TROPIX: A SOLAR ELECTRIC PROPULSION FLIGHT EXPERIMENT

J. Mark Hickman* and G. Barry Hillard**
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

Steven R. Oleson†
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

Abstract

The Transfer Orbit Plasma Interaction Experiment (TROPIX) is a proposed scientific experiment and flight demonstration of a solar electric propulsion vehicle. Its mission goals are to significantly increase our knowledge of Earth's magnetosphere and its associated plasma environment and to demonstrate an operational solar electric upper stage (SEUS) for small launch vehicles. The scientific investigations and flight demonstration technology experiments are uniquely interrelated because of the spacecraft's interaction with the surrounding environment. The data obtained will complement previous studies of the Earth's magnetosphere and space plasma environment by supplying the knowledge necessary to attain the strategic objectives of the NASA Office of Space Science. This first operational use of a primary ion propulsion vehicle, designed to withstand the harsh environments from low Earth orbit to geosynchronous Earth orbit, may lead to the development of a new class of electric propulsion upper stages or space-based transfer vehicles and may improve future spacecraft design and safety.

Introduction

Electric propulsion dates back nearly three decades. In the late 1960's and early 1970's, solar electric propulsion (SEP) spacecraft were designed and flown.[1] Proposed in the late 1970's was a mission to Halley's Comet that would have flown on the solar electric propulsion stage (SEPS). An engineering model of SEPS was tested before the program was canceled. From 1975 to 1978, mercury ion thrusters were being developed and were qualified for use on the P80–1 Teal Ruby spacecraft,[2] which was never flown and is still in storage. Since then, a variety of small station-keeping electric thrusters have been developed and flown by the United States, the United Kingdom, and the USSR. Research and development have continued,[3,4] and today Japan, Europe, and the United States are developing primary electric propulsion systems and are planning flight experiments within the next few years.

Current fiscal and political realities have forced the space community to look anew at the potential of SEP vehicles to achieve mission requirements in "smaller, cheaper, faster" ways. Because SEP provides a significant propellant mass savings over conventional chemical propulsion, it can perform better in station keeping, orbit transfer, or on-orbit maneuvering; it can deliver additional payload mass or allow the use of smaller and less expensive launch vehicles.[5,6] As smaller payloads are anticipated, generic upper stages for small expendable launch vehicles become attractive in terms of performance and cost savings.[7]

Initial designs are in progress for a solar electric upper stage that will provide a platform for the proposed Transfer Orbit Plasma Interaction Experiment (TROPIX). TROPIX will map the charged particle population of the Earth's magnetosphere and evaluate the interactions of the spacecraft with the plasma environment while demonstrating an operational SEUS. The purpose of the TROPIX mission is to return science data that could lead to improved spacecraft design, a greater understanding of the nature of the magnetosphere, and advances in the state of electric propulsion via demonstrated operational capability and technology transfer to industry.

---

*Project Study Manager, Member AIAA.
**Principal Investigator, Member AIAA.
†TROPIX Mission Analyst, Member AIAA.

This paper presents the science and technology mission objectives; the two classes of science measurements to be made during the mission; the spacecraft-plasma interactions that may occur during the mission; the design strategies that will permit measurement of interactions and ambient conditions while protecting the spacecraft from damage; and the systems of the SEUS spacecraft.

Mission Objectives

The objectives of the TROPIX mission are both scientific and technological. The following scientific objectives support the strategic goals of the NASA Office of Space Science to "understand the structure and dynamics of the magnetospheres of planets, especially that of our own Earth:"[8]

(1) Map the energy spectrum of ambient charged particles in the magnetosphere from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO) and, in so doing, validate and update models which provide information on the environmental effects on spacecraft systems.

(2) Evaluate the plasma conditions local to the spacecraft, both ambient and induced, and characterize energetic particles versus altitude.

(3) Evaluate the spacecraft/plasma interaction effects (including that of the thruster plume) and the electromagnetic compatibility of electric thrusters with spacecraft systems.

