Extending the Computer Revolution into Space

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Introduction: What is the Computer Revolution?

Extending the Computer Revolution into Space

A Recent Los Angeles Times Headline

THE CUTTING EDGE

SECTION C

MONDAY

DECEMBER 28, 1998 CC

BUSINESS

Los Angeles Times

YEAR-END TECHNOLOGY SPECIAL

Computer Age Enters Maturity

Revolutionary Internet Goes Mainstream

Stores Still Not Celebrating After Holiday

■ **Retailing:** Discounts draw bargain hunters but ho-hum revenue has failed to match ho-ho-ho forecasts. With a week left, some sellers remain hopeful.

From Times Staff and Wire Reports

But don't you believe it!

There are many future revolutions to come in information systems!

And the *computer age* is just beginning in space!

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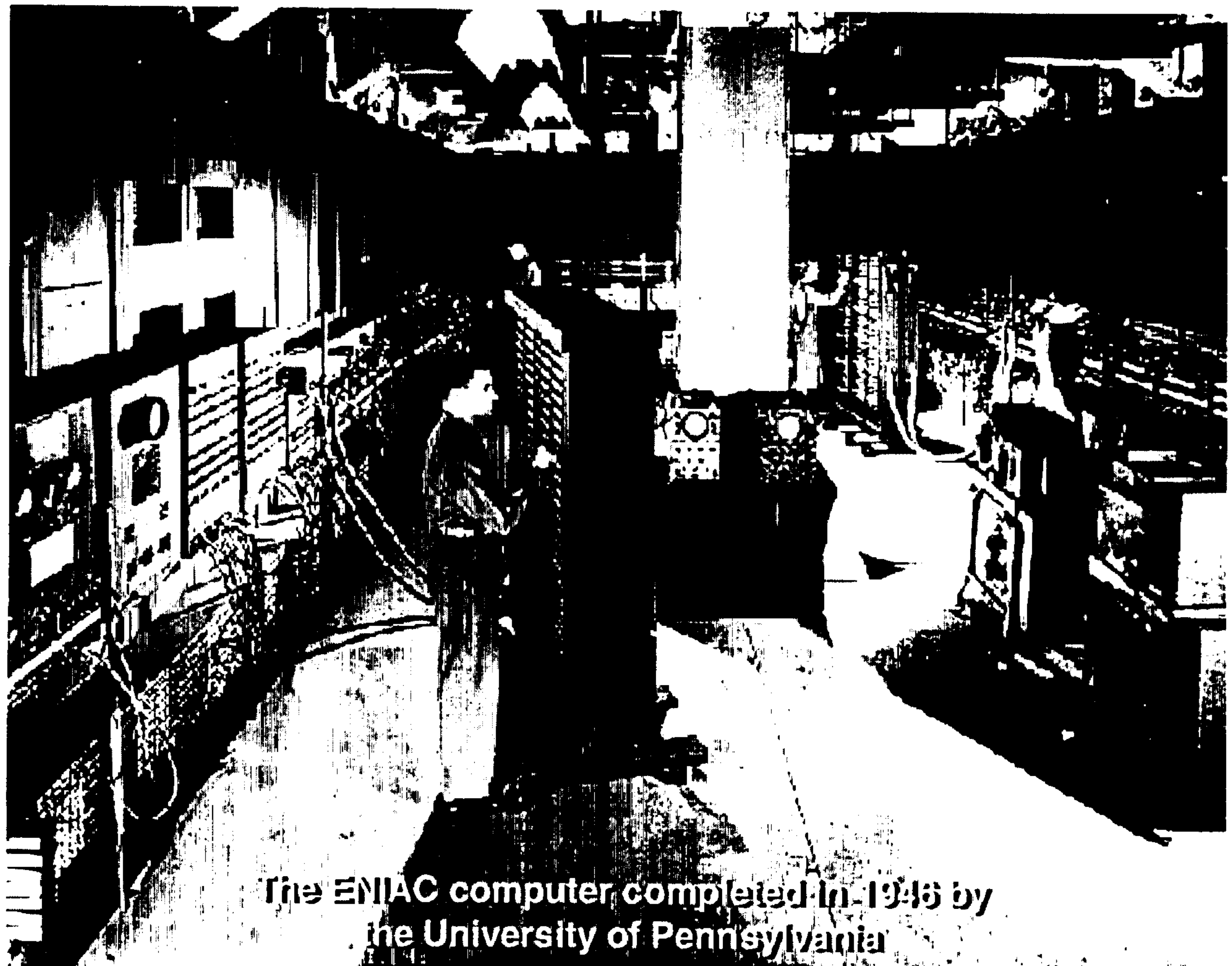
The First Digital Computers

- Modern digital computers were developed during WWII to solve weapon trajectories and other military applications
- They replaced teams of human *computers* , people (usually women) who did highly repetitive calculations by hand
- Few people saw the long-term uses for this technology



The ENIAC computer completed in 1946 by the University of Pennsylvania

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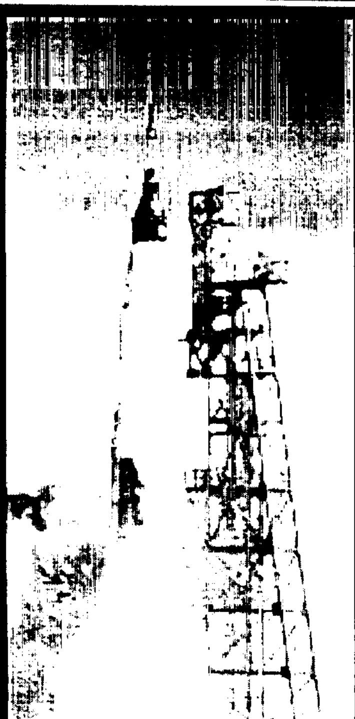
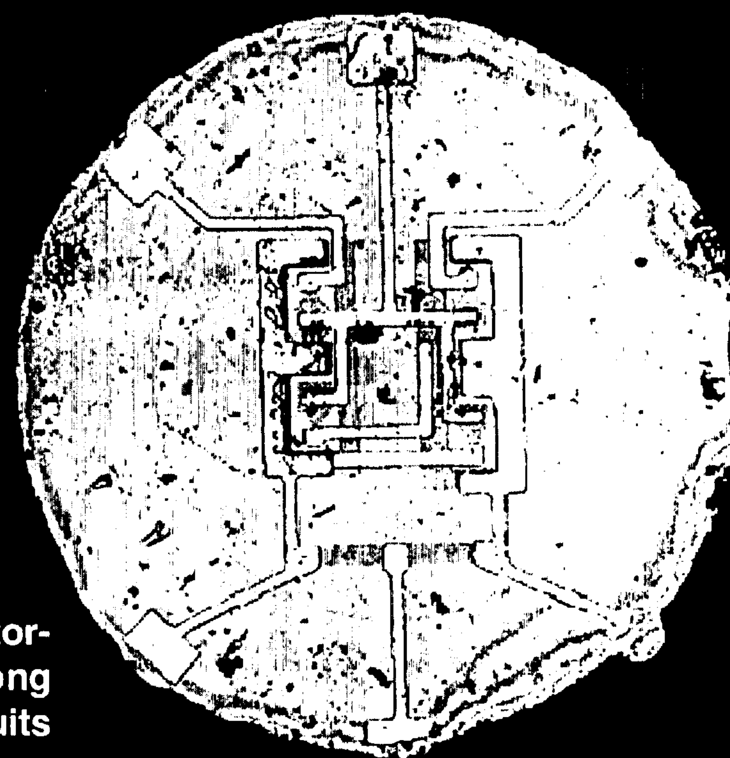
The Space Program of the 1960s



- The US and Soviet efforts to put people into space in the 1960s fostered the development of computers
- Small digital computers were required to monitor and control spacecraft
- The inventions of the transistor and the integrated circuit allowed this to happen



This 1961 Fairchild Resistor-Transistor Logic flip-flop was among the first integrated circuits

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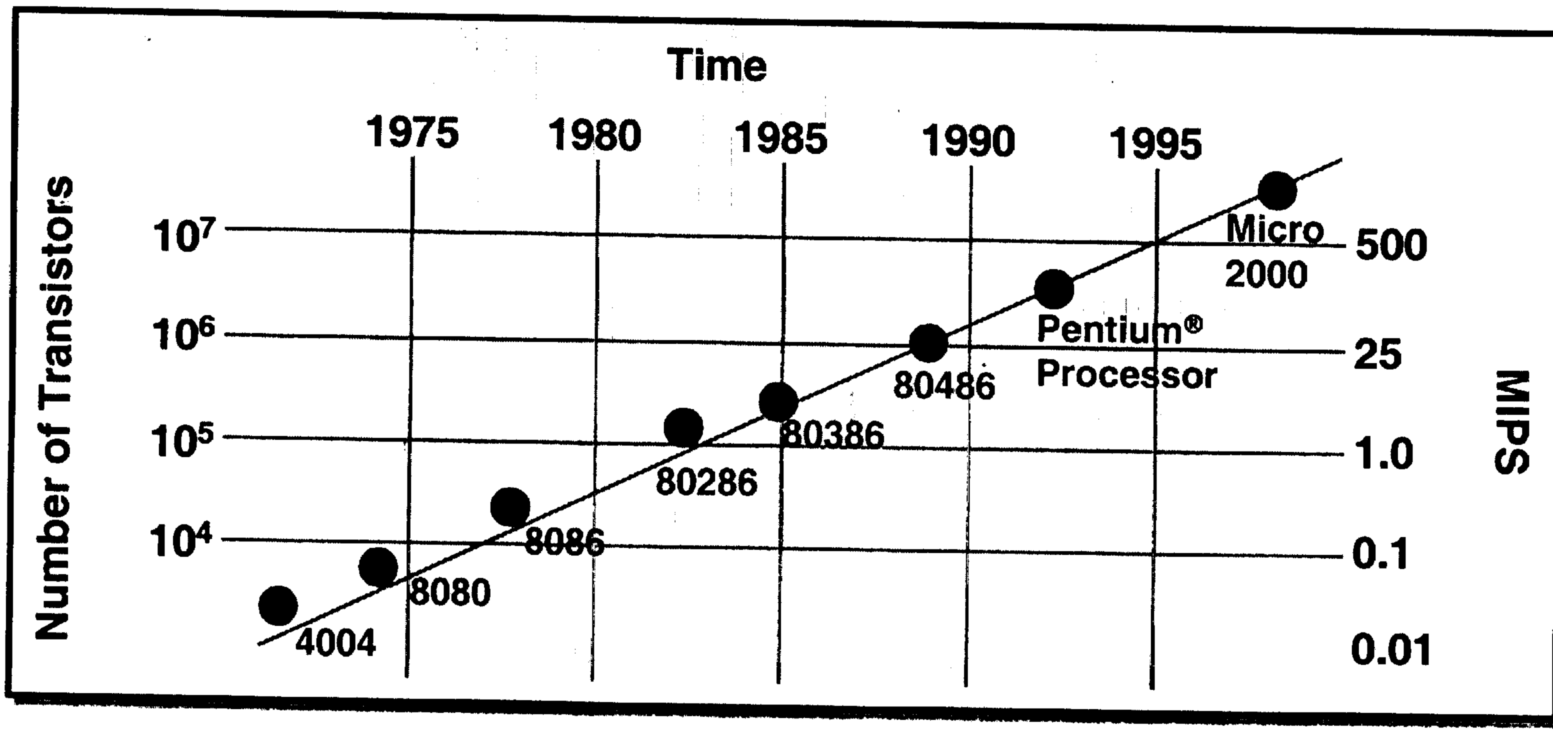
Moore's Law

- Moore's law is often used to model the development of information technology
- Moore's law states that the density of devices on a single chip grows exponentially
- Corollaries say processor speed and memory size grow at the same rate



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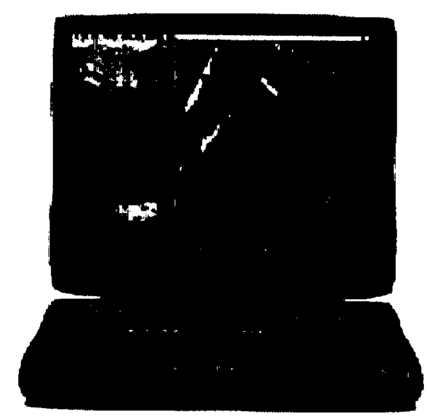
The Computer Revolution - on Earth

- Everyone can afford a computer
- Almost any task can be accomplished through writing software
- Most common tasks have cheap off-the-shelf software
- Computers are easily customized by adding boards on a standard bus
  - Processor, Memory, Interfaces, Extended capabilities, ...
- Computers *talk* to lots of other kinds of devices
  - Printers, Scanners, Speakers, Lab equipment, ...
- Computers can *talk* to each other
- Computers can communicate over great distances
- Almost any information is available almost anywhere
- Computers can share tasks when needed
  - Client/Server applications
  - Multiple-player internet games



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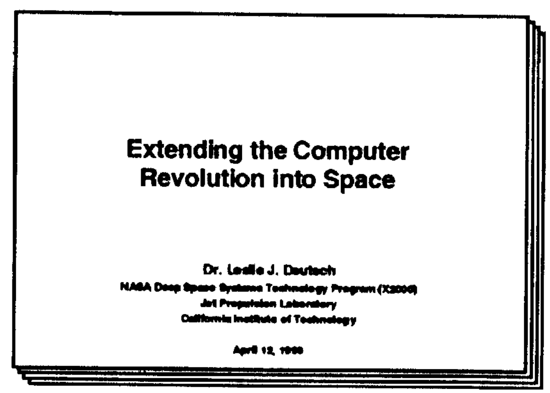
Consequences of the Computer Revolution - on Earth

- Automated factories lead to tremendous increases in production efficiency
- Scanners and computers control many aspects of retail businesses
- Digital communications enabled global commerce
- Intelligent computer systems act as assistants to professionals in many fields
- Global information exchange promotes better research



Why Does Space Information Technology Lag so Far Behind?

