Scientific Missions for Earth Orbital Tether Systems

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The current available in situ data on the physical characteristics of the 90–130 km environment depends on sounding rocket and maneuverable satellite systems for its collection. Such data are, of necessity, sporadic in both time and space. The development of tethered systems in Earth orbit will allow global, long-term observations of this environment for the first time. In addition, tethered systems will allow spacial gradiometry at altitudes from 130–400 km without the extensive celestial mechanics required to coordinate multiple satellite observing programs. This paper reviews some of the outstanding science questions for the altitude regime from 90–400 km which require the use of tethered observing systems for study. These questions involve the structure, temporal evolution, and composition of the uppermost atmosphere/lowermost ionosphere, the distribution of the high spatial frequency components of the magnetic and gravity fields, and the spatial gradients of the properties of the lowermost magnetosphere/uppermost ionosphere.

Introduction

THE advent of the Tethered Satellite System[1] (TSS) provides a means to acquire data in an altitude regime that has heretofore been accessible for no more than 20 or so min at a time. With initial operating times approaching 40 h, a few TSS missions will multiply the existing science data by a factor of 100 or more. The altitude regime from 90–400 km is a region where some of the major processes of the atmosphere/magnetosphere interface occur. In addition, this altitude regime permits potential field observations at a spatial resolution intermediate between aircraft observations and conventional satellite observations.

The initial series of TSS flights will probe the physical conditions of the boundary between 240 and 120 km. Those flights will serve to prove the TSS system in operation and to establish the realism of preflight estimates of environmental conditions at TSS altitudes. In the course of those measurements, a number of predictions crucial to engineering applications will also be tested. The first TSS mission is intended to investigate the application of electrodynamic power generation by the TSS and will establish the practicality of closing a conducting tether magnetosphere circuit to obtain high current flow through the tether and the generation of electromagnetic waves in the magnetosphere. The second TSS mission will use a nonconducting tether and will lower a subsatellite to about 130–150 km. This mission will probe the structure of the uppermost atmosphere. Subsequent flights (detailed planning has not gone beyond the third flight) will sample the same environments, but in an increasingly sophisticated manner.

Currently, TSS is limited to about 40 h of operating time by subsatellite systems and a minimum altitude of about 130 km by tether materials. Technology currently under investigation promises to extend these limits. New tether materials could permit operations down to 100 km. Heating of the tether will likely make operation at a lower altitude both difficult and expensive. A tether material for use at an altitude less than 100 km would have to retain mechanical strength at an operating temperature which quickly climbs beyond 800 deg as the altitude decreases.

The operating lifetime of TSS is limited by two considerations. First, the subsatellite is powered by onboard batteries of limited lifetime. Many modifications to the subsatellite power systems can be made to extend the subsatellite lifetime beyond 40 h. Second, the most stringent limitation is the requirement to use Shuttle orbit maneuvering system (OMS) fuel to make up for Shuttle orbit decay due to drag on the tether and subsatellite. Extended observations, especially at the lowest altitudes, will require additional OMS fuel to ensure a sufficient reserve for safety considerations.

Because of a need for global coverage, an extension of the TSS system to operation in near polar orbit is the most crucial extension that could be made (currently planned for 1994–1995). Extending the altitude regime downward to 100 km or less and increasing the operating lifetime beyond 40 h, while important, must follow an extension to polar orbit.

In addition to the benefits to be derived from measuring the environment at low altitudes, the use of extended TSS technology for magnetospheric observations on an upward deployed tether will allow gradiometric observations on a scale that is not practical with multiple-satellite observing systems. Because the major magnetospheric processes that influence the atmosphere occur over very short spatial and temporal scales for altitudes at least up to about 400 km, gradiometric measurements are the most effective way to disentangle the time and space variations. The following sections discuss some of the scientific benefits that an improved TSS system could provide in two major disciplines of terrestrial physics: the physics of the atmosphere/magnetosphere boundary and the structure and time history of the Earth's geopotential fields (gravity and magnetic). The altitude regimes of particular interest in this discussion are shown in Fig. 1. It should also be noted that the observations will be discussed in the context of Space Shuttle-based systems. Long-term operation from the various components of the space station can also make a valuable contribution.

