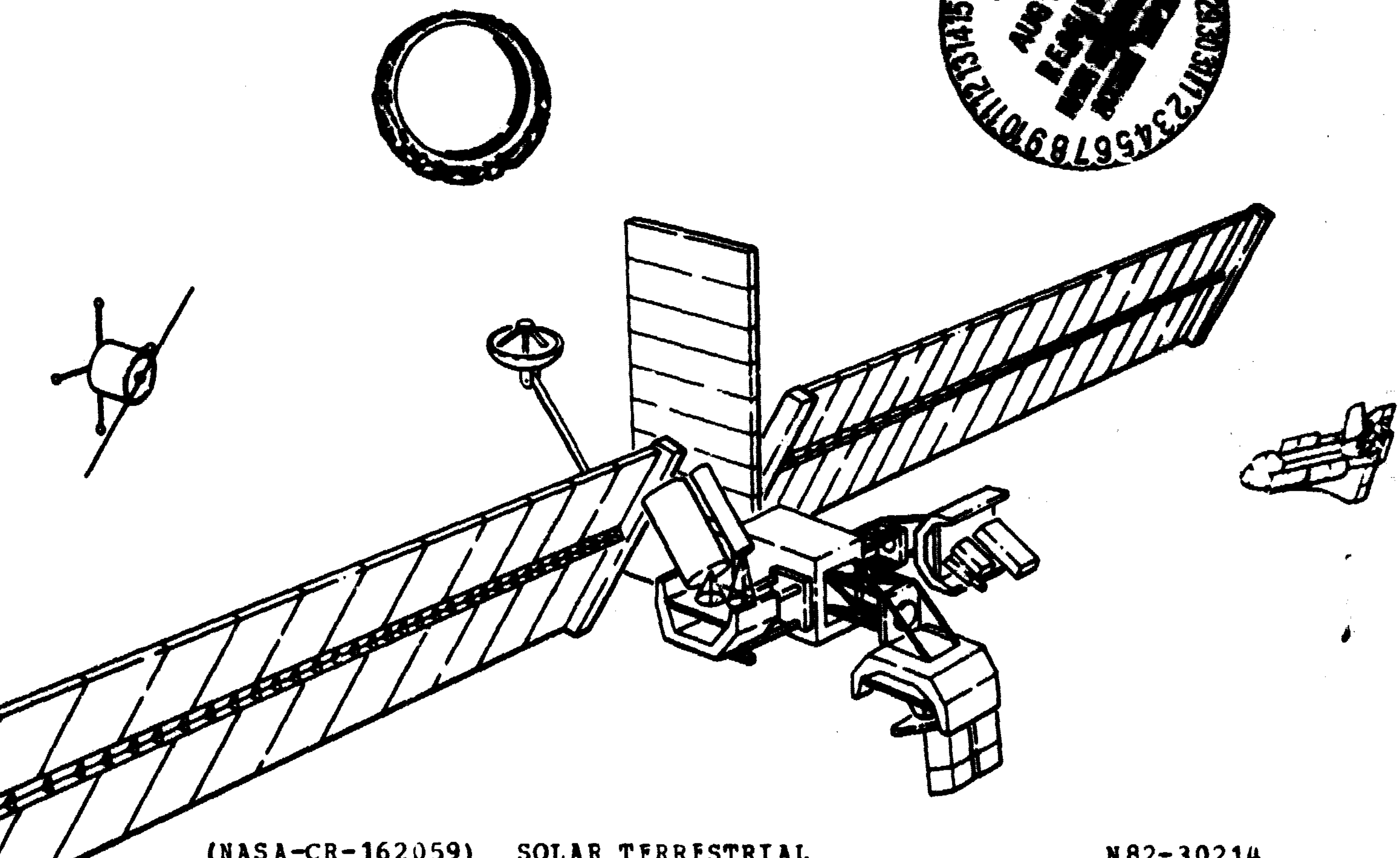
Solar Terrestrial Observatory

Final Report of the Science Study Group



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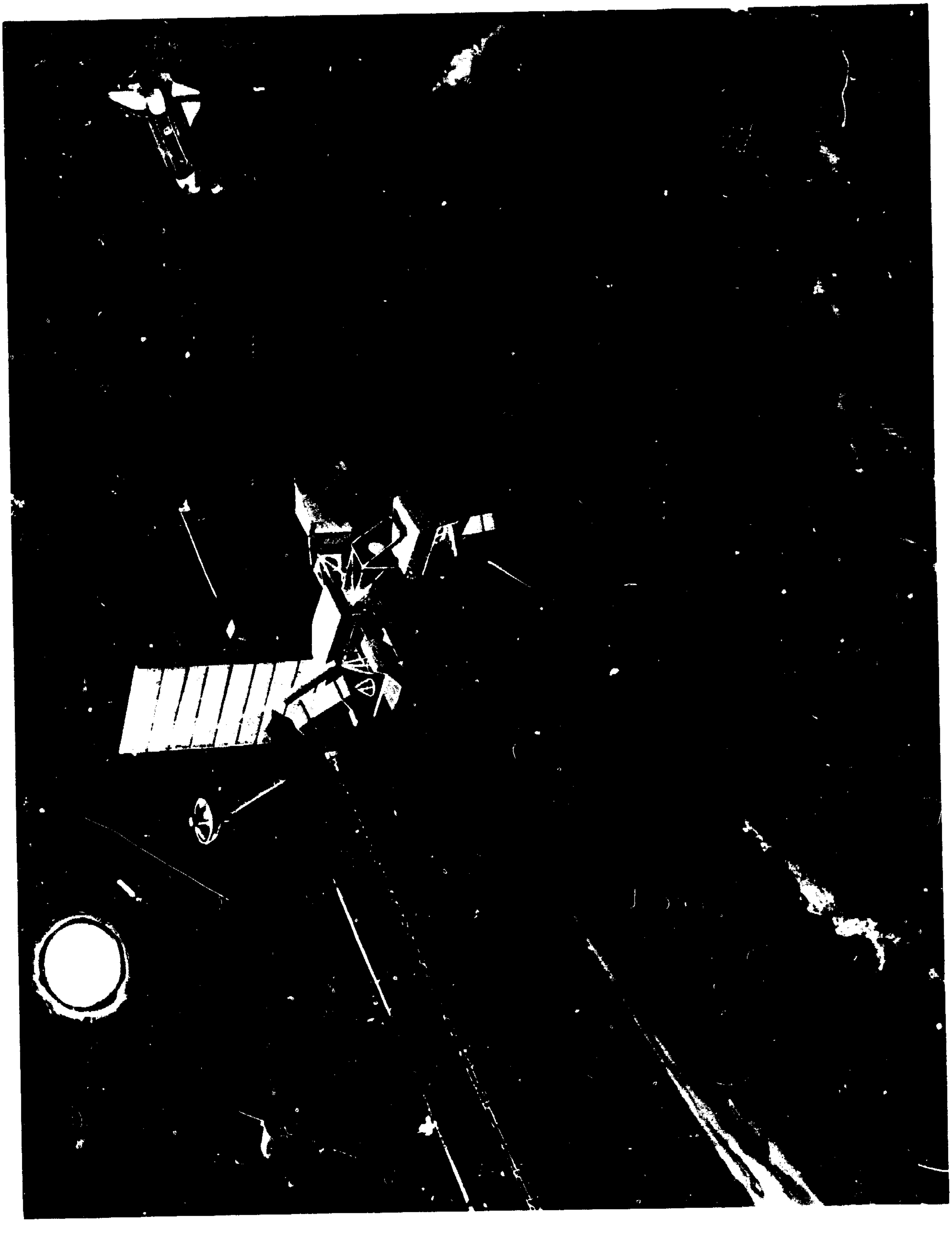

Artist's conception of a Space-Platform-based Solar Terrestrial Observatory showing platform-mounted solar, magnetospheric, and atmospheric pallets

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Abstract

The Solar Terrestrial Observatory (STO) is a specific, problem-oriented instrument payload based on a Shuttle/Platform approach, i.e., the payload is located on a space platform, and is set in orbit, serviced, and retrieved by the Space Shuttle. The central scientific goal of the STO is to understand the physical processes that couple the major regions of solar-terrestrial space. The approach to this goal encompasses the solar atmosphere, the interplanetary medium, the earth's magnetosphere and ionosphere, and the entire atmosphere of the earth.

The Shuttle/Platform approach offers a unique combination of capabilities, different from those of both conventional free-flyers and Shuttle/Spacelab. The characteristics that are important for the STO are:

- Large Shuttle-class instrumentation
- Long duration in orbit
- High power generation
- Regular in-orbit servicing
- Multidirectional pointing

In this report, the STO Science Study Group discusses eight basic solar-terrestrial scientific objectives that benefit from the Shuttle/Platform approach and a program of measurements for each. These objectives are to understand:

- Solar variability
- Wave-particle processes
- Magnetosphere-ionosphere mass transport
- The global electric circuit
- Upper atmospheric dynamics
- Middle atmospheric chemistry and energetics
- Lower atmospheric turbidity
- Planetary atmospheric waves

We develop a two-stage approach to a multidisciplinary payload: an initial STO, that uses a single platform in a low-earth orbit, and an advanced STO that uses two platforms in differing orbits. We find compelling reasons to coordinate the STO with an interplanetary companion. Finally, we emphasize that properly planned and implemented operations, data handling, data analysis, and theoretical modeling must be treated as an inseparable part of the STO mission. With the characteristics outlined above, the Solar Terrestrial Observatory can make a unique and valuable contribution to the NASA program of solar-terrestrial physics.

Preface

The Solar Terrestrial Observatory Science Study Group was established in the fall of 1979 by what was then the Solar-Terrestrial Division of NASA Headquarters, to formulate a scientific strategy for the development of a Solar Terrestrial Observatory (STO), an interdependent problem-oriented combination of solar, magnetospheric, and atmospheric instruments. The STO would be carried into orbit and serviced by the Space Shuttle, mounted on a long-lived space platform. The strategy we propose here for the use of the STO focuses on the physical processes that couple the major regions of solar-terrestrial space.

We wish to thank Sidney Bowhill, Bernard Haurwitz, and William Vaughan for their participation during the early part of this study. We also wish to thank the members of the Committee on Solar and Space Physics of the Space Science Board, and in particular William Feldman, Michael Kelley, Raymond Roble, Douglas Torr, and Donald Williams, for helping to improve this report in many ways.

Contents

I. Introduction

The strategy behind the scientific objectives, measurements and instruments discussed in this report assigns highest priority to understanding the physical processes that couple the major components of solar-terrestrial space. The role of these processes in the *variability* of the solar-terrestrial system is presently very poorly understood; they have been emphasized in developing this strategy for the STO.

Variability characterizes the entire solar-terrestrial system, from the sun to the earth. When a change occurs in the output of the sun, our earthly environment is perturbed as a consequence. Some of these perturbations have impacts on our modern technological society. They affect global communications, men and equipment in space, power distribution systems, geophysical exploration, and large pipeline systems. Beyond current impacts, we know that man has been affected by variations in world climate over all of recorded history. Recently we have been confronted with evidence that climate changes have occurred within the last several hundred years that are probably related to changes on the sun. For example, sunspots and other signs of solar activity apparently almost disappeared in a seventy-year long period from 1645 to 1715, known as the Maunder Minimum. This interval corresponds to a prolonged period of lower temperatures in Europe that was the coldest extreme of the Little Ice Age (1500-1850).

These are but a few of the many known or suspected solar-terrestrial relationships of practical importance, many of which are not understood sufficiently well to provide reliable predictive capability. In order to have any hope of achieving such a capability, it is necessary first to understand the basic mechanisms of the solar-terrestrial interaction.

We know that the earth's atmosphere and magnetosphere -- the earth's magnetic envelope -- respond in various ways to different changes in the solar output. Some changes in the solar output occur gradually as magnetic flux emerges from the solar interior into the solar atmosphere. Others are more impulsive, like the rapid energy release known as solar flares. The slow variations and abrupt perturbations both modify the flux of photons and particles from the sun. The latter contributes to the solar wind, in which the earth's atmosphere and magnetosphere are immersed. Thus, as the solar radiation and the solar wind change, so do the magnetosphere, ionosphere, and upper atmosphere. In response to a gust in the solar wind, the magnetosphere on the sunward side of Earth is compressed and electrical currents are generated, surrounding the earth and flowing through the ionosphere and magnetosphere. These currents have many practical consequences, some of which are worth mentioning here. For example, magnetospheric electrons and ions penetrate into the upper atmosphere near the poles, producing the aurora and atmospheric heating. This heating in turn leads to the generation of winds whose effects are felt throughout the upper atmosphere. These energy sources, along with variable energy deposition by solar radiation in the atmosphere, modify the production of ozone that is so important in protecting life here on the earth. Ozone is but one of many constituents of the upper atmosphere that interact chemically with one another under the changing influence of the radiation and particle input.

Although we have a superficial knowledge of many relationships among the sun, the magnetosphere, and the atmosphere, we have only an incomplete understanding of the actual physical and chemical processes that underlie these relationships. This lack of understanding precludes a reliable *predictive* capability. The Solar Terrestrial Observatory will be able to make unique measurements that will contribute in a significant way to achieving an adequate understanding of many of these processes.

II. Scientific Background

The Solar Terrestrial Observatory can contribute to improving our understanding of a wide variety of solar terrestrial problems. In this section we briefly review the background of many of them.

The solar phenomena that are of the most direct interest from the point of view of solar-terrestrial physics are temporal and spatial variations in the solar output of radiation and matter. These variations originate in the unsteady nature of the generation of the solar magnetic field, well below the visible surface of the sun. The configuration and rate of eruption of this magnetic field into that portion of the solar atmosphere from which radiation can directly escape, is the root cause of eventual terrestrial effects. The interaction of solar matter with the magnetic field in the sun's interior is responsible for many phenomena relevant to solar-terrestrial physics, including sunspots, flares, coronal holes, and the cyclic nature of solar activity.

Many terrestrial effects are known to be linked to variations in solar radiation, primarily in the ultraviolet. Solar ultraviolet radiation originates in the chromosphere, just above the visible surface of the sun, and in the overlying chromosphere-corona transition region. These layers of the solar atmosphere are highly structured and temporally variable. Thus it is no surprise that the ultraviolet radiation from the sun varies considerably, following the growth and decay of solar active regions and the 27-day solar rotation period.

In the last year it has been demonstrated convincingly that even the total solar radiative input -- at all wavelengths, from ultraviolet through the visible into the infrared -- into the earth's atmosphere is not constant, but fluctuates, apparently in association with solar activity. It is not yet known what long-term changes in solar radiation might accompany the 11-year cycle of solar activity, or even longer term changes on the sun. Recent measurements, which require confirmation, suggest that the 11-year variability of the ultraviolet irradiance may be of considerably greater magnitude than the 27-day variation and also greater than projected on the basis of the year-to-year change in the area of the sun covered by active regions.

The solar output also consists of outflowing plasma -- the solar wind -- and its associated magnetic field. The solar wind flow pattern is determined by the structure of the solar coronal magnetic field and its extension into the interplanetary medium. Figure 1 shows the corona as observed with soft X-rays. Bright loops occur where closed magnetic fields impede the solar wind expansion. The dark areas are coronal holes, where the open structure of the magnetic field permits rapid flow of solar material into interplanetary space. Coronal holes are now known to be a source of high-speed streams in the interplanetary medium, which flow at velocities of 700-1000 km/s, well above the usual 250-450 km/s of the average solar wind. The highest speeds are often associated with major solar mass ejections accompanying large solar flares; such flares also produce solar cosmic rays -- particles with energies up to 1 GeV. Galactic cosmic rays -- energetic particles that originate outside the solar system -- also travel through the solar wind and impinge upon the earth. The intensity of galactic cosmic rays at the earth is modulated by the structure and variability of the solar wind in such a way that their flux is anticorrelated with solar activity.

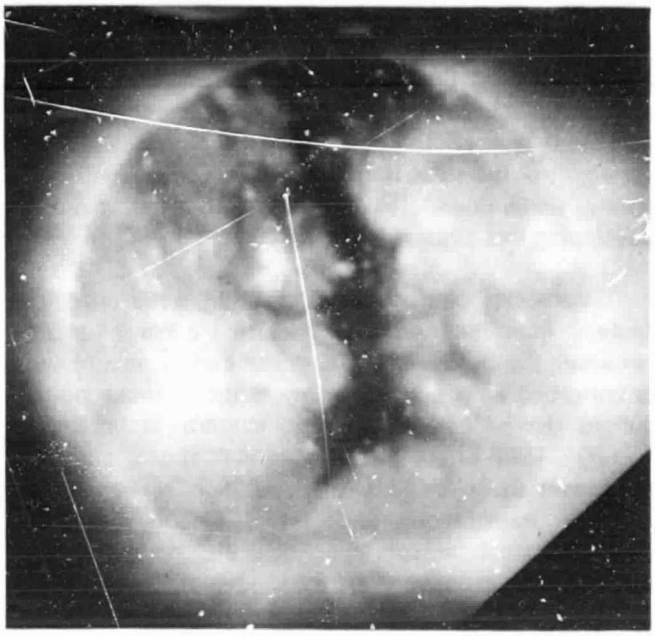

Fig. 1. The sun as seen in soft X-rays on 1 June 1973, photographed from Skylab. Both closed magnetic field regions (bright loops) and open regions (dark coronal holes) are clearly evident.

The flow of the solar wind and energetic particles varies greatly with time, on a variety of time scales. For example, during the declining phase of the last solar cycle, coronal holes and high-speed solar wind streams developed that persisted over many solar rotations, producing recurrent effects at the earth. In contrast, during the recent solar maximum, the solar wind was much less steady from one solar rotation to the next.

The plasma in the region between the solar corona and the earth's upper atmosphere is so tenuous that binary collisions between atomic particles are rare. A major physical process occurring in this region is the interaction between plasma waves and particles; wave turbulence interacts with the charged particles in such a way that energy is exchanged between the waves and the different particle populations. Such wave-particle processes are thought to play a fundamental role in the corona, in accelerating the solar wind, and in the boundaries between the solar wind and the magnetosphere, the bow shock and the magnetopause, shown in Fig. 2. Little is known about the details of the interactions or their statistics.

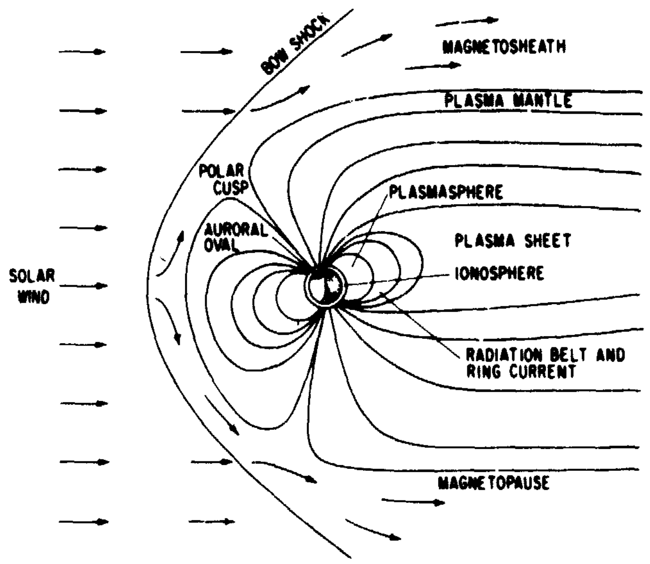

Fig. 2. The solar wind/magnetosphere/ionosphere system.

The magnetosphere is the link that serves to transfer the solar wind perturbations into the ionosphere, whose temperature and electron density structures are shown in Figs. 3 and 4, respectively. The solar wind delivers energy and momentum to the magnetosphere. It exerts stress on the earth's magnetic field, which determines the size and shape of the magnetospheric cavity and causes shear in the magnetic field of the outer magnetosphere. This shear is associated with field-aligned currents that close in the ionosphere. These transmit the drag on the magnetospheric boundary to the ionosphere and thence to the neutral atmosphere. The ionosphere has equally important effects on the magnetosphere. For example, recent measurements have revealed that species of ionospheric origin make up a significant fraction of the magnetospheric plasma. It is clear that electric fields parallel to the magnetic field play an important role in this linkage, but we do not know what causes these electric fields or how they are distributed along magnetic field lines.

