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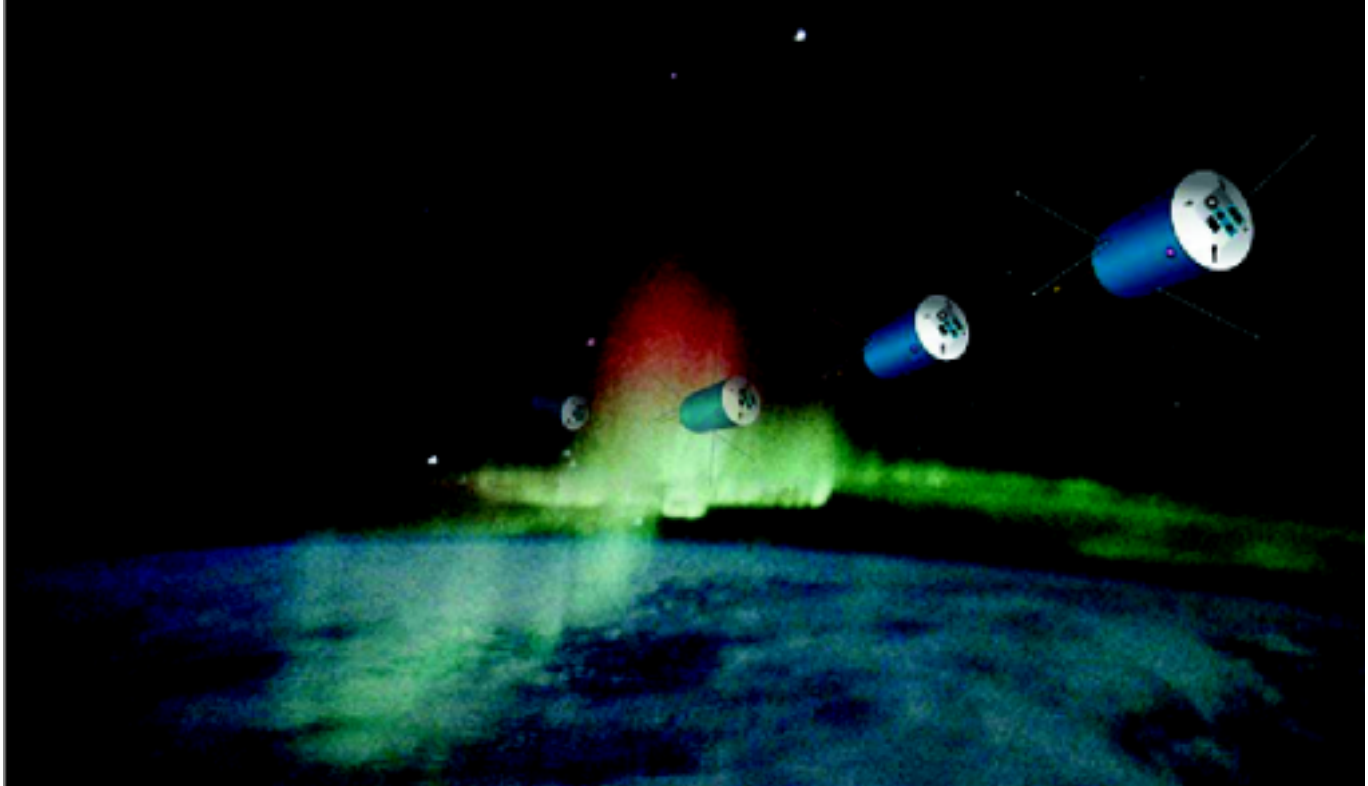
Understanding Plasma Interactions with the Atmosphere: The Geospace Electrodynamic Connections (GEC) Mission



Report of the NASA Science and Technology Definition Team for the Geospace Electrodynamic Connections (GEC) Mission

July 2001

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National Aeronautics and
Space Administration

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July 2001

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Executive Summary

The Earth's Ionosphere-Thermosphere (I-T) system is the site of complex electrodynamic processes that redistribute and dissipate energy delivered from the magnetosphere in the form of imposed electric fields and precipitating charged particles. Previous studies have revealed much about the composition and chemistry of the IT region and about its structure, energetics, and dynamics. However, a quantitative understanding of this structured and dynamic system has proven elusive because of our inability to distinguish between temporal and spatial variations, to resolve the variety of spatial and temporal scales on which key processes occur, and to establish the cross-scale relationships among small-, meso-, and large-scale phenomena.

The Geospace Electrodynamic Connections (GEC) mission is a multispacecraft Solar Terrestrial Probe (STP) that has been specifically designed to overcome these difficulties and to advance to a new and deeper level of physical insight our understanding of the coupling among the ionosphere, thermosphere, and magnetosphere. GEC is NASA's fifth STP. Through multipoint measurements in the IT system, GEC will (i) discover the spatial and temporal scales on which magnetospheric energy input into the IT region occurs, (ii) determine the spatial and temporal scales for the response of the IT system to this input of energy, and (iii) quantify the altitude dependence of the response. GEC will thereby answer the fundamental question: How does the IT system respond to magnetospheric forcing?

The IT system is not merely a passive absorber of magnetospheric energy; it is an active participant in the energy exchange process. GEC will therefore also investigate the role of the ionosphere and thermosphere in modulating the energy exchange with the magnetosphere and will address a second fundamental question: How is the IT region dynamically coupled to the magnetosphere?

The GEC spacecraft will be identically instrumented to sample in situ the ionized and neutral gases of the upper atmosphere and to measure the electric and magnetic fields that couple the IT system to the magnetosphere. The focus of the GEC mission will be on the lower reaches of the ionosphere and thermosphere, where the neutral atmosphere plays a preeminent role in processing and dissipating the electromagnetic energy received from the magnetosphere. The GEC spacecraft will use onboard propulsion to perform many excursions to altitudes below the nominal perigee of 185 km, sampling a significant portion of the Hall and Pedersen conductivity layer where significant closure of field-aligned currents and associated Joule heating begin to occur. During these low-perigee excursions and at certain other times as well, GEC in situ measurements will be coordinated with ground-based observatories. Such coordinated campaigns are an integral part of the GEC mission concept.

GEC will be launched on a Delta II 2920 and placed into an 83°-inclination orbit with an apogee of 2000 km and a perigee of 185 km. The planned "deep-dipping" excursions will take the spacecraft down to 130 km and possibly lower. The baseline orbital formation for the spacecraft is a "pearls-on-a-string" configuration with uneven intersatellite spacing that will be varied during the course of the mission. This formation will permit the resolution of multiple scales and the separation of spatial and temporal effects along the orbital track. Later in the mission this configuration will be changed to a "petal" formation to allow simultaneous sampling at different altitudes. GEC will be launched in 2008. The nominal mission duration is 2 years.

GEC is a "Total Cost-Capped" program resulting in strict yearly budget guidelines. The number of spacecraft and deep-dipping campaigns will ultimately be determined by this constraint.

1.0 Introduction

Earth's upper atmosphere, with its mixture of ionized and neutral gases, is the site of complex electrodynamic processes that redistribute and dissipate energy received from the magnetosphere in the form of imposed electric fields and precipitating charged particles. This energy originates ultimately at the Sun, with its dynamic, cyclically varying magnetic fields, and is conveyed Earthward through interplanetary space by the solar wind. Normally flowing with a speed of ~400 km s^{-1} and a density of 5-10 protons per cubic centimeter, the solar wind can "gust" to over 1,000 km s^{-1} and achieve densities of ~100 protons per c.c. during coronal mass ejections. A fraction of the energy carried by the solar wind is transferred to the magnetosphere, principally through the merging of the interplanetary and terrestrial magnetic fields. This transfer of energy drives the large-scale flow of plasma within the magnetosphere and also produces a build-up of excess energy in the magnetotail that is periodically released in explosive events known as magnetospheric substorms. Some of the energy imparted by the solar wind and processed by the magnetosphere is channeled through a complex system of electrical currents into the upper atmosphere, with profound effects on the dynamics, structure, and composition of both its neutral and plasma components. ***Understanding the physical processes that effect this flow of energy from the Sun to Earth—and its consequences for life and society—is the goal of the Sun-Earth Connection Theme of NASA's Office of Space Science.***

Significant progress toward this important goal has been made during the 40 years since the launch of Explorer 1 and the discovery of the radiation belts. However, many fundamental questions remain to be answered: How is the solar wind accelerated? How are coronal mass ejections triggered, and how do they evolve as they propagate through interplanetary space? How do reconnection, charged-particle acceleration, and turbulence operate on the microphysical level? How does the magnetotail respond to variations in the solar wind? How does the upper atmosphere process and dissipate electromagnetic energy deposited by the magnetosphere?

To answer these questions, NASA is implementing a series of Solar Terrestrial Probe (STP) missions (**Table 1.1**). Two missions—Solar-B and STEREO—focus on the Sun and the steady solar wind and coronal mass ejections and flares. Both are scheduled for launch in mid-decade. Two more STP missions target the magnetosphere, Magnetospheric Multiscale (2006) and Magnetospheric Constellation (2010), and two will explore the upper atmosphere: TIMED (2001) will investigate the structure and energetics of the mesosphere and lower thermosphere, with primary emphasis on the neutral gas, while the Geospace Electrodynamic Connections (GEC) mission (2008) will study the electrodynamic processes that couple the upper atmosphere's ion and neutral components to one another and that couple both to the magnetosphere (**Figure 1.1**).

Table 1.1. GEC is the fifth mission in NASA's Solar Terrestrial Probes program, which offers a continuous sequence of flexible, cost-capped missions designed for the systematic study of the Sun-Earth system in accordance with the four fundamental quests set forth in the *Sun-Earth Connection Roadmap: Strategic Planning for 2000-2025* [*Strong and Slavin*, 2000].

STP Mission	Description	Launch
TIMED	remote-sensing investigation of the global effects of solar radiation, auroral energy input, and upward propagating waves and tides on the structure, energetics, and dynamics of the mesosphere/lower thermosphere	2001
Solar TErrestrial RElations Observatory (STEREO)	simultaneous stereo imaging of coronal mass ejections, coupled with in situ measurements of solar wind parameters; 2 identically instrumented spacecraft in near-circular solar orbits at 1 AU, 1 leading and 1 lagging the Earth	2004
Solar-B	investigation of the evolution of the solar magnetic field in the photosphere and lower corona; coordinated optical, EUV, and X-ray imaging; full vector magnetic field measurements; Sun-synchronous polar orbit; ISAS mission with U.S. instrument participation	2005
Magnetospheric Multiscale (MMS)	in situ measurements in key magnetospheric boundary layers to study microphysics of reconnection, charged-particle acceleration, turbulence; 4 identically instrumented spacecraft in a tetrahedral formation; initial equatorial orbit; polar orbit in final mission phase	2006
Geospace Electrodynamic Connections (GEC)	multipoint in situ measurements in ionosphere-thermosphere region to determine the important spatial and temporal dimensions of ion-neutral interactions that process and dissipate magnetospheric energy input; 3-4 spacecraft; high-inclination orbit; "deep dipping" to altitudes below 185 km	2008
Magnetospheric Constellation (MC)	In situ investigation of the dynamics of the magnetotail and of magnetotail response to varying solar wind conditions; constellation of 50-100 nanosatellites	2010

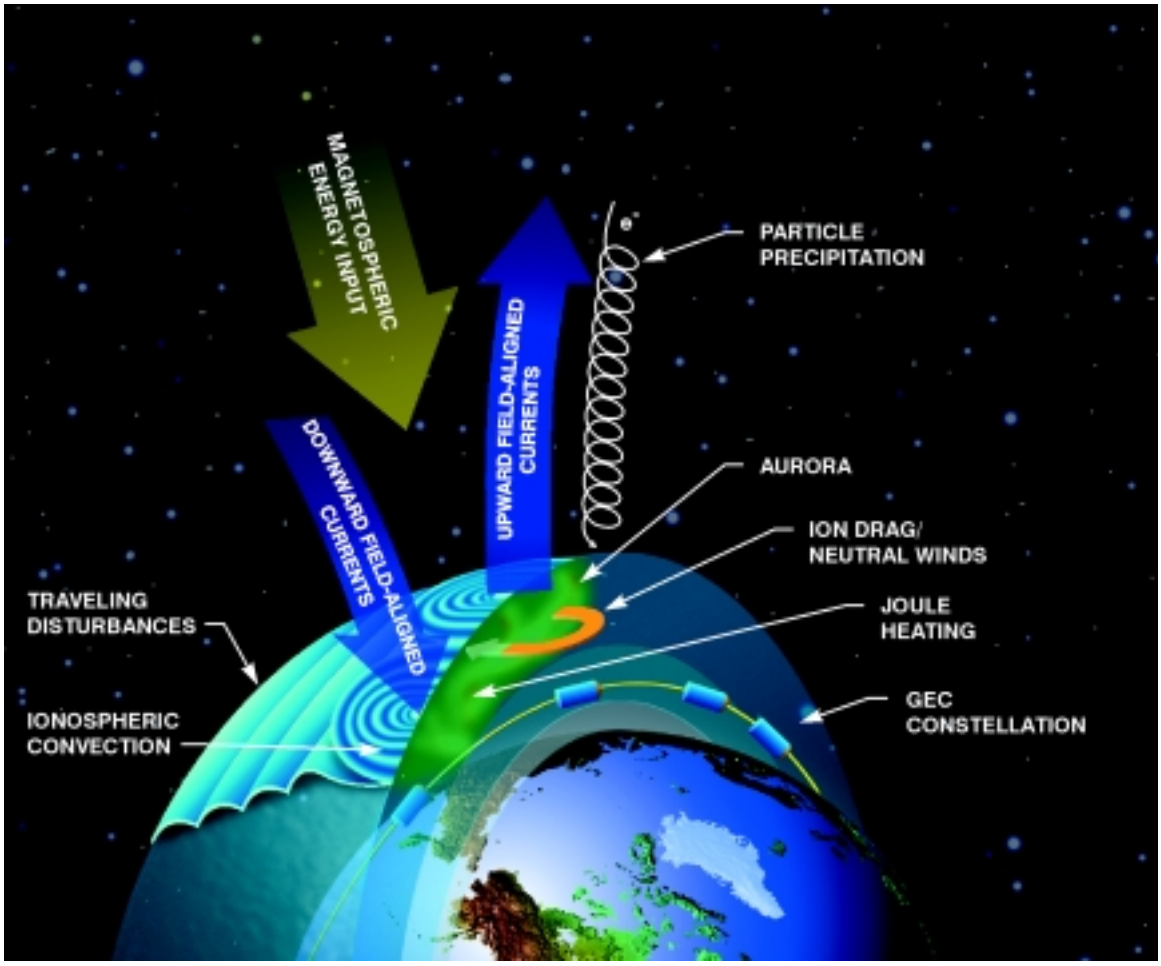

Figure 1.1. At high latitudes the Earth's upper atmosphere is coupled to the magnetosphere by electrical currents that are aligned with the geomagnetic field and that allow the exchange of energy and momentum between the two regions. Magnetospheric energy input, in the form of imposed electric fields and precipitating particles, strongly influences the dynamics, energetics, structure, composition, and chemistry of the high-latitude upper atmosphere. The goal of the GEC mission, NASA's fifth Solar Terrestrial Probe, is to understand the electrodynamic interactions between the ionospheric plasma and the thermospheric neutral gas that process, redistribute, and dissipate the energy received from the magnetosphere and modify the energy exchange process itself. The 2-year GEC mission consists of a constellation of spacecraft flying in a near-polar orbit and repeatedly dipping deep into the lower ionosphere/thermosphere.

1.1 The Geospace Electrodynamic Connections Mission: Ion-Neutral Interactions in the Upper Atmosphere

The Geospace Electrodynamic Connections mission is a 2-year mission that will place three or four spacecraft into a high-inclination elliptical orbit with an apogee of 2000 km and a perigee of 185 km. The spacecraft will be identically instrumented for in situ sampling of the ionized and neutral gases of the upper atmosphere and measurement of the electric and magnetic fields that couple this region to the magnetosphere. GEC has been specifically designed to study the transfer of energy, extracted from the solar wind by the magnetosphere, into the upper atmosphere and the subsequent processing, redistribution, and dissipation of this energy through ion-neutral interactions within the coupled ionosphere-thermosphere system. These interactions are a key link in the chain of processes that constitute the Sun-Earth connection, and they play an important role in the disturbances of the geospace environment known as "space weather." An advance in our understanding of the physics of such interactions is both of fundamental scientific interest and, within the context of our national space weather effort, of enormous practical benefit and importance.

The region of geospace that GEC will explore has already been extensively probed and studied—both remotely and in situ—with ground-based instruments, sounding rockets, and Earth-orbiting spacecraft. These studies have revealed much about the composition and chemistry of the region and about its structure, energetics, and dynamics. Of particular importance was the recognition, which emerged from the Atmospheric Explorer and Dynamics Explorer missions of the 1970's and early 1980's, that the ionospheric plasma and the neutral thermospheric gas are strongly coupled and that

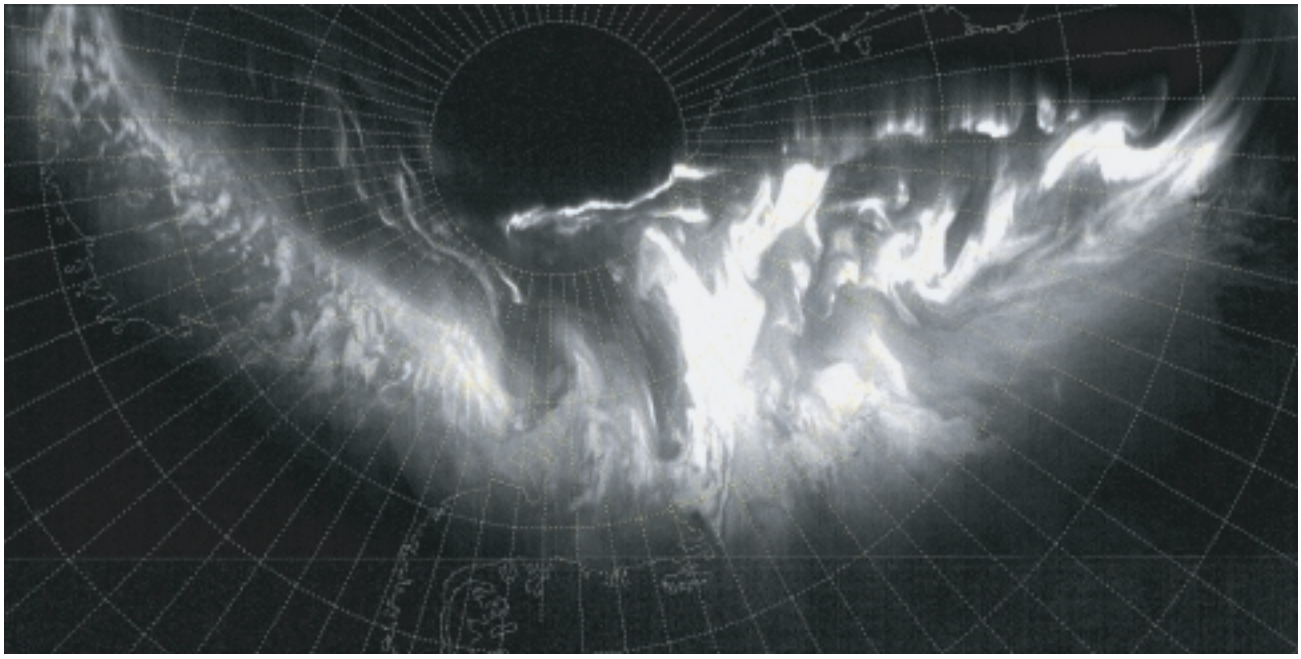

Figure 1.2. As evidenced by the complex structure and variety of spatial scales seen in this image of the aurora australis, magnetospheric energy inputs into the upper atmosphere are highly structured, with spatial scales ranging from less than 1 kilometer to over 100 kilometers. Magnetospheric energy inputs are highly dynamic as well and vary dramatically in intensity and duration over time scales of seconds to hours. The various responses of the ionosphere-thermosphere system to this energy input—changes in electron density and ionospheric electrical conductivity, fluctuations in composition, increased horizontal current flow and Joule heating, horizontal and vertical winds, etc.—are characterized by a corresponding variability in space and time. GEC will determine the spatial and temporal dimensions of the magnetospheric energy inputs and of the I-T system's responses. (Figure courtesy of NOAA's National Geophysical Data Center and the Defense Meteorological Satellite Program.)

this coupling in turn plays a critical role in the exchange of energy between the upper atmosphere and the magnetosphere. ***The goal of the GEC mission is to advance to a new and deeper level of physical insight our understanding of the coupling between the ionized and neutral components of the upper atmosphere.***

Two other important lessons emerged from previous studies as well. First, it was learned that ionospheric and thermospheric phenomena occur on a wide range of spatial and temporal scales and that they are often coupled across scales (**Figure 1.2**). Second, it became clear that simultaneous measurements from multiple spacecraft are needed to resolve the different scale sizes, to distinguish between spatial and temporal variations, and to delineate the relationships among phenomena occurring on different scales. The GEC mission addresses this need for multipoint measurements in the ionosphere-thermosphere region.* By acquiring data simultaneously from multiple satellites at different locations and at varying spacings along the same orbital track, GEC will provide unique and necessary information—not obtainable with a single spacecraft—on the persistence, simultaneity, and spatial extent and uniformity of key ionospheric and thermospheric processes and structures.

