Early Prediction of Geomagnetic Storms
(and Other Space Weather Hazards)

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Abstract

A detailed conceptual design has been developed for a mission and microspacecraft that can provide information needed to answer key questions about the physics of space weather and also both provide and validate a system for early warning of hazardous space weather. A single small launch vehicle and individually tailored Venus gravity assists disperse nine microspacecraft in a 0.53–0.85 AU band around the Sun. Collectively, the microspacecraft can investigate large-scale organization of coronal mass ejections (CMEs) and particle acceleration mechanisms near their shocks. Radial and longitudinal dependencies, magnetohydrodynamic (MHD) turbulence in the solar wind, and variations in solar wind velocities and densities can all be studied. Simultaneously, at least one of the microspacecraft is near the Sun–Earth line almost continuously and can be monitored for early warning of hazardous space weather.

Introduction

In their paper, “On Space Weather Consequences and Predictions,” *Feynman and Gabriel* [2000] conclude that an important next step in the development of the understanding and prediction of hazardous space weather is to observe CMEs at heliocentric distances significantly less than 1 AU and along the Sun–Earth line. These observations are needed to test interplanetary shock acceleration and release models for protons and ions with energies >10 MeV and to provide improved long-lead-time predictions of geomagnetic storms. High-velocity CMEs cause geomagnetic storms [*Tsurutani and Gonzalez*, 1997] and energetic particle events [*Kahler et al.*, 1984; *Gosling*, 1993] that present major hazards to both space systems and humans in space [*Feynman and Gabriel*, 2000]. As the fast CME propagates through the solar wind, it drives a shock in the wind, and it is this shock that apparently accelerates protons and ions to MeV energies per nucleon. When the shock arrives at the magnetopause, it produces the sudden commencement of the geomagnetic storm, and the rest of the storm is driven by the solar wind particles and fields within the post-shock compressed region and interplanetary CME itself [*Hirshberg and Colburn*, 1969; *Gosling et al.*, 1991; *Tsurutani and Gonzalez*, 1997]. The shock is often accompanied by very high fluxes of hazardous protons. Thus, early forecasting of major geomagnetic storms requires early, accurate measurements in CMEs of the velocities and densities of the solar wind and the directions and intensities of the magnetic fields.

Spacecraft have been positioned near the L1 Earth–Sun libration point (and thus near the Sun–Earth line) to make in situ measurements and warn of potential hazards. Unfortunately, single-location measurements within a CME are unable to resolve questions about certain key CME characteristics and processes. In addition, CMEs have already traveled 99% of the way to Earth when they reach this location, and warning times are limited to an hour or fraction of an hour. Observations made nearer the Sun, combined with three-dimensional (3D) MHD models of propagation of disturbances in interplanetary space (such as the models of *Odstricil and Pizzo* [1999 a, b]), can permit the estimation of the timing and strength (i.e., the Dst index) of the storm, its structure, and the probability as a function of time of substorm onsets throughout the storm [*Feynman and Gabriel*, 2000].

CMEs and Solar Wind Streams

High-velocity CMEs are the most important cause of the greatest geomagnetic storms and the greatest solar energetic particle events [*Tsurutani and Gonzalez*, 1997]. In contrast, geomagnetic storms caused by high-velocity solar wind streams are generally not as strong as those caused by CMEs (although they are longer lasting). Some positively charged particles may be accelerated by these streams, but they do not have high enough energies or large enough fluxes to directly constitute a space hazard. Both CMEs and solar wind streams, however, may play roles in producing the highly relativistic electrons that sporadically appear in the Earth magnetosphere [Baker et al., 1996].

CMEs and Space Weather Hazards

High-velocity CMEs cause large hazardous particle events by accelerating particles at the shock. Turbulence near the shock confines particles to the vicinity of the shock long enough to permit acceleration to high energy. Some particles leak away from the shock and propagate to Earth. The particles are both influenced by the turbulence and are a source of the turbulence. The leaking particles begin to appear at Earth within tens of minutes after CME initiation at the Sun. Other particles remain trapped near the shock and can be responsible for hazardous, major peak flux events associated with arrival of the CME shock at Earth, 1–3 days after CME initiation at the

Sun. The particle acceleration process is an area of active research and has been verified for energies <15 MeV. However, no direct verification has been possible for energies >30 MeV, much less energies >100 MeV and up to GeV. The turbulence responsible for the acceleration and confinement of the particles to the vicinity of the shock has not been observed at 1 AU, presumably because the plasma wave frequencies involved are in a range that is difficult to observe. However, at smaller solar distances, the frequencies involved are in an easily observed MHD range, as shown in Table 1.