(4) Investigate the plasma interactions of selected samples of solar cell and array technologies, microelectronics, and spacecraft materials with and without electric propulsion conditions.

The following TROPIX mission objectives support space technology transfer:

(1) Demonstrate in space a long-life electric propulsion vehicle (approx. 1 yr) and validate guidance, navigation, and control concepts.

(2) Demonstrate a spacecraft design that allows long-duration operations in either LEO or GEO environments.

(3) Measure the effect on spacecraft systems, especially solar arrays, of long exposure (months) to the Van Allen radiation belts.

(4) Evaluate ion thrusters as multiple-environment plasma contractors.

The flight demonstration and the science investigation are uniquely synergistic in that the science data are enhanced by the use of electric ion thrusters. The ambient plasma will be seen not only in its natural state but also when disturbed by the induced plasma of the propulsion system. This should lead to a new understanding of the mechanics of the charged particle population. Moreover, the instructions dedicated to measuring the ambient plasma of the magnetosphere will also monitor the flight vehicle health diagnostics, perhaps leading to improvements in solar electric propulsion design. From this kilowatt-class SEUS vehicle, a larger SEUS could evolve for planetary exploration, possibly even a megawatt-class cargo vehicle for Mars colonization.[9]

The TROPIX mission begins with a small expendable launch vehicle (Pegasus XL class) delivering the TROPIX SEUS to a 325-km, 65° inclination, circular orbit (Fig. 1). After the vehicle checkout and deployment of solar arrays and instrument booms, the SEUS spacecraft starts its two 20-cm xenon ion thrusters and begins to slowly spiral outward at a constant inclination through the radiation belts to geosynchronous altitude (35 900 km). Figure 2 presents the vehicle altitude versus elapsed mission time. The vehicle coasts during shade periods to reduce the energy storage mass requirements. Analysis has shown that coasting in shade will allow the orbital eccentricity to build up to only 0.05 early in the mission. The vehicle can return to zero eccentricity (circular orbit) at geosynchronous orbit, although there is no hard requirement to do so at this time. An eccentricity of only 0.05 means that the transfer orbit is consequently very close to circular during data collection, thus easing the data stream deconvolution. Other coast periods are expected during the mission for special data collection. The total mission time is approximately 11 months. Precession of the orbital plane over the mission period allows the science instrumentation to measure plasma properties from a nearly spherical volume within the Earth's magnetosphere (Fig. 3). The high orbital inclination satisfies the science mission requirements discussed in the following section.

Science

The highly inclined orbit is chosen so that the variable plasma conditions encountered in the polar and equatorial regions of the Earth's magnetosphere can be studied in detail. Polar regions are of particular interest because they exhibit low thermal plasma densities, high-energy-electron charging of vehicles, extreme transient effects, and magnetic cusp conditions. LEO equatorial regions exhibit high thermal plasma densities, low plasma temperatures, and uniform magnetic field conditions.

Measurements fall into two classes: interactions studies and mapping of the ambient plasma, particle, and radiation conditions. The chief interactions to be studied are the effects of current collection by electrically biased surfaces on the vehicle floating potential. Plasma current collection from such surfaces is important because the spacecraft ground potential can differ significantly from that of the ambient plasma. This difference occurs as a result of current balance. Because of their large mass and low mobility, ions collected by negatively biased surfaces result in a relatively small plasma current density. The lightweight electrons, on the other hand, are readily collected by positively biased surfaces. The spacecraft reaches equilibrium at whatever potential results in a net collection current of zero. In the case of Space Station Freedom, for example, it has been shown[10] that major parts of the structure would "float" at about 140 V negative with respect to the ionosphere, close to the 160-V maximum used by its power system. Such large potentials are expected to cause major difficulties because of arcing and sputtering. To force the structure closer to the plasma potential, an active control device, a plasma contactor, has been added to the Space Station. Basically a hollow cathode discharge device, the contactor emits a continuous cloud of plasma which will effectively "ground" the structure to the ionosphere. The contactor is remarkably similar, both in theory of operation and in practical effect, to the ion thrusters baselined for TROPIX. Although the complex interaction of high-voltage systems with such a device are reasonably well understood in LEO, little is known about the behavior of such a system in the wide range of plasma conditions that TROPIX will encounter.

