

Space Technology 5 – Enabling Future Constellation Missions Using Micro-Satellites for Space Weather

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ABSTRACT

Space Technology 5 (ST5) is a three micro-satellite constellation deployed into a 300 x 4500 km, dawn – dusk, sun synchronous polar orbit on March 22, 2006. The spacecraft were maintained in a “pearls on a string” constellation with controlled spacing ranging from just over 5000 km down to under 50 km. Each spacecraft carried a miniature tri-axial fluxgate magnetometer (MAG). Although the short 90-day mission was designed to flight validate new technologies, the constellation mission returned high quality multi-point magnetic field data through the Earth’s dynamic ionospheric current systems. These data allow us to separate spatial versus temporal structures of auroral field-aligned currents over a wide range of spatial (~ 50-4000 km) and temporal (~ 5 s-10 min) scales. The ST5 mission was designed as a pathfinder for future Heliophysics constellation missions making particles and fields measurements over large volumes of Geospace. Based on the success of ST5, we are developing the concept of a new constellation mission, called Magnetospheric Convection Explorer (CONVEX), using ~ 10 small ST5-class spacecraft, distributed in local time around the Earth to complement the THEMIS mission’s radial deployment. The science approach is to generate the first global “images” of magnetospheric convection. This will allow definitive determinations of how major types of solar events drive specific space weather response modes in the near Earth environment.

INTRODUCTION

The ST5 Mission is the fifth mission in NASA’s New Millennium Program (NMP) to flight validate new technologies built for micro-satellite. It is NASA’s pathfinder for future small spacecraft constellation missions. The ST5 mission consists of three micro-satellites and has three top level technology validation objectives:

- Design, develop, and operate three full service micro-spacecraft, each with a mass less than 25kg;
- Demonstrate the ability of these micro-satellites to return research-grade magnetic field measurements;

- Operate the 3 satellites as a single constellation rather than as individual elements.

The official NMP technologies that have been successfully validated by ST5 are described in Carlisle et al.¹ and Carlisle and Webb².

The ST5 spacecraft were launched by a Pegasus XL launch vehicle into a sun-synchronized, dawn – dusk, 300 x 4500 km, polar orbit (inclination 105.6 deg) on March 22, 2006 and operated successfully for its nominal 90-day mission. As shown in Figure 1, the satellites were maintained in a “pearls on a string” constellation. The spacecraft were spin-stabilized with periods near 3 seconds. Spin axis orientation for each

spacecraft was maintained to be within 0.5° of ecliptic normal with knowledge of $\sim 0.1^\circ$. Inter-satellite spacing was controlled using the micro-satellites' cold gas propulsion system. This propulsion system was also used to raise perigee at the beginning of the mission and re-orient some of the spacecraft spin axes for eddy current assessments and magnetometer inter-calibration³. Figure 2 displays the history of the spacecraft spacing, where the red is for the separation between the lead (155) and middle (094) spacecraft and the blue between the middle and trailing (224) spacecraft. As shown, these spacings varied between from just over 5000 km down to under 50 km.

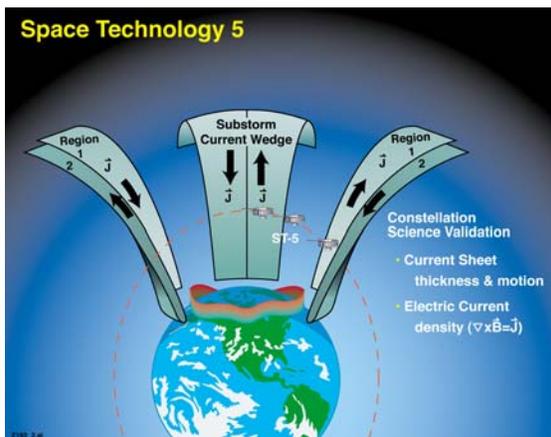


Figure 1: Illustration of the ST-5 three satellite constellation's sun-synchronous polar orbit.

