Engineering Tethered Payloads for Magnetic and Plasma Observations in Low Orbit

William J. Webster Jr.*
NASA Goddard Space Flight Center, Greenbelt, Maryland

The physical processes operating in the region between 90 and 400 km are of crucial importance in understanding the Earth's atmosphere and magnetosphere. Our current knowledge of this region is based on a modest data base of sounding rocket, maneuverable satellite, and remote sensing observations. Tethered satellites will allow much more extensive observations of two of the major components of this environment: the geomagnetic field and the magnetospheric/ionospheric plasma. However, the use of a tethered observing platform places unconventional requirements on such system design factors as attitude knowledge and dynamic isolation. This reorientation in engineering design philosophy to a recognition of the lack of dynamic independence is the most crucial factor in the systems engineering of tethered payloads for science observations.

Introduction

WHEN the Tethered Satellite System[1] (TSS) begins flying in 1990, the study of the interaction between the Earth's atmosphere and magnetosphere will be one of the first disciplines to benefit. In a recent paper, Webster[2] has examined some of the problems in the study of the atmosphere/magnetosphere boundary to which tethered satellites (and especially TSS) can contribute. The interested reader is referred to that discussion for a general review of the problems to be attacked by tethered satellites. This discussion will concentrate on the science and systems engineering of two aspects: 1) the observation of the plasma component and its dynamics and 2) the measurement of the magnetic field and the separation of the measured field into that due to the Earth's core and crust and that due to the motion of plasma.

Figure 1 shows the boundary region between the mesosphere (where neutral particles dominate) and the protonosphere (where ionized particles dominate). The TSS will operate in the 90–500 km altitude region.[1] At the high end of this region, the number density of neutrals is essentially zero. At the lower end, the plasma is very strongly influenced by the large proportion of neutrals. The altitude range likely to be accessed by tethered satellites of the TSS class spans the region of the transition from ionospheric to magnetospheric physics. In this region, the character of the observed magnetic field changes from a combination of a relatively steady field that is dominated by strong temporal variations to a relatively steady field with a modest temporal variation.

Observation of the Plasma

The initial TSS missions will begin the task of probing the plasma environment by two techniques. Conventional satellite instrumentation on the deployer and on the subsatellite yields the "traditional" kinds of data on the plasma (number density, ionic composition, velocity, and so forth). In the case of the proposed low-altitude mission (TSS-2), some means of correcting for the passage of the subsatellite through the relatively dense medium at about 130 km may be necessary. However, the Atmosphere Explorer satellite experience[3] has shown that new varieties of instrumentation are not essential until the observing altitude drops below 130 km. In addition to the direct observation of the plasma properties, the electron collection experiments planned for TSS-1 (20 km upward deployment) and TSS-3 (100 km upward deployment) are ionosphere/magnetosphere modification experiments on a scale that previously has been impossible. By deploying a conducting tether with a subsatellite that is forced to be at the potential of the local plasma, electron current derived from the plasma will flow in the tether. The tether is one leg of a circuit that includes a possible closure path in the ionosphere. Observation of the local plasma properties before and after the collection experiments will give valuable insights into the precise nature of the physical processes that mediate this closure path on both micro- and macroscales.

Although these experiments will be of extreme value in understanding the plasma properties, one essential ingredient will, of necessity, be lacking. Because only one tethered payload is planned per flight for at least the first three flights of the initial TSS campaign, only two discrete sets of measurements can be made at any one time: on the tethered payload and on the deployer (carrier). Therefore, if the scale height of a given phenomenon is greater than the tether length, the measurements of that phenomenon will be highly correlated. Conversely, if the scale height is much less than the tether length, there will be no relation between measurements at the deployer and measurements at the subsatellite. This dif-

