Science Tasks for “Profile”

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Abstract: The orbits and formations of “Profile” give an unusually versatile mission, addressing many significant questions, in several different areas. The “clean geometry” makes it possible not only to spell out science goals but also to scope out specific “experiments” each of which addresses some scientific question. This scoping-out process helps focus the mission and could be adopted by the planners of other future missions.

1. Multiprobe Constellations

Any scientific mission needs a firm, well-defined purpose. New technology and novel orbits add appeal, but scientific purpose comes first. Ideally that purpose should be defined not only in broad terms—understanding the causes of substorms, the origin of auroras, the topology of field lines, the flow of energy etc.—but a clear demonstration should also exist about how, and by what observations, this purpose can be accomplished.

“Constellation” missions are a novel mode of observation, and therefore allow existing problems to be addressed in new ways—different ones at different times of the year, as orbits sample different parts of the magnetosphere. Such problems include the substorm (its start and its propagation), magnetic reconnection, global magnetic field structure and topology, convection patterns and the propagation of shocks and waves. The options of each mission—e.g. number, orbit, size and instrumentation of its satellites, duration, data handling and choices of spin and on-board propulsion—should be chosen to provide the best coverage of such scientific targets.

2. The “Profile” mission

One attractive magnetospheric constellation is the “Profile” mission, consisting of 12 small satellites in a near-equatorial orbit, with perigee around 7000 km (geocentric) and apogee at 20 or 25 R_E [Figure 1]. The satellites would spin around an axis perpendicular to the orbital plane, and each would carry a magnetometer and a high-rate “top hat” electrostatic analyzer for ions and electrons of 0.1 to 30 keV. The detector would sample a narrow range of the rotation angle ϕ but the full range 0 to π of the angle θ to the spin axis. Using the spacecraft spin and comparing particle rates at diametrically opposite direction, one can then estimate the bulk velocity components in the spin plane.

The satellites would be simple and small, with no on-board propulsion, and the mass of each, even with current technology, could be held down to about 17 kg. The mission, and the way it would use a “centrifugal slingshot” for dispensing the satellites from a “mother ship,” are described elsewhere [*Stern, 1998*].

As a consequence of the “slingshot” release, the satellites would form two groups of 6 satellites each on two close orbits with slightly different orbital periods. Members of each group would pass perigee about 1 hour apart, but the faster (lower) group would periodically overtake the slower (higher) one—every 7 weeks for apogee at 20 R_E (periods [46, 48] hours) and every 13 weeks for apogee at 25 R_E (periods [66, 68] hours). Consequently the formations of the satellites change periodically, adding scientific versatility to the mission.

“Profile” would be a good choice for the initial constellation mission. The satellites are few enough to be manageable, and their basic formations allow some high-priority scientific goals to be addressed,

