiation but uses the temperature of the side of the heat shield radiating to the MLI as a boundary condition.

Instruments, spacecraft systems, and heaters are modelled in a box with one heat output value, one temperature on the outside of the box and one emittance value. The equation is analogous for the ion engine (in the box) and its radiator.

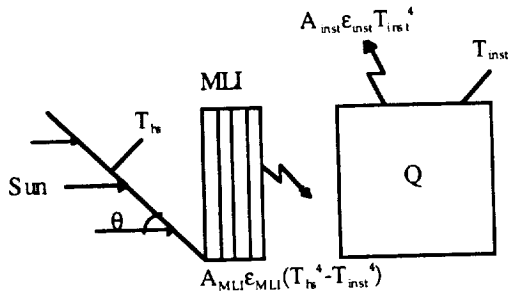


Fig. 9.8 **Thermal Model of Heat Shield, MLI, and Instruments**

$$A_{MLI}\varepsilon_{MLI}\sigma\left(T_{hs}^4 - T_{rad}^4\right) + Q = A_{rad}\varepsilon_{rad}\sigma T_{rad}^4 \tag{9.1}$$

where:

A [m²]	surface area (for MLIs: surface directly facing the heat shield)
ε	emittance (for MLIs: overall effective emittance)
(= 5.669×10⁻⁸ W/(m²K⁴)	Stefan-Boltzmann constant
Q [W]	power expressed as heat flux
T [K]	temperature
hs	heat shield
rad	radiation to deep space

General		Instruments		Ion thruster	
A_{MLI}	= 1.5 m^2	A_{rad}	= 2 m^2	A_{rad}	= 1 m^2
ε_{MLI}	= 0.015	ε_{rad}	= 0.15	ε_{rad}	= 0.8
T_{hs}	= 600 K				

Figure 9.9 shows the temperature of the instruments for various dissipation powers.

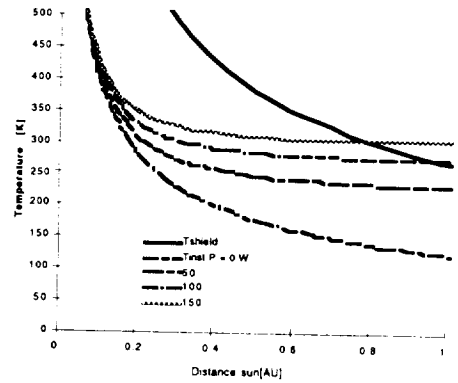


Fig. 9.9 The instrument temperature as a function of the distance from the Sun for various dissipation levels.

It can be concluded that:

- The heat shield temperature increases from 250 K, for 1 AU, up to 570 K, for 0.2 AU.

- The temperature of the instruments only varies less than 30 K for a distance from 1 AU to 0.2 AU. The thermal control can be passive by changing the emissivity of the surface in the design phase. However, when the instruments are switched off a heater must heat the critical instruments to prevent too low temperatures. The heat loading structure can transport the amounts of heat of the instruments to the surface of the spacecraft.

Figure 9.10 shows:

- The temperature of the radiator, assuming that it is perpendicularly oriented with respect to the solar radiation, is not sensitive to the distance from the Sun for a distance > 0.2 AU.
- For the assumed radiator surface of 1 m^2 and emissivity of 0.8, the temperature difference between radiator and ion thruster can be up to about 100 K, which can be obtained using a two-phase heat transport system.

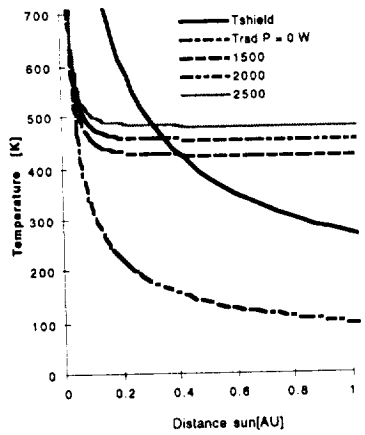


Fig. 9.10 The Ion Thruster Radiator Temperature as a Function of the Distance from the Sun for Various Dissipation Levels.

The batteries must be enclosed in a thermally controlled environment. In the SAUNA spacecraft, they get their own radiator area and thermostat-controlled heaters. The thermal dissipation from the batteries varies with temperature, charge, and charge rate and can be difficult to quantify. Therefore, the thermal control of the batteries needs special attention in a more detailed thermal design.

The propellant tanks also required a tighter temperature envelope than the electronics. The propellant tanks contain xenon in supercritical state. Xenon must be stored at >125 bar and >293 K. In the SAUNA spacecraft, the propellant tanks are in a thermally insulated environment, with their own thermal control.

Table 9.5 gives a overview of the thermal system components and the mass and power of the system.

Table 9.5 Overview Mass and Power of SAUNA Thermal Control Subsystem.

Component Thermal control	Mass [kg]	Power [W]
Heat shield	8	-
MLI	3	-
Heaters	2	20
Conductive structure (part of main structure)	5	-
Two-Phase evaporator (connected to the ion thruster)	10	-
Radiator	5	-
Control electronics	2	10
Total	35	30

9.1.9 Attitude and Orbit Control System (AOCS)

The AOCS is composed of the following elements:

- Attitude determination performed by using the measurement from star sensors and an Inertial Measurement Unit (IMU).
- Attitude control is provided by reaction wheels periodically desaturated by ion propulsion thrusters.

The operation is as follows. The measurement from the star sensors is used during nominal mode pointing towards the Sun to calculate the orientation of the spacecraft. This measurement is also used to periodically calibrate the gyrometer set drift that is used during manoeuvres mode because the star sensor can not be used. Once the orientation is calculated by the on-board computer, the computer compares this attitude with the assigned one and produces an order for the actuator to correct it. The actuators are reaction wheels which will require a desaturation mode in which the thrusters are activated.

The components of this subsystem can be the following:

- Star sensor. The Star Tracker Stellar Compass (STSC) can be used. The demonstrated accuracy is 150 μrad in pitch and yaw and 450 μrad in roll. The weight is 290g, the FOV (Field Of View) is 28.9° x 43.4° and patterns of stars as dim as mv 4.5 are measured and matched against an on-board star catalogue. Star matches are achieved in 4π steradians of the stellar sky. Two systems of this type will be implemented to achieve a redundant system. They will point towards a direction with 30° with respect to the zenith direction (to avoid antenna, solar array, and radiator interferences). The power usage is about 12 W [LLNL 1996].
- IMU. It is composed of four HRG gyrometers in a tetrahedral configuration to have redundancy. The drift is 0.006 °/h and the power usage is estimated to be 24.6 W [Randolph 1995].
- Reaction Wheels. They can be provided by Ithaco in a four wheels redundant configuration. The momentum storage is 50 Nms (3850 rpm), the maximum reaction torque is 0.3 Nm, the minimum lifetime is 8 years, the mass is 14.1 kg, the power at steady state is 35 W (3850 rpm) and the power at peaks is 200 W (3850 rpm) [Ithaco 1996].
- Thrusters. Six thrusters are located around the spacecraft to desaturate the wheels. More data is provided in the Propulsion section [section 6.4].

9.1.10 Communications

The SAUNA communications subsystem is divided into two different parts:

- housekeeping communications
- science communications

9.1.10.1 Housekeeping communications

Housekeeping communications are carried out during all phases of the mission (cruising and orbiting). A set of 4 low gain antennas (LGA) in S-band is used in order to reduce the pointing requirements. The antennas are placed in different parts of the spacecraft in order to allow communications regardless of the spacecraft attitude.

This set of antennas could also used as a backup for the transmission of science data. However, only limited science data could be sent due to the extremely low data rate achievable through the LGAs, 1.5 Kbps.

Appendix B contains the link budget analysis corresponding to the downlink of the LGAs, where the mass and power budgets are shown. The result is about 160 W (RF) divided in 4 power amplifiers, which result in an input power of 640 W (DC). This amount of power is not a problem during the orbiting phase due to the large solar arrays.

The analysis has been carried out for the worst case in terms of distance and noise temperature. Therefore, during the cruising phase the housekeeping communications link operates reliably in spite of the reduced availability of power.

9.1.10.2 Science communications

Except for the cruise-mode dust detection experiment in transfer orbit (which needs only a low data rate), substantial scientific operations are carried out only during the orbiting phase. In this phase the spacecraft is 3-axis stabilised, with the heat shield pointing towards the Sun. A high-gain antenna (HGA) with a diameter of 2 m operating in X-band is placed in the umbra, pointing roughly towards the Earth.

To cope with the varying relative orientation of the Earth and the spacecraft along the orbit, the HGA needs a pointing mechanism. The need to use moving parts (bearings and lubricants) eventually subject to an extreme and harsh environment complicates the design of the communication subsystem and reduces its reliability. Section 6.9 presents some alternatives applicable to the SAUNA mission scenario.

The baseline configuration considers a single-axis pointing mechanism for the HGA. The motion along this axis (pitch) is limited by the spacecraft structure and the limits of the umbra. The baseline considers a motion of ±90° around the zenith point. This provides a coverage of around 50% of the orbital period, or approximately 15 days, the part of the orbit nearer to the Earth. The period of exclusion due to conjunction (1.5°, for safe communications) corresponds to about 3 hours, within the coverage period (During that period, the radio system could operate in continuous wave mode as a plasma science experiment).

If the SAUNA spacecraft goes out of the ecliptic plane (e.g. to a solar equatorial orbit or to a higher solar inclination) a motion in the yaw axis must also be considered (2-axis pointing). For a solar equatorial orbit this motion is ±7°. The baseline is however not to go out of the ecliptic.

The science data communications are carried in the X band (8.4 GHz). Appendix B shows the link budget analysis corresponding to the downlink (worst case) of science communications. The result of the analysis is 40 W (RF), resulting in an input power of 110 W (DC).

The link can operate with an effective maximum data rate of 16 kbps. The data are coded using (255,223) Reed-Solomon block coding and rate 1/2 Viterbi (convolutional) coding. Using this approach a bit error rate of 10^{-6} is expected.

9.1.11 Command and Data Handling

The on-board Command and Data Handling (CDH) system consists of four main elements: The main computer, the flight software (which resides on the main computer), mass storage, and the central data bus.

9.1.11.1 Main Computer

The Main Computer is the brain of the spacecraft. In terms of hardware it needs a very fast processor for parallel and real-time operations at a high frequency:

- Execution of the GNC software
- Execution of the Vehicle Management software
- Processing of telecommands and packaging of telemetry

In chapter 6.10.3, autonomy functions for SAUNA-type missions are discussed.

9.1.11.2 Data Compression

The constraints imposed on antenna sizes and on mass and power budgets, which are especially important in the SAUNA programme due to cost constraints and to the mission scenario, limit the data rate available for science data communications. Additionally, for similar reasons, there is the need to reduce the on-board storage capacity.

These reasons point to decentralised data compression. Compression ratios of up to 40:1 can be achieved without significant degradation of the data quality. In SAUNA we propose the use of techniques providing an average compression ratio of 32:1. This results in an effective average science data rate of 512 kbps. Because high temporal resolution is desired for the ultraviolet imaging, a fast compression processor is needed.

Different techniques should be used for the different instruments, according to the particular characteristics of each instrument. Nevertheless, the basic objective is to produce virtually no degradation in the science data.

9.1.11.3 Mass Storage

The mass storage is the element where the science and housekeeping data are stored during periods of non visibility. The mass memory must be protected against the environment, and especially against radiation. The mass memory is placed in the umbra of the spacecraft and thus the temperature is maintained within reasonable limits during all mission phases, and especially during the orbiting phase, when the mass memory is used.

To reduce the mass, power and volume, advanced technology processes and high density 3-D packaging techniques must be used. The application of miniaturisation techniques is a must given the amount of data storage required and the spacecraft system budgets.

9.1.12 Ground Infrastructure and Operations

Cost concerns and the high demand placed on the tracking networks around the world have led to the selection of a single ground receiving and TTC station. This means that the spacecraft will only be tracked about 8 hours a day. The impacts on the spacecraft are discussed in section 9.1.10 above.

A high degree of on-board autonomy (as described in section 6.3.10) can reduce the required operations resources significantly with respect to past interplanetary missions. Due to the overall mission cost constraint, however, the required amount of new developments must be controlled carefully.

9.1.13 SAUNA Global Budget

In table 9.6 we present the breakdown for mass, power and cost for the SAUNA mission. For a detailed breakdown to unit level, please refer to the SAUNA Mission Data in appendix B.

Table 9.6 SAUNA Mission Budget

SAUNA MISSION - BUDGETS			
Item	Mass (kg)	Power (W)	Cost (M$)
A. Structure	32.00	0.00	4.00
B. Propulsion System	30.00	6300.00	5.00
C. Power System	35.61	0.20	2.75
D. Attitude & Orbit Control	26.88	71.60	6.80
E. Thermal Protection	35.00	35.00	10.75
F. Communications	27.00	750.00	13.00
G. On-Board Computer	2.00	9.00	6.00
H. Subtotal Spacecraft Bus:	188.49	7165.80	48.30
I. Payload	17.70	18.20	13.00
L1. Subtotal Dry Mass (1)	**226.81**	**7219.92**	**61.34**
L2. Propellant (52.5% of wet mass)	250.68		0.63
Q. LAUNCHED SUBTOTAL (2):	**541.00**	**7902.40**	**74.86**
(1) incl. harness; (2) incl. margin and launcher adapter			
R. Launcher capacity and cost:	697.00		60.00
R1. Launcher mass margin:	156.00		
S. Ground Operations			19.00
T. SAUNA Predevelopment (SPP)			22.50
U. Subtotal Cost:			176.36
V. System Cost Margin 10%			17.64
TOTAL MASS, POWER, COST:	**541.00**	**7902.40**	**194.00**

Note that the wet mass of the spacecraft in this budget is around 540 kg, which surpasses the figure of 300 kg used in the initial feasibility studies by almost a factor 2. Fortunately we still have a considerable launcher mass margin for the C_3 needed to achieve a Venus transfer orbit (the launcher referenced in this table is the Delta II (7925)).

With this large mass, the mission is still feasible. The transfer time to the 0.2 AU orbit will be significantly longer (in the order of 2.5 years), however, assuming the same 0.2 N ion thruster is used. This again means an increase in operations cost which has not been accounted for above.

The selection of subsystem components is very conservative, however, making use of existing technology rather than speculating upon the future availability of miniaturised systems and nanotechnology (which would reduce mass). This conservatism leaves room for considerable improvements in performance in the course of the further system design.

The SAUNA Predevelopment Programme (SPP) introduces an extra cost of US$ 25 million (including 10% margin), which is part of the reason why the bottom line cost figure in this table is higher than the US$ 160 million quoted elsewhere in this report. The cost could be reduced by technology transfer between potential international partnerships in the SAUNA programme. Any improvements in relevant technology in the Near- and Mid-Term up to the planned programme kick-off (mid-2001, see section 9.1.16) would contribute to a reduction in mass, power and cost. Nevertheless the risk-mitigating element of the SPP, especially with respect to the qualification of the ion engine, is an indispensable part of SAUNA.

9.1.14 Technological Issues

Due to the cost limitation we have sought to use available technology to the maximum extent. Below, we identify some technological enhancements that will increase the chances of mission success:

- Propulsion: A high-thrust (>0.2 N) ion engine needs to be flight qualified with a rating of more than 10,000 hours of continuous thrust.
- Power: More efficient solar arrays in terms of W/m^2 and W/kg; lower cost, longer life, and heat-resistant solar cells.
- Materials: Lubricants to avoid cold welding; heat shield materials; structural elements able to deal with high thermal stresses; Solar cell high temperature bonding agents.
- Thermal: Improvements in low mass radiator and heat pipe technology;
- Electronics: Radiation-hardened memories with high capacity (Gigabit class) able to resist large doses of radiation over long time spans.
- GNC: Autonomous navigation techniques; control of spacecraft with low-thrust ion thrusters;
- Communications: Use of phased arrays for long-distance transmission; optical communication; developments in solid state amplifiers; deployable/inflatable antennas;
- Reliability and Safety: The impact of the operational lifetime requirement of 5 years (total) has to be assessed for all subsystems with regard to the unusual environment encountered in orbit at 0.2 AU.

9.1.15 Policy & Legal Aspects

In the spirit of the Ra Mission Statement [chapter 1.1] we have opted not to use RTGs for power. In this respect our mission is geopolitically neutral.

The choice of a launch vehicle and launch site brings with it various political considerations; we shall not dwell on those here. However the spacecraft mass is sufficiently low to allow a wide range of optional launch vehicles.

9.1.16 Programme Timeline

The SAUNA mission can be launched as early as 2005, depending on the availability of a qualified 0.2N ion thruster or equivalent propulsion technology. With a launch date of mid-2005, the SAUNA project development scheme should take the form of figure 9.11 below:

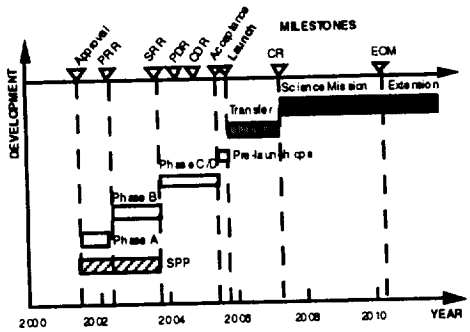


Fig. 9.11 **SAUNA Programme Timeline**

The significant elements of this programme plan are the following:

- A SAUNA Predevelopment Programme (SPP) running in parallel with Phase A and Phase B to qualify the critical technologies (with particular focus on the ion engine) before the start of Phase C/D
- A total design and development time (phase A to launch) of 4 years
- A total programme time of 9 years plus an optional mission extension.

9.1.17 Conclusion

The SAUNA mission is feasible with a Life Cycle Cost of less than US$ 200 million. The SAUNA spacecraft will perform scientific measurements in the near-Sun environment and simultaneously demonstrate long-duration survivability for missions in this region.

9.2 Solar Threat Monitoring and Early Warning Systems

This section describes the steps taken to design a Solar Threat Monitoring and Early Warning System for the Mid-Term, based on the applications needs and opportunities identified in section 5.2.

The thrust of this effort is thus to focus on the design of a dedicated solar threat monitoring mission and to evaluate its commercial viability. We therefore aim to limit ourselves to the use of existing technology and take into consideration the heritage of proven instruments and components.

After the introduction of our study approach [section 9.2.1], we determine the customer requirements [section 9.2.2]. Several mission options for a dedicated early warning system are then explored [section 9.2.3]. We describe their working principle and assess the effectiveness of the concept. Based on that, we choose an array of heliocircular spacecraft as our preferred early warning system [section 9.2.4]. A preliminary design analysis is outlined in section 9.2.5. Finally, possible alternatives and scientific opportunities are pointed out in section 9.2.6.

9.2.1 Study Logic

The following study was approached with an overall logic displayed in figure 9.12.

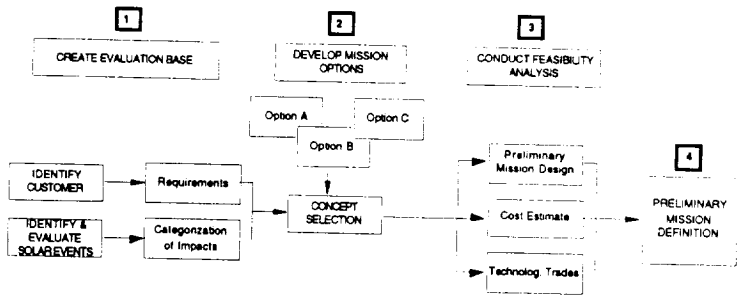


Fig. 9.12 **Logical Sequence for the Study.**

9.2.2 Requirements

This sub-section examines in sequence the customer requirements, the functional requirements, and the derived functional requirements.

9.2.2.1 Customer Requirements

The potential customers of a Solar Threat Early Warning System were identified and described in sections 4.5 and 5.2. For convenience they are listed again in table 9.7 where their requirements are also summarised.

Table 9.7 Early Warning System- Customer Requirements.

CUSTOMER	Type of Warning Required			Min. Time Required (h)
		Magnetic Storms		
	Very High Energy Radiation	High Particle fluxes	Induced Magnetic Fields	
Power grid operators			X	3
Microprocessor manufacturers		X	X	24
Geophysical surveyors			X	24
Civilian HF communications		X		24
Earth orbiting satellite operators (non-polar LEO)				
Earth orbiting satellite operators (polar LEO)		X	X	1-6
Earth orbiting satellite operators (MEO)		X	X	1-6
Earth orbiting satellite operators (GEO)		X	X	1-2 [1]
Non-Earth orbiting spacecraft operators	X			12
Military shortwave communications	X			15 min
Military radar and HF communications	X	X		15 min
Shuttle & Space Station astronauts	X			15 min
Interplanetary astronauts	X			15 min

[1] [Tedrow, 1996]

To clarify the warning categories used in table 9.7, the relation between events on the Sun [section 4.5] and effects on the possible customers [section 5.2] is summarised in the schematic of figure 9.13.

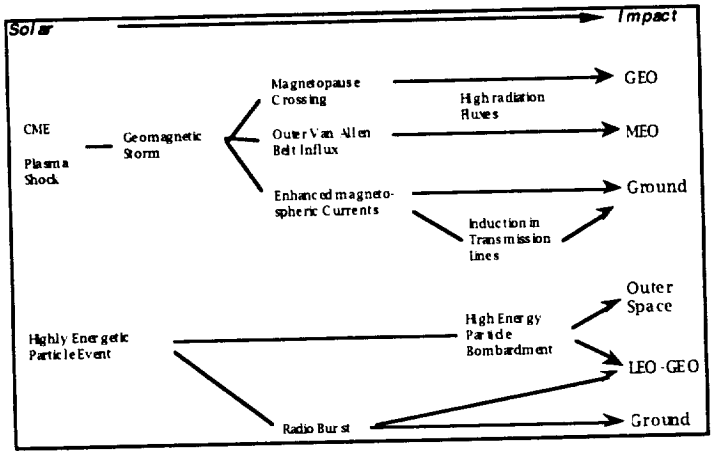


Fig. 9.13 **Connection between solar phenomena and effects on the ground and on space systems (Energetic particle emissions shown only for reference).**

Nature of early warning

The nature of the information provided to the client as part of the warning should include the following estimates:

i) *time* to impact,

ii) *severity* of impact,

iii) *duration* of impact.

Future work should examine the accuracy and tolerances with which the client requires event time, event magnitude, and event duration information.

Target market

A top level decision was made at this point to focus only on those clients which are not shaded in table 9.7. This was based on an assessment of the commercial potential of the customers. Unsurprisingly the selected clients all have systems inside the magnetosphere.

Nature of Threat

The nature of the threat for our target commercial market is thus *geomagnetic storms*. Our target product can now be described more precisely as a Geomagnetic Storm Early Warning System.

9.2.2.2 Functional Requirements

Here we specify at levels of increasing detail what functions the Geomagnetic Storm Early Warning System must be able to perform.

Level 1: GENERAL

The Geomagnetic Storm Early Warning System shall:

- notify clients of solar triggered events which threaten their systems,

- notify clients of the expected time, magnitude, and duration of impact,
- include estimates of the risk to the client's particular type of system,
- provide value added information on how the client's particular system is at risk of being affected.

Level 2: MAGNETIC STORMS

In order to provide warnings to the operators of systems within the magnetosphere, we have the derived functional requirement that the Geomagnetic Storm Early Warning System shall:

- be able to predict when magnetic storms will occur,
- be able to predict the duration of the magnetic storm,
- be able to predict the intensity of the magnetic storm.

Level 3: TIMING

Based on the Level 1 and 2 requirements, as well as the customer requirements, we can identify more specific requirements, i.e. the Geomagnetic Storm Early Warning System shall:

- be able to detect the triggering phenomenon of a magnetic storm at least 12 hours prior to storm initiation,
- be able to forecast the onset time, such that it will happen during a 90 minute alert period starting at the specified time.

Level 4: PHYSICS

Since geomagnetic storms are thought to have numerous triggering mechanisms (see the physics background of section 4.3) the early warning system must be able to detect all of these. Thus, the Geomagnetic Storm Early Warning System shall be able to detect:

- shock waves (such as those which result from Coronal Mass Ejections (CMEs) like magnetic clouds, and Corotating Interaction Regions (CIRs) caused by high speed solar wind) which threaten to impact the Earth's magnetosphere [Chen, 1996] [Farrugia, 1996] [Green, 1996],
- interplanetary magnetic fields (IMFs), with a large intensity and long duration *southward component* which threaten to impact Earth's magnetosphere [Gonzalez, 1996].

The two phenomena above will directly dictate the minimal instrumentation chosen in the scenario described below. Note that both phenomena are thought to have at their root a solar event of some kind. In particular, they have been found to occur often in the presence of, or after the occurrence of:

- a *solar flare* and
- a *radio emission burst*.

In the future, given a sufficiently accurate model, it may be sufficient only to witness the original triggering event at the surface of the Sun and compute (with knowledge of the state of the magnetosphere) whether or not a magnetic storm will result, and if so: when, for how long, and how strong. For a Geomagnetic Storm Early Warning System using current state-of-the-art models it is felt that this is not realisable in the Near or Mid-Term.

Nonetheless, performance of the Early Warning System would likely be enhanced by measurement of the above solar events.

Level 5: TRAJECTORIES

In order to be able to predict impact of the phenomena described in the Level 4 requirements it is necessary that the Geomagnetic Storm Early Warning System be able to:

- predict the trajectory and evolution of *interplanetary shock waves,*
- predict the trajectory of *southward interplanetary magnetic fields.*

This results in the derived requirement that the system be able to:

- measure the position and velocity of the given phenomenon.

9.2.3 Magnetic Storm Early Warning Operational Concepts

The Level 3 and Level 4 requirements that we introduced in the previous section imply that we need to detect triggering mechanisms for geomagnetic storms, ie. shock waves and dangerous IMF's, well in advance, before they hit the Earth.

For that we envisioned several physical methods summarised below.

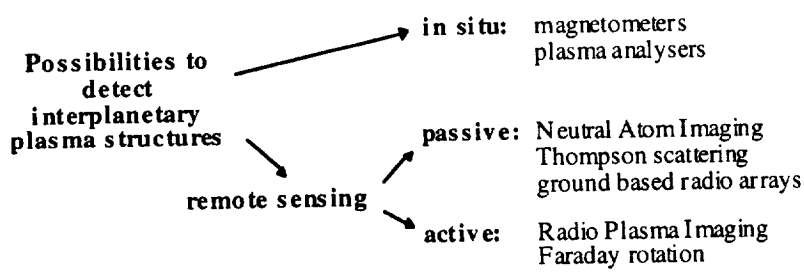


Figure: Physical methods to detect DIPS

To localise plasma inhomogeneites a variety of methods can be used, like Neutral Atom Imaging [Imager for Magnetopause-to-Aurora Global Exploration, WWW] and *in situ* plasma analysing [Mars '96 FONEMA, WWW. All of these methods will be introduced and evaluated in the different mission concepts we present in this section. However, we want to stress already now, that one needs to use *in situ* measurements to measure the strength and direction of the interplanetary magnetic field.

Several mission concepts for a dedicated early warning system are briefly explored in this section. Later, they are judged [section 9.2.4] based on their expected fulfillment of the requirements. From this assessment, an array of heliocircular spacecraft is chosen for a preliminary design analysis [section 9.2.5] and some alternatives for further study are identified [section 9.2.7].

9.2.3.1 Option A- Heliocircular Array of Spacecraft

Mission Description

This mission consists of sending a fleet of (small) satellites into an orbit around the Sun (in the ecliptic plane), performing *in situ* measurements, as shown in figure 9.14.

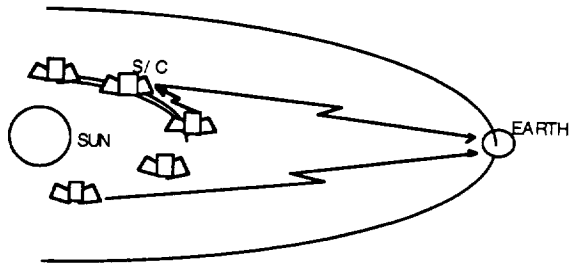


Fig. 9.14 **Orbital configuration of option A.**

Working Principle

Equipped with magnetometers and plasma analysers, this system will be capable of *in situ* measurements of both *interplanetary shock waves*, and *southward interplanetary magnetic fields.*

The spacing of the spacecraft should be dense, so that typical CMEs and magnetic clouds could be detected and information about their properties forwarded to Earth.

9.2.3.2 Option B- Indirect Sensing via Spacecraft at L4/L5

Mission Description:

Two spacecraft at Lagrangian Points L4 and L5 send pulsed radio signals to each other and analyse them. Measurements are then forwarded to Earth, as shown in figure 9.15.

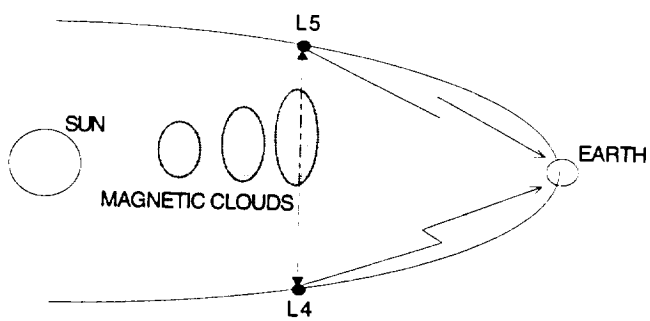


Fig. 9.15 **Orbital configuration of option B.**

Working Principle:

In order to give warning of the most serious single cause of geomagnetic storms -- large scale (prolonged), strong southward magnetic fields -- the interplanetary magnetic field could be sensed by the Faraday rotation induced in transmitted signals well above the plasma frequency. In addition, some measure of the average density could be gained from a measurement of the signal loss due to scintillation. Previous studies have considered radio sounding of solar wind on smaller scales near the magnetosphere [Green, 1996 proposal] and transmission-probing of the solar corona (with a much higher plasma frequency) from an anti-Earth orbit [Pätzold et al, 1996].

Preliminary Analysis:

The Faraday rotation angle ϕ, by which the linear polarisation of a transmitted radio wave at frequency ω is rotated, is [Benz, 1993]

$$\phi = \frac{2\pi\, e^3}{m_e^2\, c^2\, \omega^2} \int n_e\, B \cos\theta\, ds \quad ,$$

where the integration is carried out over the viewing path length, and the factor $B\ cos\theta$ sees only the magnetic field component parallel to the viewing path. This poses a couple of problems for the remote detection of magnetic cloud-like structures. First, having a spiral configuration, the strong field of a perpendicularly-oriented magnetic cloud would average to zero in the line integral. For the case of a magnetic cloud whose symmetry axis is lying in the ecliptic plane and perpendicular to the Earth-Sun line (this case has the highest southward magnetic field impacting the geomagnetosphere), there would be a net Faraday rotation, but the effective (parallel) field strength would be much less than that of the true magnitude. Unfortunately, the L4-L5 distance is about 1.7 AU, so the summed effect of many smaller-scale field variations could overwhelm the signal from a magnetic cloud even with diameter 0.2 AU, suggesting that this technique be put to use on a smaller scale. Still, assuming average magnetic cloud parameters from [Lepping et al, 1990], a Faraday measurement with signals of 30-50 MHz could give useful warning information.

Communication Considerations

Difficulties of this proposed system are required antenna size, power demand and information content of the weakened / refracted radio waves. Compressed pulse techniques similar to those used in radar should be investigated to support this option.

9.2.3.3 Option C- Solar Wind Event Imaging and Tracking (SWEIT)

Mission Description

The SWEIT (pronounced "sweet") Early Warning mission uses a combination of new kinds of imagers to detect Interplanetary Plasma Structures (IPS) which emanate from the Sun and threaten Earth satellites and Earth systems. In addition, it provides simple white light imaging of the upstream limb of the Sun.

The mission uses two identical spacecraft, one located at L4 and the other at L5, in order to provide a 3-D imaging and tracking capability, as shown in figure 9.16.

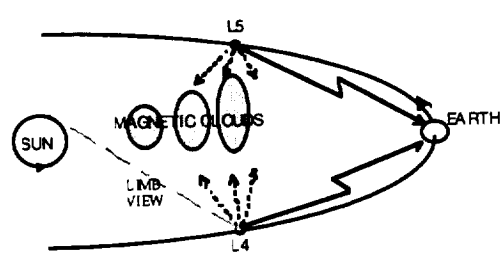


Fig. 9.16 Orbital configuration of option C..

Working Principle

A need to monitor both the activity in the near-solar corona and the form and development of IPS was perceived for effective detection of events inducing geomagnetic storms [Tschan and Lindsay, personal communication, 1996]. The trajectory and scale of slow-moving magnetic clouds can be assessed prior to their arrival at Earth, while their progenitors as well as faster-moving emissions can be detected as they leave the Sun.

The limb view from L4 allows monitoring of the Earth-facing and slightly eastward surface of the Sun, whose emissions have the most direct impact on Earth, and whose corona is not discernible against the background of the Sun from near-Earth.

For effective remote sensing of the IPS, two spacecraft provide a stereo view. The possible means of imaging are discussed in section 9.3.3.

Preliminary Analysis

Neutral hydrogen in the energy range of 10^1-10^3 keV [section 9.3.3] travels no faster than solar wind, making a neutral particle imager (NPI) with a higher energy range necessary for early warning applications. Alternatively, an instrument measuring Thompson scattering could be used, although to date only the slowly-changing structure of the quiet solar wind has been resolved with this method [Hick et al, 1991]. The power requirements for using radio sounding on an interplanetary scale were found to be impractical.

9.2.4 Trade-Off of Solar Warning Missions

The three conceptual Early Warning Mission options are compared here using a Qualitative Trade-Off Analysis, as shown in table 9.8.

Table 9.8 Early Warning System qualitative trade-off matrix.

COMPARISON FACTOR	OPTION A	OPTION B	OPTION C
sensitivity to environmental impacts	-	o	o
required Δv	-	o	o
scientific opportunities	+	+	o
advance warning time	+	+	+
complexity of the system	-	o	?
false warning rate	+	+	?
reliability of the system	?	+	+
anticipated cost	high	medium	medium
expected accuracy of event prediction:			
1 time	+	?	?
2 magnitude	+	?	?
3 duration	+	?	?
phenomena detection capability:			
1 shock waves	+	+	+
2 interplanetary southward magnetic fields	+	-	-

Performance: + good o fair - poor ? unknown

Based on the above trade-off, scenario A (the Heliocircular Array of Spacecraft) was chosen for further detailing, principally since it is anticipated to return the most highly reliable information which complies to customer needs.

Detailed assessments and further trade-offs for the Heliocircular Spacecraft Array class of mission are described in the following sub-sections.

9.2.5 Preliminary Design of Heliocircular Spacecraft Array Concept

Payload Requirement Estimates

The payload for each of the spacecraft in the heliocircular array will consist mainly of a plasma analyser and a magnetometer. Mass, power, and data rate requirements for these instruments are listed in table 9.9.

Table 9.9 Payload Estimates for Heliocircular Array Spacecraft.

Instrument	Mass (kg)	Avg. Power (W)	Data Rate (kbps)	Comments
plasma analyser	6.0	4.0	1.2	
magnetometer	3.3	1.9	0.5	Including boom

Communication Considerations

The major communications problem for the system under evaluation will be the proximity of the Sun and its noisy environment: thermal noise, solar conjunctions and scintillation. The communications architecture will have to deal with these problems through the possible use of inter-satellite links (ISL) versus on-board storage and the optimization of the communications frequency used. The detailed analysis of the trade-offs and considerations is carried out in section 9.2.5.2.