The magnetosphere imparts energy to the upper atmosphere (the thermosphere, see Fig. 5) through particle precipitation and Joule heating, and imparts momentum through the Lorentz force. The variable stress on the magnetosphere may lead to short-term energy storage and sudden release, in what is called a magnetospheric substorm. This sudden release involves rapid temporal variation of the configuration of the magnetosphere, which energizes particles well above the energies typical of the solar wind. As these particles precipitate and collide with particles in the atmosphere beneath, they are directly heating the atmosphere. We have only a very rudimentary idea of the effect of this heating on atmospheric physics and chemistry. Moreover, it takes place over extended spatial regions, which have been difficult to observe comprehensively in the past.

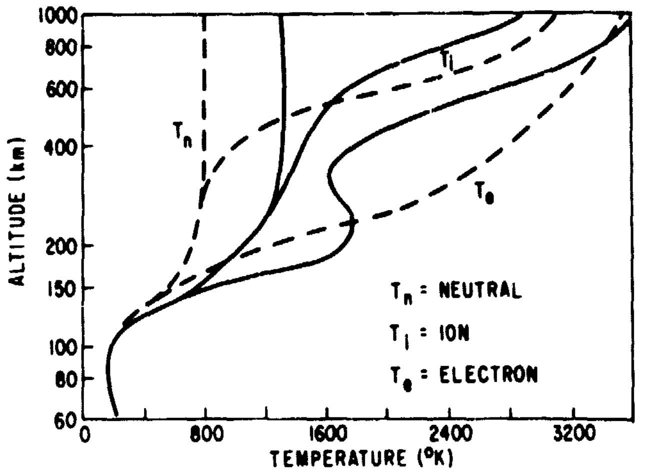

Fig. 3. Typical neutral, ion, and electron temperature profiles for a midlatitude ionosphere at sunspot maximum (solid) and minimum (dashed).

The solar wind is also largely responsible for driving the relative drift motion of the electrons and ions (i.e., currents) in the E and F regions of the ionosphere, shown in relation to the temperature structure of the atmosphere in Figs. 3 and 4. In the high-latitude auroral region, these drifting particles can reach relative velocities of 1 km/s or more because of the strong electric fields induced by the solar wind. Joule heating results, primarily from collisions between ions and neutrals. Recent work on specific events indicates that this

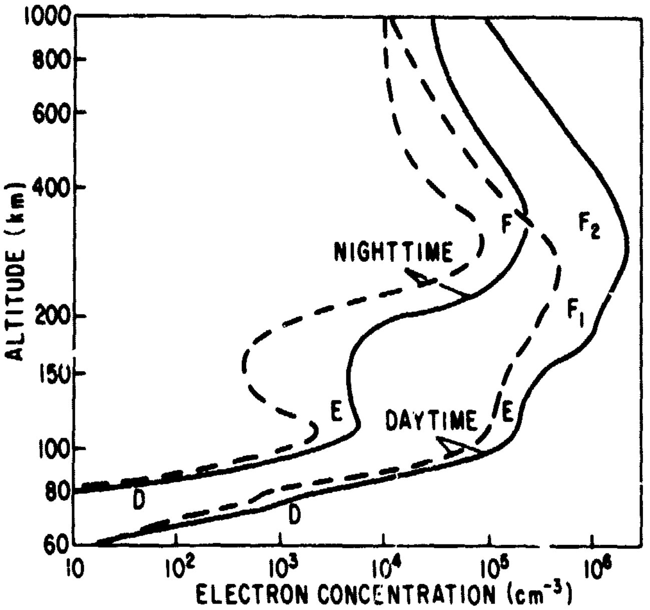

Fig. 4. Typical midlatitude ionospheric electron density profiles for sunspot maximum (solid) and minimum (dashed). The profiles mark distinct regions of the ionosphere, labeled D, E, F_1, and F_2.

heating process may be up to an order of magnitude more important than the heating of the upper atmosphere by the precipitation of energetic particles. The coupling of the neutral and ionized components of the upper atmosphere drives the neutral atmosphere into motion and results in the fastest winds observed anywhere in the earth's atmosphere. Finally, at times the direct impact of solar flare particles, in the form of solar cosmic rays, delivers considerable power to the atmosphere. In this process, the magnetosphere guides very energetic solar flare protons into the polar regions of the atmosphere.

Under quiet solar and solar wind conditions the steady-state meridional circulation and temperature structure of the thermosphere are determined primarily by the absorption of solar extreme ultraviolet (EUV) and ultraviolet (UV) radiation. However, these basic structures are perturbed considerably by the energy and momentum imparted by particle precipitation and ionospheric plasma convection. During large geomagnetic storms, for example, the thermospheric circulation pattern is completely reversed, and the circulation is toward the equator rather than the poles. To date, this picture has emerged from rather crude modeling together with mostly ground-based thermospheric observations. No data set exists at the present time corresponding to a known magnetospheric energy input. Such data, collected by STO, could be used in modeling to test our quantitative understanding of the energy transfer mechanism.

The interaction between the magnetosphere and the atmosphere is not limited to mechanisms in which atmospheric heating plays a role, but also includes a global electric circuit that couples the dynamics of the interplanetary medium to the meteorology of the lower atmosphere. Electric fields and currents are generated in the solar-wind magnetospheric interaction, in the magnetosphere itself, and in thunderstorms. These fields are thought to play an important role in linking the magnetosphere, the ionosphere, the atmosphere, and the solid earth. In the past it has been assumed that the circuit contains an upper ionospheric electrode that is perfectly conducting and uniform over all latitudes and longitudes. More recently it has been found that horizontal potential differences exist in the ionosphere that invalidate such simplifications. Much work remains to be done to measure and understand the basic mechanisms responsible for the fields and currents in the various regions that make up the global electric circuit, as well as to understand how they are coupled. Very little is known about how the electric currents influence the other behavior (e.g., chemical reactions, water vapor condensation processes, and transport) of a given region in the earth's atmosphere.

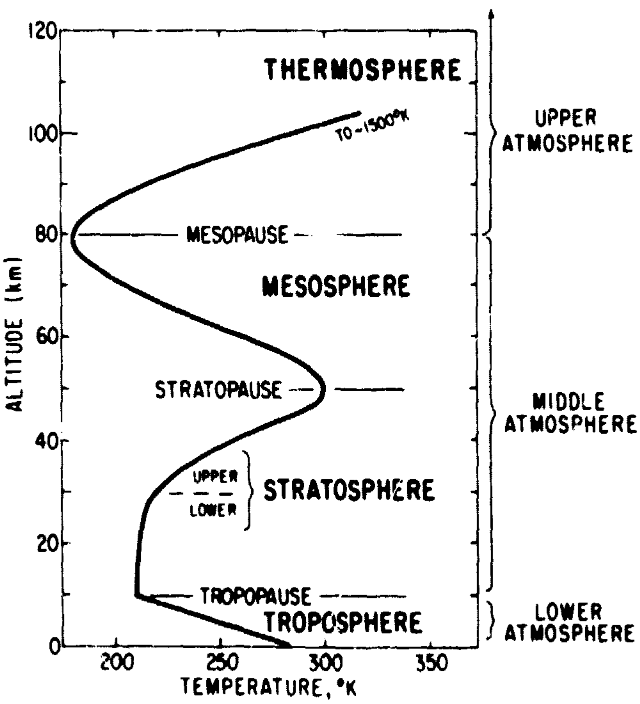

Fig. 5. The temperature structure and nomenclature of the earth's atmosphere.

The steady-state temperature distribution of the middle atmosphere (the stratosphere and mesosphere shown in Fig. 5) is determined primarily by the radiative balance between heating of the upper atmospheric constituents by ultraviolet radiation and cooling by infrared radiation. In the mesosphere and thermosphere, energy is absorbed by both atomic and molecular constituents, primarily at wavelengths shorter than 1750 Å. In the mesosphere and upper stratosphere, radiation at wavelengths between 1700 and 3000 Å is absorbed by molecular oxygen and ozone. The production of excited atomic oxygen from molecular oxygen in this region is the key to a sensitively balanced set of reactions involving the production and destruction of ozone. Variations in the incident solar radiation at these wavelengths change the equilibrium distributions of ozone and atomic oxygen. As the details of the basic energetics of the middle atmosphere have become somewhat clearer in recent years, it has become apparent that this region of the atmosphere is unusually sensitive to perturbations caused by changes in both the energy input to the system and in the composition of the stratosphere and the mesosphere. These can have potentially large effects on the middle atmosphere, on the interaction between the middle and lower atmosphere, and on conditions at the surface of the earth.

Searches for influences of long-term solar variations on the lower atmosphere have been made for many years, but no clear picture of any physical mechanism or connection has emerged. Historical and tree-ring radiocarbon data suggest that past periods when the climate was cooler than now correlate with prolonged periods of low solar activity. A good case has also been made for a correlation between the 22-year magnetic cycle of the sun and recurrent drought in the western United States, as well as for an 11-year cycle in the location of the tropopause. Statistically significant evidence has also been found for relationships between short-term changes in atmospheric circulation patterns and solar wind conditions. In almost every case, the physical mechanisms for such relationships have yet to be elucidated or verified experimentally. An obstacle to the development of almost any theory to explain the effects of the variable sun on the meteorology and climatology of the earth is the requirement that extremely small changes in the total solar energy input to the atmosphere must produce tropospheric energy changes that are orders of magnitude larger. How the atmosphere picks up and amplifies the solar signal remains to be explained. Some of the mechanisms suggested include possible effects on thunderstorms due to changes in the electrical properties of the global electric circuit; modulation of the radiative balance of the atmosphere due to variations in clouds, abundance of trace elements, or the aerosol content of the atmosphere; and dynamic modulation of the lower atmosphere by the middle atmosphere.

For virtually all of these phenomena, simultaneous observations of diverse types, crossing traditional boundaries between disciplines, are required to fill in missing information on the fundamental processes that couple solar changes to the terrestrial response.

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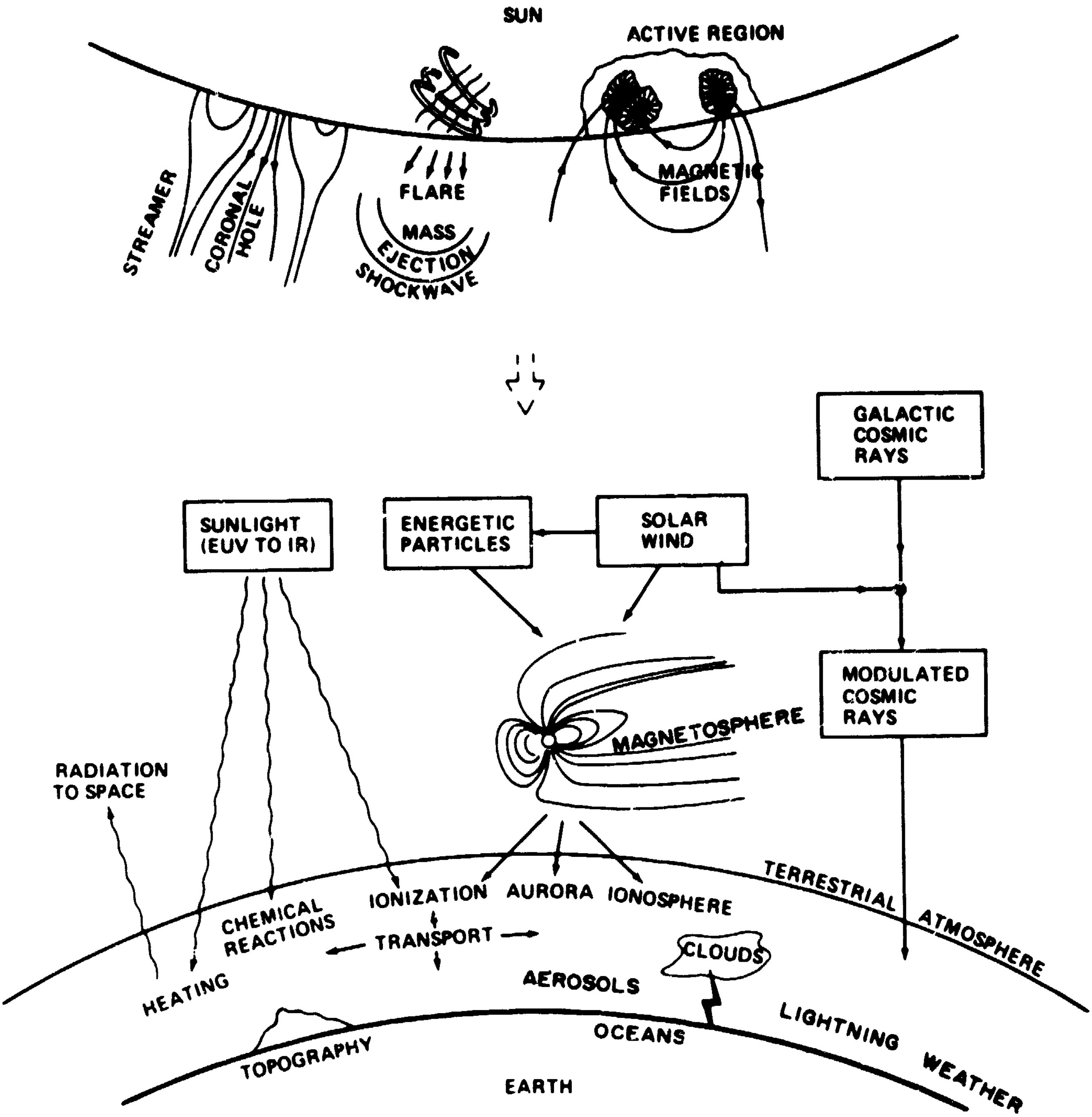

Fig. 6. Elements of the solar-terrestrial system encompassed by the objectives of the Solar Terrestrial Observatory.

III. Key Solar-Terrestrial Objectives

The overall goal of the Solar Terrestrial Observatory is to improve our understanding of the physical processes that couple the major components of the solar-terrestrial system, i.e., the sun, the interplanetary medium, the magnetosphere, the ionosphere and the atmosphere. In this section we have selected eight representative and key objectives, to whose attainment the STO can make a significant contribution different from that achievable by the use of conventional small free-flying spacecraft or ground-based measurements. For ease of exposition, we will discuss each objective separately. In fact, however, since many of the mechanisms are interrelated, the pursuit of each objective benefits greatly when observations covering a variety of related phenomena are acquired together. The eight key solar-terrestrial objectives include the phenomena and interactions shown schematically in Fig. 6.

The objectives listed here cover eight fundamental processes of the solar-terrestrial system:

(1) The mechanisms that relate the intrinsic properties of the sun to variations of the solar radiative and particulate flux into the terrestrial system.

(2) The basic physics of wave-particle processes in the solar-terrestrial environment.

(3) The role of transport of material in coupling the magnetosphere and the atmosphere.

(4) The role of electrostatic and electrodynamic processes in coupling the magnetosphere and the atmosphere.

(5) The effect of variations of solar and magnetospheric inputs on thermospheric dynamics.

(6) The relationship between mesospheric chemistry and variations of solar and magnetospheric inputs.

(7) The role of atmospheric aerosols and clouds in possible relationships between solar variability and the troposphere.

(8) The role of planetary atmospheric waves in possible relationships between the upper atmosphere and the troposphere.

We emphasize that the problems we have selected are those that will benefit most from being addressed together, which is the basis of the STO approach. We first state *why* measurements must be made (the background), followed by *what* measurements must be made. In Chapter IV, we will address the question of *how* to make the measurements using specific instruments.

1. Solar Variability

Objective. *Measure the variation of the radiative and particulate solar inputs to the earth and determine the mechanisms that are responsible for this variation.*

Overview. There are two aspects to this objective. The first is the variation of solar inputs to the earth in radiation, particles, and fields. The second is to identify the solar and interplanetary phenomena that lead to the variability of these inputs. By making both observations of the sun and *in situ* flux measurements from the STO, accompanied by a non-STO interplanetary probe, we can trace the course of solar perturbations back to the sun. Appropriate observations of the sun and the interplanetary medium before, during, and after terrestrial events will be used to pinpoint their solar causes.

Background. Fundamental to many problems of solar-terrestrial physics are questions of the variability of the various solar inputs that affect the earth's magnetosphere, ionosphere, and atmosphere. These inputs include electromagnetic radiation from the sun, solar wind and flare particles, the extended magnetic field of the sun, and, indirectly, galactic cosmic rays, which are modulated by the extended solar magnetic field.

The visible and near-infrared portions of the spectrum are the major contributors to the total solar radiative flux, the *solar constant.* This radiation heats the earth's surface and oceans as well as the lower atmosphere, providing most of the energy that drives atmospheric circulation. Sophisticated radiometers on the Nimbus 7 and Solar Maximum Mission spacecraft have documented real changes in the solar constant at the level of 0.05 to 0.3%, on scales of days to weeks. A possible secular change of about 0.4% over several years has also been suggested by recent intermittent measurements from rockets and balloons. Changes like these, if they persist, seem adequate to perturb the radiative balance of the troposphere, and hence the weather, on a global basis. A change of 1%, for example, may bring about a global temperature change of 1-2 °C, according to modern climate models.

Significant temporal variations in *solar spectral irradiance*, specifically in the shortest wavelengths (UV, EUV, and X-ray) and in the nonthermal radio emission have been clearly established, although as yet with insufficient precision and frequency to make the absolute values of the variations useful in predictive modeling of atmospheric effects. Still controversial, however, are quantitative descriptions of how solar radiation in various regions of the ultraviolet varies over years or tens of years, and specifically within what limits these emissions vary in the course of the 11- and 22-year solar activity cycles.

The properties of *solar particles* and *magnetic fields* in the near-earth environment play an extremely important role in solar-terrestrial physics. The basic properties of the solar wind at the orbit of earth, including velocity, mass flux, magnetic flux and composition, show no simple relationships to conventional solar activity indices. Indeed, in considering the solar-terrestrial system it must be recognized that the mechanisms responsible for the acceleration of the solar wind are poorly understood, partly because of the paucity of data specifying the physical parameters in the solar corona, such as temperature, density, and the strength and morphology of the coronal magnetic field.

The STO is thus designed to explore an area of solar-terrestrial physics that has received relatively little attention in observations before: the relationships between the physical properties of the solar surface and corona and transient events such as flares on the one hand, and the radiation, particles, and fields incident on the terrestrial system, on the other. The association between high-speed streams of solar wind and the occurrence of low-latitude coronal holes is one of the best established of solar-terrestrial relationships; yet it explains only a part of the real variation noted in radiation, particles, and fields in the near-earth environment. What is clearly needed is a much improved understanding of the temporal behavior at the earth of the solar irradiance, solar wind, and solar magnetic fields, and a much improved model of how these properties vary with observable solar surface features and events.

Transient events on the sun are known to produce fluctuations in the terrestrial environment. The best studied of these events are, of course, solar flares. The interception by the earth of high-energy particles, principally protons, from solar flares may have profound influence on the upper and middle atmosphere -- for example, studies indicate that the presence of an energetic solar particle flux in the stratosphere may lead to dissociation of N_2 and thus to formation of nitric oxide, which catalytically destroys ozone. The cumulative effects of such processes are not well understood.

Flares also induce large perturbations in the flow of matter and magnetic flux in the interplanetary medium. Shock waves induced by flares cause major perturbations to the geomagnetic field, which are in turn associated with auroras and geomagnetic substorms. The relationships between the terrestrial perturbations and the intrinsic properties of the flare event (e.g., energy, momentum, and magnetic environment) are largely unexplored.

The influence of the solar magnetic configuration upon the terrestrial environment is largely conjectural at present. Only recently have we begun to construct models of the global solar magnetic configuration and its outward extension into interplanetary space. The improved understanding of the nature of coronal holes recently obtained will contribute to the understanding of the influence of solar magnetic properties on the terrestrial environment.

Our knowledge of the processes that govern the solar radiative and particulate outputs is relatively rudimentary. We have a basic understanding of why the solar atmosphere expands to form the solar wind, but the detailed prediction of this expansion in the highly structured corona is beyond current capabilities. We believe that energy for solar flares is stored in the form of magnetic fields, but how this energy is released, and specifically, how it is directed to the vicinity of earth, is beyond us. A major part of our difficulty results from insufficient simultaneous, well-placed observation.