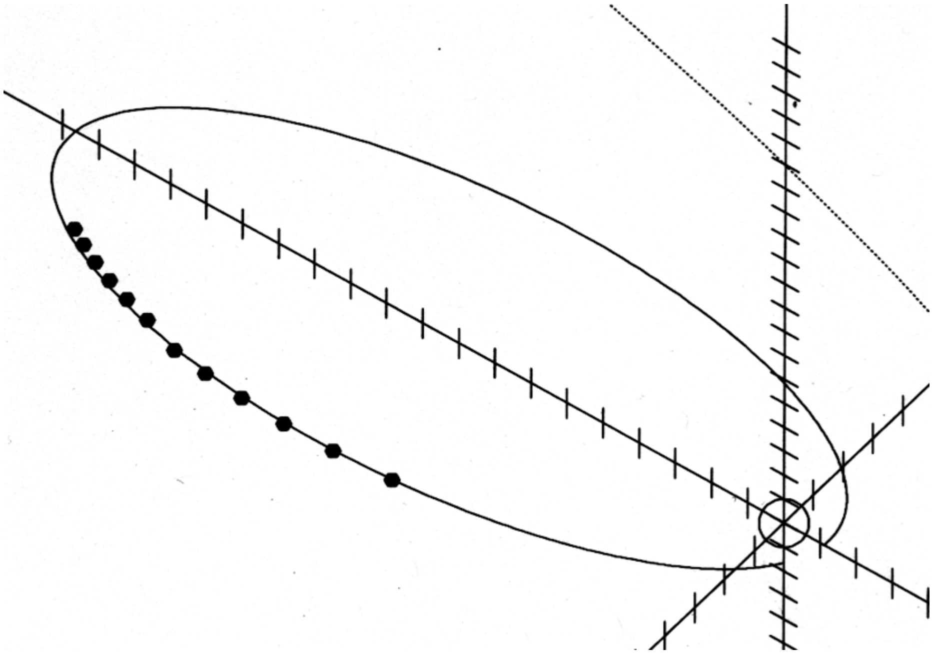

Figure 1. View of 12 “Profile” satellites in an elliptic orbit (dotted line is equatorial magnetopause).

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as discussed further below. Its stable formations as well as the uniform spin of the satellites make analysis of the data relatively "clean" and straightforward, unlike the analysis of data from randomly-placed, randomly-spinning spacecraft.

3. The Four Basic Formations

At some times the two groups would be spread out in different parts of their orbits: that is the "linear" configuration ("mode A", the first in clockwise order viewed from North in Figure 2), useful for obtaining the radial dependence of fields and particles, and for studying the earthward propagation of disturbances. At other times the groups occupy different sides of their ellipses ("mode B", not shown in figure 2), providing some 2-dimensional coverage in their orbital plane.

At still other times the formations overtake each other. If the orbital periods in each group are exactly the same (feasible with the slingshot release, required if the groups are not to disperse) members of one group will pair up with all or part of the other, each pair slowly closing the gap between them down to a fraction of 1 R_E, then pulling apart again ("mode C," third in Figure 2). This not only allows an intercalibration of instruments, but also the study of 2-point correlation functions and of small-scale phenomena.

Finally, when the overtaking groups are near apogee, a dense "supercluster" is formed ("mode D," second in Fig. 2) in which 7-12 satellites are found within a radial spread Δr of 2-3 R_E. The original plans of "Profile" called for apogee at 20 R_E, but after observations by GEOTAIL and ISEE suggested that substorms originate at around 25 R_E, an option of placing apogee at that distance was also studied, providing "supercluster" coverage for that interesting region.

4. Scientific Goals

The broad goal of "Profile" is to understand global plasma processes in the near-equatorial magnetosphere.

The motion of the Earth around the Sun rotates the "Profile" orbit among magnetospheric regions in a yearly cycle, and the goals therefore change from season to season, depending on whether apogee is in the tail, on the flanks or on the day side.

4.1 Goals in the Tail

Arguably, this is the most important part of the mission. "Profile" would seek an understanding of:

(1) The genesis of substorms and bursty bulk flows, their earthward spread and their spatial extent.

(2) The global structure of the plasma sheet, i.e. its magnetic and electric fields and its plasma parameters—during southward and northward IMF, the substorm growth phase and afterwards, different values of IMF B_y etc.

(3) The turbulent state in the plasma sheet, by obtaining two-point correlation functions (simultaneously at different distances) of **B**, n, **v** and of other plasma parameters.

4.2 Goals on the Dayside and Flanks

These would include the understanding of:

(4) Small-scale phenomena near the magnetopause, such as subsolar reconnection and flux transfer events. Multi-point observations may also help determine the spatial extent of such features.

(5) The propagation of Alfvenic disturbances and of shocks from the solar wind through the bow shock, sheath, magnetopause and magnetosphere.

(6) Magnetopause motions and erosion, the low latitude boundary layer (especially on the tail's flanks) and the noonside depletion layer.

(7) The detailed structure of the bow shock and foreshock plasma, and correlations between those regions and observations in the sheath.