Physics of the Atmosphere/Magnetosphere Boundary

The region between 90 and 400 km is crucial to a broad understanding of the nature of the interactions between the sun and the Earth. In this region, the maximum gradients in electron content and neutral temperature occur. Also, the physical processes responsible for the structure and temporal history of

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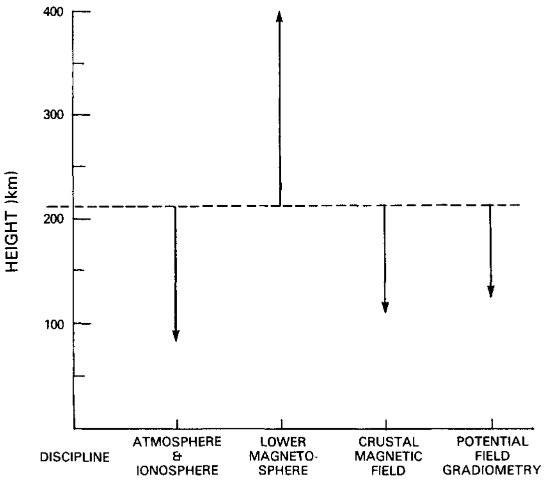

Fig. 1 Schematic representation of the altitude regimes of interest for tethered observations.

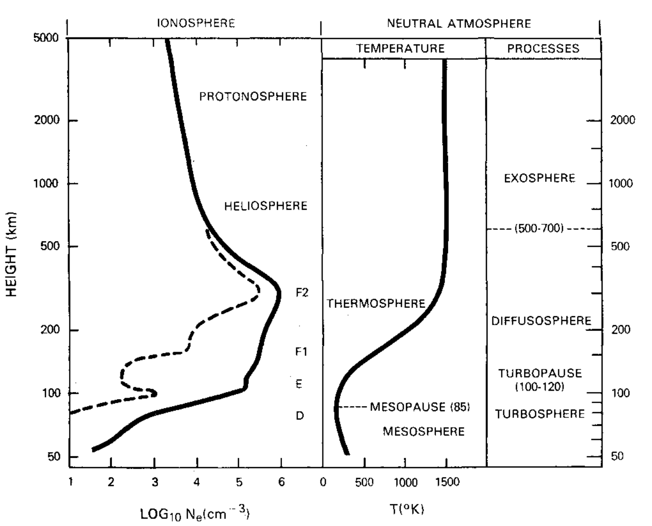

Fig. 2 The midlatitude structure of the ionosphere and neutral atmosphere and the physical processes involved.[12]

the gas change from those processes typical of the lower atmosphere to those processes more typical of the magnetosphere. Figure 2 presents a schematic representation of the typical midlatitude structure of the ionosphere and neutral atmosphere.

Past study of the lower part of the altitude range (90–120 km) has used three basic techniques: sounding rockets, maneuverable satellites, and remote sensing. None of these techniques can simultaneously satisfy needs for in situ measurements of long duration. This is not to say that these techniques are not important. For example, the first confirmation of the existence of the equatorial electrojet was by sounding rocket and, in both the polar and equatorial regions, the sounding rocket[2] continues to be a valuable tool for measuring the in situ structure of the ionosphere.[3,4] Similar examples can be easily found for maneuverable satellites[5] and for remote sensing.

The properties of the upper part of the altitude range (120–400 km) have been studied extensively since the dawn of the space age.[6] As the sophistication of space measurements has grown, it has become clear that the scale of spatial and temporal variations makes the correlation of observations an exceedingly difficult task.[7–9] In addition, the need for simultaneous observations spanning the entire altitude range has become clear. This need is particularly evident in studying the relationship between magnetic field aligned currents and the general flow of charge in the magnetic polar regions.[9,10] Simultaneous low altitude plasma observations and high altitude spectral imaging observations performed by the Dynamics Explorer satellites have shown the value of such time-correlated observing directly.[11]

Conventionally, the polar and equatorial regions are treated as separate study areas. The physical processes which are responsible for the structure observed are presumed to have differing influences in the two regions. For example, because of the convergence of the magnetic field in polar regions, charged particles tend to concentrate the deposition of energy from the magnetosphere and interplanetary space to the atmosphere in the polar regions.

In the equatorial regions, local insolation (incident solar energy) and the day-night dependence are much more important energy sources than magnetospheric deposition. Although it should be clear that these considerations are important, the more appropriate view is that, although the processes dominating the energy balance and the circulation may differ, the study of the circulation and closing of the current requires global observations. The remainder of this section maintains the artificial distinction between the polar regions and the equatorial regions and between the ionosphere and upper atmosphere. Although this is a conventional distinction, Fig. 2 makes clear the perhaps obvious point that the atmosphere, ionosphere, and magnetosphere are inseparable.