Measurements of the spacecraft/plasma interactions are made by on-board instruments that continuously monitor the potential of the vehicle with respect to its ambient environment. The study of the differences between natural and induced plasma environments is affected by the ON/OFF cycling of the ion thrusters.

In order to evaluate solar cell and array technologies, microelectronics, and spacecraft materials, an experiment plate is attached to the front of the vehicle where it will experience nearly continuous ram exposure. The samples exposed include solar cell coupons representing photovoltaic technologies of interest and materials designed specifically to study the effects of current collection. The current collection characteristics of both solar cells and spacecraft materials play a critical role in determining the final floating potential of a spacecraft. Of particular interest is the interaction of high-voltage surfaces with thruster plumes. Most of the measurement instruments as well as the basic design of the experiment plate and samples will rely heavily on experience gained from the Solar Array Module Plasma Interactions Experiment (SAMPIE),[11,12] designed for shuttle deployment in LEO.

The second class of measurements, mapping ambient conditions, is to be further defined, but a preliminary selection of instruments has been made (see Table 1). In polar regions, measurements will be made of auroral electron precipitation events. In the radiation belts, measurements will be made of the high-energy electrons and protons that occur in high densities. Measurements will be used to determine three-dimensional plasma structures in the magnetosphere and to calculate their dimensions and velocities. During substorm events, high-energy electrons and protons will be studied. Measurements made while the vehicle is in eclipse regions will allow us to study particularly low plasma densities and the increase of spacecraft charging in the absence of the photoelectric charge emission effect. The long-duration spiral orbit permits us to evaluate temporal environmental effects in many different regions of interest. The final selection of regions, measurements, and instruments is being made in consultation with the space science community and on the basis of a study[13] scheduled for completion in the fall of 1993.

Some spacecraft components will be used to serve as science instruments. In particular, the solar arrays will "sense" radiation damage by including instruments to periodically measure I–V curves for the solar cells. In addition, the ion thrusters will serve as plasma contacting devices.

Plasma Interactions

The TROPIX mission will map the charged particle energies in the magnetosphere and measure the interactions of the spacecraft with the ambient plasma under high- and low-voltage conditions with and without ion thruster contributions. During the mission, the spacecraft will electrically charge to balance incoming ambient ion and electron currents. The mechanics of spacecraft charging change as the vehicle traverses different regions in the magnetosphere.

In LEO, the spacecraft charging mechanics are influenced by ram/wake effects, the electrical grounding of the solar arrays, the exposure of high-voltage surfaces to the ambient plasma, and surface material electrical conductivity.[14] Damage to spacecraft components in LEO usually results from contamination, arcing, or sputtering, phenomena all dependent on the charging level, or floating potential, of the spacecraft.

To limit the charging effects of the spacecraft in LEO, several strategies are employed. The long axis of

the TROPIX SEUS is oriented parallel to the velocity vector for the entire mission, therefore, to reduce charging due to ram/wake effects, only the array wings need to be considered. Although the solar array cover glass is a dielectric, the kapton backs of the arrays can be coated with conductive indium tin oxide (ITO) to allow efficient ion collection in the ram direction, driving the floating potential less negative. High negative grounding voltages drive the spacecraft to very high negative floating potentials as it attempts to collect the less mobile ions more efficiently. Therefore, for bus voltages above 30 V, the spacecraft should be positively grounded, keeping the spacecraft floating potential near the plasma potential. The electrical conductivity of the spacecraft surface material also determines the charging in LEO. If the SEUS surfaces are conductive, they more readily collect electrons as the vehicle sweeps through the plasma, driving the spacecraft floating potential more negative relative to the plasma potential. However, if the surfaces are dielectric or electrically isolated, they will float near the plasma potential and thereby prevent interaction problems.