Our current inability to understand quantitatively the relevant physical processes governing the solar electromagnetic and particulate outputs translates in practical terms to an inability to predict and extrapolate. With current knowledge, we cannot look at an X-ray picture of coronal holes on the sun and predict the properties of the interplanetary medium at earth. We cannot observe an active region on the sun and determine the nature of the flare that may occur there. We cannot yet predict the terrestrial consequences of specific flares in better than general terms.

Recommended STO Measurements. Two types of measurements need to be made from the STO. The first and simplest is the measurement of the flux of radiation incident on the top of the earth's atmosphere. The second is the observation, through remote sensing, of the solar surface features that are responsible for solar flux changes at the earth.

Continuous monitoring (not just occasional samples) of the solar constant and the solar spectral

Table 1. Solar Electromagnetic Radiation Monitoring Requirements.

Spectral Interval	Spectral Resolution	Accuracy	27-Day Precision
Total (Solar "Constant")		0.1%	0.01%
10-120 nm	0.1 nm	5%	0.5%
120-200 nm	0.5 nm	5%	0.5%
200-450 nm	0.5 nm	1%	0.5%
900-4000 nm	100 nm	1-2%	0.5%

irradiance is required for the lifetime of the STO. Table 1, an extension of the recommendations of the NOAA workshop "Monitoring the Solar Constant and the Solar Ultraviolet" of August 1977, is given here as the most suitable guide to the accuracies recommended. We have added the EUV region (10 - 120 nm) because of its importance to thermospheric dynamics and chemistry.

Valuable remote sensing observations that could be made from the STO include the physical properties of the low corona (electron density, temperature, and magnetic field configuration) to make use of the close relationship between coronal holes and high-speed streams in the solar wind. Both X-ray and white light images are required to infer the magnetic field configuration of the low and intermediate corona.

The expansion velocity of material in coronal holes should be measured in two complementary ways, depending on whether the coronal hole is located at the limb or on the visible disk. Measurements of the brightness of the corona in Lyman α (1216 Å yields information on coronal holes near the limb. Direct measurements of Doppler shifts in EUV lines can be used for coronal holes located on the disk.

The physical properties of active regions, flares and mass ejection events can be determined by observations in hard X-rays and in the EUV. Spectroheliograms in the EUV, made in a Doppler-sensitive mode, can measure the spatial distribution of velocities, densities, and temperatures of flare and nonflare ejecta. These data can be used to establish the relationship between observed solar surface events and subsequent fluctuations in photons and particles at the earth.

Complementary Measurements. Though many interesting problems can be approached using the capabilities of the STO alone, the range of problems and the value of the STO would be greatly enhanced if, while the STO was in orbit, complementary interplanetary measurements were available from other spacecraft. Interplanetary measurements should be made of the basic plasma parameters: density, temperature (of ions and electrons), velocity, and magnetic field, which are important inputs to the magnetosphere. These parameters are needed as well to relate the interplanetary medium at 1 AU to the sun itself. Composition and charge measurements should be made both for identification of the solar origin of material and for comparison with magnetospheric measurements. Interplanetary measurements of cosmic ray electrons and protons, at energies below those possible from within the magnetosphere, would be extremely valuable because of their importance as ionization sources. Finally, measurements should be made of transthermal protons, electrons, and ions, as well as the frequency spectrum of magnetic and electric field fluctuations, for comparison with wave-particle studies from STO.

Various ground-based observations can support and enhance the scope of the STO objectives. These include ground-based measurements of the solar photospheric magnetic field and the inner corona, Hα, and white light patrols of flares and sunspots, and patrols of solar radio emission from active regions and interplanetary disturbances.

2. Wave-Particle Processes

Objective. *Examine the microphysical processes occurring in wave-particle interactions in space plasmas and assess the effects of these interactions in controlling energetic processes in the soler wind, magnetosphere, and upper atmosphere.*

Overview. Wave-particle interaction processes are found throughout the solar-terrestrial system. *In situ* studies of these processes have been carried out from a number of free-flying spacecraft, using passive techniques. The ability to control certain wave, particle, and plasma parameters *actively* through injection of waves, electrons, and ions from STO permits new insight into the microphysics involved, through clarification of cause and effect. The high power capabilities of the STO permit new active wave and particle injection experiments. The STO is well suited for conducting controlled perturbation experiments on wave-particle processes, as well as for the remote sensing of naturally occurring wave-particle interactions in the earth's magnetosphere and ionosphere.

Background. The plasmas that fill the space between the atmospheres of sun and earth are so tenuous that classical collisions between particles are rare. However, since energy is transferred between the various plasmas in this region, and since various plasma boundaries exist, thermodynamically dissipative processes must occur. The dominant process appears to be wave-particle interactions, in which wave turbulence interacts with charged particle populations in such a way that energy is exchanged between turbulence and the particles. As a result, wave-particle interactions tend to dominate the behavior of plasmas between the sun and the earth.

Wave-particle interactions can be found at the sun, in the solar wind, at magnetospheric boundaries and throughout the magnetosphere and ionosphere. Their effects have been invoked to explain such processes as solar wind acceleration, the formation of interplanetary shocks, thermodynamic dissipation at the bow shock and microscopic plasma processes at the magnetopause. Plasma measurements on ISEE are allowing the study of solar wind and magnetospheric boundary processes. However, in many instances, multiple plasma processes mask the specific physics involved in a given phenomenon. Some of these wave-particle processes can be studied using controlled inputs of waves, particles, and plasma within the natural plasma laboratory of the earth's ionosphere and inner magnetosphere.

Within the magnetosphere the equilibrium structure of stably trapped particles is qualitatively understood to be the result of diffusion across the field and the interaction of the particles and plasma waves. One of the wave-particle interactions thought to contribute to the equilibrium in the magnetosphere is shown in Fig. 7. Approximately guided by the earth's magnetic field, counterstreaming plasma waves and electrons trade energy in the interaction region near the equatorial plane. In the past, this interaction has been stimulated by ground-based transmitters, and amplified waves have been remotely sensed with instruments on the ground and on satellites. The region of the magnetosphere containing nonstably trapped particles is magnetically connected to the tail of the magnetosphere, and here the mix of wave-particle interactions and dynamics is not understood even qualitatively.

Ion dynamics in the magnetosphere are also expected to be strongly affected by wave-particle interactions. The ring current consists of ions in unknown relative abundances from both the magnetospheric tail and the earth's ionosphere. How the ring current is created is presently unknown. The ring current decay is affected by wave-particle interactions as well as charge exchange and Coulomb collisions. Two candidates for the responsible waves are electromagnetic ion-cyclotron turbulence and electrostatic ion loss-cone waves. The cyclotron waves would be expected in the 1-Hz frequency range and the loss-cone ion waves would be expected in the 20- to 300-Hz range.

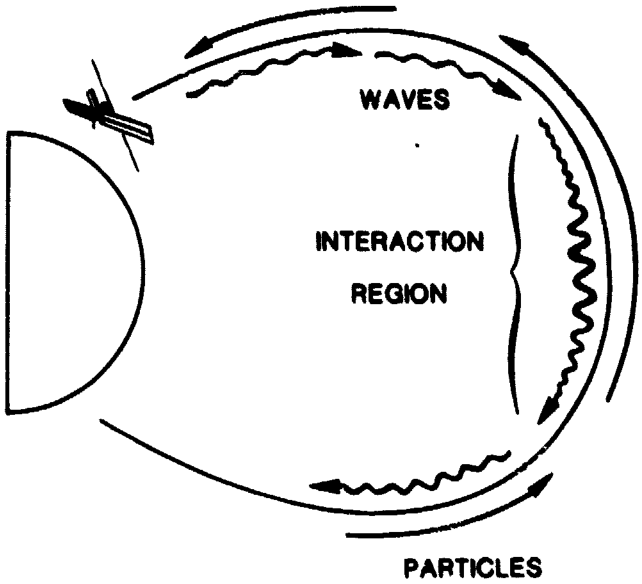

Fig. 7. Wave-particle interactions near the equatorial magnetosphere.

Low-altitude phenomena, such as auroral equatorial electrojets, auroral arcs, and F-layer irregularities, all involve wave-particle interactions. In addition, low-altitude processes can be caused by wave-particle interactions occurring at much higher altitudes. An excellent example is the stable auroral red (SAR) arc, which is produced by the interaction of protons precipitating from the ring current with the earth's plasmasphere. The ion-cyclotron turbulence thus produced is thought to be Landau-damped by electrons in the plasmasphere. The electrons so affected constitute a high-energy tail of the thermal electron distribution, which conducts heat to low altitude, causes the 6300 Å emission from neutral atomic oxygen, and produces upper atmospheric heating. So, even though the wave-particle interaction is occurring in the magnetosphere, it has an important effect in the upper atmosphere.

Many examples of magnetospheric wave-particle interactions have been identified and will be studied *in situ* by ISEE and Dynamics Explorer. However the breadth and complexity of many of these interactions require the addition of controlled probing in which certain particle or wave parameters are actively modified as a way to isolate the different plasma physics processes involved.

Recommended STO Measurements. Two general kinds of measurements from STO will improve our understanding of the wave-particle interactions, which appear to control many of the energy exchange processes in the solar system: performance of active controlled input/output experiments and the *in situ* and remote measurements of naturally occurring wave-particle phenomena. Both measurements require the large structure (antenna) and high-power capabilities of the STO. The evolution of the required measurements will be toward remote sensing of magnetospheric wave-particle features such as turbulence, shocks, and particle instabilities.

Active experiments use STO as the base for performing measurements using the ionosphere and magnetosphere as a giant laboratory. Powerful wave and particle injectors on STO will be used to temporarily modify the natural wave and particle environment so that the desired interactions will occur. The characteristics of the injectors are given in Table 2. As in any laboratory experiment, conditions in the experimental apparatus must be controlled and known. The particles, waves, and quasistatic electric and magnetic fields must be completely characterized by instruments in the interaction region. Remote diagnostics on STO, such as low-light-level television and X-ray images are required to deduce the results of the experiments. Table 2 describes the diagnostic measurements.

The thermal plasma (low-energy plasma) environment also affects wave-particle interactions, and control of that environment will be important. The thermal population in an interaction region near STO could be controllable by plasma generators. Whether controlled or not, measurements must be made of the thermal plasma to determine its characteristics. Plasma measurements required are given in Table 2.

Remote sensing of waves and particles is in its infancy. Waves and particles have been detected from the ground which are thought to have participated in the wave-particle interaction shown in Fig. 7. Other wave-particle interactions have not been remotely sensed. Indirect remote measurements of the waves and particles as they participate in interactions would allow vastly-improved knowledge of the interactions. For example, plasma turbulence should be measured remotely from the STO with coherent-scatter radar. This turbulence is thought to be associated with electrostatic shocks on field lines connected to the auroral regions. These measurements would clarify the role of field-aligned irregularities in auroral particle acceleration.

Table 2. Wave and Particle Experiments.

Injection Type	*Injection Characteristics*
Waves	Variable frequency and amplitude
Particles	Variable energy, species, pitch angle, and current profile
Plasma	Variable density, temperature, species
Measurement Type	*Measurement Characteristics*
Waves	Frequency spectra and wave normal spectra of electromagnetic and electrostatic waves
Particles	Distribution functions of all superthermal particle species
Plasma	Densities, temperatures and flows of species (minimum); thermal particle distribution functions preferred
Fields	All components of quasistatic electric and magnetic fields

In order to obtain measurements over a wide variety of ionospheric and magnetospheric plasma and wave conditions, the STO should be kept in operation at least as long as a few solar rotations. It should be kept in mind that the experiments and measurements described here can be performed simultaneously with experiments and measurements designed to meet other objectives.

Complementary Measurements. The active experiments discussed above involve measurements in the interaction regions that are both near and very far away from the STO. There exists a broad category of active experiments that can be conducted using the STO as a base and subsatellites as nearby diagnostic companions. If the deep magnetospheric probes of the OPEN mission are in operation at the same time, the scientific return will obviously be enhanced because of the ability to measure plasma and wave environments in the very remote interaction regions. In addition, the Interplanetary Plasma Laboratory (IPL) spacecraft would be a valuable aid in planning the active experiments. Data from the IPL would give an indication of future magnetospheric conditions to determine whether the Equatorial Magnetospheric Laboratory (EML) will be in the interaction region during the experiment and will give an idea of the degree of disturbance of the magnetosphere during a planned experiment from STO. Some experiments will require quiet conditions; others will require disturbed conditions, such as those during the recovery phase of a magnetic storm.

3. Magnetosphere-Ionosphere Mass Transport

Objective. *Determine what mechanisms are responsible for the exchange of plasma between the earth's magnetosphere and the ionosphere and atmosphere.*

Overview. The origin and transport of plasmas in the earth's magnetosphere continues to be a fundamental question in solar-terrestrial physics. The varying admixture of particles of solar and ionospheric origin changes continuously in response to changing solar conditions. Two investigative approaches are appropriate to the study of this problem: passive *in situ* measurements, which are part of the ISEE, Dynamics Explorer, and OPEN programs, and active ion injection techniques, which can best be accomplished by the STO. The STO combines high power and remote sensing capabilities with an operational lifetime that is capable of covering a variety of solar and magnetospheric conditions. This combination enables it to make a unique contribution to understanding magnetospheric plasma origins through experiments involving active ion injection.

Background. Beginning more than 20 years ago with the original measurement of the energetic particles trapped in the earth's radiation belts, there has been intensive research directed at gaining an understanding of the processes that supply plasma to the earth's magnetosphere. Early measurements focused on the solar wind as the primary potential source of radiation belt particles, since the source strength provided by the solar wind was roughly commensurate with that required by the particles causing the aurora, and the efficiencies of the processes required to produce the fluxes and spectra observed throughout the magnetosphere from a solar wind source did not seem unreasonable. It was suggested that measurements of the mass and charge composition of particles in the magnetosphere could provide unambiguous evidence regarding the origin of space plasmas because of the widely differing compositions provided by such candidate sources as the solar wind and the ionosphere.

In recent years measurements have shown that plasmas with apparent origin in the ionosphere make up a significant fraction of the magnetospheric plasma. These measurements of particles in the magnetosphere with energies ranging up to many keV, but with a mass spectrum strongly suggestive of an ionospheric source, caused a re-evaluation of our concepts of the origin of the magnetospheric plasma population.

Very recent measurements from the ISEE and P78-2 satellites have shown that in the outer magnetosphere there is a continuum of energies present for those particles with characteristics suggesting an ionospheric origin. A full spectrum of particles (from less than 1 eV to greater than 10 keV) thought to originate from the ionosphere seems to be present. The processes by which these particles are injected from the ionosphere and the steps by which they are energized are described by several alternative theories, which need to be tested. Our present concepts seem to be leading toward a picture of *circulation of mass* in the magnetosphere-ionosphere system: some particles are removed from the ionosphere, energized in the magnetosphere, mixed with particles whose origin is the solar wind, and then precipitated into the ionosphere, where the process may begin anew. Study of the temporal and spatial evolution of artificially injected ions, whose initial phase-space parameters are known, can be used to infer processes that link the magnetosphere and the ionosphere.

Of the several missions planned by NASA in the 1980s in magnetospheric physics, the OPEN program stands out as a comprehensive attempt to study the origin and dynamics of the plasmas in the magnetosphere. Information from the Dynamics Explorer is also expected to shed new light on the question of plasma origins. The OPEN mission will be directed toward the study of these processes through an assessment of the plasma populations entering the magnetosphere from the solar wind and from the ionosphere. The influence of the ionosphere as a source and sink for magnetospheric particles will be studied by OPEN using passive techniques only. The effectiveness of passive techniques can be greatly enhanced through complementary active experimentation, which injects tracer ions from ionospheric altitudes and studies the evolution of such tracers in phase space. Such active experimentation seems possible only through the high power and remote sensing capabilities provided by the STO. For example, ions with unique and unambiguous signatures, such as lithium, might be injected using STO capabilities and traced using both *in situ* and remote sensing techniques.

Recommended STO Measurements. In order to learn about the flow of mass between the ionosphere and the magnetosphere, a program of active experiments should be carried out using the facilities aboard the STO. These include chemical release modules as well as high-power ion injectors. By releasing or injecting tracer ions into the magnetosphere from ionospheric altitudes, one has created test particles whose changing properties are the result of the processes that energize, transport, and store ionospheric material. The atomic mass of the injected ions can be varied as well as their energies and pitch angles. Varying these parameters and tracing the subsequent particle history gives a direct measure of the magnetospheric plasma mixing processes. Such injection of plasma from within the magnetosphere is a direct analog to the injection of plasma from outside the magnetosphere on the AMPTE mission. The ion injection facilities onboard the STO must be supplemented by the capability to perform diagnostics (1) aboard the STO, and (2) in close proximity to the STO via suitably instrumented maneuverable and recoverable subsatellites and (3) remote diagnostics so that the composition of the ionosphere on the same magnetic field line as the STO can be determined via spectroscopy. Such a determination is required in order to define the boundary conditions governing the active experiments we propose. In addition, (4) the tracer ions should be measured throughout the magnetosphere, in as many locations as possible, including measurements in the solar wind ahead of the magnetosphere. This last would be extremely useful in that the "state" of the magnetosphere could be characterized, and active experiments could then be performed under well-defined magnetospheric conditions. The level and complexity of the diagnostics described above will, of course, depend on the details of design and outputs of devices discussed below in the Magnetospheric/Ionospheric Instrumentation section. None of the diagnostic requirements appears to stress existing technology.

Given the local and remote-sensing diagnostic capabilities of STO sketched above, its evolutionary growth can be envisioned in terms of two levels of capability. These are outlined in Table 3. The left column gives capabilities of STO for minimum and optimum levels. The right column indicates how these capabilities are to be used for specific measurement programs. The minimum STO uses electron and ion accelerators to generate effects that it can observe itself *in situ* and through remote sensing. The optimum STO has enhanced power capabilities.

Complementary Measurements. Several complementary capabilities would greatly augment those of the STO itself. The most important is that of chemical releases carried out separately from the STO, whose effects can be measured directly and by remote sensing from STO. Such effects can also be measured by remote sensing from the ground and balloons. It is also obvious that *in situ* measurement of ions injected from the STO, at remote locations throughout magnetosphere, is highly complementary. Such an augmentation of the STO capabilities would be possible if the OPEN mission were in operation. The basic STO capabilities would also be augmented by chemical releases from rockets and by ionospheric heating from ground-based radars.

Table 3. Active Magnetospheric/Ionospheric Experiments.

STO Capabilities	*STO Measurements*
Minimum	Using STO local wave and particle diagnostic capibilities and remote sensing/imaging capabilities, measure how identifiable sets of particles are affected by naturally occurring wave, particle, and field environment over a range of magnetospheric activity. Use STO capabilities to monitor ground based experiments related to ionospheric modifications.
A. Electron and Ion Acceleration -variable energy (100 ev < E < 100 keV) -variable species (e. p, He^+, He^{++}, N^+, O^+, Xe^+) -various pitch angles -controlled pulse shape, pulse pattern	
B. Chemical Release Techniques -gas releases -shaped charge releases	
C. Remote Sensing/Imaging -high spectral resolution imaging in visible and near UV -reconstruct velocity profiles of chemical releases using lidar	
D. Local Particle Diagnostics -ion and electron distribution functions -both injected and natural particles -high accuracy (~1%) in pitch angle distribution	
Optimum	Increase power levels sufficiently to alter properties of ionosphere. Study ionosphere-magnetosphere coupling as function of controlled properties of ionosphere. Carry out controlled modification of ionosphere over a range of magnetospheric and solar activity.
A. Increase power levels of particle acceleration	

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4. Global Electric Circuit

Objective. *Determine the nature and variability of the global electric circuit and its role in the chemistry and energetics of the atmosphere.*

Overview. Early concepts of the atmospheric electric circuit have given way to a broader view that encompasses the atmosphere, ionosphere and magnetosphere. Correlated measurements of the elements of this global circuit are in their infancy. In order to advance our understanding, a broad collection of observations must concentrate in particular on the relationship of changes in the ionospheric potential distribution to changes in the lower atmospheric electric field. The STO provides a combination of accommodations for observing the global electric circuit that are not available through traditional free-flyers or Spacelab. The combined capabilities of STO for remote sensing, high-power active experimentation, and tethered subsatellites would be enhanced further by coordination with measurements from free-flyers, the ground, airplanes, and balloons.