Selection of Orbital Radius and Number of Spacecraft

The factors driving the number of spacecraft required follow from the requirement of detecting large magnetic clouds and CIR-associated shocks, both of which can cause geomagnetic storms. Knowing the size of these features and their propagation speed, one can determine the minimum spacing of spacecraft needed to detect them all. Unfortunately, the minimum size of geodisruptive solar wind structures is not very well known. Kumar and Rust [1996] deduce that magnetic clouds expand roughly linearly with their radial propagation, at least in the lateral (perpendicular to motion) direction and outside of ~0.3 AU. Assuming a diameter of 0.28±0.1 AU for magnetic clouds arriving at 1 AU [Lepping et al, 1990], approximately 20 spacecraft are needed independent of their solar radius to ensure "complete coverage" -- i.e. that each cloud is detected at least once.

However, after further investigation it might prove that the chosen number 20 is rather generous, since computer simulations have shown that the diameter of the clouds in the propagation direction is much less than in the one perpendicular to it [Vandas *et al.*, 1995]. Also, the clouds with the most severe southward looking magnetic field usually lie in the ecliptic or are only slightly inclined, and thus the relevant cross-section would be much larger than 0.28 AU.

For lack of better understanding, we take the size and evolutionary behaviour of magnetic clouds to be representative of CMEs in general. The heliospheric array should also give ample warning of CIR-associated shocks, since these can be inferred from both

- the location of fast- and slow-moving solar wind regions, whose counterparts on the Sun are generally long-lived, and

- the location of the CIRs themselves: since they are corotating, they would often be sensed by several spacecraft in the array before reaching the Earth's solar longitude.

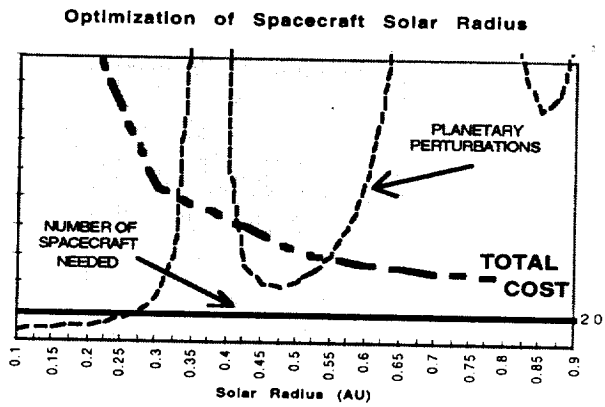


Fig. 9.17 **Optimisation of heliocentric distance. Several parameters considered in the optimisation of orbital solar radius for the spacecraft array. The "total cost" is the gross wet mass of the spacecraft fleet. The planetary perturbations are due to Mercury, Venus, and Earth.**

Based on the use of solar electric propulsion and the Δv's required for various circular solar orbits, candidate wet masses were calculated [table 9.12]. Some Examples of calculated Δv values are listed in table 9.10.

Table 9.10 **Δv values for several heliocentric distances.**

Distance (AU)	0.3	0.18	0.5
Δv (kms^{-1})	22.6	34.51	11.98

The total Earth-launch mass (plotted as "cost") of the spacecraft array is shown in figure 9.17, based on a number of spacecraft intermediate to the two extremes. Based on this cost profile and on the degree of advance warning provided by heliocentric arrays at different solar radii, which is shown in figure 9.18, an orbital solar radius of 0.5 AU was chosen for study.

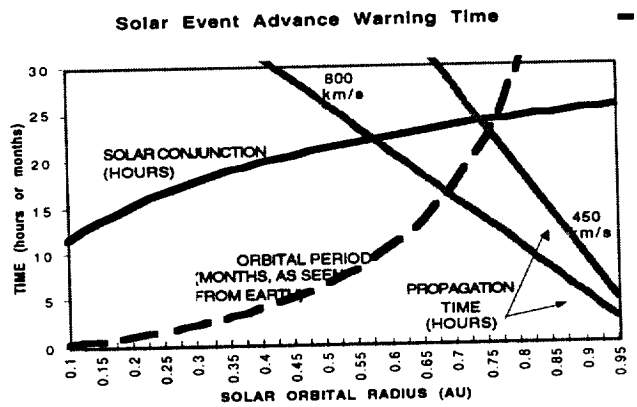


Fig. 9.18 **Solar event advance warning time. The minimum advance warning time for arrays at different radii results from the length of solar conjunction at that radius, and the time of propagation of fast solar wind structures to Earth after being sensed.**

Mass requirements

Mass requirements for a single spacecraft from the heliocircular array were estimated as seen on table 9.11. The payload and communications hardware mass were determined from the equipment described earlier in this section. A dry mass of 55 kg was then estimated from these values, based on general historical trends for small spacecraft [Larson, 1996]. This mass estimate was then used to approximate the values for the rest of the subsystems. A total spacecraft mass of 159 kg was then obtained by adding propellant and propulsion hardware mass estimates to the estimated dry mass. These requirements provide only a general idea of the mass that may be required for a single spacecraft. Further study will be needed to obtain a greater degree of confidence in the mass estimates.

Table 9.11 **Spacecraft mass distribution.**

Spacecraft Subsystem	Mass (kg)	Dry Mass (%)
Payload	9.3	17
Structures and Mechanisms	11.0	20
Thermal Protection	2.2	4
Power	16.5	30
Communications	10.0	18
Guidance, Navigation and Control	3.3	6
Propulsion (RCS)	2.8	5
Dry Mass	**55.1**	**100**
Propellant Mass	59.1	
Propulsion Hardware	44.5	
Total Mass	**158.7**	

Table 9.12 **Total mass launched vs. distance from the Sun.**

Distance (AU)	0.1	0.2	0.3	0.4	0.5	0.8
Mass Launched (kg)	1578.1	527.5	266.9	216.1	158.7	117.6

9.2.5.1 Communications Concept

The baseline for the communications is that only those spacecraft located in the arc of scientific interest will need to transmit their data. Given the constellation's distance from the Sun, on-board electronics are not an issue and can be used to reduce the transmitted data to a simple warning signal, together with some parameters characterising the phenomenon. It will significantly reduce the data rate. To cope with the solar conjunction problems, some geometrical analyses have been conducted in the following section.

Solar Conjunction

The geometry of the link is represented in figure 9.19, showing the solar conjunction cone. In figure 9.18, the loss of signal due to solar conjunction considering a Sun view of angle of 1.5° from the Earth is approximately 21 hours. This leaves enough warning time if on-board storage is considered. This latter option consists of storing detected threatening events and simply waiting for the spacecraft to exit the conjunction cone instead of using ISL.

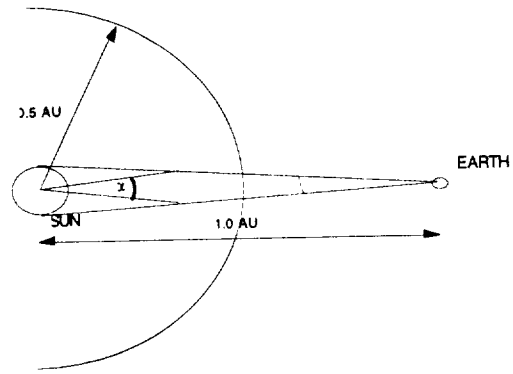


Fig. 9.19 Communications link geometry.

Thermal Noise

In order to avoid the drastic increase in thermal noise due to the Sun's background radiation, we will assume that communications are interrupted as soon as the Sun enters the major lobe of the ground station antenna.

Antennas and Transponder

In order to implement the communications design that has been discussed, each spacecraft will be equipped with a classic X band transponder. The advantages in the Mid-Term time frame of this band has been assessed in section 6.9. The spacecraft antenna will use advanced concepts such as phased array techniques that have already been addressed.

Ground Segment

Continuous coverage is required on Earth in order to monitor any threatening solar event. Therefore, it is highly unlikely that the Deep Space Network would be available continuously for our ground segment. Instead, we propose to explore the use of smaller antennas (e.g. 15 m) that are more widely spread and available [section 6.9].

9.2.5.2 Spacecraft Configuration Trades

Propulsion:

Two propulsion systems were traded to assess which one would be suitable for this particular mission. The two systems considered were chemical bipropellant and solar electric propulsion. Solar sailing was not considered due to its relative lack of heritage as compared with electric propulsion. Based on the dry weight for the spacecraft and the expected Δv for the manoeuvre from 1 AU to 0.5 AU, the propellant mass was calculated for each system. The results are in table 9.13. The additional dry mass required is the mass added to the system if solar electric propulsion is selected. However, even with the additional dry mass added, the significantly higher performance of the solar electric propulsion system yields a much lower propellant mass requirement. A comparison of the total mass launched versus target distance from the Sun is included in table 9.12.

Table 9.13 Comparison of propellant masses to propulsion systems considered for 1.0 AU to 0.5 AU

Propulsion System	I_{sp} (s)	Propellant mass req'd for Δv manoeuvre (kg)	Additional dry mass req'd for propulsion System (kg)
Chemical Bipropellant	305	2996	0
Solar Electric	3300	59.1	44.5

The solar electric propulsion system requires 2.5 kW of power, which is significantly higher than the power required for a chemical system. However, the additional mass required in solar arrays, to accommodate the power requirement, is probably insignificant compared to the additional propellant mass required if a chemical propulsion system is selected. During the preliminary design phase, there should be a trade between I_{sp} and power required for the electric propulsion system.

Solar electric propulsion has significantly less flight heritage than chemical propulsion. The lack of flight heritage could result in significant testing requirements and development cost for the solar electric system. Increased flight experience with solar electric propulsion would significantly benefit this mission by reducing the potential development cost.

The Δv required to go from 1 AU to 0.5 AU precludes the use of chemical propulsion. The propellant mass required from a chemical system to perform this manoeuvre probably outweighs any potential hardware mass savings gained from using it. The propellant mass could be reduced by using gravity assist manoeuvre to augment the chemical propulsion system. However, this option was not considered during this study due to time constraints. Attitude control will be provided by a monopropellant chemical propulsion system, which is a simple system with extensive heritage.

9.2.5.3 Environmental Disturbances

The solar environment will influence the performance and the life of the spacecraft.

The thermal control system and reliability considerations have to take into account an increased heat flux of about 5 times the value at Earth distance.

The calculated solar photon pressure is in the order of 10^{-12} Pa. Over 10 years, or 3×10^{8} s, that comes to an insignificant Δv. The magnitude of the acceleration arising from solar radiation pressure can be neglected.

The spacecraft will be affected by the gravitational effect of Mercury and Venus. The estimates forces are in the order of 10^{-5} N.

9.2.5.4 System Installation Scenario

A study should be performed to compare the cost of launching one spacecraft at a time on a small launch vehicle versus launching more than one on a larger launch vehicle. The earliest possible launch time frame would need to take into account the time for design, development and testing of the spacecraft. The time and cost for design, development, and testing could be reduced if the programme is able to take advantage of the heritage gained from vehicles with solar electric propulsion that may precede it.

9.2.5.5 Costing

The costing of Ra application project takes into account the technical specificity's (previous paragraphs) and comes from the global costing study of Ra Design project [section 9.7 and chapter 7].

Table 9.14, figure 9.20 and figure 9.21 present the Cost Break down Structure used for the cost analysis, with the assumption for this project of twenty spacecraft with from 200 to 300 kg Total mass each one and use two launchers class Ariane 5 or ATLAS II AS.

Table 9.14 Ra Applications cost matrix.

SOLAR PROBE MISSION:	RA APPLICATION NAME and REFERENCE	$COST	Ref. A TOTAL$COST
	65 RS		$ 123,513,877
GROUND SEGMENT			$ 0
TRACKING			$ 0
DATA HANDLING			$ 0
OPERATION UPLINK			
			$ 240,000,000
LAUNCHER	2 launchers ARIANE5, ATLASIIAS	$ 240,000,000	
			$ 531,961,730
SPACE SEGMENT			
	20 Spacecrafts*200 to 300 Kg, 1600 Kg		$ 485,961,730
BUS		$ 100,800,000	
Propulsion	Solar and electric	$ 36,000,000	
Power	6 KW Solar arrays	$ 60,000,000	
Structure & Materials	Standard	$ 36,000,000	
Thermal	Standard	$ 79,200,000	
Guidance, Navigation & Control	Standard	$ 57,800,000	
Communications	x-band Transponder & Ka Band	$ 72,500,000	
Information & Data	1.2 and 0.5 Kbps	$ 43,661,730	
Others (Bus)			
			$ 46,000,000
PAYLOAD	19 W	$ 46,000,000	
Instrumentations	20 Plasma analysers and 20 magnetometers	$ 0	
Communications		$ 0	
Information & Data		$ 0	
Others (Payload)			
			$ 895,475,607
TOTAL $COST			
Total			5000.00
Incl.Propellant&Info	20 Spacecrafts		5000.00
TOTAL KgMASS			

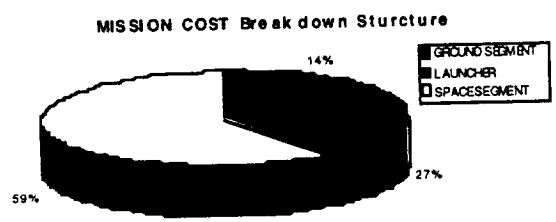


Fig. 9.20 Mission cost breakdown.

As a conclusion about the mission cost, the break down of it gives 14 % for the ground segment, 27 % for the launchers and 59 % for the Space segment.

According to the conclusion of the optimisation of the payload to the launcher capability [section 9.7], the total price of the mission is pushing down, in using only two launchers such as Ariane 5 or ATLAS II AS. But due to the heavy mass of each spacecraft, the cost percentage of the launcher (30 % of the total cost) is a normal value and cannot contribute to push the cost of the mission.

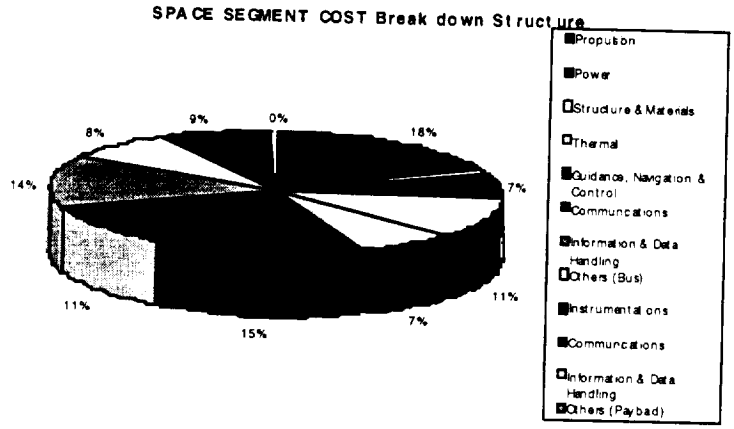


Fig. 9.21 **Cost Breakdown structure of Space segment.**

As a conclusion of the cost drivers study, for a normal spacecraft with a mass from 200 to 300 kg, for a location 65 R_S (up to 30 R_S) "the normal technology" can be used in order to push down the total price.

As a general conclusion, if the global cost is around $895 million, the learning effect has to be taken into account, because of the manufacturing of twenty similar satellites. So, the global price would have to be pushed down.

As mentioned in section 9.2.5, the space segment cost may be overrated by up to a factor of two due just to an overestimate of the number of spacecraft needed for acceptable performance.

9.2.6 Further Options and Recommendations

Due to the limited scope and depth of our study, there remain a number of possibilities for fruitful further investigation, relating both to the heliocentric array and to other mission ideas. These involve innovative funding arrangements, modularity of the proposed system, and an alternative early warning system requiring more advanced technology.

The heliocentric array lends itself well to modular deployment. Because the full system cost is likely to be prohibitive for private industry, the effectiveness of a heliocentric array could be shown with a subset of the approximately 20 spacecraft recommended. Insertion of additional spacecraft into the grid over time would still allow the benefit of the learning effect, while also offering the option of changing or augmenting the new payloads. For instance, scientific imaging instruments could be added with support from space agencies, or radio sounders could be added based on the success of the system and support from industry or military.

In fact it is of note that several of the alternatives considered in section 9.2.3 bear a resemblance to science missions. This simply reflects the crudeness of current understanding of solar causes and near-solar evolution of CMEs and the solar wind. Indeed, the heliocentric array considered here has its counterparts among scientific mission proposals, such as the "String of Pearls at 0.8 AU" and the "String of Sails at 0.5 AU" mentioned in [Russel, 1996]. It follows that "mixed funding" missions are a logical compromise, and in fact putting space weather warning instruments on various inner-solar-system science platforms may be more practical than a dedicated applications mission in the mid-term.

Solar Parachute as Alternative to the Heliocircular Array of Spacecraft

A different approach to the concept of the proposed system was referenced in a personal communication between Lt. Joel MCray and Capt. Randy Tedrow of the US Air Force dated January 16, 1996. The following information concerning stationkeeping of spacecraft between Earth and Sun by means of solar parachutes was discussed.

Inflatable solar parachute in heliocentric orbit used for station keeping for an orbit that maintains a constant Earth-Sun-spacecraft angle (4°). The solar pressure on the parachute reduce the effect of the gravity force due to the Sun, which allows the spacecraft to emulate the rotational velocity of the Earth at 1 AU from the Sun. That gives 4 hours warning.

A plasma analyser, a magnetometer and an energetic particle detector will be used.

The spacecraft will have a total injected mass of less than 156 kg, of which instruments comprise 10 kg. The instruments, which require approximately 10 W, produce data at 300 bps.

The spacecraft uses a 140 m diameter deployable kapton parachute and should be stationed at 0.4° in front of the Earth, on a circular orbit at 0.9 AU, for a period of one year. It should provide a $\Delta v=2.146\ kms^{-1}$ to achieve its final orbit. To get in such a orbit two Venus gravity assist plus perihelion and aphelion manoeuvres has been planned.

There are three important issues that determine the feasibility of this mission. The mass of the solar parachute must fit within launch vehicle weight limits. The attitude and orbit control of the solar parachute must be stable. The development cost of an inflatable solar parachute may not be excessive.

9.2.7 Conclusions

The section 'Solar Threat Monitoring and Early Warning Systems' concludes with an assessment of a proposed mission of a heliocircular array of 20 spacecraft. Their orbit is at 0.5 AU from the Sun, the overall operational time of the system is assumed to be 10 years.

This mission was selected amongst other generated options under incorporation of potential customer's requirements and an assessment of impacts of threatening Solar Events. The design was driven to a significant extent by the requirements that it be completely applications-oriented and that it be able to give warning of the *direction* of the magnetic fields impinging on the geomagnetosphere. The latter condition dictated the use of *in situ* field measurements.

The chosen mission appears to satisfy most of the requirements developed in section 9.2.2.2: it provides warning of the time of onset, the intensity, and the duration of magnetic storms caused by shock waves and southward interplanetary magnetic fields, assuming only modest performance of prediction models. It is difficult to judge whether the timing precision of the forecasts would be better than 90 minutes, and in the case of a very fast-moving CME detected during a solar conjunction, the warning time could be less than the required 12 hours.

The preliminary cost estimates for the selected mission were rather high, but may need to be supported with deeper analysis of the mission details.

9.3 Solar Stereo Mission

9.3.1 Introduction: Trends in Space Science Instrumentation

The rapid pace at which technological advance is affecting the menu and specifications of spacecraft instrumentation is extreme when compared with the normal lifetime of mission planning and design. Particle instruments are able to measure full hemisphere vector fluxes with rapidly increasing energy, mass, and temporal resolutions, while becoming ever smaller.; Vector magnetometers maximising the use of VLSI technology have achieved the size of coins. The upper energy bounds of hard X-ray and gamma-ray "imagers" change steadily, as demonstrated by the Fourier-transform imaging instruments on SOHO and on the proposed HESI mission.

As the spatial resolution of remote-sensing instruments improves dramatically, the instruments are increasingly termed "imagers", and such imagers now exist for energies from infra-red to gamma-ray. For *in situ* instruments such as magnetometers and electrometers, the complexity of interplanetary and magnetospheric plasma interactions has made multiple spacecraft increasingly desirable, as determined by physical spatial scales larger than those of a single spacecraft. The recently-attempted Cluster mission and the study and use of "picosatellite" swarms are examples of this trend.

9.3.2 Advantages of a Solar Stereo Remote Sensing Mission

Just as spatial structures cannot be adequately deconvolved in interplanetary and planetary space by the one-dimensional sampling afforded by a single spacecraft, it is increasingly evident that the critical structures near the Sun cannot be understood with two-dimensional models or a two-dimensional view afforded by a single imager. Thus, the concept of Sun-observing spacecraft well away from the Sun-Earth line is the next step in the progression towards high-resolution, 3-D remote and *in situ* sensing. The major advantages of such a mission are outlined below.

1. Although some of the spatial scales likely to be important in coronal dynamics are too small for remote observation [Emslie, private communication, 1996], the use of stereo observations in the EUV and X-ray energy regimes are virtually crucial for resolving the 3-D structures responsible for coronal heating and solar wind acceleration. This primary aspect of a stereo mission has been elaborated on elsewhere [NOAA, 1996], [Solar Stereo Mission, WWW].

2. Placing a spacecraft well away from the Sun-Earth line gives another spatial data point for *in situ* plasma measurements, in the spirit of picosatellite arrays, of Cluster, and of the ISTP satellites altogether (see above).

3. As well as providing the obvious opportunity for observation of the Sun surface over a wider range of longitude, and at a longitude more directly affecting the Earth's magnetosphere (due to solar rotation), having an observatory out of the Earth-Sun line presents an ideal opportunity for "viewing" the interplanetary space through which the Sun affects the Earth. Many missions (for instance, Ulysses, Yohkoh, SOHO) and entire campaigns (STSP) have recently focussed on the Sun's interior and near corona and on the near-Earth "geospace"; however, very little is known about the large-scale structures or the propagation of CIR's, CME's, and magnetic clouds in the interplanetary space. These interplanetary plasma structures (IPS) undergo great evolution in between where they are measured remotely through X-ray imaging on the Sun and where they are felt *in situ* as single-

point solar wind measurements near Earth or as magnetometer and other measurements inside the magnetosphere and on Earth's surface. Contributing to this poor coverage are the extremely small densities (less than 100 protons per cubic centimetre at 1 AU) of IPS outside about 30 R_S, and the extreme nature of the Sun's emissions, which prevent imaging of the Sun-Earth interplanetary space from Earth or from near-Earth orbit. Nevertheless, several methods for imaging such tenuous structures exist (section 9.3.3) and if placed on a remote "stereo" spacecraft, could (1) profoundly influence our understanding and predictive abilities of these propagating phenomena, and (2) give us up to a few days of warning when an energetic region is destined for the Earth.

4. For the previous three reasons, a solar stereo mission is an ideal candidate for industrial involvement. Even without increased predictive power, the ability to see coronal emissions from between the centre face and the east limb (as seen from Earth) of the Sun, to see the evolution and trajectories of CME's and other IPS propagating towards the Earth, and to measure the magnetic field and particle signatures of corotating structures before they reach the Earth are all very useful for providing warning of impending space weather storms at Earth. This is important for several reasons: (1) such an application is another primary objective of the Ra study [section 5.2]; (2) given the various planned megaprojects of orbital comsat arrays for the very near future, this early warning information will have a large and increasing commercial value; and (3) involving industry in the planning and financing of such a mission is an excellent paradigm for new trends in science funding, given contemporary fiscal constraints.

5. Having two spacecraft giving stereo observations will provide technical experience, incentive, and a baseline of orbital hardware needed for future tomography. Tomography, which gives a fuller 3-D reconstruction than a simple stereo view, is generally believed to require a minimum of four separate views [Marsden, 1996]. A proposal of such an array initially may be financially unrealistic, and would likely only be cut back to a stereo mission. Rather, making use of SOHO (or possibly its descendents) and adding spacecraft gradually as experience increases will be most effective and financially sound.

Thus putting spacecraft into orbits away from the Sun-Earth line for stereo imaging of interplanetary and solar structures is an effective way of addressing both primary Ra objectives, scientific and practical. Indeed, stereoscopy of the Sun's corona was among the top priorities of the solar physics researchers contacted for Ra [section 5.1].

The concept of such stereo viewing has been discussed for at least 20 years, and there are a number of proposals made recently for such a scenario, based mostly on scientific objectives [STEREO Mission Workshop, 1996][Dere, 1996]. In order to demonstrate the feasibility of such a mission and of the innovative use of industry support, an entirely applications-based stereo mission is briefly considered in section 9.2.

9.3.3 Imaging of Interplanetary Structures

Because of the tenuous nature of the interplanetary medium even amidst CME's, most normal photonic imaging techniques are not suitable for observing plasma structures in the solar wind. However, sensitive UV imaging and a new technique being applied already [Pippi Instrument Description, WWW] to denser structures (for example the Earth's magnetosphere) containing atomic hydrogen- energetic neutral atom imaging-

should be useful for obtaining invaluable large-scale remote sensing images of the inner heliosphere.

Neutral Atom Imaging

[Hsieh et al, 1992] examined the possibility of resolving CIRs, energetic solar particles (for example CMEs), anomalous cosmic rays, and the background quiet-time interplanetary (QTIP) ions, by detecting neutral (hydrogen) atoms created in charge exchange recombination between 10-10^3 keV protons and drifting local interstellar neutrals, whose density is concentrated in the near-Sun gravity well. This study concluded that if viewed from near 1 AU,

- the structure and evolution of CIRs and of energetic solar particles could be discerned,
- QTIP ions would not be discernible,
- anomalous cosmic ray ions (and thus heliopause structures) would dominate outside 5 AU.

In addition, the energy distribution of these particles would elucidate the dynamics of the respective source phenomena. Based on the proton and photon rejection rates needed for such an instrument, [Hsieh et al, 1992] conclude that it could be built now.

Plans for implementing such an instrument, alongside instruments to image the solar corona and the Earth's magnetosphere, are being made as of this writing [Green et al., 1996] [Imager for Magnetopause-to-Aurora Global Exploration, WWW] [Pippi Instrument Description, WWW].

White Light Thompson Scatter Imaging

Sensitive white light detectors can resolve sunlight that has been Thompson-scattered off free electrons in the solar wind. Therefore, plasma structures with increased electron density can be imaged; in fact, the extent and evolution of dense CME's have been imaged from 1970's HELIOS data [HELIOS CME Event Video, WWW], and a new CME imaging spacecraft using this technique has already been proposed [The Solar Mass Ejection Imager (SMEI) Experiment, WWW]. Modern CCD technology is making this a promising method which also lends itself well to stereography.

Radio Sounding

The technique of radio sounding of plasmas consists of measuring the reflected components of emitted pulses over a range of frequencies. The advantages of this active sensing method include the 3-dimensional structure and velocity structure determined from the delay and Doppler shift of the returned signals, and that plasma density, temperature, and even magnetic field information can all be constructed from the frequency dependence and the relative response of two radio modes, X and O [Reiff et al, WWW].

This technique has been put to use since 1962 for imaging magnetospheric plasmas [Reiff et al, WWW] [Imager for Magnetopause-to-Aurora Global Exploration, WWW] but for interplanetary plasmas, it requires a lot larger antennas and power levels. Nevertheless, near-Earth solar wind imaging with radio sounding has been recently proposed [Green et al, 1996].

Interplanetary Scintillation

Although impractical for space-based platforms, interplanetary scintillation is mentioned here as a useful complement to spacecraft imaging techniques. Scintillation of radio signals from narrow sources travelling through heliospheric density fluctuations can be resolved by arrays of radio telescopes ["Heliospheric tomography...", WWW]. Because a velocity of the plasma structures relative to the source is needed to measure differential scintillation, these surveys are generally averaged over a complete solar rotation; however, the resulting density maps have been shown to correlate well with active X-ray regions in the corona [Hick et al, 1996].

9.3.3 Recommendations for Future Missions

In light of the compelling motives and promising technologies for a stereo mission to image both the Sun and interplanetary space, such an undertaking forms an important part of both the solar-heliospheric science community's goals and the Ra Strategic Framework.

As discussed in section 9.4, the SOHO spacecraft is proving to be an invaluable platform for solar science. Placing a similar (but more modern) set of instruments, augmented by some interplanetary plasma imagers, at the L4 or L5 points is an obvious opportunity to efficiently deploy an initial stereo system. The extremely accurate launch of SOHO has left the spacecraft with enough fuel for 20 years of station-keeping [Huber, personal communication, 1996], so that with some extended funding it could be kept active well past its projected shutdown in 2004. This provides a motive and constraint for quickly launching a newer, cheaper, but similar system into a complementary orbit.

9.4 New Heliospheric Observing Platform

SOHO (The Solar and Heliospheric Observatory) was launched in 1995 and placed in an orbit around the Earth-Sun L1 point (see Appendix A). It is equipped with 12 experiments to use the advantageous position directly in the solar wind for examination of the medium itself and for direct observation of the Sun and its corona at several wavelengths.

After almost one year lifetime now the spacecraft has proved to be one of our most powerful tools for investigating the Sun. In this time a great deal of exciting data has been returned, and over the next few years many new discoveries are likely to be made as the data is fully analysed.

However, the lifetime of SOHO is expected to end in the year 2004. It is evident that to have at least one spacecraft at L1 is useful. With a replacement of SOHO carrying more advanced (yet smaller and cheaper) scientific instruments, this option should be one of the main issues to be considered in the Mid-Term Framework.

9.5 The Fire Mission

In this section we give a short description of the planned Russian-American solar probe mission called "Fire". We have also tried to understand how this mission fits into our "Strategic Framework" and which recommendations we can offer for both Russian and American sections.

9.5.1 Brief Description of the Fire Mission

"Fire" is a part of the joint Russian-American Project "Fire and Ice" [Vaisberg, Tsurutani, 1995] which is aimed at studies of extremes of the solar system and consists of two major parts:

- Fire: Sun flyby with Jupiter gravity assist of US Solar Probe and Russian Plamya spacecraft.
- Ice: flight to Pluto and Charon.

The general goal of the Fire mission probes is the study of the extended solar corona. It includes investigations of:

- coronal heating mechanisms and transport
- acceleration of the solar wind.

These problems cannot be solved without knowledge of the 3-D model of the solar corona structure. Such a model is necessary to define the global context for the various local measurements. A 3-D model of the solar corona can only be constructed through observations of corona images at the limb, using a white-light externally occulted coronograph during the probe perihelion part of its orbit. Therefore such an imaging experiment is an important component of the probe observational programme.

The solar disk observations will provide information on underlying solar regions, which is very important for the spatial connection of the *in situ* measurements with low coronal structures. The wide-angle observations from the Plamya will give the global structure of the corona through which the Solar Probe will pass. The white-light solar corona around the limb is usually observed as projected onto meridianal cross-sections both from the ground at total solar eclipses and from spacecraft in near Earth orbits. Of particular scientific interest, especially for the theory of the shape of the global corona, is to obtain white-light corona images in projection onto the ecliptic plane. The Fire mission will give us a unique possibility to observe the solar corona from over the solar poles.

The scientific value Fire mission measurements will significantly increase due to correlation of *in situ* measurements and remote sensing observations of the Sun both by the probes and by ground and space based observatories. Such measurements must allow us to study the mechanisms of coronal heating and acceleration of the solar wind, as well as to study the solar surface, including the insufficiently explored polar regions.

To meet the mission objectives the heliocentric orbits of the two spacecraft will have a high inclination with respect to the ecliptic plane and perihelion distances of about 4 R_s for the American Solar Probe and about 15-20 R_s for the Russian Solar Probe. The passages of the perihelion region for the two spacecraft are preferably simultaneous within about one hour. Before reaching perihelion, the Russian Plamya spacecraft will scan the solar surface with the forestalling with respect to the American Solar Probe and with the lagging after passing the perihelion.

9.5.2 Political Considerations for Fire

There are important political implications for solar and heliospheric science surrounding the Solar Probe/Plamya mission that must be considered in any evaluation of the project. The Fire mission concept has gained attention at the level of the Gore-Chernomyrdin Conference (GCC), a biannual meeting on science and technology issues between U.S. Vice-President Albert Gore and Russia Prime Minister Viktor Chernomyrdin. At present,

such high-level attention has increased political will for the project in both NASA and RSA. However, as we have learned from past international collaborations, political attention can be both good and bad for a project and its successors.

Because of the GCC attention, the political awareness surrounding any subsequent mission developments for Fire will be high; exactly what that awareness brings is difficult to predict. However, an awareness of a particular tendency of political systems can help the space science community make its ultimate determination concerning the desirability of the Fire mission.

Political systems have a great amount of *momentum*. When a political body makes a decision it creates a precedent for itself in subsequent actions. The danger therein is that *both* the *reasons* for the decision *and* the *decision itself* are rarely carried forward together in the political memory. The political attention that Fire has received means that the organisational memory for the effort is high, but the nature of that organisational memory remains unaltered. If or when Fire is funded for flight, cancelled altogether, or somehow changed into something else, there is a risk that decision brings for future efforts in solar and heliospheric space science (whatever that decision is). For example, if Fire is funded for flight there is a chance that future requests for solar mission might receive a negative response because of institutional reasoning such as, "we've already funded a solar mission, why another?" Conversely, if Fire is not funded for flight (even in the case where Fire is not funded because it is felt that the money would be better spent elsewhere in solar science), then a negative response to future initiatives could still follow with the reasoning as, "We have already told you no for one solar mission, why bother us with another?" Thus the decision itself and the reasons behind it may become decoupled and this situation poses a risk to future solar science efforts, dependent on *exactly what* political bodies recall, and the mind set that they form with those memories.

The relative risks of each of these two scenarios is beyond the predictive capability of the Ra team. What the team believes is important is that a high level of awareness is maintained concerning the long-term political implications inherent in any programmatic decisions. This is especially relevant when the programme has gained high levels of political attention, as is the case with Fire. These risks must be managed if an international framework for solar exploration and applications is to be successful.

9.5.3 Current State of the FIRE project.

The major open issue is the immediate need for RSA funding for the new generation spacecraft to be built in Russia. Possible long lead times associated with project implementation within Russia should be considered in light of a required project start in 1997 (necessary to meet the launch year objective of 2001). Should the impetus for a 2000 launch resurface within the Russian space community, early funding will become even more of an imperative. Co-operative design-integration elements lack detail. Interface definition and the establishment of technical responsibilities are required. The basis for a successful mission relies upon the early identification of technical personnel and their respective counterparts on both sides. Every effort should be made to facilitate the early establishment of the necessary interfaces, protocols, and personnel.

U.S. electronic piece parts may be provided for the new Russian spacecraft. The method by which these parts are provided is still unclear. Those parts required need to be identified as soon as possible for evaluation of long lead U.S. procurements.

NASA funding for technology and science instrument development for the U.S. Fire spacecraft needs to be addressed and funding sources identified. Key technology items

and implementation schedules have been developed with associated costs. There is a tentative NASA commitment to fund the instrument technology development.

The recommended implementation option, one U.S. and one Russian spacecraft with Proton-Star 48 launch vehicle, places most of the payload integration costs with the U.S. It is necessary to accurately estimate these design and integration costs as part of the overall project proposal to NASA.

The launch approval process required for the FIRE mission needs further definition. If the U.S. were to choose the non-nuclear power option, it is unclear what U.S. responsibilities exist with respect to compliance with national and international regulations given that the U.S. part of the payload will not contain nuclear material whereas the Russian part contains an RTG.