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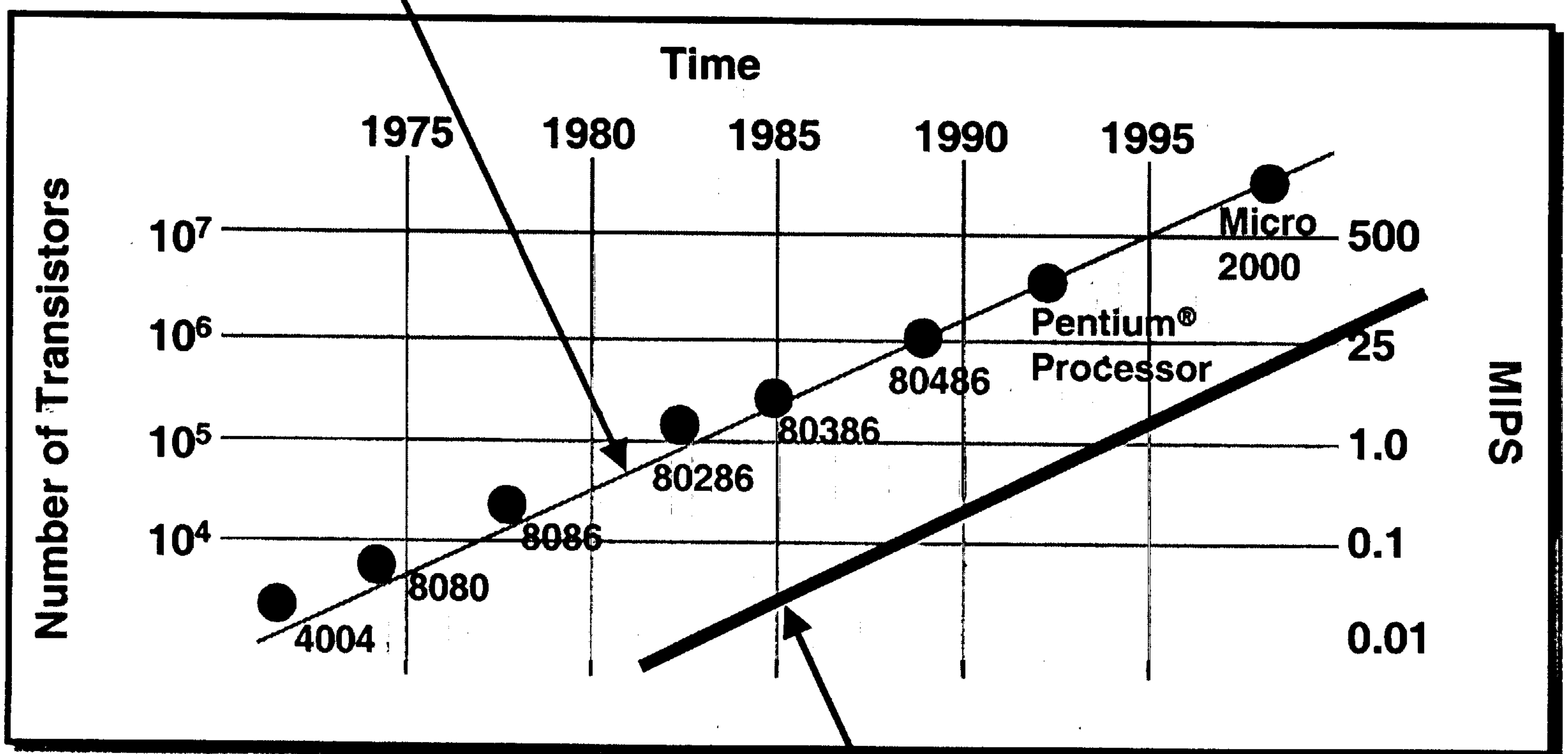
Space Systems Lag

Earth processors



Space-qualified processors

Lag Earth processors by about 3 generations!

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Why is There a Lag?

- Spacecraft take a long time to develop – typically 3-5 years
  - Information technology that was new at the start of development is obsolete by launch
- Special operating systems are often required because of the criticality of timed events during flight
  - Unlike Earth operating systems, these have not been developed concurrently with the components
- Space missions must survive for long times (often more than 10 years) in total isolation
  - Only components with lots of testing and track record can be flown in space
- Many space applications require extreme low-power electronics
  - Most commercial components must be redesigned for low-power applications
- Spacecraft designers are often scared of new technology because it leads to risk

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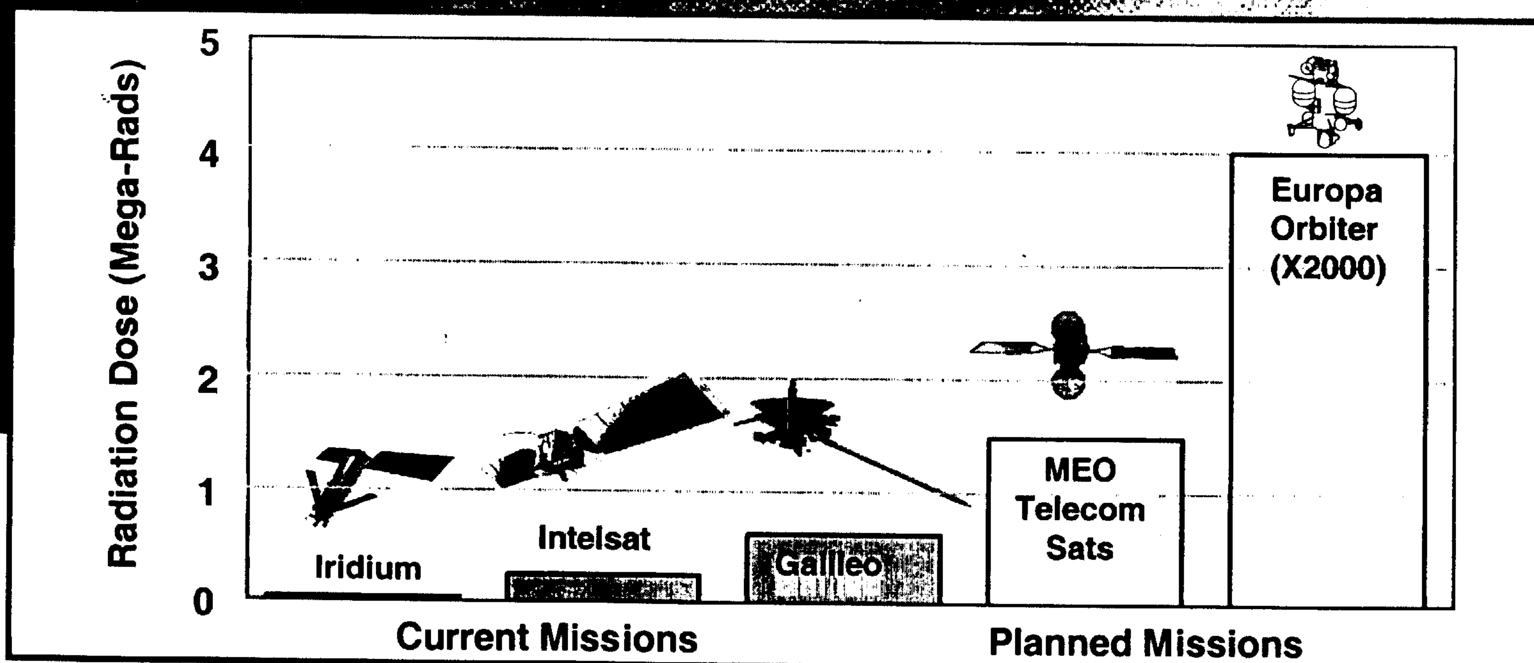
Another Difference: Radiation Effects

- Outside the Earth's atmosphere, spacecraft are bombarded by radiation
- Earth components typically are not designed work in this situation
  - Special rad-hard versions of components are developed only after the Earth version is well-tested and mature
- Even with parts designed for four MRAD of radiation, the Europa Orbiter is only expected to survive for 60 days at Europa!



The Computer Revolution is About to Move Into Space

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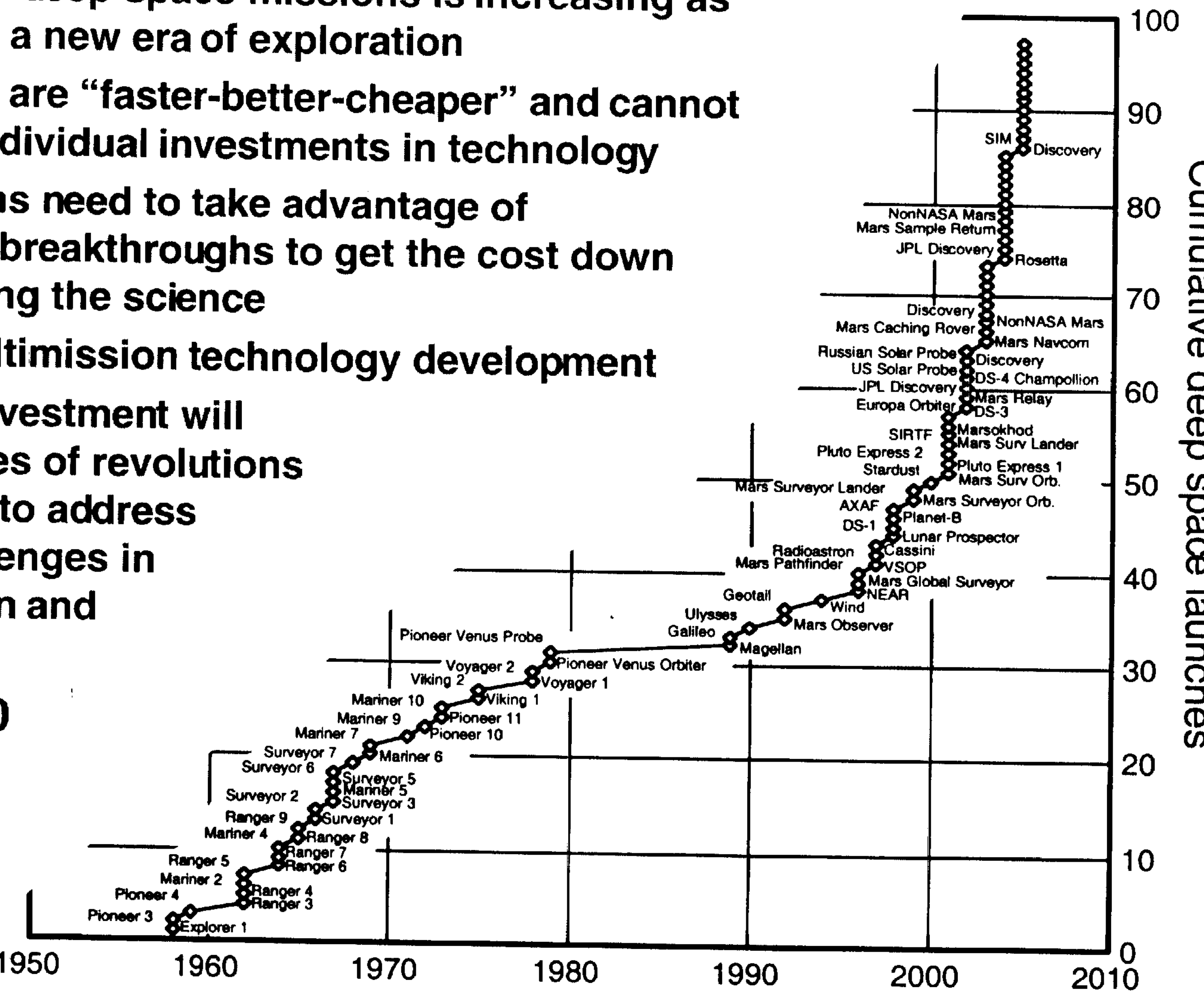
X2000 and the Future of Deep Space Exploration

- The number of deep space missions is increasing as we embark on a new era of exploration
- New missions are "faster-better-cheaper" and cannot afford large individual investments in technology
- These missions need to take advantage of technological breakthroughs to get the cost down while increasing the science
- The key is multimission technology development
- Continuous investment will provide a series of revolutions in technology to address common challenges in mission design and execution
- **This is X2000**



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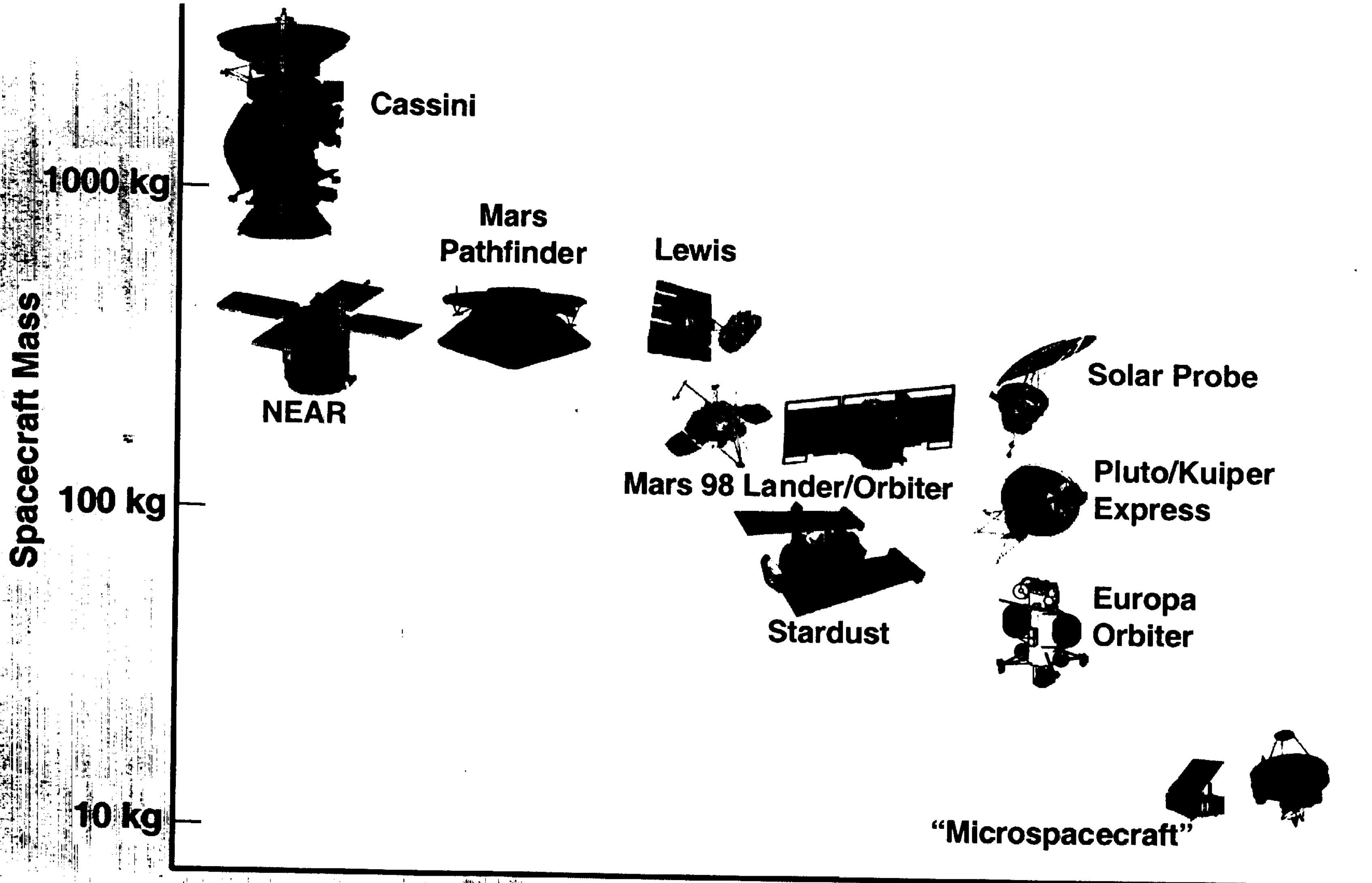
The Trend Toward Smaller Spacecraft