The threat a CME headed toward Earth poses to human interests is dependent on the characteristics of that particular CME. While early warning that a CME is coming is possible through remote observations from spacecraft at long distances from the CME, it is important to make in situ measurements to forecast the attributes of the storm. These can answer important questions about CMEs and associated processes in general, and thus help improve future early warning capabilities. Simultaneously, on their own, the measurements within individual CMEs can allow assessment of hazard potential and, when appropriate, trigger warnings.

Mission Objectives

The objectives of the mission are to better understand the physics of space weather and provide and validate early warning of hazardous space weather. Specifically, regarding the former, the mission is designed to allow the study of two scientific questions that are very important to predicting space weather hazards: the large-scale internal structure and radial evolution of interplanetary CMEs and the trapping, release, and acceleration of high-energy particles at interplanetary shocks.

Specifically, regarding the latter, the mission is designed to provide much earlier warnings of high energetic particle peak fluxes, the probability of "killer" electrons in the magnetosphere, and severe geomagnetic storms.

These objectives can be met if enough measurement locations are used, if they are well distributed around the Sun in both solar longitude and solar range, and if measurements are available almost continuously near the Sun–Earth line but much closer to the Sun than L1. Solar wind, energetic particle, and magnetic field measurements are required. These objectives, locations, and measured parameters have been incorporated in the Multimission Space and Solar Physics Microspacecraft (MSSPM) detailed conceptual design that was developed by NASA/JPL [*Collins*, 2000a].

The Mission

The MSSPM mission provides information needed to answer key questions about the physics of space weather, and it also both provides and validates a system for early warning of hazardous space weather. Preceded by related earlier studies [*Collins and Horvath*, 1995; *Collins et al.*, 1999], the MSSPM detailed conceptual design was completed in the spring of 2000. Although the microspacecraft is capable of multiple types of missions, the focus in this work is the mission described here. Nine microspacecraft, their integration system, and an upper stage can be launched by a small, Taurus-class vehicle by late 2005 or in mid-2007, a date better suited to both needed hardware development before launch and good post-launch microspacecraft dispersion around the Sun prior to the next solar max. Immediately after launch, the upper stage then injects the microspacecraft on a Type 1 trajectory toward Venus, and shortly after injection the spacecraft separate from the integration system. Each microspacecraft flies independently to Venus, where an individually customized gravity assist places it in a particular unique orbit around the Sun. The orbits are designed so that the microspacecraft gradually spread out in a band ranging from 0.53 to 0.85 AU from the Sun. Orbital periods of 6.1 to 7.8 months, perihelions of 0.53 to 0.65 AU, and aphelions of 0.75 to 0.85 AU characterize the orbits, and the geometry of the collection of microspacecraft around the Sun constantly changes. With nine microspacecraft dispersed around the Sun, most large CMEs are intercepted at multiple solar distances and longitudes. Details of the trajectory to Venus and orbit designs were presented by *Collins* [2000b].

The microspacecraft continuously acquire and analyze data. The results (and, in some cases, particularly important raw data) are compressed and stored for later transmission to Earth, which is scheduled once or twice a week and uses Deep Space Network (DSN) 34-m stations. The use of onboard analysis results in considerable reduction in needed communications and enables many microspacecraft simplifications.

The acquisition of science information utilizes all the microspacecraft. In contrast, early warning of hazardous space weather utilizes a single microspacecraft—typically the one at that time that is closest to the Sun–Earth line. As shown in Figure 1, near-continuous early warning coverage, defined as the presence of at least one microspacecraft between 0.53 and 0.85 AU from the Sun and within ±22.5 degrees of the Sun–Earth line, starts approximately 10 months after Venus gravity assist. (The ±22.5 degrees value was chosen based on an expected average CME width of roughly 45 degrees [Burkepile and St.Cyr, 1993].) Enhanced beacon-mode communications utilizes the DSN 11-m network and can provide hazard alerts (and specific data on the hazards).