Possibilities for participation by additional countries should be explored as a method of cost sharing. For example, there may be interest on the part of the French Space Agency (CNES) to produce the thermal shield required on the U.S. spacecraft in return for French participation in the scientific payload. Opportunities for participation should be identified and pursued, especially when those areas may contribute enabling technology development.

9.5.4 FIRE and Ra

The Ra team recommends to perform the FIRE mission despite all kinds of problems including technological, financial and political ones. It is essential to have both of the spacecraft in this mission since the co-ordinated measurements from the two spacecraft are one of the main ideas of the Fire mission. With only one spacecraft the mission will become much less valuable. The launch by Proton launcher is the most logical way to perform the beginning stage of the mission from the engineering point of view. The governments of Russia and, first of all, USA, must find a way to fund the mission and launch a US spacecraft together with a Russian probe with RTG aboard a Russian launcher.

We would like to emphasise that the Fire mission is supposed to meet very important but still limited range of scientific objectives. Hence it must be just one of missions and efforts on solar exploration described in the Strategic Framework. The scientific results of the Fire mission will be complemented by results of other Near- and Mid-Term research. They will also serve as a basis for future long-term missions.

9.6 Mission to Determine Biological Radiation Effects

The current knowledge relating to the effects of solar radiation has been discussed in section 4.5.2. It is recognised that the solar radiation could present a significant problem to the engineers of a future manned Mars mission. Until more information on the effects of the radiation on the human body and the effectiveness of shielding is known, a future manned Mars mission may not be possible. Secondary radiation, resulting from shielding, is potentially extremely hazardous because of high biological activity.

To quantify the radiation and shielding effects on a biological system (e.g. humans, plants, regenerative life support systems etc.), a tissue equivalent dosimeter should be flown on a spacecraft. This has already been done in LEO on-board the US Space Shuttle missions STS-60, STS-63 and STS-71. Longer duration experiments have been performed on the Russian Mir space station e.g. DOSIMIR 1, ADLET 1, ADLET 2 and ADLET 3. These test have produced useful information [Vana, 1996], but for a mission to Mars or

the Moon the effects of radiation on biological systems above the Van Allen belts needs to be investigated. Therefore an experiment should be flown on a spacecraft in GEO. This experiment would need to:

- measure the direct radiation,
- measure the effects of the direct radiation,
- quantify the usefulness of shielding, by measuring the reduction in radiation, and
- measure the effects of secondary radiation resulting from the shielding.

To study the acute early radiation effects, the biological samples would only need to be returned to Earth if methods of remotely analysing the data were not available. By developing the instrumentation the results could be numerically coded and relayed to the ground in the spacecraft telemetry. This would allow for the experiment to be flown as a payload on virtually any GEO platform. It would also be interesting to study the results along side solar event predictions.

The biological samples would need to be returned to Earth to study the delayed radiation effects. It is proposed that the samples are regularly monitored, for as long as 20 years after the samples are returned to Earth, to determine these delayed hazards. The challenge behind this mission is the data retrieval. One possible way of retrieving the sample would be to fly the experiment on a spacecraft in GEO, then to return the spacecraft to LEO were it could be collected by the US Space Shuttle. The samples could then be returned to the ground for further analysis.

Another useful mission would be to fly radiation experiments to determine a more accurate model of the radiation environment. The main factors to be determined are the temporal and spectral classifications, above the Van Allen belts. With this knowledge more accurate simulations could be performed on Earth, alleviating the need for the complex "return sample" missions.

An instrument that could be used in the above missions is a Tissue Equivalent Particle Chamber (TEPC) [Margit, 1996]. This is based on an ionisation chamber filled with tissue equivalent gas. Particles passing through the detector (mainly with cylindrical shape) ionise the gas and produce electrons and ions. The electrons and ions are collected (for this purpose a high voltage is necessary). The signal obtained is proportional to the energy deposited in the detector volume by the traversing particle. The main feature of a TEPC is that the volume simulated by the detector is in the range of microns. By variation of the pressure of the tissue equivalent gas the sensitive volume can be varied. It is therefore possible to measure the energy deposition in a volume similar to that of a cell. Using this device changes in the composition of the particle spectrum, mainly during solar flares, can be recorded.

An example of how the TEPC could be used on a satellite or space station is to measure the energy deposition every 12 hours for half an hour or in shorter periods during a solar flare. This spectrum can then be recorded on a memo card which can be analysed in the laboratory on Earth. Another possibility is an on-line measurement. For this purpose the recorded signals would be sent to the Earth about once per week.

The dimensions of a TEPC are approximately:

- detector: diameter 6 cm, length 10 cm, mass 0.75 kg
- high voltage supply: about 5 × 20 × 20 cm, 2 kg

- amplifier (including pre-amplifier): about 5 × 20 × 20 cm, 2 kg
- analysis device: about 5 kg
- power supply (220 V) is necessary

9.7 Mid-Term Costing

In this section we will look at costing for the Mid-Term programme of Ra. This stretches from 2000 to 2010 and deals with the costing of the SAUNA mission and the Early Warning System mission.

Costing must be initiated during the conceptual and pre-development phases of a project. It is used to determine the budget, make decisions about the future of the project, evaluate alternatives or compare estimates of the proposals. Science and the constraints of science are increasing [Randolph, 1996]. Costing is an important part of these constraints. It is important to minimise the costs and thereby change the public perception about the efficiency and effectiveness of our space programmes [Scoon, 1996].

The costing tends to provide a project an iterative control process. Costing can be divided into different phases depending on the type of project. Top level costing analysis is used for Ra. This is suitable for future missions where factors like technology might change. All costing in this chapter is done in 1996 US$.

9.7.1 Costing Model Used

In order to estimate the costs of the mission we use the analogy method [Wnuk, 1996]. The cost break down structure is shown in figure 9.22.

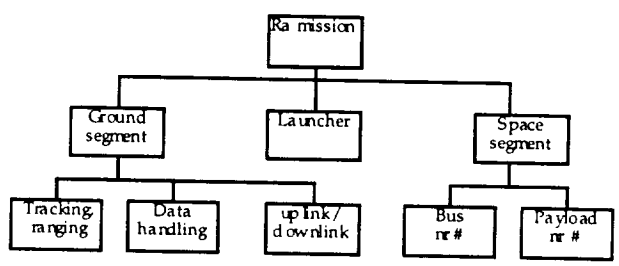


Fig. 9.22 **Cost breakdown structure.**

9.7.2 Costing Statistics

In order to see the cost trend for solar related missions, the costs of 10 solar related missions are analysed. Figure 9.23 shows, for these missions, the cost as a function of the payload mass and the distance from the Sun for 10 different solar related missions. For a detailed list of these missions see appendix A. Costing information for these can be found in appendix D.

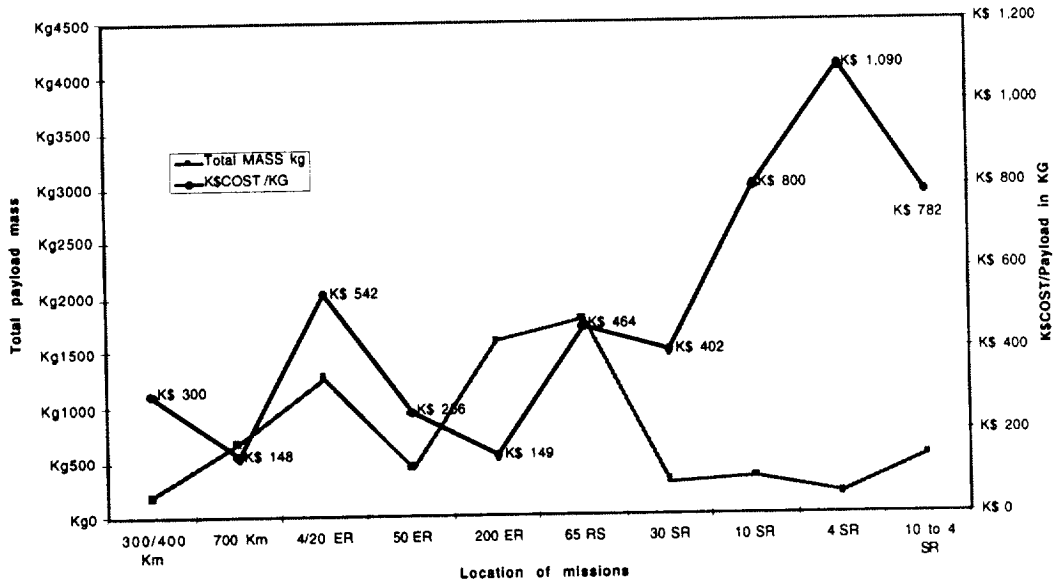


Fig. 9.23 **The cost as a function of payload mass and the distance from the Sun.**

The graph shows:

- For a mission located up to two hundred Earth radii, the average total cost is around 200 k$kg^{-1} payload.
- For a mission located between 10 and 65 R_S, the average total cost is around 400 k$kg^{-1} payload.
- For a mission located between 4 and 10 R_S, the average total cost is around 800 k$kg^{-1} payload.

For launch statistics see appendix D.

These costs are in 1996 US$. To estimate the costs for future missions the inflation must be considered.

9.7.3 Cost Minimisation Methods

Concerning the minimisation of costs, the following global approach could be applied to every future mission:

- Shorten cycle for conceptual assessment and design feasibility studies., from typically 6 months to 3 months as target for conceptual studies, and 24 months to 14 months for industrial design feasibility studies (phase A).
- Reduction of phases B, C, and D from typically 54 months to 42 months.
- Use state of the art technology or inherited space qualified hardware (no technology development in parallel with project development phases).
- A coherent development strategy for ground and on board software, utilising core software modules at subsystem, system and flight system levels.
- Utilise the appropriate level of autonomy to guarantee safety, minimise risks and reduce flight operations costs.

9.7.4 Cost Reduction on Ra Missions

Ground segment:

- Use common ground segments together with other missions and nations.
- Better data distribution by more extensive use of Internet.

Launcher:

- Use of few (combined) launchers when launching constellations.
- New and smaller technology in the space segment brings down the mass and thereby the launcher cost.

Space segment:

- Increased autonomy allows less complex communications. This affects the operation costs.
- Optimise the space segment to the launch segment. This includes mass and volume of space segment.

9.7.5 Costing of the SAUNA Mission

As it was not possible to obtain data of similar missions for all the components of the mission, some data for the costing is obtained by consultation [French, 1996]. For more details see appendix D.

In order to see the relative costs, the cost breakdown is shown in figure 9.24.

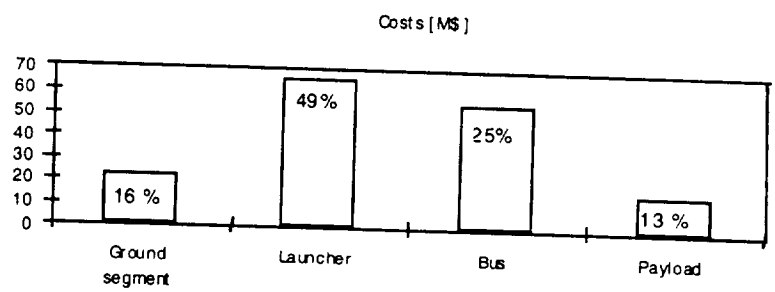


Fig. 9.24 **Cost breakdown for SAUNA mission.**

The total cost for the SAUNA mission is $126 million. In comparison with other (as similar as possible) missions, it is clear that SAUNA is a low budget spacecraft. The launch cost (Delta II) is similar for the different missions. Figure 9.25 shows that the launcher cost is the cost driver. The relative cost of the launcher for SAUNA is 48 %. This is the cost driver on a global scale.

Table 9.25 Cost comparison of SAUNA with similar missions.

MISSION	Location (R_S)	Total cost (M$)	Mass (kg)	Launcher (%)	Space segment	Cost per kg (k$)
2003 Solar Probe FIRE mission	4	218	200	31	69 %	1090
2003 Plamya FIRE mission	10	280	350	29	71 %	800
2003 FIRE mission	4-10	430	550	19	81 %	782
2006 SAUNA	40	160	314	56	44 %	520

9.7.6 Costing Early Warning System Mission

The Ra Application mission consists of 20 probes. A similar analysis as the SAUNA mission is conducted to obtain some top level costing information. Figure 9.25 shows the cost breakdown for Ra Application.

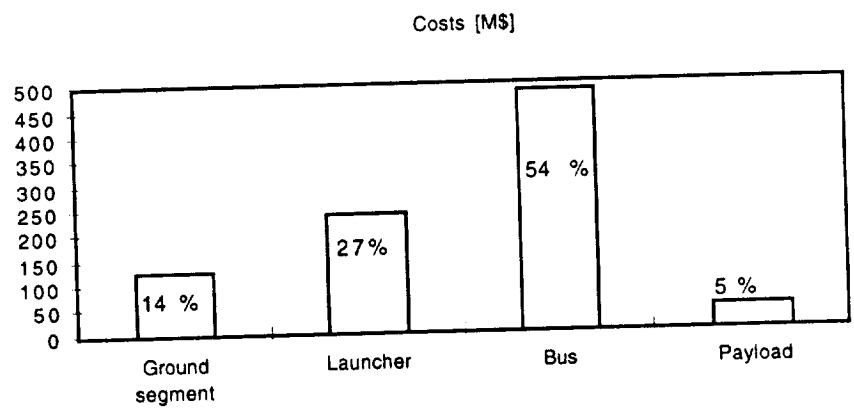


Fig. 9.26 Cost breakdown for Ra Application mission.

Major cost driver for the 20 probes is the manufacturing of the probes. However, the costs are difficult to estimate as multiple production can decrease the cost significantly. This is due to the learning process.

Up to now the costs for the ground segment are not estimated. One possibility is the use of a private distribution company which distributes the raw data and the early warnings concerning solar activity. This would mean that no cost would be related to Ra application for ground control.

Economic risk is bigger if only two big launch vehicles are used rather than if many small launchers are used, however the cost would be lower.

Total projected cost for the Ra Application mission is on the order of $896 million. This cost can be divided into modular packages, starting with a constellation of 3 probes. Instead of creating the whole constellation of 20 probes at once. One step at a time. Initially letting a contract for 3 probes, with options for more later. When these contracts are secured, the number of probes can be increased in modular steps. Table 9.27 shows the cost comparison of the Ra applications mission with other missions.

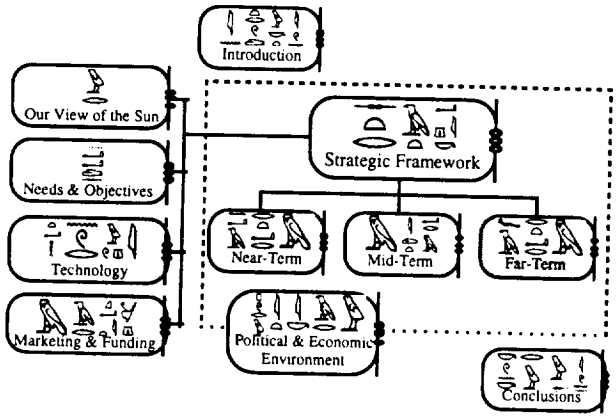
Table 9.27 Cost comparison of Ra application mission with similar missions.

MISSION	Location	Total Cost	Mass (kg)	Launcher (%)	Space segment (%)	Cost per kg
2003 Solar Probe FIRE mission	4 R_S	218 M$	200	31	69	1090 k$
2003 Plamya FIRE mission	10 R_S	280 M$	350	29	71	800 k$
2003 FIRE mission	4-10 R_S	430 M$	550	19	81	782 k$
2006 Ra Application	0.3 AU	800 M$	1800	14	86	450 k$

9.7.7 Risk

One way of costing risk is to look at the insurance cost. It reflects the estimated risk. Example on how to minimise risk could be to spread the risk by using several different launchers.

Chapter 10



Far-Term Programme

The far-term programme of the Ra Strategic Framework is designed to build on the experience gathered during the mid-term programme. We assume that more ambitious, high-cost missions are possible in the long run so long as these are balanced by a proportionally increased economic viability, in terms of commercial exploitation and direct benefits to society. We refer to the Strategic Framework [Chapter 2] where the rationale for the programme is described in detail.

In the present chapter, we will describe the various far-term initiatives in some detail. The reader should keep in mind that these ideas were conceived and elaborated with very relaxed constraints in the areas of funding, politics, and technology.

The far term initiatives which we have investigated are:

- Integrated Solar Science and Applications Programme
- Small Suicide Probes
- World-Wide Space Environment Forecasting System
- Preliminary Solar Power Applications
- Monitoring the Solar Constant and its Effect on Earth Climate

After the description of these initiatives, this chapter will conclude with a discussion of costing of the far term framework.

We urge you to approach these ideas with an open mind and to appreciate their significance in the realisation of our Mission Statement. Several of these ideas also represent logical follow-ons to the near- and mid-term programmes.

10.1 Integrated Solar Science and Applications Programme

The various missions presented in the Strategic Framework so far have been trying to achieve a balance between the two fundamental elements of the Ra Mission Statement: Science and Applications. In accordance with our belief that these two elements are complementary rather than competing interests, we propose ways to enhance this connection.

If there were funds for only one mission to the Sun, how should it be prioritised? Pure science, or direct benefits? In the perspective of the wide open future, the very premise of this question is unacceptable. As has been shown in this report, our future well-being depends both on a thorough understanding of the Sun as well as the means to deal with the threats and potential benefits of the Sun here on Earth. We therefore need a continuing effort to address both solar science *and* applications.

If we remain ignorant and do nothing about the Sun and its effects, one might ask: how much of that ignorance and passivity can we afford?

In the following, we outline ways to couple solar science and applications in an extended, mutually beneficial far-term programme. We have considered:

- Scientific payloads "piggybacking" on applications spacecraft
- Prototype applications sensors flying on science platforms
- The use of a common bus for science and applications missions

In the ensuing discussion, we hypothesise the future reality of one or more of the following possibilities:

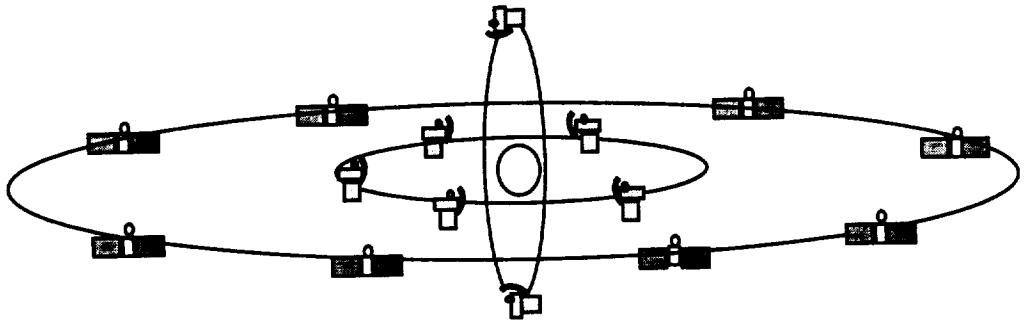


Fig. 10.1 Conceptual Future Network of Sun-Orbiting Spacecraft.

- A fleet of spacecraft could be placed in (a) low orbits around the Sun, (b) in a 1 AU orbit around the Sun, and/or (c) orbiting the Earth, to monitor the variations in the Solar environment.
- These spacecraft could be used for science, applications, or both.
- The funding of such networks would be motivated mainly by commercial applications, with spill-overs to and from science missions.

An example of a heliocentric constellation is shown in Figure 10.1.

10.1.1 Science Payloads Piggybacked on Applications Spacecraft

When a constellation of solar applications spacecraft is established, there are golden opportunities for science to benefit. Not only can the data from the spacecraft sensors be used for scientific purposes, but these spacecraft may allow for small and undemanding science payloads to be accommodated, measuring phenomena not of direct interest to the application in question.

Solar scientists could get extensive amounts of science data at a low cost, and their financial compensation may stimulate the enterprise responsible for the application. Furthermore, such opportunities will relieve space science budgets from some of the burden of dedicated, high-cost platforms.

There may even be a real demand from the commercial viewpoint; the potential competition in the future "early warning" market (reliability and timeliness of predictions) may drive businesses to look for new methods to derive early prediction of solar phenomena. Commercially sponsored scientific research can help providing these new methods by looking for new relationships in solar physics.

10.1.2 Prototype Applications Sensors Flying on Science Platforms

Our next idea is just a mirrored version of the previous one. If a commercial space venture needs to space qualify some critical new technology which would enhance their competitive edge in, for example, the early warning market, it might look for a flight opportunity other than its own operational vehicles.

Science missions could use such participation to strengthen their mission budgets, as long as it is ensured that the added instrument does not reduce the performance of the original science payload.

10.1.3 The Use of a Common Bus for Science and Applications Missions

The realisation of a large fleet of Earth-orbiting and interplanetary spacecraft for solar science and applications is constrained by cost. One possible way to reduce cost may be to introduce a standardised spacecraft bus suitable for a wide range of solar missions and payloads. An example of such a standard bus might be the SAUNA spacecraft [Chapter 9.1], the design of which is not oriented towards any particular payload (however, it *is* constrained in the variety of missions which it can efficiently support). A serial production of such vehicles would likely lead to a substantially lower cost per spacecraft.

A competing factor to standardisation is the desirability of optimisation of the spacecraft bus to the needs of a particular payload. Such optimisation leads to more efficient system performance; however, the associated development costs are higher than for a standardised multi-purpose bus. In essence we are talking about a trade-off between system efficiency and cost.

Depending on the scale of future solar spacecraft fleets, a balance between specialisation and standardisation can be established by introducing, e.g., a limited number of derivatives of a standard bus, each specialised for a certain category of payloads (e.g., imaging instruments, plasma instruments, etc.) and a certain range of missions (solar polar orbits, equatorial orbits of 0.2-0.7 AU, Earth vicinity orbits, etc.). If such a "payload-oriented" derivative bus were chosen for a mission with special needs, the penalty on system efficiency could be brought down with respect to a multipurpose bus, while the development costs for a mission-specific bus can be avoided.

The potential for savings through use of the common multi-purpose bus with derivatives is a function of the scale on which such standard payloads would be flown. The success of such a strategy would also require a strong political commitment to the continued support of a large space fleet. In chapter 3.2, we have proposed a Working Group for International Solar Exploration and Applications (WG ISEA), one of the tasks of which would be to define and support the development of standard reference buses.

Furthermore, cultural changes would be needed in space communities where mission-specific bus design is the unwritten law. Space agencies tend to support this idiom through their desire to retain control over programmatics, resulting in an apprehensive attitude towards externally imposed standards. These factors have effectively resisted moves towards standardisation in the past. A recount of these cases and details on the technical aspects of standardised buses are discussed in Chapter 6.11 of this report.

In summary, the usefulness of common buses depends on the scale of the space fleet and the limited proliferation of special-purpose derivatives from these buses. The success of the common bus concept is therefore a matter of economics and political priorities. The Ra Strategic Framework strongly supports the introduction of common buses for a long-term programme of solar science and applications in which multiple spacecraft would fly essentially identical missions.

10. 2 The Suicide Probe

The concept of a "suicide probe" merits attention when investigating the Sun. Such a probe would be delivered as close as possible to the Sun or even into its surface, depending on the mission requirements and available propulsion and thermal technology. The aim would be to relay as much data as possible before the probe eventually succumbs to the extreme environment. Such a probe would be the first real encounter with the Sun, which can inspire education and awareness [see Section 8.6].

We assume that a suicide probe is launched from a mother spacecraft. The mother spacecraft will bring the probe in the proper orbit and will take care of the communication from the probe to the Earth. From the standpoint Δv, a highly elliptic orbit of the mother spacecraft is an advantage, as we will see in the technology issues. Options for a suicide probe are:

- A piece of appropriate material, the behaviour of the material when it enters the Sun is observed by remote sensing instruments (on the Earth and the mother spacecraft);
- A deceleration triggered, chemical or physical reaction (nuclear bomb), the phenomena are observed by remote sensing;
- An instrument probe with power, thermal protection, and communication to the mother spacecraft, which relays the data to Earth; and
- A dedicated probe with various on-board instruments, thermal protection, power, and communication.

The choice of the probe depends on many factors, like:

- Available funding, which is closely related to the scientific community and the public interest;
- Scientific objectives of the suicide probe; and

- Constraints of the mother spacecraft, such as mass, dimensions and launching capability.

Also the possibilities of a number of probes must be taken into consideration. For the present discussion it is assumed that the dry mass of the mother spacecraft is 150 kg [see SAUNA, Section 9.1]. The mass of the probe should be only a small fraction of the dry mother spacecraft mass, say < 50 kg. In the next section the scientific goals and the technological issues are discussed.

10.2.1 Scientific Goals

The scientific goals of such a probe would be to make *in situ* measurements in the inner corona and deeper layers in the solar atmosphere. Plasma parameters measured *in situ* would need to be combined with good contextual remote sensing observations of the entry site (in the same way as the Galileo probe). *In situ* measurements would seem to be the priority, since higher resolution remote sensing measurements may more easily be made by improving the instrumentation's resolution than by going closer. Detailed evaluations are needed to determine whether flying closer to the Sun is really of more benefit than investing with remote sensing technology.

10.2.2 Thermal Control

Clearly, an instrumented probe presents a huge challenge for thermal protection and high-temperature, radiation-hardened electronics. The issues related to a heat shield are discussed in detail in section 6.7. The maximum temperature of a plain Carbon-Carbon heat shield (before ablation occurs) is about 3000 K. The figure below [Figure 10.2] shows the temperature of a plain Carbon-Carbon heat shield (angle of incidence is 30°). At a distance of less than 2 R_S ablation will occur, which would result in the evaporation of the probe. To go closer to the Sun other materials should be taken in consideration, such as samarium oxide, hafnium carbide and tungsten.

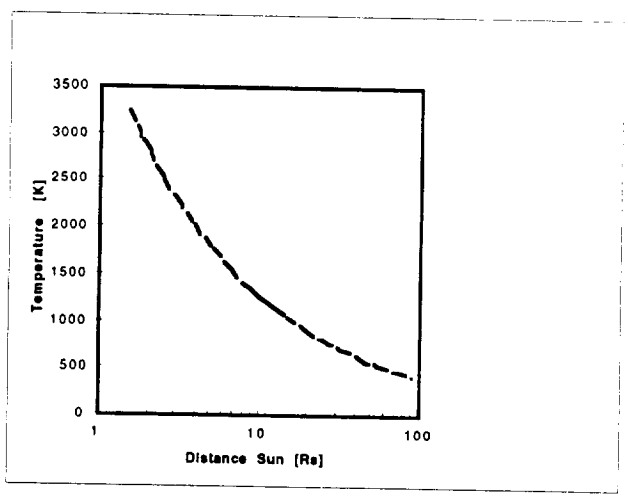


Fig. 10.2 The Temperature of the Heat Shield Near the Sun.

10.2.3 Propulsion

The propulsion system needs to provide the Δv required to cancel the orbital velocity of the mother spacecraft from which the probe is deployed. To estimate this Δv, three trajectories are analysed, from the 0.2 AU circular orbit:

1. Directly to the Sun (Circular), by decrease of the tangential velocity
2. To a gravity assist of Mercury (Mercury)
3. Increase the aphelion (from 200 - 800 R_S is about 1 AU - 4 AU) of the mother spacecraft and launch the probe at the aphelion (perihelion is 40 R_S)

The graph below [Figure 10.3] shows the Δv needed, to launch the probe from the mother spacecraft as a function of the perihelion (minimum distance from the centre of the Sun (1 - 10 R_S)).

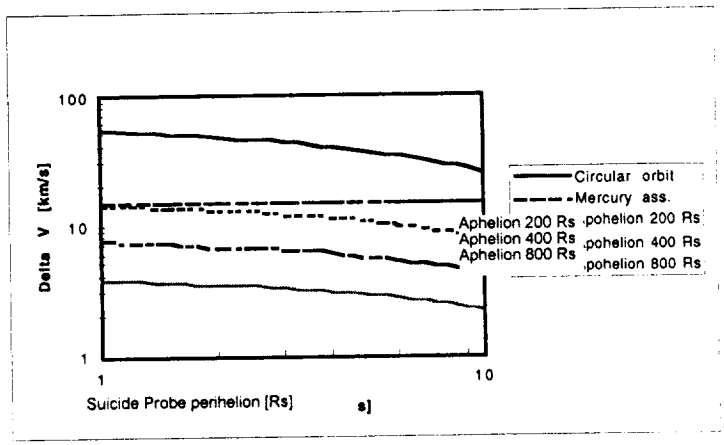


Fig. 10.3 The Required Δv as a Function of Perihelion.

It shows that only the "Aphelion 800 R_S" mission has values in the order of 3 km/s for a distance of 1 R_S from the centre of the sun. The other trajectories all have high Δv values. The next graph shows the mass fraction of a mono propellant with a specific impulse of 220 m/s as function of the distance from the Sun's centre.

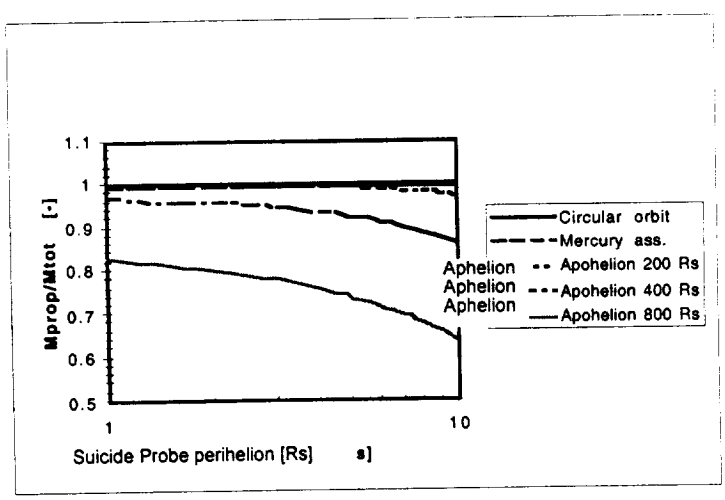


Fig. 10.4 The quotient Mass (propellant)/Mass (Total Initial Spacecraft) as a Function of the Perihelion.

The figure above shows that for a mission to a Perihelion of 2 R_S, a quotient of Mprop/Mtotal, say 0.8, is only possible for the trajectory "Aphelion 800". If the required total mass of the probe is smaller than 50 kg, the required dry probe mass is 10 kg. The

present proposed instruments (magnetometer, e.g.) have a mass of about 3 kg. Moreover, about three of these are needed to obtain valuable scientific information. Innovative design solutions, (miniaturisation) and/or the replacement of electrical systems by mechanical or optical components (nanotechnology) are needed to lower the mass of the instruments. This makes an instrumented probe more feasible.

Another option is to use high-specific impulse propulsion systems, such as an ion engine or solar sailing. However, we expect that the nanotechnology and miniaturisation will decrease the mass of the instrument significantly in the next 20 years. It will then be possible to use a known, low risk, and low cost propulsion system for the suicide probe.

10.2.4 Communication

The following section will deal with preliminary design considerations for the communication sub-system. This section will only look at the scenario where data collected by an instrumental probe needs to be relayed back to a mother spacecraft.

The closeness of the approach, and the small size of the probe, prevent RF communications altogether. The surrounding interference would simply expand the requirement for RF power or impose ridiculous sizes on the probe. It is assumed that the scientific objective for the mission would not be RF propagation study in the outer/inner corona.

Optical links are therefore the only known solution. Spatial resolution of the signal from the probe as it nears the solar disk is achievable, considering the maximum expected distance (2 R_S) before destruction. Accuracies of < 1 microradian are currently achievable [Czichy, 1996]. A more detailed analysis of the Sun's spectrum in order to do a proper selection of the frequency is necessary. A good signal to noise ratio would then be achievable.

There is no scientific requirement for the link to be duplex. The power budget will likely dictate that the probe will not be continuously broadcasting information during the whole trajectory but rather during the last phase of the mission (encounter). The probe should be fully autonomous [See Section 6.10.3] in terms of telemetry, tracking and control. Acquisition of the mother spacecraft as an open-loop system is a bit more tricky as the sensors could be blurred by the proximity of the Sun. The probe could be programmed with the relative position of the mother spacecraft with respect to the Sun or other sources.

Finally, the need for simplicity of the communication system on the probe will be met by an increase on the complexity of the receiving end at the mother spacecraft. One approach could be to have the mother spacecraft act simply as an optical repeater. The light beam could be amplified using standard optical techniques, and relayed back to Earth where coherent detection could be more easily implemented. It remains to be seen if the overall link budget would allow for this, given that amplification at the mother spacecraft would not be regenerative, and noise would be transmitted as well.

10.2.5 Alternatives Probes

An alternative to an instrumented probe is the use of an entirely passive probe. The mother spacecraft would track the projectile and observe effects remotely (the projectile could be designed to produce a known quantity of trace element into the plasma). In the case of a close perihelion instead of direct entry, the parent craft could rendezvous with the projectile afterwards to analyse the effects of the solar environment on the projectile's

constituent materials. However, detailed research is needed to determine the real value of these kinds of probes.

10.2.6 Recommendations

For a suicide probe, the primary objective is the *in situ* measurement of the inner corona and the deeper layers in the solar atmosphere. However, we think that other, more broad objectives such as entertainment and education can be used to obtain funding for the mission. Many people have dreamed for ages about an encounter with the Sun.

To reach the Sun, the probe will be "launched" from a mother spacecraft which is in a highly elliptic orbit around the Sun. We expect that the technology of miniaturisation will make it possible to manufacture low mass instruments (< 1 kg). This is required to keep the total mass of the probe low.

With the present technology of Carbon-Carbon heat shield it is possible to survive down to one solar radii from the surface of the Sun. However, to go closer to the Sun and to decrease the evaporation of the heatshield new technology needs to be developed [See Section 6.7].

The proximity of the approach and the small size of the probe prevent RF communications altogether. Optical links are a possible solution. It is expected that the technology will be available with proper power, size, and wavelength characteristics for a laser communications link with the probe.

10.3 World-Wide Space Environment Forecasting System

When a space environment forecasting system has been established, we must look at the way the information is distributed and applied: Our objective would be to maximise benefits (in the widest sense of the word) to all humankind.

It is not the intention here to sketch the specific infrastructure needed. In the following, let it suffice to characterise some of the measures which would be most effective in fulfilling the above objective:

- The operator/owner (whether commercial or public) of the space and ground segments has the right to ask compensation for the services he provides; however,
- The rates for such services would be based on a "pay according to ability" system for which the coefficients are set by the WG ISEA [see chapter 3] or the United Nations or another representative body of international politics.
- Space environment forecasting data can be compiled from a number of different space vehicles (preferably using a common telemetry format!), belonging to military, governments, space agencies, international organisations, or commercial/private entities.
- The integration of the above data will be made within a forecasting model. The reliability of the forecasts must be very good in order for the system to gain acceptance in the general public. [see section 8.3]
- Developing countries will be able to increase their benefits from the forecasting data through educational programmes run by the WG ISEA or the United Nations. These courses would be aimed at teaching how to use the forecasts to plan effective countermeasures.

- Finally: Political, social and financial interests have to converge in the long run to produce the maximum net "benefit" possible.

The realisation of the above measures can only be made possible by a strong, world-wide political consensus on how to share this data, as well as a sound and efficient global data distribution network.

10.4 Preliminary Solar Power Applications

Whereas protecting Earth and its inhabitants from the threats of our violent Sun is a priority objective in the Ra Strategic Framework, there is also a mandate to take advantage of the enormous solar energy output which continuously comes our way.