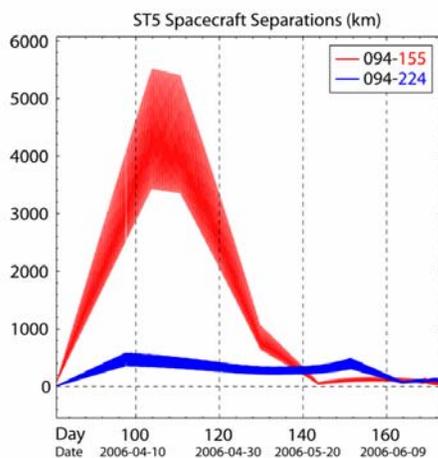


Figure 2: The history of the spacecraft separations over the ST5 mission life. The red is the separation between the leading (155) and the mid (094) spacecraft, and the blue between the trailing (224) and the mid spacecraft.

Science measurements are required to support the technology validation, especially to validate the ST5 spacecraft as a suitable platform for taking research quality measurements. The boom-mounted miniature fluxgate magnetometers are the only scientific instrument onboard each of the three ST5 spacecraft. Although the short 90-day mission is designed to flight validate new technologies, the constellation mission returned unprecedented data as they flew in formation and made simultaneous multi-point measurements of the geomagnetic field in its low Earth orbit. In addition to returning high quality magnetic field measurements of the auroral currents that flow into and out of the auroral zone, the measurements at perigee are also sensitive to horizontal currents flowing in the ionosphere and the Earth's crustal magnetic anomalies.

In this paper, we present results of ST5 science validation. We first provide some information about the magnetometer and its boom. Then, we present the science data returned from ST5 that demonstrate the capabilities of the spacecraft as a platform for research quality measurements and the high performance of the miniature magnetometers. Finally, we describe a new micro-satellite constellation mission concept, Magnetospheric Convection Explorer (CONVEX), which is being developed. Leveraged on the success of the ST5 mission, the CONVEX mission will deploy ~ 10 small ST5-class spacecraft to generate the first global "images" of magnetospheric convection. This will allow definitive determinations of how major types of solar events drive specific space weather response modes in the near Earth environment.

ST5 MAGNETOMETER (MAG)

MAG Specifications

The three ST5 magnetometers were developed by UCLA. Table 1 details the ST5 magnetometer specifications. These instruments function as "state vector machines" that deliver 16 vectors per second to the spacecraft command and data handling whenever it receives a clock signal and power. The magnetometer sensor is mounted at the end of a stiff, very low mass, self-deploying boom designed and built by GSFC. This arrangement places the magnetometer almost 110 cm from the center of the spacecraft, in order to reduce the effects of any stray magnetic fields from within the body of the spacecraft. The magnetometer boom stows by folding around the spacecraft equator and was released on-orbit using a shape memory alloy pin puller. Strain energy in the hinges, from stowing, deploys the boom. It is constructed as an assembly of graphite composite tube sections with beryllium copper "carpenter tape" hinges. It is about 225 g in mass and 80 cm in length. It has been designed to minimize

magnetic interference with the magnetometer and provide thermal and dynamic stability.

The MAG sensors have dimensions of 5 cm x 5 cm x 3 cm and the total mass of each sensor plus its electronics is approximately 570 gm. The MAG has two ranges: +/- 64,000 nT (Full-Field) and +/- 16,000 nT (Low-Field) that are controlled by each micro-satellite on the basis of the measured ambient magnetic field strength. The digital resolution of the MAG in its full and low magnetic field ranges is better than 1.25 nT and 0.30 nT, respectively. The intrinsic noise for these miniature magnetometers was < 0.1 nT rms @ 1 Hz.