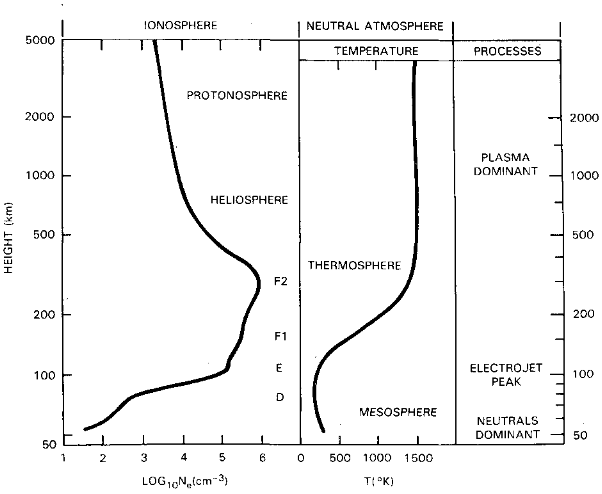

Fig. 1 Boundary region between the mesophere and the protonosphere.

Presented as Paper 88-0689 at the AIAA 26th Aerospace Sciences Meeting, Reno, NV, Jan. 11–14, 1988; received Feb. 22, 1988; revision received Aug. 9, 1988.

*Geophysicist, Geophysics Branch, Laboratory for Terrestrial Physics. Member AIAA.

ficulty is, of course, inherent in attempting to infer the spacial gradient of a physical process from measurements at only two discrete positions.

Although the physics of the plasma in the altitude region of 90–400 km has been studied from the dawn of the space age, direct observation of the properties of this altitude region has usually been the province of single spacecraft observations. As the sophistication and volume of the available data have increased, the need for simultaneous observations at multiple altitudes has become as clear as it is for the outer magnetosphere.[4] This is especially clear in the regions around the magnetic poles. The existence of extensive flows of charge, usually referred to as the Birkeland currents, which appear to close the circuit between the ionospheric currents and the magnetospheric currents, has long been known.[5] The known variations are sufficiently rapid in both space and time that observations over distances of a few hundred meters and times of a few tens of minutes will differ drastically.[6]

Perhaps less well appreciated are the similar characteristics of the current flow in the equatorial region. Observations in this orbital inclination regime are the most likely, since, for at least the near future, TSS-class missions will be restricted to near-equatorial orbits by the requirement that the system operate from the Shuttle. Measurements of the properties of the upper part of the equatorial electrojet[7] and the physics of the electrojet's merging with the lower magnetosphere by gradient techniques can make a major impact in our understanding. This discussion will show the system's engineering considerations that enter into this kind of mission design.

The ideal mechanism for making the desired observations is a combination of a tether with a length of about 100 km deployed in the downward direction from Shuttle altitude (220 km) and a second tether about 200 km long deployed in the upward direction. In each case, the tether would have multiple payloads attached at intervals determined by the physical properties of the local environment. In some cases, the scale heights of the processes to be observed could be as short as 200 m. Usually, the scale heights are a few tens of kilometers.[7] Ideally, the two tethers should be deployed simultaneously; however, the requirements this woud place on the carrier resources might be too stringent.

The predominant current flow in the equatorial region is the equatorial electrojet. This mostly east-west current follows the geomagnetic equator with a half-current width in the horizontal direction of about 4 deg and a half-current width in the vertical direction of 15 km.[7] The bulk of the current flows between altitudes of 90 and 130 km, and, although most of the flow is roughly along lines of magnetic latitude, a considerable flow also occurs in the meridional plan.[7] Variations in the flow are dependent on local solar time, the level of solar activity, and the various winds (both neutral and ion) that move the charge about.

Scale heights for electron process are determined by the electron gyrofrequencies for the altitudes considered here. The average electron motions on a larger scale are dominated by the direction and magnitude of the magnetic field as one would expect. In the heart of the electrojet (108 km for the observations analyzed by Richmond[8]), an electron current of 8.5 $\mu A/m^2$ has been reported.[8] This current is subject to reversals in direction and also to various other plasma instabilities that are characteristic of a partially ionized medium.[9] The situation is not quite so straightforward for the ion current. For altitudes below about 160 km, the ion motions are controlled by the neutral winds, and the electrons are unaffected. Above 160 km, collisional effects resulting from the neutral gas are relatively unimportant and the magnetic field controls the motion of the ions as well as the electrons.[7]