In this section we shall briefly point to two applications with a common denominator: Energy from the Sun. The first application relates to the conversion of the Sun's radiation into electric power; the other concerns the direct management of that radiation in terms of heat and light for human habitats. The objective of this part of our far term programme would be to prepare to meet the imminent global energy crisis [O'Neill, 1989]

10.4.1 Prototype Space-Based Solar Power Stations

It is well known that solar radiation can be converted into electrical energy by means of photovoltaic cells. Applying this principle on a large scale in space would provide an inexhaustible energy source. Unfortunately, the establishment of such an infrastructure is at present beyond our financial means due to the cost of space access. To provide energy to Earth at a globally significant scale, hundreds of large-scale solar power stations would have to be constructed in orbit around the Earth.

A first crucial step towards the realisation of such a system would be to set up a scale prototype of a solar power station. This prototype would serve as a demonstrator for several critical technologies related to solar power production in space:

- Assembly and control of very large flexible structures in orbit
- Highly efficient photovoltaic arrays with long lifetimes
- Microwave transmission of power from orbit: power conversion, beam characteristics, pointing accuracy, electromagnetic interference
- Integration of a space power system to existing networks on ground

The recipient of the power from this station could either be a ground station with a small local distribution system, or it could be small spacecraft in the near-Earth region with a high demand for power (e.g. ion engine spacecraft, geostationary communications satellites or Earth observation satellites using active instruments such as microwave radar).

We shall not address the specific ways to implement a large-scale solar power programme in this report; instead we refer to the report produced by the ISU Space Solar Power Program [ISU 1992].

The development of a prototype solar power station is a "second generation application" with respect to the Ra Strategic Framework; initiation of this programme is considered an important applications objective for the far term beyond the year 2020.

10.4.2 Light and Heat Management Systems

The Sun provides heat and light in significant amounts. It would make sense to use this radiation directly for heating and lighting of our houses instead of going through the inefficient process of converting solar radiation to electricity and subsequently convert electricity back to heat and light.

A heliostat (a rotating, sun-tracking mirror) on the roof of a building can channel the solar radiation to the basement. Here, the light is stripped of its thermal components through an infrared mirror. The thermal radiation is used to provide central heating, warm water, etc.; the visible light is distributed to various locations in the building through a network of optical fibres [Scoon, 1996]. The idea is sketched in Figure 10.5:

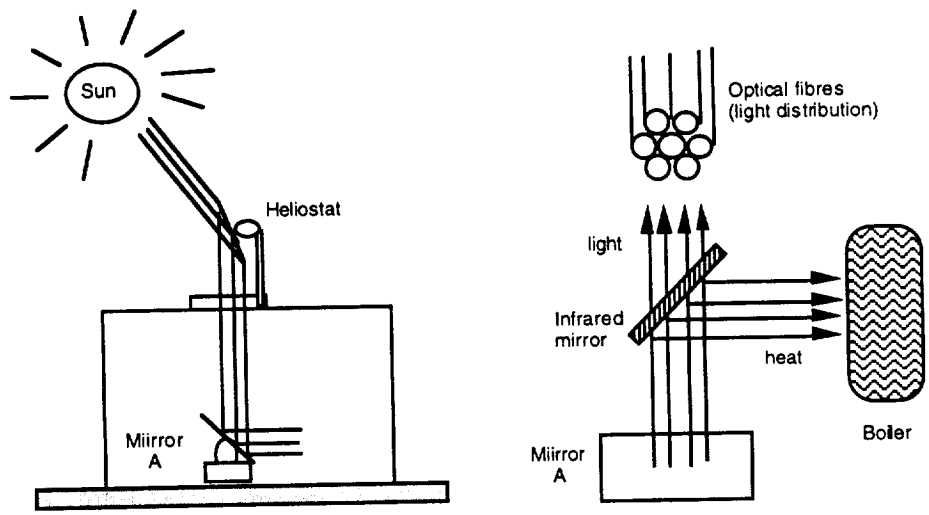


Fig. 10.5 Solar Heat and Light Distribution System for Buildings.

This system would give almost unlimited access to light and heat indoors (by careful energy management, benefits are not limited to cloudless daytime!) which translates to significant savings in electricity. The technology to do this is available now, but due to the architectural problems involved, installation of this system is generally difficult or unfeasible in existing buildings. For this reason, we emphasise the importance of keeping this technology in mind when designing the buildings of the future.

10.5 Monitoring the Solar Effect on the Earth Climate

Any long term monitoring of the solar effect on the Earth climate basically involves two processes: first, monitoring the phenomenon related to the Sun that causes the Earth climate change; and, second, monitoring the effects of that phenomenon on the Earth.

10.5.1 Monitoring the Solar Constant

One of the physical parameters related to the Sun that can be directly measured is the solar constant. Solar constant is a measure of the amount of solar electromagnetic energy that falls on a unit square area per unit time at the mean Earth-Sun distance (1 AU).

The current measured value of the solar constant is 1.37 kW/m^{-2} (± 0.02 kW). It is believed that this value of the solar constant is not actually constant with time. It has been shown by computer models that "fluctuations in the solar constant exceeding a few

tenths of a percentage would have significant climatic effects" [Evans, 1985]. Thus, an accurate measurement of the changes in the solar constant, which is possible only if the measurement is done over a long period of time, is vital to our understanding of the Earth climate.

The monitoring of the solar constant from the Earth, however, has not been accurate because the Earth atmosphere absorbs any electromagnetic radiation within the wavelength range of 2.5 μm and 0.3 μm.

Similarly, monitoring of the solar constant using space satellites, as done by the Solar Maximum Mission, is also possible only for a short duration. This is mainly due to two major problems: first, the measurements are skewed by the electromagnetic noise from the Earth; and, second, by the technical challenge of keeping a satellite, like any airborne object, in orbit for a long duration due to the problem of running out of power-supply, the possibility of the satellite spinning out of control, and the difficulty of doing any kind of maintenance work.

In contrast, if the measuring instruments were to be placed on the Moon, much of the difficulties mentioned above could be overcome. Because of ultra-vacuum on the Moon, unlike on the Earth, there is no radiation absorption by the atmosphere. And, as the distance between the Earth and the Moon is considerable, there is not much problem of electromagnetic noise from the Earth as with satellites on the Earth orbit. Furthermore, the solid ground on the Moon also provides advantages over the Earth and the satellites: the seismic activity on the Moon is very small as compared to the Earth, and thus measurements are more stable. Once the instrumentation has been left in place, it can be left alone for a long time without having to worry controlling its orbit, like in the case of a satellite.

If the instrument were to be placed on the near side of the Moon, it would be able to take fourteen days of continuous measurement of the Sun. If a second instrument were also placed on the far side, the two would provide a continuous uninterrupted measurement. But, instead of placing two instruments on two sides, it would be better to place an instrument on the North or South Pole of the Moon [Burke, 1985]. That way, using only one instrument, it would be possible to make a continuous measurement of the solar constant.

There are two instruments in use at present to measure the solar constant: the older Pyro-heliometer, and the more advanced Active Cavity Radiometer Irradiance Monitor (ACRIM).

There are some technical issues that need to be considered for any of these instruments to function properly. For example, the instrument should be placed in a very high support system to protect it from lunar dust. Some shielding should also be used to protect it from micro-meteorites; cosmic rays, as there are no radiation belts to act as natural shields; and finally, light from the Sun, and the light reflected by the Earth.

10.5.2 Monitoring the Earth Climate

The monitoring of the effects of the solar constant on the Earth climate is made difficult by the fact that the fluctuation in solar constant is only one of many factors involved in the Earth climate change. This, however, does not rule out the significance of measuring the overall climate change on the Earth from the Moon.

Like the monitoring of the solar constant, monitoring of the effects of the solar constant on the Earth can also be done either from Earth-orbiting satellites or from the Moon.

10.5.3 Conclusion

In the long term (beyond 2020), the continuous monitoring of the solar constant and its effects on the Earth climate should be given a high priority. Initially this should be done from satellites, but as technologies mature and the cost of space access goes down, a permanent observation base at one of the Lunar Poles will give the best observing conditions.

10.6 Costing of the Far-Term Programme

Due to the high uncertainties of future developments in global politics, economy, technology and infrastructure, we refrain from even attempting to cost the far-term programme for 2010-2020 and beyond. We recommend instead to take another look at the costing of this programme after the year 2005, when lessons learned from the near-term and many experiences from the mid-term programmes are available.

10.7 Conclusions

For the Far-Term Programme we advocate the following:

- Integrated Solar Science and Applications Programme
- Small Suicide Probes
- World-Wide Space Environment Forecasting System
- Preliminary Solar Power Applications
- Monitoring the Solar Constant and its Effect on Earth Climate

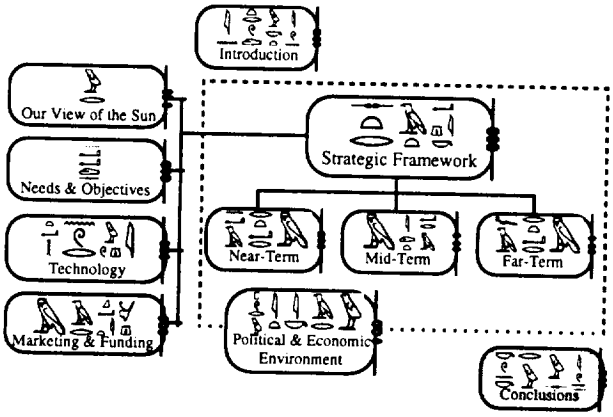
With these missions, we fulfil the following objectives:

- Reducing cost by co-operation in areas of common interest and by exploiting free opportunities
- Exploring the acceleration and heating in the solar corona by means of in-situ measurements
- Enhancing the benefits of a space environment forecasting system for all humankind
- Exploring ways to solve the imminent global energy crisis on Earth
- Study the impact of variations in the solar output on the Earth's climate

The Top-Level Recommendation for the Far-Term Programme is:

- *To focus mainly on the fulfilment of the application objectives related to the Sun as both a source and a threat as well as on the fulfilment of scientific objectives related to the solar physics and theory.*

Chapter 11



Conclusion

The Ra report is a call to action. Knowledge of the Sun is vital to us as humans and to our planet. Our star deserves our attention and study.

We, the Ra team, set out to explore strategies that would increase our understanding of the Sun and its effects, and that would help us apply solar knowledge for the benefit of humankind. We did this through an international perspective and we document our strategies here.

The potential for solar science and applications inspired us to question and to investigate various issues. Strategic planning moulded our investigations into a rationale. It enabled us to formulate a programme or, as we have called it, a Strategic Framework. Policy defined the environment in which we could organise and operate. Costing, marketing, funding, and technology all served as a check and balance, reminding us of reality.

We recommend solar explorations and applications in three time frames: a Near-Term (1996 to 2000), a Mid-Term (2001 to 2010), and a Far-Term (2011 to 2020 and beyond). Each technological, economic, and political issue fits into one of the time frames. In the realm of solar science and applications, deciding for this Strategic Framework means beginning a process that will motivate itself to maturity.

Modest yet effective steps emerge in the Near-Term programme. In it, we focus on activities that are achievable within the next few years. The elements tap into current capabilities and programmes, seeking to improve international management and co-operative structures in preparation for the future.

In the Mid-Term, we focus on more ambitious programmes. Some may require technology development, but all will have implementation times in the first decade of the next century. In this Term, we begin fulfilling high priority science objectives, and envision a continuously operating international solar threat monitoring and early warning system.

The Far-Term programme is characterised by higher risk, by the use of advanced technology, and/or by integrated programmes. Elements benefit from and build on the foundations created earlier. For example, the space threat monitoring and early warning system begun earlier should be mature enough by this time to create a global forecasting system, one that provides benefits to developing nations.

As primary areas of scientific interest, we selected the corona, the solar wind, the Sun's effect on the Earth, and solar theory and model development. In prioritising our objectives, we found it effective to justify importance based on relevance to the Earth.

In the area of applications, we viewed the Sun as a source of resources and of threats. We found it useful to search for possible application spin-offs from science missions, for missions that could be dedicated to a particular application, and for possible future applications that would require technology development. As our principal focus, we chose to focus on threat mitigation, by examining ways to improve solar threat monitoring and early warning systems.

We stress the importance of stereoscopic imaging, of observations at high spatial, spectral, and temporal resolutions, of long duration measurement to provide information on physical processes, and of exploring the Sun's polar regions. The corona must be studied from different observing locations, from closer orbits to the Sun, and by different means. The Cluster mission must be recovered. The physics of the Sun's interior should be emphasised more in the Mid- and Far-Terms. Finally, we place emphasis on monitoring the space weather, forecasting Sun-Earth interactions, and providing early warning of solar threats. All of these activities should be accompanied by continuing efforts in theory and modelling.

We found space environment forecasting to be an increasing market. Existing international solar warning and forecast data distribution networks like the International Space Environment Service will feed data into forecasts, but the advances needed to make solar warnings and forecasts relevant to potential users will require capital investment in hardware, especially in instruments placed between the Earth and the Sun. Meeting user needs will be essential to commercial opportunities within the larger government space warning and forecast services.

Improved measurements and models of the space environment will benefit both manned and unmanned space programmes and thereby constitute a ground for funding. We envision that humanity will be taking serious steps toward the establishment of manned lunar outposts or Mars explorations. Study of solar radiation effects on tissue will be essential. A small but important human dosimetry payload flown prior to any such manned programme is clearly needed. The Ra Strategic Framework has placed such an investigation in the Mid-Term.

We also suggest that entertainment and education markets can be served by the conversion of scientific results. We realise that increasing awareness of solar science and solar-terrestrial interactions beyond the scientific community will foster support for continued solar exploration and applications. Increasing public interest in the Ra programme should increase the availability of governmental funding.

There is a trend toward joint ventures between universities and industry. The universities' research is relevant to industry, and industry funds part of it. We see a trend where Sun activities are moving from being research driven to product/service driven.

The global political environment within which space activities take place is changing for a variety of economic, social, and technological reasons. The current international

situation presents both obstacles and opportunities for solar exploration and applications. We acknowledge obstacles in decreasing national space budgets, and in the relatively low budgetary priority currently placed on solar and heliospheric physics and on solar warning and forecasting services.

Nevertheless, we recognise opportunities for solar exploration and applications. Greater collaboration leads to multilateral co-operative efforts. Less commercial sectors experience enhanced co-operation because of mutual payback opportunities and decreased concern about disproportionate or unilateral technology transfer. The increasing complexity of the global space infrastructure points to an immediate need for improved solar warning and forecasting capabilities. Diminishing rivalries between the various basic and applied sciences facilitate interdisciplinary science missions, and enhance the possibility of joint science and applications endeavours.

We see the combination of diminishing national space budgets, increased opportunities for co-operation, and growing technological capabilities leading to a sustainable emphasis on smaller, modular, networked spacecraft with prioritised objectives. Disciplinary cohesion, inter-agency co-ordination, international co-operation, applications rationales, and smallsat technology offer us a combination of effective organisational means to sustain and even increase solar exploration and applications efforts.

This situation is ideal for the introduction of Ra.

Once the commitment is made to pursue solar science and applications within this Strategic Framework, the question of international organising arises. To that end, Ra has proposed the formation of a Working Group on International Solar Exploration and Applications (WG ISEA) that synchronises independent efforts in different countries and helps to combine their output into products useful on a global scale.

We believe that the WG ISEA would be another example of successful organisation, just as the Inter-Agency Consultative Group for Space Science (IACG) and the International Mars Exploration Working Group (IMEWG) have been. The WG ISEA, supported by small funding from existing sources in the participating countries, has the potential to unify the scientific community's support for solar science and to facilitate the flow from science to applications. It could be the forum for bringing into fruition new benefits for humankind and opening new areas for application and development.

We call attention to the opportune timing with which events will be unfolding during the next year. ESA will most likely be releasing a Call for Ideas for the M4 mission (part of the Horizon 2000 Plus programme). The M4 has presently been reserved for a mission concentrating on the Solar System. The IACG will likely begin the process of choosing its next focal project. Currently, it has been co-ordinating the International Solar Terrestrial Physics Program (ISTP). NASA is planning to bring its Sun-Earth Connections Roadmap to the American space science community for assessment.

Having in place a Strategic Framework dedicated to solar science and applications and a small but broadly-based international WG ISEA would prove most beneficial to the above activities. We hope that this report will help to make that happen.

Appendix A

Overview of Sun Related Missions

In this appendix are reviewed the past, current and planned missions that are related to study of the Sun and/or the Sun-Earth relationship. After a description of the missions, a table individually summarising each one of them is provided.

A.1 Past and Current Missions: Objectives, Characteristics, and Accomplishments

Interest in the Sun has always existed among the world scientific community but the first space study of our star begun only in 1949 by the launch of the U.S. NRL V -2 rocket designed for studying solar X-rays. We must wait up to 1959 with the launch of Luna 1 by USSR and of Pioneer 5 by the U.S. to find the first spacecraft carried instruments to study the Sun and its effects.

In the following lines we will have a short review of the various probes that have been launched up to now, what have been their missions and what contribution did they give to our knowledge of the Sun. The missions are classified in three categories, U.S., Russians or international missions. International missions consist of the missions planned in co-operation between different countries, national spacecraft launched by another country or national spacecraft carrying non national payloads.

A.1.1 American Missions

Skylab :

The Skylab mission was to prove that humans could live and work in space for extended periods, and to expand our knowledge of solar astronomy well beyond Earth based

observations. Skylab was on an Earth orbit, perigee: 434 km, apogee: 442 km, inclination: 50.0°.

Skylab was the first U.S. orbiting space station. It was launched on 14 May 1973, from the NASA Kennedy Space Centre by a Saturn V launch vehicle. Sixty-three seconds after lift-off, the meteoroid shield designed also to shade Skylab's workshop deployed inadvertently and was torn from the space station by atmospheric drag. When the meteoroid shield ripped loose, it disturbed the mounting of workshop solar array number two and caused it to partially deploy. The exhaust plume of the second stage retro-rockets impacted the partially deployed solar array and literally blew it into space. Also, a strap of debris from the meteoroid shield overlapped solar array number one such that when the programmed deployment signal occurred, solar array number one was held in a slightly opened position where it was not able to generate any power.

Approximately 75,000 telescopic images that the Skylab astronauts made of the Sun were added to the knowledge of our most important celestial body. The images were taken in the X-ray, ultraviolet, and visible portions of the spectrum. The pictures strengthen the evidence that the solar corona is more dynamic and complex than previously believed. On 21 January 1974, for the first time a solar flare had been recorded from beginning to end with powerful spaceborne instruments.

On 11 July 1979, Skylab re-entered the Earth atmosphere. The debris dispersion area stretched from the south-eastern Indian Ocean across a sparsely populated section of Western Australia.

Pioneer :

The Pioneer mission consisted of a series of nine spacecraft launched by the U.S. in the sixties and the seventies to study the Solar System and more particularly to collect scientific data on interplanetary environment. The information concerning the Pioneer spacecraft is summarised in table A.1.

Table A.1 Characteristics of the Pioneer satellites.

Spacecraft	Launch Date	Type of Orbit	Life-time
Pioneer 5	11/03/1959	solar orbit 0.8 AU	
Pioneer 6	16/12/1965	solar orbit 0.8 AU	30 years
Pioneer 7	17/08/1966	solar orbit 1.1 AU	29 years
Pioneer 8	13/12/1967	solar orbit 1.1 AU	26 years
Pioneer 9	08/11/1968	solar orbit 0.8 AU	15 years
Pioneer 10	02/03/1972	Interplanetary	Still working
Pioneer 11	05/04/1973	Interplanetary	22 years
Pioneer 12	20/05/1978	Venus orbit	14 years
Pioneer 13	08/08/1978	Venus orbit	Still working

Among all the information gathered by these spacecraft, several were related to the Sun. Their measurements helped to increase our knowledge about solar wind, cosmic rays, structure of plasma, magnetic fields, physics of particles and solar flares. The Pioneer probes were originally designed to last at least 6 months in the space environment, but most of them have had a life-time of over 20 years.

OSO :

The OSO (Orbiting Solar Observatory) mission consist of 8 satellites launched by the U.S. from 1962 to 1975 to Earth circular orbit at an altitude around 550 km and inclination around 33°. The information concerning the satellites is summarised in table A.2.

Table A.2 Characteristics of the OSO spacecraft.

Spacecraft	Launch Date	Type of Orbit	Life-time
OSO 1	07/03/1962	Earth orbit 575 km	1 year
OSO 2	Failure		0
OSO 3	08/03/1967	Earth orbit 550 km	2.5 years
OSO 4	18/10/1967	Earth orbit 550 km	4 years
OSO 5	22/01/1969	Earth orbit 555 km	6 .5 years
OSO 6	08/1969	Earth orbit	3.5 years
OSO 7	29/09/1971	Elliptic Earth orbit 330/575 km	3 years
OSO 8	21/06/1975	Earth orbit 550 km	3 years

The OSO mission has collected data on gamma rays, X-rays, solar flares and energy spectrum.

IMP:

IMP (Interplanetary Monitoring Platform) mission consists of several satellites launched by NASA in the seventies.

IMP 6 has been launched in March 1971 on an elliptical Earth orbit with apogee at some 200,000 km, it was designed to study gamma rays (intensity and energy) and to monitor solar flares. The mission ended on September 1972 due to a failure of the gamma rays instrument.

IMP 7 has been launched in September 1972 to replace IMP 6 and has been carrying on the same mission up to October 1978.

IMP 8 has been launched by NASA in October 1973 to make measurements on magnetic fields, plasma and charged particles in the magnetotail, magnetosheath and in the near Earth solar wind. It was sent to a near circular Earth orbit at a distance of 35 R_E. The spacecraft is still in operation today and provides valuable data very useful to understand long term solar evolution.

SOLRAD :

SOLRAD is a series of satellites launched by the U.S. Navy in the seventies to study the Sun. SOLRAD 10 launched in July 1971 was posted to an elliptical Earth orbit with apogee at 630 km, perigee at 436 km and inclination of 51°. It was carrying 14 instruments to study electromagnetic radiation coming from the Sun. SOLRAD 11 A/B were launched together in March 1976 to a circular Earth orbit at an altitude of 20 R_E. They were carrying instruments to study particles and cosmic rays.

Voyager :

The Voyager mission was composed of 2 spacecraft, Voyager 1 launched in September 1977 and Voyager 2, launched in August 1977. They were designed to follow on the Pioneer mission, by studying Jupiter and Saturn and collecting data on the interplanetary medium. Concerning the Sun, the Voyager spacecraft have carried various instruments to make measurements during their journey across the solar system. They have collected data on particles, cosmic rays and magnetic fields . By studying their radio emissions, scientist discovered that the heliopause exists some 90 to 120 AU from the Sun.

Solar Max :

The Solar Maximum Mission spacecraft was launched in February 1980 to a 28° inclined Earth orbit at an altitude of 500 km. It was designed to provide observations of solar flares during a period of maximum solar activity and then collected data on solar flares energy, particle acceleration, CMEs and formation of hot plasma. In January 1981, there was a malfunction and SMM was recovered by the Space Shuttle Challenger in April 1984 and serviced in orbit. The mission ended in November 1989.

Sampex :

Sampex stands for Solar Anomalous Magnetospheric Particle Explorer, it is the first part of the U.S. SMEX (Small Explorer) programme. It was launched in July 1992 on a 82° inclined elliptical Earth orbit, at an altitude of 520/670 km. As its mission was to make measurements on particles, its payload was composed of the most sensitive particles sensors ever flown in space at that time. Sampex studies the energy, the composition and the charge states of particles coming from solar flares. It is still in operation today.

Spartan :

Solar Spartan is a mission flown by the shuttle in August 1993. The spacecraft is launched by the shuttle, deployed in space for a certain amount of time, then recovered and returned back to Earth for data analysis and maintenance for the next mission. The orbit of Spartan is elliptical with apogee at 311 km, perigee at 295 km, and an inclination of 57°.

Spartan carries an ultraviolet coronal spectrometer and a white light coronograph to study solar wind acceleration by examining particles temperature and densities and solar wind velocities.

A.1.2 Russian Missions

USSR started to study the Sun and the Sun-Earth interactions from the very beginning of its national space programme. *Luna probe series* were the first to discover the solar wind. "Luna-1" on 2 January 1959 was the first lunar flyby. It discovered the solar wind whose existence was later confirmed by "Luna-3".

In 1960's-1980's satellites from the series *"Cosmos", "Electron", "Prognoz", "Intercosmos"* continued the Sun studies. Regular launching of the high-apogee satellites of the *"Prognoz"* series made it possible to conduct unique studies of the structure of the shock wave near the Earth. The apogee of its orbit is about 200,000 km. "Prognoz-8" studied plasma waves and accelerated electrons. Intershock experiment carried on the "Prognoz-10" measured the parameters of the plasma, energetic particles, plasma waves, electric and magnetic fields near and inside the front of the near-Earth and interplanetary shock waves, The front's structure and its dependence parameters of the plasma flow in front of the shock wave were also studied. *Oreol* satellites launched into polar orbits, made possible to investigate the regions

and mechanisms of direct penetration of the solar wind into the magnetosphere. *The Intercosmos*-Bulgaria-1300 satellite made research of the physical processes in the ionosphere and magnetosphere of Earth and their interrelationships. *Gamma Space Observatory* was operating in 1990-1992, and has registered gamma rays (1011-1012 GHz, up to 29 eV) in solar flares [Sagdyev, 1991].

CoronaS aimed to study solar activity mechanism, to improve the knowledge about its internal structure, to study of magnetosphere-ionosphere processes. "CoronaS-I" was launched on the 02 March 1994. They work only on illuminated part of orbit in two modes: 4 and 1-2 data downlinks a day corresponding to high and low solar activity, respectively. [Pazhchenko, 1993]

Interball is a part of "Space Fleet" which includes SOHO, WIND, POLAR, Interball-1&2, GEOTAIL, CLUSTER). The primary objective of the mission is detailed study of the energy, momentum and mass transfer in the critical regions of the solar wind/magnetosphere system.

The "Interball constellation" consists of 2 pairs of satellites (4 altogether): 2 for magnetospheric tail; 2 for auroral studies in polar cusps. Each pair consists of a large Russian satellite Prognoz-M2 and a smaller Czech sub-satellite "Magion". The first pair was launched on 3 August 1995; the second pair was to be launched in August 1996 [Lisov I., 1995].

A.1.4 International Missions

Helios :

Helios is a German/U.S. mission composed of two satellites. Helios 1 was launched in December 1974, started working in March 1975 and ended its mission on March 1986 after one solar cycle life-time. Helios 2 was launched in January 1976, started working on April 1976 and ended its mission on January 1981. Both of them were posted on a solar elliptical orbit, in the ecliptic plane with a 0.3 AU (64 R_S) perihelion.

They were designed to study particles, dust, cosmic radiation, magnetic fields, solar wind and to verify the theory of gravitation. Up to now, the Helios mission stills the closest mission to the Sun.

SIGNE 3 :

SIGNE 3 was a small French spacecraft launched in June 1977 by the Russians to an elliptical Earth orbit with apogee at 519 km, perigee at 459 km and inclination of 50.66°. Its has been carrying instruments to study gamma rays and solar UV radiation.

ISEE :

ISEE (International Sun Earth Explorer) programme is composed of 3 satellites, the first and third built by NASA, while the second was built by ESA. ISEE 1 and 2 were launched on October 1977 on coincident Earth orbit. ISEE 3, also called ICE, was launched on August 1978 to the L1 Lagrange point.

ISEE 3 has been designed to study solar flares and cosmic gamma rays burst. Its first mission was completed in 1982, then the satellite was manoeuvred to intercept the comet Giacobini-Zinner. It flew through its tail in September 1985. In 1990 ISEE 3 was posted to a solar orbit with an aphelion of 1.03 AU, a perihelion of 0.93 AU and an inclination of 0.1° to study CMEs.

Ulysses :

Ulysses is an international programme, done in co-operation between NASA and ESA. It was launched in October 1990 towards Jupiter and used its large gravitational field to accelerate out of the ecliptic plane. Ulysses has made observations of the southern latitudes of the Sun from June to September 1994, crossed the ecliptic in February 1995 and travelled trough northern solar latitudes from June to September 1995. As its orbital period is six years, the next high latitudes observations will be provided in 2001 during a maximum activity period of the solar cycle.

Ulysses is designed to study and monitor solar flares and detect and localise cosmic gamma rays bursts. It is the first spacecraft designed to study high solar latitudes.

Yohkoh :

Yohkoh is a Japanese satellite carrying Japanese, American and British experiments. It has been launched from Kagoshima in August 1991 on an elliptical low Earth orbit with an apogee of 730 km and a perigee of 570 km. The spacecraft is designed to make observations of high energy phenomena of the Sun such as flares and others coronal events.

Geotail :

Geotail is a Japanese/American spacecraft part of the International Solar Terrestrial Physics (ISTP) programme. It has been launched in July 1992 to an elliptical Earth orbit with maximum apogee at 200 R_E, in November 1994 the spacecraft has been manoeuvred to a near Earth orbit with an 8 R_E perigee and a 30 R_E apogee. The principal mission of Geotail is to measure the global energy flow and the transformation in the magnetotail.

Wind :

Wind is an American spacecraft part of the ISTP project. It has been launched in November 1994 to an elliptical orbit with maximum apogee of 250 R_E. It will be kept on this orbit for 2 years and then will be moved to the L1 Lagrange point. Its objectives are to collect data on plasma, energetic particles and magnetic fields, to investigate the processes of plasma and to provide information to be correlated with Ulysses measurements.

SOHO :

SOHO is an ESA/NASA programme part of the ISTP project. It was launched on December 1995 to the L1 Lagrange point where it is now able to perform permanent observations of the Sun. Its principal objectives are to provide data on the corona, the acceleration of the solar wind, the solar interior and the solar atmosphere.

Polar :

Polar is the second contribution of NASA to the ISTP project. It was launched in February 1996 to an Earth polar orbit, with a 2 R_E perigee and a 9 R_E apogee. Its principal objectives are to measure plasma particles and fields in polar regions, to study auroral plasma and to provide auroral images.

A.2 Planned Missions: Objectives, Characteristics, and Challenges

Here, we will describe today's known proposed missions. Some of them have been already approved by governments and are planned for the following years, others are advanced projects that still looking for funding up to now.

As it was done for the past and current missions, we have classified the missions by nationality. As co-operation is more and more needed in future space programmes we have found only two categories, U.S. missions and international missions.

A.2.1 American Missions

Fast :

Fast is the second SMEX spacecraft, it is planned to be launched in August 1996 by a Pegasus launcher to a polar highly elliptical Earth orbit with an apogee of 4200 km and a perigee of 300 km. The mission of the spacecraft is scheduled to last at least 1 year and consist of four experiments on electric fields, magnetic fields, ions and electrons.

ACE :

The ACE (Advanced Composition Explorer) is a NASA mission planned to be launched in August 1997 to the L1 Lagrange point. The spacecraft payload composed of nine instruments is designed to study the solar corona, the interplanetary and local interstellar medium and the galactic matter.

Trace :

TRACE (Transition Region And Coronal Explorer) is another part of the SMEX project, it is planned to be launched in September 1997 to a Sun-synchronous circular Earth orbit at an altitude of 700 km. The objectives of this spacecraft are to study the connection between the heating of the Sun's corona and the magnetic fields.

Timed :

Timed (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) is scheduled to be launched in September 1998 to an circular Earth orbit with 74.4° inclination at an altitude of 600 km. Its principal objective is to study the energetics of the MLTI (Mesosphere and Lower Thermosphere/Ionosphere) region.

HESI :

HESI is a NASA new small satellite designed to be launched not later than year 2000 by a Pegasus launcher. It will be posted to an equatorial circular Earth orbit at an altitude of 600 km. Its payload consist in only one instrument, HEISPEC (High Energy Imaging SPECtrometer) spectrometer which will provide colour movies of solar flares in X-rays and gamma rays.

IMAGE :

IMAGE (Imager for Magnetopause to Aurora Global exploration) is a MIDEX (Medium Class Explorer) class mission designed to study the response of the magnetosphere to any change in the solar wind. It will be launched to an elliptical Earth orbit with apogee at 7 R_E, perigee at 500 km and inclination of 90°.

A2.2 International Missions

Cluster :

Cluster was a 4-spacecraft combined ESA/NASA programme, part of the ISTP project, scheduled to be launched by the first flight of Ariane 5. As the flight was not a success, the four satellites were lost in June 1996.

The Cluster satellites were planned to be posted on an elliptical Earth orbit with an apogee at 19.6 R_E and a perigee at 4 R_E. They were supposed to collect data on the Magnetopause, the polar cusps, the Magnetotail, the plasma sheet boundary layer and the auroral zone.

SAC B :

SAC (Satélites de Aplicaciones Cientifícas) is a co-operation mission between NASA and the CONAE (Argentina Space Agency). The spacecraft is scheduled to be launched at the end of 1996 by a Pegasus launcher. Its orbit will be Earth circular at an altitude of 550 km with an 38° inclination. The satellite will study solar flares, gamma rays burst, X and cosmic rays and energetic neutral particles.

Plamya :

Plamya mission is the Russian contribution to the U.S./Russia Sun exploration project (see U.S. contribution below). It is expected to be launched not later than year 2003 may be in a combine Proton launch with the Solar Probe spacecraft. Plamya will be posted to an elliptical Sun orbit with a perigee at 8/10 R_S in the ecliptic plane. It will carry instruments to measure magnetic fields, particles, cosmic rays and to study corona from a very close point of view.

Solar Probe :

Solar probe is the U.S. proposed mission to be done in co-operation with Russia to investigate as far as possible into the Sun corona. Its launch date is expected not later than year 2003 to an elliptical Sun orbit with a perigee at 4 R_S in the ecliptic plane. Its mission is very ambitious and would help to answer fundamental questions on the heating of the corona and the creation of solar wind.