In GEO, the plasma is much more tenuous and lower in energy than in LEO and therefore not as damaging to spacecraft. However, in the event of a solar substorm, the low-energy plasma is replaced by a low-density, very energetic plasma, causing excessive spacecraft charging and its resultant severe damage. For example, the ATS–5 and ATS–6 spacecraft recorded floating potentials in the negative kilovolt range during a substorm.[15] Damage to spacecraft components in GEO results from electrostatic discharges due to the differential charging of different regions of the spacecraft. Transient currents in the form of electrostatic discharges occur if the electric fields between different regions exceed breakdown thresholds. These discharges cause avionics failures ranging from single-event upsets to system failure. In addition, differential charging causes "potential barriers"[16] that can disrupt the science instruments that measure the ambient plasma. The best design solution is to make all surfaces conductive and to tie them to a common ground. Dielectric surfaces such as the optical solar reflectors (OSR) and the backs of the solar arrays can be coated with a conducting material such as ITO.

One of the TROPIX science objectives is to study the plasma interactions of selected samples of solar cell and array technologies, microelectronics, and spacecraft materials at high voltages. Positioned on the ram surface of the SEUS, an experiment plate containing samples to be tested will be periodically biased +300 V relative to the spacecraft ground. Thus, the samples will collect electron currents and drive the rest of the spacecraft negative in order to collect a balancing ion current. During the operation of the experiment, the spacecraft could have a floating potential of greater than −100 V for a 30-V bus voltage. It is important, therefore, to design the spacecraft so that all other charging effects are minimized for both LEO and GEO environments.

The LEO and GEO environments drive the spacecraft design in opposite directions. The LEO environment requires that spacecraft surfaces be electrically isolated to maintain the spacecraft floating potential near the plasma ground; GEO requires that all conductive surfaces be tied to a common ground. The TROPIX SEUS will combine these disparate requirements in one design. The spacecraft main body and solar array substrate are coated with a uniformly conductive layer. An electrical isolation switch provided between the spacecraft ground and the conductive coatings will float the conductive layers in LEO and tie them to the spacecraft ground in GEO.[16] The switch may be mechanical or it may be a semiconductor material that acts as a conductor beyond a certain breakdown voltage.

SEUS Spacecraft Systems

The SEUS spacecraft is designed to accomplish the TROPIX mission but will be sufficiently generic to accommodate other SEUS missions with little or no modification. The TROPIX SEUS spacecraft design includes several systems: electric propulsion, solar power, thermal control, guidance, navigation and control, communications, command and data handling, and structural-mechanical. These systems are described briefly in the following sections.

Propulsion

The propulsion system is composed of ion thrusters, power processor units, attitude control thrusters, propellant tanks, propellant, and a propellant management system. Two gimbaled, 20-cm xenon ion thrusters are used for primary propulsion and ΔV requirements. Each thruster has an input power of 875 W at the beginning of life (BOL) and operates at 80 percent efficiency, providing a thrust level of 39 mN. The 20-cm ion thruster is a scaled version of the 30-cm thruster currently under development at the NASA Lewis Research Center. The 20-cm thruster would retain the same cathode and neutralizer as the larger thruster but would require both smaller grids and chamber.

Two 0.1-kg hydrazine thrusters are mounted on the outboard gimbal brackets that support the ion thrusters. The hydrazine thrusters are used for attitude compensation against disturbance torques in shade regions and are gimbaled to eliminate extra torques. The ion thrusters

supply attitude control in addition to primary propulsion when the spacecraft is in the Sun.

Power

The power system consists of solar arrays, an energy storage system, and a power management and distribution system. The spacecraft deploys two modified advanced photovoltaic solar array (APSA)[17]-solar array wings using 18-percent efficient gallium arsenide solar cells to produce a combined power of 2.3 kW BOL. The baseline energy storage system consists of a nickel cadmium battery configured to supply a maximum of 440 W-hr, a 100-percent depth of discharge (DOD), with an 80-percent operating DOD, and an operating charge/discharge rate of 1C.

