# What Kind of Constraints Does the Problem of Global Geospace Circulation Impose on the Specification of a Spacecraft Constellation?

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**Abstract.** One of the paramount scientific goals in Space Sciences is determining the global plasma circulation in the Earth's magnetosphere. Global circulation depends on the coupling among the solar wind, the magnetosphere, and the ionosphere and neutral atmosphere. It also depends on the coupling of processes across many spatial scales. These characteristics define space and time scales that constrain the definition of any spacecraft constellation. In this paper, we describe what we believe are the most important scales that a constellation must resolve in different regions of the magnetotail to solve outstanding problems of general circulation in the magnetosphere.

## 1. Introduction

The problem of general magnetospheric circulation defines a coupling among different regions and physical mechanisms of the solar wind-magnetosphere-ionosphere system. The electromagnetic coupling is carried out through magnetic-field aligned currents that transmit the power from the solar wind dynamo to the plasma in the magnetosphere and ultimately to the ionosphere and neutral atmosphere. The general circulation problem also defines a coupling among different space and time scales as well as a coupling of regions large distances apart via modification of particle-distribution functions. The next three sections describe the characteristics of the coupling mechanisms.

The foundation of a global picture of the general circulation in geospace has been created over three decades of spacecraft observations and theoretical studies of the Earth's magnetosphere. Although a solid framework of the average properties of the general circulation has emerged from observations and theory, key aspects of the phenomenon are poorly understood, mainly because the observations thus far have come from a single spacecraft or from a small number (two to three) of spacecraft that sample limited regions of geospace. Moreover, single-spacecraft measurements cannot separate the effects of time dependence and spatial gradients. Also, the present formalism is lacking an adequate description of processes that can be described only with a kinetic formalism.

The requirement to achieve certain space and time resolutions imposes specific constraints on the characteristics of any spacecraft constellation. The following sections discuss the different spatial and temporal scales that need to be resolved in different regions of the magnetotail to adequately resolve present phenomenological ambiguities. Consideration is also given to the constraints imposed on spacecraft distribution by requiring mapping between magnetospheric regions and their ionospheric footprints, and identification of the current circuits that couple them.

## 2. Space and Time Scales of Convection in the Magnetotail

The traditional paradigm of transport in the plasma sheet consists of laminar earthward convection from a reservoir in the far tail [e.g., Vasyliunas, 1970, 1972; Wolf, 1970; Jaggi and Wolf, 1973; Southwood, 1977]. But this may not be necessarily the case, as impulsive and possibly even turbulent transport over a wide range of distances appears to be fairly common. Observations from AMPTE/IRM [Baumjohann et al., 1988, 1989, 1990] have shown that, most of the time, the ion flow velocity in the plasma sheet is slow (i.e., less than 100 km/s) but interrupted by short-lived intervals of fast flows ($V_i$>400 km/s).

AMPTE/IRM, ISEE and Geotail observations have shown that a significant fraction of the transport of energy and magnetic flux in the magnetotail is likely to be accomplished via high-speed flows within the plasma sheet that last a few minutes [Baumjohann et al., 1989, 1990; Angelopoulos et al., 1992]. These flows have a characteristic duration of 10 min and a substructure of 1 min. The 10-min timescale structures have been termed "bursty bulk flows" (BBFs) and the 1-min structures "flow bursts." Flow bursts correlate positively with magnetic field dipolarizations and ion temperature increases and negatively with ion density. BBFs have been argued to contribute 60-100% of the measured earthward mass energy and magnetic flux transport past the satellite in the high-B plasma sheet, despite being observed only 10-15% of the time in the midnight plasma sheet [Angelopoulos et al., 1994, 1996]. Multipoint measurements suggest that flow bursts are confined to narrow channels with a Y-Z extent of a few $R_E^2$ and ~20 $R_E$ or more length in X [Angelopoulos et al., 1996]. Therefore, it is possible that individual flow bursts could account for virtually the entire earthward transport of flux in a plasma sheet that otherwise shows weak earthward convection and non-laminar flow. Analysis of ISEE observations of convection in the tail distance range X~-20 $R_E$ has confirmed that the plasma circulation is seldom laminar and frequently has characteristics of turbulent flow, with a mixing length of order 1-2 $R_E$ and autocorrelation time ~2 min [Borovsky et al., 1997]. These observations strongly suggest that transport in the magnetotail may be accomplished by a combination of diffusion and short-lived convection.