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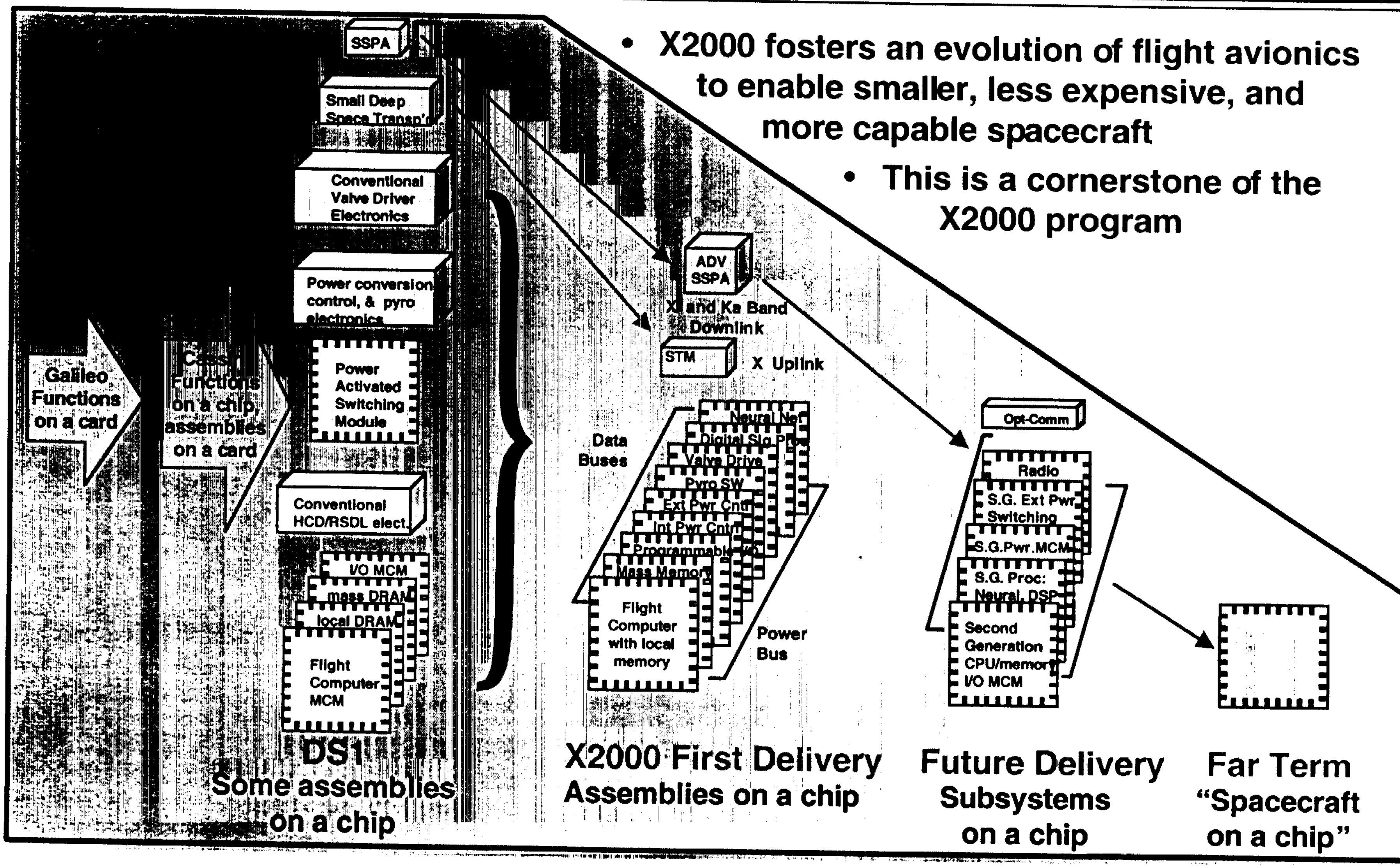
X2000 and Avionics Miniaturization

- X2000 fosters an evolution of flight avionics to enable smaller, less expensive, and more capable spacecraft
  - This is a cornerstone of the X2000 program



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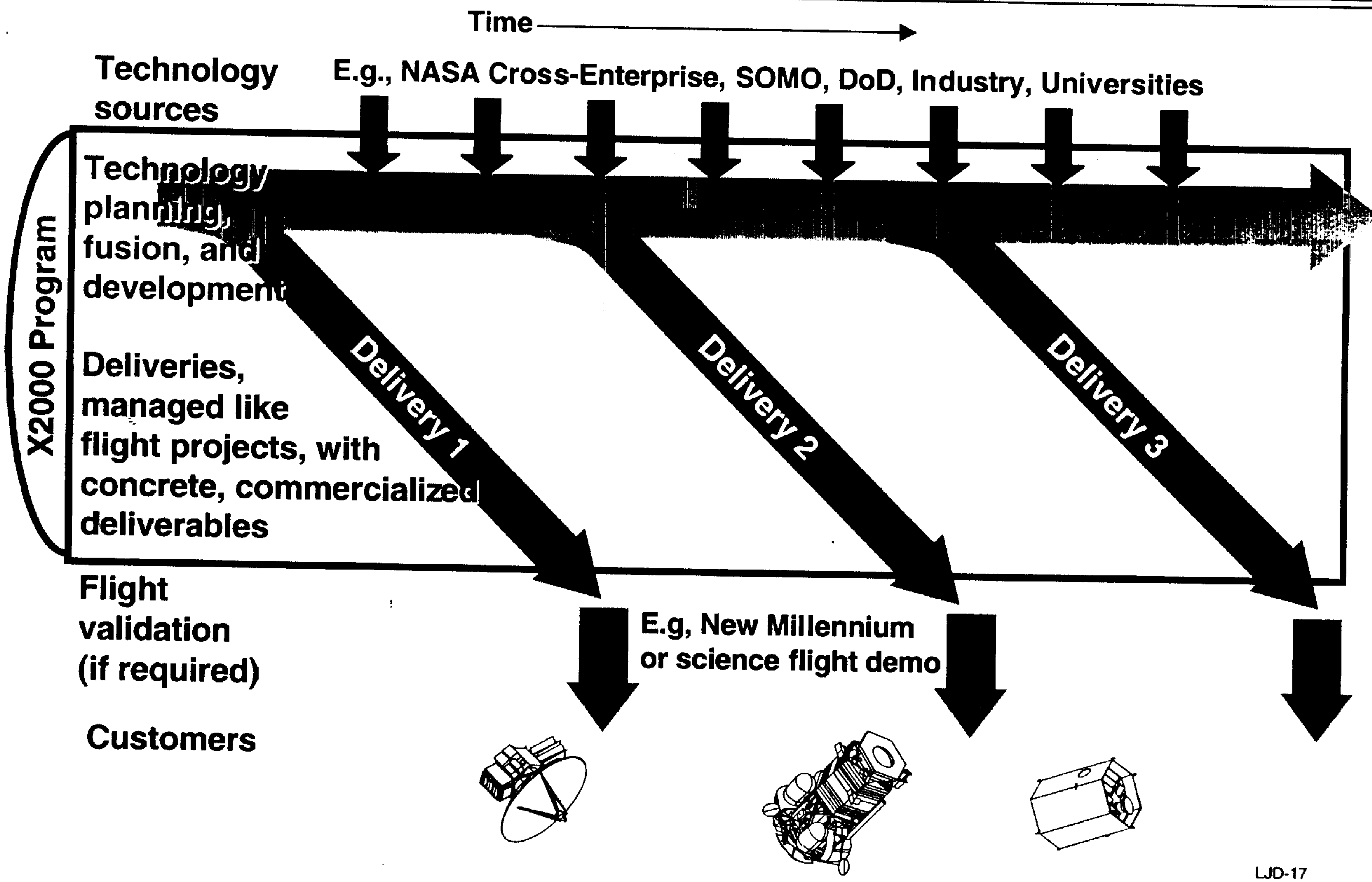
The X2000 Concept



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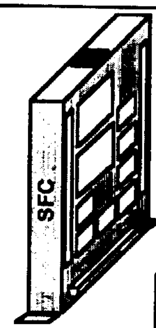
Avionics Building Blocks – 10 Slices to Mix and Match

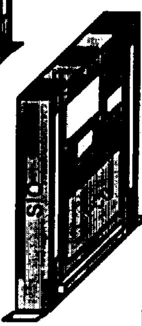
- X2000 avionics is being built using slices based on the CPCI standard
- The whole system is plug-and-play
- Both PCI and IEEE 1394 buses are supported

Command and Data Handling Slices

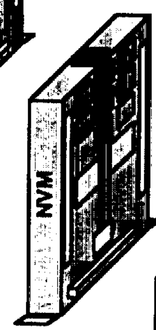
"Flight Computer" Slices



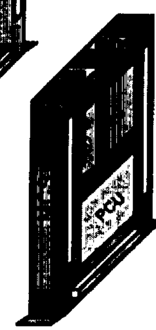
SFC - System Flight Computer
- PCI based
- Baseline 100 MIPs



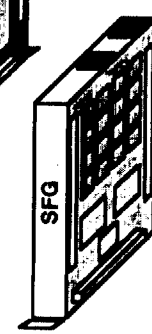
SIO - System Input/Output
- PCI/1394/I²C Bridge



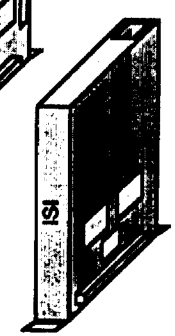
NVM - Non Volatile Memory
- 1 Gbit/slice Flash Memory
- Additional RAM for security against radiation



MCS - Microcontroller Slice
- General purpose controller for spacecraft peripherals

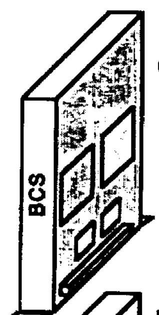


SFG - SRU Frame Grabber
- 4 Mb RAM min (16 MB target)

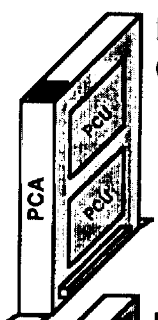


ISI - IMU/SSA Interface
- SSA sensor conditioning
- serial interface IMU

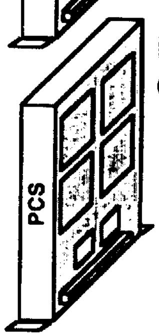
Power Subsystem Electronics Slices



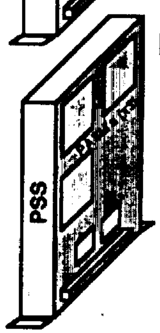
BCS - Battery Charge Slice
- Charge/discharge battery control



PCA - Power Converter Assembly
- Primary to secondary power conversion
- 10W or 30W versions
- Power 1394 & I²C buses



PCS - Power Control Slice
- Primary s/c power bus regulation
- Shunt regulator ASIC



PSS - Power Switch Slice
- Switch power loads, valves & pyros
- 12 switches/slice
- Software bypass safety inhibits for ground testing

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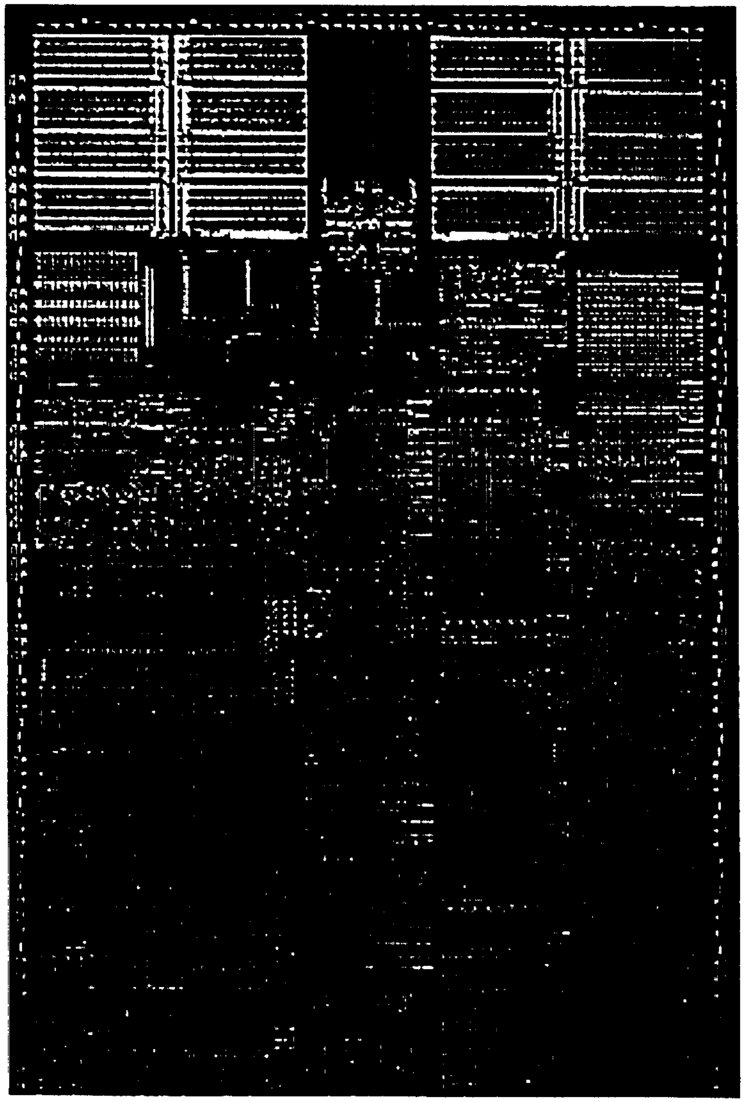
A 100 MIPS Flight Computer



- There are many options here that are being pursued
- The baseline is to develop a 1 MRAD hard version of the Motorola 603 *PowerPC*® processor
- JPL will integrate the chip with other systems to create the flight computer