Thermal Control

The thermal control system (TCS) consists mainly of passive elements. Resistive heating may be required for some spacecraft components to maintain a critical temperature range. To insulate the internal components from the heat of the thrusters, the rear (wake) surface of the spacecraft is covered with multilayer insulation (MLI). The sides of the spacecraft are covered with OSR to prevent solar insolation and infrared energy from entering the SEUS bus.

Guidance, Navigation, and Control

The guidance, navigation, and control (GN&C) system is still under consideration but will consist of attitude control thrusters, an inertial measurement unit (IMU), an on-board flight computer, and some combination of sensors that will yield power and thrust vector control, possibly semiautonomous orbit determination. Sensors being considered are sun sensors, horizon sensors, star trackers, and a global-positioning satellite (GPS) receiver. The IMU will be used to establish an inertial reference frame for attitude determination. Hydrazine thrusters are sufficient for attitude control, eliminating the need for other attitude control devices.

Communications

The communications system consists of a NASA standard near-Earth transponder, two hemispherical antennas, and an antenna diplexor unit. The transponder operates at S–band frequencies and has a 5-W rf transmission power. The ground control is located at the Wallops Flight Facility. Communications contact occurs when the spacecraft is viewed by the Earth station at an elevation angle exceeding a minimum of 10°. The uplink command data rate is 2 kbps. The downlink includes a 4-kbps channel for the spacecraft health and safety monitoring.

Science data are collected and stored on board the spacecraft at an average rate of 800 bps. When the spacecraft is in contact with the Earth station, the science data are forwarded at a burst rate that allows the complete transmission of all data stored since the previous ground contact. The downlink burst data rate is a function of the range, the worst case occurring at geosynchronous altitude. The amount of data transmitted in a given ground contact is a function of the view time and data rate. A communications link analysis showed that a data rate of 100 kbps is achievable in geosynchronous orbit and is sufficient to transmit all stored data in the minimum view-time case of 11.6 min/day.

Command and Data Handling

On-board command and data-handling (C&DH) functions are performed by the TROPIX spacecraft computer. Spacecraft commands are periodically required to reconfigure the plasma interaction/magnetosphere mapping sensors, to start and stop the electric propulsion system for either orbit control or plasma contacting, or to reconfigure the spacecraft systems after the occurrence of unexpected conditions.

The spacecraft telemetry consists of mission data from the science instrument suite and spacecraft health and status data, including robust instrumentation of the electric propulsion system. During the early low orbit portion of the mission, the spacecraft will be experiencing the most rapid change in electromagnetic field characteristics, which will require a relatively frequent sampling of mission data. Spacecraft health and status monitoring will also be more important during the early portion of the mission. Later in the mission, telemetry requirements will be relaxed because the orbit periods will be longer and hence the mission data sampling rates lower. These sampling rates are adjustable via ground command.

Structural/Mechanical

The structural/mechanical system of the spacecraft includes a cage that supports and protects the instruments and internal systems, two solar array wing motors and deployment system, an instrument boom deployment system, and a thruster gimbal system. The gimbal system supports both the xenon ion thrusters and the hydrazine attitude control thrusters. Each hydrazine thruster is attached to the outer side of an ion thruster mounting bracket. The hydrazine attitude control

system (ACS) counteracts disturbance torques during shade periods whereas the ion thrusters maintain three-axis stabilization and provide steering for the mission during sun periods. The ion thrusters or the hydrazine thrusters can be independently gimbaled in either of two axes. Sufficient control to impart yaw, pitch, or roll maneuvers is realized by gimbaling the thrusters up to $\pm 15°$.

The spacecraft structure will protect the avionics and science instrument electronics from the radiation environment, especially during the long transit through the Van Allen belts. A 2-mm aluminum shield should be sufficient to limit the radiation dose to 100 krads.