Geotail, AMPTE and ISEE observations suggest that BBFs might be formed by the same sporadic bursts of reconnection that also produce plasmoids, activation of lower energy ion flux in the plasma sheet boundary layer, and energetic particle bursts. Localized bursty events occur at a variety of distances downtail in the 30-70 $R_E$ range. Statistical maps of plasma flows in the magnetotail using Geotail [see, for example, Nagai et al., 1998 and references therein] have established that fast tailward convection flows with strongly southward magnetic fields are frequently observed near the neutral sheet in the premidnight magnetotail region beyond X=-20 $R_E$. The observed properties of the fast flows and the electron distributions have been interpreted as signatures of magnetic reconnection. Single spacecraft observations therefore identify the typical site of reconnection in the premidnight plasma sheet between X = -20 $R_E$ and X = -30 $R_E$. They also identify a time scale of 10 min for the typical duration of reconnection.

The apparent highly localized nature of BBFs in Z and Y and the mixing scales involved in the turbulent flow require a spacecraft distribution capable of resolving lengths scale sizes of order ~0.5x0.5x0.5 $R_E^3$ in X-Y-Z in the vicinity of the current sheet. Spacecraft separation need not be as tight everywhere. The last section of this paper discusses possible configurations that would allow high spatial resolution

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in certain regions while achieving radial and azimuthal coverage of wide sections of the magnetotail.

## 3. Distribution of Thermodynamic Parameters and Electric Current in the Magnetotail

The macroscopic description of the magnetotail has been inferred from studies using in situ measurements by satellites [Baumjohann et al., 1989, 1990; Spence et al., 1989; Kistler et al., 1992, 1993; Lui and Hamilton, 1992; Angelopoulos et al., 1993; Huang and Frank, 1986, 1994]. These studies have used AMPTE/IRM and ISEE observations in the magnetotail region defined by $-22 < X < -7\ R_E$ and $-15 < Y < 15\ R_E$. Equatorial maps of scalar pressure, density, and temperature obtained show pronounced azimuthal and radial gradients of these quantities. Results of different studies do not necessarily coincide quantitatively or, in some cases, even qualitatively. This inconsistency is due to the fact that the measurements involved in the analyses were obtained at different stages of solar cycle and geomagnetic activity, and were grouped in bins of different dimensions. Instantaneous longitudinal and radial profiles of thermodynamic quantities are needed to determine the macroscale distributions related to the fluid equilibrium of the magnetotail, and mesoscale measurements are needed to isolate the contribution due to BBFs.

Despite its powerful applications, the fluid approach has important shortcomings. For example, it cannot describe dissipative processes in localized regions. These processes are extremely important because they are associated with nonideal electric fields that control the time scale of the large-scale dynamics. Different methods have been used to circumvent this limitation. For example, MHD models of substorm onset rely on ad-hoc distributions of "anomalous" resisitivity that dictates how and when reconnection in the tail occurs. This resistivity is used as a proxy that is assumed to reflect the actual kinetic processes involved in reconnection. However, the process which generates resistivity or an equivalent deviation from MHD, such as collisionless tearing mode instability, has not been clearly identified but likely involves nonadiabatic motion of particles inside the current sheet [e.g., Chen and Palmadesso, 1986]. The particle motion in this situation is nonintegrable, and the phase space describing it is partitioned into distinct regions corresponding to three basic classes of trajectories: stochastic, transient, and regular. These regions have the property that they cannot communicate with each other. Therefore, they respond to external influences on different time scales. In particular, different regions of phase space retain the memory of the existing particle distribution for different lengths of time. Such "differential memory" implies that a plasma distribution function has a tendency to develop non-Maxwellian features in response to changes in physical conditions. As a particle traverses the equator, its contribution to the current due to the shift in the guiding center will depend on the kind of orbit that it has. Particles with regular orbits, for instance, carry no net current. The stochastic contribution to the total current is much less significant than the transient contribution for most values of the Hamiltonian [Burkhart and Chen, 1991]. As a result, in an ensemble of particles, the relative population of transient versus stochastic particles is a key factor in determining the total cross-tail current. The relative time scales also show noticeable differences. For example, given 1 keV protons in a taillike field of magnitude 20 nT, a normal component $B_n$~2 nT, and a current sheet characteristic scale ~0.1 $R_E$, ions with transient orbits can traverse the system in ~15 sec, while stochastic orbits can be randomized in ~5 min. These time scales are comparable to the time scale of flow bursts explosive growth phase [Ohtani et al., 1992], and auroral arc breakup [see, for example, Rostoker, 1996 and references therein]. Full particle distribution measurements with a ~15 sec time resolution are required.