4.3 Additional Goals

(8) Check the Newtonian approximation for the flaring angle of

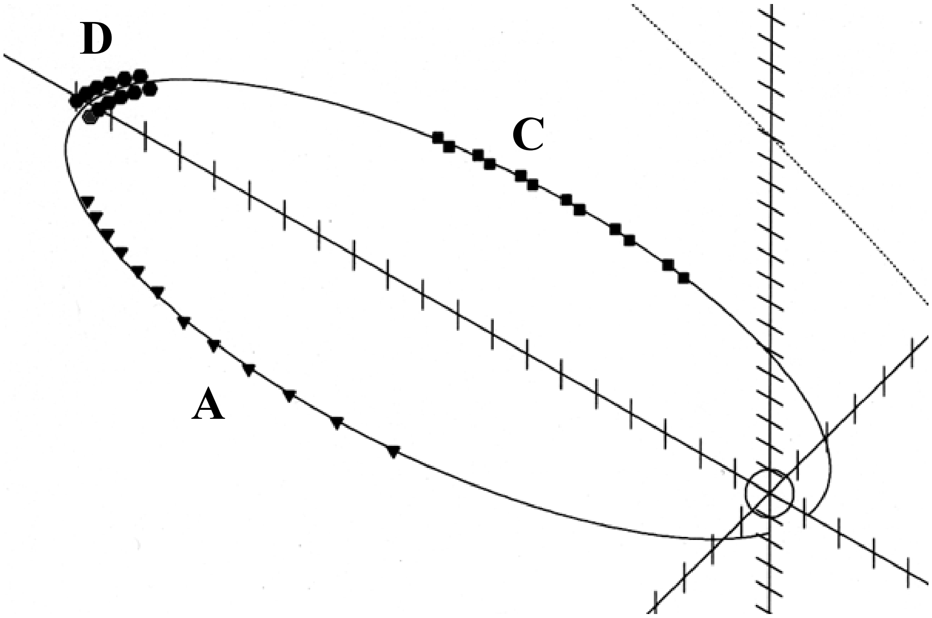

Figure 2. Various formations of "Profile" satellites, shown on a sample orbit and produced by a Keplerian code. Clockwise from Earth: a "linear" formation for radial profiles, a "supercluster" near apogee and an "overtaking" formation, used for 2-pt correlations and intercalibration. Formation "B" (simultaneous coverage on both sides of the orbit) is not shown, because it would have overlapped formations "A" and "C".

the magnetopause on the tail flanks, observe the tail's expansion in the substorm growth phase and its shrinkage afterwards, and correlate its changes with simultaneous observations in the nearby magnetosheath.

(9) Observe the variation of the ring current by up to 4 rapid traverses per hour, at two separate longitudes.

(10) Make possible better models of the magnetospheric field **B** by greatly increasing the number of available observations of **B** and also of crossings of the bow shock and magnetopause. Unlike existing models, these could also be fitted to multi-point data.

4.4 Science Tasks

"Profile" has gone beyond the definition of science goals, to spell out more than 20 "science tasks", i.e. selected "experiment" with specific targets. Each task fits one of the 4 listed formations and is appropriate to the time of the year when the orbit covers a specific part of the magnetosphere.

The mission was also simulated on a computer, for different launch options, to make sure the formation required by each task actually occurred frequently enough; details and results are given by *Stern [1998]*. A more detailed version of the list below was presented as poster SM12A-3 "Science Closure of the Profile Multiprobe Mission" at the 1996 Fall Meeting of the AGU (copies available from the author upon request). In each entry, a key phrase is set apart in **bold** type, to serve as a subhead.

4.5 Tasks in the Geotail

(1) Cover the region of **substorm origin** with a "supercluster" formation (D), to obtain insights about the process taking place there and the role of magnetic reconnection there *[Kan, 1998; Kan et al., 1998].*

This task is the main motivation for raising apogee to 25 R_E. "Superclusters" then form only 3 times a year, and the orbital period may have to be adjusted to ensure one of them occurs when apogee is near midnight.

Note that unfortunately (Table 1, *[Stern, 1998]*), superclusters are quite rare if a short-eclipses-only orbit is chosen. However, many "regular" apogee clusters of 6 satellites from the same group still occur in that case.

(2) Observe the **earthward propagation** of substorm disturbances and their earthward progress, using the electron flux for accurate timing. Formations are (A), (C) and in-between states.

(3) Measure the spread of substorm disturbances **across** the plasma sheet, using simultaneous plasma and field observations on both sides of the orbit, in formation (B).