Summary

The proposed Transfer Orbit Interaction Experiment (TROPIX) will add substantially to our knowledge of the Earth's magnetosphere and will demonstrate an operational solar electric upper stage (SEUS). This upper stage is designed to be a high-power, low-mass, low-volume, long-life bus capable of being launched by a small launch vehicle. Included in the SEUS design are strategies that will limit the amount of spacecraft charging and the resultant damage to spacecraft components. The TROPIX mission does not separate the vehicle from the science instrumentation; rather, it exploits the unique capabilities offered by solar electric propulsion to enhance the science return. By understanding the interactions of the vehicle with the charged particle population, not only is our knowledge of vehicle design improved, but we gain a better understanding of the ambient plasma and its temporal changes. The scientific investigations and flight demonstration technology will hopefully lead to the development of a new class of electric propulsion upper stages or space-based transfer vehicles and to improvements in spacecraft design and safety.

References

1. Kerslake, W.R. and Ignaczak, L.R., "Development and Flight History of SERT II Spacecraft," NASA TM–105636, 1992. (Also, AIAA Paper 92–3516, July 1992.)

2. Power, J.L., "Planned Flight Test of a Mercury Ion Auxiliary Propulsion System, I—Objectives, System Descriptions, and Mission Operations," NASA TM–78859, 1978.

3. Sovey, J.S., Curran, F.M., Haag, T.W., Patterson, M.J., Pencil, E.J., Rawlin, V.K., and Sankovic, J.M., "Development of Arcjet and Ion Propulsion For Spacecraft Stationkeeping," NASA TM–106102, 1992. (Also, IAF Paper 92–0607, Sept. 1992.)

4. Sovey, J.S., Hamley, J.A., Patterson, J.J., Rawlin, V.K., and Sarvey-Verhey, T.K., "Ion Thruster Development at NASA Lewis Research Center," NASA TM–105983, Jan. 1993.

5. Avila, E., "ELITE Program Overview," AIAA Paper 92–1559, Mar. 1992.

6. Meissinger, H.F., "A Small, Primary Solar-Electric Propulsion Demonstration Satellite," AIAA Paper 92–1566, Mar. 1992.

7. Reitan, T., "Small Upper Stage, An Orbit Enabling Hydrazine Propulsion Stage For The Small Satellite Community," AIAA Paper 92–1670, Mar. 1992.

8. "Space Science and Applications: Strategic Plan 1991," NASA TM–107811, 1991, p. 58.

9. Hickman, J.M., Curtis, H.B., Kenny, B.H., and Sefcik, R.J., "Systems Analysis of Mars Solar Electric Propulsion Vehicles," AIAA Paper 90–3824, Sept. 1990.

10. Purvis, C.K., "Environments Workbench Analysis of On-Orbit Floating Potentials of Space Station Freedom," To be presented at the 28th IECEC, Atlanta, GA, Aug. 8–13, 1993, paper 93IEC–278AP–9.

11. Hillard, G.B. and Ferguson, D.C., "The Solar Array Module Plasma Interactions Experiment (SAMPIE): Science and Technology Objectives," To be published at the Journal of Spacecraft and Rockets, 1993.

12. Hillard, G.B. and Ferguson, D.C., "The SAMPIE Flight Experiment Final Technical Requirements Document," NASA TM–106224, 1993.

13. Russell, C.T., "Magnetospheric Mapping Sampling Study," Grant number NAG3–1503, Work in progress, University of California, Los Angeles, CA, 1993.

14. Herr, J.L. and Chock, R., "TROPIX Spacecraft Interactions Group Preliminary Report," NASA CR–191149, 1993.

15. Rubin, A.G. and Garrett, H.B., "ATS–5 and ATS–6 Potentials During Eclipse," Spacecraft Charging Technology, 1978, NASA CP–2071, 1978, p. 38.

16. Mandell, M.J., et al., "The Decrease in Effective Photocurrents Due to Saddle-Points in Electrostatic Potentials Near Differentially Charged Spacecraft," IEEE Trans. Nucl. Sci., Vol. NS–25, Dec. 1978, pp. 1313–1317.