The requirements for observing the in situ properties of this plasma have been reviewed by Webster[2] and are reproduced in Table 1. A typical instrument complement must span observations of the neutrals, plasma, and the local electric and magnetic field to be complete. The volume and mass of such a payload on a single satellite are best illustrated by the low-altitude satellite of the Dynamics Explorer project [Dynamics Explorer-2 (DE-2[4])]. The DE-2 volume (a 1-m diagonal polygonal surface with a height of 1.5 m) is set by the shroud size of the Delta launch vehicle and the presence of DE-1. The mass is about 400 kg. The mass and volume of the DE-2 spacecraft are clearly too large to allow the tethering of multiple DE-class satellites from a central deployer on the Space Shuttle unless there is a major improvement in the properties of tether materials.[10] At low altitudes, the tether payload probably will be restricted to less than 100 kg at the far end of the tether by aerodynamic effects on even special chosen tether materials. If we consider a tether of length 110 km deployed from a carrier at 220 km altitude, present-day TSS technology would probably place even more stringent limitations on the end mass. We should expect that about 600 kg will be the maximum total tethered payload weight.[1] Of that mass, probably no more than 50 kg will be permitted at 100 km altitude unless new tether materials are employed for the section of the tether that experiences the greatest aerodynamic effects.[10] This situation improves somewhat at 110 km altitude. With conventional materials, perhaps 75 kg of payload would be allowed.

In engineering a suitable science observing payload, one must therefore select the precise instrument complement for each of the multiple payloads with care. The deployer payload should concentrate on the plasma component, with emphasis on the distribution and motion of the electrons, since these dominate at the deployer altitude. The far end mass should concentrate primarily on the ion current and the neutral winds. The magnetic field (which will be caused by both the current and the geomagnetic field) need only be measured at the deployer (outside the current) and at some point within the current. As is previously noted, at least initially, mass restric-

Table 1 Ionosphere/magnetosphere boundary observations requirements[2,3]

Plasma observations	
Altitude regime	100 km and up
Position accuracy	Tens of meters
Attitude knowledge	Axis orientations to 10 deg
Instrument complement	
Electron spectrometer	
Electron current magnitude and direction sensor	
Ion spectrometer	
Ion current magnitude and direction sensor	
Vector electrometer	
Vector magnetometer	
Instrument performance	
Spectrometers	Incremental energy/total energy, −2%
Direction/magnitude	5 deg, 10^{-11} A
Electrometer	1 mV/m per axis
Magnetometer	6 nT/axis
Neutral component	
Altitude regime	10–160 km
Position accuracy	Tens of meters
Attitude accuracy	Axis orientations to 20 deg
Instrument complement	
Mass spectrometer	
Kinetic temperature probe	
Pressure transducer	
Vector neutral velocity sensor	
Instrument performance	
Mass spectrometer	Concentrations to 10–15%
Kinetic temperature	0.5 K at 120 km
Pressure	1% at 120 km
Velocity	2 m/s per axis

tions will probably limit the spacing and total number of payloads. Until sufficient experience with the detailed physical properties of the environment is available, two payloads separated by 10 km essentially within the current and two payloads well outside the bulk of the current and separated by 50 km will likely suffice together with instrumentation on the deployer. A suggested instrument complement for each of the tethered packages and the deployer package is given in Table 2.

Provided some stabilization can be provided by the low-altitude end mass, perhaps by some form of drag stabilization, it should be possible to provide the 10 deg per axis attitude knowledge required to maintain the data quality at a level comparable to the DE and Atmosphere Explorer experience. The principal problems to be attacked in maintaining and improving on this quality is to damp short-term and long-term dynamics of the tether sufficiently well that their effect can be detected in the attitude measurements and removed in postprocessing and to measure these motions with sufficient accuracy and time resolution to allow postprocessing correction. This consideration is much different from the conventional problems treated in the attitude control and stabilization of "independent" satellites. Here, dynamic perturbations are continuously applied to the payload from an external source. The damping and measurement of these perturbations is essential to minimize the demands on the attitude control system.