(4) Quantify the **stretching and rebounding** of the plasma sheet during a substorm, and its magnetic structure during quiet and disturbed times *[Peredo and Stern, 1993; Rostoker and Skone, 1993; Tsyganenko, 1995]*, by using multiple satellites in the plasma sheet in linear formations such as (A) and (C). At other times, when such formations cover (mainly) the lobe, the variation and profile of B_x will provide data for better modeling of the geotail *[Stern and Tsyganenko, 1992]* as well as an estimate of the stored energy. Lobe-sheet transitions at such times track variations of plasma sheet thickness.

(5) With apogee in the tail but at an appreciable distance from midnight, use formation (B) to simultaneously observe $\mathbf{B_z}$ **across the plasma sheet.** When cross-tail current is diverted into field-aligned Birkeland currents, B_z is expected to vary with y.

The same formation can also map the cross-tail structure of **hot and cold** plasma sheet regions, recently reported by *Phan et al. [1998].*

(6) Determine the structure of the plasma sheet at times of **northward IMF**, polar cap arcs and theta auroras. At such times the topology of open and closed field may be more complex *[Huang et al., 1987; Chang et al., 1998]* with bundles of closed flux bounded by lobe-like open flux. This task resembles (4) above, and different formations can be used here to cover different aspects of the structure.

(7) Determine the large-scale **pattern of convection** in the tail (using all formations), a problematic area also addressed by the two tasks that follow. Taking average convective motions in the polar cap and using averaged global magnetic field models to map them into the tail *[Donovan and Rostoker, 1991; Toffoletto and Hill, 1989, 1993],* convective velocities were obtained which were several times larger than the ones observed *[Huang and Frank, 1986; Angelopoulos et al., 1993]*. It could be that the electric field **E** contains an inductive component, which keeps **E** out of the tail and does not allow flux to return earthward except through substorms and BBFs (task 8 below). Unlike data from isolated satellites which can only be studied statistically, simultaneous global observations would give the actual pattern of convection.

(8) Find the spatial **extent of bursty bulk flows** (BBFs) *[Angelopoulos et al., 1992]* with overtaking pairs of satellites (formation D) as variable-length baselines. So far few such observations exist *[Angelopoulos et al., 1996a,b]*.

(9) Determine the extent to which tail motions are adiabatic ($pV^{5/3}$ = const.) and the significance of the **Erickson-Wolf effect.**

This area is also controversial and unclear. *Erickson and Wolf [1980]* simulated the evolution of a convecting plasma sheet, assuming its plasma stayed within flux tubes and obeyed the adiabatic law. They found (with certain assumptions) that force balance caused such configurations to evolve until, around x = -10 to -12 R_E in the midnight equator, the plasma pressure became very high and equatorial **B** became very weak. The end point of the process remains unclear *[Erickson, 1992]*, and some have proposed it might be the substorm. "Profile" would be able to track the evolution of the convecting plasma and see to what extent it actually follows this scenario.

(10) Observe the **2-point correlation functions** in the near-equatorial plasma sheet of **B**, the density *n* and the bulk flow components $\mathbf{v}_{xy}$, and find their radial dependence.

The 2-point correlation function $F(\mathbf{r}_2 - \mathbf{r}_1)$ gives the average variation of a physical quantity at two separated points $(\mathbf{r}_1, \mathbf{r}_2)$ as function of $(\mathbf{r}_2 - \mathbf{r}_1)$ and characterizes turbulent motion. It is simplest for isotropic turbulence, where F depends only on the distance $|\mathbf{r}_2 - \mathbf{r}_1|$ and not on the orientation of $(\mathbf{r}_2 - \mathbf{r}_1)$. Formation (D), with pairs of satellites approaching each other and then receding again, can then estimate F, simultaneously at several distances.

(11) Determine the extent and motion of **dispersion-free injections,** sudden increases in particle fluxes, associated with substorms and occurring simultaneously (or nearly so) across the entire energy spectrum *[DeForest and McIlwain, 1971; Mauk and Meng, 1987].* Simultaneity suggests local acceleration, since with particles accelerated elsewhere, higher energies would arrive ahead of the rest. Originally observed in synchronous orbit but also reported at greater distances, these events are poorly understood. Formations such as (A) and (C) are particularly useful here.