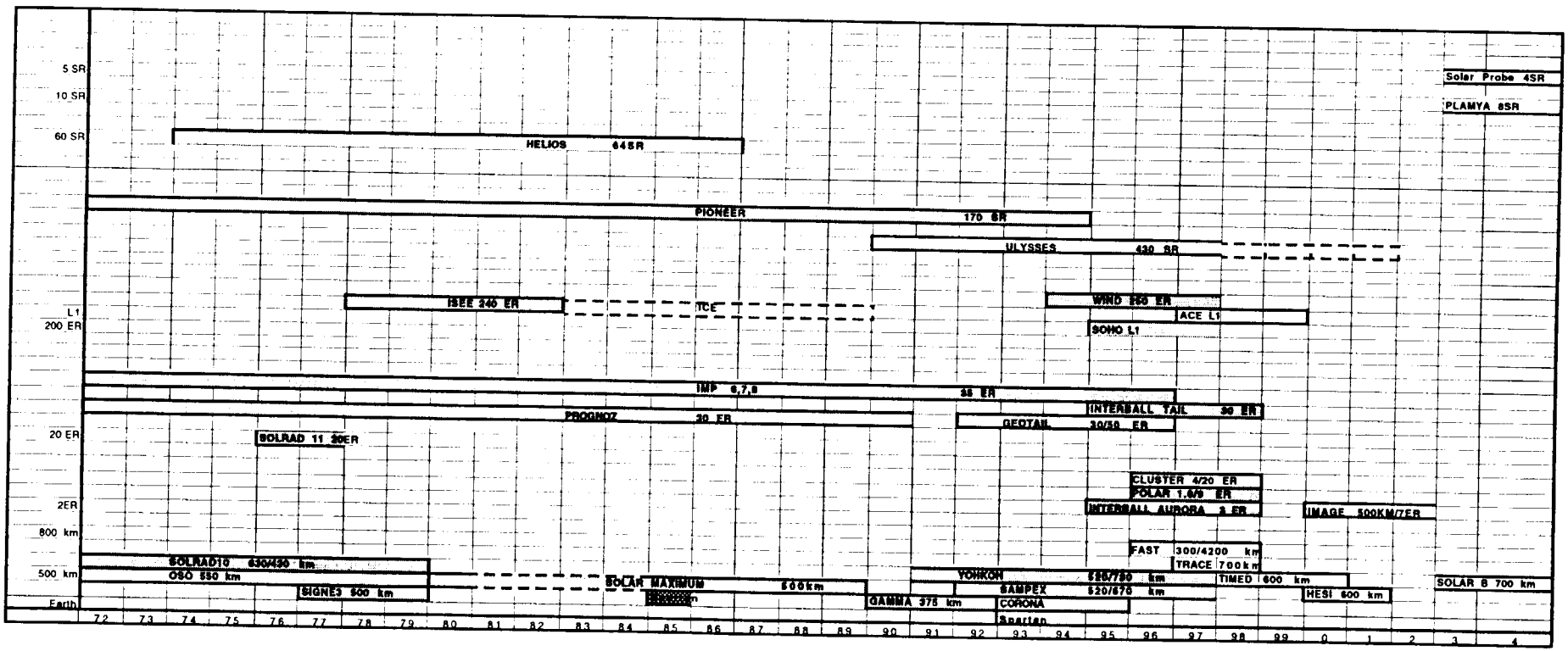
Solar B :

Solar B is a co-operation between Japan, USA and the UK to follow on the Yohkoh mission. It is scheduled to be launched in August 2003 on a circular, polar, Sun-synchronous, Earth orbit at an altitude of 700 km and an inclination of 97.9°. Its objectives will be to provide co-ordinated measurements of optical radiation, EUV and X-rays coming from the Sun to improve our knowledge of solar activities.

A.3 General Synthesis

The history of solar exploration is synthesised in table A.3. It contains all the spacecraft we have presented before except Voyager and Luna which are on interplanetary trajectories. The x-axis consists of the time line, from 1972 to 2004 while the y-axis represents the location of the satellite between the Earth and the Sun. For Earth orbits the distance is in kilometer, for near Earth orbits the distance is in R_E from the Earth, for intermediate and close to the Sun orbits the distance is in R_S from the Sun. As the reference is the ecliptic plane Ulysses does not fit very well in this chart but its mission is too important and for the moment unique so we think we have to show it anyway.

Table A.3 History of the Sun's observation.



Mission Name: HELIOS 1/2

Germany, USA

Launching date: H1 10/12/74, H2 15/01/76

Life-time: H1:, 05/03/86, H2: 08/01/81

Launcher: TITAN CENTAUR

Launching site: Cape Canaveral

Size:

Mass: 370 kg

Trajectory: Elliptic Sun orbit in the Ecliptic plane, Pe = 0.29 AU, Ap = 1 AU

ACS: Single spin 1 rps

Source of Power: Solar cells,SI

Electrical Power:

Communications: S Band

Data Flow: 8 to 4096 bps

Instrumentation:

- Dust particle recorder and analyser, Particle analyser
- Triaxial fluxgate magnetometer mounted on a 2.75-m boom to make magnetic field measurements up to 4 Hz. Two measurement ranges were used, ±100 and 400 nT with resolutions of ±0.2 and 0.8 nT
- Boom-mounted, triaxial-fluxgate magnetometer, four ranges ±16, 48, 144,and 432 nT per sensor, resolutions of ±0.03, 0.09, 0.28, and 0.84 nT, respectively
- Magnetometer designed to investigate the magnetic component of electromagnetic waves up from plus or minus 8.75 nT to ±275 nT in three orthogonal directions from 4 to 128 Hz
- 1 antenna and 2 radio wave receivers, cosmic ray detector
- Zodiacal light photometer, Transponders of 2 spacecrafts H1 & H2

Mission Name: IMP-8

USA

Launching date: 26/10/1973

Life-time: on going

Launcher: DELTA

Launching site: Cape Canaveral

Size: diam=1.35m, height=1.57m

Mass: 371 kg

Trajectory: Near circular at 35 R_E

ACS:

Source of Power: Solar arrays

Electrical Power: 150 W

Communications: VHF

Data Flow: 1600 bps

Instrumentation:

- Magnetic Field Experiment: triaxial fluxgate magnetometer w/ 3 dynamic ranges of ± 12, ±36, and ±108 nT
- Solar Plasma Faraday Cup: Electrons: 17 eV - 7 keV; Positive Ions: 50 eV - 7 keV
- Solid-State Detectors: energies 0.1 to 10 eV per charge in 12 bands; charges of Z = 1 - 8
- Measurement of Low-Energy Protons and Electrons: 16 energy intervals between 5 eV and 50 keV, Energetic Electrons and Protons, Electrons and Hydrogen and Helium Isotopes
- Cosmic Ray Nuclear Composition
- Charged Particle Measurements Experiment (CPME), Solar and Cosmic-Ray Particles, Solar Plasma Electrostatic Analyzer
- Electrostatic Fields: pair 70 m antennas; 1 Hz - 1 kHz, intrinsic sensitivity of 1.0E-5 V/m
- Electrostatic Waves and Radio Noise: three antenna system; E-field: 0.3 Hz - 200 kHz; B-field: 20 Hz - 200 kHz

Mission Name: ISEE (International Sun-Earth Explorer)

USA, Europe

Launching date: ISEE 1&2 on 22/10/1977,
ISEE 3 on 12/08/1978
Life-time: ISEE 3 operational
Launcher:
Launching site:

Size: **Mass:** 390 kg

Trajectory: 1982:L1, 1990:Heliocentric orbit Ap=1.03 AU, Pe=0.93 AU

ACS: Single spin 20 rpm

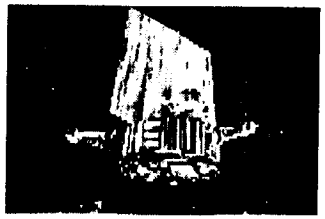
Source of Power: Solar cells **Electrical Power:** 173 W

Communications: **Data Flow:** 2048 bps

Instrumentation:

- Solar wind plasma, 2-D & 3-D distribution fonctions proton: 150eV - 7keV; electron: 10eV-1keV
- Vector Helium Magnetometer
- Low-Energy Cosmic Rays
- Medium Energy Cosmic Rays, 1-500 MeV/n, Z = 1-28; Electrons: 2-10 MeV
- High-Energy Cosmic Rays, H to Ni, 20-500 MeV/n
- Cosmic-Ray Energy Spectrum, H-Fe 30 MeV/n - 15 GeV/n, Electron: 5-400 MeV
- Plasma Waves Spectrum Analyzer 17 Hz - 100 kHz (E); 0.3 Hz-1 kHz (B)
- Energetic Particle Anisotropy Spectrometer (EPAS)
- Interplanetary and Solar Electrons 2 keV to > 1 MeV
- Radio Mapping of Solar Wind Disturbances (Type III bursts) in 3-D; 30 kHz - 2MHz
- Solar Wind Ion Composition, 300-600 km/s 840 eV/Q to 11.7 keV/Q; M/Q = 1.5 to 5.6
- Cosmic Ray Isotope Spectrometer 5-250 MeV/n; Z=3-28; A=6-64; (Li-Ni) - Ground Based Solar Studies
- X- and gamma-Ray Bursts, 5-228 keV
- Gamma-Ray Bursts, 0.05-6.5 MeV Direction, Profile, Spectrum

Mission Name: OSO series (1-8)



USA

Launching date: OSO 1on March 1962, OSO 8 on June 1975
Life-time: Average of 2 years
Launcher: Delta
Launching site: CapeCanaveral

Size: diameter 1.2 m **Mass:** 200 kg

Trajectory: Earth circular orbit 575 km

ACS: Single spin 1.7 s period

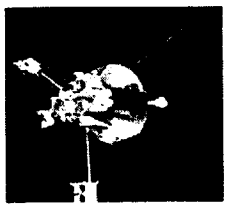
Source of Power: Solar cells **Electrical Power:**

Communications: **Data Flow:** 200 bps

Instrumentation:

- X ray detector,
- Gamma ray experiment: measurement of intensity, directional properties

Mission Name: Pioneer series



USA

Launching date: P5 on 11/03/1959, P13 on 08/08/1978
Life-time: Nearly 25 years
Launcher: Atlas / Centaur
Launching site: Cape Canaveral

Size: long: 2.9 m, diam: 2.7m **Mass:** 270 kg

Trajectory: Asteroid belt, Jupiter, Saturn,....

ACS: Spin Stabilized

Source of Power: 4 RTG **Electrical Power:** 480 W

Communications: S Band **Data Flow:** 49 kbits Storage

Instrumentation:

- Charged particle instrument,
- Trapped radiation detector,
- Cosmic ray telescope,
- Geiger tube telescope,
- IR imager,
- UV photometer,
- Helium Vector magnetometer,
- Flux gate magnetometer
- Plasma analyser

Mission Name: Prognoz

USSR, France

Launching date: Prognoz 1 14/04/1972, Prognoz 10 26/04/1985
Life-time: 13 years
Launcher: Molnia M
Launching site: Tyuratam

Size: diam=2m, height= 0.925m **Mass:** 900 kg

Trajectory: Earth elliptic Orbit, Pe=600km, Ap=200.00km

ACS: Single spin

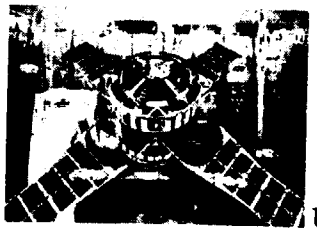
Source of Power: Solar cells, Batteries **Electrical Power:** 250 W

Communications: **Data Flow:**

Instrumentation:

- SIGNE X-ray and Gamma ray detector, 8 channels (0.4 to 11.8 MeV)

Mission Name: SIGNE 3



USSR, France

Launching date: 17/06/1977
Life-time: 2 years
Launcher: MOLNIAM
Launching site: Tuyratam

Size: diam=0.7m, height=0.8m **Mass:** 103 kg

Trajectory: Elliptical Earth orbit Pe=459 km, Ap=519 km, I=50.66°

ACS: Single spin, cold gas jets

Source of Power: Solars cells **Electrical Power:**

Communications: **Data Flow:**

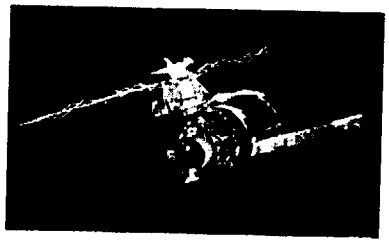
Instrumentation:

Gamma ray telescope,

Gamma ray spectrometer,

UV experiment

Mission Name: Skylab



USA

Launching date: 15/05/1973
Life-time: 6 years
Launcher: Saturn V
Launching site: Cape Canaveral

Size: **Mass:** 90607 kg

Trajectory: Earth orbit Ap=442km, Pe=434km, I=50 °

ACS:

Source of Power: Solar arrays **Electrical Power:**

Communications: **Data Flow:**

Instrumentation:

- Imaging cameras
- White-light coronagraph
- Ultraviolet scanning polychromator-spectroheliometer
- Extreme ultraviolet and X-ray telescope
- Space manufacturing experiments
- Externally mounted Earth resources instruments included a multispectral imaging camera, an Earth terrain camera, an infrared spectrometer, a multispectral scanner, a microwave radiometer and altimeter, and an L-band microwave radiometer

Mission Name: SMM (Solar Maximum Mission)

USA

Launching date: 14/02/1980
Life-time: 14/02/1980 - 02/12/1989
Launcher: DELTA
Launching site: Cape Canaveral

Size: diam=2.3m, length=4m **Mass:** 2315 kg

Trajectory: Circular Earth orbit, altitude=500 km, I=28 °

ACS:

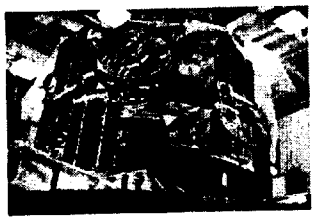
Source of Power: Solar cells **Electrical Power:** 3000 W

Communications: **Data Flow:**

Instrumentation:

- Coronograph polarimeter
- Ultraviolet spectrometer and polarimeter
- X-ray polychromator
- X-ray imaging spectrometer
- X-ray burst spectrometer
- Gamma ray spectrometer
- Active cavity radiometer irradiance monitor

Mission Name: SOLRAD



USA

Launching date: Solrad 1008/07/1971, Solrad 11 A?B 15/03/1976
Life-time: Solrad 10: 8 years, Solrad 11: 1 year
Launcher:
Launching site: Cape Canaveral

Size: diameter 0.76m, height 0.59 m **Mass:** 118 kg

Trajectory: Solrad 10 elliptical Earth orbit Ap=630 km, Pe=436 km, I=51 deg

ACS: single spin 60 rpm

Source of Power: Solar cells **Electrical Power:**

Communications: **Data Flow:**

Instrumentation:

-2 Gamma ray burst instrument, 4 channels (0.2-0.3, 0.3-0.4, 0.4-0.6, 0.6-2 MeV)

Mission Name: Voyager

USA

Launching date: V1 on 05/09/1977, V2 on 20/08/1977

Life-time: up to 2015

Launcher: Titan 3 Centaur

Launching site: Cape Canaveral

Size:

Mass: 721 Kg and 825 kg

Trajectory: Interplanetary gravity assist

ACS:

Source of Power: Nuclear batteries

Electrical Power:

Communications:

Data Flow:

Instrumentation:

Imaging system
Infrared spectrometer
Ultraviolet spectrometer
Photopolarimeter
Planetary radio astronomy
Magnetometers
Plasma particles detector
Low particles detector
Low energy charged particles detector
Plasma waves radio receiver
Cosmic ray telescope

References:

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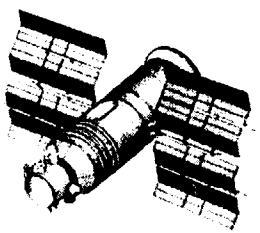
  " Mashinostroenic" 1991
  Pashchenko A: Aviation and Cosmonautics
  " Aristotel and Coronas"
- DLR: http://www.op.dlr.de/wt-rm

Mission Name: GAMMA



Launching date: 11/07/1990

Life-time: 2 years

Launcher:

Launching site: Plesetsk

Russia / France

Size: **Mass:**

Trajectory: Circular Earth orbit Alt = 375 km, I = 51.6°

ACS:

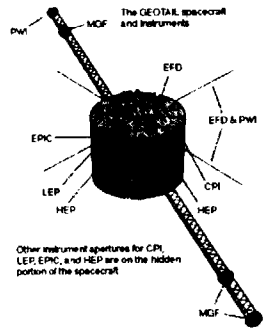
Source of Power: **Electrical Power:**

Communications: **Data Flow:**

Instrumentation:

Gamma 1 telescope, disk M telescope, Pulsar X2 telescope

Mission Name: GEOTAIL



Launching date: July 1992

Life-time: Continues

Launcher:

Launching site: Cape Canaveral.

Japan / USA / ISTP

Size: D = 2.2 m, H = 1.6 m **Mass:**

Trajectory: Earth elliptical orbit Ap = 200 ER, Pe = 8 ER, I = 85 deg.

ACS: Single spin, 20 rpm.

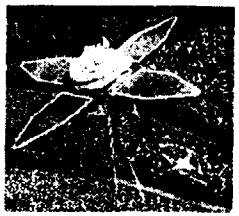
Source of Power: solar cells, batteries.. **Electrical Power:**

Communications: X band **Data Flow:**

Instrumentation:

- CPI = Imaging mass spectrometeres, hot plasma analyser, Solar wind analyser,
- EPIC = Spectrometers and velocity/energy detectors
- LEP = Velocity distribution spectrograph, electroststics analysers, energetic ion mass spectrometer
- EFD = 2 odubles probes on wires booms in the satellite spin plane
- HEP = Low energy particle detector, burst detector, medium energy Isotope detector, high energy isotope detector
- PWI Multichannel analyser and 3 receivers
- MGF Magnetometers

Mission Name: INTERBALL-Auroral Probe



Russia/France

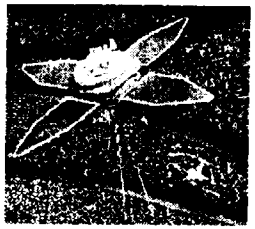
Launching date: 1rst 03/08/1995,
2nd 08/1996
Life-time:
Launcher: Molnyia M
Launching site: Plesetsk

Size: **Mass:** 1270-1400 kg
Trajectory: Earth elliptic orbit: Ap = 20,000 km, I = 62.8°
ACS: Single spin
Source of Power: Solar arrays **Electrical Power:** 250 W
Communications: **Data Flow:**

Instrumentation:

- Measure spectra of electrons and ions and anisotropy of electrons. SK3, ION
- Ion composition and 3D energy distribution. PROMICS-3
- Ion composition and 3D distribution functions. Hyperboloid
- Temperature of cold electrons
- Thermal plasma ion flux. KM 7
- Magnetic field. IMAP-3. Electric field and ULF waves. IESP-2M
- Auroral kilometric radiation. POLRAD. Electromagnetic waves in wide band. MEMO
- VLF electromagnetic waves. NVK-ONCH
- Energy spectra, angular distributions and time variation of electrons and ions. DOK-2
- UV auroral imager. UVA1. UV auroral oxygen emissions. UVSIPS

Mission Name: INTERBALL-Tail Probe



Russia/France

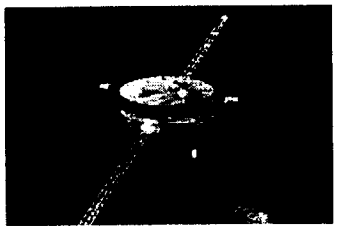
Launching date: 1st in 03/08/1995,
2nd in 08/1996
Life-time:
Launcher: Molnia M
Launching site: Plesetsk.

Size: **Mass:** 1270-1400 kg
Trajectory: Earth elliptical orbit Ap = 200,000 km, I = 62.8°
ACS: Single spin.
Source of Power: Solar arrays. **Electrical Power:** 250 W
Communications: **Data Flow:**

Instrumentation:

- 3D distribution and spectra of ions: SCA-1
- 3D measurements of electrons component of the plasma: ELECTRON
- Ion composition and 3D energy distribution: PROMICS
- Omni directional fast measurements of integral ion or electron fluxes and their direction: VDP
- Energy spectra of heavy ions at all directions: AMEI-2
- Measurements of solar wind ion fluxes: MONITOR
- Angular energy ion distribution: CORAL
- Thermal plasma ion flux: ALPHA
- Analysis of spectra and plasma waves: ASPI
- Analysis of electric fields: OPERA, KEM
- Analysis of magnetic fields: MIF-M, ADS, FGM-1, KEM-3, PRAM, FM-31
- Measurements of ions and electron flux fluctuation: IFPE
- Radioemission: AKR-X
- Composition and anisotropy of charged energetic particles: SKA
- Spectra, distribution and time variation of electrons: DOK-2
- Solar X-ray burst spectra: RF-15-1
- Dosimetric measurements and ionizing radiation: SOSNA-2, RKI-2

Mission Name: POLAR (Polar Plasma Laboratory)



USA (ISTP)

Launching date: 24/02/1996
Life-time: 1.5 years, optional extension
Launcher: Delta II
Launching site: Vandenberg.

Size: diam = 2.8 m, lenght = 1.25 m **Mass:** 1300 kg orbit dry mass

Trajectory: Earth orbit, 1.8 x 9 Re, 18h period, I = 90°, perigee near north pole. Chemical thruster, 500 m/s delta V capacity.

ACS: Dual spin stabilised, 10 rpm (despun instrument platform), spin axis normal to orbit plane. Infrequent attitude updates by propulsion system.

Source of Power: body mounted solar cells **Electrical Power:** 333 W

Communications: Store and dump. **Data Flow:** Capable to send high rate data from PWI instrument. TTC 41.6 kbps, (nominal dump 250 kbps, max rate 600 kbps (PWI real time).

Instrumentation:

PWI - Plasma Wave Instrument E/M & plasma wave detector. Spectral & wave vector characteristics 0.1Hs-800kHz
No physical characteristics of the PWI have been found.

HYDRA - Fast Plasma Analyzer:
No sensor-specific information has been found.

MFE - Magnetic Fields Experiment 2 (redundant) triaxial fluxgate magnetometers ("mag-core" type) mounted on the 6m boom; mass = 1350 kg total (including electronics), power = 4.35W, range: ±649 nT up to ±46700 nT

TIMAS - Toroidal Ion Mass Spectrograph m =15.7kg, power = 14W, size = 33 cm diameter, angular resolution: 11.5x11.5 °. Energy range: 0.015 up to 32 keV. Telemetry = 4.1kbps, Temporal resolution: 4pi sr in 3 seconds

EFI - Electric Fields Instrument Deploys 3 pairs of spheres on long wires (100m and 130m length) and on boom (14m)
Frequency range DC to 20kHz; sensitivity to E-fields 0.02 to 1000 mV/m. Total mass (booms, spheres, electr): 35k, Total power: 12.4W

TIDE - Thermal Ion Dynamics Experiment: Did not find functional desciption., Energy range 0.1 - 500eV, mass=17.1kg, power=9.1W; telemetry 4 kbps

PSI - Plasma Source Instrument: produces low-energy local plasma to provide a charge-balancing ion current (to aid TIDE), power=15W nominal (45W at start-up)

UVI - UltraViolet Imager: Wavelengths: 130-190nm. Very high sensitivity and resolution (spatial: 0.036°, temporal: 1 image every 37 sec.),. mass = 21kg, power = 21W, telemetry 12kbps

VIS - Visible Imaging System: 3 low-light cameras. No dimensions found.

PIXIE - Polar Ionospheric X-ray Imaging Experiment: Energy range 3-60keV. mass=24.5kg, power=11W, telemetry 3.5kbps.

CAMMICE - Charge and Mass Magnetosphe-ric Ion Composition Experiment: is actually 2 instruments: HIT and MICS.No performance information was found.

CEPPAD/SEPS - High-energy particle detection for energies from 0.02 up to 30 MeV per electron or ion. (both are basically mass spectrometers)

Mission Name: SAMPEX

USA

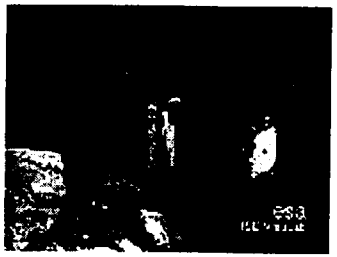
Launching date: 03/07/1992
Life-time: 3 years, but still continuing
Launcher:
Launching site: Vandenberg WTR.

Size: lenght = 1.5 m. **Mass:** 250 kg
Trajectory: Earth elliptical orbit Ap = 670 km, Pe = 520 km, I = 82°
ACS: Momentum wheel and torques
Source of Power: Solar arrays **Electrical Power:** 200 W
Communications: **Data Flow:**

Instrumentation:

- Measurements of heavy ionsfrom He to Fe: HILT instrument
- Low energy ions composition analyse: LICA Mass spectrometer
- Isotopic compositionof elements: MAST instrument
- Enery spectra and relative composition of protons and helium nuclei: PET instrument

Mission Name: SOHO (Solar and Heliospheric Observatory)



ESA / NASA

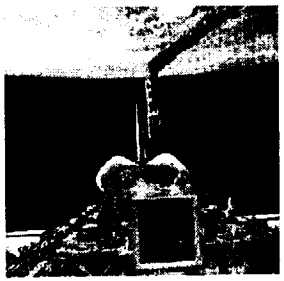
Launching date: 02/12/1995
Life-time: 2 years
Launcher: Atlas 2AS / Centaur
Launching site: Cape Canaveral

Size: H= 3.65 m, L= 3.65 m (9.5 m deployed) **Mass:** 1850 kg (launch), 610 kg payl
Trajectory: Halo orbit around Sun-Earth L1 libration point, 1.5 Mkm sunward from Eart
Hydrazine thruster.
ACS: 3-axis stabilised with continuous fine pointing to Sun.
Source of Power: Solar cells. **Electrical Power:**
Communications: **Data Flow:** 200 kbps.

Instrumentation:

CDS (Coronal Diagnostic Spectrometer) m=105 kg, P=40 W, D = [280x64x40, 30x30x15] cm3
CELIAS (Charge, element and Isotope Analysis Sistem)
EIT (Extreme Ultraviolet Imaging Telescoe) m=16 kg, P=30 W, D= [40x20x10] cm3
COSTEP (Comprehensive Suprathermal and Energetic Particle analyser) m= 7 kg, P=5 W, D=[4x(10x6),16x15x12] cm3
ERNE (Energetic and relativistic Nuclei and Electron experiment)
SWA (Solar Wind Analyser) M=13.25 kg, P= 11 W, D= [2x(15x15x13), 60x30x30, 20x10x10] cm3
GOLF (Global Oscillations at Low Frequencies)
VIRGO (Variability of Solar irradiance and Gravity Oscilations)
UVCS (Ultraviolet Coronograph Spectrometer)
SUMER (Solar Ultraviolet Measurements of Emitted Radiation)
LASCO (Large Angle and Spectrometric Coronagraph)
MDI/SOI (Michelson Doppler Imager/ Solar Oscillations Investigations)

Mission Name: SPARTAN



Launching date: 04/08/1993
Life-time:
Launcher: Shuttle
Launching site: Cape Canaveral

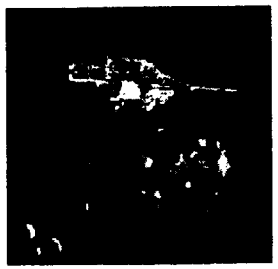
USA

Size: diam=3 m, lenght=0.43 m **Mass:**
Trajectory: Circular Earth orbit Pe = 295 km, Ap = 311 km, I = 57 °.
ACS: Pneumatic, gas jets.
Source of Power: Batteries. **Electrical Power:**
Communications: **Data Flow:** recorded on board.

Instrumentation:

- Measure temperature and density of hydrogen, protons and electrons. Ultraviolet corona spectrometer
- Solar wind velocities in different corona structures. White light coronograph.

Mission Name: Ulysses



Launching date: 06/10/1992
Life-time: 6 years
Launcher: Shuttle, Discovery
Launching site: Cape Canaveral

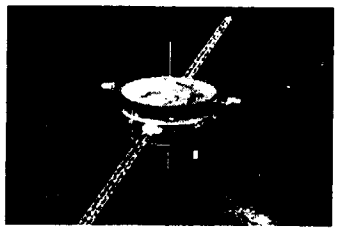
ESA / NASA

Size: **Mass:** 366 kg at launch
Trajectory: LEO 300 km, Jupiter fly-by, elliptical orbit inclined at 80.2 ° from solar equator. Hydrazine.
ACS: spin stabilised 5 rps.
Source of Power: RTG. **Electrical Power:**
Communications: 20 W in X-band, 5 W in S-band. **Data Flow:**

Instrumentation:

Spatial and temporal variation of Sun magnetic Field: VHM (Vector Helium Magnetometer)
FGM (Flux Magnetometer). Elemental and ion-charge composition; temperature and speed of solar ions: SWICS (Solar Wind Ion Compositions)
Solar wind ions and electrons: SWOOPS (Solar Wind Plasma Experiment)
Cosmic rays and energetic particles: COSPIN (Cosmic, Rays and Solar Particle Experiment)
Solar Flare X-ray bursts in the 15-150 keV energy range. Interplanetary energetic ions and electrons: GBR
HI-SCALE (Heliosphere instrt for Spectra Composition and Anisotropy al low Energies)
P= 4 W M= 5.775 kg. Particulate matter in the 10^{-16} to 10^{-16} g range: DUST
Density, velocity and turbulence spectra in the corona and solar wind: SCF (Corona Sounding)
Doppler shift in spacecraft radiosignal due to gravitational waves.: GWE (Gravitational Waves Experiment) Study of local plasma waves, magnetic field. Direction, angular Size and polarisation of radio sources for remote sensing of the heliosphere: EPAC/GAS, URAP (Unified Radio and Plasma Wave Instrument)

Mission Name: WIND



Launching date: 01/11/1994
Life-time: 1.5 years
Launcher: Delta II
Launching site: Vandenberg

USA/France/Russia

Size: diam=2.8 m, lenght=1.25 m **Mass:** 1300 kg

Trajectory: Solar orbit with Ap = 250 R_E then positioned at L1 point.

Chem Thrusters.

ACS: Dual Spin at 10 rpm

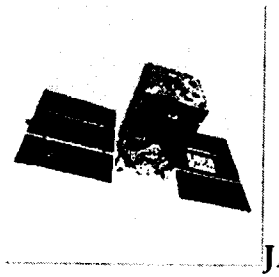
Source of Power: Solar arrays **Electrical Power:** 330 W

Communications: Store and dump. **Data Flow:** TTC 41.6 kbps, Data: 250-600 kbps.

Instrumentation:

- Measurements of radio waves of the plasma. Waves experiment
- Study of energetic particle acceleration and transport process. EPACT instrument
- Measurement of ions and electrons in interplanetary medium. 3D Plasma analyser
- Detection of gamma rays bursts. TGRS spectrometer and Konus spectrometer
- Investigation of structure and fluctuation of magnetic fields. MFI instrument
- Measurement of ions and electrons in the solar wind to deduce solar wind velocity, density,temperature and heat flux. SWE experiment
- Measurement of the abundance, composition and energy spectra of solar wind ions. SMS instrument

Mission Name: Yohkoh



Launching date: 30/08/1991
Life-time: Continues
Launcher: M-3SII
Launching site: Kagoshima

JAPAN / USA / UK

Size: 100 x 100 x 200 cm **Mass:** 390 kg

Trajectory: Near circular Earth orbit: Ap = 375 km, Pe = 570 km

ACS: Actuators: momentum wheels, magnetic torques. Control: Gyros

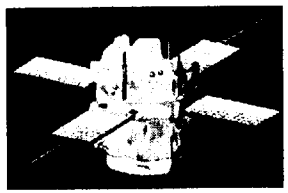
Source of Power: Solar Arrays **Electrical Power:** 250 W

Communications: **Data Flow:** stored and dumped, 42 mn record time.

Instrumentation:

- X-rays (1-100 keV). Particles study:Fe, Ca,S.
- BCS = Bragg crystal spectrometer
- HXT = X-ray Telescope.
- SXT = Soft X-ray Telescope
- WBS = Wide Band Spectrometer

Mission Name: ACE



USA

Launching date: 21/08/1997
Life-time:
Launcher:
Launching site:

Size: diam=1.6m, Heigh=1m **Mass:** 785 kg

Trajectory: L1

ACS: Single spin 5 rpm

Source of Power: Solar arrays **Electrical Power:** 500 W

Communications: **Data Flow:** 6.7 kbs

Instrumentation:

- Solar wind ion mass spectrometer
- Solar wind ion composition spectrometer
- Ultra low energy isotope spectrometer
- Solar Energetic particle ionic charge analyser
- Solar isotope spectrometer
- Cosmic ray isotope spectrometer
- Solar wind electron, proton and alpha monitoring
- Energetic electron, proton and alpha monitoring
- Magnetometer

Mission Name: CLUSTER

Europe/USA

Launching date: 04/05/1996 (failure)
Life-time: 2 years
Launcher: ARIANE 5
Launching site: KOUROU
Replacement in study: Phoenix project

Size: diam=2.9m, height=1.3m **Mass:** 1200 kg

Trajectory: Elliptical Earth orbit, Ap=19.6R_E, Pe=4R_E, 4 S/C in formation

ACS: Single spin, 15 rpm

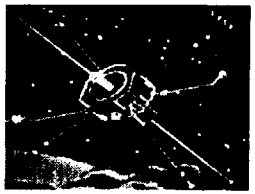
Source of Power: Solar cells **Electrical Power:** 224 W

Communications: **Data Flow:** 2 to 262 kbits/s

Instrumentation:

- STAFF: Spatio temporal Analysis of Field Fluctuation experiments
- EFW: Electrical field and Wave Processing experiment
- Whisper: Waves of High Frequencies and sounder for probing of density by relaxation experiment
- WBD: Wideband Data instrument
- FGM: Fluxgate Magnetometer
- EDI: Electron drift Instrument
- ASPOC: Active spacecraft Potential control experiment
- PEACE: Plasma electron and current analyser
- CIS: Cluster Ion spectrometry experiment
- RAPID: Research with Adaptative Particle Imaging Detectors

Mission Name: FAST



USA

Launching date: 18/08/1996
Life-time: 1 year
Launcher: Pegasus XL
Launching site: Vandenberg

Size: diam=1m, height=1m **Mass:** 200 kg

Trajectory:~ Polar elliptical Earth orbit, Pe=350km, Ap=4200km, I=83°

ACS: single spin 12 rpm

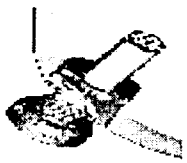
Source of Power: Solar cells& batteries **Electrical Power:** 60 W

Communications: S band **Data Flow:** max=2.2 Mbps

Instrumentation:

- Fast electron Spectrographs (FES)
- Stepped electron electrostatic Analyser (SESA)
- Electron electrostatic analyser (EESA)
- Ion electrostatic analyser (IESA)
- Time of flight Energy angle mass Spectrograph (TEAMS)
- Electric field probe experiment
- Tri axial Fluxgate and search coil magnetometers

Mission Name: HESI



USA

Launching date: 2000 TBC
Life-time:
Launcher: Pegasus XL
Launching site:

Size: long=2.1m, diam=1.1m **Mass:** 230 kg

Trajectory: Circular Earth equatorial orbit, altitude=600 km

ACS: Single spin 15 rpm

Source of Power: Solar cells **Electrical Power:** 120 W

Communications: S band **Data Flow:** Store and dump

Instrumentation:

- HEISPEC (High Energy Imaging SPECTrometer)

Mission Name: IMAGE

Launching date: TBD
Life-time: 2years
Launcher: TBD
Launching site: TBD

USA/International TBD

Size:

Mass: 280 kg

Trajectory: Elliptical Earth orbit, Ap=7R_E, Pe=500km, I=90 °

ACS: single spin

Source of Power: Solar cells

Electrical Power: 130 W

Communications: S band

Data Flow: 2.2 Mbps

Instrumentation:

Neutral atom imaging instrument
- Low Energy Neutral Atom imager
- Medium Energy Neutral Atom imager
- High Energy Neutral Atom imager

Far UV imager
- Spectrographic imager
- Wideband imaging camera

He + Imager

Radio plasma Imager

Mission Name: Plamya

Launching date: 2003 TBC
Life-time: 1 year
Launcher: Proton
Launching site: Baikonour

Russia/USA TBC

Size:

Mass: 350 kg

Trajectory: Solar orbit, Pe=8R_S

ACS: 3 axis

Source of Power: RTG

Electrical Power: 150 W

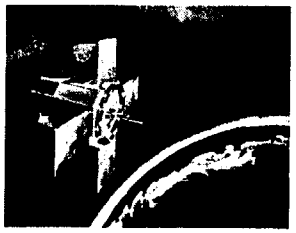
Communications: X band

Data Flow: 32 kbps

Instrumentation:

- Plasma analyser
- Plasma wave analyser
- Magnetometer
- Particle analyser
- Spectrometer
- Coronograph

Mission Name: SAC-B



Launching date: End of 1996
Life-time: 3 years
Launcher: Pegasus XL
Launching site: Wallops

Argentina/USA

Size:

Mass: 181 kg

Trajectory: Circular Earth orbit, altitude=550km, I=38°

ACS:

Source of Power: Solar Cells

Electrical Power:

Communications:

Data Flow:

Instrumentation:

- 2 X-rays and gammas rays burst detectors (CXRE)
- Diffuse X-ray background detector (CUBIC)
- Energetic neutral neutrons measurements (ISENA)

Mission Name: Solar Probe

Launching date: 11/2003
Life-time: end after Solar encounter (perihelion) 07/2007
Launcher: TBD
Launching site: TBD

USA/Russia TBC

Size: height=3.11m, width=2.05m

Mass: 200 kg

Trajectory: Jupiter gravity assist into 90° solar orbit, Pe=4R_S

ACS: 3 axis

Source of Power: Solar arrays, batteries

Electrical Power: 103 W

Communications: X band

Data Flow: 500 bps

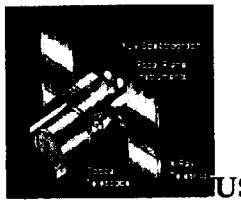
Instrumentation:

Science payload characteristics: 8 kg, 8 W, 500 bps

In-situ: (Mass: 4 kg, Power: 7 W)
1) Plasma electrons (0.01-30 keV) and ions (0.1-30 keV/Q)
2) Energetic particles:
- Ions (>100 keV)
- Electrons (25 keV - 4.5 MeV)
- Protons (400 keV - 45 MeV)
- Alpha particles (1.3 - 180 MeV)

3) Waves (1 Hz - 10 kHz)
4) Magnetic field (+/- 0.2 G)
Remote sensing: (Mass: 4 kg, Power: 1 W)
1) EUV imaging (171 and 304 angstroms)
2) Visible imaging (4308 angstroms)

Mission Name: SOLAR-B



USA/Japan/UK

Launching date: 08/2003
Life-time: 3 years
Launcher: ISAS MV
Launching site: Kagoshima

Size:

Mass: 875 kg

Trajectory: Polar, sun-synchronous Earth orbit,Altitude=700km,I=97.9°

ACS:

Source of Power: Solar arrays

Electrical Power: 500W

Communications: S band

Data Flow: 5 Mbps

Instrumentation:

Optical Telescope: Gregorian or Cassegrain, 60 cm aperture, light weight glass composite
Angular Resolution: Diffraction limited at 0.64 cm (175 km on the Sun)
Wavelength Range: 480-650 nm
Polarimetric Accuracy: 10E-4
Vector Magnetograph: Magnetic Lines: 525 nm FeI, 630.2 nm FeI, Continuum: 524.6 nm,
Velocity: 532.4 nm FeI
Field of View: 2x4 arcmin squared or 4x8 arcmin squared
Magnetic Sensitivity: B(longitudinal) = 1-5G, B(transverse)=30-50G
Temporal Resolution: 5 min., Detectable change in active region magnetic energy: 10E30 erg
X-ray telescope: Temperature Range: 1-10 x 10E6 K
Angular Resolution: 1.0 to 2.5 arcsec
XUV spectroheliograph: Pixel Size: 1.5 arcsec x 0.002 nm
Field of View: 400 arcsec
Wavelength Range: 25-29 nm
Temperature Range: 1 x 10E5 - 2 x 10E7 K
Spectrograph: Littrow type echelle. Spectral resolution: 2.0 nm

Mission Name: TIMED

USA

Launching date: 09/1998
Life-time: 2 years
Launcher: Taurus class
Launching site:

Size:

Mass: 675 kg

Trajectory: Circular Earth orbit, altitude=600km, I=74.4 °

ACS: 3 axis momentum bias

Source of Power: Solar cells

Electrical Power: 300W

Communications: S band

Data Flow: 19.2 kbps

Instrumentation:

- **SEE** - Solar EUV Experiment
- **TIDI** - TIMED Doppler Interferometer
- **GUVI** - Global Ultraviolet Imager
- **SABER** - Sounding of the Atmosphere using Broadband Emission Radiometry

Mission Name: TRACE

USA

Launching date: 09/1997
Life-time: 1 year
Launcher: Pegasus
Launching site: Vandenberg

Size:

Mass: 225 kg

Trajectory: Circular sun-synchronous orbit, altitude=700 km

ACS: 3-axis stabilized, 20 arcsec pointing

Source of Power: Solar arrays

Electrical Power: 250 W

Communications: S band

Data Flow: 1800 kbps

Instrumentation:

- Multiple UV and normal incidence EUV channel telescope to capture digital images of the solar plasma at temperatures between 10^4 to 10^7 K, Spatial resolution: 1 arc second, Temporel resolution: 1 second

Appendix B

SAUNA Mission Data

The following information on the SAUNA mission is included here:

- Reference low-thrust transfer trajectory.
- Detailed budgets (mass, power, cost) supporting Table 9.6.
- Communication link budget analysis.