Consider the results that would result from one 20-h on-station operating session of such a system. Assuming that the system is flown from the Space Shuttle in a 28.5-deg inclination orbit, as Fig. 2 shows, about 30 vertical profiles through the electrojet would be obtained. Although no repeat geographic coverage could be obtained until the observing time exceeds one day, the observations would cover the entire range of local solar time with a spacing of profiles of 22.7° of longitude along the equator.[11] Note that Davis et al.[12] required nine rocket flights to obtain a single partial profile of the eletrojet currents between 90 and 130 km. Gradiometric systems such as those considered here are a different engineering challenge from conventional single satellites, since it is now necessary to be concerned with profiling by arrays of instruments that are extensive in space and that must function both independently and in a connected way. The most efficient allocation of power, command, and control components and data management in a distributed way is a problem that has only been faced in extremely large projects such as the Space Station. Tethered gradiometric observations will force the adaptation of this experience to a much smaller scale of project.

It should be noted that repeated profiling from a 28.5-deg orbit will also establish the detailed closure path of the meridional circulation that is a part of the electrojet phenomenon. Numerical modeling of the jet leads to the conclusion that the meridional currents close at least 10° poleward of the equator.[13] However, the closure path has only been crudely observed directly by sounding rocket.[14] The system designer will thus be faced with the need to maintain a traceable calibration over a distributed system throughout multiple missions.

Such time- and space-correlated observations provide the means to determine which of the previously observed phenomena are artifacts of the difficulties of making correlated observations by conventional techniques and which phenomena are indications of the physical processes that are dominant. The reorientation of system design philosophy to a lack of dynamic isolation and the treatment of the need to damp out and measure the influence of especially the short period dynamics represent the main engineering challenges.

Table 2 Multiple instrument deployment on a long tether

Deployer altitude	220 km
Tether length	110 km
Total number of payloads	5 (including deployer)
Deployer	
Ion spectrometer	
Ion current magnitude/direction sensor	
Vector neutral velocity sensor	
Kinetic temperature probe	
Vector magnetometer	
Vector electrometer	
Intermediate payloads (50 km spacing)	
Mass spectrometer	
Neutral pressure	
Electron spectrometer	
Electron current magnitude and direction	
End payloads (10 km spacing)	
Vector electrometer (upper payload)	
Vector magnetometer (lower payload)	
Electron spectrometer	
Ion spectrometer	
Neutral vector velocity sensor (upper payload)	
Neutral temperature sensor (lower payload)	

Magnetic Field

Throughout the altitude regime under consideration, one of the major physical processes is the interaction of the ions and electrons with the magnetic field. This process strongly influences the motion of the currents and also interferes with the separation of the observed field into the planetary field and the field due to the currents. To the geophysicist studying core or crustal magnetism, the magnetospheric and ionospheric fields are noise sources that must be rigorously suppressed. To an ionospheric physicist, the planetary field is a driving mechanism that must be measured. From the current generated field, one can determine both the magnitude of the charge flowing and, with suitable vector observations, the direction and extent of this flow. General mission design principles have been discussed from the point of view of a geophysicist interested in the core and crustal field by Webster et al.[15] Hereafter, the combined ionospheric/magnetospheric field will be referred to as the magnetospheric field.