(12) Map the **structure** of a localized region of the plasma sheet. A "supercluster" (D) in the plasma sheet, at quiet times, would allow more accurate modeling of the sheet's features, for instance, the variation of **j** and any large-scale flapping of the sheet.

4.6 Tasks on the Flanks

(13) Measure the **flaring angle** of the tail magnetopause and test the Newtonian approximation. By that approximation, widely used in

the interpretation of observations *[Spreiter and Stahara, 1980; Sotirelis, 1996]* , the normal pressure on an area element **dA** of the tail-flank magnetopause (balanced by magnetic and plasma pressures on the inside) is $k\rho v^2 \sin\chi$ dA, where ρ and v are density and velocity of the solar wind ahead of the magnetosphere, k is a constant close to 1 and χ is the "flaring angle" between **dA** and the flow direction of the distant solar wind. By comparing near-simultaneous magnetopause crossings by several "Profile" satellites at different distances x along the Sun-Earth axis (formation (B) or (D)), χ can be estimated. For testing the relation, a separate solar wind monitor ahead of the magnetosphere is also needed.

(14) Determine the thickness, structure and variation of the **low latitude boundary layer** (LLBL). Some theories see the LLBL as the source of region 1 Birkeland currents *[Sonnerup, 1980; Siscoe and Maynard, 1991].* Its field lines may be open or closed, and its properties are especially interesting at the plasma sheet-magnetosheath boundary, where it may form the transition between two quite different plasmas, with relatively small magnetic pressures. The thickness of the LLBL and the relation between plasmas of the LLBL and those of the adjoining regions can be closely observed at times when a "supercluster" (D) straddles the layer. If a monitor is available in the solar wind, correlations between the LLBL and the IMF are also readily obtained.

(15) Observe the **variations of the LLBL** with distance x down the Sun-Earth axis. This can be studied with formation (B), when satellites cross the LLBL at two different distances.

(16) Study **waves and ripples** propagating along the magnetopause. The Kelvin-Helmholtz instability, in particular, has been credited with such waves, sensed by isolated satellites as closely spaced multiple crossings. "Profile" satellites in formation (B) can correlate such changes at two different distances, and "superclusters" (D) can study them on a more local scale.

4.7 Tasks Involving the Day Side

(17) Track the **response of the magnetopause** and the LLBL to variations of the IMF and of the dynamic pressure of the solar wind, as well as to shocks and Alfvenic disturbances. Observations and theory suggest that following a southward turning of the IMF, the magnetopause "erodes," and magnetic flux which used to close on the dayside is then swept into the tail *[Aubry et al., 1970; Coroniti and Kennel, 1972; Holzer and Slavin, 1978; Sibeck et al., 1991].* "Profile" can observe such changes by formation (C) which places a dense string of satellites across the magnetopause and adjacent regions, and with lesser resolution by other formations as well. With a distant solar wind monitor available, this also allows a check on the Spreiter-Stahara model and on MHD simulations.

(18) Track the **propagation and evolution of shocks** *[Rufenach et al., 1989]* and of Alfvenic disturbances *[Tsurutani et al., 1987; Roberts and Goldstein, 1990],* from the solar wind through the bow shock, sheath and magnetopause, into the inner magnetosphere. The linear formation (A) often stretches from the solar wind to the inner magnetosphere, allowing the progress of such phenomena to be followed and timed.

(19) Study the detailed **structure** of the **Earth's bow shock** [*Kennel, 1981]* using the dense coverage of a supercluster (D), at the appropriate time of the year. Pairs of satellites (formation C) would also give (among other things) the variation of ion and electron spectra across the shock.

(20) Observe the **response of the bow shock** to changes in the solar wind and IMF *[Fairfield, 1971, Slavin and Holzer, 1981],* and monitor the jump conditions across it. Formations (A) and (C) are the ones most appropriate here.

(21) Multi-point analysis of the **foreshock** region and of the solar wind ahead of the bow shock. Such studies are particularly appropriate if the more distant apogee of $25R_E$ is selected, because then the satellites in the noon quadrant spend most of their time ahead of the bow shock. All formations may be useful, but especially superclusters (D); traveling waves, 2-point correlations and superthermal ions can all be observed and correlated between spacecraft.