B.1 Reference Low-Thrust Transfer Trajectory

These input parameters were fed to SKYNAV [Appendix C]:

> Positioning Manoeuvre/Initial Mass 300kg/Exhaust Velocity 45911 m/s/Thrust 0.200N/Solar-Electric Propulsion Thrust Radius 1.00rr/Thrust Exponent 1.700/Initial Delta-V 0.00m/s/Initial orbit pericenter radius 0.722rr/excentricity 0.16/Final orbit pericenter radius 0.200rr/Excentricity 0.000/Angles [deg]: Initial Orbit pericenter/Node Axis: 180.00, Node Axis/Final position 1970.00 [all other angles 0.000]

The results of the SKYNAV optimisation were:

- Total Delta-V Requirement: 34.19 km/sec
- Total travel time: 507 days, whereof first 90 days spent coasting

Figure B.1 shows a graphical output as provided by SKYNAV. The total delta-V is higher than for impulsive (Hohmann) manoeuvres since more losses are incurred as a result of continuous thrusting against various external influences. The transfer time is a direct function of the number of spiralling turns needed to reach the 0.2 AU orbit (in this case 5.5 rounds).

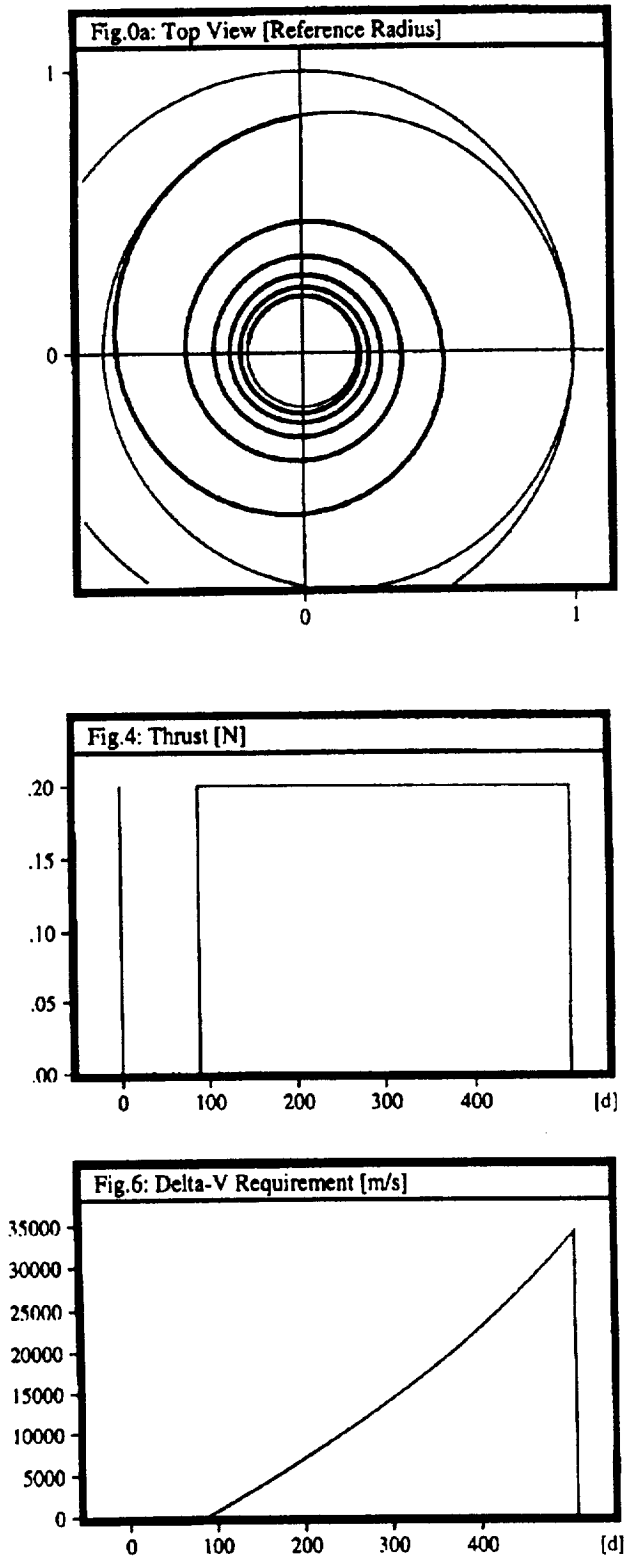


Figure B.1 SAUNA Reference Trajectory Characteristics

B.2 Detailed SAUNA Budgets

SAUNA BUDGET	Mass	Power	Cost		Page 1/2
Item	(kg)	(W)	(US$ M)	Remarks	Coefficients
A1. Primary Structure	25.00	0.00	2.00		
A2. Secondary Structure	7.00	0.00	2.00	for instrument support, etc.	
A. Structure	**32.00**	**0.00**	**4.00**		
B1. Main Ion Thruster	20.00	6300.00	2.00	Ion propulsion UK-25E at 0.2N	
B2. Propellant Tank	10.00	0.00	3.00	Sizing needed for specific propellant	
B. Propulsion System	**30.00**	**6300.00**	**5.00**		
C1. Solar Panels	31.61	0.00	2.00	M=0.016Ptot/4; ISS/Lockheed Martin Flexible	
C2. Batteries	3.00	0.00	0.50	Storage capacity TBD	
C3. Power Control Electronics	1.00	0.20	0.25		
C. Power System	**35.61**	**0.20**	**2.75**		
D1. Star Trackers (2x)	0.58	12.00	2.00	STSC [LLNL 1996]	
D2. Inertial Measurement Unit	0.20	24.60	1.00		
D3. Ion RCS Theusters (6x)	12.00	0.00	1.80	Assume RCS OR Main, never both	
D4. Reaction Wheels	14.10	35.00	2.00	[Ithaco 1996]	
D. Attitude & Orbit Control	**26.88**	**71.60**	**6.80**		
E1. Heat shield	8.00	0.00	4.00		
E2. Conductive structure	5.00	0.00	1.00		
E3. Multilayer Insulation (MLI)	3.00	0.00	1.00		
E4. Radiator	5.00	0.00	2.00		
E5. Two-Phase Evaporator	10.00	5.00	2.00		
E6. Heaters	2.00	20.00	0.25		
E7. Control Electronics	2.00	10.00	0.50		
E. Thermal Protection	**35.00**	**35.00**	**10.75**		
F1. High Gain Antenna	15.00	0.00	5.00	2m dish [Appendix F]	
F2. Low Gain Antenna	4.00	0.00	2.00	4x S-band [Appendix F]	
F3. Antenna Drive mechanism	2.00	0.00	2.00		
F4. X-band Transponders 2x	2.00	110.00	2.00	Pluto	
F5. S-band Transponders 4x	4.00	640.00	2.00		
F. Communications	**27.00**	**750.00**	**13.00**		
G1. CPU	1.20	3.00	2.00		
G2. Mass Memory	0.60	4.00	2.00		
G3. Data Bus	0.20	2.00	2.00		
G. On-Board Computer	**2.00**	**9.00**	**6.00**		
H. Subtotal Spacecraft Bus:	**188.49**	**7165.80**	**48.30**	[A+B+C+D+E+F+G]	

SAUNA BUDGET	Mass	Power	Cost		Page 2/2
Item	(kg)	(W)	(US$ M)	Remarks	Coefficients
I1. Plasma Analyzer	3.70	2.70	3.00		
I2. Magnetometer	2.50	1.50	3.00		
I3. EUV Telescope	6.00	5.00	3.00		
I4. X-Ray detector	2.00	4.00	3.00		
I5. Dust detector	0.50	2.00	0.50		
I6. Common electronics box	3.00	3.00	0.50		
I. Payload	**17.70**	**18.20**	**13.00**		
J. Subtotal Bus (dry) + Payload	**206.19**	**7184.00**	**61.30**	[H+I]	
K1. Harness mass	**20.62**			Percentage cable mass of above:	10
K2. Harness power loss		**35.92**		18V Bus, Average Power Loss %:	0.5
K3. Harness cost			**0.04**	Cost harness mass per kg, $	2000
L1. Subtotal Dry Mass	**226.81**	**7219.92**	**61.34**	[J+K]	
L2. Propellant (52.5% of wet mas	**250.68**	**n.a.**	**0.63**	52/48 fuel/mass; Xe gas $/kg:	2500
M. Subtotal Wet Mass	**477.49**	**7184.00**	**61.97**	[L1+L2]	
N. Margin	**47.75**	**718.40**	**12.39**	10% for mass & power, 20% for cost	
O. Total Wet Mass Spacecraft:	**525.24**	**n.a.**	**74.36**	[M+N]	
P. Launcher adaptor:	**15.76**	**n.a.**	**0.50**	3% of wet mass	
Q. LAUNCHED SUBTOTAL:	**541.00**	**7902.40**	**74.86**	[O+P]	
R. Launcher Capacity and Cost:	697.00		60.00	Delta II (7925) C3 Table see =>	
R1. Launcher mass margin:	156.00			Initial tx orbit periapse < 0.5AU	
				Requires C3>30km2/s2	
S. Ground Operations			**19.00**	Annual MODA 3.8M*5yrs (MOCM)	
T1. Ion Engine Qualification			11.00	10 kh lifetime certification; space qual;	
T2. Solar cells technology			3.50	Resistance to high-T degradation	
T3. High-T bonding agents			2.00	Resistance to high-T degradation	
T4. Autonomy software			3.00	Navigation, FDIR; prototyping	
T5. All other predevelopment			3.00	Tribology, rad-hard electronics, thermal	
T. SAUNA Predevelopment (SPP)			**22.50**		
U. Subtotal Cost:			**176.36**	[Q+R+S+T]	
V. System Cost Margin 10%			17.64		
TOTAL MASS, POWER, COST:	**541.00**	**7902.40**	**194.00**	**[U+V]**	
Launched Mass/C3 Function for Delta II (7925)					
Current C3 Pointer:	Mass (kg)	C3 (km2/s2)			
	277.1	75			
	308.3	70			
	379.7	60			
	465.7	50			
XXXXXXXXXXXXXX	569.9	40			
	697	30			

B.3 Link Budget Analysis for SAUNA HGA

DIRECT RF LINK (HGA)		
Concept	**Value**	**Observations**
Frequency (GHz)	**8.40**	X-band
Transmitter RF power (W)	**40.00**	SS:110 W DC,1.2 Kg x 2
Transmitted power (dBW)	16.02	
Transmitter losses (dB)	**-1.50**	
Transmit antenna diam (m)	**2.00**	19 Kg
Transmit antenna gain	17023	
Transmit antenna gain (dB)	42.31	
Tx 3 dB Beamwidth (deg)	1.25	
EIRP (dB)	**56.83**	
Sun apparent angle (deg)	0.27	
Distance from Sun center (AU)	**0.20**	
Max Margin Angle (deg)	11.04	
Margin angle (deg)	**11.00**	
Min SEP Angle (deg)	11.27	
Path length	1.02	
Path loss (dB)	-274.59	
Implementation loss (dB)	**-2.00**	
Polarization mismatch (dB)	**-0.01**	
Receive antenna diam (m)	**30.00**	
Receive antenna gain (dB)	65.83	
Rx 3dB Beamwidth (deg)	0.0833	
Antenna pointing loss (dB)	**-0.35**	
Antenna noise temperature (K)	50.00	
Feeder noise temperature (K)	**270.00**	
Connection loss (dB)	**-1.00**	
Receiver noise temperature (K)	**50.00**	
System noise temperature (K)	145.25	
Noise spectral density (dBW/Hz)	-206.98	
G/T (dB/K)	**44.21**	
C/No (dBHz)	**52.70**	
Max Info. Data rate (kbps)	**16.00**	
Channel Code rate	0.44	RS(255,223)+Conv.(7,.5)
Overall Data Rate (kbps)	36.59	
Eb/No (dB)	**7.06**	
Implementation loss (dB)	**-0.50**	
Required Eb/No (dB)	2.50	RS/Viterbi BER+1e-6
Margin (dB)	**4.06**	

B.4 Link Budget Analysis for SAUNA LGA

DIRECT RF LINK (LGA)		
Concept	**Value**	**Observations**
Frequency (GHz)	**2.20**	S-band
Transmitter RF power (W)	**160.00**	SS: 640 W DC 12 Kg
Transmitted power (dBW)	22.04	
Transmitter losses (dB)	**-1.50**	
Transmit antenna diam (m)	**0.64**	5 Kg
Transmit antenna gain (dB)	27.12	4-antenna array
Tx 3 dB Beamwidth (deg)	15.00	
EIRP (dB)	47.66	
Path length	1.20	
Path loss (dB)	-264.40	
Implementation loss (dB)	**-2.00**	
Polarization mismatch (dB)	**-0.01**	
Receive antenna diam (m)	**30.00**	
Receive antenna gain (dB)	54.20	
Rx 3dB Beamwidth (deg)	0.32	
Antenna pointing loss (dB)	**0.00**	
Antenna noise temperature (K)	50.00	
Feeder noise temperature (K)	**270.00**	
Connection loss (dB)	**-1.00**	
Receiver noise temperature (K)	**50.00**	
System noise temperature (K)	145.25	
Noise spectral density (dBW/Hz)	-206.98	
G/T (dB/K)	32.57	
C/No (dBHz)	42.43	
Max Info. Data rate (kbps)	**1.50**	
Channel Code rate	0.44	RS(255,223)+Conv.(7,.5)
Overall Data Rate (kbps)	3.43	
Eb/No (dB)	7.08	
Implementation loss (dB)	**-0.50**	
Required Eb/No (dB)	2.50	RS/Viterbi BER+1e-6
Margin (dB)	4.08	Conv. BER=1e-6

Appendix C

Technology Challenges and Issues

C.1 In-situ Instrumentation for Various Missions

Table C.1.1 Minimum Solar Mission Instrument and Measurement Parameters

Measurements	Spectral Parameter	Spectral Resolution	Integration Time	Observational cadence	Mass [kg]	Power [watts]	Cost [$m]
Plasma							
Plasma Electron	.01-30 keV	30 %	10 s	100 s	4	7	8.1
Plasma Ions (p,alpha, oxygen)	.01-30 keV/Q	7.05%					
Energetic Particles							
Ions	>100keV	100 %	10 s	100 s	4	7	8.1
Electrons	25 keV - 4.5 MeV						
Protons	400 keV - 45 MeV						
Alpha	1.3 - 180 MeV						
Wave	1Hz-10kHz	N/A	10 s	100 s	4	7	8.1
Magnetic Field	+/- 0.2 G	N/A	0.1 s	100 s	4	7	8.1

[W.I.Axford, 1996, "Minimum Requirements For A Solar Probe Mission", Adv.Space Res. Vol. 17, No. 3, pp. (3)85 - (3)90]

Table C.1.2 Russian FIRE Spacecraft Payload

Experiment	Mass [kg]	Power [W]	Bit rate [kbit/s]	Requirements
Plasma Analysis	6	6		2×2π FOW ions Electron sensor on the boom Sun-directed hole required Aspect precision 1°, knowledge 0.2°
Magnetometer	4	3	0.5-5.0	2 sensors on the boom
Energetic Particles	3.5	4.5	0.3-1.0	Measurements in 4 directions
Plasma Waves	1.5	6	< 15	2 booms 1m each Current collectors on thermal screen
Interplanetary neutrals	1.5	2		
Neutrons and γ	3.5	3.5	16/day	

Table C.1.3 German M3 Mission

Instrument	Mass [kg]	Power [W]	Telemetry [bits/s]	Time Resolution [s]	Field Strength	Frequency Range [Hz]
Solar Wind Plasma Particle Analyser						
Plasma Wave						
Search-coil Magnetometer (low-frequency)	3	0.1			0.1 nT - 0.1G	1 - 10k
Search-coil Magnetometer (high-frequency)	0.5	0.5			0.1 nT - a few tens of nT	10k - 50M
Electric Field Instrument	2	1.5				1 - 500 & 500-50M
Digital Wave Processing	1.2	3				
Particles						
Suprathermal Sensor	.4030	2500	700		20 - 1000 keV	
Solar Energetic Particle Analyser	3.5	4			50keV-50MeV electrons 4keV-10MeV	
Dust						
Detector for Interplanetary Dust Particles	1.2	1	< 100			
3-D Ion Velocity Spectrometer						
Proton Alpha Sensor	.250 - .320	0.6				
Thomson Parabola Analyser	.300 - .730	2.0				
Electronics box & connectors	.525					
Tilt table & electronics	1.0	0.1				
Total	3.125	2.7	2000			
Ions						
Heavy Ion Analyser	3.5	3.5	100	10		
3-D Elect Velocity Spectrometer	3.0	3.0	4000			
Magnetometer	4.1	5200m	1mT/32nT 6400nT/2nT 3200nT/0.1nT 256nT/8pT			

[V.N.Oraevsky and V.D. Kuznetskov, 1996, "Instrument For The Russian Solar Probe Mission", Adv.Space Res. Vol. 17, No.3, pp. (3)103 - (3)110]

Table C.1.4 YOHKOH

Instruments	Resolution	Time Resolution
Spectrometer		
Bragg Crystal Spectrometer (BCS)		
Sxv (5.0160-5.1141Å)	3.232 mÅ	0.125
Ca xix(3.1769Å)	0.918 mÅ	
Fexxv(1.8509Å)	0.710 mÅ	
Fexxvi(1.7780Å)	0.565 mÅ	

[Y.Uchida, The YOHKOH Mission, *Solar Physics*, Vol. 136, No. 1, 1991, pp. 69 - 88]

Table C.1.5 Russian Solar Probe Mission Complex of Electromagnetic Remote and *In-situ* Measurements (CERIM)

Instruments	Mass [kg]	Power [W]	Data [kb/sec]	Frequency Range [Hz]
Magnetometer	4	3	4	
Electron Gun	3	5	5	
Solar Radiospectrometer	2	5	2	100k - 30M

SOHO

CDS (Coronal Diagnostic Spectrometer)

CELIAS (Charge, Element, and Isotope Analysis System)

COSTEP (Comprehensive Suprathermal and Energetic Particle Analyser) from the University of Kiel, Germany

ERNE (Energetic and Relativistic Nuclei and Electron experiment)

GOLF (Global Oscillations at Low Frequencies) from the Institut d'Astrophysique Spatiale, France

SWAN (Solar Wind Anisotropies) from FMI, Finland

[*Esa Bulletin*, ESA/ESTEC, pp. 96-105, 1996]

Solar Maximum Mission

Coronagraph/Polarimeter 4465 - 6583A, 1.5 - 6 sq.solar radii fov. 6.4 arcsec res.

Gamma-ray Spectrometer NaI(T1), 0.01-100 MeV in 476 channels, 16.4 s per spectrum

Active Cavity Radiometer Irradiance Monitor **0.001 - 1000 micrometer solar flux**

C.2 The Solar Sailing Trajectory Program

C.2.1 Introduction

During the ISU summer session, a software was created to compute solar sail trajectories for spacecraft already orbiting in a circular fashion around the sun. The code of the program was written in FORTRAN and was based on previous studies made during the ISU Summer Session Program of 1994 in Barcelona. Berry Sanders helped in acting as the scientific adviser for the Sailing program.

You will find, in the first section of this appendix, the complete code in FORTRAN, and the main output file that was generated with the program for the following values: mass=250kg, sail area=9000 m2, starting distance from the sun: 150e6 km, and an angle of attack of 45 degrees for the sails, relative to the incoming solar pressure.

C.2.2 FORTRAN Code

```
cccccccccccccccccccccccccccccccccccccccccccccccccc
C Solar sailing ISU-96 Solar Probe Design Project
C       SAILING.FOR
C Design & Programming:  Marc Abela
C Creation:  August 25 1996
C Completion: August 27 1996
C Comments, suggestions and scientific advices:
C                                Berry Sanders
cccccccccccccccccccccccccccccccccccccccccccccccccc


      Implicit double precision (a-h,m,p-z)
      Dimension y(4)
      logical kop
      external esail
      common mass,sailarea,alpha,muesun,asail,ar,al

C Main constants used through out the program
      n=4
      pi=3.1415926535
      muesun=1.327e20

      write(6,*) 'Enter the mass of spacecraft (kg)'
      read(5,*) mass
      write(6,*) 'Enter the solar sail area (m^2)'
      read(5,*) sailarea
      write(6,*) 'Enter the starting distance (km) from the Sun'
      read(5,*) distance
C Convert distance from km to meters
      distance=distance*1000
      write(6,*) 'Enter the angle of attack of the sail (degrees)'
      read(5,*) alpha
C Convert alpha from degrees into radians
      alpha=alpha*pi/180
      write(6,*) 'Enter the complete duration of the trajectory (days)'
      read(5,*) tinte
C Convert tinte from days into seconds for the duration of the flight
      tinte = tinte*24*60*60
      write(6,*) 'Computing. Please wait...'

C Open the file pipes and initialize the content
      open(unit=7,file='sailing1.out',status='old')
      open(unit=8,file='sailing2.out',status='old')
      open(unit=9,file='sailing3.out',status='old')
      write(7,*) 'time','  r','lambda','  vt', '  vr'
      write(8,*) 'time','  r','asail','    ar','   al'
      write(9,*) 'time','  rp','   ra'

C Kop is for the integration routine no stdio (Kop means head in Dutch)
      kop = .false.
C Tint1 is the beginning of the integration step
      tint1 = 0.0d0
C Tint2 is the end of the integration step
      tint2 = 0.0d0
C Step size for the integration
      stepnum = 5000.0d0
      time = 0.0d0

C Initialization
C y(1) is set to the distance from the sun (in meters)
C y(2) is set to the radial velocity (in meters per second)
C y(3) is set to the starting angle value (in radians)
C y(4) is set to the angular velocity (Vt/R) (in radians per second)

      y(1)=distance
      y(2)=0.
      y(3)=0.
      y(4)=sqrt(muesun/distance**3)

C While end of integration is not reached
111      if (tint2.lt.tinte) then
           tint2=tint1+stepnum
           time=tint2
C The next line calls in the Runge-Kutta integration routine
           call ruks(n,tint1,y,tint2,1,0,esail,kop)
           if (i .ge. 150) then
              i=0.0d0

              vi=sqrt((y(4)*y(1))**2 + (y(2))**2)
              h0=y(1)*vi**2./muesun
              a=y(1)/(2.-h0)
              gai=atan(y(2)/(y(1)*y(4)))
              enc=sqrt(1-h0*(2-h0)*(cos(gai))**2)
              hap=a*(1+enc)
              hep=a*(1-enc)

C Time is converted in days, distance in AUs, velocity in km/s, alpha in degrees
              timeindays=time/(24*60*60)
              write(7,*) timeindays,y(1)/149.6E9,
     $         y(3)*180/pi,y(4)*y(1)/1000,y(2)/1000
              write(8,*) timeindays,y(1),asail,ar,al
              write(9,*) timeindays, hep/149.6e9, hap/149.6e9
          endif
          i = i+1
          tint1=tint2
          goto 111
        endif

C Close the file pipes
         Close(unit=7)
         Close(unit=8)
         Close(unit=9)
         stop
       end

       Subroutine esail(time,y,f)
       Implicit double precision (a-z)
       dimension y(4),f(4)
       common mass,sailarea,alpha,muesun,asail,ar,al

C This routine is called by the integration routine (Runge-Kutta)

C Note that muesun is equal to 1.327E20 (gravity constant of the sun)
C y(1) is R
```

```
C y(2) is Rdot
C y(3) is Lambda
C y(4) is Lambdadot
C ar is acceleration in radial direction away from the sun
C al is acceleration in tangential direction
C asail is the acceleration provided by the solar sails
C These are the default acceleration values for attraction from sun body
C ar=-(muesun)/(y(1)**2.)
C al=0
C Note that y1 in the equation needs to be expressed in AU's
C Please refer to the following book for more information on Solar Sails and
C mathematical equations
C       Space Sailing, Jerome L.Wright, Gordon and Breach Science Publishers,
C          1994

C T is computed as the thrust generated due to the presence of the sail
        T=0.9216E-5*((Cos(alpha))**2.)*sailarea/((y(1)/149.6e9)**2.)
C asail represents the acceleration generated by the above thrust
        asail=T/mass
        ar=-(muesun)/(y(1)**2.)+asail*Sin(alpha)
        al=-asail*Cos(alpha)
        f(1)=y(2)
        f(2)=ar+y(1)*y(4)**2.
        f(3)=y(4)
        f(4)=al/y(1)-2.*y(2)*y(4)/y(1)
        return
        end
```

C.2.3 References:

ISU Summer Session '94, Solar System Exploration Design Project, ISU, Summer 1994

C.3 The MIDAS Trajectory Optimisation Program

C.3.1 Introduction

During the ISU summer session, the MIDAS software was introduced to the Solar System Exploration design project to assist in the computation of interplanetary trajectories. It was therefore installed on a Sun workstation and several students were trained to use it by Stacy Weinstein from JPL, USA. MIDAS is a program developed at JPL. It is capable of optimising interplanetary trajectories by using a patched conic approximation [Sauer, 1994]. It is written in FORTRAN and runs on both DOS and UNIX computers. MIDAS can compute direct flights, one or more gravity assists and deep space manoeuvres to a selected target. It is possible to perform a fly-by, a rendezvous or an orbit around the target.

C.3.2 The Patched Conic Approximation

MIDAS uses a patched conic approximation for the computation of interplanetary trajectories. The patched conic method uses ideal Kepler orbits for the different phases of the flight. MIDAS then connects them at the beginning and end points.

To illustrate this, let us take the example of a flight to Mars. The departure from Earth is a hyperbolic Kepler orbit around the centre of the Earth. The flight from Earth to Mars is an ellipse around the Sun, while the arrival at Mars is again a hyperbolic orbit around the centre of Mars. In this case MIDAS computes the different Kepler orbits roughly. Midas then changes the orbits to connect them at the Earth and Mars orbits to form one consistent trajectory. Of course, the patched conic approach is not limited to two bodies and three trajectory parts, more can be included in MIDAS to form gravity assist trajectories and multiple flybys. MIDAS also has the possibility to include deep space manoeuvres to make gravity assist trajectories possible.

C.3.3 Possibilities of MIDAS

MIDAS can compute trajectories with up to eight deep space manoeuvres and several gravity assists from larger bodies. It is also possible to visit one body more than once. Asteroids and other small bodies are included in a separate table which can be called upon by MIDAS so flights to nearly all the small bodies can be computed.

The input to MIDAS is a file composed of several lines, describing the starting body, the target, the intermediate bodies which will be visited and the time frame in which the flight

will occur. MIDAS will find the optimal launch date around the dates given by the user and it will vary the flight time within the limits given by the user. that way, the user can pick the optimal flight time. Also, the user has to specify whether he wants to make a fly-by at the target or orbit it. In the last case he also has to specify the orbit.

The output of MIDAS can be given in different forms, both abridged and extended output files can be generated. With the help of the K-plot program, it is also possible to generate a plot of the trajectory.

A separate program called LV can be used to assess the interplanetary performance of different Western launch vehicles with and without upper stages.

C.3.4 Optimisation Method Used in MIDAS

MIDAS uses a gradient search method to optimise the trajectory. It minimises the total velocity of a trajectory by taking an initial estimate and computing the gradient towards the lowest velocity for the mission. It then starts searching in the direction of this minimum for a given duration of the flight. The danger of this method is that the program can trace a local minimum and that there might be another global minimum with a lower velocity requirement. Therefore, the result have to be interpreted with some care.

C.3.5 Concluding Remarks

MIDAS was used quite extensively in the Ra design project for the different feasibility studies, using Venus, Mercury, and Jupiter flybys and proved to be a very valuable tool for our project. However, due to the fact that it is an expert tool, the output was often difficult to interpret for a person with little experience with the program.

C.4 The SKYNAV Trajectory Optimisation Program

C.4.1 Introduction

During the ISU summer session, the SKYNAV software was introduced to the Ra design project to assist in the computation of interplanetary trajectories. It was installed on a laptop computer and several students were trained to use it by Berry Sanders from Bradford Engineering. SKYNAV is a program developed by Ingenieurbuero "Dr. Schlingloff", from a program originally developed for European ion propulsion missions. It is capable of optimising interplanetary low thrust trajectories. It is written in FORTRAN and C and runs on DOS computers. SKYNAV can compute low thrust flights and deep space manoeuvres to a selected orbit.

C.4.2 Possibilities of SKYNAV

SKYNAV can compute low thrust trajectories with varying thrust and specific impulse throughout out the trajectory or an orbiting spacecraft using electric propulsion (EP) as its main source of thrust. It is also possible to visit more than one planetary body (for example, when rendezvous with asteroids and other small bodies or the solar system).

The input to SKYNAV is a file composed of several lines, describing the nature of the initial and final orbits, the mass and the propulsion of the spacecraft thought out its trajectory. SKYNAV will find the optimum low thrust trajectory between the given initial and final orbits based on the Hamilton-Lagrange optimisation theory. The user can therefore pick the optimal flight time and propulsion management schemes. The user can also specify whether he wants to make for example a plane change or modify other orbit parameters.

The output of SKYNAV can directly be given in graphical and numerical forms. It is therefore possible to generate databases as well as graphs of the trajectories selected by the software. Due to the direct graphical output, it is feasible to visualise and assess the nature of the optimum trajectory for instantaneous feed-back.

C.4.3 Optimisation Method Used in SKYNAV

SKYNAV uses the Hamilton-Lagrange theory to optimise trajectories. It minimises the total Delta V of the selected trajectory by taking an initial estimate for the Lagrange multipliers and by computing simultaneously the equations of motions which describe the trajectory and the optimality conditions. It then starts searching in the direction of a minimum for a given travelled angle of flight.

C.4.4 Operation of SKYNAV

The user needs to first set up the nature of the problem and then initialises it. The program will now solve the problem using impulsive shots. The user will then, in successive runs, try to lower the thrust in order to create a low thrust trajectory. This operation is a iterative process that needs to be carried all the way until the desired thrust level is achieved. When the given mission angle is not sufficient to achieve the required Δv, the mission angle should be enlarged accordingly.

C.4.5 Concluding Remarks

SKYNAV is a very useful program for the computation of optimal low-thrust trajectories. We used SKYNAV to establish (among other things) the feasibility of the SAUNA mission. Although other advanced features like gravity assists are not included among the options in this program, its simplicity of use makes it ideal for simple feasibility assessment of low-thrust interplanetary missions.