The primary focus of the GEC mission will be on multipoint measurements at altitudes below 300 km, the region where the direct contribution of the neutral atmosphere to energy dissipation is important. **A distinctive feature of GEC is the plan for several week-long "deep-dipping" campaigns, during which onboard propulsion will be used to perform excursions below the nominal perigee altitude of 185 km,** well into the region where ion motion is deter-

*Statistical studies based on data from a single spacecraft have made valuable contributions to our understanding of the ionosphere-thermosphere system; however, they are limited by their inability to resolve space-time ambiguities. Moreover, while they are useful for characterizing behavior on large temporal and spatial scales, they cannot capture important smaller-scale phenomena [cf. the study by *Codescru et al.*, 1997]. Ground-based measurements can distinguish between spatial and temporal variations, but are limited in their geographical coverage and thus cannot provide information about the global distribution of the spatial and temporal dimensions of the processes that couple the ionosphere and thermosphere. Also, ground-based measurements do not measure all of the local parameters that play a role in the underlying physics.

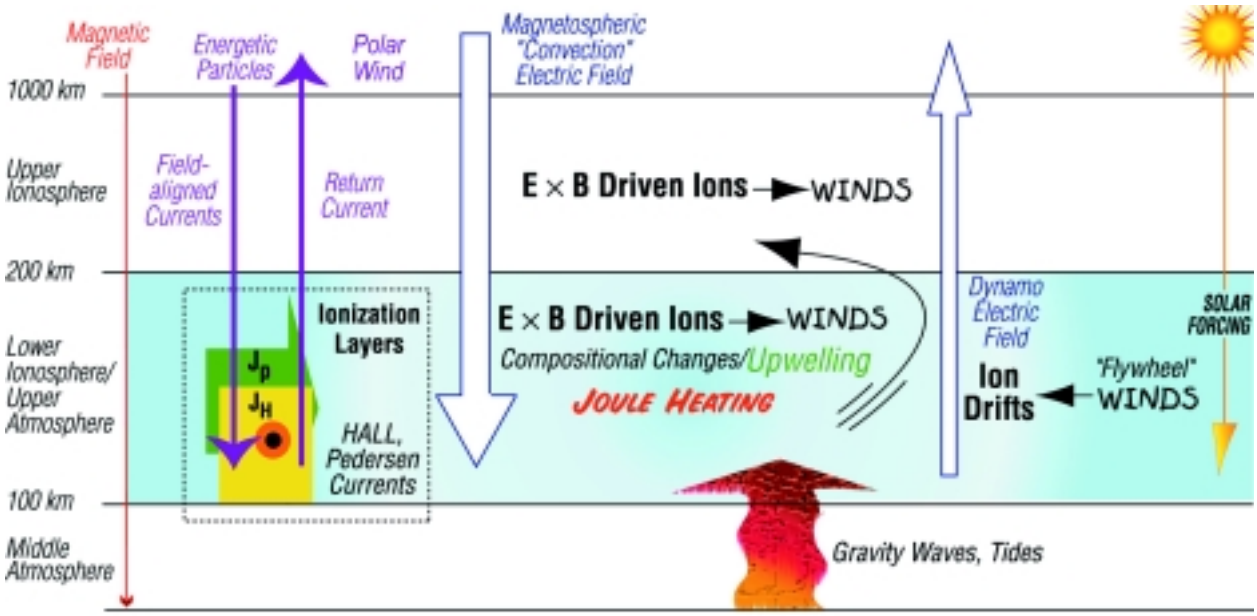

Figure 1.3. Electrical and particle kinetic energy imparted by the magnetosphere to the Earth's upper atmosphere is processed and redistributed within the ionosphere-thermosphere system by means of a variety of physical processes involving interactions between the ionized and neutral gases. For example, ion-neutral coupling is responsible for large-scale neutral winds that are driven by the flow of the ionospheric plasma, whose circulation is driven by the imposed magnetospheric electric field. Following a rapid change in the convective forcing of the system, these neutral winds can sometimes act as a "flywheel" to reverse the direction of the energy transfer. In the lower ionosphere, the field-aligned currents that channel electrical energy from the magnetosphere into the atmosphere are closed by Pedersen currents, which dissipate their electrical energy through Joule heating of the neutral gas. The heating produces vertical winds that affect the composition and ion concentration at higher altitudes through the upwelling of air enriched in molecular nitrogen. At middle and low latitudes, the primary forcing of the ionosphere-thermosphere region is by atmospheric tides and winds driven by solar heating. (Figure is adapted from *Volland* [1996].)

mined as strongly by neutral collisions as by the geomagnetic field and where significant closure of field-aligned electrical currents and associated Joule (frictional) heating in the electrically resistive neutral atmosphere begin to occur. Successful low-perigee passes into this region during the mid-to-late 1970's by the Atmospheric Explorers—whose emphasis was on chemistry and composition rather than electrodynamics—demonstrated that such excursions are well within our technical capability.

1.2 The Science Objectives of the GEC Mission

Through multispacecraft sampling of the ionosphere-thermosphere region over a broad range of magnetic latitudes and local times and through focused dipping campaigns in the most important coupling zones, GEC will answer two fundamental questions:

- *How does the I-T system respond to magnetospheric forcing?*
- *How is the I-T system dynamically coupled to the magnetosphere?*

Each of these broadly formulated questions can be broken down into a set of more narrowly focused questions that defines the specific science objectives of the GEC mission. These objectives are introduced briefly below. They, along with the measurement requirements that follow from them, will be discussed in detail in Section 2 of this report.

1.2.1 How does the ionosphere-thermosphere system respond to magnetospheric forcing? At high latitudes both electrical energy and particle kinetic energy are delivered to the upper atmosphere from the magnetosphere via field-aligned currents that are closed by horizontal currents in the ionosphere, in the so-called dynamo region (90-200 km), where the electrodynamics is strongly influenced by ion-neutral collisions. Collisions between the thermospheric neutral molecules and the ions that carry the horizontal currents result in the conversion of electrical energy into heat and mechanical energy through Joule (resistive) heating and momentum exchange, respectively, which in turn profoundly affect the circulation and composition of the upper atmosphere (**Figure 1.3**). The large-scale horizontal motion of the ionized component of the I-T system is dominated at high latitudes by the magnetospheric electric field, which is imposed on the ionosphere and which drives and organizes

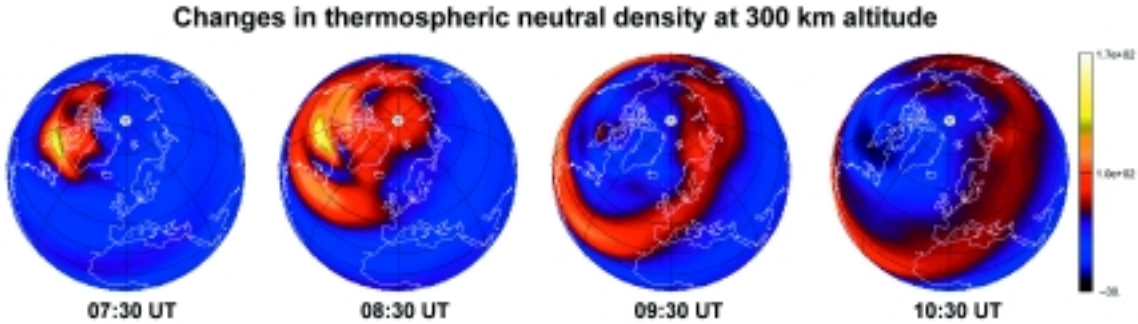

Figure 1.4. Impulsive increases in Joule heating in the high-latitude ionosphere-thermosphere during periods of increased geomagnetic activity produce density variations in the thermosphere that propagate globally toward lower latitudes. Associated with such traveling atmospheric disturbances (TAD's) are traveling ionospheric disturbances (TID's). The development and global propagation of a TAD shown here is based on an NCAR TIEGCM simulation of the atmospheric response to the January 11, 1997, magnetic storm. With its variably spaced satellites, GEC will be able to study the initiation of such disturbances in small-scale heating regions in the auroral zone and track their evolution over increasingly larger scales. (Images courtesy of G. Lu/NCAR.)

the horizontal (i.e., convective) flow of the ionospheric plasma. During periods when the convection electric field pattern in the ionosphere is steady, the transfer of momentum from the convecting ions to the neutrals by collisions produces horizontal neutral winds whose large-scale flow pattern mimics the ion convection pattern.

In the case of particularly intense geomagnetic activity, the effects of magnetospheric energy input are not restricted to the high latitudes but propagate to the middle and low latitudes as well. These middle- and low-latitude effects include the ionospheric disturbance dynamo, the penetration of the high-latitude convection electric field to lower latitudes, the development of rapid east-west ion drifts at subauroral latitudes, and the equatorward propagation of impulsive I-T waves and disturbances (**Figure 1.4**). In addition, the composition in these latitude regimes can be dramatically altered, leading to large changes in the morphology of the ionosphere.

GEC will address four specific science questions relating to the response of the I-T system to magnetospheric forcing:

- *How are the magnetospheric electric field and particle inputs into the I-T system structured in time and space?*
- *How does Joule heating affect the I-T system?*
- *How do electric fields affect winds and composition in the I-T system?*
- *How do magnetospheric influences extend to middle and low latitudes?*

1.2.2 How is the ionosphere-thermosphere system dynamically coupled to the magnetosphere? Although originating in the magnetosphere, the transfer of energy into the high-latitude upper atmosphere is not determined solely by magnetospheric processes but is also influenced by the response of the I-T system itself. The current flow between the magnetosphere and the I-T system is regulated by the magnitude, distribution, and variability of the electrical resistance (or conductivity) of the I-T system. The resistance of the I-T system is, in turn, modulated in a complex fashion by the effects of the electrical energy dissipation: the electrically driven ions lose momentum to the neutrals, which tends to reduce resistance by reducing the relative ion-neutral velocity, while changes in ion chemistry (resulting from Joule-heating-driven changes in neutral density, composition, and temperature) act to lower ion concentrations relative to the neutrals and thus increase resistance.

The behavior of the neutral winds, as they are changed in response to magnetospheric energy inputs, is another key factor in determining the feedback from the I-T system that affects the coupling between the upper atmosphere and the magnetosphere. A well-known example of this feedback is the modification of energy transfer between the ionosphere and the magnetosphere due to the high-latitude neutral wind dynamo. That is, neutral winds set in motion by convecting ions continue to circulate after geomagnetic activity subsides and ion convection slows; this neutral wind "flywheel" transfers momentum to the plasma and moves it through the geomagnetic field, thus generating electric currents and fields that contribute to the electrodynamic interaction between the magnetosphere and the I-T system. The effects of such feedbacks on the coupling to the magnetosphere are not understood, and only now are the first attempts being made to incorporate them into models of the coupled magnetosphere-ionosphere-thermosphere system.

GEC will address three unresolved questions relating to I-T system feedbacks into magnetosphere-ionosphere coupling:

- *How do atmospheric dynamo processes modify the energy flow between the magnetosphere and the I-T system?*
- *What controls the connections among horizontal gradients in conductivity, electric fields, currents, and neutral winds?*
- *How does the I-T system affect field-aligned currents and Alfvén waves that connect it to the magnetosphere?*

1.3 GEC Mission Concept and Strategy

In order to provide definitive, quantitative answers to the science questions listed above, it is necessary to determine the dominant temporal and spatial scales on which energy is imparted to the upper atmosphere from the magnetosphere and on which it is processed and redistributed within the I-T system. Moreover, it is necessary to distinguish between spatial and temporal variability and to be able to track the persistence and evolution of a particular feature or process with time. Finally, because energy transfer and redistribution processes within the I-T system are often strongly coupled across scales, it is necessary to be able to perform simultaneous measurements over a range of scale sizes. GEC has been designed to satisfy these requirements.

The GEC mission concept calls for three or four spacecraft, equipped with onboard propulsion, to be deployed in an 83°-inclination orbit with an apogee of 2000 km and a perigee of 185 km. Each of the GEC spacecraft will be identically instrumented to measure neutral, ion, and electron density and temperature; neutral and ion composition and velocity; DC electric and magnetic fields; and AC electric and magnetic fields. In addition to the I-T state variables and fields, each spacecraft will measure auroral particle precipitation, which is an important source of both energy and ionization at high latitudes.

The high-inclination orbit has been chosen to allow sampling of the high magnetic latitudes, where the bulk of the energy exchange between the magnetosphere and the upper atmosphere takes place. Because the ionospheric plasma and the thermospheric neutral gas become increasingly coupled with decreasing altitude, repeated deep-dip-

Figure 1.5. The GEC baseline orbital configuration is a "pearls-on-a-string" formation, illustrated here. Flying in this formation, the GEC spacecraft will measure latitudinal gradients and temporal variability of energy transfer and dissipation processes in the coupled ionospheric-thermospheric system. Later in the mission, the orbital configuration may be changed to a "petal" formation to allow simultaneous sampling of key parameters at different altitudes.

ping excursions to altitudes below the perigee altitude of 185 km will be performed. The nominal GEC orbit provides for broad local time coverage and for deep-dipping at high, middle, and low latitudes. The nominal mission will last 2 years.

The primary orbital formation for the GEC spacecraft is a "pearls-on-a-string" configuration (**Figure 1.5**) with uneven intersatellite spacings that will be systematically increased during the course of the mission. This configuration limits the GEC measurements to two dimensions (latitude and time). However, the restriction to one spatial dimension does not compromise the ability of GEC to accomplish its science objectives because the physics underlying the structures of interest to GEC (e.g., auroral arcs, subauroral ion drifts (SAID's), troughs) is more prominently revealed by the gradients in their latitudinal distribution. Moreover, information on the other two dimensions (longitude and altitude) will be provided by coordinated measurements with ground-based radars and by auroral imaging (both from the ground-based cameras and imagers on spacecraft that are operating at the time of the GEC mission). During the later phases of the mission, the spacecraft formation may be reconfigured through separation of the arguments of perigee of each spacecraft into a "petal formation" to allow simultaneous sampling of a given latitude region at different altitudes.

GEC's in situ investigation of the I-T system will be closely coordinated with supporting observations from ground-based facilities—in particular, the incoherent scatter radars—and will be conducted in a series of campaigns, the scientific focus of which will be determined by the latitude and local time of perigee. Data acquired during earlier campaigns will be promptly analyzed and used in the planning of subsequent campaigns.

1.4 Benefits of the GEC Mission

The GEC mission will lead to significant advances in our knowledge of basic physical processes in a medium that is unique within the geospace environment. The processes that occur outside the I-T system in the different regions and boundary layers of the Earth's magnetosphere are primarily *collisionless plasma* processes, involving interactions among various charged-particle populations, electric and magnetic fields, and currents. In contrast, those that operate in the I-T system are dominated by the interactions between the ionospheric plasma and the thermospheric neutral gas. Here *collisional* processes play a fundamental role in the transfer and redistribution of energy and in the coupling of the collision-dominated I-T regime to the collisionless regime of the magnetosphere.

The lessons learned from GEC about the electrodynamics of ion-neutral processes will not be restricted to the geospace environment alone but will be applicable to other planetary settings as well, both within our solar system and in extrasolar planetary systems. For example, the giant outer planets all have intrinsic magnetic fields and magnetospheres that exchange energy with the planetary upper atmospheres. This energy exchange certainly involves Alfvén waves and field-aligned currents that close in the planetary ionosphere and couple the planet to the magnetosphere. In the case of Jupiter, this coupling also involves electrodynamic interactions with its satellite Io, with field-aligned currents closing in the Jovian ionosphere at one end and in Io's ionosphere at the other. The information provided by GEC about the terrestrial I-T system will provide an invaluable observational basis for comparative planetological studies of magnetosphere-ionosphere-thermosphere coupling at other planets.

In addition to its scientific value, the understanding that the GEC mission will yield has practical benefits as well. These derive from the sensitivity of modern society to ionospheric and space "weather." The energy delivered to the upper atmosphere during magnetospheric disturbances leads to physical changes in the I-T system (**Figure 1.6**) that can have adverse effects on a variety of technological systems important to a world that is increasingly dependent on a globally distributed and space-based high-technology infrastructure. Communications and navigation systems such as the Global Positioning System (GPS) are particularly susceptible to ionospheric disturbances, which can degrade or completely disrupt their operation. Further, ionospheric currents resulting from increased geomagnetic activity can induce currents in power networks, severely disrupting power distribution, as occurred in Quebec, Canada, in March 1989, when 6 million people were without power for 9 hours in the aftermath of a particularly severe geomagnetic storm [*Joselyn*, 1998]. Ionospheric weather also affects the orbits of spacecraft operating in low-Earth orbit, including the Hubble Space Telescope and the International Space Station. Heating and upwelling of the atmosphere during geomagnetic storms increases atmospheric drag, causing changes in spacecraft orbits. In some cases, spacecraft whose orbits have been unexpectedly altered by increased drag have been temporarily lost to ground-tracking stations. Understanding the variable behavior of the I-T system in response to magnetospheric forcing is thus of crucial importance if the adverse effects of ionospheric weather on advanced technological systems are to be anticipated and mitigated.