Table 1: Magnetometer Specifications

	Specifications
Dynamic Range	0 - ±64,000 nT (Full-Field) 0 - ±16,000 nT (Low-Field)
Digital Resolution	< 1.25 nT (Full-Field) < 0.30 nT (Low-Field)
Intrinsic Noise	< 0.1 nT rms @ 1 Hz
Data Rate	- 16 vectors per second - simultaneous 17 bit per axis data sample
Power	570 mW at 7.2 V (77.8 mA)
Mass	Sensor Head: 290 g Electronics Box: 570 g Cable: 90 g Total: 910 g
Size	Sensor Head: 5cm×5cm×3cm Electronics Box: 10cm×12cm×7.6cm

MAG Performance

The ST5 spacecraft were developed with a magnetic cleanliness program, which screens parts to avoid using magnetic materials and carefully layouts the electronics to avoid generating a net magnetic field by current loops. Pre-launch testing in the Goddard Space Flight Center Magnetic Coil Facility has showed that any stray magnetic fields due to the satellite at the MAG sensor location will be less than 1 nT.

In flight, the ST-5 magnetic field data were taken in the spinning spacecraft platform. The MAG data processing software converts the raw telemetry counts in the spinning platform into the calibrated magnetic field data in physical units and geophysical coordinate systems. The MAG data processing involves several steps: (1) applying pre-launch ground calibration data to the spinning raw counts; (2) calibrating the spinning data based on sine wave fittings to determine the sensor orthogonality matrix and offsets; (3) despinning the

data into the fixed spacecraft frame using the sun sensor data; (4) calibrating the despun data with the Earth’s internal magnetic field model, and (5) transforming the calibrated data into geophysical coordinate systems using the spacecraft attitude data. Our results show that the ST5 magnetic field data are of very high quality. The observed magnetic field along the ST5 orbit agrees well with the prediction of the International Geomagnetic Reference Field (IGRF) model. With preliminary calibrations, we have achieved the MAG data accuracies of 0.1° in pointing knowledge and better than 0.1% in field strength. Magnetic signatures of science events as small as a few nT can be readily identified in the data with a background field up to ~ 50,000 nT. We do not see any effect of nutation or coning of the spacecraft, or contamination due to unstable spacecraft magnetic field. These inflight MAG data have further validated that the ST5 spacecraft are magnetically clean and meet full success requirements.

ST5 SCIENCE VALIDATION

The fundamental measurement strategy of all micro-satellite constellation missions is to synthesize higher order physical quantities from the collective measurements made by the individual satellite elements. The ST5 mission provides validation for this measurement concept by using three micro-satellites through the coordinated collection and analysis of magnetometer measurements over the Earth’s auroral ovals in low Earth orbit. In addition to returning high quality magnetic field measurements of the electric currents that flow into and out of the auroral zone, the measurements at perigee are also sensitive to horizontal currents flowing in the ionosphere and the Earth’s crustal magnetic anomalies. In this section, we present examples of ST5 science measurements to demonstrate the quality of the ST5 data and how the constellation measurements enable new science.

Temporal Variability of Field-Aligned Currents

The auroral ovals are annular regions a few degrees of latitude in width that encircle the north and south magnetic poles of the Earth. These regions are unique because they constitute magnetic “foot prints” of the external boundaries of the geomagnetic field where solar wind energy from the sun enters the system on the dayside and the flanks. Most of the solar wind energy is eventually transferred and dissipated to the Earth’s ionosphere and upper atmosphere. There primary mechanism for this transfer of energy to the ionosphere and upper atmosphere is the formation of intense electric currents that flow along the geomagnetic lines of force emanating from the auroral ovals. These currents are termed “field aligned currents” or “FACs”

because they are guided by and follow the geomagnetic lines of force. The excitation of neutral atmospheric oxygen and nitrogen atoms by the energetic electrons that are the primary carriers of these electric currents result in the beautiful and scientifically complex auroral optical displays that have captivated high latitude human civilizations for millennia.