Single-spacecraft measurements in the vicinity of the near-Earth current sheet have shown that shortly before onset, increases occur in cross-tail electric current density, duskward ion bulk flow (to magnitudes near the ion thermal speed), plasma pressure and its isotropy, and B. At the same time, the vertical thickness of the plasma sheet decreases to about the thermal ion gyroradius [Mitchell et al., 1990; Sergeev et al., 1990]. Ions with energy ~50 eV have a gyroradius ~100 km in a 10 nT magnetic field, while the radius for 5 keV ions is ~1000 km.

It has been argued that intense cross-tail current is produced by the relative drift between ions and electrons. This situation could generate current-driven instabilities which in their nonlinear stage would cause current disruption [see, for example, Lui, 1996 and references therein]. Therefore, in the near-Earth tail, the spatial resolution must be high enough to allow measurements of the scale length for the pressure gradient, $L_g$, and the radius of field line curvature, $L_c$. In a stationary anisotropic plasma, the current density perpendicular to the magnetic field is related to a term proportional to $P\perp/(BL_g)$, and to the product $(P\|-P\perp)/(BL_c)$, where B is the local magnetic field. These conditions require a spacecraft distribution capable of resolving length scale sizes of order ~$0.2\text{x}0.2\text{x}0.2\ R_E^3$ in X-Y-Z because that is the scale length for the current-driven microinstabilities believed to be involved in current disruption. It is also the scale length involved in the pressure gradients that precede current disruption. Therefore, an adequate spacecraft configuration would involve several tetrahedron clusters with a scale of 0.1 $R_E$ and whose centers of mass would be separated longitudinally and in the north-south direction by 0.5 $R_E$.

In the mid-tail region, where reconnection is believed to occur, a spacecraft constellation must be able to sample the current sheet during its evolution from a quiet state configuration (thickness ~2 $R_E$) to a substorm growth phase configuration (~0.5 $R_E$).

## 4. Electric Current Distribution in the Magnetosphere-ionosphere System

The problem of general geospace circulation defines a coupling among the solar wind, the magnetosphere, and the ionosphere and neutral atmosphere.

An MHD formalism has been developed for the last thirty years to describe the macroscopic properties of the coupling [e.g., Vasyliunas, 1970, 1972; Wolf, 1970; Jaggi and Wolf, 1973; Southwood, 1977, Siscoe, 1982]. In MHD, the electric field and the particle distribution in the magnetosphere are simultaneously calculated from a self-consistent chain of equations. For example, given an electric field distribution in the magnetosphere, the magnetospheric plasma responds by establishing a certain distribution of ions and electrons, and hence a plasma pressure at any point. From gradients in plasma pressure, the electric current perpendicular to the magnetic field is known. Then, field-aligned currents flowing between the magnetosphere and the ionosphere are established by the divergence in the perpendicular currents. The requirement that the field-aligned currents be closed by perpendicular ohmic currents in the ionosphere imposes an electric field distribution in the ionosphere. Mapping of this electric field into the magnetosphere —and the requirement that it agree with the magnetospheric electric field assumed at the outset— closes the system of equations. The same effects are invoked in models of generation of substorm wedge current system, the Harang discontinuity, and polar cap boundary field-aligned currents.