2.0 Science Questions and Measurement Requirements

The goal of the GEC mission is to achieve a detailed, quantitative understanding of the ion-neutral interactions by means of which Earth's I-T system (i) processes, redistributes, and dissipates energy received from the magnetosphere and, through its response to magnetospheric forcing, (ii) dynamically influences the energy transfer process itself. Such

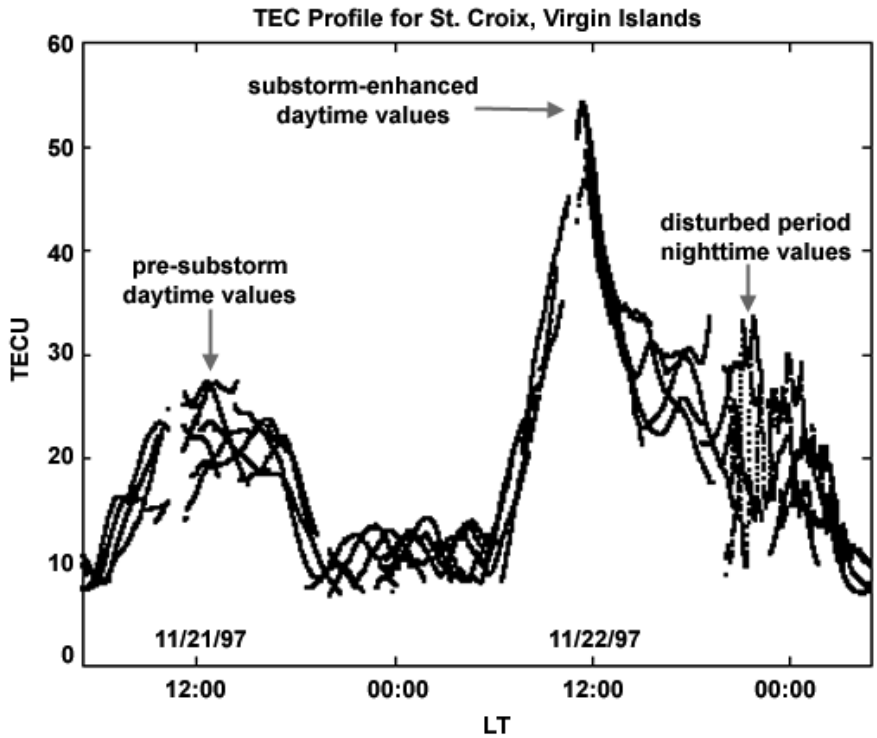

Figure 1.6. Ionospheric total electron content (TEC) (10^{16} electrons/m^2) over the Virgin Islands vs. local time before and during a geomagnetically disturbed period. The daytime values during the substorm are twice the presubstorm values, and the nighttime values during the disturbed period are higher than the presubstorm noon maximum and more irregular. Such geomagnetically induced disturbances of the mid-latitude ionosphere were not expected by researchers and represent a potentially serious source of disturbance for HF transionospheric communication and navigation systems such as GPS. Airglow observations made during the active period show a wavelike alternation of increased and depleted ionospheric plasma, corresponding to the fluctuations seen in the nighttime TEC during the substorm period. GEC is ideally suited to investigate such mesoscale structures, which are poorly understood. (Adapted from *Kelley et al*. [2000].)

understanding requires knowledge of the spatial and temporal scales on which energy transfer and dissipation processes operate within the I-T system and of how these processes couple across scales. Previous space-based measurements of all the relevant parameters date back more than 20 years and are confined to the upper thermosphere, where the direct contribution of the neutral atmosphere to the energy dissipation process is small. Ground-based measurements have provided tantalizing views of the important physical processes that couple the ion and neutral gases but leave open questions about the range of temporal scales and spatial variability that are present and about the large-scale distributions of these attributes.

To advance our understanding of the coupled I-T system and of its coupling to the magnetosphere, we must first be capable of describing the spatial and temporal morphology of the magnetospheric inputs to the system. Then we must discover how the I-T system responds to the different inputs. GEC has been designed specifically to provide this knowledge, through simultaneous measurements from three or four co-orbiting spacecraft at different locations in the I-T system and through successive sampling of the same region by the GEC spacecraft. The specific science questions that GEC will address are described in detail in the discussion that follows. This discussion is organized in two main sections, corresponding to the two fundamental GEC science questions (cf. Section 1.2). Section 2 concludes with a summary of the measurement requirements that follow from the GEC science objectives.

2.1 How Does the Ionosphere-Thermosphere System Respond to Magnetospheric Forcing?

Energy is transferred from the magnetosphere to the I-T system in the form of electromagnetic energy, delivered via field-aligned currents and their associated electric fields, and in the form of kinetic energy, delivered through the precipitation of energetic particles. In order to understand the behavior of the I-T system, it is essential that a quantitative description of these inputs be obtained. Our physical understanding tells us that the system's response will depend on the spatial scales and temporal persistence of the inputs, but almost no systematic information about these attributes is available. In addition, these inputs will transfer energy differentially with height due to the transition within the I-T

system from a nearly collisionless plasma at high altitudes to a collision-dominated gas at low altitudes. As a consequence, the I-T system will respond quite differently at different altitudes. Thus a complete description of the response of the I-T system to both modes of magnetospheric energy input requires in situ measurements of electric fields, currents, and energetic particles at different spatial and temporal scales, and in particular over an altitude range where the exchange of momentum and energy between the charged and neutral species changes dramatically. This is the altitude range—from 300 km down to 130 km (and perhaps lower)—that the GEC spacecraft will probe at perigee and during the immediate pre- and post-perigee legs of their orbits. The following subsections discuss specific questions that GEC will address.

2.1.1 How is the magnetospheric electric field and energetic particle input into the I-T system structured in time and space? Electric fields, field-aligned currents, and energetic particle fluxes are all imposed on the I-T system from the magnetosphere. The imposed magnetospheric electric field is the principal driver for the ion motion at high latitudes. Specification of this motion is needed to understand the transport of ionization, the ion-drag force on the neutral gas, the frictional heating of both ion and neutral species, and the free energy available in spatial gradients that may result in plasma instabilities. Energetic particle precipitation, through impact ionization of the neutral species, is frequently the dominant source of ionization at high latitudes; as such, it can control the ionospheric conductivity and thus the efficiency of ion-drag to the neutral atmosphere.

The effects of electric fields and particle precipitation on the I-T system depend strongly on the spatial coherence/stability and the temporal duration of these magnetospheric inputs. For example, temporal changes in the forcing of the neutral gas by electric fields are produced by time changes in the electric fields themselves and/or by changes in the location of imposed electric field structures. Short-lived or nonstationary fields can produce impulsive heat sources with little direct momentum transfer. Alternatively, long-lived stationary structures can provide a heat source that decreases with time and an effective momentum source.

In the altitude range between 300 km and 130 km, the spatial and temporal scales important to ion-neutral interactions are a strong function of altitude. With decreasing altitude, the ion gyrofrequency and the ion-neutral collision frequency become comparable and the ion motion increasingly deviates from that specified by $\mathbf{V} = \mathbf{E} \times \mathbf{B}/B^2$ (**Figure 2.1**). The ion motion depends additionally on the neutral density, the ion composition, and the bulk motion of the neutral gas, the very parameters that are themselves changed by the interaction between the ion and neutral species and the energy deposited by the magnetosphere. Such complicated feedbacks between the ion and neutral species mean that a thorough specification of the electric field, the ion and neutral motion, and the ion and neutral density is essential for furthering our understanding of the I-T system. To proceed efficiently ***we must understand any systematic relationships between the spatial scales and temporal persistence of the electric field and energetic particle inputs into the I-T system***.

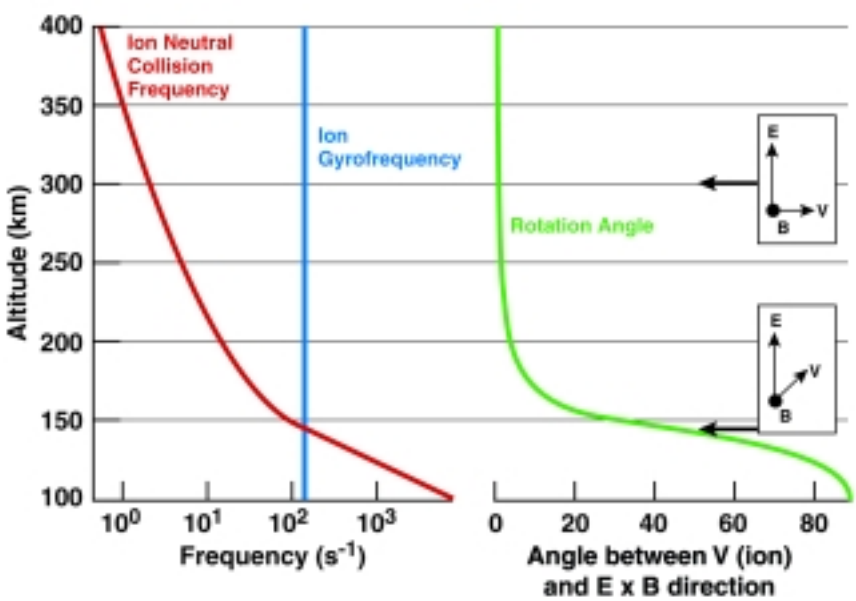

Figure 2.1. The ion-neutral collision frequency increases with decreasing altitude. As a result, the motion of the ions is strongly influenced at altitudes below 200 km by interactions with the neutral gas and deviates increasingly from the **E x B** direction.

These inputs, as manifested in the global convection pattern and the auroral oval, have been well-characterized on large spatial and temporal scales (from 1000's of kilometers to 100's of kilometers and from a few minutes to several hours). They are known to be closely related and to change in accordance primarily with the orientation of the interplanetary magnetic field. Moreover, on scale sizes of tens of kilometers to hundreds of meters to a few meters, data from previous satellite missions such as Dynamics Explorer have provided a first-order description of the electric field structure and plasma structure in the F region [*Heppner et al.*, 1993; *Kivanç and Heelis*, 1998]. Similarly, space-based and ground-based observations have provided information about smaller-scale structures in the particle precipitation and electric field configuration. ***What is missing from the present picture is knowledge of the temporal duration of the electric field and its relationship to the particle precipitation signatures at different scale sizes.*** This information is key to completing our understanding of the magnetospheric inputs to the I-T system. To address these issues GEC will

- *measure the vector electric field with a temporal sampling that allows static structures with 50-m scale size or greater to be resolved;*
- *measure the auroral particle energy flux with a temporal sampling that allows static structures with 1-km scale size or greater to be resolved; and*
- *determine the temporal persistence of E-field and particle structures by cross-correlating the time series from each spacecraft with temporal spacing ranging from 5 seconds to 10 minutes.*

2.1.2 How does Joule heating affect the I-T system? The dissipation of electromagnetic energy through collisions between the ion and neutral species occurs predominantly in the form of Joule heating. Using a hemispheric average and steady-state model, [*Lu et al.,* 1995] determined that less than 10% of the electromagnetic energy input is dissipated through the exchange of momentum between ions and neutrals via ion drag, with the rest of the energy deposited as heat. This partitioning of energy between heat and momentum will be different at different altitudes and will be very different for different spatial and temporal scales, as discussed in the previous section.

Frequently, the Joule heating rate is expressed as a height-integrated quantity based on estimates of the large-

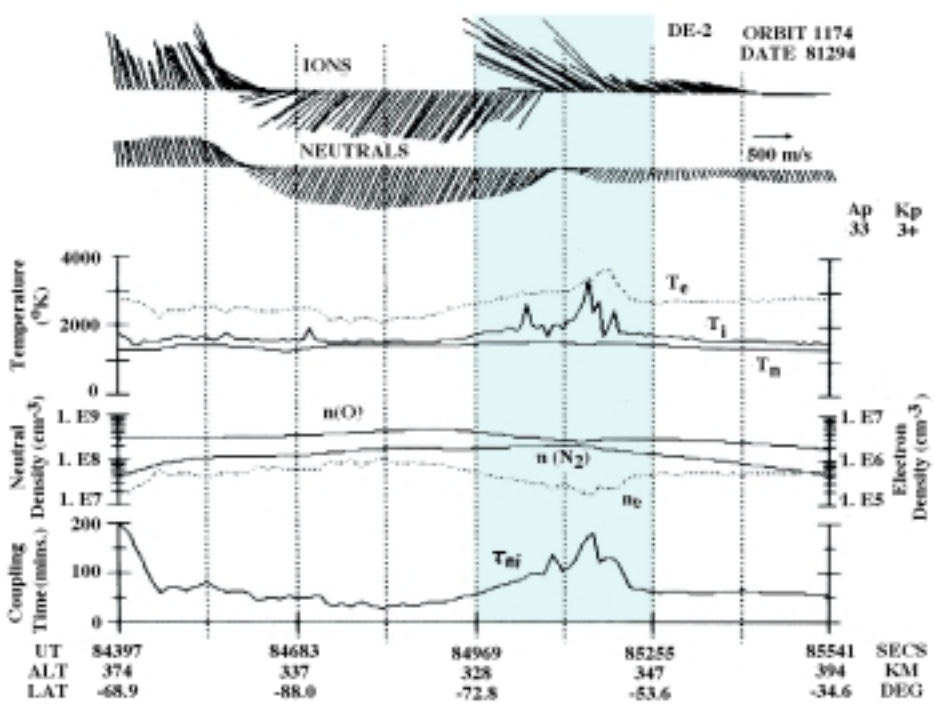

Figure 2.2. Data from the Dynamics Explorer 2 spacecraft acquired during an October 1981 pass over the southern polar region show a rise in the ion and electron temperatures relative to the temperature of the neutral gas (second panel from the top). This temperature enhancement is associated with the large difference between the ion and neutral velocities observed between 72.8° and 53.6° S (top panel). These data illustrate the role of ion-neutral velocity differences in the frictional heating of the ion gas. GEC will reveal these similar dependencies at altitudes below 200 km, where the relevant time scales for the I-T system response are poorly understood. [Figure: *Killeen et al.*, 1984]

scale distribution of the Pedersen conductivity and the electric field. Over the entire high-latitude region, such a specification serves as a useful proxy for the temporal variation in the magnetospheric electromagnetic energy dissipated in the I-T system, which we will discuss later. However, such a specification tells us little about the response of the I-T system to the input.

The Joule heating rate of the ions and the neutrals is given by

$$Q_{in} = \frac{m_i m_n}{m_i + m_n} \upsilon_{in} N_i \left| \vec{V} - \vec{U} \right|^2$$

while the force per unit mass on the ions due to collisions with the neutral gas is given by

$$\vec{F}_{in} = \upsilon_{in} \left(\vec{U} - \vec{V} \right)$$

In these expressions m is the mass, υ_{in} is the collision frequency, and N is the number density. Subscripts refer to ions and neutrals, while V and U are the ion and neutral velocities, respectively. Both these terms are smaller at high altitudes than at lower altitudes, but the effects of other physical processes, such as cooling, must also be considered in order to understand how the system responds. The Dynamics Explorer mission has shown quite dramatically that near 300 km altitude Joule heating produces a large temperature difference between the ion and neutral gases because rapid heat conduction serves to minimize the effect on the neutral gas. However, at this altitude, the collisional force can act quite effectively on the neutral gas over time scales of tens of minutes to produce a neutral circulation that mimics the ion convection. Both these effects are seen in **Figure 2.2**. At lower altitudes this physical picture will change dramatically. The Joule heating rate increases dramatically, but so too does the cooling rate. Here, Joule heating results in heating of the ions and the neutrals and the resulting change in neutral pressure induces a neutral circulation. Momentum transfer to the neutrals has a considerably longer time constant and is less effective than at higher altitudes. We must know how the heating and momentum transfer rates are distributed in altitude and we must know how the temperature and velocity of the ion and neutral species are related to these rates if we are to understand the I-T system response.

Our physical understanding highlights the important roles played in Joule heating by the electric fields, which drive the ions and through ion drag the neutral gas. Ion drag changes the neutral winds, altering the ion-neutral velocity difference and thus modifying the ionospheric conductivity, which depends on the ion-neutral collision frequency and the plasma density. For example, models [e.g., *Thayer et*

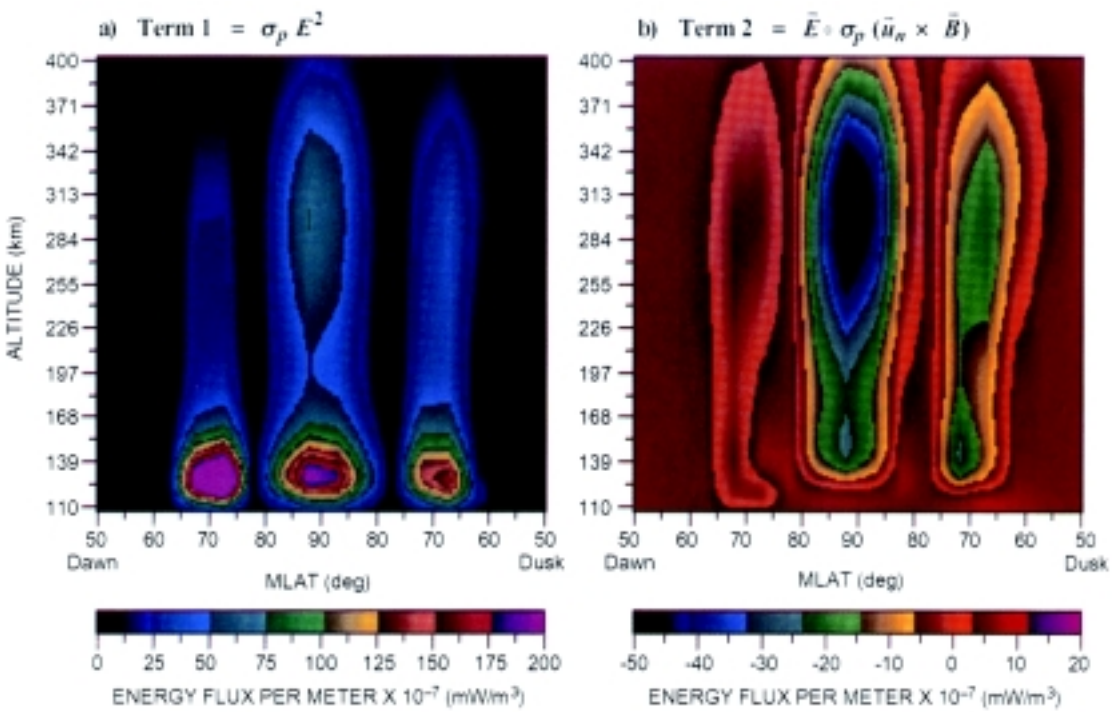

Figure 2.3. Model calculations of the Joule heating rate at high latitudes clearly show the influence of a two-cell convection pattern imposed at high latitudes. Panel a) shows the results for the case without convection. Here the Joule heating rate maximizes near 120 km with a strong altitude gradient between 120 km and 200 km. When convection is included, the effects of the induced neutral wind motions can be distributed over a much larger altitude range, as shown in panel b). However, the validity of this large-scale representation below 200 km is not known. GEC will quantify the magnitude and spatial distribution of Joule heating rates below 200 km; more importantly it will establish the time and spatial scales that produce dynamic responses of the I-T system to Joule heating. [Figure: *Thayer et al*., 1995]

al., 1995] have calculated the altitude distribution of the Joule heating rates resulting from the electric field imposed at high latitudes on a stationary atmosphere and the modification produced by the resulting neutral wind motion (**Figure 2.3**). The results of such studies show large altitude gradients in the heating rate in the region between 200 and 120 km and demonstrate the important influence of neutral winds, and they are qualitatively consistent with height-resolved Joule heating rate profiles derived from ground-based radar measurements. However, the radar data reveal more extensive structure in the distribution of the heating than is evident in the model. ***At present we cannot observe the electric field and plasma density on the spatial and temporal scales required to resolve the observed thermospheric temperature structure.*** While ground-based observations are a valuable source of data with high temporal resolution, they are limited in their latitudinal and longitudinal coverage. Measurements over the entire range of polar latitudes are needed to understand the system response to Joule heating.