The Ionosphere

The physical characteristics of the Earth's ionosphere change with time (local solar time, season, and time in the solar cycle), altitude, and geographic position. The altitude dependence is determined by the ionization and recombination rates, which are in turn determined by the chemical composition, insolation spectrum, and the magnetic field.[12] The geographic position dependence is dominated by the magnetic field and the position of the terminator.[12] Because of the convergence of the magnetic field at the poles, the arctic and antarctic regions show intense, complex, and highly time-variable ionospheric structure. Near the magnetic equator, the structure of the ionosphere is somewhat more stable. For example, one of the major currents in the Earth's current system, the equatorial electrojet, flows more or less continuously in an east-west direction. In order for these regions to be observed, instruments must be operated at 110 km or lower altitude.

The equatorial electrojet[4] flows at an altitude of between 90 and 130 km with a half-current density width of about 15 km. It is relatively confined in geomagnetic latitude and has a half-current width of about 4 deg (E-W component) centered on the geomagnetic equator. The jet has a complex current structure which, in addition to a local solar time variation, shows both meridional and latitudinal current flow. In addition, the flow of charge is irregular, depending on very high-altitude winds and on the level of solar activity. The precise relationship between this irregular flow and other physical phenomena observed in the equatorial regions (such as sporadic E radio propagation and field aligned current flow) is one of the major unsolved problems. The magnetic polar regions are also regions of intense and magnetic polar regions. These are also regions of intense and time variable ionosphere activity.[13] In addition to an average current flow in latitude and longitude throughout the polar regions, currents into and out of the ionosphere flow along the magnetic field directions.[14] These currents, called Birkeland currents, appear to close the current loops with the outer magnetosphere. The total currents in the Birkeland flows are large (as much as 3.5×10^6 A) and time and space variable (by a factor of 2 or more).

For altitudes down to about 110 km, no new instrument development for ionospheric measurements is required. The kind of instruments used on the Atmosphere Explorer[15] and Dynamics Explorer satellites can be adapted to tethered observations. Below 110 km, effects due to the motions of the payload through the ionosphere may make it impossible to infer

Table 1 Space plasma observations payload[5]

Altitude regime	100–130 km and up
Position accuracy	Tens of meters
Attitude knowledge	Axis orientations to within 10 deg
Instrument complement	
Electron spectrometer	
Electron current direction and magnitude sensor	
Ion spectrometer	
Ion current direction and magnitude sensor	
Vector magnetometer	
Vector electrometer	
Instrument performance	
Electron spectrometer	$\Delta E/E - 2\%$
Electron current direction and magnitude sensor	5 deg, 10^{-11} A
Ion spectrometer	$\Delta E/E - 2\%$
Ion current direction and magnitude sensor	5 deg, 10^{-11} A
Vector magnetometer	6 nt/axis
Vector electrometer	1 mV/m per axis

the characteristics of the undisturbed plasma with conventional instruments. New developments in spectrometry may help solve this problem.

A payload suitable for deployment should be capable of operation for at least 2 days near 110 km. Positioning with respect to the deployer should be accurate to within tens of meters. A telemetry line either to the deployer or TDRS will be essential to long duration operations. Table 1 summarizes the operating requirements and a potential instrument complement.

The Lower Magnetosphere

As the altitude of observation increases above 120 km, the properties of the environment change from ionosphere/upper atmosphere characteristics to properties typical of the magnetosphere. As Fig. 1 shows, the kinetic temperature rises to values typical of the exosphere and the electron density passes through its maximum value. In addition, diffusive processes begin to dominate the chemical composition and the density of neutral species drops to a very small (but important) percentage of the total particle density.

This transition region, which we will call the lower magnetosphere, is also a region of extensive temporal and spatial variation. As is well known,[7,12] this region responds to a wide variety of spatially and temporally variable stimuli. As the altitude increases, the geometry of the magnetic field dominates both the geographic and altitude dependence of the observed properties. The diurnal variation in insolation also becomes less important and the influence of the solar wind becomes more consequential.

The first flight of the TSS will observe the properties of this region.[1] This mission is expected to provide information on the coupling between the lower magnetosphere and thermosphere. In situ measurements of the ion, electron, and neutral distribution and motion, as well as the local electric field, will aid in establishing the ways in which the flows of electron and ion current between the ionosphere and magnetosphere are closed.

In the regions near to the magnetic poles (i.e., within the auroral oval), the altitude and spatial variations are especially strong. The variations can be attributed to the Birkeland currents and the variation in the deposition of energy from the outer magnetosphere among other processes.[13] In this region, the geometry of the magnetic field dominates the directionality of processes. Since the field is nearly radial, the average flow of charge tends to be radial. In the equatorial regions, the magnetic field geometry is also a dominant factor. Here, however, the geometry is cylindrical and processes tend to be stratified in the radial direction. In both of these regimes, gradiometric measurements provide the best hope for disentangling the time and space variation which the existing data show.