Background. The global electric circuit, driven in part by thunderstorm currents, in part by fields generated within the magnetosphere, and in part by the interaction of the solar wind with the magnetosphere, has been postulated to play a very important role in connecting the atmosphere, ionosphere, and magnetosphere. Until very recently, the various components of this global electric circuit had only been considered and studied separately. Historically, the greatest attention has been paid to electric fields in the lower atmosphere, where, according to the "classical picture" of atmospheric electricity, the totality of thunderstorms acting together at any time charges the ionosphere to a potential of several hundred thousand volts with respect to the earth's surface, as shown schematically in Fig. 8. This potential difference drives a vertical electric current downwards from the ionosphere to the ground in all nonthunderous or fair-weather regions. The fair-weather electric current varies according to the ionospheric potential and the total column resistance between the ionosphere and the ground.

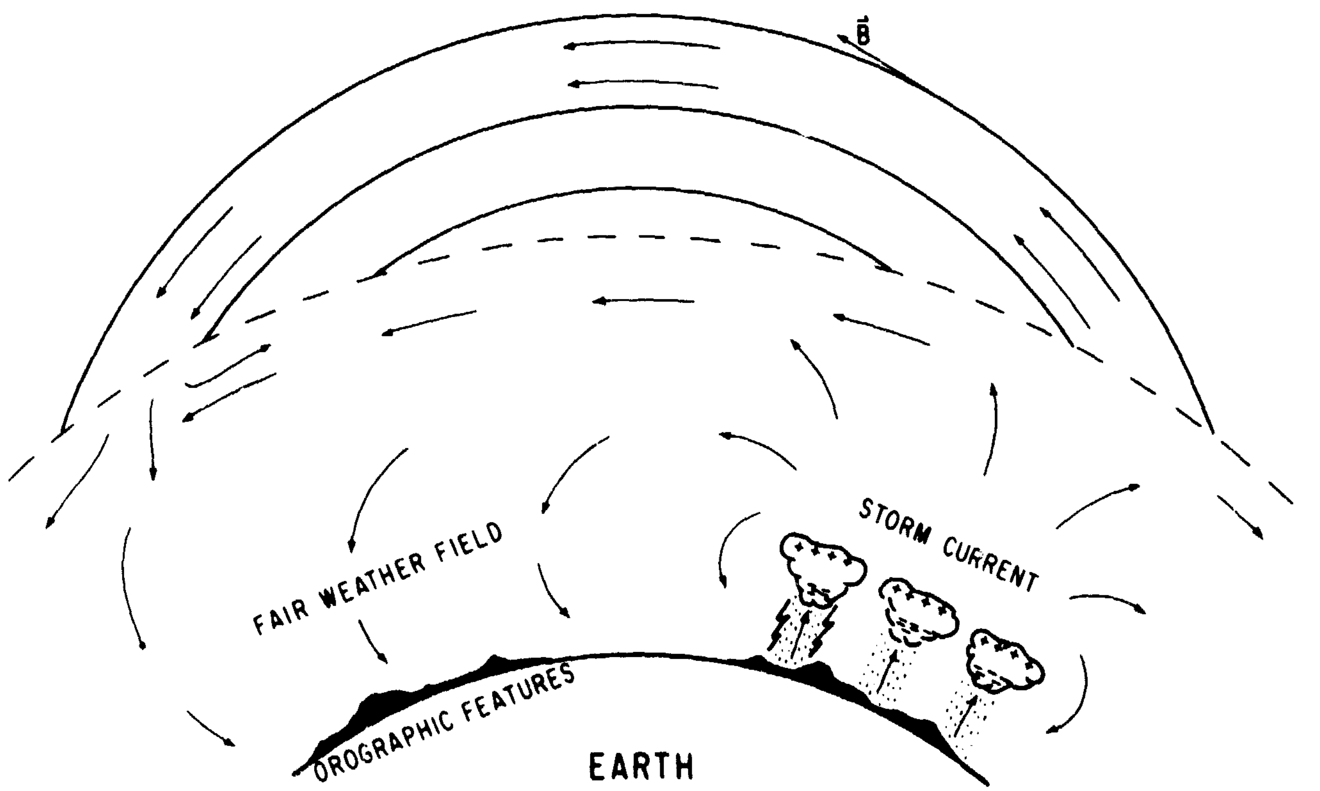

Fig. 8. A schematic model of the global electric circuit (from Hayes, P.B., and Roble, R.G., 1979: *J. Geophys. Res.* ***84*****, 3291).**

In the past it has been assumed that the "upper electrode" of this global electric circuit has the same potential at all latitudes and longitudes. The atmospheric electric equalizing layer of this classical picture is located in the mesosphere, where, within a relatively short vertical distance, the conductivity increases by orders of magnitude, thus constituting a quasi-electrode. Recent studies have suggested that it may be important to consider the large horizontal potential differences which are known to be present at ionospheric heights. Some of the major sources of these potential differences are the various ionospheric dynamo systems and the high-latitude generator associated with the magnetospheric convection fields.

The magnetospheric convection electric field is caused by the interaction of the solar wind with the magnetospheric cavity. This interaction causes the plasma deep in the magnetosphere to circulate. The electric field arising from this plasma circulation is mapped down to the ionosphere along magnetic field lines, which are usually good conductors. The mapping of the magnetospheric electric field onto the ionosphere is not perfect. In some regions, the magnetic field lines are not good electrical conductors and parallel electric fields arise. The potential drops appear to be distributed along the field lines and to extend to high ionospheric altitudes. However, this has not been shown unambiguously, nor do we know what process leads to the breakdown in the electrical conductivity.

The cosmic ray flux that bombards the earth's atmosphere produces the ionization that maintains the electrical conductivity of the atmosphere below about 60 km. This cosmic ray flux varies with magnetic latitude due to magnetic shielding of particles by the earth's magnetic field. During solar proton events, magnetic storms, and Forbush decreases, the bombarding cosmic ray flux is modulated by processes in the heliosphere.

We are just beginning to assemble information on the contributions of the different circuit elements to the overall global electric circuit. Of primary importance is the testing of the postulated linkage between the electric fields present in the lower atmosphere and those of the ionosphere, which in turn are closely linked to the magnetosphere. Are there thunderstorm signatures in the ionospheric convection patterns? Do large magnetospheric storms affect the fair-weather electric field? Do solar flares cause direct changes in the ionospheric potential and the air-earth currents? All of these questions are part of a larger problem of determining the linkages that contribute to the global electric circuit.

Recommended STO Measurements. STO observations of the global circuit will be very exploratory in nature. A key element to be determined initially is the relationship between changes in the magnetosphere and ionospheric potential and changes in the tropospheric electric field. This implies a need for coordinated measurements of electric fields from or near STO using subsatellites, chemical releases, and the tethered particles and fields probe and in the lower atmosphere using ground-based, tethered balloon, balloon, and aircraft electric field, current, and conductivity measurements. One series of experiments might look for changes in the ionospheric electric field near STO during the occurrence of thunderstorms below or at the conjugate point to STO. A corollary experiment might search for changes in the tropospheric electric field in the tropics during disturbed magnetospheric conditions or following solar flares observed by STO. Direct STO measurements of precipitating magnetospheric energetic particles and the effects of solar proton events can be compared with changes in the fair-weather electric field and currents or the ionospheric potential.

It is also possible to develop a series of information sets on other elements of the global circuit. These include remote probing of parallel potential drops using chemical releases and particle injection, multipoint measurements of field-aligned currents from subsatellites, two-dimensional measurements of electric field patterns using a coherent-scatter radar on STO, and tethered satellite measurements of currents closing through the E region. A final stage of the measurements could involve the active modification of the circuit using chemical releases or electron beams to change the ionospheric conductivity. Throughout these measurements the low-altitude electric field, currents, and conductivity would be continuously monitored in a coordinated manner.

Measurements of the dawn-dusk potential difference along the orbital path should be conducted from the STO and compared with measurements in the lower atmosphere. These measurements can be correlated with interplanetary measurements, and used to test theories of their relationship. From an advanced STO, lightning occurrence measurements should be made and compared with STO electric field measurements. These measurements, combined with those of operational meteorological satellites, will permit studies of the relationships between solar flares, thunderstorms, and world-wide cloudiness. STO contributes key capabilities for all these studies.

Complementary Measurements. The STO can make major advances toward this objective on its own. However, various supporting measurements would appreciably enlarge the value and scope of the studies. Complementary measurements should be made of the lower atmospheric electric field, from the ground, tethered and free-flying balloons, and aircraft. In the ionosphere, subsatellites and multiprobes should be used in conjunction with STO chemical releases and remote sensing. The interplanetary and solar measurements described in Objective 1 should be made to determine the solar and interplanetary parameters associated with atmospheric and magnetospheric electric field perturbations. Operational meteorological satellite data can be used for global cloud cover information. Electric fields across the polar cap as measured by a series of barium releases can be compared with aircraft measurements of the tropospheric electric field below. Finally, measurements of the particle population from STO can be combined with cosmic ray data from the ground and a companion spacecraft in the interplanetary medium. These flux measurements will then be used to calculate the height, latitude, and time variations of electrical conductivity and space charge deposition rate to evaluate their effect in perturbing the global electric circuit.

5. Upper Atmospheric Dynamics

Objective. *Establish the nature of the dynamic response of the upper atmosphere to solar-induced changes in the energy and momentum input.*

Overview. The motions of the upper atmosphere are dramatically influenced by changes in the energy input from the sun, both directly and by way of the earth's magnetosphere. Through remote sensing, the STO will be able to observe the major inputs to the upper atmosphere over large areas of the earth while also observing the heating and winds that constitute the atmosphere's dynamic response. The STO combines the capabilities of simultaneous solar and terrestrial pointing, considerable instrument size, and long duration to cover a variety of solar and magnetospheric conditions.

Background. The upper atmosphere responds dynamically to variations of the solar irradiance, the solar wind, and energetic particles. Solar irradiation influences the conductivity and heating of the thermosphere. The irradiation varies on a wide variety of time scales, down to even a few seconds. While the earth's ionosphere is known to respond to these variations down to the shortest time scales, the variations of interest for this objective are on scales of roughly tens of minutes or greater.

In addition to the solar radiative output, the behavior of the solar wind is also relevant to this objective, because of its interaction with the neutral atmosphere through the magnetosphere. Variations in the solar wind speed and magnetic field direction incident upon the magnetosphere occur both because of the structure of streams in the solar wind as they are swept past the earth by solar rotation and because of transient perturbations in the solar wind caused by stream-stream interactions, solar mass ejection events, and solar flares. Thus, both the interplanetary field direction and the solar wind velocity are a result of coronal magnetic structures that were originally present at the sun and propagated to earth.

The earth's magnetosphere is a link in the transfer of solar wind perturbations into the upper atmosphere. The magnetospheric energization effects in the upper atmosphere are caused by two primary processes -- particle precipitation and Joule heating.

The solar wind induces a dynamic circulation within the magnetosphere. This circulation causes a motion of the magnetospheric plasmas which can lead to their energization and subsequent precipitation, leading to direct heating of the atmosphere owing to a variety of inelastic processes. The spatial and temporal variations of the precipitating particles have not been routinely observed over broad spatial areas of the auroral oval. It is this large-scale deposition of energy that is instrumental in thermospheric heating.

In addition to the modification of energetic particle dynamics, the solar wind also drives the drift motion of the ionospheric particles of the E and F region. In the high-latitude auroral region, these particles can reach velocities of 1 km/s or more driven by strong electric fields resulting from solar wind influences. At thermospheric altitudes the drifting ionospheric particles collide with the atmospheric neutrals, resulting in heating and consequent neutral winds. This heating process can be comparable in magnitude to the direct particle-precipitation-induced heating of the auroral ovals and can thus strongly affect thermospheric dynamic processes. As in the case of the precipitating particles, the spatial and temporal variations of the Joule heating during different solar wind and hence different magnetospheric conditions are not well known. The accurate understanding of the atmospheric response is dependent on knowing the distribution and changes of this energy source.

The unperturbed mean meridional circulation and latitudinal temperature structure in the thermosphere are

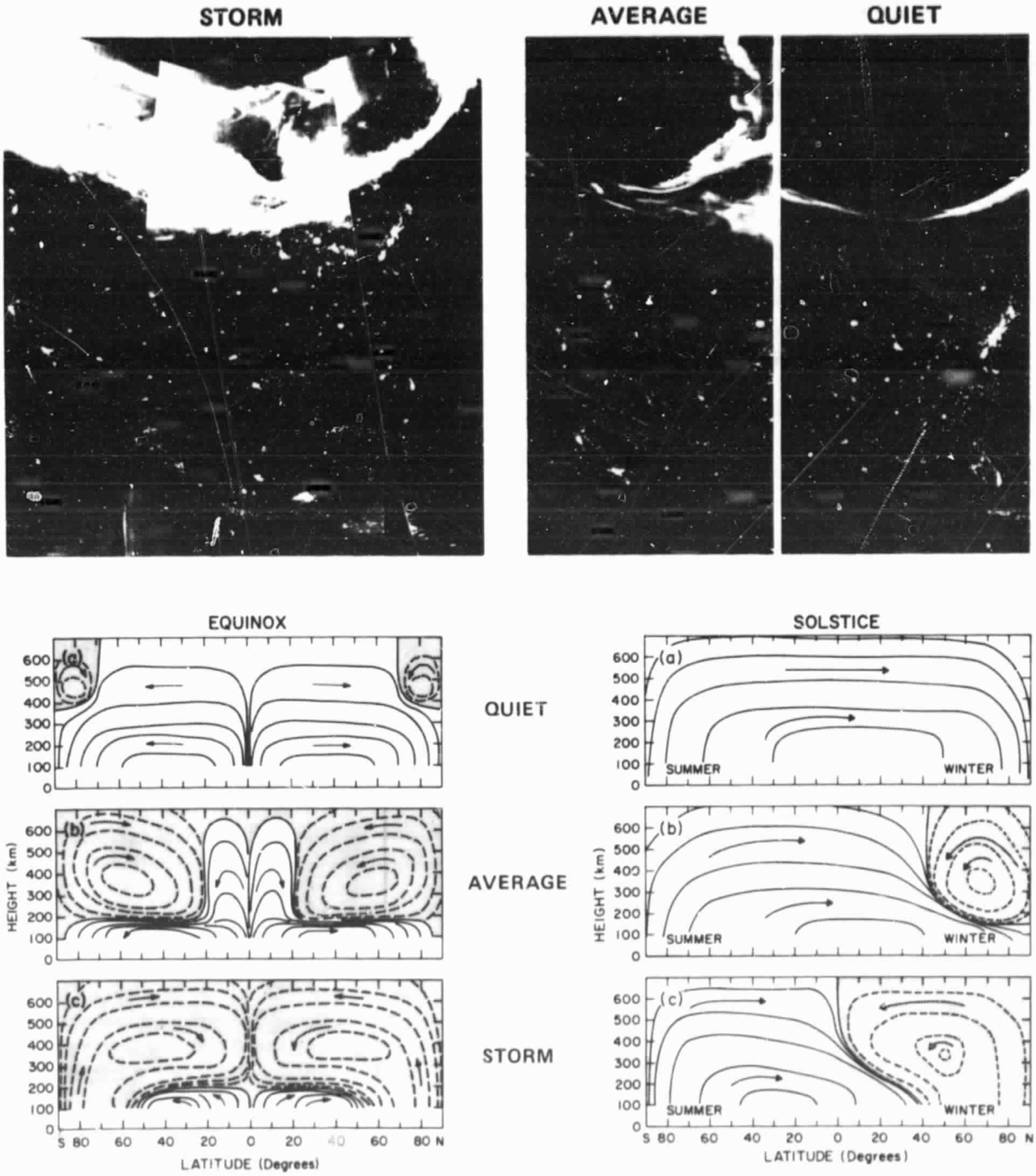

Fig. 9. Effects of geomagnetic storms on thermospheric winds. Corresponding auroral structures (above) and wind patterns (below) are shown. The shaded areas indicate wind directions, opposite to those driven by solar EUV and UV heating alone, which are caused by plasma convection and particle precipitation.

primarily controlled by heating due to the absorption of solar EUV and UV radiation. However, this basic structure is perturbed by the heat and momentum sources derived from the interaction of ionospheric plasma convection and auroral particle precipitation with the earth's atmosphere. Rather simple modeling efforts guided by experimental measurements have led to a crude understanding of the mean meridional circulation in the thermosphere (see Fig. 9). If only solar heating is used to drive the thermosphere in these models, as might occur during very quiet geomagnetic periods, the mean circulation during equinox is from the subsolar point over the equator to high latitudes. For average geomagnetic activity, a high-latitude heat source associated with auroral activity (i.e., Joule and particle heating) is superposed upon the basic solar heating distribution. During equinox, the high-latitude heating is found to be sufficiently large to reverse the direct solar-driven circulation above about 150 km to 40° latitude.

Models of the thermospheric mean meridional circulation, guided by experimental results, suggest that the global high-altitude energy input varies by a factor of about 4-5 between solar minimum and solar maximum and that there is 2-3 times more auroral heating in the summer hemisphere than in the winter. These modeling results also show that the high-latitude energy input is redistributed globally by dynamical processes before being conducted downward to the vicinity of the mesopause. Direct information about high magnetic latitude energy input due to auroral and high-latitude processes along with information about the ultimate disposition of this energy is sparse, however.

The rather spotty thermospheric measurements that have been made so far reveal various phenomena that are probably of global importance. However, these measurements suffer greatly from a lack of global coverage. What is needed to achieve understanding of upper atmospheric dynamics is a more *global* set of wind measurements, including both diurnal effects and disturbed conditions, at several heights within the thermosphere. These will make a major step toward understanding what happens to the solar energy put into the terrestrial system and how it couples through the magnetosphere into upper atmospheric dynamics, chemistry, and radiation.

There now exists a theoretical understanding of thermospheric dynamics that goes beyond the simple longitudinally averaged picture of Fig. 9. Predictions exist of how wind systems depend on latitude, longitude, and nonsteady heating. What is needed to test these theories is a global observing capability. This is now possible, through the unique capabilities of the STO.

Recommended STO Measurements. The origin of Joule and particle heating as well as the atmosphere's dynamic response entails measurements of the sun, the magnetosphere, and the earth's atmosphere.

Since the energetic chain begins at the sun, measurements of both the sun's electromagnetic energy and corpuscular output are required. Measurements of the solar irradiance at wavelengths shorter than 2300 Å, the range of importance to mesospheric and thermospheric heating should be made. The EUV irradiance at wavelengths from 100 to 1030 Å is doubly important since it both ionizes and heats the thermosphere. Measurements to link the magnetosphere to the interplanetary medium obviously cannot be made from the STO, but require the complementary measurements discussed below.

The measurement program to understand the role of the magnetosphere in the global determination of the energy deposited in the upper atmosphere by particle precipitation and Joule heating can best be accomplished through the use of remote sensing techniques, which have first been calibrated through simultaneous remote sensing from STO and *in situ* measurements from subsatellites. Later, the visible and ultraviolet spectral images of the aurora which are obtained from the STO can be used to infer the particle spectral characteristics and pitch-angle distributions. From the STO, two-dimensional mosaics of the aurora can be built up, as a function of position and time. These images then provide a spatial and temporal measurement of the energy deposition by precipitating particles.

The determination of Joule heating characteristics follows a similar approach, through remote sensing measurements that have been calibrated through *in situ* subsatellite measurements. In this case, the remote sensing is accomplished through coherent-scatter measurements made from the STO. These radar measurements are used concurrently with the optical measurements to study broad swaths adjacent to the orbital track. The optical spectral signatures give information on the precipitating particle spectra, from which a vertical ionospheric density profile and hence conductivity model can be derived. The radar measurements of the ion drift give a two-dimensional distribution of the perpendicular electric fields in the same spatial area. Finally, the ion drift and particle precipitation information are combined into a mosaic which builds up a spatially and temporally evolving picture of the large-scale energy depostion, thus providing a global picture of the energy input.