Even in the F region, little is known about the global distribution of spatial and temporal scales on which effective Joule heating occurs. Yet this information is essential to understanding the I-T system's response to magnetospheric electromagnetic energy inputs. Broadly speaking, the time constant for ion response ranges from less than a minute to a fraction of a second over the altitude range from 300 km to 130 km. The response of the neutral gas, on the other hand, ranges from tens of minutes to a few hours over the same altitude range. Thus, at the higher altitudes, we are able to compare simultaneous measurements of the temperature and velocity of the ion and neutral species and reconcile them with our physical description of the heat balance. At lower altitudes, however, the time constants are longer, and the temperature of the gases is more closely dependent upon the temporal history of the dynamics. Thus it becomes essential that the temporal evolution of Joule heating events be described. This can only be achieved with the multiple satellite configuration of the GEC mission, which will measure the temporal evolution of the key parameters over periods ranging from a few minutes to over an hour and their behavior over spatial scales ranging from many hundreds of kilometers to a few kilometers. ***Furthermore, observations at altitudes down to 130 km are needed to understand how the spatial and temporal scales are related to the different physical processes.*** To address these issues GEC will

- *measure the ion-neutral velocity difference for determination of the Joule heating rate;*
- *measure the constituent ion and neutral constituent densities allowing a reliable measure of the effective collision frequency;*
- *measure the density and temperature of the ion and neutral gases to determine their pressures;*
- *make measurements at different altitudes to describe heating and momentum transfer effects; and*
- *correlate variations in heating rate and ion-neutral motions from satellites with temporal spacings ranging from 1 minute to 30 minutes to determine response times at different altitudes and scale sizes.*

2.1.3 How do electric fields affect winds and composition in the I-T system? Electric fields imposed by the magnetosphere on the I-T system affect the motion of the neutral atmosphere directly through the drag forces exerted by the convecting ions and indirectly through changes in the

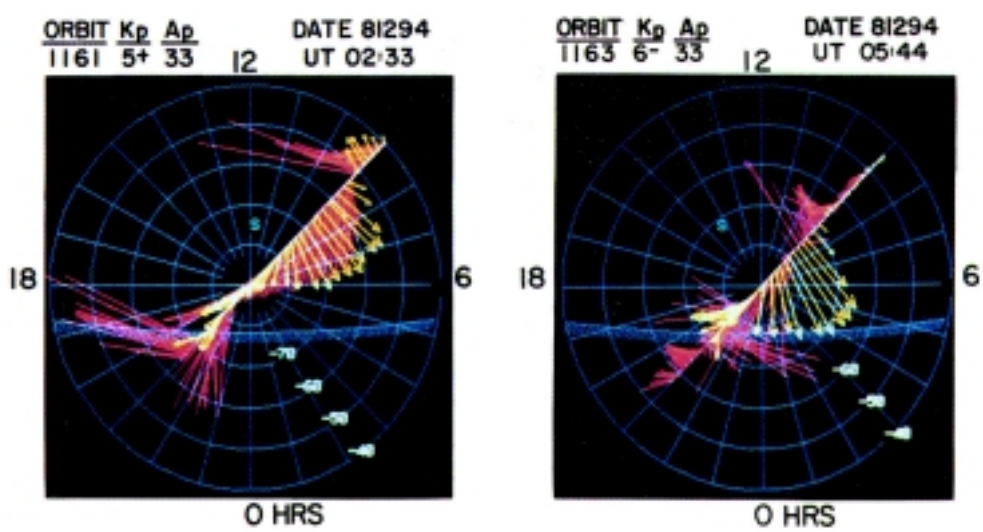

Figure 2.4. Neutral winds (yellow arrows) and ion drifts (red lines) measured over the south polar region by Dynamics Explorer-2. The curved shaded line indicates the solar terminator. The observations in the two panels were made 3 hours apart, during which time the ion convection pattern changed. The observations in the left panel were made during a period of enhanced geomagnetic activity (AE ~400). The ions are driven anti-Sunward by a strong convection electric field, and the neutral winds, driven by ion drag forcing, clearly mimic the ion flow. The data in the right panel were acquired after geomagnetic activity had lessened (AE ~100 and Bz weakly northward). Although the ion drifts no longer show organized anti-Sunward flow seen during orbit 1161, the neutral winds have not responded to the change in ion convection and maintain their anti-Sunward flow. [Figure: *Killeen et al.,* 1984]

neutral atmosphere pressure resulting from Joule heating. The most recent satellite observations pertaining to the coupling between ion and neutral dynamics were made about 20 years ago by Dynamics Explorer-2 (DE-2). **Figure 2.4** shows two examples of neutral wind and ion drift signatures observed during DE-2 passes across the southern high-latitude region near 350 km altitude. The first example (left panel) is for a period of southward Interplanetary Magnetic Field (IMF) and strong ionospheric convection. In this case, the ion and neutral flows show many similarities, indicating that sufficient temporal stability in the convection electric field exists to allow ion drag forces to drive the neutral atmosphere along trajectories similar to those followed by the ions. The data shown in the second example (right panel) were taken immediately following a change in the orientation and magnitude of the IMF, which resulted in a change in the magnetospheric forcing. In this case, the ion drifts and neutral winds are radically different. The decoupling of the ion and neutral motions evident in this example results from the ability of the ions to respond rapidly to changes in the magnetospheric electric field, while the thermospheric neutral gas responds more sluggishly. The DE data (cf. **Figure 2.2**) also show that the ion temperature maximizes and the ion composition changes in regions where, owing to the longer time constant of the neutral response, the ion-neutral velocity difference is greatest.

This picture of neutral winds driven by ion drag is well-established at F-region altitudes. However, ***almost no information about the global-scale connection between high-latitude neutral winds and electric fields is available at altitudes below 300 km.*** Of particular interest are those altitudes below 200 km, where the Joule heating rate is much larger than at higher altitudes and where the neutral wind motion produces dynamo electric fields. Here, ion motions result in Joule heating of the ions and neutrals; and resulting neutral wind systems, driven by pressure gradient forces and horizontal and vertical viscosity, can exist over spatial and temporal scales that are much larger than the originally imposed ion drifts. The larger-scale neutral motion can then influence the electric field at the larger scales through the dynamo action of the neutral winds. ***The ability to characterize ion-neutral coupling across different spatial scales is crucial to our understanding of the response of the I-T system to magnetospheric inputs.*** The GEC mission will provide the first complete characterization of the ion and neutral composition and gas motions at altitudes between 300 km and 130 km, which will allow us to determine the important dynamic coupling processes that control the I-T system response to magnetospheric forcing.

At altitudes below 300 km Joule heating produces vertical mixing of thermospheric constituents through the vertical motions that it induces. The amount of mixing at auroral latitudes is likely to depend not only on the magnitude of the heating rate and on its vertical distribution, but also on the horizontal scale and temporal persistence of the electric field structure. Heating that is concentrated in small regions may be more effective in producing vertical mixing than the same amount of heating distributed over a larger region, since the magnitude of the vertical velocity will be larger for the concentrated heating. Induced vertical motions in the neutral gas change the absolute density and the relative concentrations of the major constituents O and N_2 at any given altitude. These changes can in turn modify the ion chemistry, resulting in changes in the ion density and thus the ion drag. Little information is available about this important coupling between composition and dynamics because of the coarse temporal and spatial sampling provided by single satellite observations. This lack of knowledge leads to associated deficiencies in our description of the I-T system [*Codrescu et al.,* 1997]. Through multipoint measurements at altitudes between 300 km and 130 km, GEC will be the first mission capable of providing the required information, thus making possible a huge leap in our understanding of the response of the coupled I-T system to magnetospheric forcing. To address these issues GEC will

- *measure the vector electric field to specify the magnetospheric driver over scales from 10 kilometers to several hundred kilometers;*
- *measure the ion and neutral drifts over an altitude range that allows a departure from E x B drift of the ions to be considered;*
- *measure the temperature and density of the ion and neutral gases to locate variations in pressure related to E-field and neutral wind variations;*
- *measure the constituent ion and neutral composition to determine the connection to vertical winds and heating;*
- *correlate time series from spacecraft with temporal spacings ranging from 1 minute to 30 minutes to determine the time evolution of specific events; and*
- *assemble measurements from a petal configuration to discover the vertical and horizontal circulation.*

2.1.4 How do magnetospheric influences extend to middle and low latitudes? The effects of magnetospheric inputs are strongest at magnetic latitudes above 60°, where the I-T system and magnetosphere are most strongly coupled. However, the energy delivered by the magnetosphere to the upper atmosphere at high latitudes can also influence the I-T system at middle and low latitudes, as is illustrated schematically in **Figure 2.5**, which shows how heating at high latitudes can alter the global circulation in the thermosphere. This influence is exerted predominantly through the penetration of high-latitude electric fields to lower latitudes, the dynamo action of neutral winds driven equatorward by auroral heating, and the equatorward propagation of impulsive I-T waves and disturbances.

Magnetospheric Leakage Fields at Middle Latitudes. Electric fields applied at high latitudes are effectively shielded from middle and lower latitudes by the differential motion of charged particles in the magnetosphere. However, the

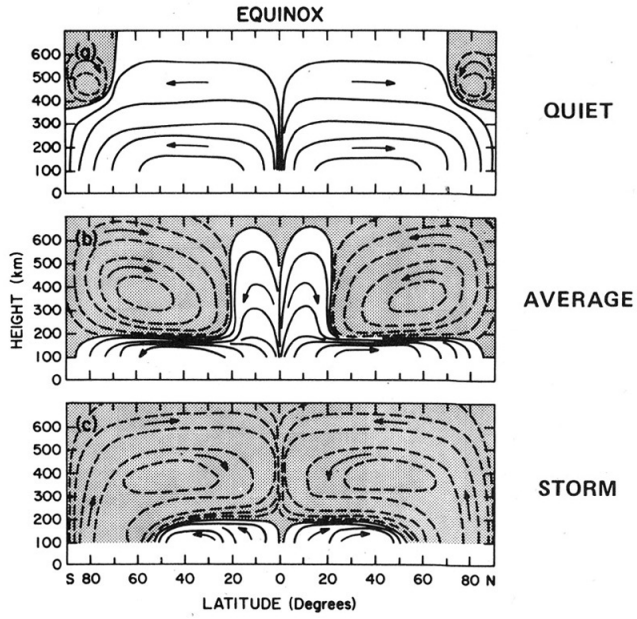

Figure 2.5. Schematic illustrating the influence of magnetospheric energy input, through high-latitude heating, on the global circulation of the thermosphere. During geomagnetically quiet times (top panel), the flow is predominantly poleward and is driven by solar EUV heating. In contrast, during periods of enhanced geomagnetic activity, high-latitude heating drives strong equatorward flows to middle and low latitudes and even as far as the equator, as shown in the middle panel for average activity and in the bottom panel for a major geomagnetic storm. GEC will provide a description of the propagation of high-latitude magnetospheric influences to lower latitudes and thus complete our understanding of this important space weather phenomenon. [Figure: *Roble*, 1977]

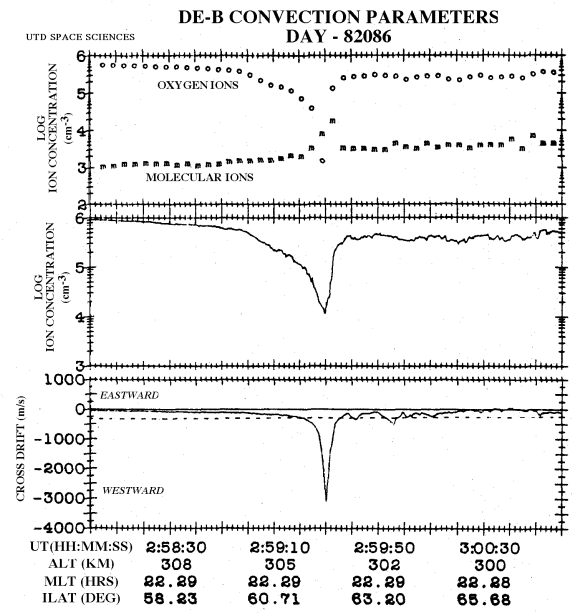

Figure 2.6. Ion drift meter and retarding potential analyzer data from Dynamics Explorer-2 acquired during an encounter with an SAID event. The rapid (3000 m s^{-1}) westward drift (bottom panel), the narrow latitudinal extent of the event, its location equatorward of the auroral zone, and the ionization trough (middle panel) are all distinctive SAID features. The depletion in the O^+ concentration (o) and enhancement in the abundance of molecular ions (m) seen in the top panel result from an increase in the rate of the charge exchange reaction between O^+ and N_2 that occurs when the ion bulk flow velocity is large relative to the velocity of the neutral flow. GEC will reveal the temporal evolution of these events, thus exposing how the I-T system is dynamically coupled to the inner magnetosphere. [Figure: *Anderson et al.*, 1991]

shielding is never perfect, and during reconfigurations of the magnetosphere associated with sudden quieting or enhancements in magnetic activity called storms and substorms, large electric fields may penetrate all the way to the equator. When they are present, these leakage fields are usually larger than the ever present internally generated dynamo fields. ***The growth and decay of these fields is poorly understood owing to our inability to characterize the key ionospheric parameters over latitude ranges extending from the equator to the auroral zone and on time scales of tens of minutes to an hour.***

SAID's are one manifestation of the leakage field that challenges our understanding. **Figure 2.6** shows the typical signature of a SAID that is supported by the simultaneous appearance of large latitudinal gradients in the ionospheric conductivity. The SAID's and associated conductivity gradients have a significant effect on the Joule heating rate in the subauroral region. They produce enhanced recombination, resulting in lower plasma concentrations near the F peak on the magnetic field lines that thread the inner edge of the ring current. Significant thermal electron heating may occur at this "trough" in the ion concentration, producing the red emissions at 630.0 nm known as Stable Auroral Red (SAR) arcs. Despite the wide range of phenomenology associated with SAID's, however, little is known about their temporal and spatial development, which is a key to understanding linkages between the magnetosphere and the I-T system. ***Our limited knowledge is principally attributable to the lack of data sets with the latitude coverage and time resolution (tens of minutes) required to describe the evolution of penetration fields.***

The Ionospheric Disturbance Dynamo. Joule and auroral particle heating at high latitudes produce neutral winds that extend away from the auroral zone to middle and low latitudes (cf. **Figure 2.5**). Such neutral winds can drive dynamo currents and create polarization electric fields in the middle- and low-latitude I-T system. This process constitutes the so-called *ionospheric disturbance dynamo*. Electric fields observed at middle latitudes are frequently not consistent with those produced by the tidal wind dynamo responsible for the dayside Sq (solar quiet) current system. In such cases, the disturbance dynamo is thought to contribute significantly to the electrodynamics of the region. However, ***the spatial and temporal scales over which the distur-***

bance dynamo develops are poorly understood, and its effects are correspondingly difficult to isolate.

The electrodynamic response of the I-T system at middle and low latitudes to winds propagating from the auroral zone is determined by the characteristics of the winds and the conductivity of the ionosphere. At middle latitudes, ionospheric conductivity is quite well-behaved, with substantial contributions from both the E-region and the F-region during the daytime, but with a dominant F-region contribution in the nighttime. The effects of the disturbance dynamo thus depend upon the extent of the neutral wind perturbation in altitude. For example, polarization fields produced by F-region wind perturbations during the daytime will be shorted through the E-region and be ineffective. However, the same perturbation at night may produce significant electric fields throughout the middle-latitude ionosphere. In order to understand these influences, ***it is necessary to establish the relationships between latitudinal profiles in the electric field and the temporal variations in auroral zone particle precipitation, electric fields, and neutral winds.***

Propagating Storm-time Perturbations. In the preceding discussion of magnetospheric influences at middle and low latitudes, the emphasis has been on effects, indirect as well as direct, of magnetospheric forcing on the electric fields. It is important to recognize that the neutral atmosphere may be globally influenced by magnetospheric forcing as well. To date, the response of the neutral atmosphere to these magnetospheric influences has been demonstrated most dramatically in numerical simulations. ***The least understood of these influences is the response of the atmosphere to impulsive changes in the electric field and particle precipitation that mark the start of a geomagnetic storm.*** These impulsive changes produce gravity waves with periods from minutes to hours that propagate toward the equator (cf. **Figure 1.4**). Such equatorward-propagating perturbations of the neutral atmosphere are known as traveling atmospheric disturbances (TAD's). The changes produced by TAD's in the composition and density of the neutral gas are very large. For example, large-scale TAD's can cause the neutral density to vary by a factor of two over a period of 1 to 3 hours. Associated with TAD's are traveling ionospheric disturbances, or TID's, that are characterized by perturbations in the charged particle densities that are often larger in magnitude than those observed in the neutral atmosphere. Particularly large amplitude waves have been observed to increase electron densities by an order of magnitude in the F region ionosphere. Global disturbances of the I-T region initiated by auroral forcing have important practical implications for satellite operations, because the neutral density changes are capable of significantly perturbing the satellite orbits and of inducing oscillations in the spacecraft as they pass through density irregularities. ***Key information required to understand these perturbations is a characterization of the horizontal wavelength and the propagation velocity of both the neutral and ionized disturbance features.***

GEC will for the first time allow multisatellite observations from high to low latitudes, thus making it possible to describe the connection between high-latitude events and middle- and low-latitude responses. Specifically GEC will

- *measure latitude profiles of neutral winds, ion drifts, electric fields, and particle precipitation with temporal separations between 1 minute and 30 minutes allowing the evolution of penetration events to be studied;*
- *provide a petal orbit configuration allowing middle-latitude neutral thermospheric and ionospheric parameters to be observed at different altitudes during auroral activity; and*
- *measure neutral wind and composition at middle and low latitudes allowing storm time responses to be described with time scales from 10 minutes to 1 hour.*

2.2 How Is the I-T System Dynamically Coupled to the Magnetosphere?

The first fundamental question on which the GEC investigation is focused concerns the response of the I-T system to the input of energy from the magnetosphere. An important aspect of this response is the modification, through a variety of processes, of the conductivity or, equivalently, the effective resistance of the ionosphere. However, the input of electromagnetic energy from the magnetosphere depends on this very parameter and can be modulated by changes in it. Moreover, in addition to being affected by changes in ionospheric conductivity, the exchange of electromagnetic energy between the I-T system and the magnetosphere is also influenced by the dynamo action of the neutral winds that have been set in motion through the drag force of convecting ions (cf. section 2.1.3). Such feedbacks make clear that the I-T system must be understood not merely as a passive absorber of magnetospheric energy but also as an active element in the electrical connection to the magnetosphere.* The investigation of the active role that the I-T system plays in the geospace electrodynamic circuit is the second fundamental focus of the GEC mission.

2.2.1 How do atmospheric dynamo processes modify the energy flow between the magnetosphere and the I-T system? Most of the electromagnetic energy flowing between

*Most of the energy fed back into the magnetosphere is electromagnetic. However, a small fraction is associated with ion outflow, principally the polar wind. The small amount of energy associated with ion outflow is transmitted at thermal speeds and thus has the potential to be involved in long-term feedback effects. Ion outflow and the polar wind are not a fundamental focus of the GEC mission but could be investigated with enhanced instrumentation.