17. "Advanced Photovoltaic Solar Array Prototype Fabrication, Phase IIB," TRW Report No. 51760–6003–UT–00, May 1990.

Table 1.—TROPIX Payload Measurement Instruments

Instrument	Energy range	Species
SAMPIE[a]-derived		
Langmuir probe	0.1 to 20 eV	Electrons and ions
V-body probe	±20 eV	
Neutral pressure gauge	10^{-7} to 10^{-4} torr	
Electrometers	10 nA to 10 mA	Oxygen, xenon, and hydrogen
Arc counters	0 to 1000/sec	Electrons and ions
Electronics and high-voltage power supplies	±300 V	
Mid-energy-range particle detectors	2 to 10 eV	Electrons and two-ion species
High-energy particle detectors	50 to 2000 keV 50 to 5000 keV 500 to 1500 keV	Electrons Protons Helium ions

[a]Solar Array Module Plasma Interactions Experiment.

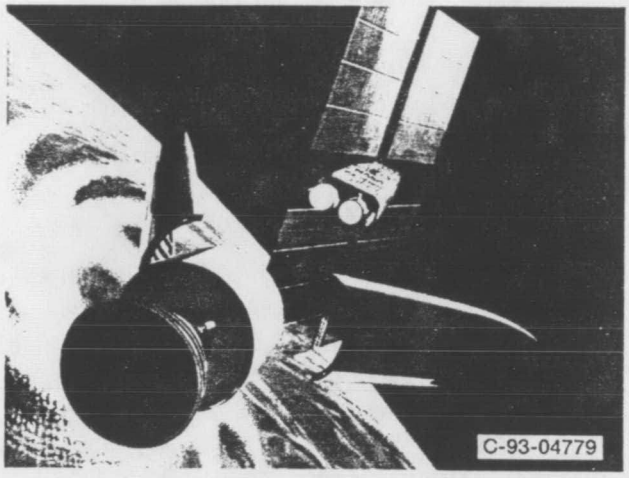

Figure 1.—Conceptual rendering of TROPIX after launch and deployment.

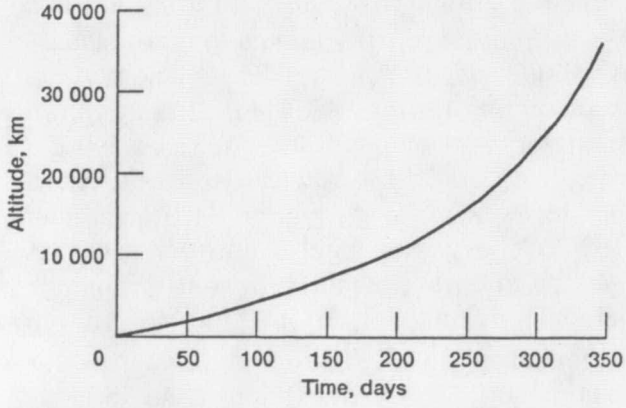

Figure 2.—Spacecraft altitude versus time for TROPIX mission.

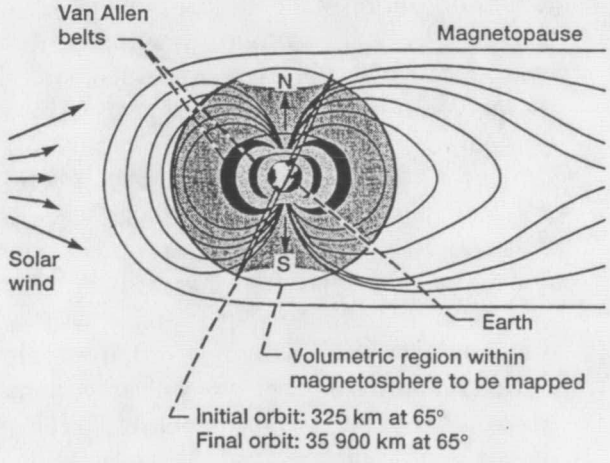

Figure 3.—TROPIX mapping region within Earth's magnetosphere.