A final element of energy input studies in the atmosphere concerns the measurement of very high energy particles during polar cap absorption (PCA) and relativistic electron precipitation (REP) events. Here, direct measurements of the spectra of the 100 eV - 5 MeV electrons and 10 keV - 100 MeV protons are combined with imaging of the bremsstrahlung X-rays (10 keV - 1 MeV) to determine to extent of the energy input. Spatial coverage of the PCA events is limited to discrete measurements along the satellite track while the X-ray information covers a two-dimensional area.

Finally, the response of the atmosphere to the changed solar and magnetospheric inputs must be measured. This is done through interferometric remote sensing of the profiles of a variety of ultraviolet, visible and infrared emission lines. The interferometer is scanned both parallel and perpendicular to the earth's limb. From the emission line measurements, the temperature and velocity will be determined, with the desired resolution in temperature (a few K), height (a few km), and velocity (a few m/s). In this way one measures over a wide swath near the STO orbit the temperature and wind response that is due to the measured changes in the EUV and UV solar output, precipitating particles, and currents.

Along with the dynamic effects, chemical changes take place, which can also be measured from STO. These are discussed primarily in Objective 6. However, we mention here the value of STO measurements of nitric oxide and atomic nitrogen, which are very important not only for chemistry, but also for dynamic solar-terrestrial processes. STO will be able to measure the particle influx, the amount of NO produced, the transport of NO by the wind system generated by the auroral activity and magnetospheric convection, and finally the cooling of the auroral regions by NO radiation.

With the STO it will be possible to do a particularly good job of determining how far down into the atmosphere (say the ionospheric E-region or the D-region) auroral forcing of neutral dynamics is important. Determinations can be made of whether these E region effects are confined to high latitudes or are more global in nature. More importantly, STO will be able to provide enough simultaneous solar and magnetospheric data to determine *why* the observed effects occur.

The measurements for this objective must be carried out over a long period of time in order to determine the atmospheric response to the broad variety of magnetospheric conditions induced by changing solar events. It is insufficient to depend on separate flights of short one-week periods to cover these broad, changing solar conditions.

Complementary Measurements. The energy input and the atmospheric response can obviously be measured adequately from STO alone. It would, however, enhance the scientific return if the more coarse global auroral imaging systems on Dynamics Explorer and OPEN could be brought into play. These continuous global images would complement the high-resolution images made from STO. In addition the IPL spacecraft from OPEN could measure the changing solar wind parameters as advance warning for changing energy input conditions. Ground-based coherent and incoherent scatter radar facilities would be most complementary to the STO measurements, since they sweep out a changing local time view of the auroral oval as compared to the changing latitudinal mosaic view from the STO orbit. Finally, ground-based measurements (riometers and optical instruments, for example) will help in determining the morphology of the very high latitude energy input.

6. Middle Atmospheric Chemistry and Energetics

Objective. *Determine the effects of changes in the solar energy input on the chemistry and energetics of the stratosphere, mesosphere, and lower thermosphere.*

Overview. The chemistry of the middle atmosphere is very sensitive to both solar radiative inputs and cosmic, solar, and magnetospheric particle inputs. From the STO one can sense both these inputs and their terrestrial consequences over major areas of the earth. The measurements for atmospheric chemistry call for instrumentation of considerable size and mass. The STO makes it possible to place such instruments in orbit long enough to sample a wide variety of solar-terrestrial events, as well as to observe the solar and magnetospheric energy inputs simultaneously.

Background. Major changes in the flux of energetic particles into the upper atmosphere and changes in the ultraviolet radiant input from the sun can significantly perturb the delicately balanced chemistry and energetics of the upper atmosphere. The steady-state energetics and chemical composition of the upper atmosphere at low latitudes are determined almost entirely by the solar radiant input at UV and visible wavelengths. Solar and galactic energetic particle inputs play a rather minor role. However, perturbations from major energetic particle precipitation events can be of comparable magnitude to those occurring as a result of changes in the solar radiant input. For this objective we describe the deposition of UV solar radiation and both solar and magnetospheric energetic particles, as they affect primarily the perturbations to the steady-state chemistry of the stratosphere and mesosphere. Of course, the energetics, chemistry, and dynamics of the atmosphere are closely coupled, but for purposes of discussion we focus on chemistry and energetics.

Molecular oxygen dominates the absorption of solar ultraviolet radiation from the lower thermosphere down to the stratosphere. The photodissociation of oxygen and ozone is thus directly related to the intensity of the shortwave solar radiation from X-rays through 3100 Å. The current state of knowledge of the spectral variability of the solar UV and EUV radiation, and the relationship between these variations and solar activity, have been reviewed under Objective 1.

Sources of ionization in the upper atmosphere are important in the energetics and the chemistry of the minor species. Large variations in the ionization may also affect aerosol formation in the stratosphere and modulate atmospheric electricity through conductivity variations. Our understanding of this aspect of the response of the atmosphere to its energetic environment is in a relatively early stage. It is important to determine, for the middle atmosphere as a whole, the relative significance of the ionization rates from the steady-state (quiescent) sources and to compare these with the response of the atmosphere to transient phenomena. The energy ranges of interest here are radiation from short UV wavelengths to X-rays, electrons from about 10^4–10^7 eV, and protons with energies $\geq$ 10 MeV. The ionization, which is strongly dependent on latitude and altitude, results from solar UV radiation, nonflare and flare-associated solar X-rays, magnetospheric electron precipitation, X-ray bremsstrahlung, and solar and galactic cosmic rays. These inputs have both steady (quiet) levels and major variations.

Dramatic effects occur due to both direct solar radiative inputs from flares and precipitation of electrons from the magnetosphere. Large fluxes of solar flare protons (with energies >10 MeV) cause prolonged, intense ionization at all altitudes from the stratosphere to the thermosphere over the polar regions. The ionization rates during solar proton events are far in excess of those from any other sources from the mesopause down to the lower stratosphere. A feature of the resultant ionization rate profiles is that the maximum occurs at altitudes that vary between 40 and 80 km, suggesting that the energy distributions of individual events may vary considerably. This may result in significantly different effects in terms of the persistence and propagation of the chemical impact of the event.

The dominant chemical processes occurring throughout the stratosphere, mesosphere and lower thermosphere involve oxygen and ozone. Ozone is produced as a result of the combination of oxygen atoms and oxygen molecules in the presence of a third molecule, nitrogen or oxygen. The ratio of atomic oxygen to ozone is a key characteristic of the differences in the chemistry and transport effects that occur in each of the altitude ranges of interest.

The catalytic cycle involving hydrogen is of particular interest, since it can be significantly modified under conditions where the solar or energetic particle input undergoes a major change.

Recommended STO Measurements. In order to test for perturbations to the steady-state chemistry, simultaneous measurements of O_3 and the reactive nitrogen species should be made through the stratosphere and mesosphere, and of O_3 with the water-related species through the mesosphere and lower thermosphere. In addition, the O_3 photolysis rate in the mesosphere and thermosphere should be monitored, by measuring the emission from excited-state molecular oxygen ($^1\Delta_g$) and OH respectively. The ozone concentration can be measured up to ~70 km by the now standard method of inversion of its 9.6 μm limb radiance, and by high-resolution occultation or limb emission observation for altitudes up to ~100 km. The stratospheric NO abundance can be observed from the 5.3 μm fundamental in the ground state, and the excited vibrational states used for NO in the upper mesosphere and lower thermosphere. The measurement of NO_2 (0.44 μm and 6 μm band absorptions) together with O_3 will give the destruction rate of odd oxygen in the region of the peak ozone abundance. Water vapor can be measured by broadband limb radiance inversion (6.3 μm band) up to ~60 km; with moderately high spectral resolution the altitude range can easily be extended to the lower thermosphere. These measurements differ from those to be made on the Solar Mesospheric Explorer (SME) in the greater range of species to be monitored and particularly in the extended altitude range (into the lower thermosphere) of the STO measurements. The individual species to be monitored are summarized in Table 4; in conjunction with these, the temperature and wind field and the radiant and energetic particle input should also be measured as discussed under other objectives.

Table 4. Summary of Recommended Measurements for Middle Atmospheric Chemistry and Energetics.

1. Solar radiation, energetic particles (See Objective 1)
2. Temperature: global, 20-120 km, Δz = 2 km; ΔT = 2 K.
3. Winds: Horizontal component, Δu = 5 m/s (See Objective 5)
4. Atmospheric radiation:

Species	Wavelength Range (μm)	Objective
O_2	1.27, 1.68	Photolysis rate
O_3	9 - 11	Chemistry, Energetics
OH	1.5 - 4	Chemistry, Energetics
H_2O	6.5 - 25	Dynamics, Chemistry
NO	5.3, 2.8	Chemistry, Exchange Procedures
NO_2	0.4, 6	O, O_3 Destruction
CO	4.7	Dynamics, Energetics
CO_2	2.8, 4.3, 10.6, 15	(Temperature), Energetics, Dynamics

The effects of transport on the local chemical balance in the region of the mesopause can be determined from high-spatial-resolution measurements of the vertical distribution of H_2O and CO. Important indicators of the vertical (eddy) circulation of C, H, and O, its effects on the photochemical equilibrium, and changes to the balance that may occur from energetic events, can be gained by monitoring the profiles of the pairs of related species CO and CO_2, H and H_2O, O and O_2 in the region across the mesopause into the thermosphere.

For energetics of the mesosphere and the thermosphere, measurements should be made of the emission from the many infrared vibration-rotation bands of CO_2 and O_3 that can provide the radiation paths for the removal of absorbed solar energy. Also important as an indicator of the complex dynamics and energy exchange processes taking place in this region of the upper atmosphere is the OH chemiluminescence (airglow) which radiates over a wide wavelength range in the near-infrared. The OH emission, which results from the reaction between atomic hydrogen and ozone molecules, shows variability in intensity and spectral structure in response to geomagnetic activity, but the detailed mechanisms of the energy transfer are not known. As mentioned earlier, the oxygen airglow, which is produced by dissociation of O_3 (Hartley bands) and radiates at altitudes above about 50 km, provides a direct indication of the rate of ozone photolysis. Observations of these emissions throughout the mesosphere and lower thermosphere, together with monitoring of the radiant and particulate energy input, should lead to a clearer understanding of the detailed energetics of the upper atmosphere. An overall summary of these measurements is given in Table 4.

Complementary Measurements. The complementary measurements appropriate for this objective are the same as those for Objective 5.

7. Lower Atmospheric Turbidity

Objective. *Establish the nature of the relationship between the variable solar input and the properties, extent, and radiative effects of aerosols and clouds in the lower atmosphere.*

Overview. Atmospheric turbidity (aerosols and thin clouds) may be affected significantly by changes of ionization or ultraviolet radiation in the lower atmosphere. These changes may be caused by solar activity directly or indirectly through stratospheric ozone. The relationships among these quantities lack observational verification. This objective requires at least several months of observation of the solar radiative input and lidar measurements of atmospheric aerosols and clouds. The STO provides the necessary combination of long-duration operation with the high power and volume required by the lidar.

Background. The radiative balance of the atmosphere is substantially affected by its turbidity, which is produced by various sources. If atmospheric turbidity is significantly affected by solar activity, the turbidity variations may provide a connection between solar variability and lower atmospheric energetics. Figure 10 illustrates some paths by which this connection might possibly occur.

Cirrus clouds are an essential component of the path on the left-hand side of Fig. 10, in which solar activity changes the flux of ionizing radiation, which affects cirrus cloud formation. Changes in the clouds' radiative effects might then alter pressure and circulation over large regions of the atmosphere. Neither this chain of interactions nor any of its major links has yet been demonstrated to occur with the necessary frequency to be a significant sun-weather link. For example, the only solar influence on ionization that has been shown to extend so deeply into the atmosphere with sufficient frequency and strength is solar modulation of galactic cosmic rays. The increased protons and X-rays emitted directly by the sun during solar active periods are expected to be insignificant as a sun-weather link, because they very rarely penetrate to the tropopause. Another possible means of solar influence on near-tropopause ionization is downward transport of ions

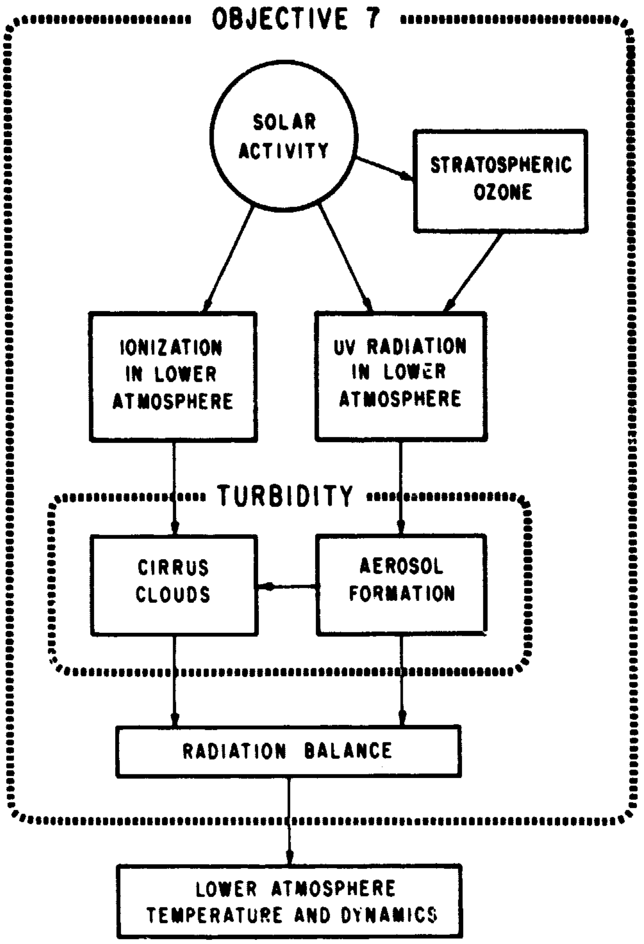

Fig. 10. Possible links between solar activity, turbidity, and lower atmospheric energetics. Objective 7 is contained in the outer dashed box.

generated higher in the atmosphere. This possibility cannot be ruled out, but its time scale and ultimate effectiveness remain to be evaluated. The link between ionization and cirrus cloud formation also remains to be demonstrated.

The alternate path on the right side of Fig. 10 may provide a solar-cirrus connection that does not depend on ionization. It depends on a solar-induced change in lower-atmospheric ultraviolet irradiance, which would in turn affect those atmospheric aerosols (stratospheric, urban, vegetative) that are in part formed from photochemically active precursor gases. The magnitude of the effect of irradiance-induced aerosol variability on the radiation balance or on cloud formation has not been studied quantitatively.

The last major link of the paths considered here is between cirrus clouds or aerosols and the earth-atmosphere radiative balance. Cirrus and aerosol radiative effects can be significant in both the solar ($\lambda \geqslant 3$ μm) and terrestrial ($\lambda \leqslant 3$ μm) parts of the spectrum. For the common case of horizontally extensive cirrus or aerosol layers, current radiative transfer models can predict these radiative effects if they are given sufficient inputs on the cirrus or aerosol optical properties (i.e., spatial and temporal extent, optical thickness, and particle composition, phase, shape, size distribution, and orientation). However, obtaining an adequate specification of these optical properties for given regions and periods has been essentially impossible in the past. (See Measurements section below.)

The nature, extent, and radiative effects of aerosols and clouds are the subject of several current and planned NASA missions. Current and planned sensors of stratospheric ozone are also of interest to this objective, because of ozone's role in determining tropospheric ultraviolet radiation and the role of UV in determining aerosol precursor gas concentrations. However, STO is unique in its attempt to document links between solar variability and lower atmospheric turbidity, or indeed even to make a systematic global survey of tropospheric aerosols and tenuous clouds. STO will build on other missions and programs in two principal ways: (1) by combining the solar-variability-oriented and atmosphere/radiation-oriented measurements and analyses; (2) by providing long mission duration, as required to develop the large data base necessary for confirming a solar-induced "signal" among the vast amount of "noise" created by other atmospheric influences on turbidity and radiation.

Recommended STO Measurements. To establish whether or not there are significant links between solar activity and lower atmospheric turbidity, STO will make measurements from the sun to the lower atmosphere.

Table 5 lists the measurements required for Objective 7, grouped into minimal, improved, and optimal sets. The table is largely self-explanatory, but the following points should be noted.

For the solar output and magnetospheric precipitation subsets of the *minimal* set, specific particle types and energies have not been listed, because accurate determination of the necessary ranges requires careful study of the existing data on particle fluxes and ionization profiles, plus calculations that link the two. Such a study should be conducted before making the final determination of flight hardware.

Table 5. Summary of Recommended Measurements for Lower Atmospheric Turbidity

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Minimal Set

Solar Radiation. Measure the solar electromagnetic radiation in the wavelength range 2900 to 3500Å. Accuracy: 10% in spectral intervals of $\Delta\lambda \approx 50$Å.

Magnetospheric Precipitation. Measure fluxes of high-energy electrons.

Aerosols and Thin Clouds. Altitude Z = 0-20 km; ΔZ = 1 km. Measure vertical position and horizontal extent, optical density in visible and infrared. Sensitivity: to detect layers of optical thickness $\delta \geq 0.01$.

Earth Radiation Budget. Measure incoming and outgoing radiation in broad and narrow spectral bands of the solar and terrestrial spectrum (as with ERB sensors). If possible match field of view to aerosol and cloud measurements. Accuracy: 0.5%.

Improved Set, add

Stratospheric Ozone. Measure column content, C, above tropopause. Accuracy: $\delta C \sim 0.01$ atm cm. This accuracy permits determining the transmission, $T(\lambda)$, to an accuracy of ~10% at λ = 3000Å.

Optimal Set, add

Temperature, Humidity, Pressure. Z ~ 0 to 30 km; ΔZ = 1 km. Accuracy: 1°C, 10% relative humidity, 1 mb.

For aerosols and thin clouds, the requirement for 1-km vertical resolution stems from the fact that these constituents frequently form (and persist) in such thin layers. Similarly, the requirement to detect optical thicknesses of 0.01 comes from the need to observe turbid layers in their earliest formative stages, when they are very tenuous.

The minimal set of measurements listed in Table 5 would provide an improved data base in which to search for correlations between solar activity and aerosol and cloud behavior, plus an improved data base on directly measured radiative effects of aerosols and thin clouds. However, improved measurements would be required to test specific links in the proposed chains and to understand the physical bases for any observed correlations. The additional measurements listed in the *improved* set would quantify the ultraviolet variations available to influence aerosol formation.

In the *optimal* set the requirement for vertical resolution of 1 km stems from the fact that aerosol and cloud layers are frequently this thin, and they interact with temperature and pressure differences on such a fine vertical scale.

Finally, because there are many factors that affect aerosol and cirrus formation independent of solar activity, any survey type of study (as enabled by the minimum measurement set) requires a long data base initially of at least several months, in order to confirm a solar "signal" in the vast amount of natural "noise."

Complementary Measurements. Though STO itself can carry out the measurements of the minimal set well, complementary measurements made from other spacecraft, the ground, and the atmosphere will serve a useful purpose. Interplanetary measurements of high-energy particles will support STO measurements of precipitating particle fluxes, to help test some particulate ionization mechanisms. Ground-based cosmic ray monitors test another ionization mechanism. Lidars and radiometers in airplanes (or failing that, on the ground) provide a ground truth measurement of aerosol and cloud profiles and of the downward radiation, complementing the STO measurement of incident and upward radiation. From the air, *in-situ* samples of clouds and aerosols give clues as to formation mechanisms. In the improved set, balloons and/or aircraft can provide *in situ* particle and ion density and ultraviolet irradiance measurements. In the optimal set, they can provide measurements of composition and size distribution of ions, aerosols, and cloud particles.

8. Planetary Atmospheric Waves

Objective. *Determine the nature of possible influences of solar variability on tropospheric waves of planetary scale.*

Overview. This objective calls for testing the hypothesis that the structure of tropospheric waves of planetary scale is influenced by stratospheric conditions, especially winds, which are affected by solar activity. This requires the multiple pointing capability of the STO to observe the sun, the input of solar radiation and energetic particles to the atmosphere, and the temperature and pressure in the stratosphere simultaneously.