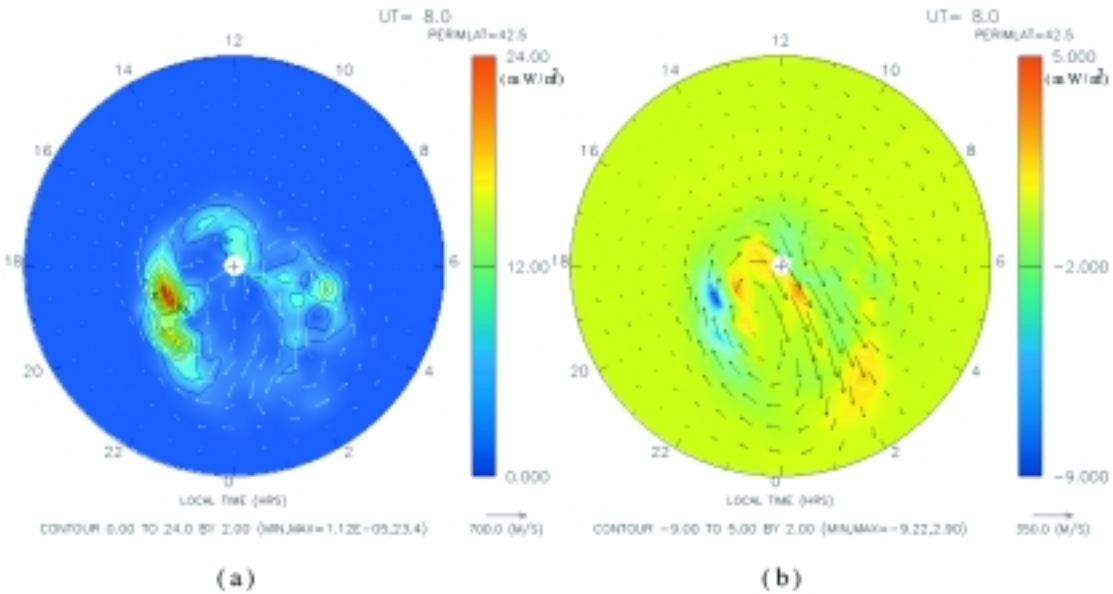

Figure 2.7. (a) Height-integrated electromagnetic energy transfer rate from the magnetosphere to the ionosphere neglecting thermospheric winds and (b) modifications produced by the winds calculated with the NCAR TIGCM and the assimilative mapping of ionospheric electrodynamics (AMIE) algorithm. The plots are centered on the geographic north pole and extend equatorward to 42.5° N. The color bars give the power intensity in mW m^{-2}. The arrows indicate ion drifts (a) and neutral winds (b). GEC will discover how the magnetospheric and ionospheric wind dynamos are coupled in time and space, thus allowing the development of models that properly describe the I-T system feedback to the magnetosphere. [Figure adapted from *Lu et al.*, 1995]

the I-T system and the magnetosphere originates from the magnetosphere-solar wind interaction. At the largest spatial and temporal scales, electric fields existing within the field-aligned current systems provide the elements of a conduit along which the electromagnetic energy is transferred. On a global basis more than 90% of this energy is dissipated by Joule heating in the I-T system. The Joule heating rate itself depends upon the ion-neutral velocity difference, and numerical simulations have shown that the induced neutral gas motion may decrease the heating rate by as much as 25% from the rate that would exist with a fixed electric field in a stationary atmosphere [*Lu et al.*, 1995]. The net energy transfer results from an interaction between the magnetospheric dynamo and the dynamo action of the neutral winds in the I-T system (**Figure 2.7**).

Over large spatial scales, the magnetospheric dynamo dominates the energy transfer between the I-T system and the magnetosphere. However, the magnetospheric dynamo can change quite rapidly, as magnetospheric inputs change, while the neutral winds respond much more slowly and can act as a flywheel that may reverse the direction of the energy transfer (**Figure 2.8**). This is especially important where the wind is strong and directed opposite to the ion convection velocity. In fact, regions of upward Poynting vector, calculated from spaceborne observations of electric fields and magnetic perturbation fields, are most often seen near convection reversal boundaries and in the dawn sector, where large gradients in the ion drifts exist and changes in the ion mo-

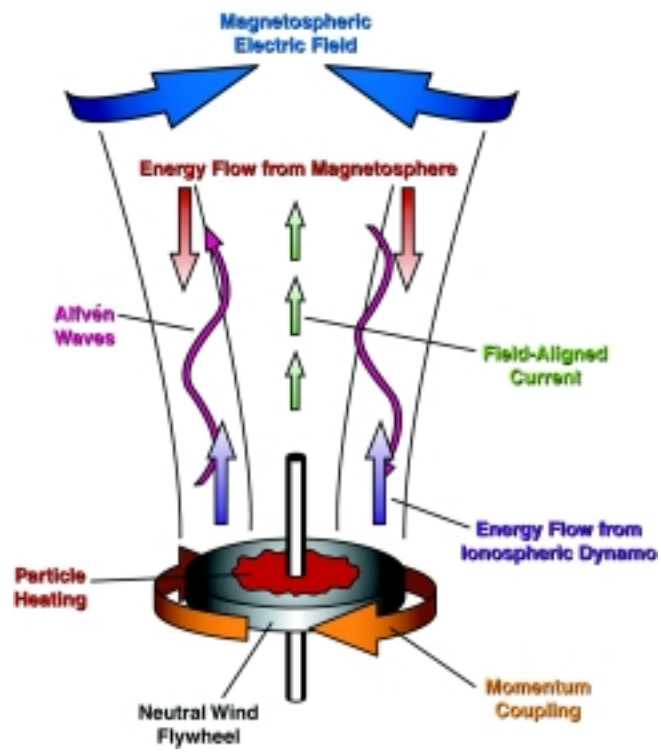

Figure 2.8. Cartoon illustrating the neutral wind "flywheel" effect, by which neutral winds, originally set in motion as a result of momentum received from convecting ions, function as a dynamo to modify the net electromagnetic energy transfer rate between the magnetosphere and the ionosphere. This effect results from the fact that the neutrals respond much more slowly to changes in magnetospheric inputs than do the ions.

tion cannot be easily followed by the neutral gas [*Gary et al.*, 1995].

There is little observational information about the range of spatial and temporal scales over which the dynamo processes operate; yet this information is crucial to understanding the active electrical coupling between the I-T system and the magnetosphere. At present we have no information about neutral winds over the extensive range of spatial scales exhibited by both field-aligned currents and electric fields. Moreover, ***we have no information about how temporal variations in the field-aligned currents and electric fields are related to the neutral winds and conductivity, information that is critical to understanding the interaction between the magnetospheric and ionospheric dynamos.*** This information will be provided for the first time by GEC through multipoint measurements in the altitude range below 300 km, where the dynamo action of the neutral winds becomes effective. Specifically, GEC will

- *measure the electric fields, magnetic fields, particle precipitation, and neutral winds allowing the relationships between changes in the neutral dynamics and the net energy flow to be established at different altitudes; and*
- *measure the neutral wind, ion drift, and electric field from satellites with temporal spacings ranging from 1 minute to 30 minutes to determine response times at different altitudes and scale sizes.*

2.2.2 What controls the connections between horizontal gradients in conductivity, electric fields, currents, and neutral winds? The electromagnetic energy transferred between the I-T system and the magnetosphere is carried by electric fields and magnetic field perturbations associated with field-aligned currents and propagating Alfvén waves. Alfvén waves are discussed in the next section. Here we consider the dynamic response of the I-T system to changes in the electric fields and currents that couple the upper atmosphere and magnetosphere.

Currents perpendicular to the magnetic field are associated with the electric field originating in the magnetosphere and from the dynamo action of neutral winds in the I-T system itself. A net field-aligned current flowing into or out of the I-T system will result when the height-integrated divergence of the horizontal current is non-zero. Such field-aligned currents are frequently accompanied by horizontal gradients in the electric field.

A field-aligned current must be consistent with the gradient in the horizontal current, and the horizontal current is dependent upon the electric field, the neutral wind, and the conductivity. These parameters are strongly coupled as we have seen from previous discussion, and thus a change in any one of these parameters will result in a change in the others. Such changes can affect the nature of the electromagnetic energy transfer seen by the magnetosphere. For example, the electric field imposed from the magnetosphere may remain fixed. If changes in the neutral wind alter the effective resistance of the ionosphere, then the horizontal current—and thus the field-aligned current—must change as well. If the field-aligned current is to remain constant, then changes in the effective resistance of the I-T system must result in changes in the electric field. It is also possible that changes in the I-T system occur while the electromagnetic energy transfer rate remains fixed. In such a case, the changes in the I-T system must occur in a way that keeps constant the effective resistance of the system.

Evidence from previous satellite measurements suggests that the behavior of the magnetosphere that drives a current or a voltage is dependent on scale size [*Vickrey et al.,* 1986] and location [*Keady and Heelis*, 1999]. However, our knowledge is limited largely to the behavior of the fields, and ***we have almost no information on how the I-T system evolves in the presence of the magnetospheric driver to maintain a given parameter.*** We know that this evolution takes place over a range of spatial scales and that processes occurring on one scale are coupled to those occurring on smaller or larger scales. Field-aligned currents exist over latitudinally confined (1°-5°) regions. The ionization produced in these regions by energetic particle precipitation is transported away, thus changing the ionospheric conductivity over spatial scales larger than the dimensions of the field-aligned current regions where the original ionization enhancement occurred. These more global changes in ion density in turn modify the ion drag forcing of the neutral gas, thereby affecting the neutral motions over spatial scales that are again larger than the scale size of the regions of field-aligned currents. The resulting changes in the neutral wind can modify the effective resistance of the ionosphere, with corresponding adjustments in either the driving field-aligned currents or the electric field, as described above. ***Elucidating the coupling of these various processes across multiple scales is key to understanding the dynamic influence that the I-T system exercises on magnetosphere-ionosphere coupling.***

To determine the cross-scale linkages among the relevant parameters, it is necessary to determine how changes in the I-T system are related to changes in the energy flow and how those changes are manifested (as changes in the electric field or changes in the magnetic field perturbations or both). The required measurements of fields, particles, and neutral winds must be made in the region below 300 km, where the effective resistance of the I-T system can be observed. Furthermore, the changes must be observed over temporal scales of minutes and greater, commensurate with the response of the neutral atmosphere to magnetospheric forcing. Specifically, GEC will

- *measure electric and magnetic fields to distinguish changes in energy flow produced by changes in currents from those produced by changes in electric fields; and*

• *correlate measurements of the fields, particles and neutral motions with temporal spacings ranging from 1 minute to 30 minutes to determine the coupling between scale sizes.*

2.2.3 How does the I-T system affect field-aligned currents and Alfvén waves that connect it to the magnetosphere? Field-aligned currents represent one of the most fundamental means by which electrical processes occurring in the ionosphere and magnetosphere are coupled. Sources and loads generally exist where the electric field and the current are antiparallel and parallel to each other, respectively, and are most usually associated with currents and electric fields that are perpendicular to the magnetic field. Notable exceptions to this configuration exist at high altitudes, where field-aligned electric fields are associated with particle acceleration. Under quasi-steady conditions, field-aligned currents form part of a current loop connecting sources and loads that may be distributed in the ionosphere and the magnetosphere. Under time-varying conditions, changes in currents or electric fields in the magnetosphere or ionosphere are communicated by the propagation of Alfvén waves.

From a magnetospheric perspective, it is the height-integrated effects of the I-T system that are important. Within the I-T system, however, ***the contributions of neutral winds and electric fields at different altitudes are important for correctly describing how the I-T system affects coupling to the magnetosphere.*** A fixed field-aligned current density incident from the magnetosphere must be equal to the height-integrated divergence in the horizontal current. In principle, this integral begins at the top of the conducting ionosphere, around 350 km, and proceeds downward until the slab thickness is sufficient to conduct the current horizontally. It is traditional to assume that this slab thickness extends to altitudes below 120 km, where the ionospheric conductivity is a maximum. For large-scale field-aligned currents of sufficient intensity, this assumption is usually valid, but for smaller scales and/or smaller intensities little is known about the effective thickness of the ionosphere. By examining the magnetic field perturbations produced by field-aligned and horizontal currents at different altitudes, the effective thickness of the ionosphere for field-aligned currents of different scale sizes and intensities can be described. With this foundation the influence of winds and electric fields on ionospheric conductivity as described in the previous section can be targeted to identify the important scale sizes at different altitudes.

If we are to consider how the I-T system evolves in the presence of magnetospheric inputs over time-scales on the order of a few minutes (the Alfvén wave travel time), then the role played by traveling Alfvén waves in magnetosphere-ionosphere coupling must be understood. Conductivity changes, initially produced by precipitating particles, will launch Alfvén waves that propagate to the magnetosphere. The magnetosphere's response reflects the wave back to the

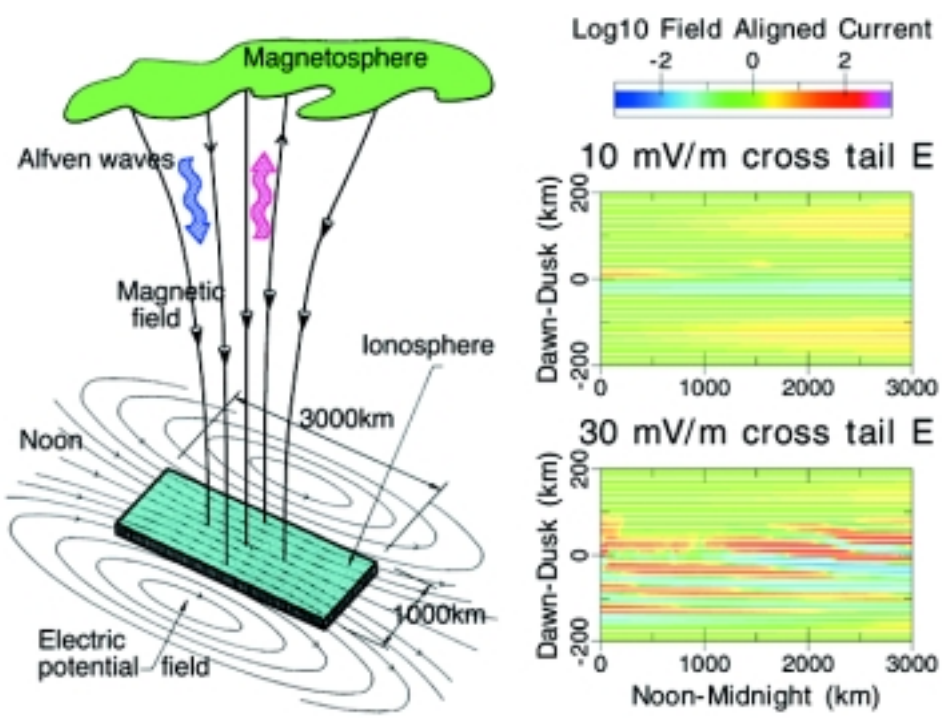

Figure 2.9. The two panels on the right show simulated Sun-aligned arcs for two different cross-polar-cap electric fields. The arcs are shown as regions of upward and downward field-aligned currents. Precipitation-induced changes in ionospheric conductivity propagate as Alfvén waves between the ionosphere and the magnetosphere producing the structure seen in the field-aligned current region in the bottom right panel. This process is illustrated in the cartoon on the left.

ionosphere and thence back to the magnetosphere. Calculations suggest that this process produces multiple arcs such as are frequently observed in auroral images [S*ojka et al*., 1994] (**Figure 2.9**). While ground-based images provide some assurance that Alfvén wave coupling is important, the model of multiple arc formation as a result of Alfvén wave propagation remains unverified owing to the lack of sequential observations through a limited volume of space.

The GEC mission will allow the role played by Alfvén wave coupling between the I-T system and the magnetosphere to be adequately characterized for the first time on the basis of time- and space-resolved in situ data. Specifically, GEC will

- *measure the fields and particles from satellites with temporal spacings ranging from 10 seconds to 30 minutes to determine the temporal evolution of auroral features; and*
- *measure the ratio of the electric and magnetic perturbation fields to determine the contributions or waves and static currents at different spatial scales.*

2.3 Required Measurements

Two fundamental observational requirements must be met to advance our understanding of the behavior of the I-T system and of its coupling to the magnetosphere. First, we must be able to specify how the particle and electromagnetic energy flow between the I-T system and the magnetosphere is changing while we observe simultaneously the behavior of the I-T system as it absorbs and modulates this energy flow. Such a requirement can only be satisfied by making particle and field measurements, together with measurements of the neutral atmosphere and ionospheric plasma, in the altitude range between 300 km and 130 km. In this region the charged and neutral particles are strongly coupled and large spatial gradients in the state variables exist. Secondly, these simultaneous measurements must be made over time scales that allow the evolution of the I-T system to be specified. This requirement can only be accomplished by making measurements in a relatively small volume of space with time separations of a few seconds to an hour. The GEC mission has been specifically designed to meet these requirements, which no previous geospace mission has been able to satisfy. The GEC mission will thus make possible a significant step forward in our understanding of the near-Earth geospace environment.

Table 2.1 lists representative temporal and spatial scales of features and phenomena that the GEC satellites will encounter. This table, based on experience with previous observations, can be used to specify the range of instrument sampling rates and satellite temporal spacings.

Tables 2.2 and **2.3** summarize the key mission requirements to accomplish the GEC science objectives. For each geophysical parameter, the range is dictated by its expected geophysical variability. This variability results from the need to sample over all local time regions and over an altitude region where the ion-neutral coupling varies considerably. The accuracy is dictated by the magnitude of changes associated with the magnetospheric drivers and the I-T system response. For example, to measure changes in the field-aligned currents will require a sensitivity in the measurement of magnetic field perturbations of a 10 nT. Changes in vertical neutral winds resulting from localized Joule heating will require a sensitivity of a 5 m s^{-1}.

3.0 GEC Science Requirements: Implications for the Mission Design

As pointed out at the beginning of Section 2.0, achieving the scientific objectives of the GEC mission requires measurement of the spatial and temporal scales on which electromagnetic energy is exchanged between the I-T system and the magnetosphere and processed and dissipated within the I-T system. The coupling of the energy transfer and dissipation processes across scales must also be under-

Table 2.1. Representative temporal and spatial scales of electrodynamic phenomena in the I-T system.

Phenomenon	Temporal Scale	Spatial Scale
Substorm	10 min - 90 min	500 km
Auroral Arc	5 min	10 km
Gravity Wave	10 min	200 km
Boundary Feature	10 min - 30 min	100 km
SAID	10 min - >60 min	100 km
Joule Heating	10 sec - 60 min	100 m - 500 km
E-field Fluctuations	10 s - 60 s	10 km - 100 km
Field-aligned Current	1 s - 10 min	1 km - 50 km

Table 2.2. Measurement requirements pertaining to the I-T system response to magnetospheric inputs.

MEASUREMENTS			**SCIENCE QUESTIONS**			
Parameter	Range	Accuracy	Mag. Inputs Heating	Joule and Comp	Winds	Middle & Equat. Latitudes
Electric Field	± 300 mv/m	0.1 mV/m	R	R	R	R
Ion Velocity	±3 km/s	3 m/s	R	R		R
Neutral Velocity	± 2 km/s	5 m/s		R	R	R
Magnetic Field	± 65000 nT	± 10 nT	R			R
Energetic e^- 0.1-100 keV	10^{-6} - 1 erg/	$\Delta E/E = 0.2$				
32 energies 12 angles	$cm^2/s/st/eV$	$\Delta a=10^o x 20^o$	R		R	R
Energetic p^+ 0.1-50 keV	10^{-7} - 10^{-1} erg/	$\Delta E/E = 0.2$	E		R	R
32 energies 12 angles	$cm^2/s/st/eV$	$\Delta a=10^o x 20^o$				
Ion & Elec Temperature	500 - 10000 K	± 5%		R	R	
Neutral Temperature	500 - 5000 K	± 5%		R	R	
Ion Density	10 - 10^7 cm^{-3}	±º 1%	R		R	R
Ion Comp 1-60 amu	10 - 10^6 cm^{-3}	± 10%		R	R	
Neutral Comp 1-60 amu	10^6- 10^{12} cm^{-3}	± 10%		R	R	
OPERATIONS						
Static Spatial Resolution			>1 km	>1 km	>1 km	>10 km
S/C Temporal Spacing			10 sec-30 min	1-30 min	10 -60 min	10 - 90 min
Baseline Orbit			R	R	R	R
Deep Dipping			E	R	R	E
Petal Orbit			N	E	R	E

R=Required : E=Enhanced Science : N=Not Required for Objectives

Table 2.3. Measurement requirements pertaining to coupling between the I-T system and the magnetosphere.