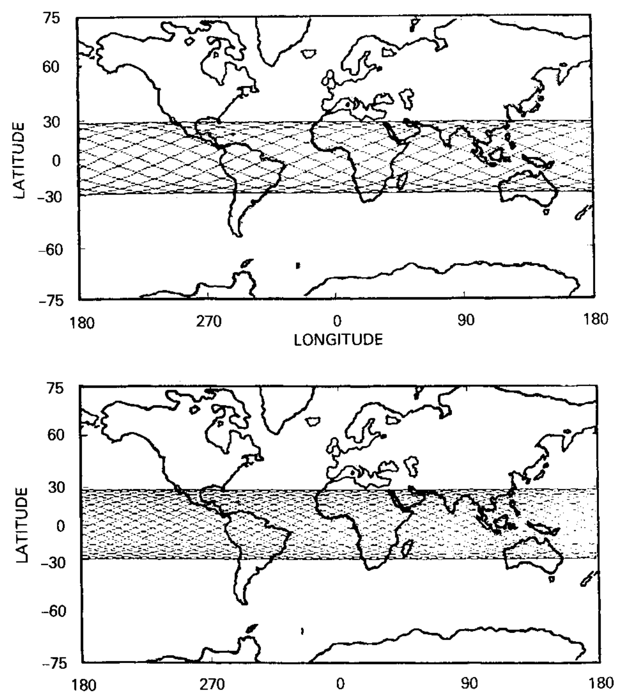

Fig. 2 Ground truck distribution of vertical profiles obtained through the electrojet when the system is flown from the Space Shuttle in a 28.5-deg inclination orbit.

Up to the present, the total field vector has been most precisely measured by a three-component vector magnetometer and an absolute scalar magnetometer. The measurements of the norm of the field vector by the scalar magnetometer are used to calibrate the instrumental constants of the vector instrument during operation and to monitor the stability at the measurement time. The main difficulty with this measurement system is that the separation of the planetary field from the current-caused component is an exacting judgment-based task.[16] With only the three vector components of the total field to work with, there is no objective way to take any given measured vector and decompose it into the three constituents (core, crust, and magnetosphere) by itself. Conventionally, observers make use of repetitive geographic coverage to recognize observations "free" from a major contribution of the magnetospheric field. From the resulting subset of the observations, they determine a core field and a crustal field using the principal that the lowest-order spacial harmonics must be exclusively due to the core field.[17] From the resulting planetary field model, it is now possible to go back to the totality of the observations and isolate the magnetospheric field.

Instrument technology has only just reached the point where measurements that would allow an objective separation are possible. If one were to measure all of the components of the gradient tensor (a total of nine partial derivatives) at a particular location in space, one could directly separate the current-generated field from the core and crustal fields regardless of whether the observations were made within a current. The separation is made possible by the fact that the core and crustal fields (the so-called curl free fields) make little contribution to the off-diagonal elements, whereas the current-generated field (the nonzero curl field) makes the largest contribution to the off-diagonal elements.

Webster[2] has pointed out that physically small gradiometric sensors that are capable of performing such observations with the required precision are, of necessity, cryogenic devices. Room temperature devices do not have sufficient sensitivity to observe the total gradient tensor over small distances well enough to detect the relatively small off-diagonal terms. The design of cryogenic magnetic gradiometers is discussed in the work of Hastings et al.[18] Gradiometers should be operated in an altitude regime where the gradient is large but not at so low an altitude that the plasma that would form around the payload screens out the field. Webster et al.[18] established that the screening effect is negligible for altitudes of 120 km and above. Note that this lower limit is consistent with current TSS technology.

To recover the gradient tensor with as little contamination from spacecraft orientation as possible, it is more important to know the long period changes in orientation to high accuracy than to control them. To produce field vectors for both current and noncurrent fields with the same level of accuracy as for the Magsat data, it is necessary to know the orientation of the principal axes of the tensor to within 20 arc seconds. Note that knowledge of the principal axis orientation does not translate into the required attitude knowledge directly. To establish this, the gradient tensor is calculated from a field model that is convolved with sensor attitude. The results of several of these calculations are compared to establish the level of attitude knowledge that yields the principal axis orientation to the required accuracy. The results of such a calculation indicate that attitude knowledge at an accuracy of 15 arc seconds is required.

A priori, there should be no need for a high level of long period (period of a few minutes) attitude stability for magnetic gradiometry. A precise measurement of the gradient tensor together with the required attitude knowledge should allow a correction for the effects of attitude changes. However, since the cryogen is liquid helium, an important source of instrumental noise is the applied acceleration caused by anomalous sound propagation in the liquid helium. In addition, other short-period accelerations cause an increase in the instrument noise due to the flexing of sensor elements in response. Although both of these effects can be minimized by careful design, their effect is still such that active attitude stabilization at 20 arc second would be required for periods less than 2 min.