C.5 Data used for trajectories

Table C.5.1 Data of Potential Gravity Assist Planetary Bodies

Planet	Equatorial radius (km)	Mean distance from the Sun (million km)	Sidereal period	Escape velocity km/s	Mass (Earth = 1)
Mercury	2335	57.9	57.9 days	4.2	0.06
Venus	6200	108	224.7 days	10	0.82
Earth	6385	149.6	365.3 days	11	1
Mars	3880	227.7	687.0 days	6.4	0.11
Jupiter	71500	777.8	11.86 yr	59.7	318

Table C 5.2 Common Distance Units

Acronym	Name of the Unit	Value	Definition
AU	Astronomical Unit	149,689,534 km (approx.: 150 M km)	Mean distance between the Earth and the Sun
R_S	Solar Radius	696,000 km (approx.: 0.7 M km)	Radius of the Sun

C.5.1 Plamya

This Russian mission is being proposed to fly with the US's Solar Probe on a joint mission called Fire. Plamya and the Solar Probe would be launched on a Proton launcher for a Jupiter gravity assist. The Plamya trajectory is very similar to the solar probe's (perpendicular to the ecliptic), except perihelion will be ~10 solar radii (~0.05 A.U.)

C.5.2 SOHO

The Solar and Heliospheric Observatory (SOHO) is designed to study the internal structure of the Sun, its extensive outer atmosphere, and the origin of the solar wind - the stream of highly ionised gas that blows continuously outward through the Solar System. It will also study the vibration of the Sun with a very high spatial and temporal resolution. SOHO was launched on December 2, 1995, by an Atlas 2AS/Centaur from Cape Canaveral, Florida, USA. The spacecraft has been injected into a Halo orbit around the L1 Libration point of the Earth-Sun system, approximately 1.5 million km sunward from the Earth., requiring a Δv= 1.35 km/s. Halo orbits around the L1 point are unstable, and small correction manoeuvres must be applied to prevent excessive departure from the nominal orbit. SOHO 's orbital period is six months.

C.5.3 Solar Probe

The Solar Probe mission, studied by NASA, is a planned fast flyby of the Sun. The trajectory relies on a Jupiter gravity assist to crank the orbit perpendicular to the ecliptic and approach within four solar radii (~0.02 A.U.). Due to the gravity assist all the way out at Jupiter, the time from launch to perihelion is over 4.5 years. However, the primary advantage is that the spacecraft propellant required is very small, only for orbit corrections and attitude control. The velocity increment required for injection to Jupiter is ~ 8.8 km/s which is provided by the launch vehicle and upper stage.

C.5.4 Ulysses

The Ulysses Mission is the first spacecraft to explore interplanetary space at high solar latitudes. Its primary mission is to characterise the heliosphere as a function of solar latitude, with particular emphasis on the regions above the solar poles. The spacecraft was launched on October 6, 1990, by the Shuttle Discovery with two upper stages, during the 5-23 October Jupiter window.

Since direct injection into a solar polar orbit from the Earth is not feasible with chemical propulsion, a gravity-assist is required to achieve a high-inclination orbit. For that reason, Ulysses was launched at high speed (Δv=11.4 km/s) towards Jupiter, after being deployed from Discovery in a 300 km circular low-Earth orbit. Following the fly-by of Jupiter in February 1992 and the resulting large gravity assist, the spacecraft was injected into an orbit out of the ecliptic plane with a perihelion of 1.34 AU. The spacecraft is now travelling northwards in an elliptical heliocentric orbit inclined at 80.2 degrees to the solar equator. Ulysses achieved its maximum southern latitude of 80.2 degrees on September 13, 1994. It travelled through high northern latitudes during June through September of 1995. Ulysses' orbital period is six years.

C.6 Optical Communications

C.6.1 Concept

Free space optical communications offer a substantial increase in link capacity. This increase comes as a result of the much smaller wavelength associated with optical carriers. Smaller

wavelengths result in narrower transmitted beam divergences and hence more concentration of the power on the intended target receiver. For example, if one compares X-Band (3 cm) RF with visible light (0.5 micro-m), the ratio of power concentration is 95 dB. Not all of this gain results in link advantage however. The basic process of photo detection is less efficient than for RF due to quantum noise effects. When these effects are taken into account, the resulting overall link benefit is typically about 71 dB [Shaik 1995] over an RF system.

C.6.2 Environment interference

The Sun is, of course, a very bright source from the Earth's point of view in the optical and near-infrared bands. Direct Sun is a powerful source of optical radiation. The spectral irradiance of the Sun peaks at 460 nm, as expected from black body considerations, and decreases with increasing wavelength [Shaik 1995]. In the far infrared, the Sun output decreases to an acceptable level [Mendell 1996] It is thus possible to use a laser source (*e.g.* CO_2, 10.6 micron) that will possibly have a lower background noise.

C.6.3 Implementation

Because of the narrow beamwidths of optical systems, and due to the finite speed of light, optical communications signals must be pointed ahead of the apparent location of the intended target receiver so that the transmitted beam will intercept it. The magnitude of this point-ahead angle depends on the relative cross velocity of the two communication terminals and can be as large as 500 micro-radians in some planetary applications [Lesh 1992]. The transmission path steering mirrors are used to introduce this offset angle.

It is highly desirable to develop optical communication systems around Fraunhofer lines where the Sun's spectral irradiance is substantially low. However, assuming present technology, it is difficult to see how this information can be used to an advantage. It is a technical challenge to produce an optimal match between the laser wavelength and a strong Fraunhofer line, and in addition, most practical lasers for optical transmitters have broader line widths than the fine atomic dark lines in the Sun's spectrum [Shaik 1995].

By far the most complicated problem is to have a coherent beam. Firstly, the frequency accuracy of the diodes is of paramount importance. Presently, the stability of the frequency output of most diodes is questionable. Furthermore in a diode array, the coherence of the signal will be tricky as the exact timing of signal generation in each diode will be hard to implement.

Coherent detection will be equally difficult. Any drift at the emitting end will have to be closely calculated. The Doppler effect of a probe moving at high velocities throughout the solar system while the Earth is orbiting will induce a trajectory-dependant Doppler shift which will have to be known precisely in order to have (1) adaptive filtering and (2) adaptive coherent signal recombination.

C.6.4 Acquisition

Contrary to a typical near-Earth crosslink the one-way beam propagation time for deep space communications can be from several tens of minutes to several hours. Furthermore, by the time the beam reaches the other terminal, the original platform may no longer be in that location. Thus, an acquisition, tracking and pointing strategy which does not require two-way beam propagation is needed [Lesh 1992]. Fortunately, at planetary distances, nature can provide the necessary spatial references in the form of the solar-illuminated planets themselves. As soon as there is a clear path to the Earth, a telescope can be pointed in that direction. Once Earth is acquired, a two-dimensional detector array can resolve the image and, by locking onto that image with sufficient accuracy, adequate knowledge is available to

point and fire the return communication laser beam at the Earth receiver. Since the solar-illuminated Earth image is always available at the distant location (except when going behind the Sun) the entire acquisition tracking and return beam pointing process can be accomplished in a relatively short time period (likely under 30 seconds)[Lesh 1992]. This permits almost instant communications as soon as line of sight is established.

C.6.5 Ground segment

There are no ground segment yet available for optical communications, or more precisely for deep space communications. There are two possibilities: either the receptors are placed in space, or on Earth. Spaceborne receptors have already been discussed in Chapter 6.

To correct for atmospheric effects for Earth based receptors, one would have to use a variety of techniques. The sitting of the receivers on high ground would in the first place alleviate for atmospheric absorption. Observatories with clear and dry skies have been in place for quite a number of years. Filtering of the incoming signal is necessary. Again, astronomy has been filtering light for years, and adaptive filters to work at the desired frequency pose no problems. Adaptive optics will be required for atmospheric turbulence.

A ground based interferometry system could be developed to increase the amount of energy collected. Early designs [Lesh 1994] for interstellar missions had 10-m diameter telescopes at the receiving end. Reducing this by one order of magnitude, it is possible to imagine a global receiving network of multiple 1-m sized telescope. A number of solar observation telescopes are in place around the world today. A number of old astronomical telescopes are still quite usable. They could be converted for our use with proper filtering, conducting observations of the sky by night and communications by day.

If interferometry is used on the receiving end, the position of the receiving antenna becomes critical, within fractions of the wavelength. In our case, optical wavelengths are in the order of micrometers. This means that any variation in the position of the telescopes (solar photon pressure for orbiting receivers, any type of ground movement around the Earth-based telescopes) would be sufficient to lose signal lock. Of course, a variety of techniques could be used to counter movement, especially on the ground. Low-temperature physicists have long ago recognised that problem and this type of movement accuracy is achievable.

Time tagging of data in interferometry is also of paramount importance. It remains to be seen (calculated) if the best atomic clocks/GPS systems available now can provide the required timing.

C.7 Ground Station Block Diagram

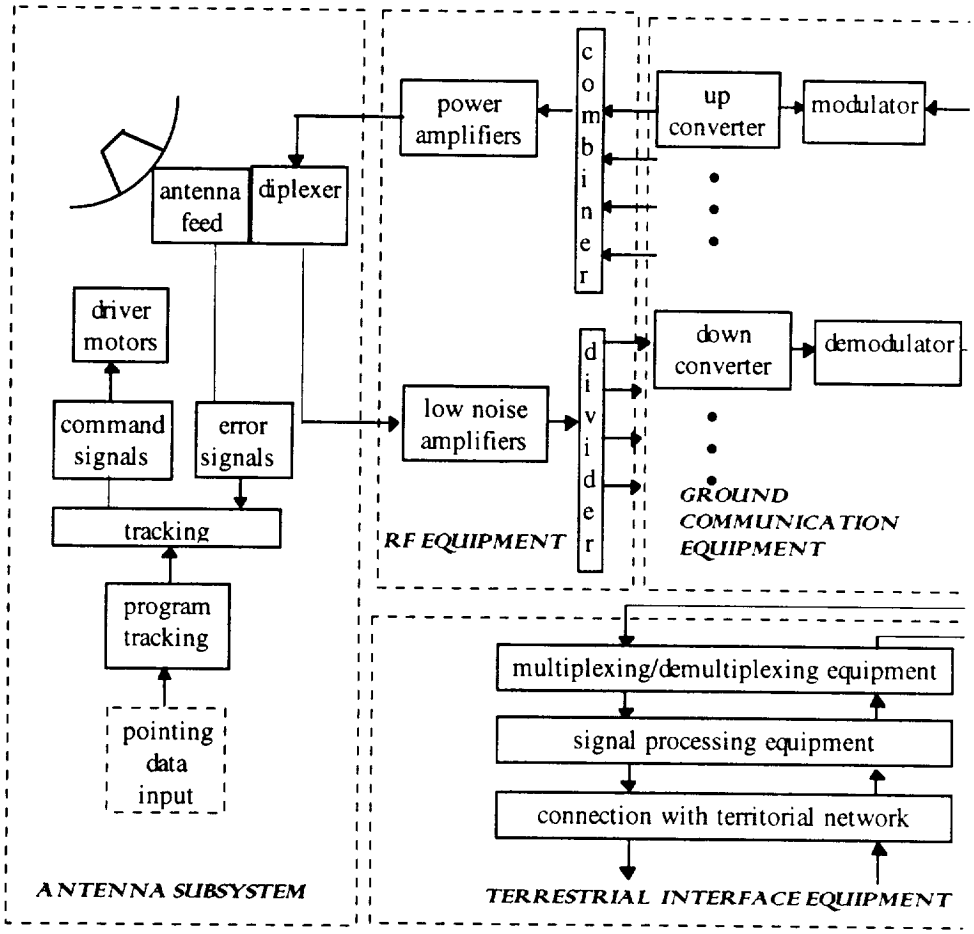


Fig. C.7.1 Typical ground station block diagram

The German Space Operation Centre, that is operated by the DLR, offers a good example of a typical earth station that is an alternative to the DSN for supporting the Ra missions. The centre located at Weilheim/Lichtenau offers a variety of antennas and associated buildings that can provide support for missions using S-band for the two way links and X- or C-band for the downlink. It consists of a 30 m antenna and two others of 15 m. [DLR Ground stations at WEILHEIM, Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V., WWW]

Appendix D

Costing

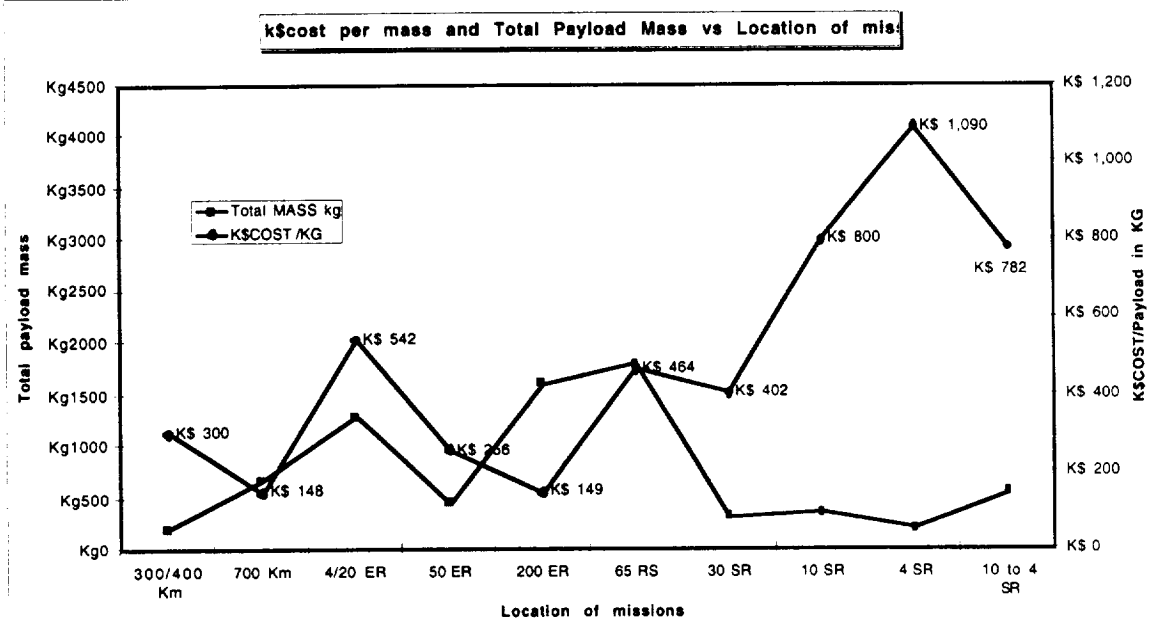
Cost database of different Near-, Mid- and Far-Term missions are presented in this appendix, in the following order :

- Cost per mass and Total Payload mass vs location of mission (Cost missions).
- Cost of Launchers (CostLaunchers).
- Cost matrix of CLEMENTINE 2 (CostCLEMENTINE2).
- Cost matrix of CLUSTER (CostCLUSTER).
- Cost matrix of FAST (CostFAST).
- Cost matrix of SOHO (CostSOHO).
- Cost matrix of TIMED (CostTIMED).
- Cost matrix of FIRE Mission, Solar probe (CostFIRE Solarprobe).
- Cost matrix of FIRE Mission, Plamya (CostFIREplamya).
- Cost matrix of FIRE Mission, Plamya and Solar probe (CostFIRE Plamya&solarprobe).
- Cost matrix of RA Application (CostRA-Application).
- Cost matrix of SAUNA (CostSAUNA).

The * represents missing values.

Cost per mass and Total Payload mass vs location of mission

MISSIONS	FAST	TIMED	CLUSTER	CLEMENTINE2	SOHO	RA application	SAUNA	PLAMYA	SOLAR PROBE	FIRE
Year	1996	1998	1996	1992	1995	2003	2003	2003	2003	2003
Location of	300/400 Km	700 Km	4/20 ER	50 ER	200 ER	65 RS	30 SR	10 SR	4 SR	10 to 4 SR
Global COST	K$ 60,000	K$ 100,000	K$ 690,000	K$ 116,000	K$ 240,000	K$ 835,900	K$ 126,200	K$ 280,000	K$ 218,000	K$ 430,000
Launcher COST K$	K$ 15,000	K$ 18,000	K$ 0	K$ 35,000	K$ 114,000	K$ 120,000	K$ 60,000	K$ 80,000	K$ 114,000	K$ 114,000
Space Segment K$	K$ 45,000	K$ 82,000	K$ 690,000	K$ 81,000	K$ 126,000	K$ 715,900	K$ 66,200	K$ 200,000	K$ 104,000	K$ 316,000
Total MASS kg	Kg200	Kg675	Kg1272	Kg464	Kg1608	Kg1800	Kg314	Kg350	Kg200	Kg550
K$ COST	K$ 300	K$ 148	K$ 542	K$ 256	K$ 149	K$ 464	K$ 402	K$ 800	K$ 1,090	K$ 782



Reference: See cost matrix in the next pages.

Cost of Launchers

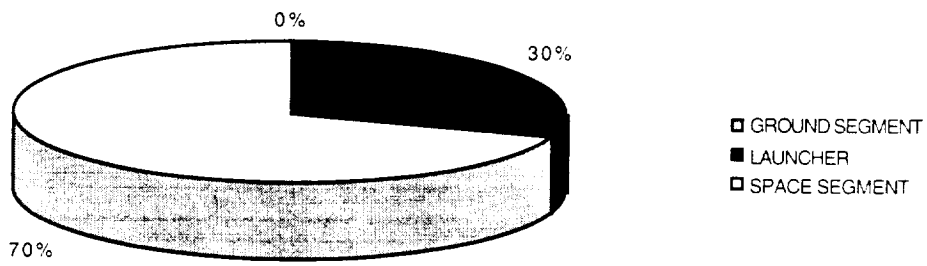
LAUNCHER NAME	LEO PAYLOAD Kg	GTO PAYLOAD Kg	LAUNCHER COST M$	LEO COST/Kg k$	GTO COST/Kg k$
ARIANE 40	4900	2000	60	12.24	30.00
ARIANE 42P	6100	2700	62	10.16	22.96
ARIANE 42L	7400	3200	85	11.49	26.56
ARIANE 44P	6900	3000	65	9.42	21.67
ARIANE 44LP	8300	3900	90	10.84	23.08
ARIANE 44L	9600	4700	140	14.58	29.79
ARIANE 5	18000	6800	126	7.00	18.53
ATLAS I	5580	2250	65	11.65	28.89
ATLAS II	6395	2680	70	10.95	26.12
ATLAS II A	6760	2810	80	11.83	28.47
ATLAS II AS	8390	3700	110	13.11	29.73
DELTA I 6920	3990	1450	40	10.03	27.59
DELTA II 7925	5045	1820	45	8.92	24.73
H2	10500	4000	150	14.29	37.50
M5	1950	1215	40	20.51	32.92
LONG MARCH 1 CZ-1D	750	200	10	13.33	50.00
LONG MARCH 2 CZ-2C	3200	1000	16	5.00	16.00
LONG MARCH 2 CZ-2E	9200	3300	40	4.35	12.12
LONG MARCH 2 CZ-2E/H0	13600	4500	50	3.68	11.11
LONG MARCH 3 CZ-3	5000	1500	20	4.00	13.33
LONG MARCH 3 CZ-3A	7200	2500	30	4.17	12.00
LONG MARCH 4 CZ-4	NA	1100	18	NA	16.36
STS (SHUTTLE)	24400	5900	350	14.34	59.32
TITAN 2	1905	NA	35	18.37	NA
TITAN 3	14515	5000	130	8.96	26.00
TITAN 4 CCAFS	17700	8620	230	12.99	26.68
TITAN 4 VAFB	17700	8620	230	12.99	26.68
VOSTOK	4730	NA	20	4.23	NA
SOYUZ	7000	NA	15	2.14	NA
KOSMOS	1350	NA	6	4.44	NA
TSYKLON	4000	NA	12	3.00	NA
ZENITH	13740	4300	25	1.82	5.81
PROTON	20000	5500	80	4.00	14.55
ENERGIA SL-17	88000	NA	80	0.91	NA
PEGASUS	455	125	13	28.57	104.00
TAURUS	1451	NA	18	12.41	NA
LLV-1	794	NA	16	20.15	NA

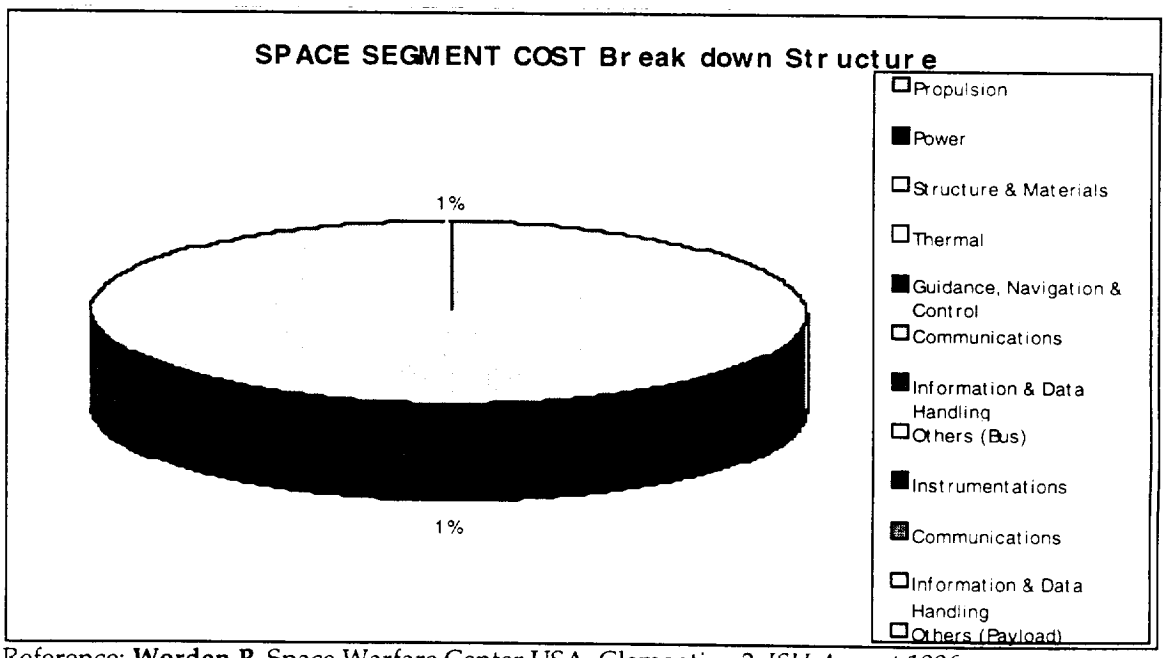
Reference: **Isakowitz.S.J**, *International Reference guide to launch Systems*, AIAA 1995.

Cost matrix of CLEMENTINE 2

SOLAR PROBE MISSION:	CLEMENTINE II	1999	Ref. A
	NAME and	$COST	TOTAL $COST
GROUND			•
TRACKING			•
DATA			•
OPERATION			•
LAUNCHER			$ 35,000,000
	TITAN2G	$ 35,000,000	
SPACE			$ 81,000,000
	360W		
BUS	MotherSAT (Earth		•
Propulsion		•	
Power		•	
Structure &		•	
Thermal		•	
Guidance, Navigation &		•	
Communications		•	
Information & Data		•	
Others (Bus		•	
PAYLOAD	MicroSAT,20 Kg		•
Instrumentations		•	
Communications	100 MIP Onboard processor	•	
Information & Data		•	
Others (Payload)		•	
TOTAL $COST			$ 116,000,000
Total exc. Propellant			227.[illegible]
incl. Propellant/Iftof			454.[illegible]
TOTAL			454.[illegible]

MISSION COST Break down Sturcture

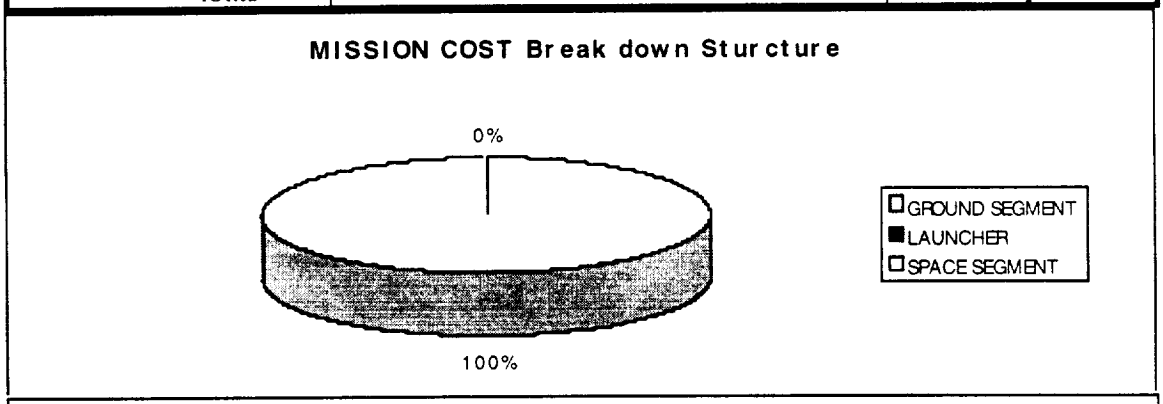


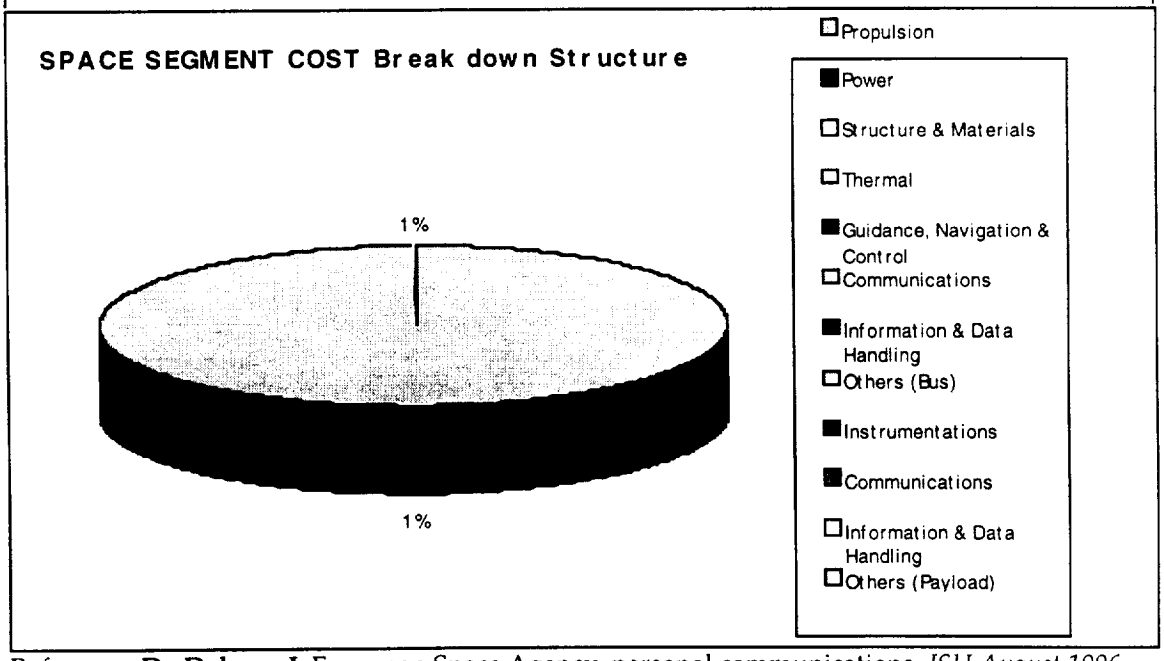


Reference: **Worden.P**, Space Warfare Center USA, Clementine 2, *ISU August 1996.*

Cost matrix of CLUSTER

SOLAR PROBE MISSION:	CLUSTER	1996	Ref. A
	NAME and	$COST	TOTAL $COST
GROUND			•
TRACKING			•
DATA			•
OPERATION			•
LAUNCHER			•
	ARIANE 5	•	
SPACE			$ 690,000,007
BUS	Apogee 19.6 Earth Radius & Perigee 4 Earth		$ 690,000,007
Propulsion	Bi-propellant	•	
Power	Solar array 224W, Electrical power 47W	•	
Structure &		•	
Thermal		•	
Guidance, Navigation &		•	
Communications		•	
Information & Data		•	
Others (Bus		•	
PAYLOAD			•
Instrumentations		•	
Communications	Telemetry downlink bit rate2 to 262 Kbits/s	•	
Information & Data		•	
Others (Payload)		•	
TOTAL $COST	FY 95$		$ 690,000,007
Total exc. Propellant			550.00
incl. Propellant/lftof			1275.00
TOTAL			1275.00

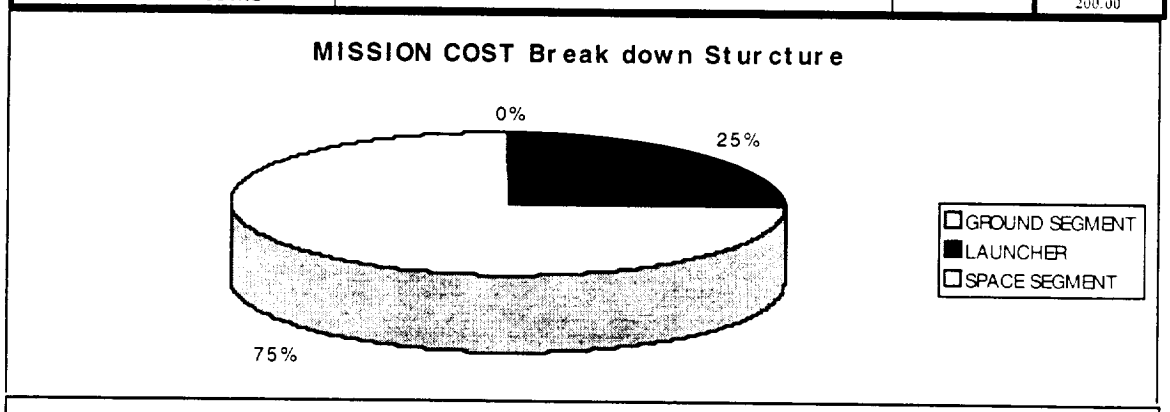


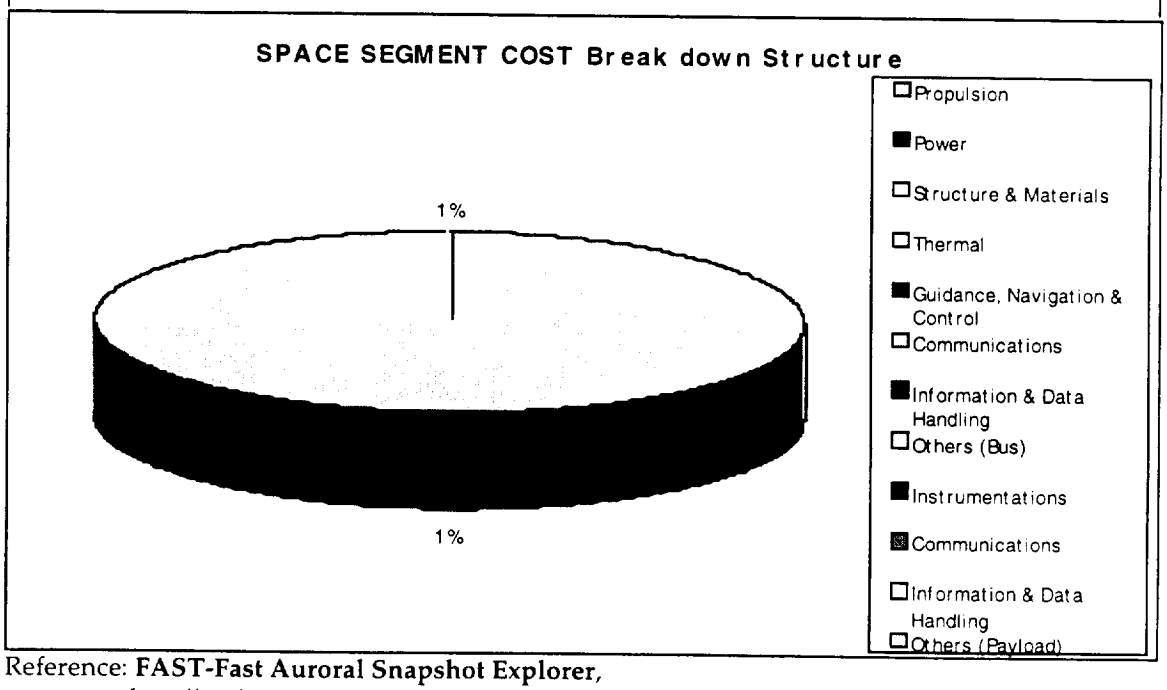


Reference: **De Dalmau.J**, European Space Agency, personal communications, *ISU August 1996.*

Cost matrix of FAST

SOLAR PROBE MISSION:	FAST	1996	Ref. A
	NAME and	SCOST	TOTAL SCOST
GROUND			
TRACKING			•
DATA			•
OPERATION			•
LAUNCHER			$ 15,000,000
	Pegasus XL, from L-1011 aircraft	$ 15,000,000	
SPACE			$ 45,000,000
BUS	50 to 60W		•
Propulsion		•	
Power	Solar cells (galluim arsenide), NiCad batteries	•	
Structure &		•	
Thermal		•	
Guidance, Navigation &		•	
Communications		•	
Information & Data		•	
Others (Bus)		•	
PAYLOAD	Nearly polar (83 inclination, 350 km by 4200 km)		•
Instrumentations	19 W, 65Kg	•	
Communications	s-band telemetry	•	
Information & Data	maximum rate 2.2 Mbps	•	
Others (Payload)		•	
TOTAL SCOST			$ 60,000,000
Total exc. Propellant			[illegible]
incl. Propellant/Ifto			[illegible]
TOTAL			200.00



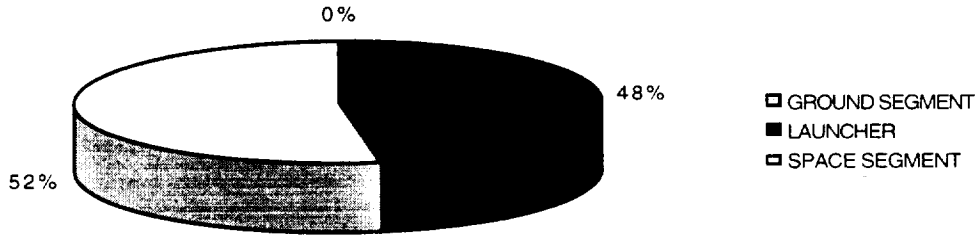


Reference: **FAST-Fast Auroral Snapshot Explorer,**
http://sunland.gsfc.nasa.gov/smex/fast/fast_top.html, NASA.