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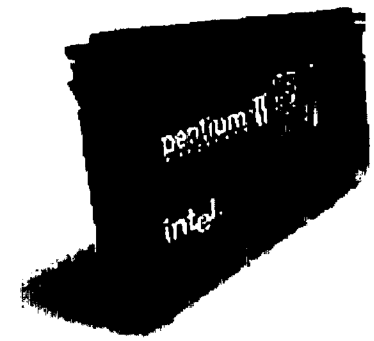
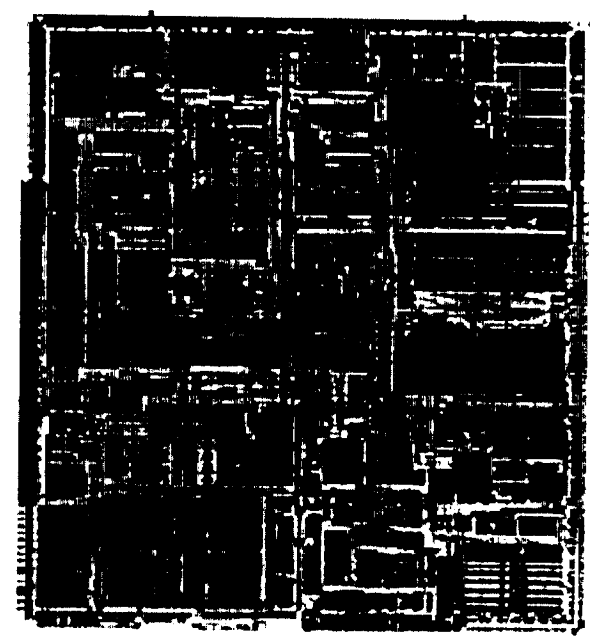
The Space Pentium®

- In December, 1998, Intel announced it was giving the rights to the Pentium® processor to the US Government for use in space and defense applications
- Sandia National Laboratory will space-qualify the chip
- JPL will participate to insure that the finished chip supports a space computer system that is both low power and radiation hard
- The finished space Pentium® is expected in 2002





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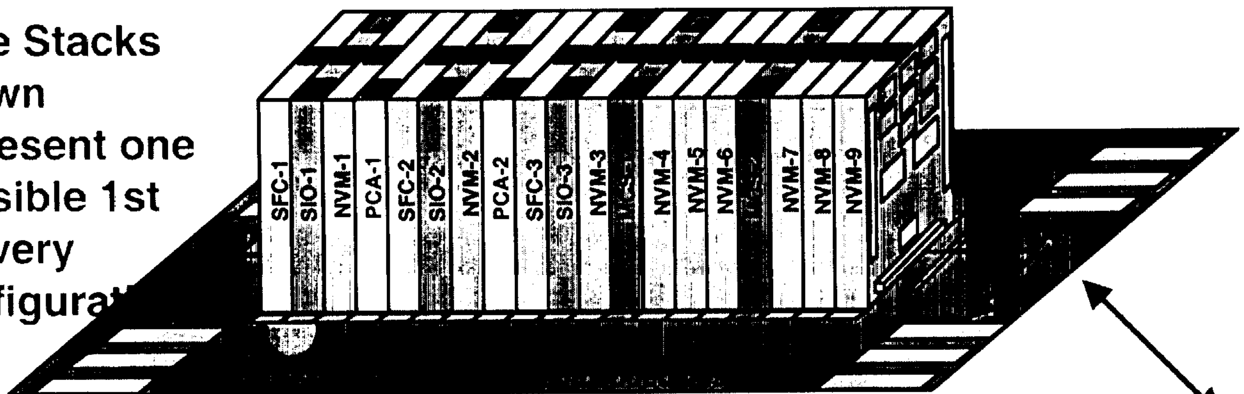
System Construction

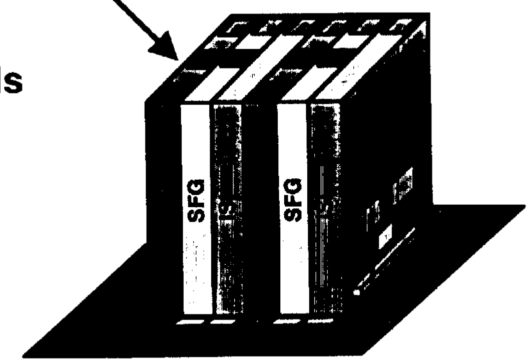
Slice Stacks shown represent one possible 1st delivery configura



CDH Stack

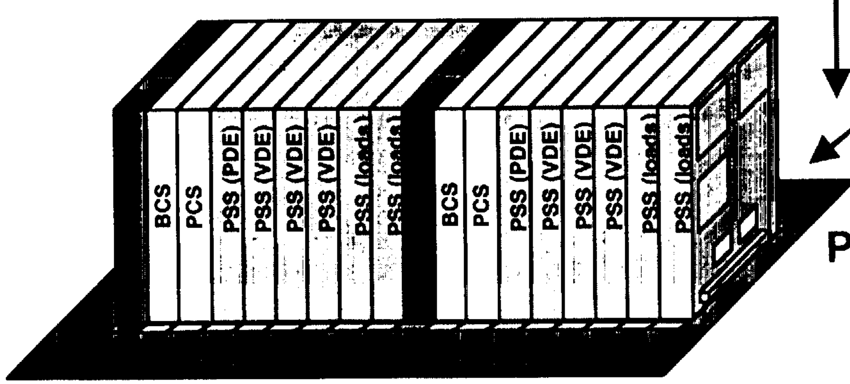
- *3 computers*
- *Global NVM*
- *Test & launch vehicle access*

1. Design embedded network bus using slice CAD models
2. Allow for test and traditional connector access
3. Populate with slices
4. Test!
5. Continue with System Integration



ACS Interface Stack

- Block redundant
- Each half interfaces to one of 3 attitude determination sensors



PSE Stack

- Twin Microcontrollers (MCS) plus cross strapped I^2C subsystem bus
- Slice compliment based on EM1

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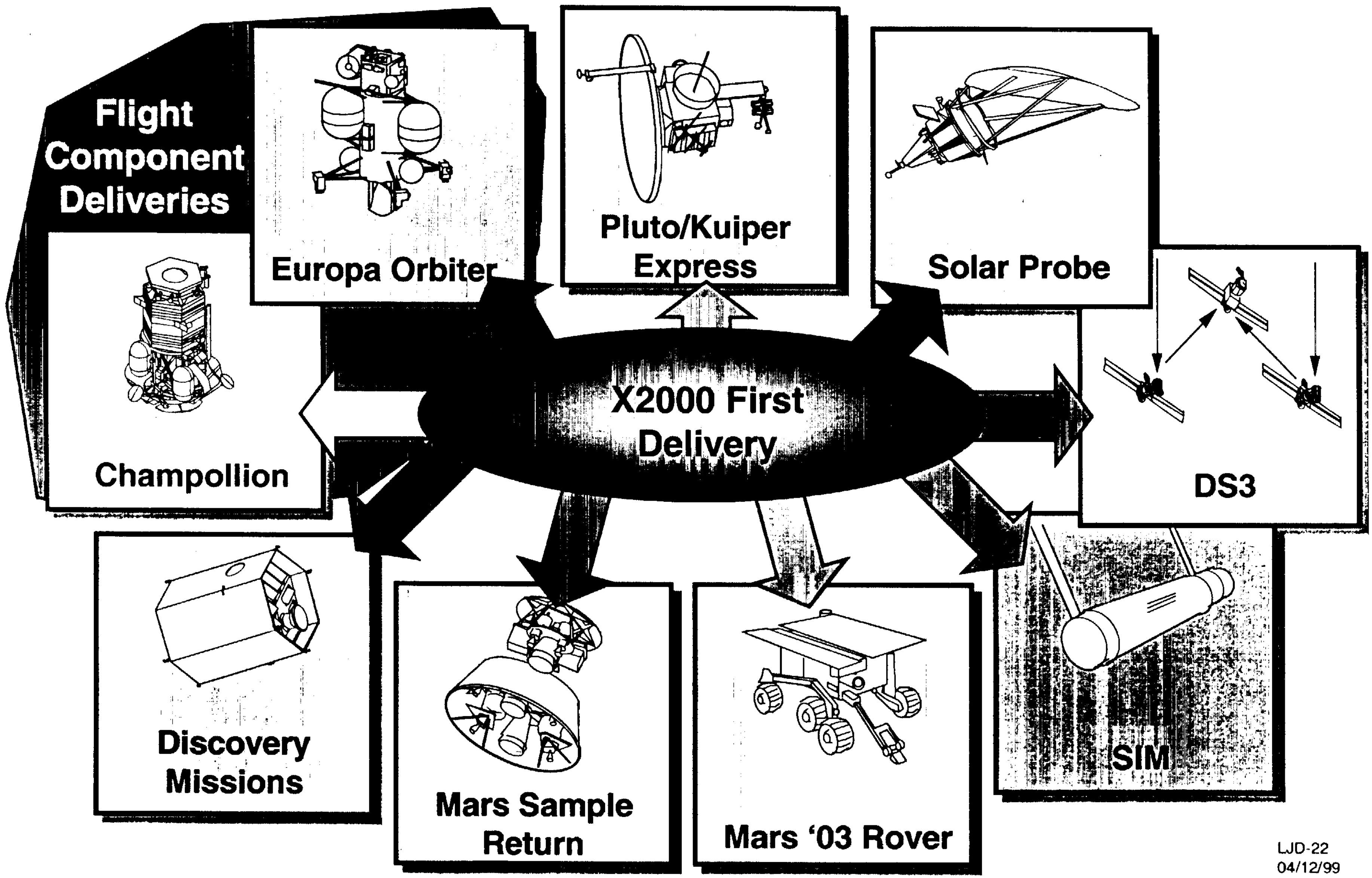
Customers for X2000 First Delivery



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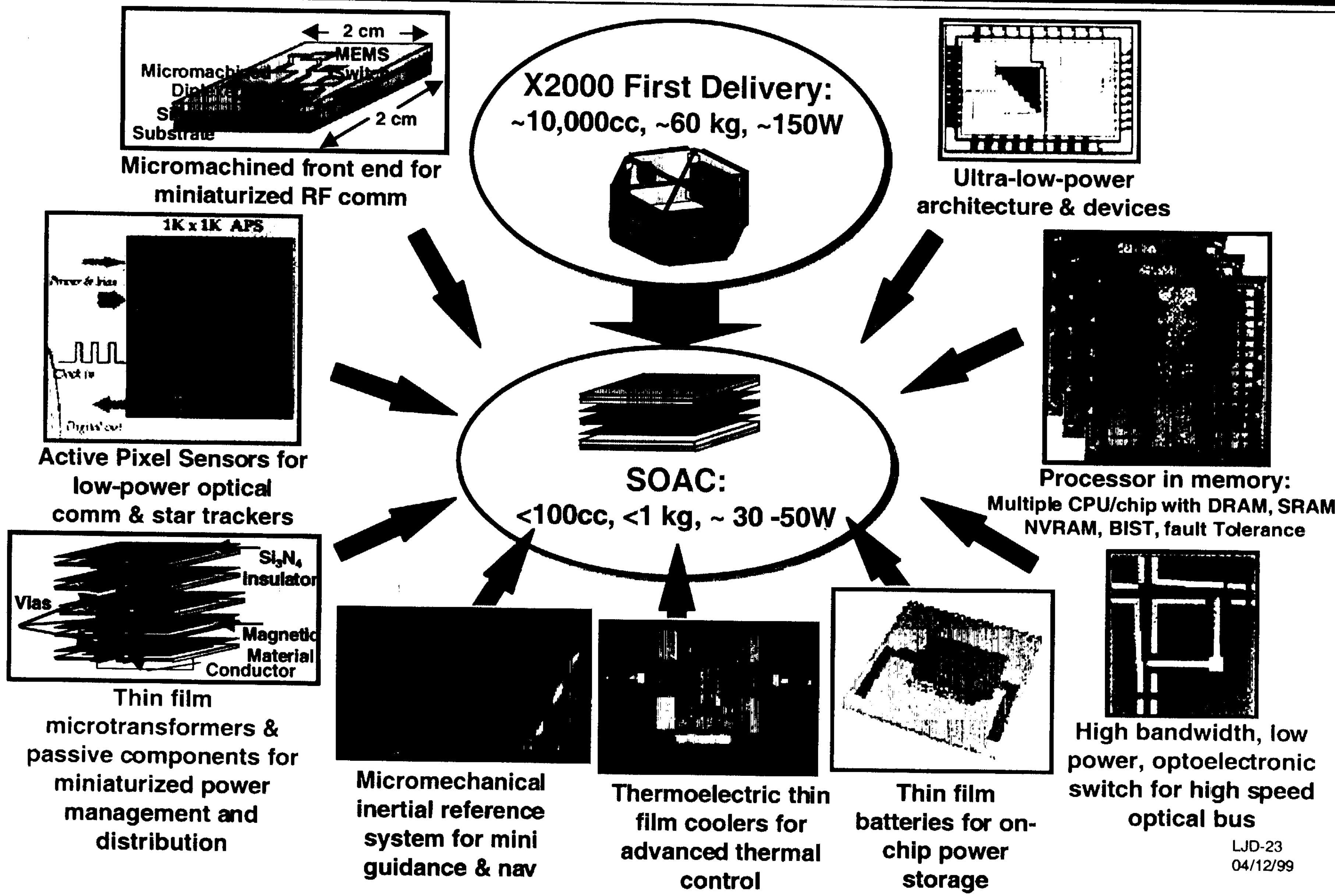
System on a Chip (SOAC)



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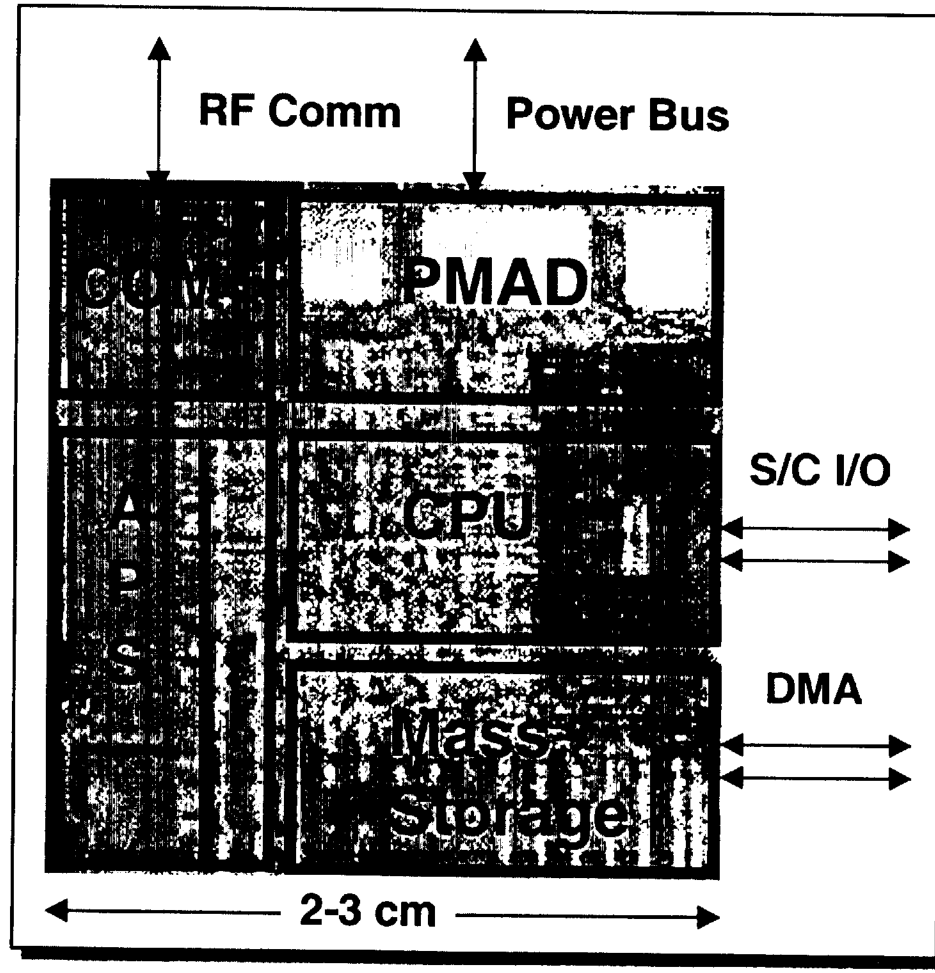
System-on-a-Chip (SOAC) Vision