Background. The topography of the earth's surface and the global distribution of heating and cooling force wave disturbances in the tropospheric air flow. These include waves of planetary scale which propagate their energy upwards. The vertical structures of the stratosphere and mesosphere, especially the wind distribution in these layers, play a dominant role in determining the "refractive index" for these long waves, and this index in turn determines the transmission and reflection of these waves. Thus, changes of the air flow in the middle atmosphere might lead to changes of the tropospheric amplitudes and phases of planetary waves. The energetics of these changes are such that relatively small amounts of solar energy may give rise to significant changes in the middle atmosphere where the density is low, but these middle-atmospheric variations produced by solar activity act merely to modulate the effect of fixed terrestrial energy sources in the troposphere.

Recent calculations indicate that such solar-induced changes in the middle-atmosphere flow must penetrate downward at least to the middle stratosphere in order to affect the tropospheric planetary waves significantly. There are several published studies that indicate variations in stratospheric temperatures and winds consistent with changing solar activity during the past solar cycle. No accepted theory exists for solar-activity-induced changes in the stratospheric parameters determining wave energy transfer, but given the important role of ozone in the physics of the stratosphere and the nature of ozone photochemistry, one may conjecture that stratospheric ozone modulation by solar activity may provide the link between solar fluxes and changes in the wind and temperature distribution of the middle atmosphere.

Ozone may be modulated by solar activity through a number of mechanisms. Both observation and theory indicate that solar proton events should lead to an increased production of NO_x compounds in the stratosphere, with a resulting increase in the catalytic destruction of ozone. Two other processes also might modulate stratospheric and mesospheric ozone through the production of NO_x and the subsequent catalytic destruction of ozone. In one process, the NO_x production is due to relativistic electron precipitation events; in the other, NO_x production is due to cosmic rays. Both cosmic rays and relativistic electron precipitation are known to be modulated by solar activity, although in the opposite sense, and recent work has indicated an excellent correlation between the observed galactic cosmic ray flux at the earth's surface and the relative size (area) of polar coronal holes, at least during solar cycle 19. A further mechanism by which solar activity may affect ozone and hence stratospheric structure involves variations in the solar ultraviolet radiation flux, which is suggested by recent irradiance observations. One dimensional photochemical models using variations in the ultraviolet radiation suggested by some observations have given a solar modulation of atmospheric temperature consistent with observations.

Recommended STO Measurements. To study the entire chain of events leading to solar activity influence on the middle atmosphere and the hypothesized effects on the troposphere calls for observations of solar coronal structure, interplanetary energetic particles, the solar irradiance, galactic cosmic rays, and composition, winds and temperature in the stratosphere and in the troposphere. However, some of the measurements appear of more importance than others to check the hypothesis which attempts to link solar activity and the propagation of long atmospheric waves.

In the first place, the solar flux in the ultraviolet region of the spectrum between 1200 and 3000 Å should be measured because of its effect on ozone variations in the middle atmosphere. For this objective, 10% accuracy is required; irradiance measurements are discussed more fully in Objective 1.

Measurements of relativistic (several hundreds of keV) electron precipitation events should be made as described in Objective 5, *Upper Atmospheric Dynamics*, owing to the possible relevance of these electrons in the balance between NO_x and ozone.

Stratospheric composition and temperature must be measured by remote sensing over extended time periods to establish, for example, if ozone variations in the upper stratosphere due to solar activity significantly affect lower stratospheric, and hence total, ozone amounts. The most pronounced changes in ozone density would probably occur in the upper stratosphere, so that temperature measurements of this layer from the STO will be necessary to supplement the routine observations of the lower stratosphere made by the meteorological networks. The winds in the upper atmosphere can be derived from the measured pressure and temperature distributions, with an accuracy which is sufficient for the present purpose, by assuming geostrophic or gradient wind balance. However, the situation could be improved significantly if direct wind measurements were made from the STO; this would permit determination of the horizontal wind to higher accuracy, of order 5 m/s, in the stratosphere.

Complementary Measurements. Various non-STO measurements could help pin down specific mechanisms. Interplanetary measurements of high-energy flare protons should be made, because of their role in the production of NO_x and destruction of ozone. Cosmic ray measurements from the ground would also be appropriate, for the same reason. Interplanetary measurements, as discussed in Objective 1, should be made simultaneously to establish the causal relationships for electrons precipitating from the magnetosphere.

Routine measurements by the meteorological network will provide lower atmospheric pressure and temperature, from which the structure of tropospheric planetary waves can be derived.

IV. Instrumentation

We define STO instruments to be those that are either physically attached to the space platform or in orbit in the vicinity of the platform, functioning as a coordinated part of the STO mission. Such instruments fall into three categories--solar, magnetospheric, and atmospheric--and are discussed in this section. Because the interplanetary medium plays a central role in so many of the physical processes that couple the major regions of solar-terrestrial space, the study group considers it imperative that there be an interplanetary companion to STO. The method chosen to implement such an interplanetary companion is not within the purview of the study group, but the specification of its instrumental capabilities is. Hence, we follow the discussion of STO instrumentation with a specification of the interplanetary instrumentation necessary from the point of view of the STO Objectives.

1. Solar STO Instrumentation

The interdisciplinary objectives of the STO require observations of a wide variety of physical phenomena. A knowledge of the solar input, in its broadest sense, to the terrestrial and interplanetary system is a requirement of virtually all objectives. A balanced complement of solar instruments is needed to achieve this goal. The solar STO instruments can be divided into three types, which are treated below. The first type is non-imaging; these instruments measure the solar irradiance. The second type consists of imaging instruments appropriate during times of low solar activity, oriented primarily toward global (large-scale) structure. The third type, also imaging instruments, is oriented toward solar activity and, in particular, solar flares.

The first group of instruments in Table 6, *Solar Instruments*, measures the solar irradiance, i.e., the solar radiative flux per unit area incident upon the earth's atmosphere. The total radiative input to the vicinity of the earth (the "solar constant") is obviously of central importance to a number of the objectives; in addition, the particularly crucial role of solar ultraviolet flux in upper atmospheric processes, and its own large variability, require high accuracy monitoring of the ultraviolet spectral irradiance. The range between 1200 and 3000 Å is of special interest because of its possible influence on ozone variations (Objectives 5, 6, 7, and 8); the soft X-ray and EUV ranges are of importance in bulk ionization and heating of the thermosphere, which influence atmospheric dynamics and chemistry (Objectives 5 and 6); for these spectral irradiance measurements, we should strive for the capabilities given in Table 1. The primary goal of the solar constant and spectral irradiance instruments is to measure *changes* in the parameters specified, not their absolute value.

The second group of instruments in Table 6 makes measurements that bear on the global structure of the sun's coronal magnetic field and its role in directing the outflow of the solar wind. The global structure of the outer solar magnetic field can be discerned through wide-field observations in soft X-rays and white light, with particular efforts to ensure overlapping fields of view. The X-ray observations are particularly useful in illuminating small- and intermediate-scale closed magnetic fields in the lower corona and the presence of coronal holes, as well as structures on the solar disk, in contrast to those on the solar limb. White-light coronagraph observations show the large-scale pattern of the solar magnetic geometry near the solar limb and reveal, for example, the configuration of the interplanetary "neutral sheet" near the sun, which in turn is reflected in the interplanetary sector structure. From these two instruments one can then derive the geometry of the intermediate and large-scale solar coronal magnetic field and the density of the outer coronal medium. High-spectral-resolution observations of the Doppler shift of EUV lines measure the velocity of moving material in the transition region and low corona. These data are most reliable for solar longitudes facing the earth, and hence complement the measurements of those coronal structures measured with the soft X-ray telescope. Limb observations from resonance-line coronagraphs may be employed with white light coronagraphs to infer the coronal temperature (through line profile studies) and the expansion velocity (through the Doppler-dimming technique) of both magnetically open (coronal hole) and quasi-closed (streamer) structures located near the limb. The extension of these resonance-line observations to include a variety of ions will permit a mapping of the ionic structure of the expanding corona over a broad range of velocities -- thus allowing a mapping of the structure of the observed solar wind from 1 AU down to the low coronal regions.

The third group of instruments in Table 6 makes observations of solar flares and other eruptive phenomena that lead to major perturbations in the vicinity of the earth. The XUV Doppler spectroheliograph is the core instrument of this group, for several reasons. The XUV spectral range offers the ability to observe the intrinsic nature of eruptive events at the sun over a range of temperatures from about 10^4 - 10^7 K, as well as their density, morphology, and timing. This proposed instrument differs from previous XUV spectroheliographs in that it has the capability to distinguish Doppler shifts

Table 6. Strawman Solar Instruments for STO*

Instrument	Function	Specification
Solar constant monitor	Integral of solar irradiance over the entire spectrum	See Table 1
Spectral irradiance monitor	Spectral irradiance in X-ray, EUV and UV Spectral range	See Table 1
Soft X-ray telescope	Magnetic field morphology of the inner corona, coronal holes, active regions	Spatial resolution of a few arc seconds; simultaneous full sun field of view out to several solar radii; images through broad-band filters in 5-60 Å range
White light coronagraph	Magnetic field morphology of the outer corona, electron density, transient eruptions	Spatial resolution 5-10 arc seconds; field of view from ~1.2 solar radii to 5-10 solar radii
Resonance line coronagraph	Morphology and amplitude of radial motions in corona, temperature distribution	Spatial resolution in 10-20 arc second range; field of view like white light coronagraph above
EUV spectrograph	Line of sight velocity at base of coronal holes	Spatial resolution in 10-20 arc second range; simultaneous field of view of at least a few arc minutes; velocity resolution of about 10 km/s.
XUV Doppler spectroheliograph	Velocity, temperature, density, composition configuration and timing of flares and eruptions	Spatial resolution of a few arc seconds; simultaneous full sun field of view; about 10 km/s velocity sensitivity
Hard X-ray spectrometer	Number and spectrum of electrons accelerated near the sun	Full sun field of view; spectral resolution $E/\Delta E \approx$ 10-100, Energy range 10-300 keV.
Radio spectrograph	Detect presence of shock waves and high energy particles in outer corona	Frequencies less than 20 MHz, full sun field of view, moderate spatial resolution

* These instruments are "strawman" instruments, which have been identified to satisfy the measurement requirements specified. Their capabilities are not necessarily completely defined, nor are the instruments unique. We anticipate that the actual STO instruments would be chosen from responses to an Announcement of Opportunity.

from spatial shifts with about 10 km/s velocity sensitivity. The other two instruments in the group cover higher energies and emphasize the processes that accelerate high-energy particles. The hard X-ray spectrometer measures the number and spectrum of moderately high energy electrons accelerated near the solar surface and in the inner corona. In advanced versions of the STO this instrument should have imaging capability, whereas for the first STO, a full-sun (non-imaging) instrument is called for. The radio spectrograph detects flare-associated shocks and high-energy electrons as they are accelerated and propagate in the outer corona and the interplanetary medium. Through this instrumentation, combined with the information on the global morphology of the magnetic field from the soft X-ray telescope, one can identify the energy and momentum inputs at the flare site, the intermediate-scale structure of the magnetic field configuration in which the event took place, and the trajectory of propagation to the vicinity of earth.

The entire instrument complement permits those observations necessary to study the solar origin of the physical processes that are significant in the terrestrial context. The proposed variety of instruments would encompass a wide range of solar activity and thus be appropriate at any phase of the solar cycle.

2. Magnetospheric and Ionospheric STO Instrumentation

The instrumentation required for magnetospheric measurements from the Solar Terrestrial Observatory includes perturbers, *in situ* sensors, and remote sensors. These instruments use the unique capabilities offered by the Shuttle and Space Platform, which are quite different from those of traditional free-flyers. These capabilities enhance the effectiveness of both remote sensing and active experimentation. Through remote sensing, one can sample large volumes of space instead of being limited to *in situ* probing along the orbital track. The ability to deploy and control multiple subsatellites also extends the degree of spatial and temporal sampling that can be done in conjunction with the Space Platform. In addition, the relatively new area of active experimentation can be exploited. In this approach, active probing is carried out to trace magnetospheric processes and to initiate controlled magnetospheric response to small perturbations.

The STO instrumentation for magnetospheric and ionospheric physics can be divided into three groups, according to overall function, as in Table 7. The first group is for active experimentation; these instruments serve to inject chemicals, particles, and waves respectively. The second group consists of imagers, that remotely sense the effects induced by the instruments of the first group, as well as naturally occurring phenomena. Finally, the third group consists of single-point and/or multipoint *in situ* sensors, which serve to calibrate the imaging systems, i.e., to determine the relationship between the remotely sensed parameters and *in situ* measured properties. This third group also measures the perturbations injected by the active experimentation and monitors the background plasma medium.

The first group in Table 7, the active experimentation injection instruments, includes a chemical release module, which will be used to trace out the electric and magnetic field structures of parts of the magnetosphere and ionosphere, using releases of tracer chemicals under appropriate geomagnetic conditions. Later uses of the chemical release module will involve larger injec-

Table 7. Strawman Magnetospheric/Ionospheric Instruments for STO*

Instrument	Function	Specifications
Chemical release module	Determination of perpendicular and parallel electric fields and conductivity modification.	Maneuverable release module with a set of release canisters using Ba, Li, O, SF_6.
Particle (electron/ion) injector	Modification of local plasma and injection of electrons and ions.	Variable energy, density, species (H^+, He^+, He^{++}, N^+, O^+, Xe^+). Electron energies (100 eV → 100 keV). Ion energies (100 eV → 100 keV). Variable pitch angles and controlled pulse pattern.
Plasma wave injector	Stimulation of wave-particle processes by wave injections at a variety of wave normal angles with respect to B.	Transmitters and antennas (1 Hz to $\geq$ 30 MHz).
Low light level television	Auroral imaging in visible, UV, vacuum UV.	Spatial resolution of 10 meters x 10 meters/pixel with time resolution of 10 seconds per frame.
X-ray telescope	Imaging of backscattered X-ray radiation.	Imaging capability for X-rays 10 - 500 keV.
Coherent scatter	Two- and three-dimensional ion drift fields.	Coherent-scatter radar based on ground-based concept (1 - 500 MHz). Desired ion velocities of 10 m/s at densities of > 10 cm^3.
Multiple subsatellites	Multipoint determination of auroral and ionospheric characteristics.	Ions/Electrons 0 - 100 MeV. Ion drift > 10m/s. Ion composition density 10^1 - 10^6 cm^{-3}. Magnetic field > 1 nT.
Recoverable subsatellite	Comprehensive measurement of plasma and plasma wave characteristics.	Plasma waves (1 - 10^7 Hz). Ion and electron composition and distribution function (0 - 100 MeV). Neutral density and magnetic field.
Maneuverable subsatellite	Measurements similar to recoverable subsatellite.	Specifications similar to recoverable subsatellite with propulsion capability.
Tethered particles and fields probe	Low-altitude *in situ* measurements and ionospheric perturbations.	Magnetometers (> 1 nT), electric field probes (> 1 mV/m), and ion mass spectrometer (1 - 56)

* See note, Table 6.

tions to modify ionospheric conductivities. The second instrument, the particle injector, will be used to probe the potential drops parallel and perpendicular to magnetic field lines. The position of the injected beam will be measured by imagers and *in situ* probes. For studies of transport of material between the magnetosphere and the ionosphere, the particle injections will include not only electrons, but also a variety of ions with a variety of pitch angles and injection patterns. Later STO flights will use accelerators with enhanced power; the ion and electron injectors will be used to launch beams that can modify natural magnetospheric particle populations and conductivities. The large STO power will permit the injection of powerful particle beams that can be used to generate waves and to inject large quantities of tracer ions into the magnetosphere as a probe for magnetospheric energization and transport process.

The third instrument, the wave injector, will consist of powerful transmitters and large antennas. The transmitters will operate from one Hz to about 30 MHz and at a few higher frequencies. This frequency range spans the characteristic frequencies of the plasma to allow the stimulation of wave-particle interactions of interest. The basic transmitters should deliver 1 to 2 kW of power to the antenna. The enhanced instrument should be able to deliver 10 kW of power to the antenna continuously and peak powers during pulsed operation up to 1 MW. Antennas required will probably be long wires for the lower frequencies and dish antennas for the highest frequencies for high-directivity, high-gain measurements.

The second group of instruments consists of imagers that sense remotely both actively injected and naturally occurring magnetospheric phenomena. These instruments are pointed independently of the platform base to build up pictures of tracer distributions, particle deposition patterns, and high-resolution auroral morphology. The most basic instruments are the low-light-level television and the X-ray telescope. These together constitute an imaging system that covers the spectral range from a few to 10,000 Å. The more advanced instrument is the coherent-scatter radar. This technique uses the scattering of 1-500 MHz waves from plasma turbulence to remotely sense the ion drift patterns in the F-region of the ionosphere. The radar can give two-dimensional measurement of the ion velocity fields from which the electric field patterns can be derived. This technique is in an early phase of conceptual study and hence would be a later addition to the STO payload.

The third and final group of instruments in Table 7 consists of single and multipoint subsatellites that serve to measure natural magnetospheric properties and to calibrate the remote sensing observations. The multiple subsatellites include instruments to measure energetic particles, electron and ion densities, ion drifts, and magnetic fields. These multiple subsatellites orbit in formation with the STO to unravel spatial/temporal uncertainties in the auroral oval, in addition to their role as calibrators of remote sensing optical and radar techniques measuring particle deposition and ion drift processes. The recoverable subsatellite offers a more comprehensive plasma measurement capability and adds the measurement of plasma waves. The maneuverable subsatellite extends this capability even further by adding propulsion. The tethered particle and field probe utilizes a long wire tether (up to 100 km) to maneuver an instrument package down to the E-region of the ionosphere (< 125 km altitude). This probe will measure ionospheric currents that close in this region.

3. Atmospheric STO Instrumentation.

The atmospheric instruments summarized in Table 8 must make five main categories of measurements: (1) neutral polar molecular and particulate (cloud and aerosol) constituents, (2) excited-state and ionized atomic and molecular species, (3) temperature distribution, (4) wind field, and (5) terrestrial reflected and emitted radiation.

The relative concentrations and variability of the reactive neutral minor and trace gases located above the tropopause can be monitored by limb absorption or emission observations using high-resolution spectrometers. These instruments should have the capability of mapping species present at relative concentrations of 10^{-6} to 10^{-12} throughout the stratosphere and 10^{-6} to 10^{-9} in the mesosphere and lower thermosphere. In order to discern changes to the steady-state distributions resulting from changes in the energy input to the atmosphere, the observations should be made with a spatial resolution of 1-2 km in altitude and ~100 km horizontally; the corresponding maximum sampling times for the observations are 1 s for absorption measurements and 10 s for observations made in emission. With the exception of OH, all of the neutral gaseous species of importance to the atmospheric objectives of the STO can be monitored with the necessary accuracy and over the required altitude range by the advanced interferometric spectrometers currently under development.