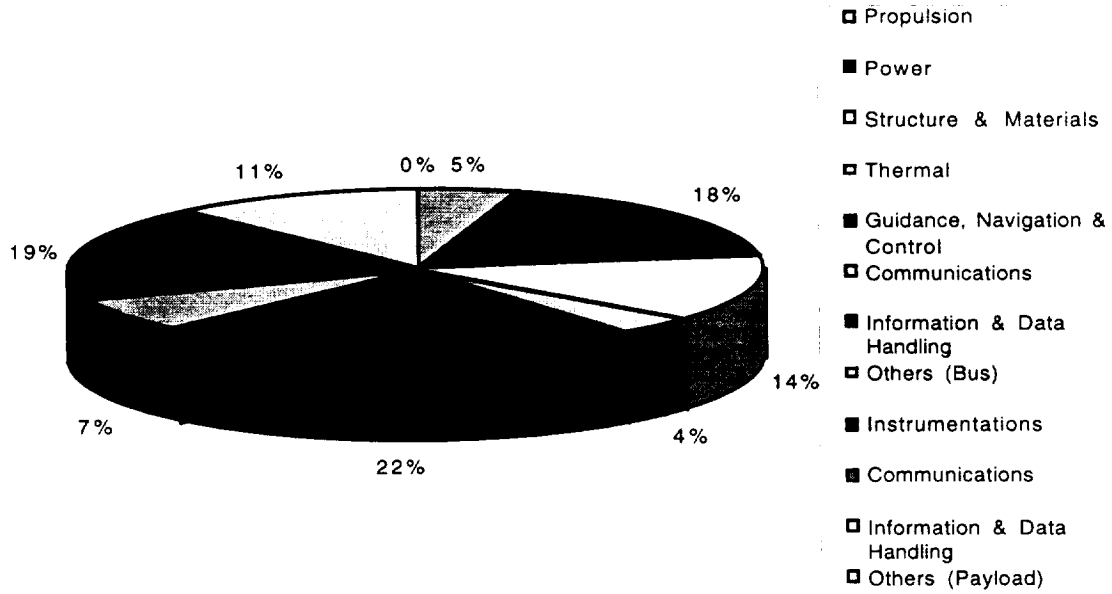
Cost matrix of SOHO

SOLAR PROBE MISSION:	SOHO	1995	Ref: A
	NAME and	$COST	TOTAL $COST
GROUND			•
TRACKING			•
DATA			•
OPERATION			•
LAUNCHER			$ 114,000,000
	Atlas II AS/Centaur	$ 114,000,000	
SPACE			$ 125,760,417
BUS	1.5 km sunward from		$ 125,760,417
Propulsion	Hydrazine thruster	$ 5,831,700	
Power		$ 22,560,825	
Structure &		$ 17,028,741	
Thermal		$ 4,688,883	
Guidance, Navigation &		$ 28,112,879	
Communications		$ 8,889,822	
Information & Data		$ 24,290,397	
Others (Bus)	Payloadmodule,SVM,centralOBS,Ground Support Eq	$ 14,357,170	
PAYLOAD	610Kg		•
Instrumentations		•	
Communications		•	
Information & Data	200 kbits/s	•	
Others (Payload)		•	
TOTAL $COST	FY 965		$ 239,760,417
Total exc.Propellant			1366.80
incl.Propellant/Iftot			1608.20
TOTAL			1608.20

MISSION COST Break down Structure



SPACE SEGMENT COST Break down Structure

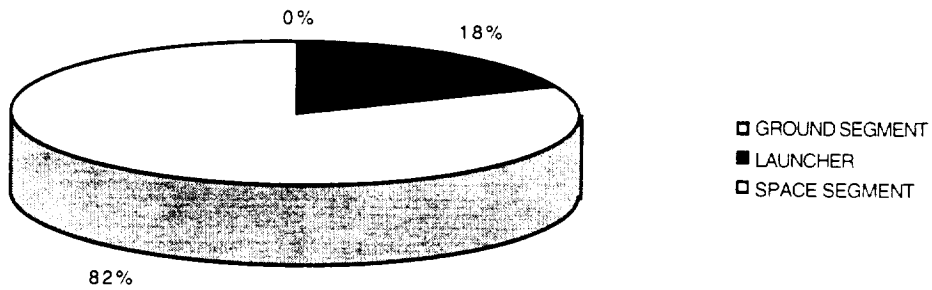


Reference: **Wnuk.G**, European Space Agency, personal communications, ISU August 1996.

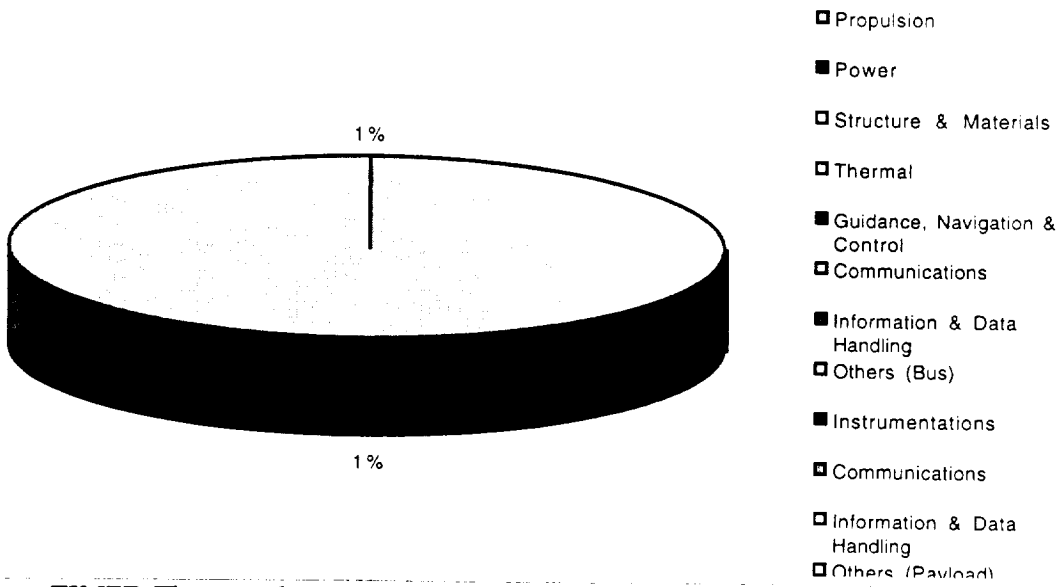
Cost matrix of TIMED

SOLAR PROBE MISSION:	TIMED	1998	Ref. A
	NAME and	SCOST	TOTAL SCOST
GROUND			
TRACKING			•
DATA			•
OPERATION			•
			•
LAUNCHER			$ 18,000,000
	Taurus class (LEO)	$ 18,000,000	
SPACE			$ 82,000,000
	675Kg, 300W		
BUS			•
Propulsion		•	
Power		•	
Structure &		•	
Thermal		•	
Guidance, Navigation &		•	
Communications		•	
Information & Data		•	
Others (Bus)		•	
PAYLOAD	112Kg, 150w, 600Km circular with 74.4 degree inclination		•
Instrumentations		•	
Communications	s-Band, STDN compatible	•	
Information & Data	Telemetry 19.2 kbps, 2 GB solid state recorder	•	
Others (Payload)		•	
TOTAL SCOST			$ 100,000,000
Total exc. Propellant			[illegible]
incl. Propellant/Ifto			[illegible]
TOTAL			[illegible]

MISSION COST Break down Sturcture



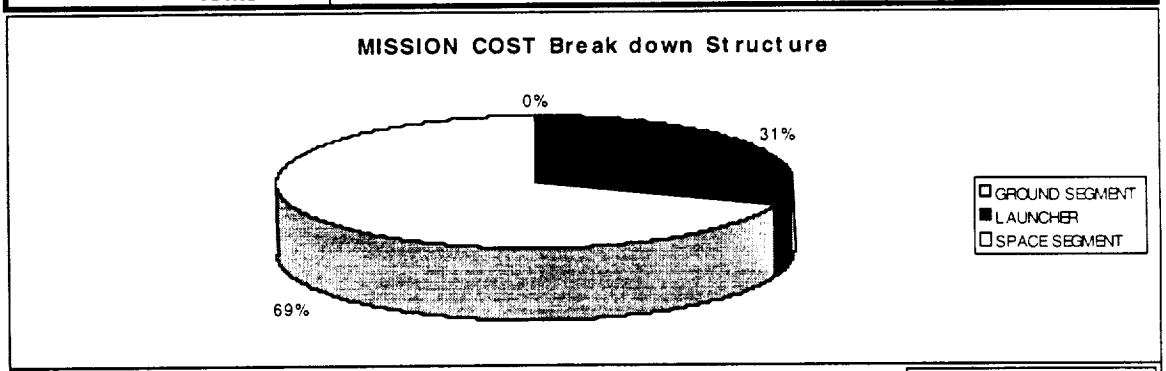
SPACE SEGMENT COST Break down Structure

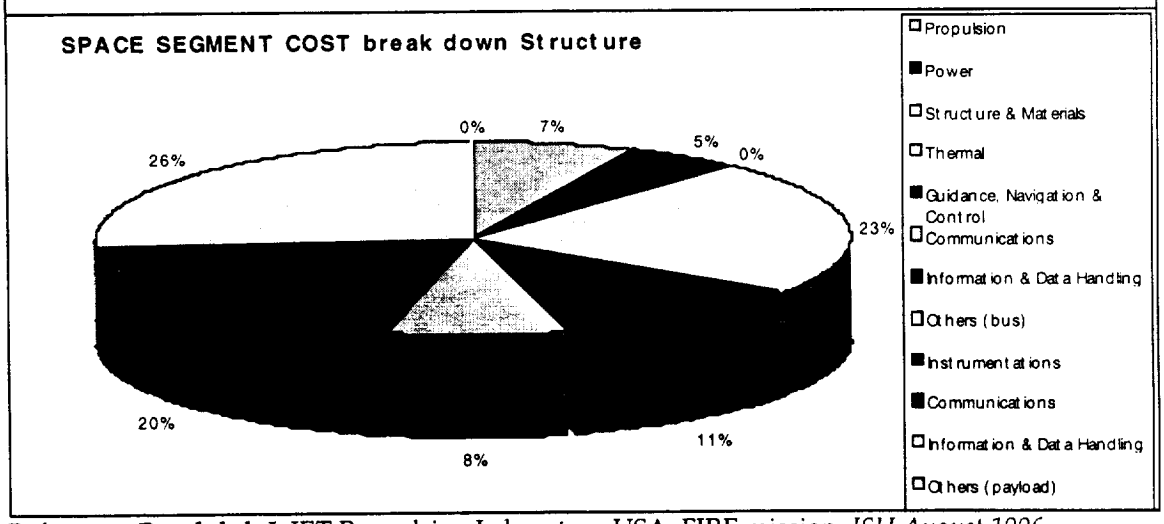


Reference: **TIMED-Thermosphere Ionosphere Mesosphere Energetics and Dynamics**, *http://sd-www.jhuapl.edu/TIMED/overview.html*, NASA.

Cost matrix of FIRE Mission, Solar probe

SOLAR PROBE MISSION:	(Solar Probe)FIRE	2003	Ref: A
	NAME and	SCOST	TOTAL SCOST
GROUND			•
TRACKING			•
DATA			•
OPERATION			•
LAUNCHER			$ 68,000,000
	Delta II 7925/Star 30 BP	$ 68,000,000	
SPACE			$ 150,000,000
BUS			$ 150,000,000
Propulsion	Conventional solution, Hydrazine thrusters for Attitude Control &	$ 10,500,000	
Power	Primary Battery 0.2 AU to 0.2AU	$ 7,500,000	
Structure &	Radiative shield with minimum sublibation, Carbon-Carbon		
Thermal		$ 34,500,000	
Guidance, Navigation &		$ 16,500,000	
Communications	Antenna with 0.4 degrees	$ 12,000,000	
Information & Data	Processor 2-20 MIPS; RH6000	$ 30,000,000	
Others (bus)	Fee, SD&I, GSE	$ 39,000,000	
PAYLOAD	Perihelion of 4 Rs		•
Instrumentations	8Kg, 8W, 500 bps	•	
Communications	X-band link, use antenna integrated with heat shield	•	
Information & Data	Minimum 500 bps	•	
Others (payload)		•	
TOTAL SCOST	FY 92$		$ 218,000,000
Total	Chemical (fuel is hydrazine)		155.00
incl Propellant/lifto			200.00
TOTAL			200.00

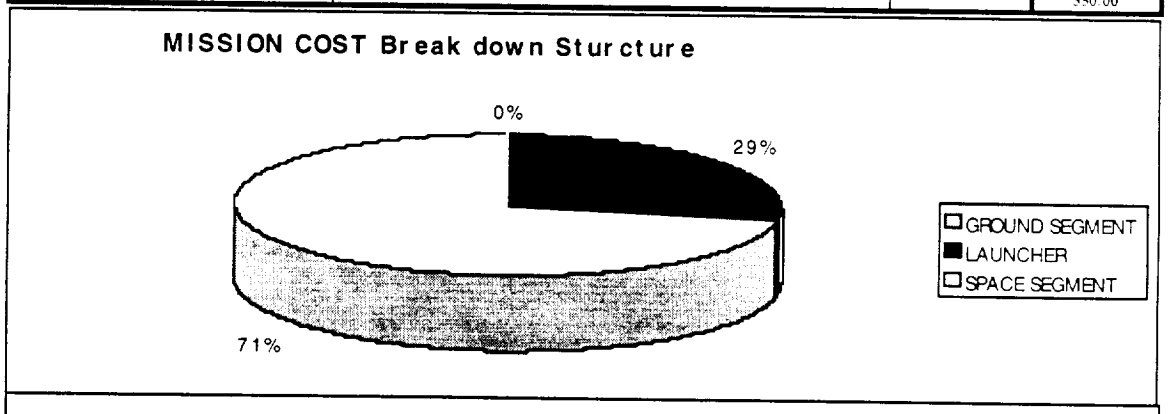


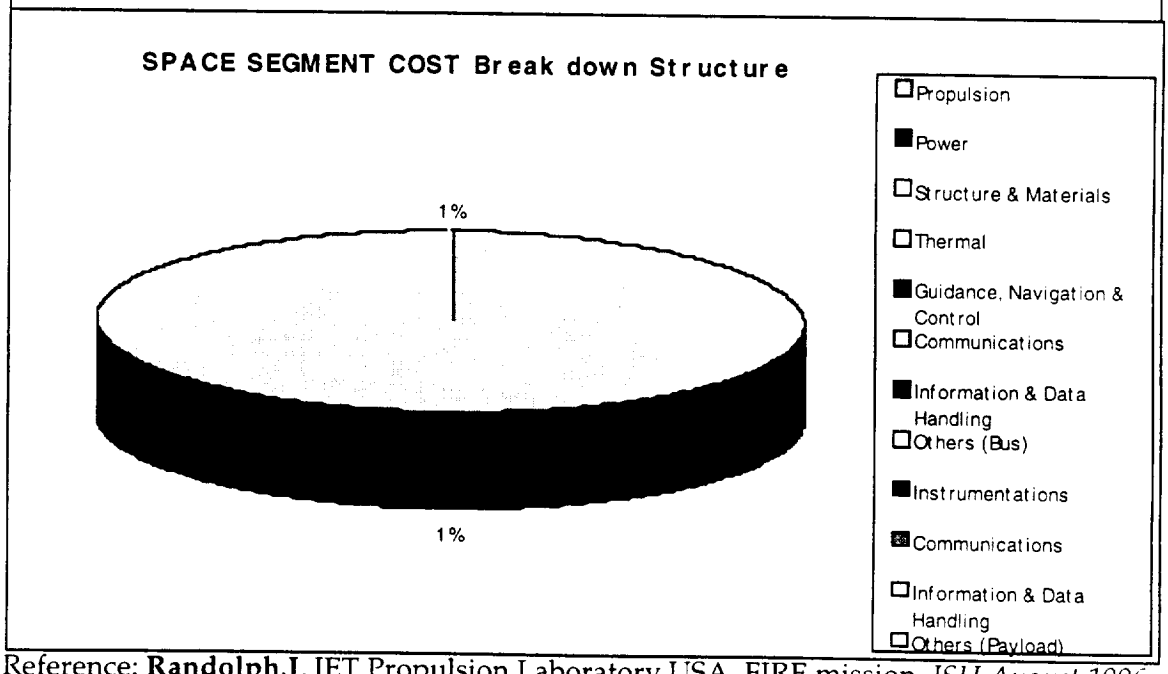


Reference: **Randolph.J**, JET Propulsion Laboratory USA, FIRE mission, *ISU August 1996.*

Cost matrix of FIRE Mission, Plamya

SOLAR PROBE MISSION:	(Plamya) FIRE	2003	Ref. A
	NAME and	$COST	TOTAL $COST
GROUND			
TRACKING			•
DATA			•
OPERATION			•
			•
LAUNCHER			
			$ 80,000,000
	Proton	$ 80,000,000	
SPACE			
			$ 200,000,000
	350Kg, 350W		
BUS			
Propulsion			$ 200,000,000
Power	RTG powered	•	
Structure &		•	
Thermal		•	
Guidance, Navigation &		•	
Communications		•	
Information & Data		•	
Others (Bus)		•	
		•	
PAYLOAD	Perihelion = 10Rs		•
Instrumentations		•	
Communications		•	
Information & Data		•	
Others (Payload)		•	
		•	
TOTAL $COST			$ 280,000,000
Total exc. Propellant			0.00
incl. Propellant/liftof			350.00
TOTAL			350.00

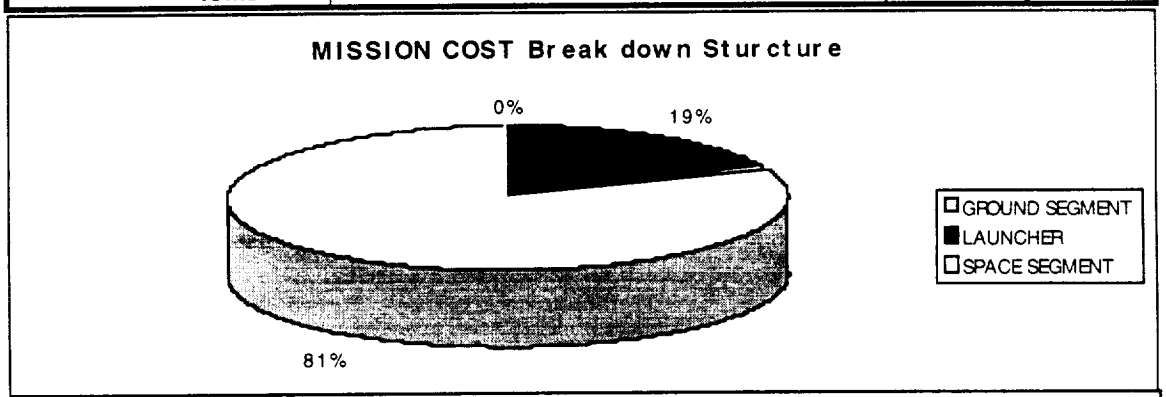


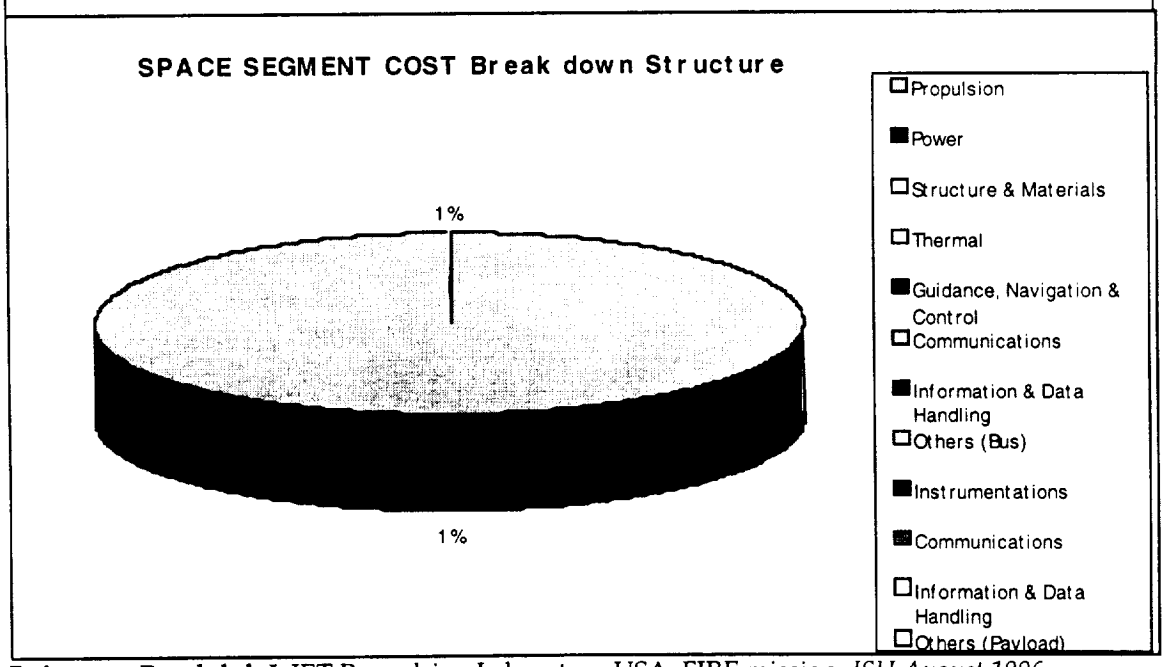


Reference: **Randolph.J**, JET Propulsion Laboratory USA, FIRE mission, *ISU August 1996*.

Cost matrix of FIRE Mission, Plamya and Solar probe

SOLAR PROBE MISSION:	(Plamya and Solar probe)	2003	Ref: A
	NAME and	$COST	TOTAL $COST
GROUND			•
TRACKING			•
DATA			•
OPERATION			•
LAUNCHER			$ 80,000,000
	Proton	$ 80,000,000	
SPACE			$ 350,000,000
BUS			$ 350,000,000
Propulsion		•	
Power		•	
Structure &		•	
Thermal		•	
Guidance, Navigation &		•	
Communications		•	
Information & Data		•	
Others (Bus)		•	
PAYLOAD	4Rs and 10Rs		•
Instrumentations		•	
Communications		•	
Information & Data		•	
Others (Payload)		•	
TOTAL $COST			$ 430,000,000
Total exc. Propellan			0.00
incl. Propellant/Iftot	Plamya and Solar probe		550.00
TOTAL			550.00

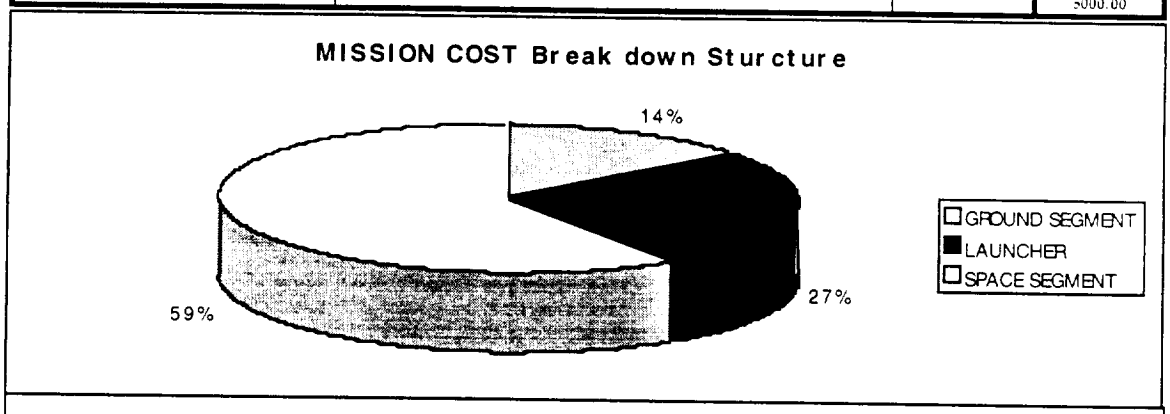


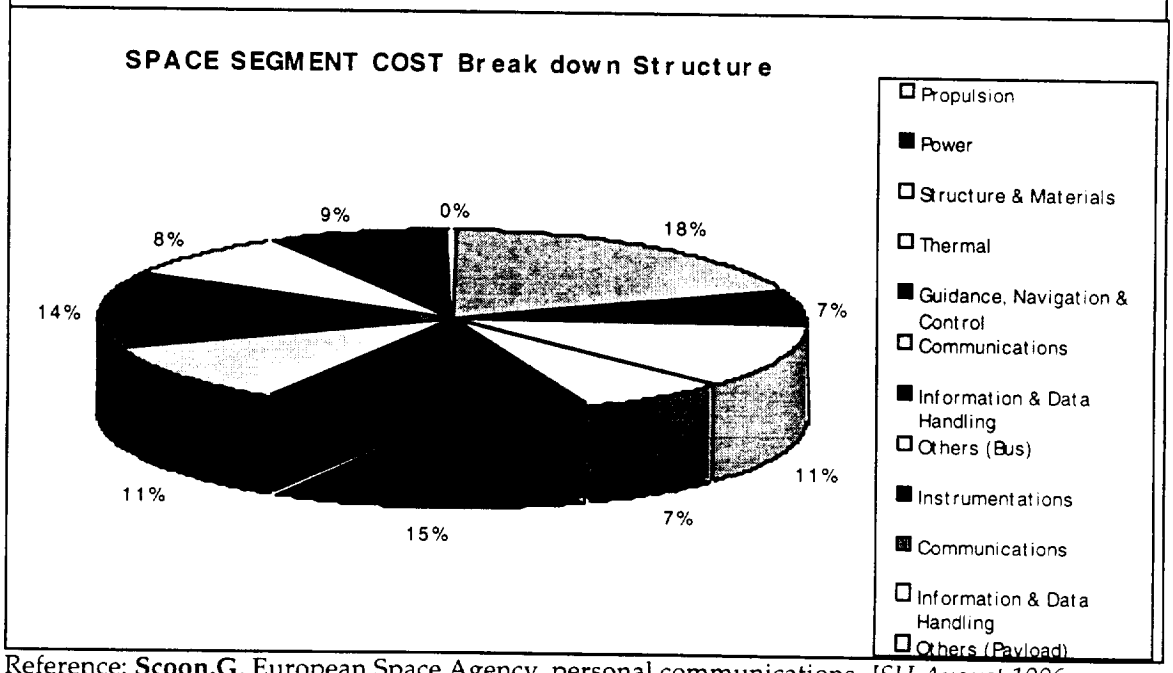


Reference: **Randolph.J**, JET Propulsion Laboratory USA, FIRE mission, *ISU August 1996.*

Cost matrix of RA application mission

SOLAR PROBE MISSION:	RA APPLICATION		Ref. A
	NAME and	$COST	TOTAL $COST
	65 RS		
GROUND			
TRACKING			$ 123,513,872
DATA			•
OPERATION			•
			•
LAUNCHER			
	2 launchers ARIANE 5, ATLAS II AS	$ 240,000,000	$ 240,000,000
SPACE			
	20 Spacecrafts*200 to 300 Kg, 1800		$ 531,961,730
BUS			$ 485,961,730
Propulsion	Solar and	$ 100,800,000	
Power	6 KW Solar arrays	$ 36,000,000	
Structure &	Standard	$ 60,000,000	
Thermal	Standard	$ 36,000,000	
Guidance, Navigation &	Standard	$ 79,200,000	
Communications	x-band Transponder & Ka	$ 57,800,000	
Information & Data	1.2 and 0.5 Kbps	$ 72,500,000	
Others (Bus)	Assembly, Integration and Verification	$ 43,661,730	
PAYLOAD	19 W		$ 46,000,000
Instrumentations	20 Plasma analysers and 20 magnetometers	$ 46,000,000	
Communications		•	
Information & Data		•	
Others (Payload)		•	
TOTAL $COST			$ 895,475,607
Total exc. Propellant			
incl. Propellant/liftof	20 Spacecrafts		5000.00
TOTAL			5000.00

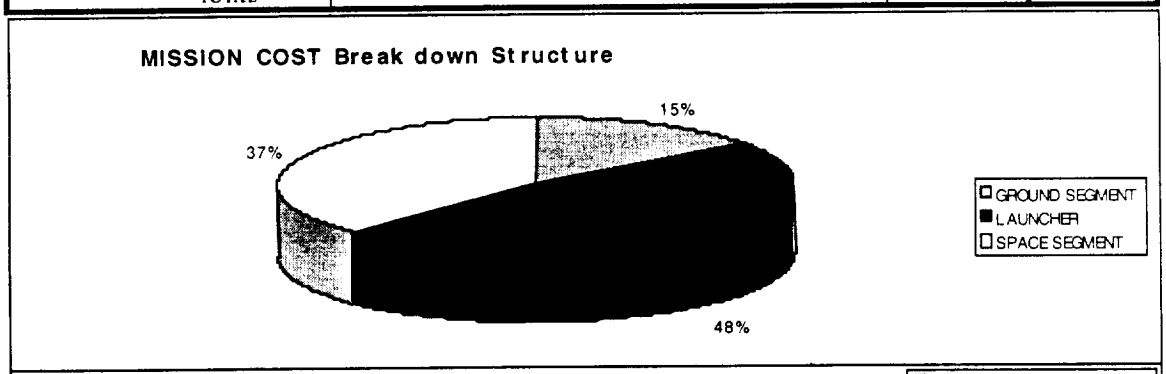


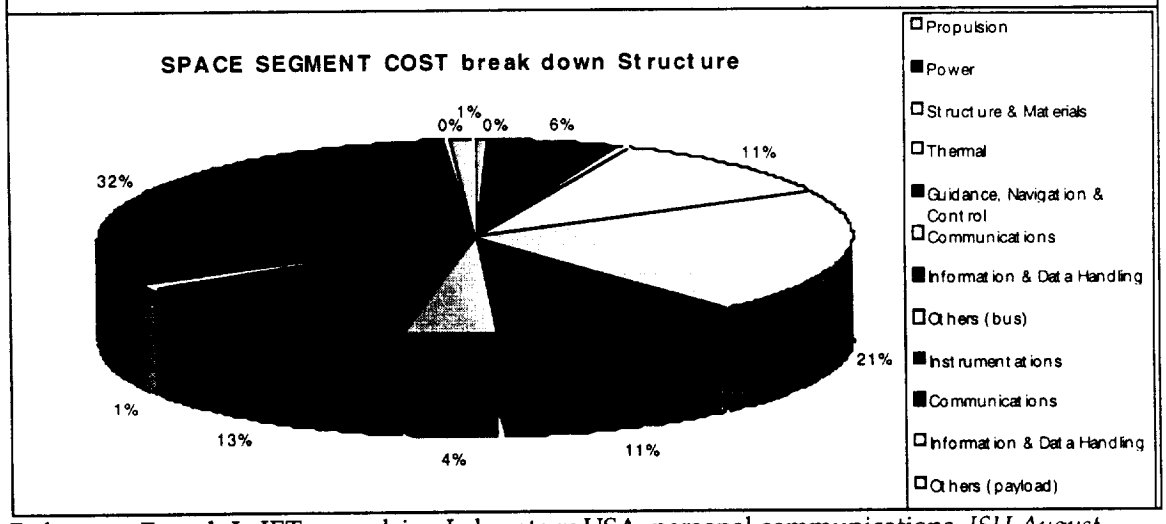


Reference: **Scoon.G**, European Space Agency, personal communications, *ISU August 1996.*

Cost matrix of SAUNA

SOLAR PROBE MISSION:	SAUNA	2006	Ref. A
	NAME and	$COST	TOTAL $COST
GROUND			$ 19,000,000
TRACKING	(I decided not to use this breakdown), my figure comes from the Mission Operations Cost		•
DATA	Model of NASA and includes all of these items. It is 3.8M / year for 5 years)		•
OPERATION			•
LAUNCHER			$ 60,000,000
	Delta II (7925) - ref. Stacy Weinberg JPL	$ 60,000,000	
SPACE			$ 47,200,000
BUS			$ 31,700,000
Propulsion	1x UK-25E thruster + tank (source: AEA Technology, developer of	$ 200,000	
Power	6kW solar array, electronics & array drives	$ 3,000,000	
Structure &	guess	$ 5,000,000	
Thermal	guess	$ 10,000,000	
Guidance, Navigation &	educated guess (adjusted by Lloyd	$ 5,000,000	
Communications	guess	$ 2,000,000	
Information & Data	educated	$ 6,000,000	
Others (bus)	harness, etc. guess	$ 500,000	
PAYLOAD			$ 15,500,000
Instrumentations	5 science instruments at 3M each (guess)	$ 15,000,000	
Communications	not applicable to payload	•	
Information & Data	shared with main bus	•	
Others (payload)	boom for magnetometer	$ 500,000	
TOTAL $COST	FY 96$		$ 126,200,000
Total			155.00
incl. Propellant/liftof			159.00
TOTAL			314.00





Reference: **French.L**, JET propulsion Laboratory USA, personal communications, *ISU August 1996*.

Appendix E

Existing and Proposed Early Warning Systems

This appendix lists some of the solar environment monitoring and early warning agencies which operate today and provide forecasting and alert services. In section E.2 proposed systems are described.

E.1 Existing Space Environmental Forecasting Services

U.S Systems

The Space Environment Center (SEC) which is part of the National Oceanographic and Atmospheric Administration (NOAA) in co-operation with the 50th Weather Squadron (50th WS) of the United States Air Force (USAF) provide a number of space environmental products to customers in the United States. The two agencies share resources and divide their customer base in order to serve both military and civilian users which include the NASA, the Federal Aviation Administration (FAA), HF and SF radio operators, power companies, satellite operators, radar user, researchers and many more.

SEC and 50th WS use a number of observations in order to issue warnings concerning a geophysical event, provide short and long term forecast information of space environmental conditions and to provide anomaly analysis to determine whether a problem experienced by a customer was related to the space environment. Data is acquired from:

- 2 GOES (Geostationary Observational Environmental Satellite) vehicles operated by NOAA measuring X-rays, charged particle flux and magnetic field flux at Geosynchronous altitude.

- 2 DMSP (Defense Military Satellite Program) vehicles operated by the USAF measure precipitating particle and plasma flux (which give information about the aurora) along with magnetic variations in low earth polar orbits.
- WIND (Weather Information Display System) operated by NASA provides two hours of real-time solar wind measurements per day.
- Various other military satellites provide magnetic field flux and particle fluxes in a variety of orbits.
- The Solar Electro-Optical Network (SEON) operated by the USAF employs five SOON (Solar Observation Optical Network) telescopes along with four RSTN (Radio Solar Telescope Network) telescopes providing continuous solar data from six locations world-wide. SOON provides information concerning the photosphere and active surface regions (white light images), the chromosphere (Hydrogen alpha line) and the corona (Calcium K line) while RSTN measure the Sun's output at a variety of radio frequencies.
- Numerous magnetomers operated by the United States Geological Survey provide data on the Earth's magnetic field at the surface.
- Various Ionospheric Measuring Systems (IMS) determine the height of the various layers of the ionosphere and measure total electron content (TEC).
- A riometer provides ionospheric absorption level information at the poles.
- A Neutron monitor measures high-energy particle fluxes at the surface.

Data is collected from the various sources and fed into models that generate warnings, alerts and forecast information. The Magnetospheric Specification Model (MSM) designed at Rice University provides data on the magnetosphere while other models used provide data concerning other regions.

Australian Systems

The IPS Warning Centre in Australia has optical and radio observatories in Culgoora (near Narrabri, NSW), and Learmonth (near Exmouth, WA). The Learmonth observatory is jointly operated with the United States Air Force.

Canadian Systems

The Geomagnetic Laboratory, a division of the Geological Survey of Canada, provides geomagnetic storm alerts and forecasts to Hydro-Quebec's Transmission Control Centre.

E.2 Proposed Solar Threat Monitoring & Early Warning Systems

Under study as of this writing by NASA, the US Air Force, and the University of Birmingham (U.K.) is a science and applications mission which will have considerable impact on space weather forecasting systems. The Solar Mass Ejection Imager (SMEI) will image the Thompson - scattered white light from dense structures in the interplanetary solar wind. This method is described in Section 9.3.4, and is expected to enable SMEI to image and track solar mass ejections (CME) and determine with 1 to 3 days notice when one will impact the Earth. SMEI will image the inner interplanetary region from Earth orbit every 90 minutes and is hoped to be launched before the next solar maximum in 2001. While this mission could be extremely valuable for both scientific and applications interests, it is worthwhile noting that using remote sensing it will not measure the interplanetary magnetic fields destined for Earth and thus does not satisfy the requirements derived and outlined in Section 9.2.

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