There remains the technically difficult requirement that a gradiometer payload requires that short-period changes in its attitude be both known and stabilized at the 20-arc-second level. As is well known,[20] tethered systems are subject to both long- and short-period perturbations resulting from various dynamic effects. As long as the attitude is determined to the required 20-arc-second accuracy, long-period effects (periods greater than a few minutes) can be corrected for by mathematically rotating the observed tensor so the principal axes are properly aligned with the local coordinate system. Although this operation is "compute intensive," it is well understood. Because the short-period perturbations act to increase the instrument noise by changes within the sensor elements, after the fact correction is not possible. For operation at 120 km and with an applied acceleration specrum based on the work of Gullahorn et al.,[20] the signal-to-noise ratio for the norm of the field vector degrades to half that obtained with Magsat.

Clearly some form of damping of the short-period oscillations is also required. One possibility is to use the kind of dynamic isolation system that has been proposed for the Geopotential Research Mission (GRM) satellite. The GRM system, called DISCOS (for Disturbance Compensation System) is a variant of the system that flew on the TRIAD spacecraft.[21] This system consists of two concentric spheres. The outer sphere measures the position of the inner sphere and uses cold gas jets to avoid contact with the inner sphere. Such a system probably can be made sufficiently nonmagnetic to be adaptable to magnetic gradiometry. Other less conventional approaches may be required to avoid instrument/system magnetic fields.

A suitable gradiometer payload would mass about 150 kg for the instrumentation alone. The actual sensor and processor electronics can be contained in a cylinder about 8 in. long and 3 in. in diameter. This cylinder would be contained in a liquid helium dewar (designed for 3 days lifetime so that on-orbit replenishment of the cryogen would be unnecessary) which could be the inner sphere of the DISCOS. Instrumental accuracy should be less than 5×10^{-7} nT/m. Attitude determination should be to within 15 arc seconds and the attitude stabilization by the DISCOS should be within 20 arc seconds for periods shorter than 2 min. The preferred orbit for the determination of the planetary field is sun synchronous-polar. This orbit is also of interest in measuring the magnetosphere field as well. The performance of the gradiometer in decomposing the observed field can be tested by repeated observations of the equatorial electrojet from a 28.5-deg inclination orbit. Because of the magnetic perturbations caused by a tether carrier such as the Space Shuttle, the gradiometer must be operated at least 10 km from the carrier.[19] Data rates are likely to be modest and near to 15 kilobits/s continuous duty.

Conclusion

The unique characteristics of tethered systems (known distance, known relative position for multiple payloads, and long-term access to low altitudes) can have important consequences for all of the disciplines concerned with the atmosphere/magnetosphere boundary. In the case of both the plasma and the magnetic field, fundamental advances in our understanding of the physics are possible through the use of gradiometric techniques. The systems engineering of the necessary observing systems, however, represents a significant departure from the development of conventional single satellites.

All tethered payloads, whether single-instrument packages or multiple packages on one tether, operate subject to continuously applied dynamic perturbations of both long and short period. In some cases, both accurate measurement and accurate damping to at least a portion of the frequency spectrum of these perturbations is required. In designing spatially extended arrays of instruments on tethers, one is concerned with the distribution of the functions of a conventional satellite over several attached payloads. This distributed-design philosophy has been more typical of extremely large projects such as the space station. In dealing with tether-based gradiometry, one must deal with distributed design on a small scale.

References

[1]Bekey, I., "Tethers Open New Options in Space," *Astronautics and Aeronautics*, Vol. 28, April 1983, pp. 33-39.

[2]Webster, W. J., Jr., "Scientific Purposes of Earth Orbital Tether Operations," *Tethers in Space, Advances in the Astronautical Sciences*, edited by P. M. Bainum, I. Bakey, L. Guerriero, and P. A. Penzo, Vol. 62, Sept. 1988, pp. 51-61.

[3]Spencer, N. W., "Scientific Results of Atmosphere Explorer," NASA, July 1977, p. 1050.