For the excited-state species throughout the middle atmosphere (i.e., from 40 to 120 km) and for the

Table 8. Strawman Atmospheric Instruments for STO*

Instrument	Function	Specifications
Lidar	Determine the height, thickness, and distribution of aerosol layers and thin clouds in the troposphere and lower stratosphere	Nadir looking: 1-m receiver; ~ 20 W transmitted at 2 or 3 wavelengths ~ 0.33 - 1.5 μm; vertical resolution < 1 km.
Radiation balance monitor	Determine effect of aerosol/cloud layers on local radiation balance. Measure outgoing reflected solar and emitted radiation reaching spacecraft from below.	Earth radiation budget sensor; two-channel radiometer 0.3 - 3.0 μm, 1 - 20 μm. For incoming solar radiation, see solar measurements.
IR emission spectrometer	Vertical profiles and latitude variability of minor and trace species, energetics of mesosphere and lower thermosphere.	Limb viewing, cryogenic interferometer spectrometer 2 to 20 μm range (500 - 5000 cm^{-1}), spectral resolution of 0.1 cm^{-1}; scan time $\leqslant$ 10 s.
IR absorption spectrometer	Vertical profiles and latitude variability of neutral minor and trace species; dissociation levels and energetics of mesosphere and lower thermosphere.	High resolution occultation interferometer, 2 - 16 μm (600 - 5000 cm^{-1}), spectral resolution 0.01 cm^{-1}. Solar aquisition and tracking; scan time 1 s.
UV and visible spectrometer	Spatial distribution and variability of ionized and excited-state species in thermosphere down to 80 km; excited-state species in mesosphere and stratosphere to ~40 km.	Multichannel grating spectrometer, 20 - 1200 nm, spectral resolution < 1/2 Å. Focal plane arrays imaging field with 1 km resolution.
Upper atmospheric wind sensor	Horizontal components of wind field in upper stratosphere, mesosphere, and lower thermosphere.	Zonal and meridional wind velocity to 4 m/s (2 m/s for advanced system) 25 to 100 km altitude range, vertical resolution 2 km. Fabry Perot interferometer, gas correlation spectrometer or μ wave radiometer.
Upper atmospheric temperature sounder	3-dimensional temperature field from tropopause to ~120 km.	Temperature precision 1K, accuracy 3K. Vertical resolution $\leqslant$ 2 km with horizontal sampling element of 100 km. Limb emission radiometer to 60 km, PM or Advanced Temp. Sounder to 30 km. Combination of emission or absorption spectrometer and PMR above LTE limit.
Lightning mapper	Global lightning intensity and distribution, sferics	Optical array techniques; millisecond time resolution; 5 - 10 km spatial resolution

* See note, Table 6.

ionized molecules of importance in the lower thermosphere (80 to 120 km), a multispectral imaging spectrometer is required. Focal-plane arrays having a spectral coverage from 20-40 nm, with a resolution of <0.1 nm, should provide adequate discrimination for mapping the distributions of the species of interest. Improvements to the spatial and spectral performance of this instrument, and changes to the channel wavelengths selected on the basis of the results of the initial STO mission, would be incorporated into the version to be flown on the advanced mission. The improved performance would be of particular importance, for example, in refining the observations of the spatial and temporal characteristics of auroral emissions.

Measurements of the wind and temperature fields are important throughout the middle atmosphere where part of the absorbed radiant and particle energy is dissipated as thermal radiation and motions. Remote sensing measurements of temperature for the STO objectives require an accuracy of 3 K, a precision of 1 K and a vertical resolution of 2 km. The profiles should extend from 25 to 120 km altitude with a horizontal spacing of not more than 100 km. These requirements exceed the capability of the instruments that have been flown to date; advanced systems currently under development, however, should achieve the required performance and be available for STO. The payload should include a very-high-resolution sounder, such as a limb-viewing pressure modulated radiometer (PMR), together with a high-resolution spectrometer to give rotational and vibrational temperatures which can be used to aid in the interpretation of the PMR radiance data.

The zonal and meridional components of the wind field in the upper stratosphere, mesosphere, and the thermosphere up to 100 km should be measured globally, with a vertical resolution of about 2 km. For the initial payload a minimum wind velocity resolution of some 4 m/s is desirable and should be achievable using one of several instruments currently under development, viz, Fabry-Perot interferometers, gas correlation spectrometers, and microwave radiometers. Wind velocity resolution is expected to be improved during the next few years to 2 m/s, and such improvement would be available for the advanced payload.

In the lower atmosphere, the objective of the STO measurements is to determine the effect that changes in the input radiative and particle energy may have on the distribution of aerosol and thin cloud layers in the troposphere and lower stratosphere and which, as a consequence, modify the radiative and thermal balance of this region. The height, thickness, and spatial extent of the layers are sensed using a downward-looking lidar system that should achieve a vertical resolution better than 1 km using current technology. The initial lidar would be nadir-viewing, capable only of measuring clouds and aerosols directly beneath the STO. An advanced version would add a scanning capability to allow more complete spatial coverage. In addition, an advanced tunable lidar could provide temperature, humidity, and pressure measurements with the fine vertical resolution (~1 km) required to discern effects caused by aerosol and cloud layers. A radiation balance monitor, co-aligned with the lidar, would document the effect of lidar-measured clouds and aerosols on terrestrial reflected and emitted radiation in broad spectral intervals.

The need to measure both the global distribution of lightning and the intensity of lightning calls for a Lightning Mapper. This instrument consists of an optical sensor that uses large CCD arrays and background subtraction electronics to achieve detection efficiencies approaching 90% during both daytime and nighttime observation. The required spatial resolution of the sensor is 5 to 6 km. Global lightning statistics can be obtained initially from the STO in low earth orbit. However, later continuous global coverage will require satellites in appropriate geostationary orbits.

4. Interplanetary Companion Instrumentation

The interplanetary particles of interest to STO span extremely broad ranges in energy, composition, and dynamic range. For example, solar wind thermal electrons have energies between 0 and ~100 eV, solar wind thermal protons have energies between ~100 eV and 10 KeV, solar flare particles have energies ranging from ~100 KeV to 100 MeV, and galactic cosmic rays have energies extending up to 1 BeV and beyond. Protons, electrons, alpha particles, and a wide range of mass and charge states of heavier ions (such as oxygen, silicon, and iron) are important constituents of the interplanetary particle population. Flux levels of these particles within the overall energy range of interest differ by more than 20 decades.

No single-particle instrument is capable of providing the necessary measurements of this diverse particle population. Only a combination of different measurement techniques focused on particular subsets of this particle population can do the job. Table 9 lists a combination of particle instruments which, acting together, can provide a complete specification of the phase space densities of interplanetary electrons and the major ions of interest at all energies ranging from 0 eV to greater than 250 MeV. Instruments similar to these are presently operating on ISEE 1, 2, and 3 or are under development for ISPM or the IPL of OPEN. The first group of instruments in Table 9 comprises the solar wind particle instruments, which will provide monitoring of the bulk flow properties (velocity, density, temperature, etc.) of the solar wind incident on the earth's magnetosphere. They will also identify composition (mass and charge) anomalies useful both for identifying the coronal source of the flow, as well as tracing the entry of the plasma into the magnetosphere. Finally, they will be well suited for studying and analyzing transient solar wind phenomena associated with solar activity.

The second group in Table 9, the suprathermal and transthermal particle instruments, will determine the flux and composition of particles energized by solar flares and by shocks in interplanetary space and will allow the study and identification of various acceleration processes. The next group, the cosmic ray instruments, will of course provide a continuous monitoring of the cosmic ray flux incident upon the earth's magnetosphere and upper atmosphere.

The final group of instruments in Table 9 starts off with a magnetometer, since the interplanetary magnetic field plays an important role in virtually all solar wind processes. This instrument will measure the sense of

Table 9. Strawman Interplanetary Companion Instruments*

Instrument	Function	Specifications
Cold plasma analyzer	Velocity, density, and temperature of solar wind protons and alphas	0 - 15 keV/Q
Cold plasma mass and charge spectrograph	Ion and charge composition of solar wind	0 - 15 keV/Q
Hot plasma analyzer	Velocity, density, and temperature of electrons and suprathermal ions.	0 - 50 keV/Q
Energetic particle telescope	Transthermal proton flux	20 keV - 2 MeV
Hot plasma spectrograph	Composition of transthermal ions	3 keV - 1 MeV
Transthermal electron analyzer	Transthermal electron flux	30 keV - 1 MeV
Energy loss particle telescope	Cosmic ray ion flux	1 - 250 MeV
Cerenkov detector	Cosmic ray electron flux	1 - 250 MeV
Magnetometer	Interplanetary DC magnetic field strength and direction	$f < 1$ Hz, 0 - 100 γ
Electric field spectrum analyzer	Interplanetary electric field temporal fluctuations	1 - 10^5 Hz
Magnetic field spectrum analyzer	Interplanetary magnetic field temporal fluctuations	1 - 10^4 Hz

* These instruments are "strawman" instruments, which have been chosen to satisfy the measurement requirements identified. Of course, their capabilities are not necessarily completely defined, nor are these instruments unique. We anticipate that the payload of the Interplanetary Companion will depend on the means chosen by NASA to respond to these requirements, bearing in mind the nature of interplanetary instrumentation that is operational at the time of STO.

the field, i.e., its polarity, which provides information on the solar origin of particular volumes of solar wind plasma. Finally, the field polarity, its direction relative to the earth's dipole field, and its magnitude are important determinants of geomagnetic activity.

Two types of instruments are needed for the measurement of the essential field characteristics. The first of these is a dc magnetometer that determines the magnetic field at frequencies below about 1 Hz over a range of field strengths from 0 to ~100 gamma. The second type of instrument is a spectrum analyzer for both electric and magnetic field fluctuations at the much higher frequencies associated with plasma turbulence and the various wave modes (e.g. whistler, ion acoustic) associated with plasma instabilities.

V. Multidisciplinary Approach

1. Introduction

The Solar Terrestrial Observatory is a multidisciplinary Space Platform instrument payload that addresses *all eight key scientific objectives*, using solar, magnetospheric and atmospheric *Shuttle-class instrumentation*. Much of this instrumentation is in development for the relatively short Shuttle Spacelab flights, and the larger instruments are possible only because of the Space Shuttle's ability to carry heavy loads into orbit. The Space Platform extends these capabilities to offer much longer duration and higher power levels. By combining these instruments into a multidisciplinary solar-terrestrial payload, STO can address comprehensive solar-terrestrial objectives, largely because the payload has been defined with the highly interactive nature of the key scientific objectives in mind.

We recommend a two-stage, evolutionary approach to STO. The first stage is the Initial STO, discussed in Section 2 below. It is the simplest payload that can address a meaningful fraction of the objectives identified in this report, yet it requires only a single Space Platform of modest size. The second stage is the Advanced STO, discussed in Section 3. It addresses all of the eight objectives identified in this report in a complete manner The Advanced STO requires two platforms that differ primarily in orbital characteristics. One platform is in a high-inclination orbit, for coverage of the auroral zone; the other is in a medium-inclination orbit. In Section 4 we elaborate on the two-stage implementation of STO in terms of shared and dedicated platforms. In Section 5 we discuss the characteristics required for effective operations and data handling during the STO missions. In Section 6 we discuss the theoretical and data analysis capabilities that must be also developed along with the specific STO payload.

2. Initial Solar Terrestrial Observatory

The Initial STO is the simplest payload compatible with a *multidisciplinary* approach to the scientific objec-

Table 10. Initial STO: Instrumentation for Individual Objectives*

Objective	STO Instruments	Objective	STO Instruments
1. Solar variability	Total irradiance monitor UV irradiance monitor Soft X-ray telescope White light coronagraph Resonance line coronagraph	5. Upper atmospheric dynamics	UV irradiance monitor Multiple subsatellite Recoverable subsatellite Low-light-level television Upper atmospheric wind sensor Upper atmospheric temperature sounder IR emission or absorption spectrometer
2. Wave-particle processes	Plasma wave injector Particle injector Recoverable subsatellite Low-light-level television X-ray telescope	6. Middle atmospheric chemistry and energetics	Total irradiance monitor UV irradiance monitor Recoverable subsatellite Multiple subsatellite Low-light-level television Infrared absorption spectrometer UV and visible spectrometer IR emission spectrometer
3. Magnetosphere-ionosphere interaction	Particle injector Chemical release module Multiple subsatellites Recoverable subsatellite Low-light-level television X-ray telescope UV and visible spectrometer	7. Lower atmospheric turbidity	Total irradiance monitor UV irradiance monitor Multiple subsatellite Recoverable subsatellite Low-light-level television Lidar Radiation balance monitor
4. Global electric circuit	UV irradiance monitor Multiple subsatellite Recoverable subsatellite Particle injector Low-light-level television X-ray telescope	8. Planetary atmospheric waves	UV irradiance monitor Multiple subsatellite Recoverable subsatellite Low-light-level television IR emission or absorption spectrometer Upper atmospheric wind sensor Upper atmospheric temperature sounder

* See note, Table 6.

tives identified in this report. The payload of the Initial STO has been established by first identifying, for each key scientific objective, the instruments required to address the objective using a *single-objective approach*. This is done in Table 10. For each objective we show the instruments that are recommended to be part of the Initial STO within the framework of this objective alone.

The reasoning that leads to the choice of these specific instruments for the Initial STO (as opposed to the Advanced STO) is as follows:

Solar Variability: Priority is given to solar constant and spectral irradiance measurements and solar coronal structures, at the expense of solar flare diagnostics. Priority is also given to better defined and/or developed instrumentation.

Wave-Particle Processes: Priority is given to the study of wave-particle interactions that can occur near the STO, since those interactions will be more easily stimulated at the lower power levels that may characterize the Initial STO.

Magnetosphere-Ionosphere Interaction: Priority is given to ion injection using accelerators and study of evolution of the injected particles.

Global Electric Circuit: Priority is given to determining the ionospheric electric potential in the vicinity of the STO orbit, as the instrumentation for this objective exists or is being developed.

Upper Atmospheric Dynamics: Priority is given to using *in situ* measurements of magnetospheric energy inputs into the upper atmosphere to calibrate the evolving remote measurement techniques. Priority is also given to the better defined and/or developed atmospheric instrumentation.

Middle Atmospheric Chemistry and Energetics: Priority is given to neutral composition and structure, at the expense of energetics. Priority is also given to instrumentation that is presently in development.

Lower Atmospheric Turbidity: Priority is given to documenting simultaneously: (1) changes in solar UV irradiance, (2) aerosol and thin cloud layers, and (3) effects of these layers on the radiation balance.

Planetary Atmospheric Waves: Priority is given to using *in situ* measurements of magnetospheric energy inputs into the upper atmosphere to calibrate the remote measurement techniques. Priority is also given to the better defined and/or developed atmospheric instrumentation.

Table 11 shows the complete strawman payload of the Initial STO. This payload is highly synergistic; many instruments are appropriate to several objectives, and together, they are capable of making a valuable contribution to most of the scientific objectives identified in this report. Moreover, since these objectives deal with processes that are themselves physically interactive, putting these instruments together has the advantage that it explicitly addresses this interactive nature by enabling coordinated acquisition of the different types of measurements.

Table 11. Initial STO: Complete Strawman Payload*

Spatial Region	Instrument
Sun	Total irradiance monitor
	UV irradiance monitor
	Soft X-ray telescope
	White light coronagraph
	Resonance line coronagraph
Magnetosphere and Ionosphere	Chemical release module
	Particle injector
	Plasma wave injector
	Low-light-level television
	X-ray telescope
	Multiple subsatellites
	Recoverable subsatellite
Atmosphere	Lidar
	Radiation balance monitor
	IR absorption or emission spectrometer
	UV and visible spectrometer
	Upper atmospheric temperature sounder
	Upper atmospheric wind sensor

* This payload is based on the strawman instrumentation, which is not necessarily completely defined or unique. The final payload will, of course, be selected on the basis of responses to an Announcement of Opportunity.

We estimate that the solar and magnetospheric instrument modules will require about one Shuttle pallet each, and the atmospheric instruments approximately two Shuttle pallets. Mission planning and integration studies should examine this estimate. The total payload should be placed on a single platform in this configuration for at least six months and preferably for one year or longer. Six months is the minimum duration to cover several solar rotations. One year permits at least a single sample of seasonal effects in both hemispheres. A low-altitude (300-400 km) orbit at inclination 57 degrees or above is satisfactory. It is essential that there be no intentional releases, especially water, within

100 km of the platform and that there be careful control of electromagnetic interference and outgassing (e.g., water, cryogens).

3. Advanced Solar Terrestrial Observatory

The payload of the Advanced STO is capable of a multidisciplinary approach to the scientific objectives identified in this report, at the level described. Following the same procedure used in the previous section, the payload of the Advanced STO has been established objective by objective, and the instrumentation required for each objective has been listed separately in Table 12.

The issues that have caused us to identify these instruments for the Advanced STO, and which relate the instrumentation of the Advanced STO to the Initial STO, are as follows:

Solar Variability: Solar flare capability is added to the Initial STO payload, both by adding an X-ray and EUV irradiance monitor and by adding instruments for determining the intrinsic energetic and dynamic properties of flares and eruptions.

Wave-Particle Processes: The increased transmitter power available for the Advanced STO will allow stimulation of wave particle interactions throughout a large portion of the magnetosphere, probing a larger volume of parameter space than available to the Initial STO.

Magnetosphere-Ionosphere Interaction: Power levels are increased in particle accelerators to carry out active

Table 12. Advanced STO: Instrumentation for Individual Objectives†

Objective	STO Instruments	Objective	STO Instruments
1. Solar variability	Total irradiance monitor X-ray, EUV, and UV irradiance monitors Soft X-ray telescope White light coronagraph Resonance line coronagraph XUV Doppler spectroheliograph Hard X-ray spectrometer EUV spectrograph Radio spectrograph	5. Upper atmospheric dynamics	EUV and UV irradiance monitors Low-light-level television X-ray telescope Coherent-scatter radar Upper atmospheric wind sensor* Upper atmospheric temperature sounder IR emission or absorption spectrometer*
2. Wave-particle processes	Plasma wave injector* Particle injector* Low light level television X-ray telescope Multiple subsatellites Maneuverable subsatellite	6. Middle atmospheric chemistry and energetics	Total irradiance monitor X-ray, EUV and UV irradiance monitors Multiple subsatellite Low-light-level television X-ray telescope UV and visible spectrometer Infrared emission or absorption spectrometer* Upper atmospheric wind sensor*
3. Magnetosphere-ionosphere interaction	Particle injector* Low-light-level television X-ray telescope Chemical release module* Maneuverable subsatellite	7. Lower atmospheric turbidity	Total irradiance monitor EUV and UV irradiance monitors Low-light-level television X-ray telescope Multiple subsatellite Maneuverable subsatellite Lidar* Radiation balance monitor UV and visible spectrometer
4. Global electric circuit	X-ray, EUV, and UV irradiance monitors Low-light-level television X-ray telescope Coherent scatter radar Chemical release module* Particle injector Lightning mapper Tethered particles and fields probe	8. Planetary atmospheric waves	EUV and UV irradiance monitors Maneuverable subsatellite Infrared emission spectrometer* Upper atmospheric wind sensor

* Upgraded (see Chapter IV)
† See note, Table 6

experimentation on how wave-particle interactions induced from STO affect the circulation of matter in the magnetosphere-ionosphere system.

Global Electric Circuit: Instrumentation requiring advanced development, such as the coherent scatter radar and the tethered subsatellite, is added to remotely probe the electric field. Correlations with tropospheric weather are examined through use of the lightning mapper and coordination with ground-based programs.

Upper Atmospheric Dynamics: The calibrated remote sensing measurements of global magnetospheric energy inputs into the upper atmosphere are used, including the spaceborne coherent-scatter radar, and improved atmospheric instrumentation is used. EUV irradiance measurements are added.

Middle Atmospheric Chemistry and Energetics: Instrumentation presently at an earlier stage of development, notably the infrared emission line spectrometer, is added to provide a more comprehensive capability for observing reactive species. The advanced payload has sufficient capabilities to study atmospheric energetics.

Lower Atmospheric Turbidity: Spatial scanning and spectral flexibility are added to the lidar to achieve both better spatial coverage and temperature, humidity, and pressure measurements with the fine vertical scale of aerosol and thin-cloud layers.

Planetary Atmospheric Waves: Improved plasma diagnostic measurements are used. EUV irradiance measurements are added, and improved atmospheric instrumentation is used.

Table 13 shows the complete strawman payload of the Advanced STO. As is also true of the Initial STO, the *combination* of instruments for specific objectives into a single payload has the advantage that it properly addresses the interactive nature of the objectives. If adequate platform space and power were available, the STO could evolve from the Initial STO to the Advanced STO as fast as instrumentation became available.

We estimate that the advanced payload will require approximately eight Shuttle pallets. These pallets should be shared among two separate platforms. The first should be in a 90 ± 10 degree low-altitude (200-250 km) orbit. Magnetospheric instrumentation with a requirement to observe the auroral oval and atmospheric instrumentation for which the widest range of coverage in latitude is required, comprise the payload of this platform. The choice of a low altitude of this platform is driven primarily by the requirement for the tethered particles and fields probe. The second should be in the same $\geqslant 57$ degree inclination 300-400 km altitude orbit as the Initial STO. This orbit is satisfactory for the solar instrumentation, and preferable for some magnetospheric and atmospheric experiments. These two platforms should be in orbit for at least one year in order to sample all seasons in both hemispheres. The same controls over the near-STO environment are necessary as for the Initial STO. A mission planning and integration study should be carried out to firm up the payload size estimates, as well as to look at the division of the payload between the two platforms.