Therefore, in the fluid approach, instantaneous maps of the equatorial distribution of magnetospheric plasma pressure and electric field are central to the elucidation of how the coupling occurs. If a spacecraft constellation is to provide these maps, the spacecraft separation must provide enough spatial resolution at the regions where the coupling is expected to be most effective. These regions include: the earthward boundary of the plasma sheet, where anti-earthward pressure gradients produce Region-2 currents; the low-latitude boundary layer, across which Region-1 currents are proposed to flow in the circuit between the generator in the polar cap and the poleward ring of the auroral oval [Siscoe et al., 1991]; and the near-earth magnetotail region, where Region-1 polarity field-aligned currents are thought to be produced at the onset of the current disruption [see, for example, Lui, 1996 and references therein].

Particularly relevant to the problem of the source of large-scale Region-1 current is the local time distribution of the low-latitude boundary layer. Current MHD models of the convection current system predict a low-latitude boundary layer with thickness comparable to that of the dayside magnetopause. Evidence shows that the boundary layer at the dayside magnetopause has a thickness of only 400-2000 km [Berchem and Russell, 1982] but becomes increasingly thicker with increasing distance down the flanks. The boundary layer also narrows significantly toward the nose of the magnetosphere [Mitchell et al., 1987]. It remains to be determined whether the Region-1 currents flow mainly within a few hours local time of the nose boundary layer or are distributed over wider regions along the flank boundary. Placing three spacecraft tetrahedrons with local time separation of ~1 $R_E$ in orbits skimming the dayside flank magnetopause should provide an adequate means to identify the variation of boundary parameters with longitude.

## 5. Combination of Ionospheric and High-altitude Measurements

A spacecraft constellation is important for resolving multiple scales in the magnetosphere. However, ground-based global measurements of conductivity, electric field, and electric currents are essential to complete the picture of current closure between the magnetosphere and the ionosphere.

Ionospheric Hall and Pedersen conductivities are essential quantities in substorm current disruption models such as the magnetosphere-ionosphere coupling model [e.g., Kan et al, 1988; Rothwell et al., 1988] and models of magnetosphere-ionosphere coupling in general. Some statistical models of ionospheric conductivity are currently applied in the assimilative mapping of ionospheric electrodynamics such as AMIE [Richmond and Kamide, 1988]. However, conductivities develop steep spatial and temporal gradients beyond the capabilities of statistical ionospheric conductivity models. This situation is expected to occur for BBFs whose 1-3 $R_E$ azimuthal size in the near-Earth tail should map to ionospheric regions 5-15° wide. They can be measured accurately only by techniques such as incoherent scatter radar (ISR) and global (orbiting) imagers with adequate filters and spatiotemporal resolution. The network of ISRs can provide direct measurements of Hall and Pedersen conductivities, electric currents, and electric field over wide regions of the auroral oval and a portion of the polar cap. The first truly global measurements within the polar cap over short time scales (~10-20 min) will be possible with the deployment of an ISR near the center of the polar cap. Furthermore, a combination of global electric field measurements from SuperDarn HF radars and conductivity measurements from a polar orbiting imager can complement the view of horizontal current distribution in the auroral ionosphere.

The coupling between the ionosphere and the magnetosphere is inherently dynamic in nature. The energy involved is carried from the source of the convection potential by the Region-1 Birkeland current to the ionosphere and from there by the Region-2 Birkeland current to the ring current. Energy transfer into the ring current can occur only by means of a time variation in the potential across the Region-2 ring [e.g., Siscoe, 1982]. A time variation in this potential can be produced by a change in ionospheric conductivity or by a change in the applied potential. In this scenario, the high-latitude ionosphere may be acting as an intermediary primarily involved in transferring electromagnetic energy from the magnetosphere to the ring current. A sudden increase in the cross-cap potential produced, for example, by a southward turning of the IMF creates a fringing field before the Region-2 potential has had time to respond. The Region-1 Birkeland currents enter the ionosphere in the belt of positive applied potential and exit in the belt of negative potential. Therefore, they drain energy from the source of applied potential. Since the Region-2 currents are oppositely directed to Region-1 currents, the fringing field corresponds to a source of energy for the Region-2 circuit. The energy delivered to the ring current is converted to energy of compression as the ring current expands earthward in response to the fringing potential. When used in combination with ionospheric measurements, spacecraft constellation measurements can be used to establish the rate and direction of flow of energy exchange between the ionosphere and the magnetosphere. The expanded capabilities should allow also the measurement of spatial mesoscale and temporal dependence across the tail of bursty convection and turbulence, and the concomitant coupling to the ionosphere.