(22) Track the motion of **flux transfer events** (FTEs) on the day side and determine their spatial extent. FTEs *[Elphic, 1995]* are characteristic oscillations of the magnetic field vector in the dayside magnetosheath, observed primarily during southern IMF and claimed to signify "patchy reconnection." First reported in 1979 *[Russell and Elphic, 1979]*, they were extensively studied by single spacecraft, but their origin, motion, ultimate fate, extent and significance remain unclear. In the "paired" formation (C), "Profile" satellites would observe FTEs at different separations, tracking their extent, motion and evolution, and could also seek correlations with other observed features.

(23) Study the pattern of field lines, flows and plasmas associated with **dayside magnetic reconnection** *[Sonnerup, 1981; Hones, 1984; Lee, 1995].* Also, find where in the subsolar region the LLBL begins, and how. Unfortunately the distant apogee keeps "superclusters" out of the interesting region of the subsolar magnetopause; at most the region has pairs of satellites close to each other (formation C), or crossing the magnetopause at well-separated points (formation B). Still, such pair-crossings occur frequently and are supported by simultaneous data from the nearby sheath and magnetosphere, and they should therefore improve our picture of the dayside reconnection process.

(24) Map the "**depletion layer**" on the day side, flux tubes plastered against the magnetopause, from which plasma is squeezed out by the upstream sheath, increasing **B** and reducing β *[Zwan and Wolf, 1976; Phan et al., 1994].* The multiple satellites of formation (B) could observe how far the effect extends and could relate it to the conditions in the sheath observed by other satellites, more distant from the magnetopause.

4.8 Other Regions and Tasks:

(25) Map the evolution of the **ring current** *[Daglis et al., 1998]*, especially after magnetic storms. In formation (C), satellites produce 4 traverses of the ring current per hour—two inbound and two outbound. Assuming ions and electrons follow adiabatic paths, this gives a rather detailed information about the evolution of the ring current. Unfortunately, only the lower part of the energy spectrum is covered (up to 30 keV). Still, such observations would complement and help check the results of remote sensing of the ring current as is being planned for IMAGE.

(26) Improve existing **global models** of the magnetosphere *[Tsyganenko, 1995; Stern, 1994]* and test MHD simulations. The great number of magnetic observations returned by "Profile" will not only allow the creating of better Tsyganenko-type models of the field, but will allow better characterization of actual variations, by fitting multi-spacecraft data, e.g. the "instantaneous" profile of **j** along the plasma sheet or Δ**B** between points in the lobe at different distances from Earth.

5. Conclusion

This study has examined the science planned for the "Profile" mission, going well beyond the usual description of scientific goals to explicitly outline various "experiments" by which such goals would be addressed. The list of those experiments should be compared to coverage statistics such as those of Table 1 of *Stern [1998]*, especially the last panel of that table, which suggest that the required formations do in fact occur frequently enough.

In the course of a year, as different regions of the magnetosphere rotate through the " Profile" orbit, different experiments become possible, relevant to tail convection, substorms, boundary layers, collision-free shocks and other key features. All these have been described in some detail. Not every mission allows such a specific listing of tasks, or simulations of their feasibility such as those conducted for "Profile". However, where such detailed planning is possible, it is highly recommended, since it helps focus the science and choose the best options.

The nominal duration of " Profile" is two years, allowing two passes through every region. Yet such is the diversity of possible "experiments" and the wealth of information provided by them, that it may well be worth while to collect data for a longer time, which is why a 10-year lifetime was planned. The wide range of observations and experiments also suggests that this mission would probably do well as a shared facility, whose data are available throughout the scientific community. The principal investigators would be responsible for the operation of on-board instruments and for data retrieval, and would be supported accordingly, but the data analysis would be shared by the entire community.

Appendix: the 2001 AGU Fall Meeting

Following below is a fanciful listing of "Profile" tasks and goals, in the guise of talk titles at a future AGU meeting. Where the proposed observation is meant to decide between two possibilities, one of them (randomly selected) is stated as fact while the other is given in parentheses. This list was distributed at the 1996 AGU Fall Meeting *[Stern, 1996].*

A1 Session SM11-A: "Profile" discoveries in the geotail

Profile data support (deny) near-Earth substorm origin.