Table 13. Advanced STO: Complete Strawman Payload†

Spatial Region	Instrument
Sun	Total irradiance monitor
	X-ray, EUV, and UV irradiance monitors
	Soft X-ray telescope
	White light coronagraph
	Resonance line coronagraph
	XUV Doppler spectroheliograph
	Hard X-ray spectrometer
	EUV spectrograph
	Radio spectrograph
Magnetosphere and Ionosphere	X-ray telescope
	Low-light-level television
	Coherent scatter radar
	Plasma wave injector*
	Particle injector*
	Chemical release module*
	Multiple subsatellites
	Maneuverable subsatellite
	Tethered particles and fields probe
Atmosphere	Lidar*
	Upper atmospheric wind sensor*
	Upper atmospheric temperature sounder*
	UV and visible spectrometer
	IR emission or absorption spectrometer*
	Radiation balance monitor
	Lightning mapper

* Upgraded as per Chapter IV, *Instrumentation*.
† See note, Table 11.

4. Evolution and Implementation

The Initial STO has size, power, and orbit requirements that are appropriate for a first platform that is shared among several disciplines. We presume that this platform will be shared primarily by sharing in time rather than space, i.e., most of the payload capacity of the platform would be cycled in and out with a characteristic time on the platform on the order of a year, and only a small fraction of the payload would be dedicated to small long-duration experiments (e.g., measurement of the solar constant). We recommend that the Initial STO be a problem-oriented payload on the first shared platform, with a duration of at least six months, and preferably one year, for the reasons discussed above.

It is clear to us that within a few years after the first shared platform becomes available, the individual solar-terrestrial disciplines will each have requirements for space platforms that will exceed the capabilities of a single shared platform. Space will also be required for individual PI instruments, individual multi-user class (facility) instruments and combinations of the two that make up problem-oriented observatories like STO, but with different scientific objectives. At that time it will be appropriate to have a dedicated solar-terrestrial platform. It is likely that a platform in a high-inclination orbit will be desirable for this, thus we recommend that the Advanced Solar Terrestrial Observatory be implemented by means of a dedicated solar-terrestrial platform at high orbital inclination and a shared platform at 57° orbital inclination.

5. Operations and Data Handling

Because of the multidisciplinary character of the scientific objectives of STO, a key element in its successful implementation will be the coordinated operation of the observatory in orbit and the coordinated interactive analysis of the data returned. In studying the solar-terrestrial system with its interconnecting physical linkages, the observations must be organized through a central control center set up to allow the scientists to tailor observations and experiments to specific solar, magnetospheric, and atmospheric conditions arising during the mission. This centralized operational approach will permit joint observing programs to follow physical processes that couple through the system, such as a passage of a coronal hole by the solar central meridian, its influence on the solar wind velocity and magnetic field, the resultant magnetospheric storm response, and its subsequent influence on the dynamics of the upper atmosphere. The fact that the STO will carry most of the instrumentation required for these studies on the same spaceborne cluster will greatly enhance the ability to plan and carry out these joint observations.

The idea of joint observing programs is not new to STO. The solar community first gained valuable experience in such coordinated observations during the Skylab mission in the operation of the Apollo Telescope Mount experiments. This experience was extended by the Solar Maximum Mission and, most recently, the Shuttle/Spacelab program through procedures being implemented by the investigator working groups for the different Spacelab missions. This experience will be ideally suited to carry forward into the Shuttle/Space Platform era and will be extended to accommodate joint observational needs throughout all of the solar-terrestrial disciplines.

Many of the scientific objectives would benefit from joint measurements between STO and other programs in operation at the same time. These joint measurements would require close communications among the different spacecraft control centers. Close communications will be required in the analysis of the resulting data as well. The requirement for both data and operational information exchange suggests the need for a data network in which the investigators are linked through remote terminals to the operations centers for all other missions. A prototype of this approach was carried out in the Atmosphere Explorer program with great success, and has been suggested for OPEN and UARS. This network approach would represent a strong step toward the establishment of the solar-terrestrial data network which has been discussed extensively within the solar-terrestrial scientific community. The achievement of free and easy access by the individual scientist to the different operations and data-handling centers or nodes of the network would facilitate the coordinated studies that are required in the analysis of coupled solar-terrestrial scientific problems. A possible scenario for the operations and data-handling network for the Solar Terrestrial Observatory is shown schematically in Fig. 11. It is patterned after previous free-flyer missions and incorporates the idea of data exchange between mission operations centers.

An additional consideration for the STO operations will be the periodic presence of people in orbit to carry out some of the experiments. The STO Platform will be serviced in orbit by the Space Shuttle. During times when the Shuttle is docked with the Platform it will be possible for the payload specialists or mission specialists on board to carry out a set of experiments or calibrations. This might be particularly important during the replacement or installation of a new instrument. The early manned operation would assure that the instrument is operating correctly prior to leaving it in automated or remotely controlled operation. This is the approach that is currently used, for example, in many cases during the installation of field instrumentation in the auroral zone.

In summary, STO instrumentation capabilities offer exciting new opportunities for solar-terrestrial studies. The coordinated interactive operation of these instruments and analysis of the resulting data are keys to the

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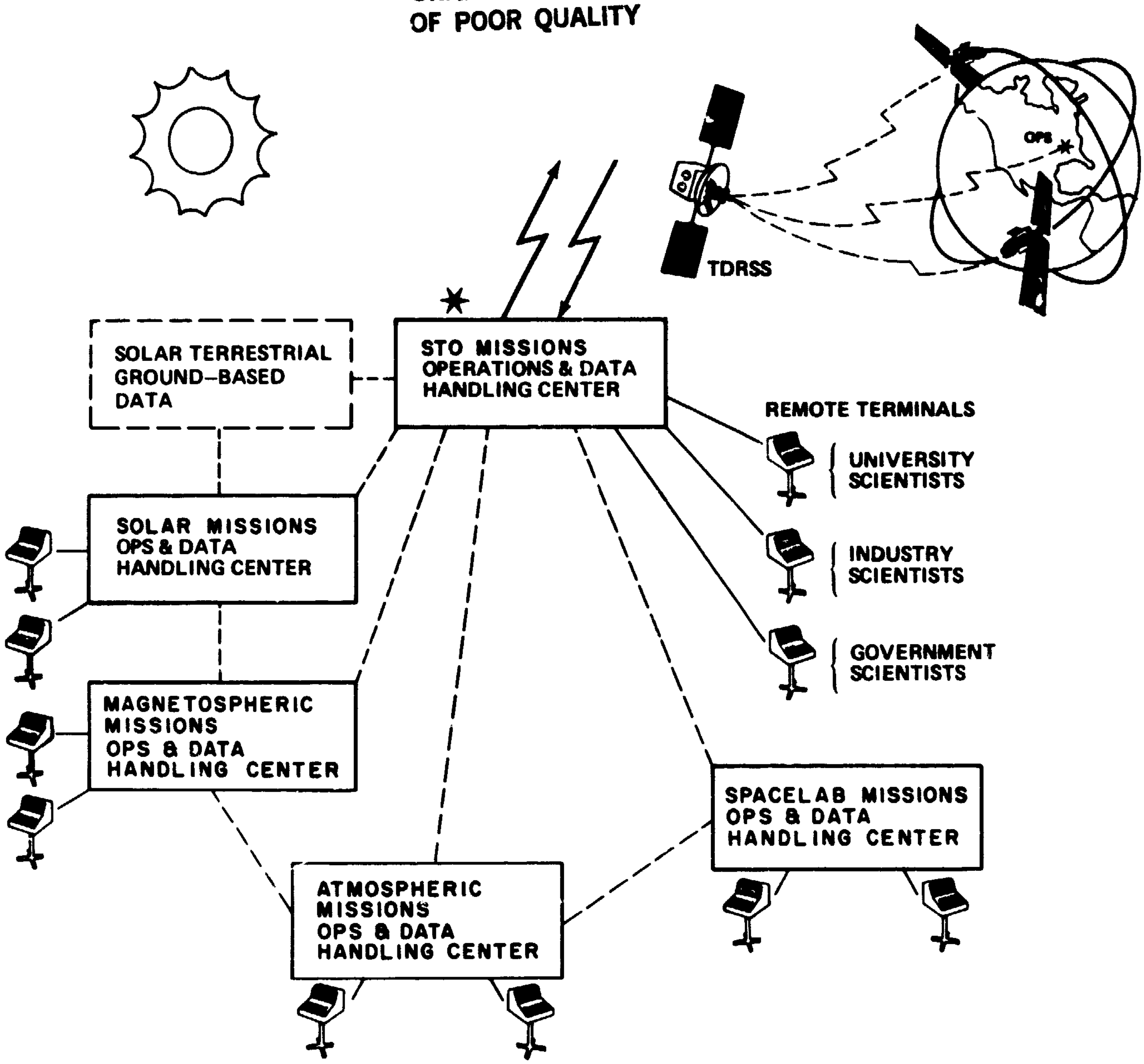

Fig. 11. Solar Terrestrial Observatory operations and data handling.

success of the mission. This success will be even further enhanced by the establishment of a solar-terrestrial data network that links the different mission operations centers and makes them easily accessible to the solar-terrestrial scientist.

6. Data Analysis and Theoretical Modeling

The scientific objectives of the Solar Terrestrial Observatory involve a complex interplay of radiative, chemical, dynamic, and electromagnetic processes that occur on the sun, in the solar wind, in the earth's magnetosphere and ionosphere, and in the earth's atmosphere. They require a multidisciplinary approach. In the data-acquisition phase, this implies that measured quantities must promptly be processed into physical units, diagnostic analyses must be carried out to the point where meaningful comparison can be made both among the observed phenomena and with theoretical predictions, and finally, theoretical modeling efforts must be undertaken in an effort to understand the observed phenomena in terms of basic physical processes. These activities must be carried out both within each discipline and in an interdisciplinary setting in which physical processes are followed *throughout their sphere of influence* rather than being terminated at the traditional boundaries between disciplines.

In order to integrate the observational data with appropriate theory and to insure that the measurements are of direct relevance to the scientific objectives of STO, it is essential that from the very beginning a strong role be played by an Investigator Working Group composod of instrument principal investigators and theoretical principal investigators. These individuals must have expertise in one or more of the disciplines encompassed by the STO and should include strong advocates of the interdisciplinary aspects of the STO scientific objectives. This structure of the Investigator Working Group will promote the essential rapid distribution of the scientific data to all investigators, experimental and theoretical, in a format conducive to the performance of comparative and diagnostic studies both within and across disciplines.

It is anticipated that the members of the Investigator Working Group will participate on an equal footing -- with commensurate benefits and responsibilities -- in the following tasks:

1. Optimization of the scientific return from the STO, once an instrument complement has been selected in response to the Announcement of Opportunity.

2. Recommendation of the best course of action during major tradeoff decisions that arise in the definition and development phases of the STO instrumentation.

3. Development of specific operational methods that are responsive to the STO objectives, e.g., joint observing programs, methods of data handling and exchange, modes of interaction between the STO instruments, and modes of interaction with other space and ground-based operations and data-handling centers.

4. Implementation of these operational methods on a daily basis during the flight of STO.

5. Completion of individual and joint observational and theoretical research projects related to the objectives identified. The development of theoretical models relevant to the coupling processes that are the main thrust of STO is particularly important.

The Solar Terrestrial Observatory Science Study Group believes that theory and data analysis are of the same importance to the scientific objectives of the STO program as is the acquisition of the primary data.

VI. Summary

The Solar Terrestrial Observatory is a synergistic, problem-oriented instrument payload for the Space Platform, serviced by the Space Shuttle. The central scientific problem that defines this payload is the understanding of the physical mechanisms that couple the major regions of solar-terrestrial space. The eight specific scientific objectives chosen for discussion benefit in a variety of ways from the unique capabilities inherent in the combined Shuttle/Platform approach.

The scope of the STO scientific objectives covers the region of space from the bottom of the visible solar atmosphere through interplanetary space and the magnetosphere to the bottom of the terrestrial atmosphere. Within this volume of space one can identify many problems to which the combination of the Shuttle, Shuttle/Spacelab instrumentation, and a platform can make an important contribution very different from a conventional free-flyer approach or Spacelab itself. Many of the physical mechanisms that couple the major regions of solar-terrestrial space are ill understood, partly because coherent, coordinated observations of sufficient scope have never before been obtained. As a result of poor understanding, we lack a predictive capability; if we possessed this predictive ability, both scientific and practical benefits would certainly follow.

In this report we identified for exemplary purposes eight basic objectives of solar-terrestrial physics to which the STO can make a unique and valuable contribution. There are, of course, more such objectives, some of which will only become clear as our understanding of the solar-terrestrial environment evolves.

There are two aspects to our studies of solar variations. The first is the variation of solar inputs to the earth, in radiation, particles, and fields. The second is to identify the solar and interplanetary phenomena that lead to the variability of these inputs. By making both observations of the sun and *in situ* flux measurements from the STO, accompanied by a non-STO interplanetary probe, we can trace the course of solar perturbations back to the sun. Appropriate observations of the sun and the interplanetary medium before, during, and after solar-terrestrial events will be used to pinpoint their solar causes.

Wave-particle interaction processes are found throughout the solar-terrestrial system. *In situ* studies of these processes have been carried out from a number of free-flying spacecraft, using passive techniques. The ability to control certain wave, particle, and plasma parameters *actively* through injection of waves, electrons, and ions from STO permits new insight into the microphysics involved, through clarification of cause and effect. The high power capabilities of the STO permit new active wave and particle injection experiments. The STO is well suited for conducting controlled perturbation experiments on wave-particle processes, as well as for the remote sensing of naturally occurring wave-particle interactions in the earth's magnetosphere and ionosphere.

The origin and transport of plasmas in the earth's magnetosphere continues to be a fundamental question in solar-terrestrial physics. The varying admixture of particles of solar and ionospheric origin changes continuously in response to changing solar conditions. Two investigative approaches are appropriate to the study of this problem: passive *in situ* measurements, which are part of the ISEE, Dynamics Explorer, and OPEN programs, and active ion injection techniques, which can best be accomplished by the STO. The STO combines high power and remote sensing with an operational lifetime that is capable of covering a variety of solar and magnetospheric conditions. This combination enables it to make a unique contribution to understanding magnetospheric plasma origins through experiments involving active ion injection.

Early concepts of the atmospheric electric circuit have given way to a broader view that encompasses the atmosphere, ionosphere and magnetosphere. Correlated measurements of the elements of this global circuit are in their infancy. In order to advance our understanding, a broad collection of observations must concentrate in particular on the relationship of changes in the ionospheric potential distribution to changes in the lower atmospheric electric field. The STO provides a combination of accommodations for observing the global electric circuit that are not available through traditional free-flyers or Spacelab. The combined capabilities of STO for remote sensing, high-power active experimentation, and tethered subsatellites would be enhanced further by coordination with measurements from free-flyers, the ground, airplanes, and balloons.

The motions of the upper atmosphere are dramatically influenced by changes in the energy input from the sun, both directly and by way of the earth's magnetosphere. Through remote sensing, the STO will be able to observe the major inputs to the upper atmosphere, over large areas of the earth, while also observing the heating and winds that constitute the atmosphere's dynamic response. The STO combines the capabilities of simultaneous solar and terrestrial pointing, considerable instrument size, and long duration to cover a variety of solar and magnetospheric conditions.

The chemistry of the middle atmosphere is very sensitive to both solar radiative inputs and cosmic, solar, and magnetospheric particle inputs. From the STO one can sense both these inputs and their terrestrial consequences over major areas of the earth. The measurements for atmospheric chemistry call for instrumentation of considerable size and mass. The STO makes it possible to place such instruments in orbit long enough to sample a wide variety of solar-terrestrial events, as well as to observe the solar and magnetospheric energy inputs simultaneously.

Atmospheric turbidity (aerosols and thin clouds) may be affected significantly by changes of ionization or ultraviolet radiation in the lower atmosphere. These changes may be caused by solar activity directly or indirectly through stratospheric ozone. The relationships among these quantities lack observational verification. This objective requires at least several months of observation of the solar radiative input and lidar measurements of atmospheric aerosols and clouds. The STO provides the necessary combination of long-duration operation with the high power and volume capability required by the lidar.

Finally, progress in understanding the importance of planetary atmospheric waves requires the testing of the hypothesis that such waves are influenced by stratospheric conditions, especially winds, which are affected by solar activity. This requires the multiple pointing capability of the STO to observe the sun, the input of solar radiation and energetic particles to the atmosphere, and the temperature and pressure in the stratosphere simultaneously.

The Solar Terrestrial Observatory approach is to place on the Space Platform a multidisciplinary instrument payload that addresses all eight key scientific objectives, using solar, magnetospheric, and atmospheric shuttle-class instrumentation Much of this instrumentation is in development for relatively short Shuttle/Spacelab flights, and the larger instruments are possible only because of the Space Shuttle's ability to carry heavy loads into orbit. The Space Platform extends these capabilities to offer much longer duration and higher power levels. By combining these instruments into a multidisciplinary solar-terrestrial payload, STO can address *comprehensive solar-terrestrial objectives*, largely because the payload has been defined with the highly interactive nature of the key scientific objectives in mind.

The platform-based STO payload consists of solar, magnetospheric/ionospheric, and atmospheric instruments. The scientific objectives and operational strategy dictate a two-stage, evolutionary approach. The first stage, the Initial Solar Terrestrial Observatory, consists of approximately four Shuttle pallets of instruments on a 57° inclination low-earth-orbit platform for a mission of at least six months and preferably one year. The payload of the Initial Solar Terrestrial Observatory is listed in Table 11. The payload of the second stage, the Advanced Solar Terrestrial Observatory, which is listed in Table 13, is divided among two platforms. These share approximately eight Shuttle pallets of instrumentation and have a mission duration of at least one year. One of these platforms is to be in a 57° inclination orbit, the other in a near-polar orbit. Both the Initial and Advanced STO payloads have the same characteristic: they are problem-oriented and their combined capabilities far exceed those of the individual instruments flown singly. This is particularly beneficial for studying the basic coupling processes of solar-terrestrial physics, which are highly interactive and nonlinear.

The broad objectives of the STO cannot be met fully without a companion interplanetary spacecraft. There are several ways in which this interplanetary companion could be provided, including (1) coordination of the STO with a mission having an interplanetary element, such as OPEN; (2) coordination with an interplanetary explorer; or (3) a spacecraft whose primary purpose is to serve as the Solar Terrestrial Observatory interplanetary companion. The means chosen by NASA to implement this interplanetary companion are beyond the purview of the Science Study Group. However, it is essential that there be an interplanetary companion throughout both Solar Terrestrial Observatory missions. The scientific bonus that follows from the simultaneous presence of the Solar Terrestrial Observatory and an interplanetary companion makes the combination of compelling value.

Finally, scientifically successful missions require well planned operations, data handling, data analysis and theoretical modeling. The multidisciplinary nature of the STO objectives makes these aspects doubly important. This mission requires a centralized, operational approach with joint observing programs, as well as free and easy exchange of operational information and data promptly processed into physically meaningful units. Ample resources for data analysis and interpretation should be an intrinsic part of the mission, as should a strong contribution of theoretical modeling relevant to the objectives of the mission.

With the characteristics outlined above, the Solar Terrestrial Observatory can make a unique and valuable contribution to the NASA program of solar-terrestrial physics.

VII.Appendices

1. Figures

2. Tables

3. Acronyms and Abbreviations

AMPTE	Active Magnetospheric Particle Tracer Experiment
AU	Astronomical Unit
EML	Equatorial Magnetosphere Laboratory (of OPEN)
ERBSS	Earth Radiation Budget Satellite System
GTL	Geomagnetic Tail Laboratory (of OPEN)
IPL	Interplanetary Physics Laboratory (of OPEN)
ISEE	International Sun-Earth Explorer
ISPM	International Solar Polar Mission
OPEN	Origin of Plasmas in the Earth's Neighborhood
PCA	Polar Cap Absorption
PMR	Pressure-Modulated Radiometer
PPL	Polar Plasma Laboratory (of OPEN)
REP	Relativistic Electron Precipitation
SCE	Solar Coronal Explorer
SME	Solar Mesospheric Explorer
STO	Solar Terrestrial Observatory
STOIC	Solar Terrestrial Observatory Interplanetary Companion
STS	Space Transportation System (Shuttle)
UARS	Upper Atmosphere Research Satellite