For nearly three decades, extensive investigations using single spacecraft have shown that the auroral field-aligned currents usually appear as quasi-planar “sheets” that tend to loosely parallel to lines of constant geomagnetic latitude. However, our knowledge about the properties of field-aligned currents are derived by assuming these current sheets to be stationary and time independent since the single spacecraft measurements are not able to discern their motion and temporal variations. ST5 has provided for the first time simultaneous multi-point measurements of field-aligned currents at low altitudes. From March 26 (after the magnetometer booms from all three spacecraft were deployed) to the end of the mission, the constellation made over 2000 passes over the Earth’s auroral ovals at 300-4500 km altitudes. The data allow us to measure important physical parameters of FACs that cannot be determined unambiguously by single spacecraft, such as the motion, the thickness, the current density, and the temporal variability.

Figure 3 shows one example of the field-aligned currents observed by the three ST5 spacecraft on April 13, 2006. The top panel of Figure 3 shows the trajectory of the spacecraft’s ionospheric footprints. During this interval, the ST5 spacecraft move from the dawn to dusk over the southern polar cap in a string-of-pearls configuration, where the leading, mid and trailing spacecraft are 155 (red), 094 (black) and 224 (blue), respectively. The leading spacecraft 155 had a large separation distance from the trailing two. The separation between the leading and middle spacecraft (SC 155 – SC 094) is 3388 km. The separation between the middle and trailing spacecraft (SC 094 – SC 224) was 368 km.

The bottom panel of Figure 3 contains the magnetic field residual data (ST5 data with the internal IGRF model magnetic field removed), including the three components of the magnetic field residual vector in the solar magnetic (SM) coordinate system as well the residual of the magnetic field strength. The labels for the spacecraft position on the bottom of the panel are for spacecraft 094 only. The large perturbations of the magnetic field component signal the encounters of FAC sheets. The first encounter of the FACs starts at ~ 0938 UT by the leading spacecraft SC155 and then at ~ 0948 UT by the mid-spacecraft SC094 and ~ 0949 UT by the

trailing spacecraft SC224. The altitude of the spacecraft is ~ 3200 km. The ionospheric footprints of the current sheets are in pre-dawn sector near 04 hour local time. After crossing the polar cap toward the dusk sector, the spacecraft once again detect the current sheets at ~ 4600 km altitude near the dusk, starting at ~ 1005 UT by SC155, then at ~ 1015 UT by SC094 and at ~ 1016 UT by SC224.

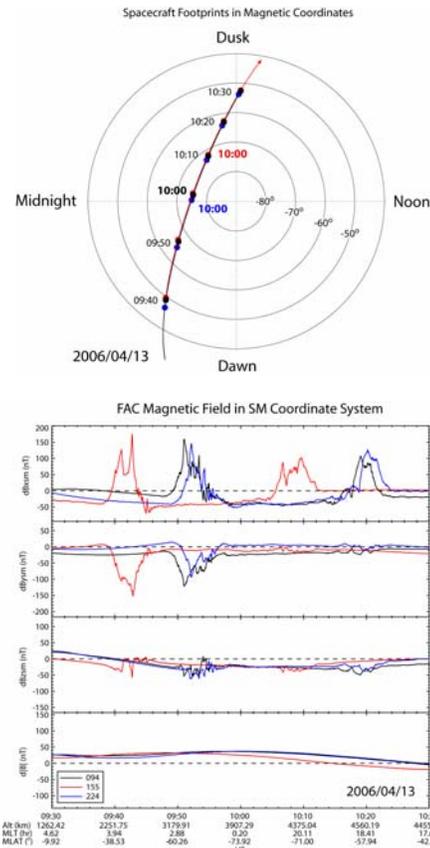


Figure 3: ST5 observations of field-aligned currents during a southern polar cap pass. The top panel is the spacecraft ionospheric footprints in magnetic coordinates, where the nested circles represent constant magnetic latitudes separated by 10° and centered at the Earth’s magnetic South Pole. The bottom is an overview of ST5 magnetic field perturbations generated by the field-aligned currents on April 13, 2006. The three components of the magnetic field residual vector (ST5 data with the internal IGRF model magnetic field removed) are shown in Solar Magnetic Coordinates. The labels for the spacecraft positions (altitudes, magnetic latitudes and magnetic local times) on the bottom for mid-spacecraft SC094 (black) only.