- Definition:
  - Highly capable, autonomous avionics system which includes CPU, mass memory, power management and distribution, telecomm, and sensors; all integrated into a monolithic unit.
- Benefits:
  - Volume/Mass reduction
  - Improved performance and reliability
  - Power reduction
- Applications:
  - Spacecraft
    - Micro Spacecraft
    - Science Craft
    - Micro Probe
  - Micro and Nano Rovers
  - Aerobots



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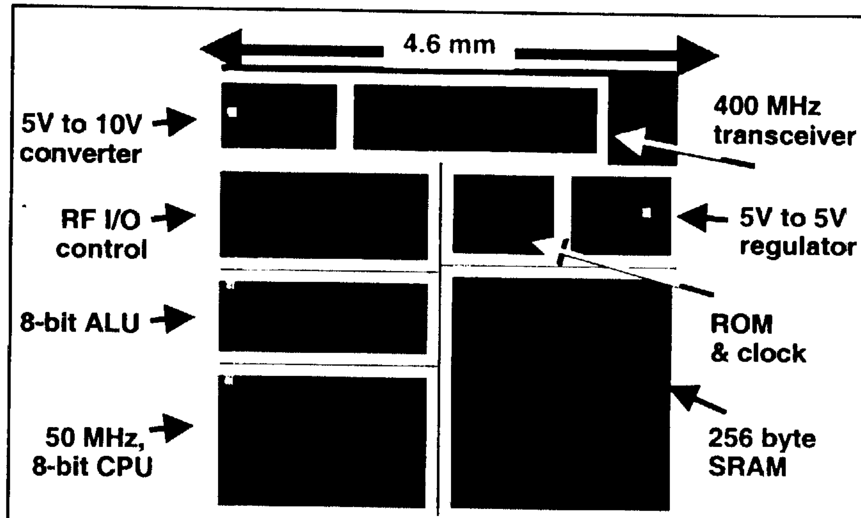
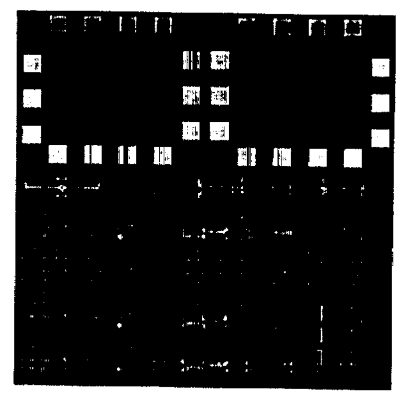
First Generation Integrated Chip

- Work performed in collaboration with the University of Illinois, Chicago
- The first generation integrated chip was selected for DARPA run at MIT Lincoln Lab.
- Designed entire chip in < 7 weeks (generated own libraries)
- Implemented a variety of designs with varying degrees of functionality to ensure we understand the process and are able to assess limitations for future developments
- Designed "test chip" with variety of test structures – important to understand Silicon-On-Insulator (SOI) CMOS process and capability
- This effort helped to highlight challenges of existing design tools and provide valuable lessons learned



1.2-micron bulk CMOS technology
Area: 80% digital, 20% analog



Test chip

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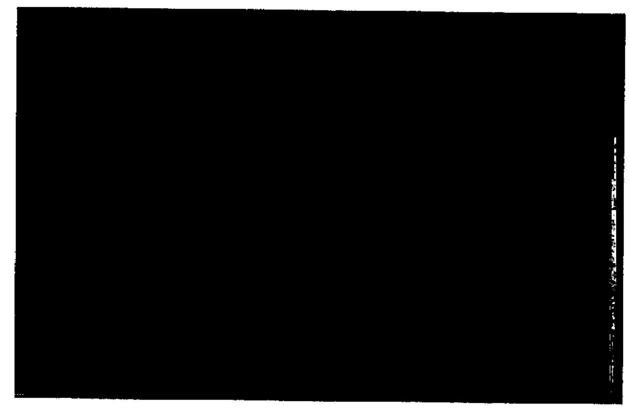
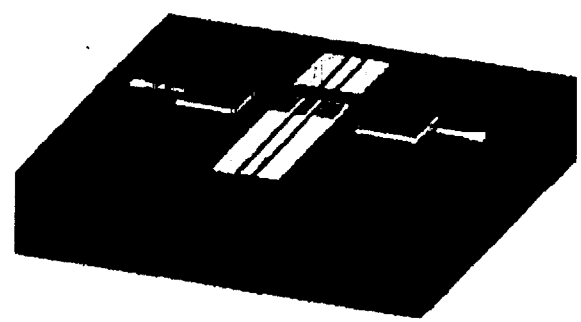
Radio Frequency (RF) Front End

- Work performed in collaboration with the University of Michigan
- Completed simulations of two types of switches:
  - A compliant switch for low activation voltage and high power handling capability
  - A switch pair for high isolation
- Fabricated a high isolation switch prototype
- Developed new fabrication process for filters
- Designed the high power multifinger SiGe HBT



SiGe 3-stage amplifier



RF switch

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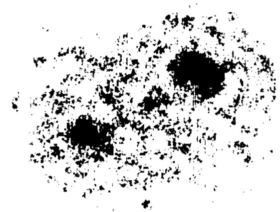
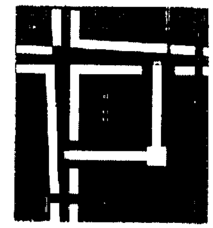
Revolutionary Computing Technologies

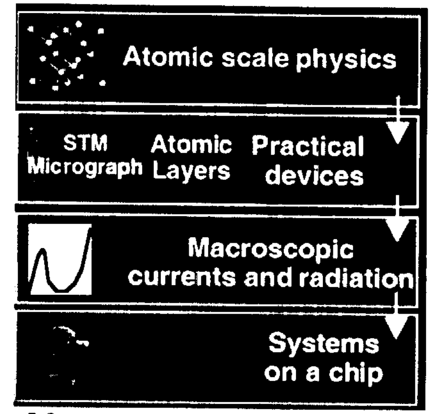
Quantum Dots



Quantum Computing

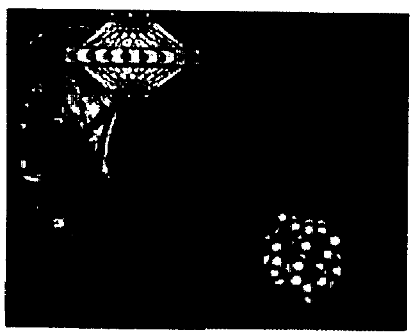


Optical Computing

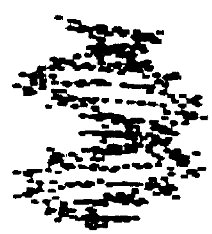


Nano-technology Modeling

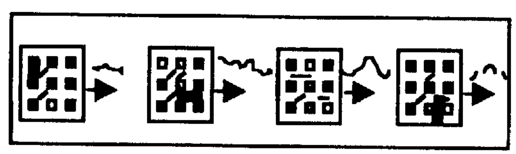
"Mission - inspiring"
Breakthrough
Revolutionary Computing
Technologies &
Architectures



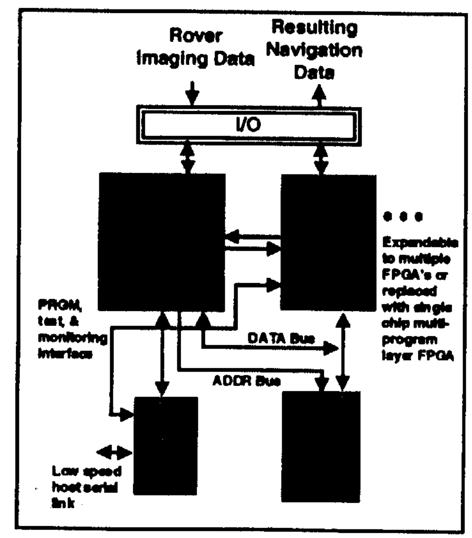
Biological Computing



DNA Computing



Evolvable Hardware



Reconfigurable Computing

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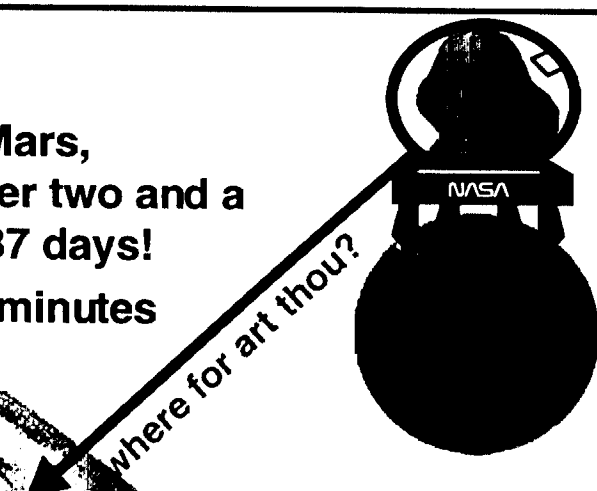
Communication Latency

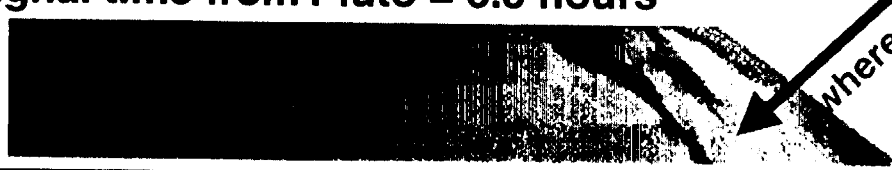
- It takes a long time (five minutes to 12 hours) for communications signals to travel between a deep space spacecraft and the Earth
- Deep space missions must be more autonomous than Earth orbiters
  - Critical events, like trajectory changes or flyby science acquisition, are planned in advance and programmed into the spacecraft's computer
- Spacecraft reaction to anomalous events must occur autonomously
- The information sent from Earth to deep space is generally not used for real-time control

Signal Latency:

With half the actors on Earth and other half on Mars, Shakespeare's *Romeo and Juliet* would take over two and a half days to complete! At Pluto, it would take 187 days!

Signal time from Mars to Earth = 4.4 minutes
Signal time from Pluto = 5.3 hours





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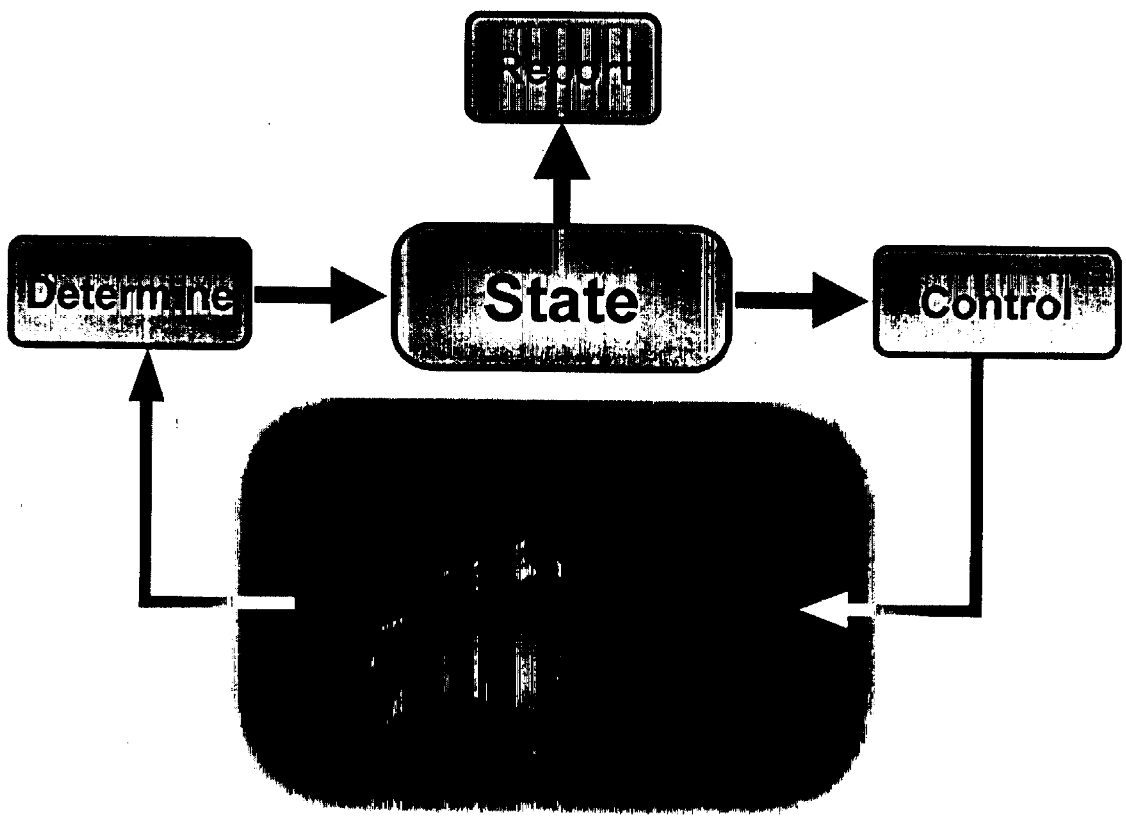
The Mission Data System (MDS)

- The MDS is the glue that holds all the components of X2000 together
  - Includes all flight and ground software required to provide delivered functionality
  - Embodies the end-to-end system architecture
- "State" is the central concept to the MDS
- Spacecraft and ground states are managed rather than individual low-level controls