The Microspacecraft

The microspacecraft detailed conceptual design was documented by *Collins* [2000a], and top and side views of the microspacecraft are shown here in Figures 2 and 3. Excluding its narrow low-gain antenna and magnetometer boom, the configuration looks somewhat like an octagonal bobbin that is approximately 32-cm high and 65-cm wide from corner to corner. The microspacecraft is spin stabilized, and its spin axis goes through its center as well as the centers of the low-gain antenna on top of the microspacecraft and a recessed, downward-pointing star camera/tracker near its bottom. The spin axis is maintained perpendicular to the Sun–microspacecraft–Earth plane, and the solar arrays are illuminated from the side as the microspacecraft spins. Also as it spins, four switched, phased-array antennas de-spin the downlink beam and point it at Earth. A Sun camera/scanner is located on the opposite side of the microspacecraft from the energetic particle detector (EPD), which can be seen in Figure 3, and the fields of view of the scanner, electron and ion analyzer (E&IA), and EPD sweep through the Sun during each revolution. Sensitivity ranges for the instruments are selected to be able to accommodate hazardous space weather [*Feynman and Gabriel*, 2000]. For example, the E&IA can measure solar wind up to 2000 km/s; the EPD can identify penetrating protons up to 100 MeV; and the magnetometer range extends to ±200 nT in each vector. Each microspacecraft also has the capability of the constrained accommodation of a selected unit, an extreme ultraviolet monitor, for instance. The total mass of each microspacecraft, including 35% contingency and including propellant, is 15 kg.

Energetic Particle Forecasting

As discussed by Collins and Feynman at the March 2000 Chapman Conference on Space Weather, the mission can contribute to the new science needed to enhance solar energetic particle forecasting. It can provide information on the turbulence in the solar wind in front of the shock at solar distances substantially less than 1 AU. This knowledge, obtainable only through in situ measurements, is necessary to test present models for particle acceleration to energies much greater than 15 MeV. The mission also permits the radial and longitudinal dependence of the fluxes and fluences to be measured. Lack of knowledge concerning the radial dependence of the flux of high-energy particles trapped in the vicinity of the shock is currently a major deficiency in construction of prediction models.

The mission can also directly support the forecasting of peak fluxes and high flux duration. By measuring the particle flux at the shock much nearer the Sun than would be the case from L1, the microspacecraft, for the first time, can provide information that can be used for early prediction of peak fluxes at Earth. The length of time the fluxes remain high depends on the shock speed and particle release, which MSSPM can observe. Also, its observation of the pre-shock interplanetary medium permits improved prediction using 3D MHD propagation models.

A contribution can also be made to forecasting of highly energetic electrons in the magnetosphere. There is not as yet general agreement in the scientific community as to the process causing very high energy relativistic electrons in the magnetosphere, but they often appear in association with very highly varying solar wind velocities and densities. These can be measured by MSSPM and propagated to Earth using existing or improved 3D MHD models, thus providing data that are likely to be helpful in forecasting.

CME Geomagnetic Storm Forecasting

The mission can contribute to the new science needed to enhance CME geomagnetic storm forecasting. Using its multipoint observations can lead to understanding CME internal large-scale organization (counter-streaming particles, magnetic clouds and flux ropes, and compositional anomalies). The observed propagation of CMEs can be compared with that expected according to MHD propagation models, and the models can be validated or refined as necessary.

The mission can also directly support the forecasting of CME-initiated geomagnetic storms. An important parameter for geomagnetic storm prediction is the rate at which the southward component of the interplanetary field is brought up to the magnetopause. The quantities needed for prediction are primarily the solar wind velocity and the strength and direction of the magnetic field at the magnetopause. The mission can utilize a microspacecraft close to the Sun–Earth line to observe velocities and magnetic fields at distances that are substantially nearer the Sun than 1 AU, and alerts can be issued when appropriate. The information acquired can be used as initial conditions in the propagation models to forecast the arrival and intensity of major storms at Earth. The probability of substorms can also be evaluated but not the onset of individual substorms. Much earlier prediction of hazardous space weather can be expected.