MEASUREMENTS			**SCIENCE QUESTIONS**		
Parameter	Range	Accuracy	Flywheel	Currents & Conductivity	Alfvén Waves
Electric Field	± 300 mv/m	0.1 mV/m	R	R	R
Ion Velocity	±3 km/s	3 m/s	R	R	
Neutral Velocity	± 2 km/s	5 m/s	R	R	R
Magnetic Field	± 65000 nT	± 10 nT	R	R	R
Energetic e^- 0.1-100 keV	10^{-6} - 1 erg/	$\Delta E/E = 0.2$	R	R	R
32 energies 12 angles	$cm^2/s/st/eV$	$\Delta a=10^o x 20^o$			
Energetic p^+ 0.1-50 keV	10^{-7} - 10^{-1} erg/	$\Delta E/E = 0.2$	R	R	R
32 energies 12 angles	$cm^2/s/st/eV$	$\Delta a=10^o x 20^o$			
Ion & Elec Temperature	500 - 10000 K	± 5%			R
Neutral Temperature	500 - 5000 K	± 5%			R
Ion Density	10 - 10^7 cm^{-3}	± 1%	R	R	R
Ion Comp 1-60 amu	10 - 10^6 cm^{-3}	± 10%			R
Neutral Comp 1-60 amu	10^6- 10^{12} cm^{-3}	± 10%			R
OPERATIONS					
Static Spatial Resolution			>1 km	>1 km	>1 km
S/C Temporal Spacing			1-30 min	1-30 min	1 -60 min
Baseline Orbit			R	R	R
Deep Dipping			R	R	E
Petal Orbit			E	E	N

R=Required : E=Enhanced Science : N=Not Required for Objectives

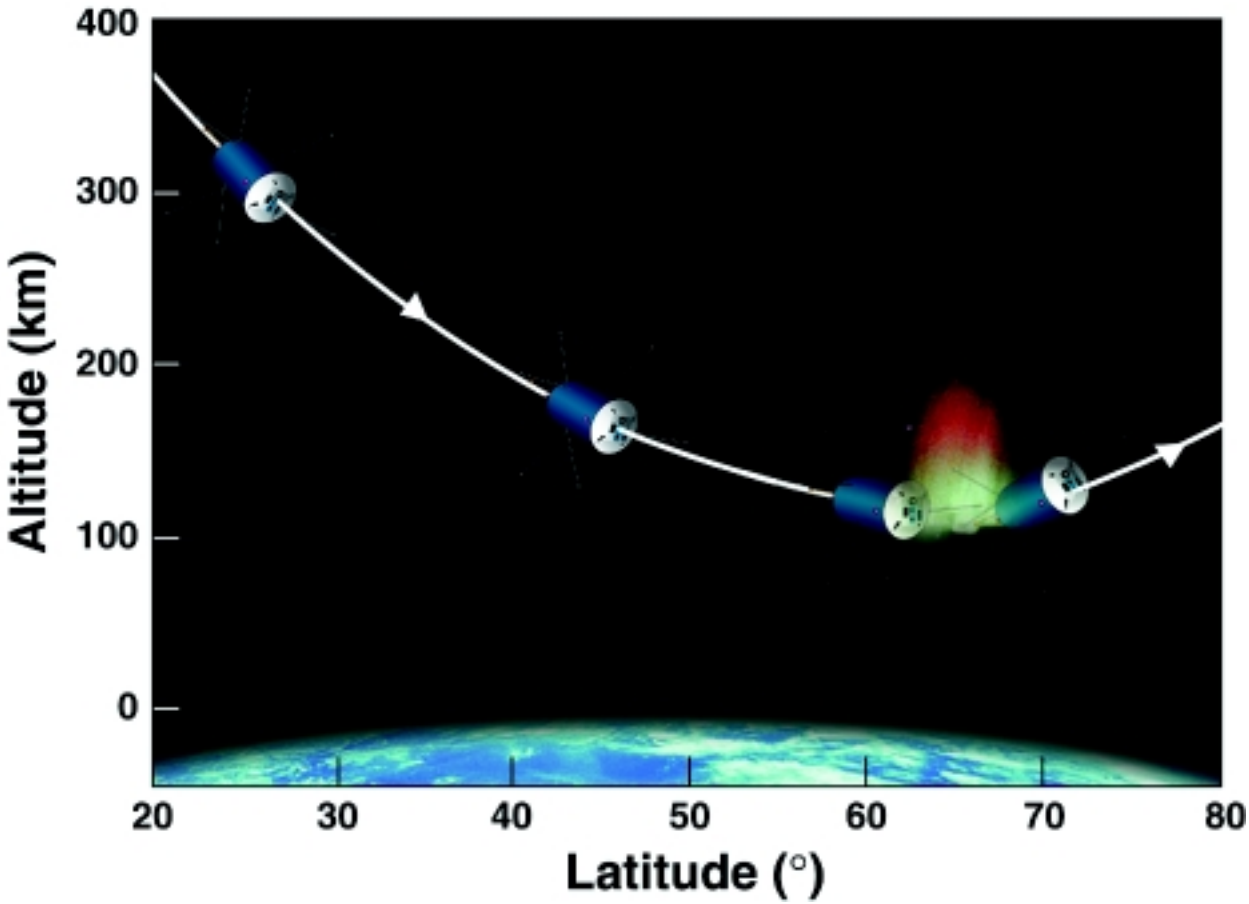

Figure 3.1. "Pearls on a string"—the baseline GEC orbital formation.

stood. This section sets forth the rationale for the GEC mission design, the details of which are presented in Section 4. The discussion here addresses the selection of a pearls-on-a-string formation as the baseline orbit, the need for multipoint measurements to provide the spatial, temporal, and cross-scale information required by the GEC science objectives, the role of deep dipping in the GEC mission, and the decision not to include optical remote sensing in the GEC strawman payload.

3.1 The "Pearls-on-a String" Formation

The GEC spacecraft will be placed in a high-inclination (83°) orbit to allow repeated sampling of the high-latitude regions where the bulk of the energy exchange between the I-T system and the magnetosphere occurs. The baseline orbital formation is a pearls-on-a-string configuration (**Figure 3.1**). This formation will allow the spacecraft to make successive measurements at the same latitude or, alternatively, to provide simultaneous measurements over varying spatial (or, equivalently, temporal) scales at different points across a latitudinally extended region. The choice of the pearls-on a-string baseline orbit rests on two considerations.

First, the processes that couple the magnetosphere and the I-T system are known to occur in well-defined latitudinal bands (e.g., auroral arcs, Region 1 and 2 field-aligned currents, SAID's, etc.) and are assumed to be sufficiently homogeneous along their longitudinal or local time extent that the critical space- and time-resolved measurements can be obtained through sampling of the latitudinal distribution of the target processes. It is this assumption of longitudinal homogeneity in the phenomena of interest that justifies the choice of the pearls-on-a-string orbital configuration for the GEC spacecraft. The validity of this assumption cannot be tested by measurements from the GEC spacecraft themselves, however. Owing to the precession of the orbit in longitude/local time, the GEC satellites will sample a different volume of space with each successive orbital pass and thus can provide no information about the stability or variability of conditions in the longitudinally adjacent volume sampled ~100 minutes earlier during the previous pass. Such comparative information can be obtained, however, from coordinated observations with ground-based radars, which will supply the missing second dimension for the GEC measurements during the planned deep-dipping campaigns.

Second, with the proper intersatellite spacing the pearls-on-a-string configuration is ideally suited to resolve the spatial and temporal scales of key processes and structures in the I-T system. With a latitudinal speed in the ionosphere of 8 km s^{-1}, intersatellite separations of 8 km (≤ 0.1°

in latitude) and 4800 km (~48° in latitude) correspond to time intervals of 1 second and 10 minutes, respectively. These spatial and temporal separations—which are used here solely as examples—cover the important temporal and spatial scales listed in **Table 2.1**. Moreover, as discussed in Section 3.3 below, with uneven spacing between four (three) spacecraft, GEC would be able to resolve six (three) different temporal and spatial scales simultaneously, making it possible to characterize the coupling across scales of energy transfer and dissipation processes in the I-T system.

3.2 Separating Spatial and Temporal Effects with GEC

A fundamental problem in the interpretation of data acquired by a single spacecraft at a single point in space is the impossibility of distinguishing between signals produced by spatial features and those produced by temporal effects. A typical time series of data from a single satellite is defined by an outer scale, which is the time between the first and last sample, and an inner scale, which is the time between each sample. The inner scale is usually fixed by the instrument measurement scheme, while the outer scale can be chosen with some science rationale to lie between twice the sample period and much larger periods encompassing one or more orbit periods. Within the outer scale, the satellite provides a series of discrete measurements at particular locations and particular times. No information about the temporal evolution at a fixed location or the spatial variation at a fixed time is available, and thus an interpretive ambiguity exists since the same signal can be produced by either time or space variations. In addition, any latitudinal region can only be sampled with a temporal separation equal to the orbit period (~100 minutes). This sample period is very long compared to the expected evolution of many features and produces a longitudinal separation of 2400 km (between consecutive samples in the same latitude band) that in some cases (e.g., auroral arcs) may be too great.

The space-time ambiguity inherent in observations from a single spacecraft represents a fundamental impediment to efforts to advance our understanding of the structures and dynamics of the geospace environment. This difficulty can, however, be overcome through the deployment of multiple spacecraft in an appropriate orbital configuration. The multispacecraft strategy is being employed in magnetospheric missions (e.g., Cluster II and MMS) and is the solution to the problem of distinguishing between spatial and temporal effects in the I-T system.

Spatial structures can be identified in the GEC satellite data by correlating the measurements between spacecraft, allowing for the temporal separation of the satellites. Time offsets between correlated events from one spacecraft to the next can be interpreted as a bulk flow of the feature. Changes in amplitude with no temporal offset may be interpreted as temporally evolving but spatially fixed features. Some assumptions about the orientation of the structure with respect to the satellite velocity are required to determine the structure's motion. However, these assumptions, such as longitudinal homogeneity or alignment along the magnetic field, can be verified when observation campaigns are combined with ground-based measurements that provide time and altitude variations at a fixed location.

3.3 How GEC Provides the Required Multiscale Coverage

In order to quantify the spatial and temporal regimes over which the various energy exchange and dissipation processes in the I-T system operate and to characterize the cross-scale interactions among these processes, GEC must be able to acquire data over a wide range of temporal and spatial scales. The range in temporal scales is exemplified by the difference between characteristic ion response times to changes in the imposed electric field (a few seconds to a few minutes) and those of the neutral gas (tens of minutes to hours) (cf. Section 2.1.3). The spectrum of spatial scales is seen in the complex interplay among currents, conductivity, ion density, and neutral winds discussed in Section 2.2.2.

A constellation of three or four spacecraft is needed to encompass adequately the temporal and spatial scales relevant to the GEC investigation. To maximize the spectrum of scales being measured, the spacecraft must be unevenly spaced. As can be seen from Figure 3.2, more spacecraft provide simultaneous coverage of more spatial and temporal scales. Four unevenly spaced satellites can provide coverage of six different temporal and spatial scales. In contrast, three spacecraft measure three different scales, while two satellites can cover only one scale. If four GEC satellites, traveling at 8 km s^{-1}, have a temporal spacing of 10, 20, and 40 seconds, then they will make measurements at time intervals of 10, 20, 30, 40, 50, and 70 seconds with corresponding spatial scales of 80, 160, 240, 320, 400, and 560 km. Comparison of these values with the representative temporal and spatial scales listed in Table 2.1 shows that four spacecraft provide the best multiscale coverage required to achieve the GEC science objectives. A mission of three satellites would require different spacing scenarios to accomplish the goals of the GEC investigation. (Note: the satellite spacings given here are representative of spacings likely to be used during one phase of the mission; satellite spacing will in fact be varied over the course of the mission.)

3.4 The Role of Deep Dipping in the GEC Mission

As noted throughout the discussion in Section 2, many of the most significant gaps in our knowledge of the I-T system's response to magnetospheric forcing involve ion-neutral interactions occurring at altitudes below 200 km and characterized by strong altitude gradients. Achieving the sci-

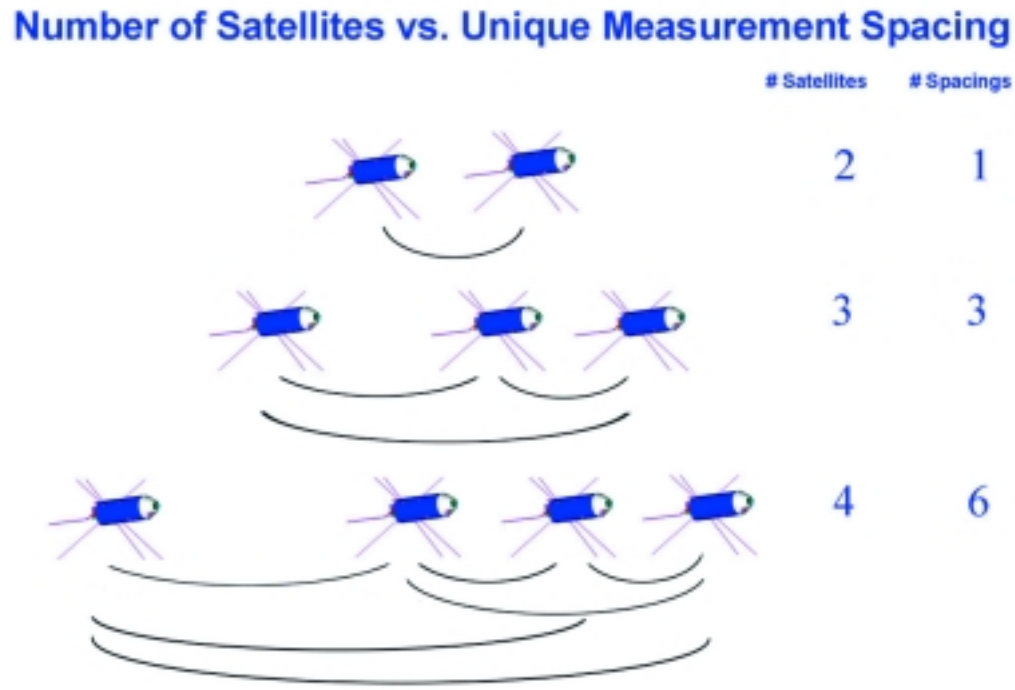

Figure 3.2. With uneven spacing among four (three) spacecraft, GEC will be able to cover six (three) spatial/temporal scales simultaneously. The interspacecraft distances will be varied during the course of the 2-year mission and will range from 1 second (~8 km) to 24 minutes (~one quarter of an orbit).

entific objectives of the GEC mission requires that this important region be repeatedly probed and that the altitude dependence of key parameters be determined. The GEC mission design therefore provides for a series of deep-dipping campaigns, during which the spacecraft will use onboard propulsion to perform excursions to an altitude of 130 km and possibly lower. Excursions to this altitude were performed by Atmospheric Explorer C (1975) with no known degradation of instrument or spacecraft performance. During perigee passes the spacecraft provide data over a horizontal extent of ~1000 km while the altitude changes by only ~2 km. The GEC dipping capability, strawman dipping campaigns, and technological issues relating to dipping are discussed in Section 4.

3.5 The "Petal" Formation

A number of the phenomena of interest to GEC show large altitude gradients (e.g., the Joule heating rate—cf. Section 2.1.2). Simultaneous measurement of the relevant parameters at different altitudes would therefore enhance the scientific yield of the GEC mission and, as indicated in **Table 2.1**, is required to fully characterize the effect of electric fields on winds and composition. Information on altitude variations will be obtained from coordinated ground-based measurements; however, these data will be restricted to a specific geographical location. Thus, upon completion of the pearls-on-a string campaign the orbits will be modified to explore additional spatial variations, specifically for altitudes from 130 km to 180 km during the low-perigee periods. This modification of the orbit will be accomplished through separation of the arguments of perigee of each spacecraft so that they sample different altitudes at nearly the same location over the Earth. This new orbital configuration is known as the "petal" formation (**Figure 3.3**).

3.6 Synergy between GEC and Other Measurements

The study team recognized the potential value of optical remote sensing as a source of contextual information for the GEC in situ measurements. Optical imaging can provide information on the longitudinal extent of auroral forms and on the global configuration of the auroral oval and particle input from the magnetosphere. Valuable insights linking horizontal profiles of ion and neutral composition with altitude profiles of the same parameters can be obtained from limb imaging. However, the major GEC objectives, which concern the temporal evolution of electrodynamic features with scale sizes between 1 km and 500 km (**Table 2.1**), require in situ measurements of the key I-T system state parameters (**Tables 2.2** and **2.3**) from multiple spacecraft in highly elliptical orbits. Such a satellite configuration is not optimized to provide the imaging capability that would enhance the GEC mission objectives. Furthermore, the imaging capability cannot be achieved within budgetary constraints without compromising the primary in situ measurements. While imaging is not specifically included in the initial mission definition, the STDT expects that future consideration will be made of ways to include the imaging capability through collaboration with other ongoing missions.

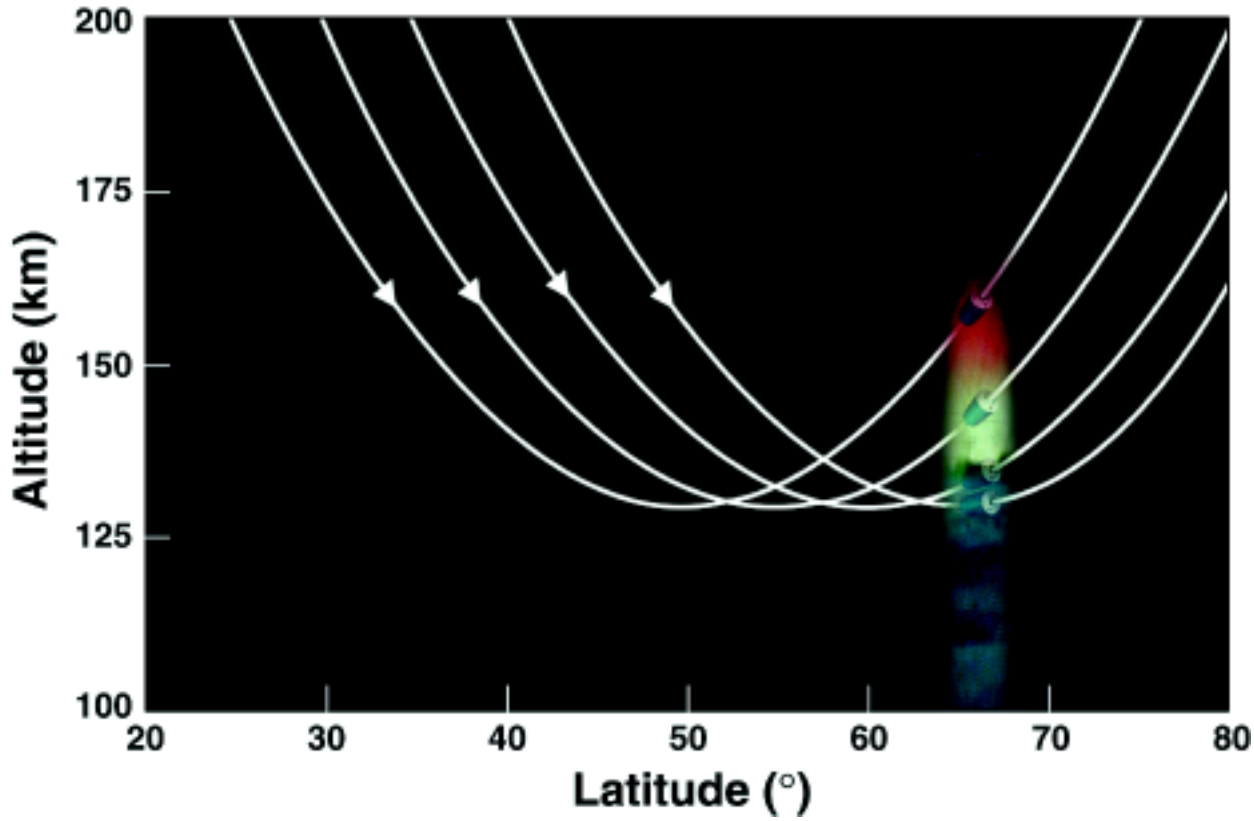

Figure 3.3. The GEC spacecraft flying in petal formation. In this formation, for example, GEC will investigate heating and momentum transfer effects at different altitudes.