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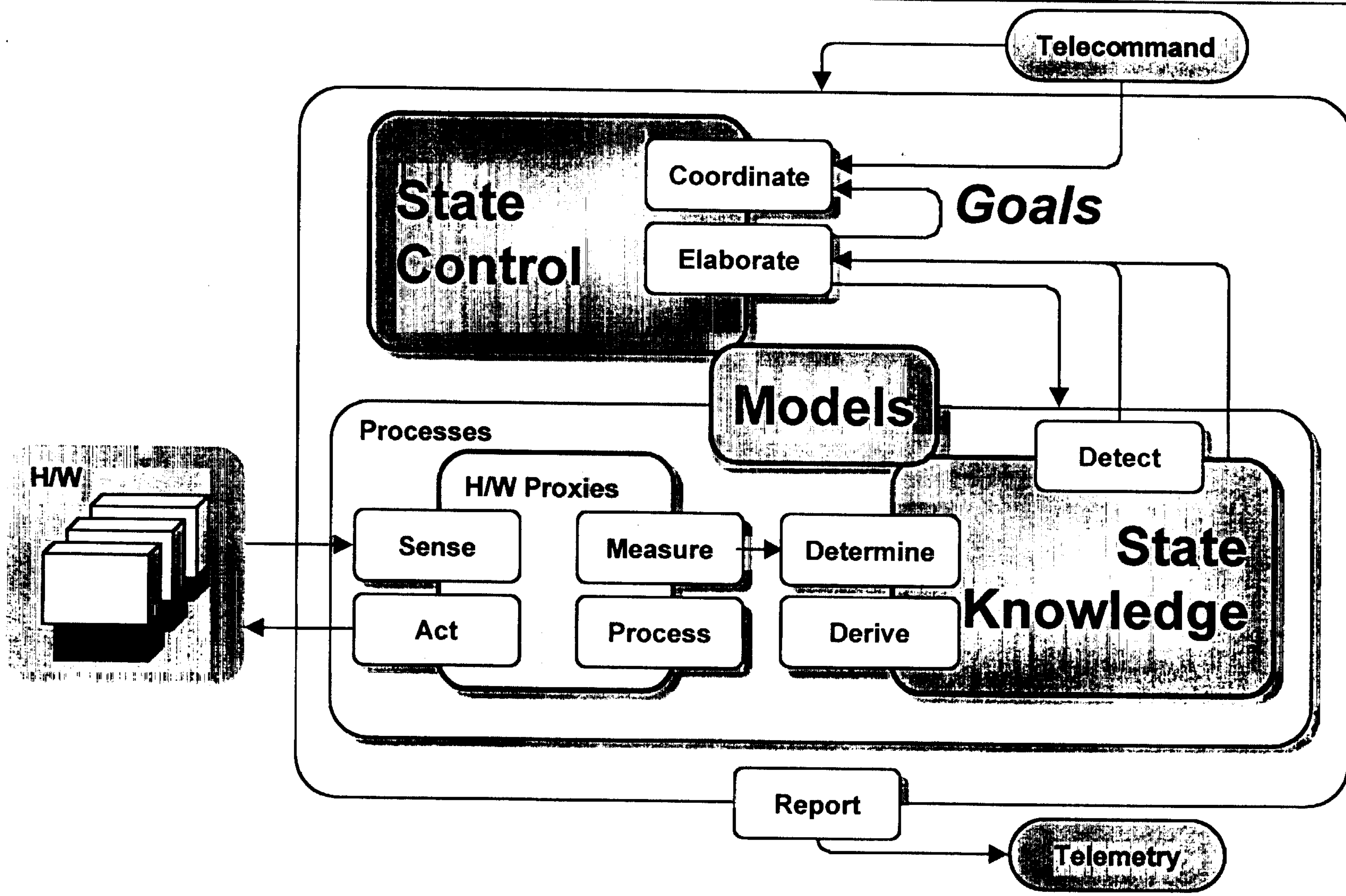
MDS Goal-Oriented Automation



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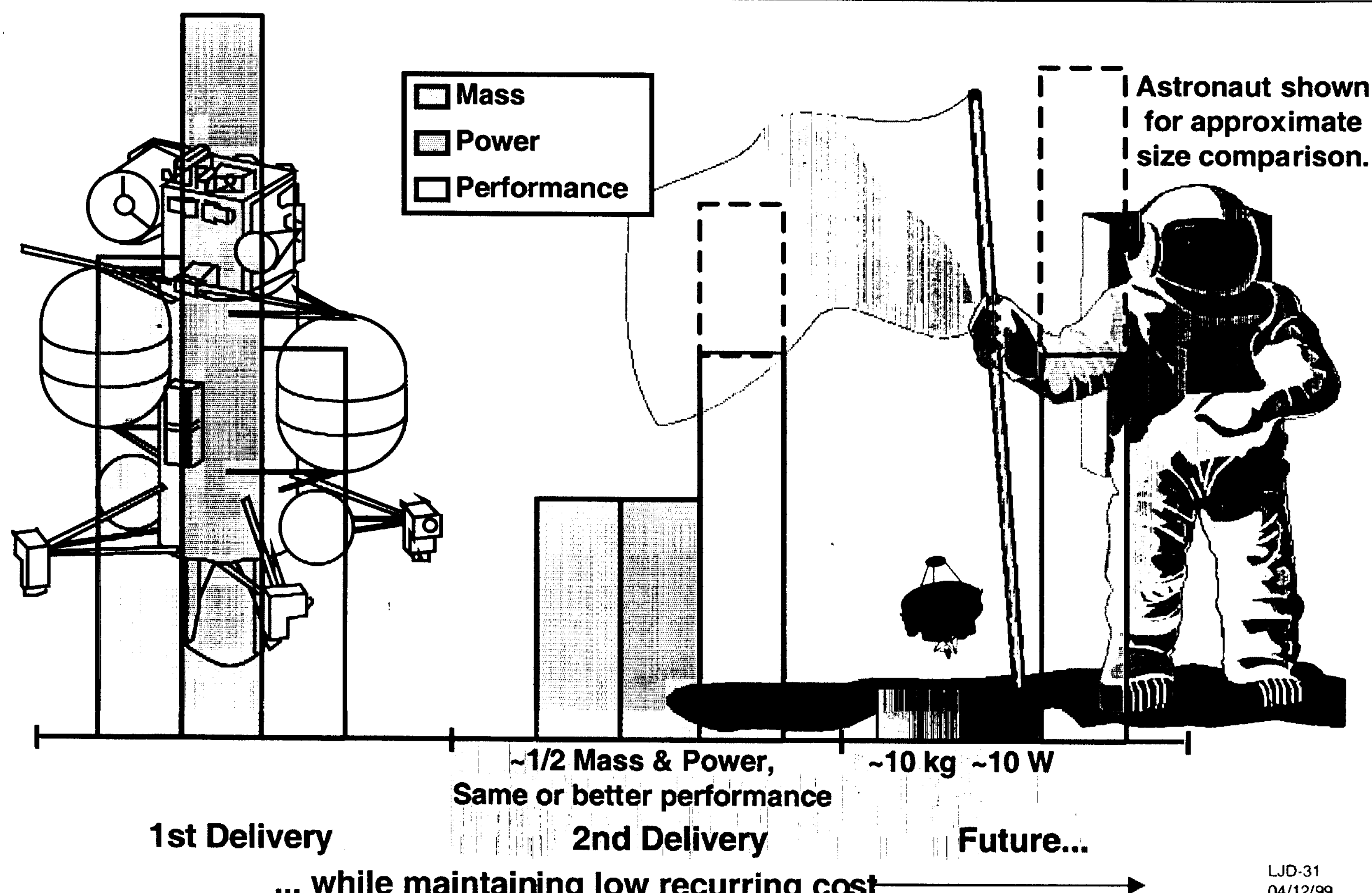
X2000 – Trends in Future Deliveries



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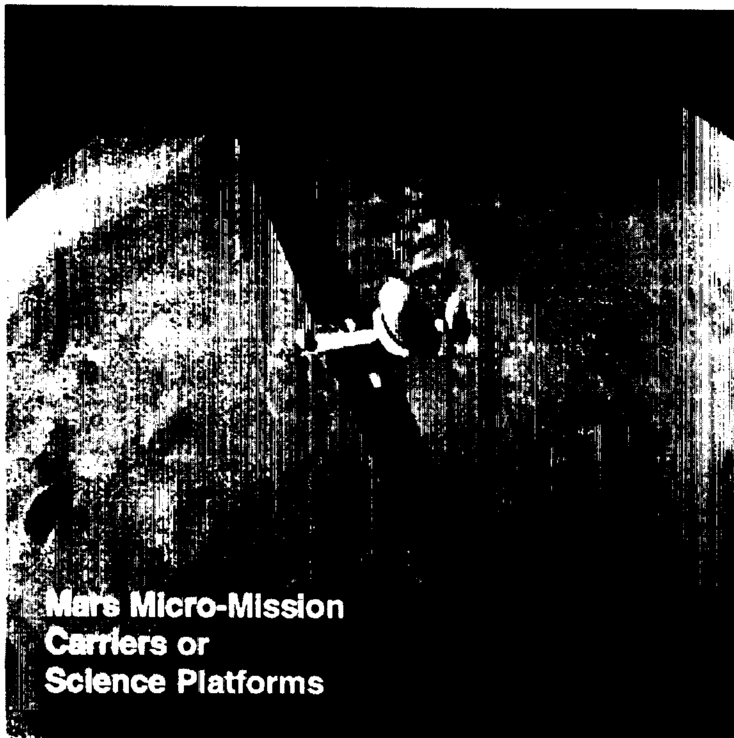
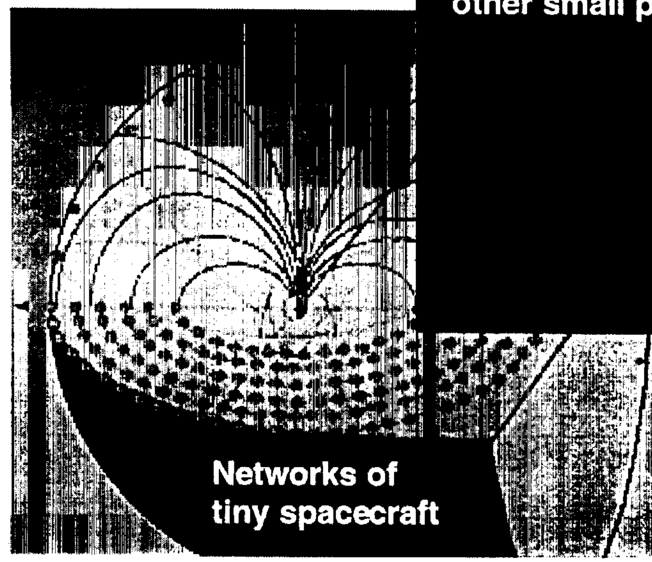
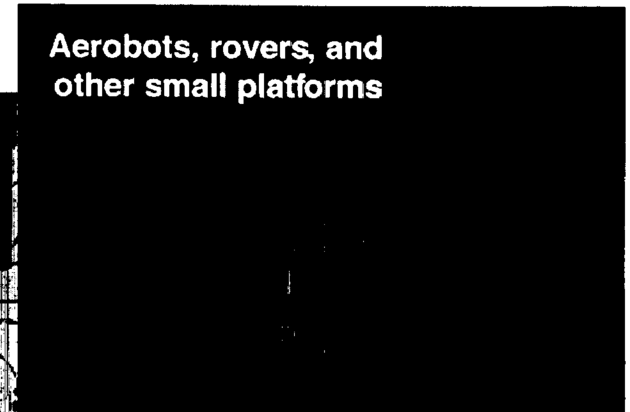
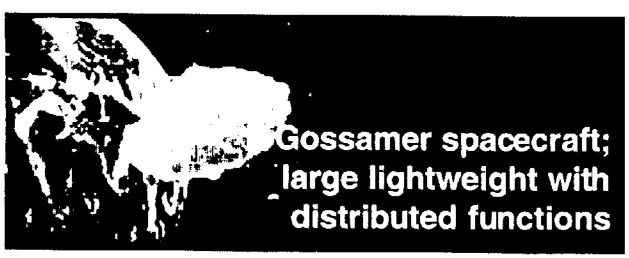
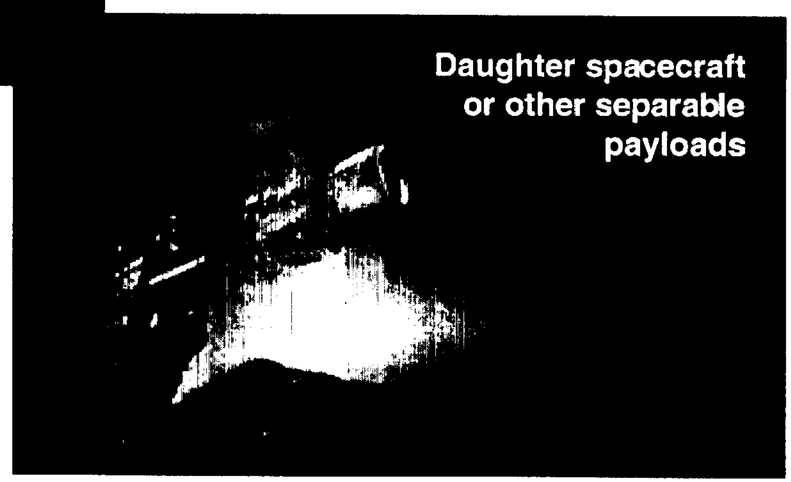
Some Missions that will be Enabled by X2000 Future Deliveries











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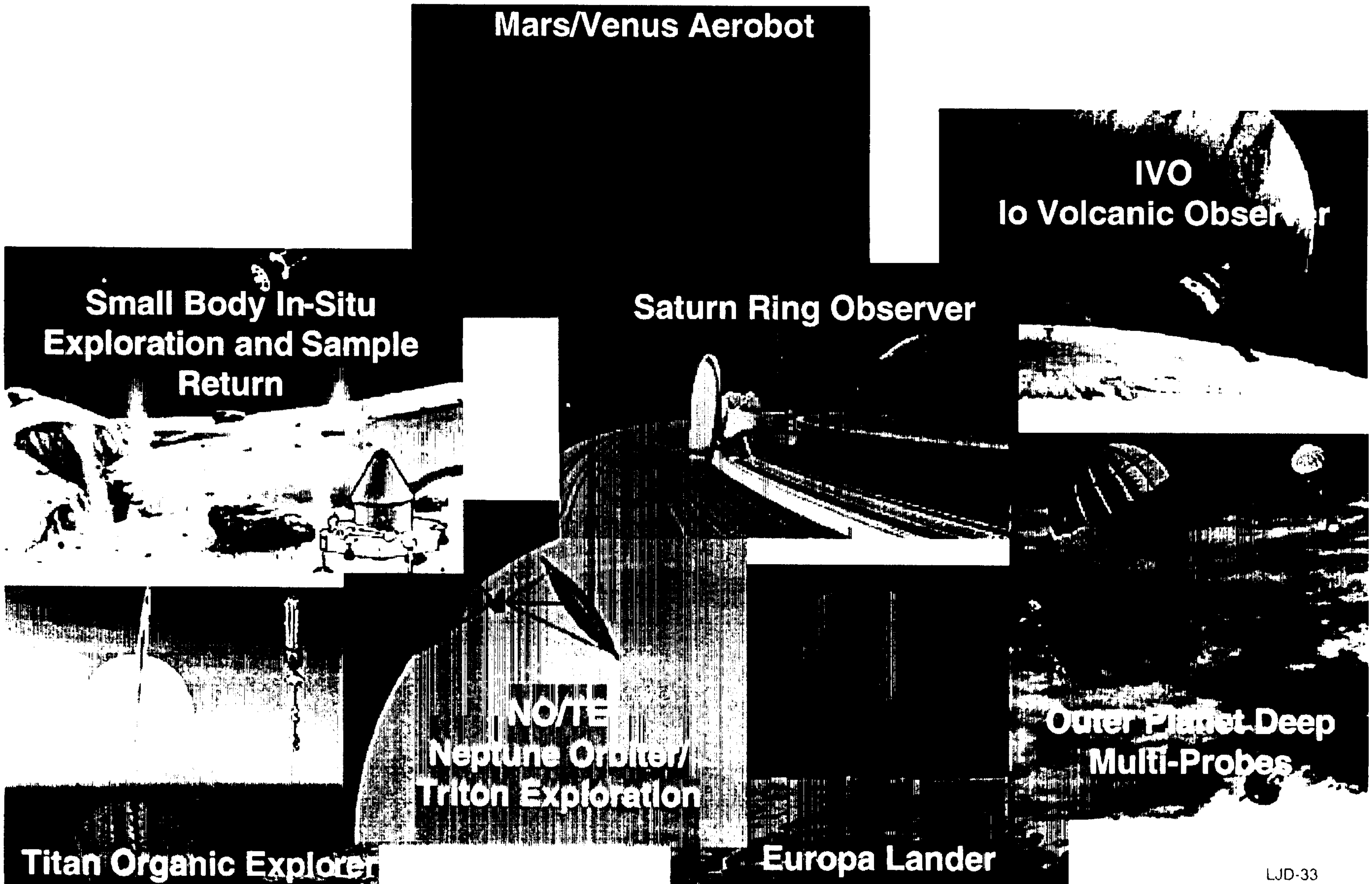
Extending the Computer Revolution into Space

Some Missions that will be Enabled by X2000 Future Deliveries



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What Will be Possible in the Next Decade?