Conclusions

The MSSPM study [*Collins,* 2000a] concluded that the mission and flight system are technically feasible, would greatly expand knowledge of the physics of space weather, and would provide hours-to-days warning of hazardous space weather.

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FIGURE CAPTIONS

Figure 1: Warning Coverage Within ±22.5 Degrees of Sun–Earth Line. Each row shows the coverage for a particular microspacecraft. The length of gaps in the overall coverage are identified at the top of the figure.

Figure 2: Microspacecraft Top View

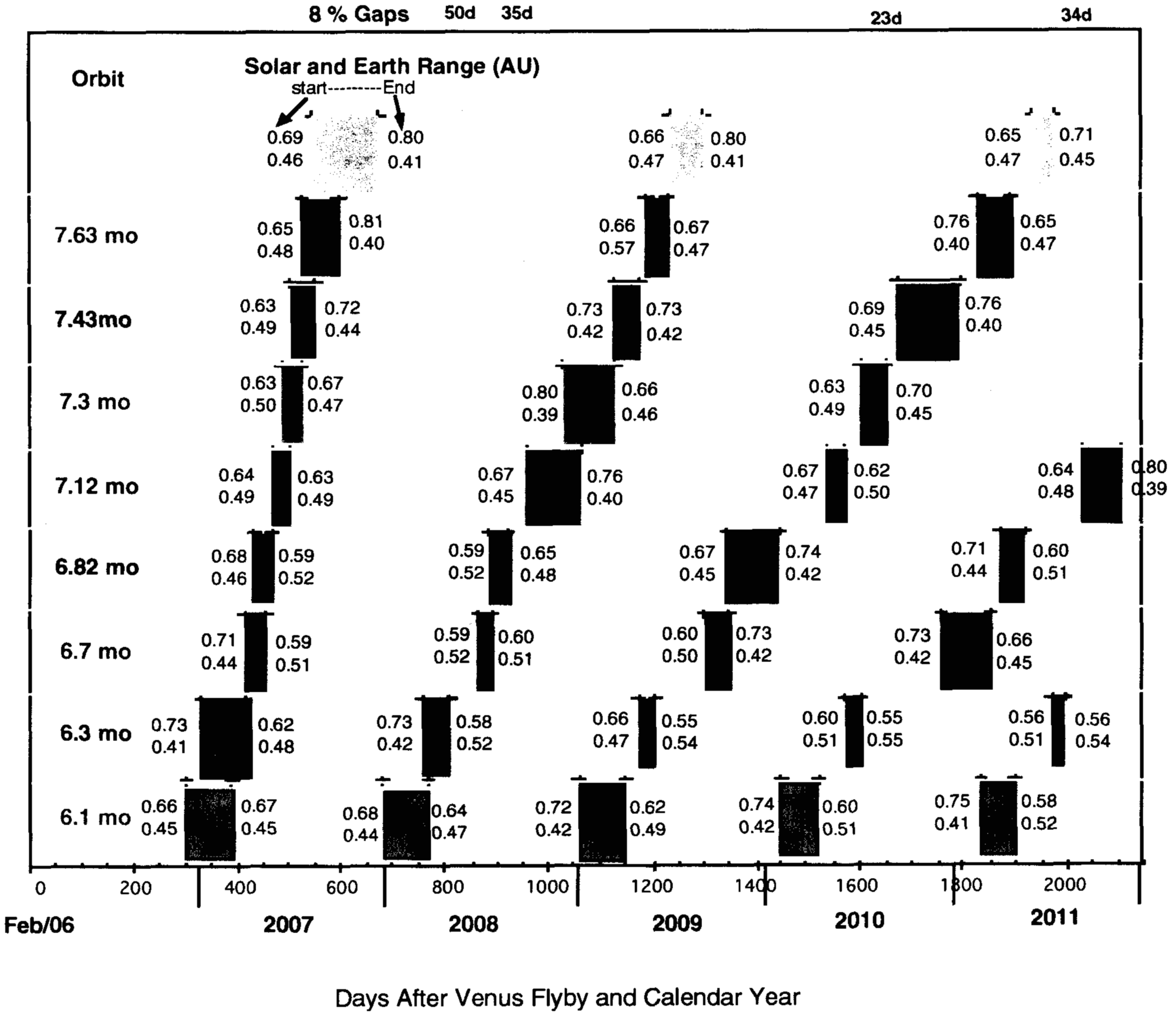
Figure 3: Microspacecraft Side View

TABLES

Table 1: MHD Wave Periods

Energy (MeV)	Solar Distance (AU)	Period of Waves (min)
10	0.5	8
10	0.8	13
500	0.5	60
500	0.8	95