Recent work [Wing and Newell, 1998] has inferred a statistical view of the pressure distribution in the central plasma sheet from ionospheric observations. These maps are important because they allow sampling of plasma pressure of a magnetospheric volume much larger than that allowed by single spacecraft or even multiple spacecraft. Therefore, polar orbiting satellites are also obvious candidates to complement magnetospheric in situ measurements of pressure in the central plasma sheet.

## 6. Discussion of Possible Spacecraft Distributions

This paper presents arguments that identify the regions in the magnetotail that must be targeted by any constellation mission to definitively solve outstanding problems in particle and magnetic field transport. Also, arguments are presented to identify the space and time scales that any constellation ought to resolve for an unambiguous measurement of physical quantities. Definition of the problem may require spatial measurements ranging from micro- (ion gyroradius) to macroscale (several Earth radii). Temporal resolution may range from a few seconds (ion gyroperiod) to several minutes.

The density of spacecraft in a given magnetospheric volume can in principle be designed to accommodate different space and time scales. Resolving micro- and mesoscale structures of magnetospheric circulation will require positioning spacecraft tetrahedrons spaced at intervals defined by the macroscale of the problem. Distribution of spacecraft in the Z direction must cover a distance ~2 $R_E$ north and south of the nominal current sheet at X~-20 $R_E$ to allow the entire cross section of the current-carrying region to be measured, even when the magnetotail is undergoing flapping, breathing or twisting motion. A vertical distribution of spacecraft is also important to intersect the entire cross section of BBFs. The north-south span to be covered in the near-Earth region is closer to ~1 $R_E$ —the estimated thickness of the large field fluctuation region that develops during the current disruption.

Placing a constellation of spacecraft with such dense distribution everywhere in the magnetotail is clearly beyond the capabilities of the current concept of a constellation. Nevertheless, it is important to keep in mind the need to resolve multiple space and time scales simultaneously in different regions of the magnetosphere. Different scenarios can be envisioned to deploy spacecraft distributions that can adequately measure the required parameters using a realistic number of spacecraft.

Azimuthal coverage can be attained by alternating tetrahedron configurations with single spacecraft along the same orbit. Azimuthal coverage at different distances down the tail can be obtained by repeating the same kind of spacecraft distribution for orbits with different apogees. The separation between successive apogees can vary with distance down the tail since coverage in the X direction need not be as dense in all regions. Finer grids should be possible at the center of the near-Earth region $(-10 < X < -6\ R_E)$ and at the center of the mid-tail region $(-30 < X < -20\ R_E)$. Coarser grids would be required for the region in between these, although alternating tetrahedrons with single spacecraft is still necessary. Given the nature of the gradients in the thermodynamic quantities and the apparent long extent of the BBF channels in the X direction, it is highly desirable to place spacecraft in orbits spaced every 5 $R_E$ between the near-Earth and mid-tail regions. Orbits with apogee at $\sim 13\ R_E$ and $\sim 18\ R_E$, respectively would provide the required coverage. Likewise, the Y-Z grid need not be as dense everywhere. Furthermore, the orbits' configuration must be such that a group of tetrahedrons passes through their near-Earth apogee at least some of the time in synchrony with the group of tetrahedrons passing through their mid-tail apogee. Simultaneous dense coverage must occur in these two regions if the problem of substorm origin and propagation is to be resolved. It does not suffice to establish unequivocally whether current disruption and reconnection occur; it is imperative to establish when they occur and how they propagate. This question is central, particularly in the controversy involving whether a near-Earth neutral line precedes or even causes current disruption.

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