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Extending the Computer Revolution into Space

Autonomous Navigation

- Deep Space One (DS-1) is a technology demonstration spacecraft
- DS-1 is on its way to an asteroid
- It will navigate itself in the vicinity of the asteroid using images from its camera

- In the future, autonomous navigation will allow constellations of spacecraft to perform tasks together without human-intensive planning and control

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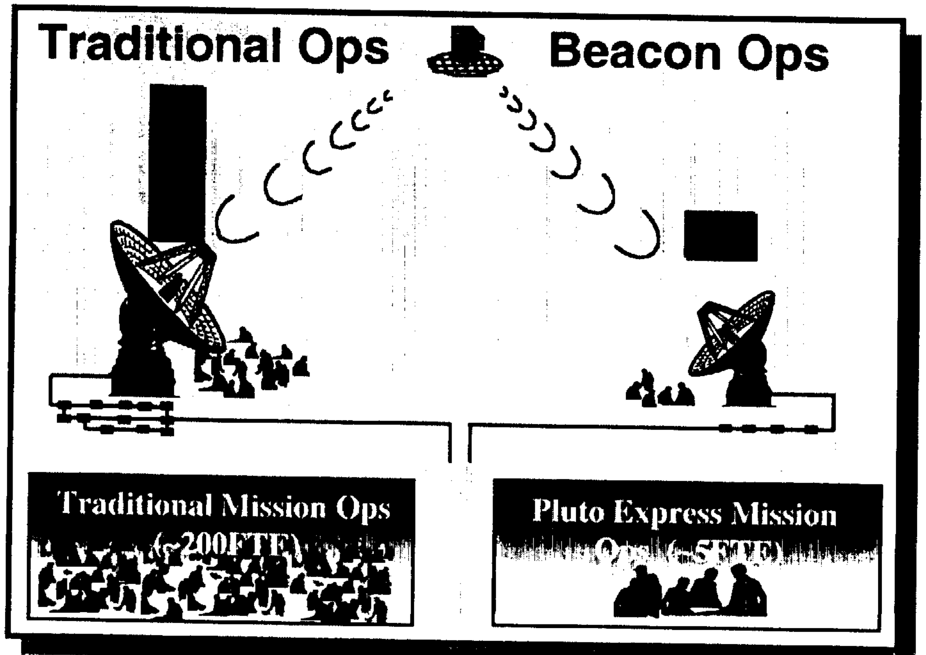
Extending the Computer Revolution into Space

Autonomous Health Monitoring

- Today, up to 25% of the bandwidth from deep space to Earth is used for spacecraft engineering data for monitoring spacecraft health
- DS-1 carries an experiment to determine its own health and signal the Earth with either "I'm OK" or "I need assistance."
- This signal can be added to regular telemetry or sent as a beacon tone



- In the future, spacecraft will not only be able to detect their own problems, but will fix many of them autonomously

Extending the Computer Revolution into Space

Goal-Oriented Spacecraft

- Goal-oriented commanding, as being implemented in the X2000 Mission Data System will revolutionize spacecraft operations
- The spacecraft will be given high-level goals, or missions, to perform
- The spacecraft will then attempt to fulfill these goals with no human intervention
- This will enable new kinds of exploration
  - Exploration far from Earth, such as interstellar probes
  - Exploration within the solar system where decision times are small compared to the round-trip light time
    - Io volcano mission
- This will also enable new services to be performed by commercial spacecraft
  - Personal communications
  - Personal weather and crop monitoring

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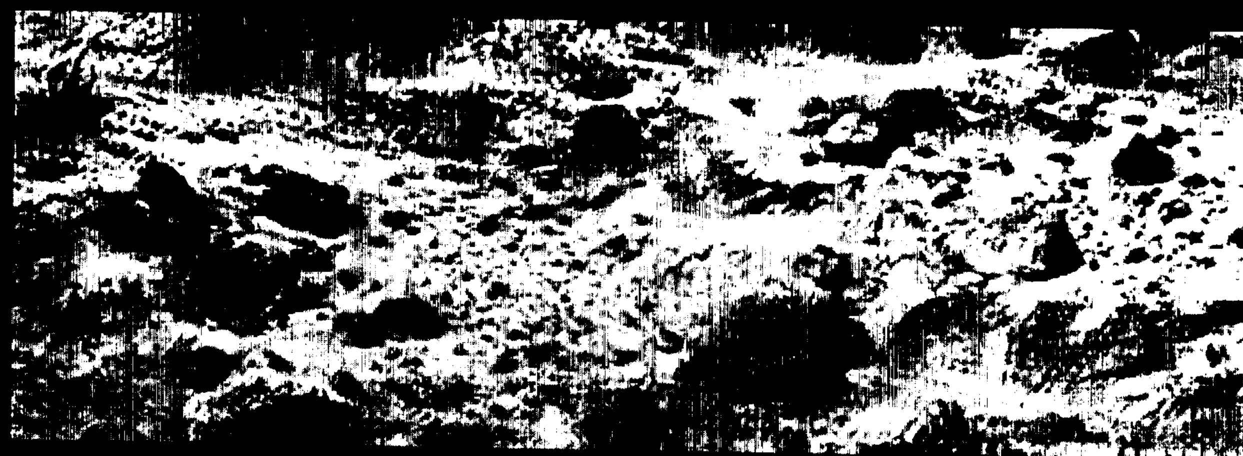
On-Board Science Data Analysis

- Mars pathfinder used a stereo camera to send 3D images back to Earth
- These images were used both to navigate the rover and for science analysis

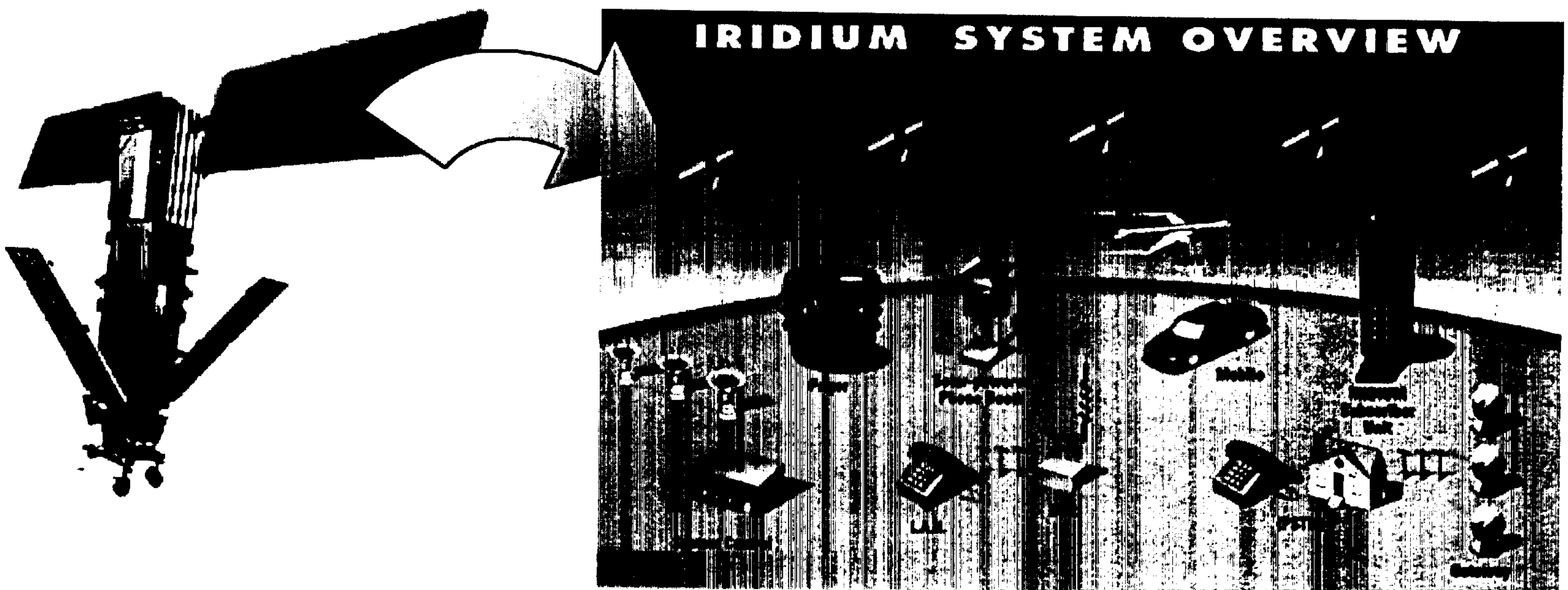


- In the future, 3D image processing will be performed on board the spacecraft
- Many other kinds of science processing will be possible on bpoard, leading to both decreased bandwidth requirements to the Earth, and increase automation
  - Synthetic Aperture Radar (SAR)
  - Imaging spectrometers
  - Tomography

Extending the Computer Revolution into Space

Further Communication Satellite Revolutions

- Most communication satellites today are still "bent pipe"
  - They simply receive a signal and retransmit it without understanding its content
- The new LEO communication constellations, like Motorola's Iridium use information content on board
  - They use high-level protocols to switch messages to their destination
  - The can route message through multiple crosslinks



- In the future, radiation hard computers will allow these services to be provided from Medium Earth Orbit (MEO)

Extending the Computer Revolution into Space

Going Beyond Communications

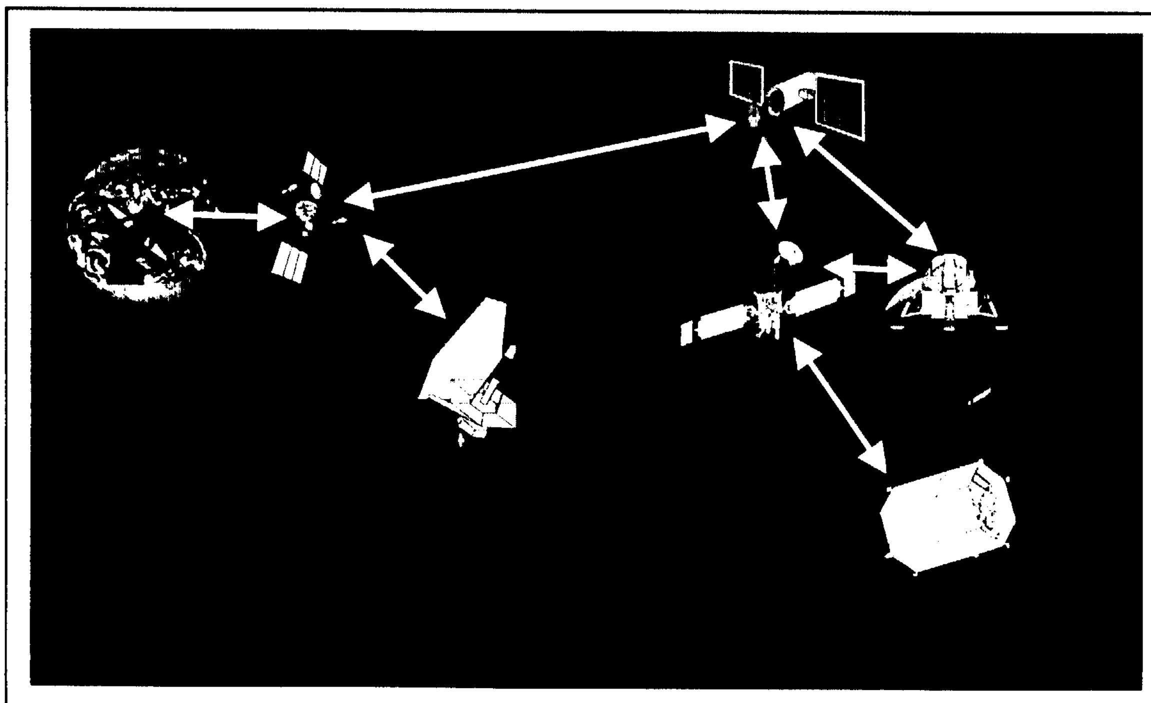
- Global satellite networks will enable new services
  - Global sharing of information at bandwidths orders of magnitude beyond today's
  - Global sharing of computing resources
  - Distributed computing across the Earth in the same way that we currently distribute computing across a room
- Computing will tend to follow individuals around, wherever they go
- In the future, most people will not know where their information processing tasks are being performed

The Further Future

Extending the Computer Revolution into Space

A Solar System Wide Area Network

- New communications protocols and paradigms: *Internet in the Sky"*
  - Communication relays on Mars and the Moon
  - Routers and relays at RF and optical wavelengths
  - File and message transfer with store and forward relaying
  - Automated station handover and data object re-assembly
  - Object oriented distributed infrastructure in space and on the ground
  - Demand access communication and demand driven response