Profile observations of the reconnection region: "classical" structure seen (not seen).

Stretching and relaxation of field lines in three isolated substorms, observed by Profile over the range 6 to 18 R_E.

Profile demonstrates that substorms in the plasma sheet spread faster (slower) than the local Alfven velocity.

The lateral spread of substorms: Profile observations.

Comparison of tail stretching between 7 and 19 R_E with northward and southward IMF, from Profile.

The x-dependence of the penetration of IMF B_y into the plasma sheet from 5 to 18 R_E, observed by "Profile."

First "Profile" maps of convection in the geotail: slow near midnight, faster (slower) near the flanks.

Profile shows that Bursty Bulk Flows extend far along the plasma sheet (are local to small sections of the plasma sheet),

Profile shows that Bursty Bulk Flows extend far (very little) across the plasma sheet.

Check of the adiabatic law by "Profile" in the tail suggests that magnetic flux tubes are tight (leaky) containers of plasma.

Profile verifies (contradicts) that convection drives the tail towards crisis, as predicted by Erickson and Wolf.

Profile mapping of B_z across the tail shows little effect (a major signature) of Region 1 Birkeland currents from the diversion of cross-tail flow.

The cross correlation of B between "Profile" satellites suggests neutral sheet plasma is well ordered (largely turbulent).

"Profile" associates dispersionless ion injections in the plasma sheet with the arrival of substorm disturbances (shows location of dispersionless ion injections is unrelated to the spread of substorms).

Profile supercluster points out filamentary nature (large-scale coherence) of plasma sheet convection.

"Profile" satellites track the spread of the "wedge current" from a substorm current diversion.

"Profile" data allow precise mapping to the geotail of features seen by an auroral imager.

A2 Session SM12-A : Profile Results from the Magnetosphere's Flanks

"Profile" tracks flank magnetopause motions following a sudden rise of solar wind pressure.

The flapping of the magnetopause revealed by "Profile" supercluster. Structures fit (do not fit) Kelvin-Helmholtz theory.

"Profile" casts doubt on (confirms) the validity of the continuity equation for Low Latitude Boundary Layer (LLBL) flow.

"Profile" maps elusive LLBL, finds its width correlates with (is unrelated to) Birkeland current intensity.

Profile multiprobes pinpoint effects of a northward turning of the IMF on LLBL width and flux.

The propagation of an interplanetary shock from the sheath to the plasma sheet, tracked by Profile.

Profile finds significant deviations (no significant deviation) from Newtonian pressure balance on the flank magnetopause.

Profile shows that the LLBL on the tail flank disappears (widens) away from the neutral sheet.

Near-flank convection observed by Profile in the plasma sheet contradicts (supports) viscous-like momentum transfer from the solar wind.

A3 Session SM21-A: Profile observations on the Dayside

Interplanetary Alfvén waves tracked by "Profile" through the bow shock and magnetopause.

A detailed picture of the Earth's foreshock by a Profile "supercluster."

"Profile" follows the propagation of interplanetary shocks through the bow shock and magnetopause.

Motion and structure of the Earth's bow shock, analyzed by a Profile "supercluster."

The propagation of FTEs through space, as seen by "Profile" multiprobes. (or maybe:"Profile solves FTE puzzle"?)

"Profile" correlates FTEs with field variations near the subsolar point.

The motion of the subsolar magnetopause, linked by "Profile" to interplanetary variations.

"Profile" correlates the dayside LLBL properties at locations 5-6 R_E apart, a clue to the origin of the LLBL (or "solves LLBL puzzle"?)

"Profile" multiprobes inside and outside the magnetopause fit together the factors in subsolar erosion.

The extent and variation of the depletion layer outside the reconnecting magnetopause, mapped by "Profile."

Signature of subsolar reconnection, as seen by two closely spaced "Profile" multiprobes, related to simultaneous changes in the sheath and magnetosphere.

The effect on subsolar erosion of interplanetary B_y, seen by "Profile."

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