Table 2 Upper atmosphere observations payload[5]

Altitude regime	100–600 km
Position accuracy	150–50 m
Attitude accuracy	Principal axis orientations to within 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 probe	0.5 K at 120 km
Pressure transducer	1% at 120 km
Vector neutral velocity sensor	2 m/s per axis

Gradiometric observations with precise time and space correlation can be performed by attaching several identical instrument packages at strategic locations along an up-tether. The tether length would most probably be limited not by scientific requirements but rather by the dynamics of extremely long tethers. Should dynamical considerations allow, lengths of 200 km or more would be useful. The instrument complement of the individual packages should resemble the Dynamics Explorer low-altitude satellite and have instrument properties similar to those listed in Table 1.

The Neutral Atmosphere

Because the neutral atmosphere and the ionosphere are inseparable, it is difficult to deconvolve the problems of upper atmospheric observations from those of ionospheric observations. Although the bulk of the neutral atmosphere is below about 90 km, sufficient neutral species remain up to about 120 km (end end of the turbopause), so that the composition, motion, and distribution are major factors, in the overall structure of the atmosphere.

Two major problems that require direct and extensive measurements are the temporal energetics of the uppermost neutral atmosphere and the global distribution and motion of the major neutral constitutents. To date, the data set consists of measurements from the maneuverable satellites of the Atmospheric Explorer series,[5] sounding rockets, and remote sensing (spectroscopy). Of these three data types, the remote sensing observations are the most extensive in time. A major attack on the problems must include in situ measurement of the neutrals as well as the ions. Remote sensing observations, while exceedingly valuable, are one or more additional steps removed from the physical processes involved compared to in situ observation.

In situ observations at altitudes as low as 93 km have been attempted with the Atmosphere Explorer C Satellite.[7] Below about 100 km, correction for the effects and the motions of the satellite through the surrounding atmosphere becomes exceedingly difficult. Accordingly, 100 km is likely to be a firm lower limit with conventional instrumentation.[16,17] Imaging spectrometers and interferometric spectrometry may help solve this problem.

In order to address the temporal energetics and the global distribution and motion, measurements of temperature, vector velocity, and composition are required for an altitude range that should be as low as is feasible (about 100 km), up to 120 km. Conventional measurement techniques can cover altitudes above 120 km and, without new instrument technology, must suffice for altitudes down to 100 km. Because of the nature of the energy input mechanisms, intensive coverage of both the polar and the equatorial regions is essential. In the polar regions, electrodynamic forces, joule heating, and particle inputs are strong in restricted geographic regions and results in large density and temperature excursions over small regions of the thermosphere. Accordingly, coverage from a polar orbit (which would see each polar region once per orbit) is essential. Because the equatorial regions are dominated by atmospheric tides and insolation, the 28.5 deg inclination of TSS is ideal for dense spatial and temporal coverage at the equator.

The operating requirements for an atmosphere observations payload are similar to ionosphere observations. Because one is concerned with the neutral component, the charged particle instrument functions are replaced with mass spectrometers. In order to assess the energy input, ultraviolet photometers and charged particle spectrometers would be required. Because the support needs of atmosphere and ionosphere observations are similar, the two kinds of instruments could easily be combined into one payload. Although Tables 1 and 2 list the two payloads separately, they are more likely to be combined in practice. Table 2 gives the operating requirements and instrument complement for an upper atmospheric observations payload.

Geopotential Fields

The magnetic and gravity fields of the Earth have been probed with increasing accuracy and precision since the beginning of the space age.[18] Measurements of both fields have reached a high degree of completeness. In the case of the gravity field, meaningful structure in the spatial distribution can be discerned for wavelengths greater than about 550 km. The measurement of the gravity field has progressed from the initial study in 1959[19] to an average error of 10 milligalileos in a block size corresponding to 550 km.[20] A corresponding advance may be discerned in measurements of the magnetic field which have culminated in the measurements made by the recently completed Magsat mission.[21]

Further major advances in our understanding of the spatial and temporal structure of the gravity and magnetic fields are dependent on improvements in the measurements of the high-order spatial wavelength components of both fields. Below 100 km wavelength, surface, aircraft, and ship data are available for a significant fraction of the Earth's surface. For wavelengths above 500 km, conventional satellite observations are available. However, there is a gap in the measurement of the spatial wavelength distribution in the region from about 100 km to about 500 km. On both sides of the gap, it appears that the spatial wavelengths sensitivity degrades as the gap is approached.