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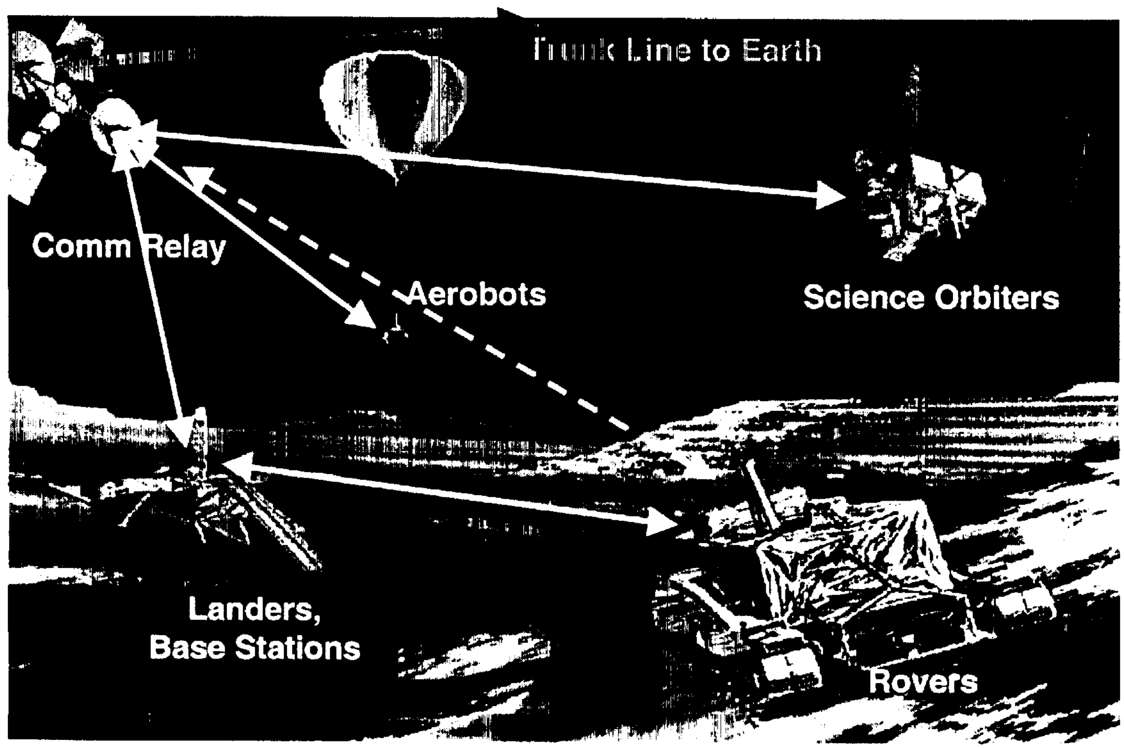
Virtual Presence Throughout the Solar System

- NASA's Strategic Plan calls for "establishing a virtual presence throughout the solar system"
- The public has gotten used to immediate access to information all over Earth – we will provide virtual access to space for everyone



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Colonization of Mars?

- Although human colonies on Mars will have to wait for many decades, robotic colonies may be possible by 2010
- Robot colonies on other planets will explore the surface, subsurface, and atmosphere extensively
- Working together, they will be able to analyze results much more quickly than single spacecraft
- Mars robot colonies can also pave the way for the coming of humans by gathering resources, synthesizing needed materials (like water and fuel) and preparing a stie for human landing and shelter

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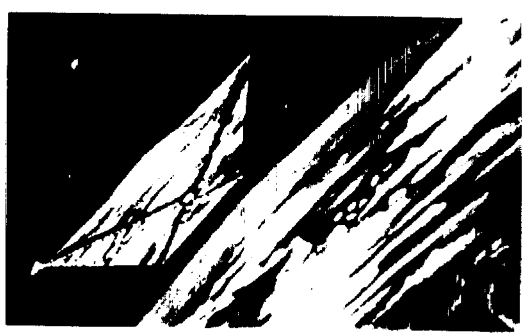
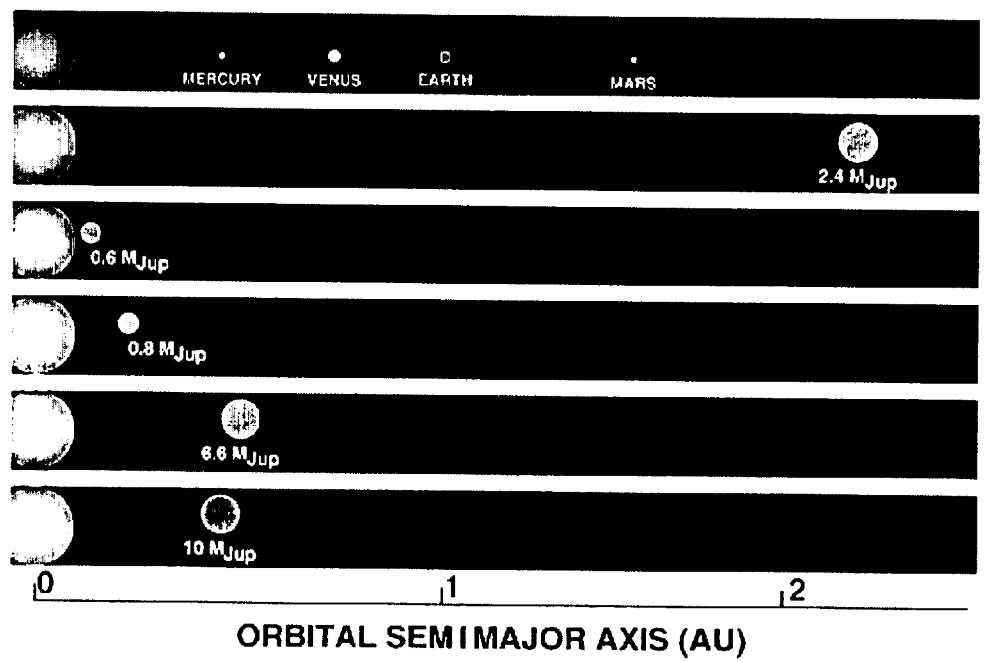
Extending the Computer Revolution into Space

Beyond the Solar System

- Up until a year ago, there were no known planets other than our Solar System's nine
- Now there are 20 planets that have been detected at other stars – most known planets are outside the Solar System!
- NASA has challenged JPL to create an interstellar mission within 25 years
  - Will travel up to 40 light years to study other planets
- Communications challenges are enormous
  - Giant optical apertures?
  - Spacecraft learning?
  - Faster-than light communications?





Extending the Computer Revolution into Space

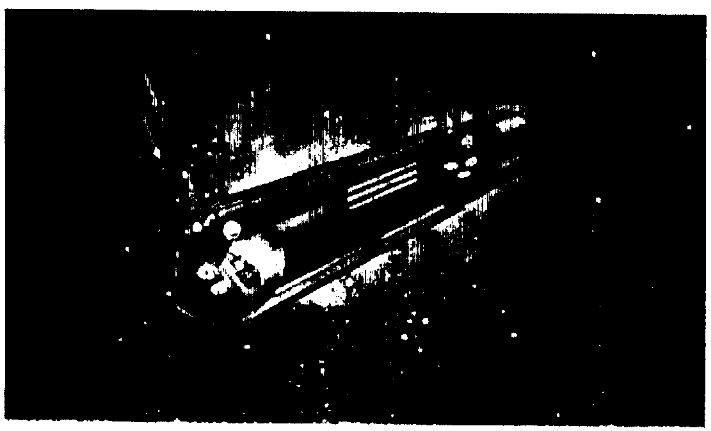
How Will We Get to Other Solar Systems?

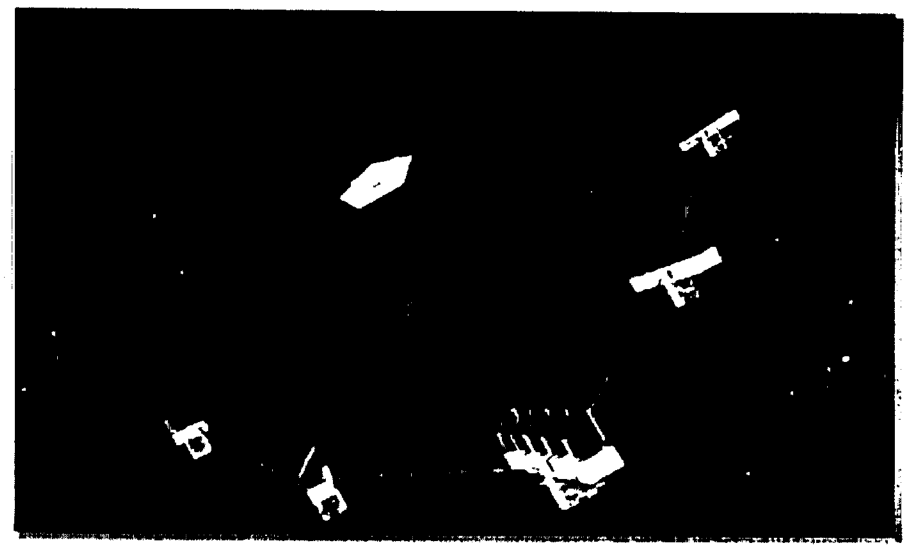
- First we must find the right ones
  - Detecting planets around other stars is at today's state of the art
  - We will need to go further:
    - Study individual planets from Earth
    - Understand their chemical compositions, temperatures, pressures, ...
- We need propulsion technology to allow us to send spacecraft to other stars in a *reasonable* amount of time
  - Speeds up to 0.2 of the speed of light!
  - Mission durations as little as 80 years – two human generations
- We need communication technology to get information to and from the spacecraft
  - Downlink so we can learn about the other planets
  - Uplink so the spacecraft can stay up-to-date
- Spacecraft learning will be a critical technology for such missions

Extending the Computer Revolution into Space

Inteferrometry in Space – Picking the Right Planets to Visit

- Space Interferometer Mission (SIM)
  - Optical interferometer in space
  - Will directly detect other planetary systems





- Terrestrial Planet Finder (TPF)
  - Several free-flying spacecraft working together
  - Large space space interferrometry
  - Will study chemical composition of planets in other solar systems

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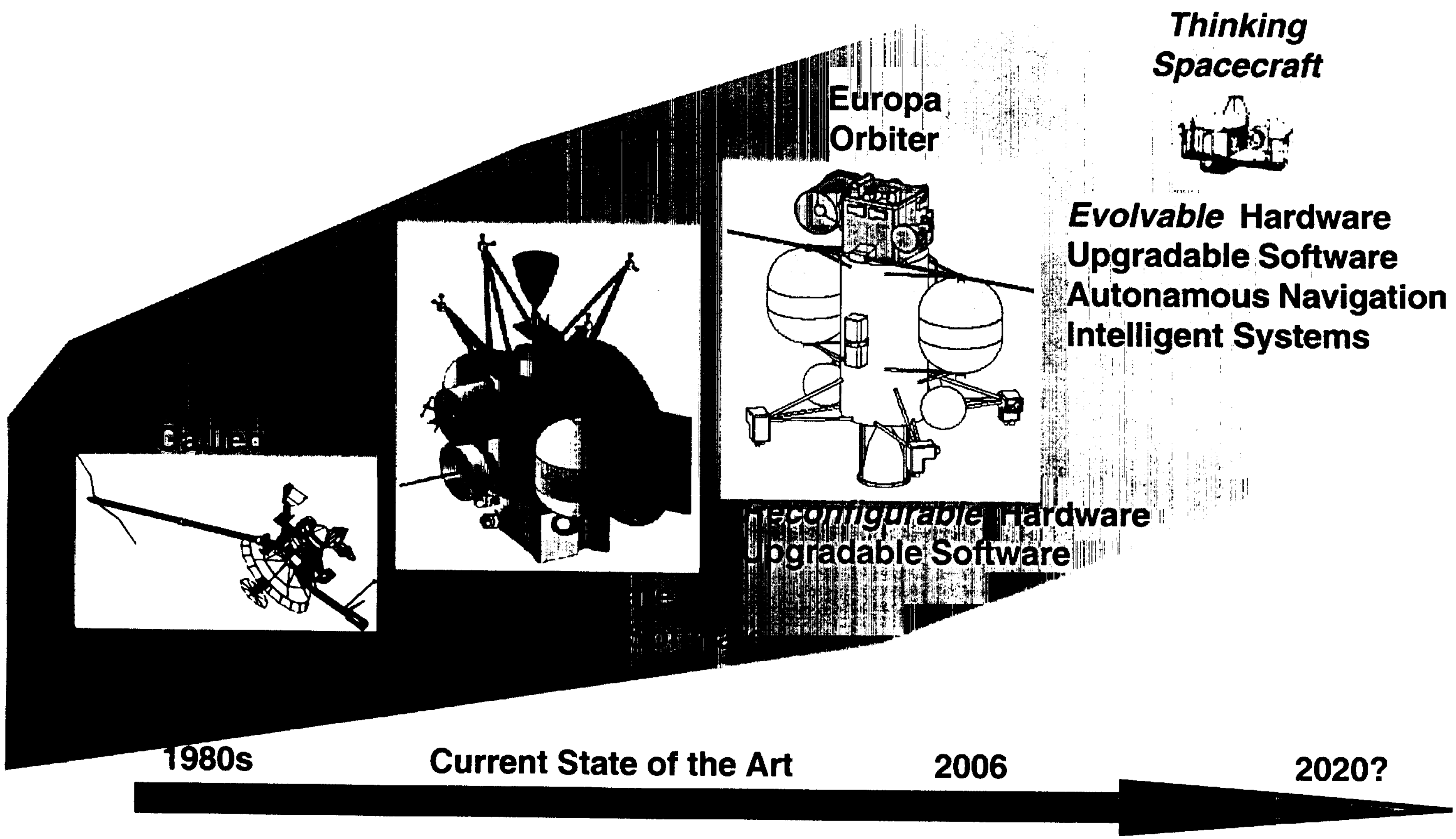
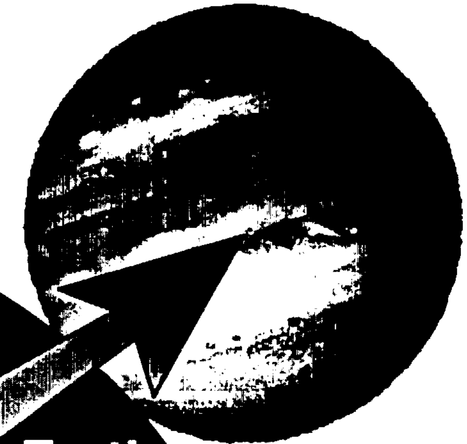
Toward a Thinking, Evolvable Spacecraft



Conclusion:



- The computer revolution is far from over on Earth
- It is just beginning in space
- We can look forward to an era of enhanced scientific exploration of the solar system and even other start systems
- We can look forward to the benefits of this space revolution to commercial uses on and around Earth