The GEC mission will be conducted while other missions are being undertaken and while the extensive capabilities of ground-based instrumentation can be utilized. Ground-based observations in support of dedicated campaigns, discussed below in Section 4.3, will include, for example, continuous observation of large-scale electric fields with SuperDARN, augmented by observations with the National Science Foundation (NSF) chain of Incoherent Scatter Radars (ISR). In addition, given the importance of auroral imaging as a diagnostic of magnetospheric activity, it is likely that a polar-orbiting spacecraft with ultraviolet (UV) imaging capability will be operational during the time of the GEC mission to provide, through regular monitoring of the aurora, information on the variable input of energy from the magnetosphere and the I-T system's response. Another source of supporting contextual information from spacecraft operating at the time of the GEC mission would be spectral data such as provided by ARGOS from which, through the inversion of I-T emission lines, height profiles of both neutral and ionospheric density can be obtained.

3.7 Secondary High-Altitude Science Objectives

The principal focus of the GEC mission, with its emphasis on ion-neutral interactions, is on phenomena occurring below 300 km, and the measurements requirements set forth in **Tables 2.2** and **2.3** have been defined accordingly. For a good portion of their orbit, however, the spacecraft will fly at higher altitudes, up to their nominal apogee 2000 km. The higher-altitude segments afford GEC an opportunity to pursue an additional set of important science objectives. Secondary high-altitude science objectives that GEC might address include questions relating to plasmaspheric refilling, ring current processes, polar outflow, and auroral energization.

4.0 The GEC Reference Mission

The GEC mission will consist of multiple spacecraft, each carrying identical sets of approximately eight instruments capable of measuring in situ the parameters listed in **Tables 2.2** and **2.3**. The prime mission will last 2 years. A key feature of the mission is the capability of performing repeated low-perigee excursions, to altitudes as low as 130 km, to sample the critically important region of the I-T system where the plasma begins to drastically lose its energy and momentum to the neutral gas. This deep-dipping capability, along with the need for minimal disturbance of the plasma and field environment, entails significant design requirements regarding aerodynamics, materials selection, efficient propulsion, fuel storage and usage, electrically conductive surfaces (solar arrays), and electromagnetic disturbances. Further requirements—concerning station keeping,

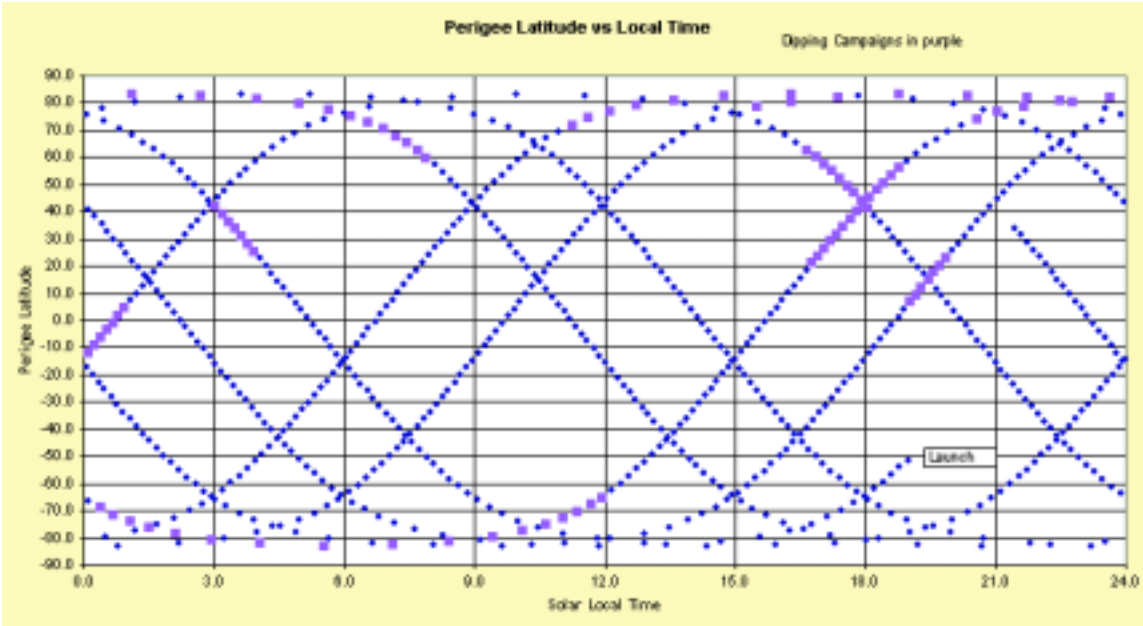

Figure 4.1. Perigee latitude and local time coverage for a 2-year mission. The orbit is 185 x 2000 km, with 83° inclination. Potential deep-dipping campaigns are highlighted. The actual scenarios will be decided by the science team.

commanding, communications and control—derive from the fact that GEC is a multispacecraft mission. The Integrated Mission Design Center (IMDC) at the NASA Goddard Space Flight Center has developed a sample spacecraft design and mission operations concept to meet these requirements. The results of the IMDC study are described in Section 5. The actual spacecraft and instrument complement will be determined by a competitive selection process later in the Formulation Phase. In this section, we discuss the nominal GEC orbit and possible orbital scenarios to be employed later in the mission, the deep-dipping capability, and strawman mission scenarios, including coordinated GEC and ground-based radar campaigns.

4.1 The GEC Orbit

The GEC spacecraft will be placed in a 185 km x 2000 km high-inclination orbit. The baseline orbital scenario for the mission has been designed with four objectives in mind:

- *provide coverage from magnetic pole to magnetic pole*
- *sample during different seasons and local times*
- *take measurements at different spatial and temporal scales*
- *sample to low altitudes, where the neutral atmosphere plays a pre-eminent role in processing and dissipating the electromagnetic energy received from the magnetosphere*

Table 4.1. Parameters for the GEC parking and deep-dipping orbits.

Parking Orbit		Comments
Apogee	2000 km maximum	Will be allowed to decay to 1500 km before reboosting.
Perigee	185 km	Penetrates below the main ionosphere layer and maximizes mission life while allowing efficient dips.
Inclination	83°	Orbit cuts across auroral regions and reaches magnetic poles.
Rate of argument of perigee change	41 days from equator to 83°	Allows low-altitude measurements at low- and high-latitude regions of interest.
Rate of mean local time change	Average 2 hours per week	Provides sampling of high- and low-latitude regions at all local times, yet allows week-long dipping campaigns to be performed without significant local time changes.
Deep-Dipping Orbits		Comments
Apogee	2000 km maximum	Varies depending on scientific objective and effects of drag at perigee.
Perigee	~ 130 km	Trade-off among the desire to go deep into the E-region, fuel usage, and aerodynamic torques.
Inclination	83°	Reaches low altitude in auroral zone and polar cap.
Dipping campaign duration	7 days or more	Perigee & local time chosen for specific objective.

The first two objectives are met by selecting an orbital inclination of 83°, which provides the desired pole-to-pole coverage and ensures that perigee moves through all the regions of scientific interest during the course of the 2-year mission. (**Figure 4.1** depicts the local time/latitude coverage at perigee.) The third objective will be satisfied by varying the separations between the spacecraft along the track from a few seconds (1 second corresponding to approximately 10 km) to 24 minutes (corresponding to one quarter of an orbit). The fourth objective will be achieved through the planned deep-dipping maneuvers that will decrease perigee from 185 km to 130 km or lower. Each spacecraft will carry a sufficient amount of fuel to perform many deep-dipping campaigns, each about 1 week in duration. The parameters for the primary parking orbit and the deep-dipping orbit are summarized in **Table 4.1**.

GEC will be launched from Vandenberg Air Force Base, California, in fourth quarter 2008 on a Delta 2920 launch vehicle. After second-stage engine cutoff, the spacecraft will be deployed sequentially from the Delta, with the launcher performing a small separation maneuver after each spacecraft deployment. After the status of the free-flying spacecraft has been verified, the thrusters on each spacecraft will be fired, one spacecraft at a time, to position the spacecraft with a spacing of 10's of km from each other along the orbit to form the initial pearls-on-a-string formation. This configuration will be maintained for the 30-day initial checkout period, instrument intercalibration, and for the first phase of the GEC science operations. Because GEC will be providing data from multiple sets of identical instruments, a thorough interspacecraft calibration of the instruments with the satellites as close together as possible is required.

For most of the 2-year mission, the GEC spacecraft will be in the 185 km x 2000 km parking orbit. This orbit places the spacecraft below the most damaging radiation and above the altitudes where atmospheric drag would begin to be a serious problem. Orbital decay will necessitate periodic reboosting of the spacecraft back to the nominal apogee of 2000 km; to conserve fuel, apogee will be allowed to decay to 1500 km before reboosting is performed. At the end of the mission, the spacecraft will be placed in a suitable terminal orbit. As discussed above in Section 3, the spacecraft will fly in the pearls-on-a-string formation for most of the mission, changing later in the mission to a petal formation. The two GEC orbital formations are illustrated in **Figure 4.2.**

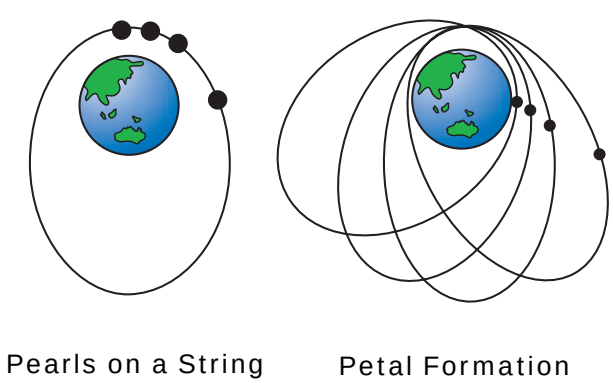

Figure 4.2. The primary GEC orbital formation will be the pearls-on-a-string formation. Later in the mission the spacecraft will be maneuvered into a petal formation to permit sampling of the same latitude region at different altitudes.

4.2 Dipping Capability

The major focus of the GEC mission is on low altitudes, where effects of the neutral atmosphere on the plasma are predominant. Thruster firings will be used to execute several focused science campaigns with week-long satellite excursions down to 130 km or lower. (In actuality, the mission is designed to penetrate to an atmospheric density of 6.7 x 10^{-9} kg/m^3—should the launch date change from the baseline date to one with different atmospheric conditions, then the altitude of lowest perigee would also change). The parking orbit perigee of 185 km was selected, in part, because it was the lowest parking perigee from which the maximum number of deep-dipping campaigns could be executed. During the mission definition phase, an alternate mission concept dedicated to making measurements below 125 km was considered. It was found that the spacecraft propellant, power, and weight resources needed to execute several deep-dipping campaigns while maintaining desired attitude and thermal control could severely detract from the resources needed for the desired science objectives. A previous NASA mission, Atmosphere Explorer C, actually penetrated to altitudes near 129 km (albeit only for a few days) without any deleterious effects on spacecraft systems [*Burgess et al.*, 1987]. Further, there were no recorded cases of insurmountable anomalous instrument responses due to the dense atmosphere at this altitude. Further evidence for instrument capability to make valid measurements at this height is provided by science measurements taken on Pioneer Venus Orbiter late in its mission (see the papers in the special issue of *Geophysical Research Letters* on the Pioneer Venus Orbiter entry phase, volume 20, 2715-2782, 1993). Instruments on the latter mission provided valid plasma, field, and neutral measurements at dynamic atmospheric pressures, in the heavy CO_2-dominated Venus atmosphere, equivalent to what a satellite in low-Earth orbit would encounter below 130 km. Thus, acquiring all of the desired GEC science measurements at altitudes in the vicinity of 130 km should pose few difficulties, particularly if the instrument designs take into account atmospheric effects at low altitudes.

Although GEC is designed around attaining a minimum perigee altitude of 130 km, the dipping experience with Atmosphere Explorer C provides information showing that GEC may be capable of safely dipping to altitudes even lower

than 130 km. This capability makes it possible to keep open the option, during the later phase of the mission, of a dipping campaign to altitudes lower than 130 km. An excursion below 130 km will only be undertaken, however, after the dynamic and thermal performances of the spacecraft and instrument behavior are known with confidence, and a safe lower altitude limit verified; moreover, it would only be performed if, based on early mission analyses, it is considered scientifically valuable enough to justify the extra propellant needed for such a maneuver.

4.3 Dedicated Campaigns

Two major types of campaigns will contribute to a successful GEC mission, namely, periods of deep dipping and coordinated overpasses of extensive ground-based facilities that are operating in conjunction with GEC. A preliminary plan for possible locations of the deep-dipping campaigns is highlighted in **Figure 4.1**. Deep-dipping campaigns will occur mostly in the northern hemisphere such that the perigee passes have the highest probability of also passing over, or near, ground-based facilities. The campaigns will further emphasize perigees over auroral and polar latitudes. Coordinated overflight campaigns, and one in particular, could be targeted by judicious selection of the GEC launch window. The NSF has a chain of ISR which are operated in campaign mode. Scientific collaboration between this ISR chain and GEC will lead to considerable synergistic benefit. A possible key campaign objective would be a 2-week dipping campaign that would occur with perigee over the auroral oval between the Millstone Hill ISR and the Sondrestrom ISR at a solar local time near the dusk terminator. During this 2-week campaign the solar local time would drift 2 hours in local time and perigee would drift 30° in latitude centered on an auroral latitude between Millstone Hill and Sondrestrom. **Table 4.2** provides a potential list of focused

Table 4.2. A strawman GEC campaign plan based on an October 29, 2008, launch.

Perigee-changing Maneuvers	**Date**	**Lat. of Perigee**	**Solar Local Time**
Phase 0: All spacecraft are launched in to 2000 km x 185 km x 83°; argument of perigee = –52°. Spacecraft are placed in a string-of-pearls configuration with a separation of 10's of km. Spacecraft checkout, instrument turn on and intercalibration will last approximately 2 months	29-Oct-08	-51°	18:59:00
Campaign 1: Lower perigee in stages over a period of 2-4 weeks to 130 km. First dipping campaign at high northern latitudes at noon	17-Jan-09	77°	12:07:00
Campaign 2: Two-week dip at high northern hemisphere latitudes at dawn	27-May-09	81°	4:00:00
Campaign 3: Two-week dip at mid- to low-northern latitudes at dusk	16-Jun-09	40°	17:48:00
Campaign 4: Two-week dip at southern hemisphere polar cap from dayside cusp to near midnight	2-Aug-09	-83°	7:07:00
Campaign 5: Dedicated overflight of Millstone Hill and Sondrestrom at equinox at dusk	21-Sep-09	44°	17:55:00
Campaign 6: One-week dip at equator near midnight	11-Nov-09	0°	21:39:00
Campaign 7: One-week dip at northern hemisphere mid-latitude before dawn	26-Jan-10	31°	3:38:00
Campaign 8: One-week dip at northern hemisphere auroral region near midnight	14-Feb-10	80°	22:47:00
Campaign 9: One-week dip at the equator after dusk	29-Jul-10	7°	19:02:00
Form petal formation with ~3° between petals	12-Aug-10		

science deep-dipping campaigns, based on an October 2008 launch and the occurrence of the Millstone Hill/Sondrestrom perigee overflight at equinox. The specific campaigns will be selected by the mission science team before launch and adjusted during the mission if appropriate.

5.0 Spacecraft System/Payload Interface Constraints

A preliminary design of the GEC mission was undertaken by GSFC's IMDC. Section 5 of this report summarizes the IMDC flight system design for the GEC mission. The flight system for the reference mission will provide engineering subsystems (mechanical, thermal, attitude control, power, telecommunications, command and control, propulsion, and radiation control) in support of the science instrument suite, including three pairs of booms for electric field measurements and one boom for magnetic field measurements. The strawman instruments are listed in **Table 5.1**. Preliminary views of the spacecraft and instruments are shown in **Figures 5.1** and **5.2**. Each spacecraft is cylindrical in shape, approximately 1 meter in diameter and 2 meters long, with body-mounted solar arrays and electric and magnetic field detectors mounted on booms to minimize electromagnetic and plasma disturbances caused by the spacecraft.

The unique capabilities provided by GEC are also the sources of its major design and engineering challenges. Communicating with and controlling multiple spacecraft, fitting them within a single launch vehicle, and timing the manufacture and integration of multiple copies of instruments and spacecraft subsystems will be a schedule, budget, and logistical challenge. The low altitudes reached during the dipping campaigns require that the spacecraft design provide maximum aerodynamic stability, in addition to minimizing the disturbances of the electromagnetic and plasma environments. In practice, this requires body-mounted solar arrays and flush-mounted communication antennae. This requirement limits the solar array area and power and limits the antennae gain and beam width.

5.1 Fields of View

The spacecraft is 3-axis stabilized to provide consistent pointing. It has a relatively flat surface in the ram direction for unobstructed in situ thermal ion/neutral particle measurements (including concentration, velocity, and temperature). The apertures of the ram-facing instruments are flush-mounted to avoid interfering with each other. Electric field detectors are on long booms with the detectors 8-10 meters from the spacecraft in order to avoid the plasma disturbances caused by the spacecraft and to provide the desired sensitivity of the E-field measurements (cf. **Figure 5.2**). The magnetometer will be placed on a trailing boom away from the fields of the spacecraft. The short, cylindrical shape of the spacecraft provides minimal obstruction and electromagnetic disturbances for all instruments. This design is also intended to minimize shadowing of the E-field booms in sunlight, which leads to measurement complexities because of

Table 5.1. The expected distribution of resources for sensors to measure all the GEC required parameters.

Required Parameter	Generic Instrument Heritage	Mounting Location	Characteristic mass (kg)	Nominal Power (W)	Nominal Data Rate (kbps)
Ion Temperature, Density, & Velocity	AE, DE -2, DMSP, San Marco	RAM	3.5	3.5	2.5
Neutral Composition & Temperature; Neutral Winds; Ion Composition	AE, DE, San Marco (Specs refer to one instrument. Multiple instruments may be preferred.)	RAM	9	24	1.5
Electron Temperature	AE, DE-2, PVO	perpendicular to s/c velocity	1.5	2	1
Energetic Electrons & Ions	Polar, Freja,	on s/c azimuth sides flush or on short boom	4	9	64
Magnetic Field	DMSP, MGS, ACE, NEAR, WIND	on boom 2X s/c radius	2.5	3	1
Electric Field	DE-2, San Marco	body, 6 places	31	14	50

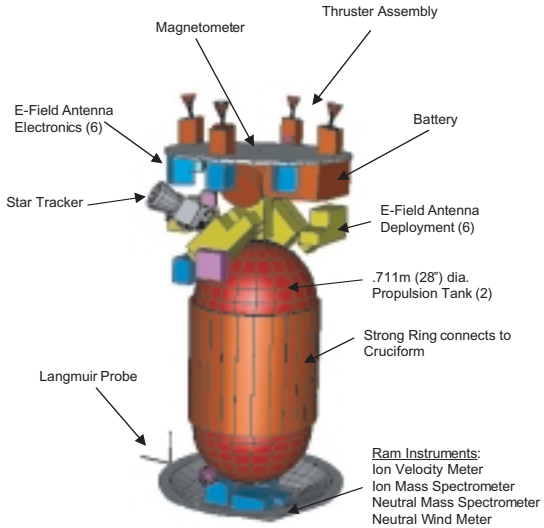

Figure 5.1. Interior view of the GEC spacecraft, showing the instruments (except for the energetic particle detectors, which are mounted externally) and some subsystems.