Figure 3 shows the performance obtained with the current global gravity models, represented by the GEM (Goddard Earth Model) 10 B. With the current state-of-the-art, the gravity field models contain information on only the largest size-scales of the gravity expression of geologic structures.

Future conventional satellite missions[22] (i.e., GRM, the Geopotential Research Mission) promise to improve upon this situation drastically, but not eliminate the problem.

Similar considerations apply to the study of the Earth's magnetic field.[23] One major complication, however, is the temporal variability of at least the lowest spatial frequencies[24] of the field. The variation, although perhaps linear on a long time scale,[25] may be subject to variation on a short time scale.[26] There are two lines of potential field investigations which will likely require a tethered satellite: mapping the global magnetic field due to the crust of the Earth (the crustal field) at high spatial resolution, and mapping the gravity field and the total magnetic field with gradiometric techniques.

The crustal field at 300 km represents no more than 0.1% of the magnitude of the total field.[27] Since time variable fields due to magnetosphere and ionosphere currents can reach 10% of the magnitude of the total field, it is clear that the crustal field is a weak source which is best observed at the lowest feasible altitude. An altitude of between 110 and 120 km will probably be the lowest feasible altitude, because below 100 km the

Table 3 Crustal field mapping[28]

Altitude regime	110–120 km
Position accuracy	60 m or better
Attitude knowledge	0.2 deg
Instrument complement	
Absolute scaler magnetometer	
Vector magnetometer	
Instrument performance	
Absolute scalar magnetometer	0.5 nt
Vector magnetometer	0.5 nt axis

Table 4 Potential field gradometry[28]

Altitude regime	120 km
Position accuracy	10–30 m
Attitude knowledge	2 arc min
Instrument complement	
Cryogenic gravity gradiometer	
Cryogenic magnetic gradiometer	
Instrument performance	
Cryogenic gravity gradiometer	$10^2 E/(\mathrm{Hz}^{-1/2})$
Cryogenic magnetic gradiometer	5×10^8 nt/m

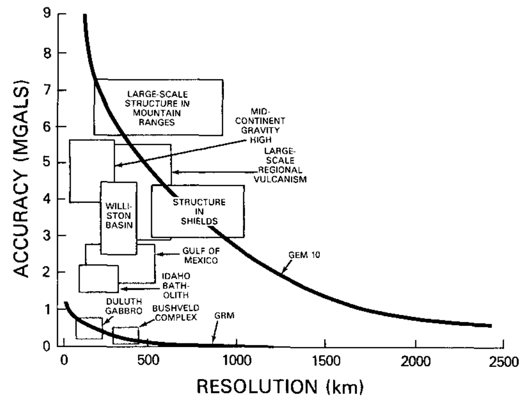

Fig. 3 Information content of current gravity field models and the improvement to be expected from GRM.

screening caused by plasma forming around the sensor will prohibit detection of the crustal field.[28] Table 3 gives the operating requirements and instrument complement for a crustal field mapping mission.

Potential field gradiometry promises to provide information on the small spatial scale features of the fields, which is nearly impossible to obtain by conventional means. Gradiometer observations are best conducted at altitudes where the gradient in the field is as large as is practical. Gradiometric observations of the gravity field, for example, should be made at the lowest practical tether altitude.[29,30] A recent conference on gravity gradiometry recommended 125 km as a goal,[31] in spite of potential problems with acceleration noise due to atmospheric granularity. Although noncryogenic instruments would be the easiest to implement, recent work[30] has shown that, by themselves, noncryogenic gradiometers will not improve on the current state-of-the-art in measurement.

High-sensitivity gradiometers are cryogenic instruments[32,33] and accordingly would require regular servicing to maintain the cryogenics. Since the gravity field is mostly stable over extended periods of time, one mapping should suffice for a time period of at least a decade. However, a remeasurement at 10 year periods might detect gravity field perturbations at the smallest spatial scales, due to the motion of the tectonic plates. Because the main and magnetosphere magnetic fields are time variable, as continuous observations of the global magnetic field as possible are indicated.[23] Table 4 gives the operating requirements and instrument complement for a potential field gradiometer system.

Conclusion

The physics of the boundary between the Earth's atmosphere and magnetosphere and the physics of the gravity and magnetic fields are central to a fuller understanding of the Earth as a "typical" terrestrial planet. The direct probing of the boundary and the fields at low altitudes on a global basis is made possible through the use of tethered payloads. By means of such observations, the time and space histories of the properties of this environment can be separated in an objective manner, and the complex interactions of the various physical processes which control the environmental properties will be deconvolved.

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