FIGURES (are on following sheets)



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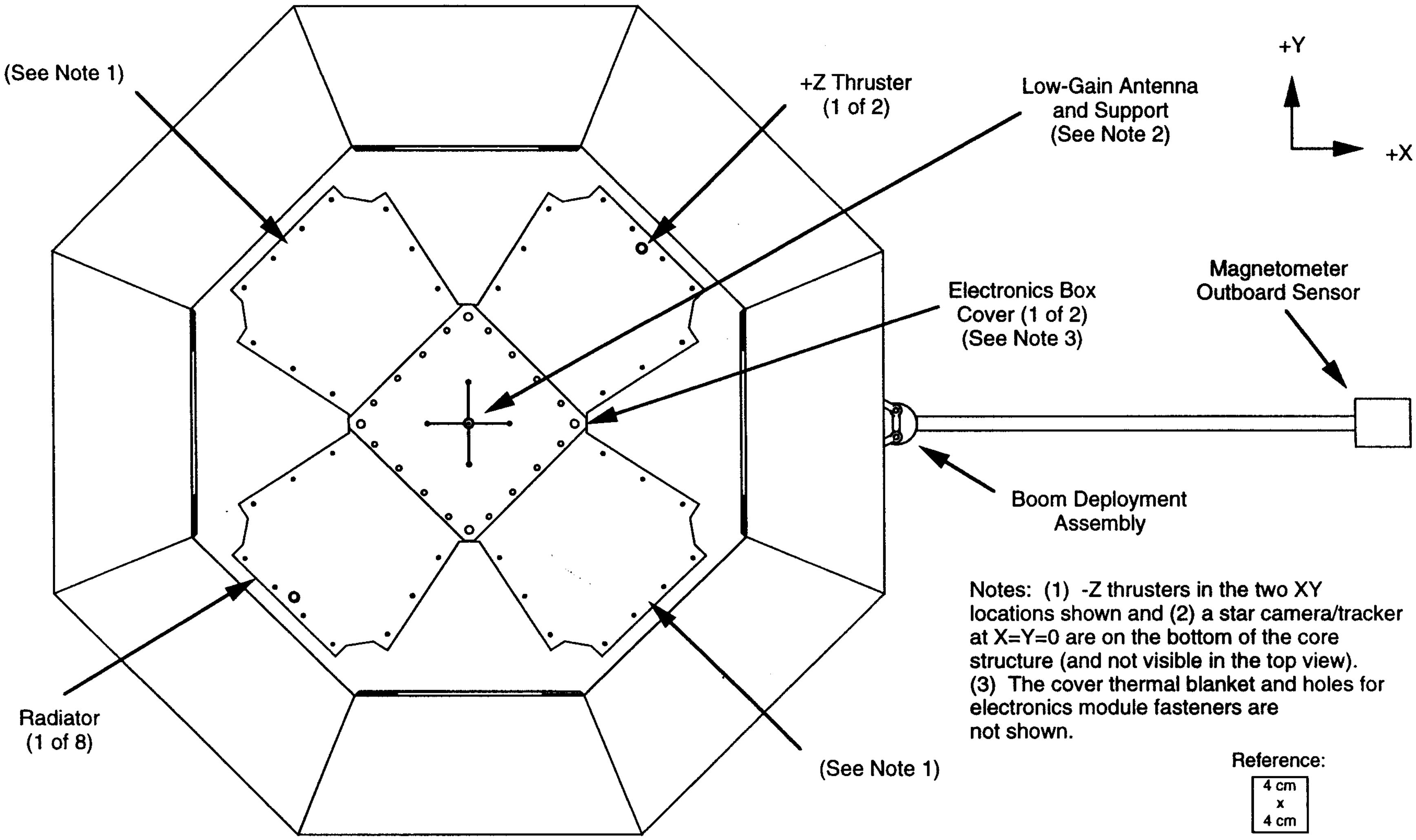

Notes: (1) -Z thrusters in the two XY locations shown and (2) a star camera/tracker at X=Y=0 are on the bottom of the core structure (and not visible in the top view).
(3) The cover thermal blanket and holes for electronics module fasteners are not shown.