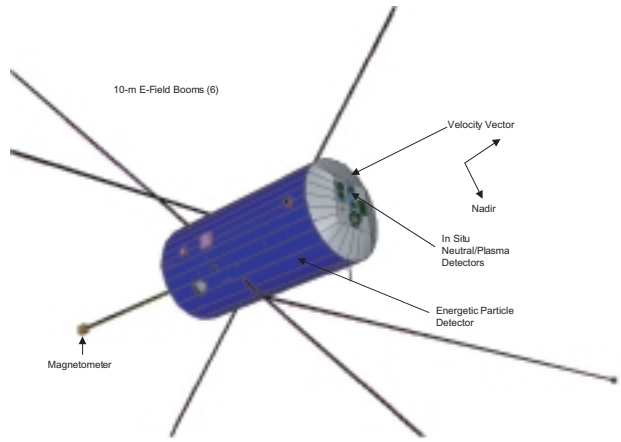

Figure 5.2. Exterior view of the GEC spacecraft. The E-field booms are not shown at their full length.

different photo-emission currents on the probes. To further minimize shadowing and spacecraft wake effects, particularly on the electric field detectors, the spacecraft size is minimized by body-mounting the solar arrays rather than placing them on extended panels.

5.2 Mechanical Design/Thermal Control

The structural design of the GEC spacecraft is constrained by the requirement for minimum drag, reasonable aerodynamic characteristics, and minimal disturbance of the environment while simultaneously allowing for solar arrays and spacecraft cooling. The body-mounted solar arrays are an impediment to thermal design. Circumferential heat pipes overcome this difficulty by distributing heat around the circumference of the body to equalize the thermal gradients. For aerodynamic stability, the propellant tanks are mounted as far forward as possible while still accommodating the ram-facing instruments. This tank location is also close to the spacecraft center of gravity (CG) to minimize CG shifts. **Table 5.2** shows the mass breakdown for the different spacecraft systems. Each spacecraft is kinematically attached, near the fuel tanks, to a cruciform strong back adapter for the Delta launch vehicle.

5.3 Attitude Control System (ACS)

Each GEC spacecraft flies with the bow pointed in the velocity vector direction. The ACS will keep the spacecraft aligned with the velocity vector to an accuracy of 3° and knowledge of 0.01°. Attitude knowledge is provided by a star tracker, gyros, and Sun sensors. Attitude control is provided by the momentum wheels and by four 5-N thrusters. The thrusters make up for drag losses and provide momentum unloading.

Table 5.2. Mass breakdown for each spacecraft and 326 kg of hydrazine. (An optimum constellation size of four spacecraft is assumed.)

Subsystem for each spacecraft	Current Mass Estimate (kg)
Instruments	55
ACS	55.9
C&DH	3.6
Mechanical/Structure	153.5
Power	58.2
Propulsion	326
Communications	5.1
Thermal	21.5
Total Each	673.7
Four Spacecraft + Deployer	2785
Delta 2920 Mass to Orbit	3049

The ACS will be 3-axis stabilized with a large momentum bias. The momentum vector will be parallel to the orbit normal; this arrangement will allow the spacecraft to have one face nadir-pointing in spite of large aerotorques near the low-altitude perigees. The primary driver for the ACS design is the need to counteract the large aerodynamic torques during perigee passage. The initial ACS design assumes that the spacecraft will be aerodynamically stable, a reasonable assumption based on the Atmospheric Explorer C performance at similar altitudes. GEC aerodynamic stability studies were initiated in 1999 and will conclude in 2001.

5.4 Power

The power system design for the GEC mission is challenging. The solar arrays are body-mounted to minimize disturbance to the plasma environment and minimize shadowing of the electric field sensors. The orbit varies from no eclipse to a maximum eclipse of 40 minutes and the ACS subsystem requires high peak currents and high power to react to the large aerodynamic torques. As a result of these requirements, the power system in GEC's nominal attitude is unable to supply enough power to the spacecraft to support all the load at all beta angles (angle from orbit plane to the Sun vector). This difficulty will be mitigated, with minimal effect on the science objectives, by reorienting the spacecraft above 1500 km to allow the solar arrays to point normal to the Sun. Even with this mitigation, the power system is unable to supply all the loads at all beta angles, requiring at times a restriction of measurements at high altitudes in order to ensure that the mission's prime low-altitude experiment objectives can be met.

A plot of the instrument duty cycle throughout the mission is shown in **Figure 5.3**, and **Table 5.3** shows the estimated spacecraft power based on the IMDC design and strawman instruments.

Initial studies looked at trailing the solar array in the wake of the spacecraft to attain enough power for 100% duty cycle operation of the instruments. This combination resulted in unfavorable shadowing of the electric field sensors and creation of plasma disturbance. Since the diameter of the spacecraft has to be minimized to reduce drag and fit within the launch vehicle, and the length is minimized to avoid plasma disturbance, the resulting body-mounted solar array

Table 5.3. Orbit Average Power.

Subsystem for each s/c	Parking Orbit Power (W)	Dipping Orbit Power (W)
Instruments	56	56
Power	22.4	22.4
Propulsion	2	2
ACS	47.7	97.7
C&DH	12.5	12.5
Communications	7.5	7.5
Electrical	5	5
Thermal	0-30 depending on beta angle	0-30 depending on beta angle
Total orbit average per s/c	178.1	228.1

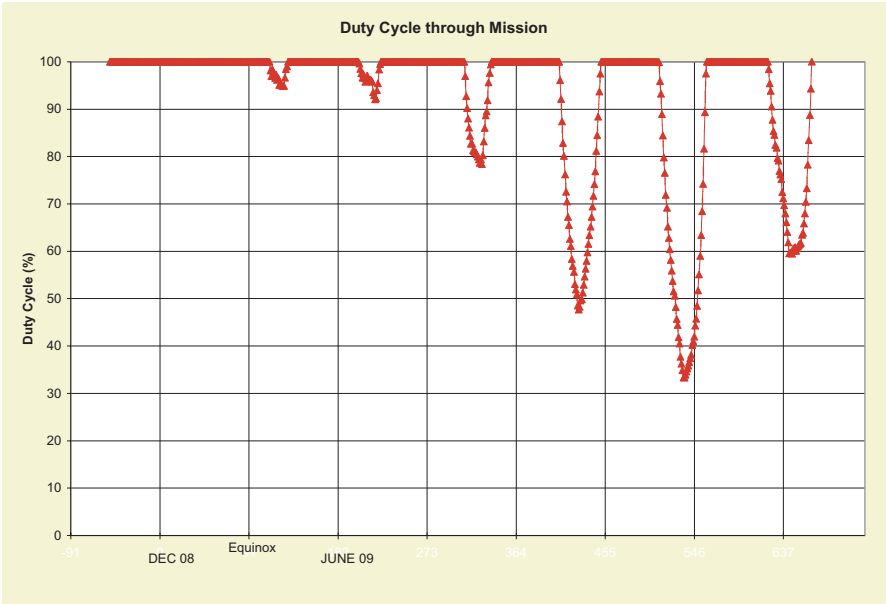

Figure 5.3. Plot showing the GEC instrument duty cycle throughout the mission.

area and available power profiles are limited. The IMDC study and the prediction in **Figure 5.3** assumed a solar cell efficiency of 21%. Recent solar cell developments for commercial satellites are routinely producing cells that are 24% to 26% efficient, which will increase the available power with the same solar array configuration by 14% to 24%.

5.5 Telecommunications

The simplest communications approach is to use two high-latitude ground stations, one in the northern hemisphere and one in the southern hemisphere. This approach provides enough coverage on nearly every orbit to downlink all data. There are several northern stations that meet the requirements, and some may be able to provide real-time data during the simultaneous spacecraft and ground-based observation campaigns. Spreading the northern apogee downlink between two northern high-latitude stations would provide redundancy and the ability to provide high peak data volumes if needed for little or no extra cost per bit.

The only high-latitude southern station is McMurdo, in Antarctica. The lack of population centers above 50° S makes operations expensive; it is unlikely that any additional stations will become available or be significantly cheaper. However, McMurdo can be replaced by two mid-latitude stations (Santiago, Chile, and Wallops Island, Virginia) for nearly the same cost per bit as that for the northern high-latitude stations. Using these two stations instead of McMurdo would require that enough data storage be provided on the spacecraft to hold 4 to 5 orbits of data. It is also recommended that about 5% of the southern contacts (about one every 3 days) be through McMurdo so that it will be available to pick up missed passes and other emergencies.

The communications strategy is to purchase time at the stations. The spacecraft will store science data between passes and dump the data when in view from a ground station for a long enough time to be cost-effective—normally near apogee. The deep-dipping campaigns can be covered in the same way, with the additional option of passing low-rate science data through the Tracking and Data Relay Satellite System (TDRSS) for real-time investigations. The spacecraft will have flush-mounted antennas, either patch or phased array, in order to minimize drag and plasma disturbances. This type of antenna will not allow large-bandwidth transmission to TDRSS, so the real-time data available during dipping campaigns might be limited. A single S-band 5-W transponder is sufficient to provide command and telemetry interfaces with the ground system.

5.6 Command and Data Handling (C&DH)

The spacecraft C&DH system will consist of a conventional system made up of uplink and downlink cards, CPU, bulk memory, ACS interfaces, and an industry-standard interface bus. Systems already exist that would meet the GEC requirements, and future systems are expected to be smaller and more capable. The instrument interface will be a high-speed serial bus such as Mil-STD-1773 (1 or 20 Mbps), Firewire (under development at the Applied Physics Laboratory (APL)), or I2C (in use at the Jet Propulsion Laboratory (JPL) and APL). The actual choice of bus will be determined by instrument capabilities, power, and speed desired. The bulk memory will be sized to store multiple orbits of telemetry based on an instrument aggregate data rate of 50 kbps. GPS receivers will be used for orbit determination. The data system is depicted in **Figure 5.4**.

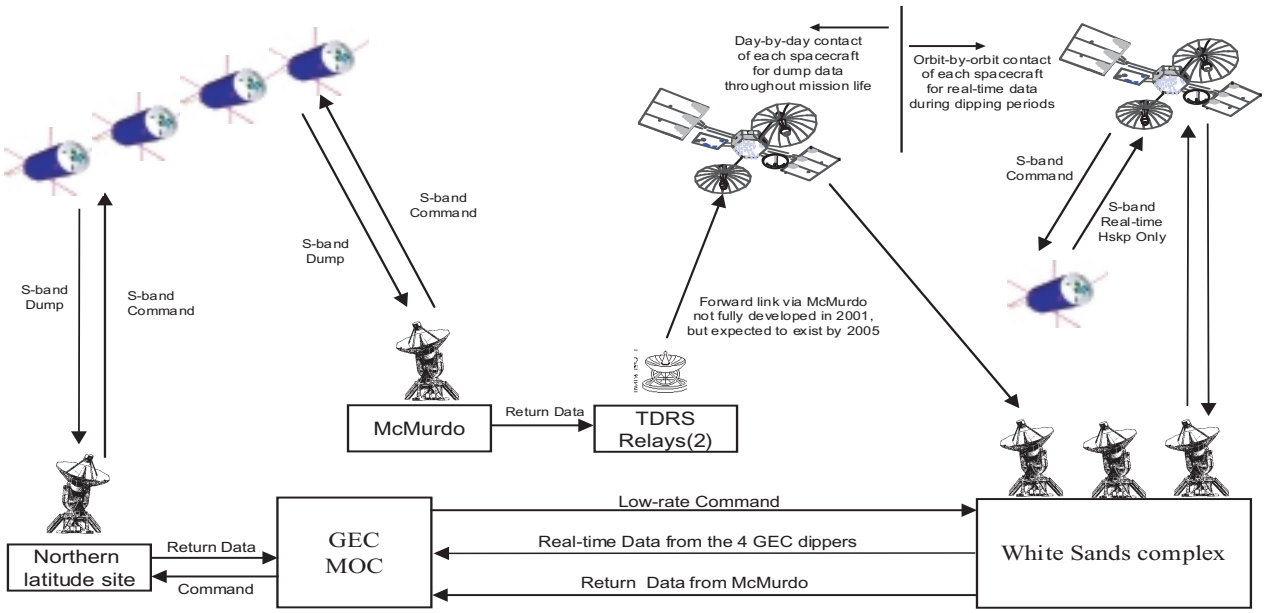

Figure 5.4. The GEC data system.

5.7 Propulsion

The propulsion system will consist of a simple blowdown, monopropellant hydrazine system. The major drivers for the design of the propulsion system are the potential for fuel slosh during perigee and the cleanliness requirements of the instruments. The cleanliness requirement favors the use of hydrazine. Metal diaphragms can be used to prevent the fuel from moving as the spacecraft experiences the milli-g's of perigee passage. If mass margin permits, a pressurant tank and regulator can be added to increase the amount of fuel loaded in the tank. The four thrusters have a small cant angle away from the negative velocity vector to allow control about all three control axes.

5.8 Radiation

The radiation environment for the 2-year mission is relatively modest at 20 krad (silicon). Spacecraft avionics are easily available to meet this requirement. Due to the focus of the mission on the lower ionosphere-thermosphere system, the parking orbit apogee was set at 2000 km, which reduces the increasing impact of radiation that would occur at higher altitudes.

5.9 Mission Operations Concept

The GEC mission will leverage state-of-the-art technologies for mission operations to reduce operations costs and make possible collaboration of science and engineering data analysis. NASA GSFC has a major initiative in place to develop autonomous operations systems for constellations of satellites. This initiative will drastically reduce the operations costs for future missions. STP Program personnel are participating in these activities, and GEC will incorporate the results of these developments in its operations system. These developments include communicating with an autonomous constellation of four satellites; Web-enabled mission operations, allowing remote mission operations from anywhere in the world (GSFC will be the home base); synchronizing data downlink from four satellites at different times and orbits; and accurate and stable pointing of onboard instruments.

5.9.1 Autonomy. Autonomy will play a major role in the operations of each single spacecraft and of the constellation. However, the mission operations system will be instrumental in validating and verifying the constellation orbits and constellation health and safety. Verification of onboard resources, such as fuel, will be monitored closely by both the onboard autonomous system and the mission operations system.

The onboard autonomous system will also be used for orbit determination during the pearls-on-a-string dipping sequences. The atmospheric drag created by deep dipping significantly changes the orbital parameters with each and every dip, reducing the orbit period. The operations for dipping campaigns will initially be fully staffed, using real-time engineering telemetry via TDRSS, until the engineering and operations teams are satisfied that the autonomous systems are accurately predicting the orbits and making appropriate corrections as required.

5.9.2 Secure Internet Access. Upon an anomalous condition, the remote user can be called or paged automatically by the mission operations system at the GSFC. The remote user can then automatically download health and safety data to the remote node for further analysis. The remote user will have the ability to download both housekeeping data and science data for analysis and trending. Data analysis, for anomaly resolution, will occur in near real-time. The remote user will be able to monitor a single spacecraft and the health and safety of the entire constellation.

Each remote user will communicate with the mission operations center at the GSFC as a mission node on a Wide Area Network (WAN). Each remote unit also functions as a collaboration node that is capable of sharing data with other Web-enabled missions.

5.9.3 Formation Flying. The mission operations system will be able to verify and validate the orbit and dipping schedules of the autonomous GEC spacecraft. Corrections to the dipping orbits and schedules can be uploaded from the mission operations center. New orbit maneuvers can be executed from either the onboard autonomous spacecraft or from a command via the mission operations center. The amount of actual control a remote user will have with respect to orbit maneuvers and downlink schedules will be determined by the Mission Director and mission science team. However, full capability will be built into the mission operations system and remote-user nodes.

6.0 Ground Data System and Mission Operations

GEC will produce science data products both from individual instruments and from the merged data sets of multiple spacecraft. The ground data system must support nominal instrument operations, instrument calibration, instrument monitoring, production of combined data streams for GEC unique products, nominal spacecraft operations, and dipping campaign management. Close coordination between the science team and the operations team is desirable during the dipping campaigns.

One way to implement these functions is to split operations among closely coordinated operations centers: individual Instrument Operations Centers (IOC's), a Science Operations Center (SOC), and a Mission Operations Center (MOC).

The IOC's will be provided and run by the instrument principal investigators. The IOC's will support the operation of the instruments, including instrument calibration and monitoring; perform low-level data analysis and provide those data to the SOC; and perform higher-level data analysis to support the science investigations performed by the instrument principal investigators' teams. The SOC will perform higher-level science data processing, including generating GEC-unique data products from the combined spacecraft data streams, and manage the dipping campaign planning. The MOC will operate the spacecraft, send and receive command and telemetry loads to the spacecraft and instruments, and perform health and safety monitoring.

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Appendix B: Acronyms

ACS	—	Attitude Control System
APL	—	Applied Physics Laboratory
C&DH	—	Command and Data Handling
CG	—	Center of Gravity
EUV	—	Extreme Ultra Violet
GEC	—	Geospace Electrodynamic Connections
GPS	—	Global Positioning System
GSFC	—	Goddard Space Flight Center
HF	—	High Frequency
IMDC	—	Integrated Mission Design Center
IMF	—	Interplanetary Magnetic Field
IOC	—	Instrument Operations Center
ISR	—	Incoherent Scatter Radars
I-T	—	Ionosphere-Thermosphere
JPL	—	Jet Propulsion Laboratory
MC	—	Magnetospheric Constellation
MOC	—	Missions Operations Center
MMS	—	Magnetospheric Multiscale
NASA	—	National Aeronautics and Space Administration
NCAR TIEGCM	—	National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynamics General Circulation Model
NOAA	—	National Oceanic and Atmospheric Administration
NSF	—	National Science Foundation
SAID	—	Subauroral Ion Drift
SAR	—	Stable Auroral Red
SOC	—	Science Operations Center
Sq	—	Solar Quiet
STDT	—	Science and Technology Definition Team
STEREO	—	Solar Terrestrial Relations Observatory
STI	—	Scientific and Technical Information
STP	—	Solar Terrestrial Probes
TAD	—	Traveling Atmospheric Disturbance
TDRSS	—	Tracking and Data Relay Satellite System
TEC	—	Total Electron Content
TID	—	Traveling Ionospheric Disturbance
UV	—	Ultraviolet
WAN	—	Wide Area Network

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The Geospace Electrodynamic Connections (GEC) mission is a multispacecraft Solar-Terrestrial Probe that has been specifically designed to advance the level of physical insight of our understanding of the coupling among the ionosphere, thermosphere, and magnetosphere. GEC is NASA's fifth Solar-Terrestrial Probe. Through multipoint measurements in the Earth's ionosphere-thermosphere (I-T) system, GEC will (i) discover the spatial and temporal scales on which magnetospheric energy input into the I-T region occurs, (ii) determine the spatial and temporal scales for the response of the I-T system to this input of energy, and (iii) quantify the altitude dependence of the response.

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