[4]Hoffman, R. A., Hogan, G. D., and Maehl, R. C., "Dynamics Explorer Spacecraft and Ground Operations System," *Space Science Instrumentation*, Vol. 5, Dec. 1981, pp. 349-367.

[5]Davies, K., *Ionospheric Radio Waves*, Blaisdell, Waltham, MA, 1969.

[6]Kisabeth, J. L. and Rostaker, G., "Modeling of Three-Dimensional Current System Associated with Magnetic Substorms," *Geophysical Journal of the Royal Astronomical Society*, Vol. 49, June 1977, pp. 655-683.

[7]Forbes, J. M., "The Equatorial Electrojet," *Review of Geophysics and Space Physics*, Vol. 19, Aug. 1981, pp. 464-504.

[8]Richmond, A. D., "Equatorial Electrojet. II. Use of the Model to Study the Equatorial Ionosphere," *Journal of Atmospheric and Terrestrial Physics*, Vol. 35, June 1973, pp. 1105-1118.

[9]Fejer, B. G. and Kelley, M. C., "Ionospheric Irregularities," *Review of Geophysics and Space Physics*, Vol. 18, May 1980, pp. 401-454.

[10]Baracat, W. A. and Gartrell, C. F., "Critical Space Technology Needs for Tether Applications," *Tethers in Space, Advances in the Astronautical Sciences*, edited by P. M. Bainum, I. Bakey, L. Guerriero, and P. A. Penzo, Vol. 62, Sept. 1988, pp. 645-666.

[11]Vane, D., "Mission/Orbit Considerations for Earth Resources Research Aboard the Space Shuttle: Part II," Jet Propulsion Lab., Pasadena, CA, JPL D-409, Sept. 1982, p. 364.

[12]Davis, T. N., Burrows, K., and Stolarik, J. D., "A Latitude Survey of the Equatorial Electrojet with Rocket-Borne Magnetometers," *Journal of Geophysical Research*, Vol. 72, April 1967, pp. 1845-1861.

[13]Sugiura, M. and Porous, D. J., "An Improved Model Equatorial Electrojet with a Meridional Current System," *Journal of Geophysical Research*, Vol. 74, Aug. 1969, pp. 4025-4034.

[14]Maynard, N. C., "Measurements of Ionosphere Currents off the Coast of Peru," *Journal of Geophysical Research*, Vol. 72, April 1967, pp. 1863-1875.

[15]Webster, W. J., Jr., Taylor, P. T., Schnetzler, C. C., and Langel, R. A., "The Magnetic Field of the Earth: Performance Considerations for Space-Based Observing Systems," *IEEE Transactions on Geoscience Remote Sensing*, Vol. GE-23, July 1985, pp. 541-551.

[16]Langel, R. A. and Estes, R. H., "The Near-Earth Magnetic Field at 1980 Determined from Magsat Data," *Journal of Geophysical Research*, Vol. 90, Feb. 1985, pp. 2495-2509.

[17]Langel, R. A. and Estes, R. H., "A Geomagnetic Field Spectrum," *Geophysical Research Letters*, Vol. 9, April 1982, pp. 250-253.

[18]Hastings, R., Mahler, R. P. S., Schneider, R., Jr., and Eraker, J. H., "Cryogenic Magnetic Gradiometers for Space Applications," *IEEE Transactions on Geoscience Remote Sensing*, Vol. GE-23, July 1985, pp. 552-561.

[19]Webster, W. J., Jr., Frawley, J. J., and Stefanik, M., "Observations of the Earth's Magnetic Field from the Space Station: Measurement at High and Extremely Low Altitude Using Space Station Controlled Free-Flyers," NASA TM-86119, May 1984.

[20]Gullahorn, G. E., Fuligni, F., and Grossi, M. D., "Gravity Gradiometry from the Tethered Satellite System," *IEEE Transactions on Geoscience Remote Sensing*, Vol. GE-23, July 1985, pp. 531-540.

[21]Yionoulis, S. M. and Piscane, V. L., "Geopotential Research Mission: Status Report," *IEEE Transactions on Geoscience Remote Sensing*, Vol. GE-23, July 1985, pp. 511-516.