Figure 2: Microspacecraft Top View

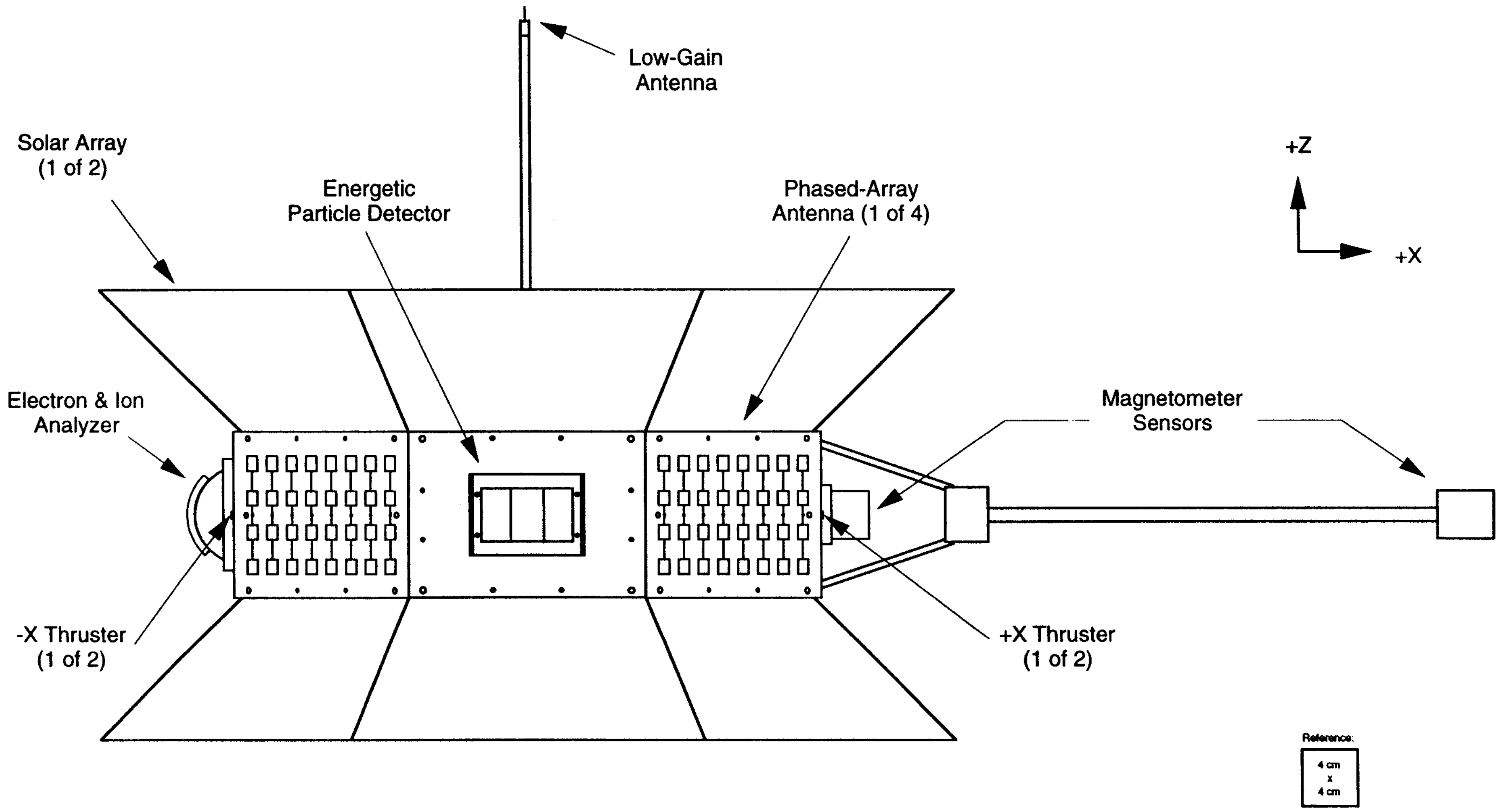

Figure 3: Microspacecraft Side View