The magnetic field profiles at the three spacecraft enable us to separate spatial variations from temporal ones. When the three spacecraft cross the current sheet successively along the same trajectory, their magnetic field profiles would exactly track each other except with time delays if the magnetic variations are all spatial and the FAC structure does not experience any temporal variation. Otherwise, differences in the magnetic field profiles would indicate temporal changes in current structures. Separating temporal variations from spatial features is not possible with single spacecraft observations. With ST5's multi-point observations, we are able to evaluate FACs' temporal variability. To do so, we compare the east-west components of the magnetic field data from the three spacecraft by time-shifting the data to match the large-scale structure of the observations. Figure 4 shows the comparison for the FACs observed near the dusk in Figure 3. Here the times on the horizontal axes are for SC094 and the times for SC155 and SC224 are shifted by the amount determined from the cross-correlation analysis. After lining up the large-scale spatial structures at the three spacecraft, the FACs temporal variations are very evident. Observed about 10 min differences in time, the magnetic field profile of SC155 exhibits large differences from those of SC094 and SC224, especially the meso-scale structures within the large-scale current sheets. We have examined ST5 FAC observations at various inter-spacecraft separations to study their temporal variability at various time scales, and found that meso-scale current structures are generally very dynamic in time scales of ~ 10 min. These temporal variations are associated with dynamic variations of their particle carriers (mainly electrons) as they respond to the variations of the parallel electric field in auroral acceleration region.

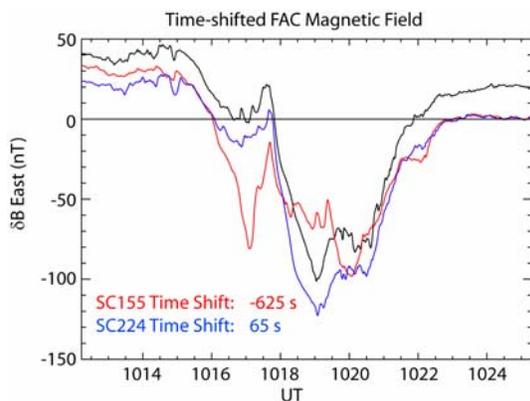


Figure 4. The time-shifted east-west components of the FAC magnetic field from the three ST5 spacecraft. The time shifts are determined by lining up the large scale current structures.

Gradiometer Analysis of Current density

Based on Ampere's Law, the density of the electric current can be directly inferred from the curl of the magnetic field. Thus, measuring current density requires measuring the spatial gradient of the magnetic field. If we only have data from a single spacecraft, we have to make the assumption of stationary current sheet, i.e., the current sheet does not change with time and does not move in space. This way, we measure the gradient of the magnetic field by flying through the stationary current sheet. Simultaneous multi-point ST5 data allow us to directly measure the gradient of the magnetic field without the need to make stationary current sheet assumption. The technique to obtain the current density by directly measuring the gradient of the magnetic field is called gradiometer analysis. It uses two-point simultaneous measurements to obtain the spatial gradient of the magnetic field. In this method, the spacing of the two spacecraft has to be smaller than the thickness of the current sheet (so that the both spacecraft can be within the current sheet at the same time). The thickness of the auroral current sheet is typically $\sim 500 - 1000$ km. Thus, ST5 data provide many such opportunities for gradiometer analysis of the current density.

Figure 5 is an example of the gradiometer analysis using the magnetic field data from SC094 – SC224 pair on March 31, 2006 (Y. Wang, unpublished work). The magnetic field data were taken near the dawn at ~ 500 km altitude in the northern hemisphere. The current density using the gradiometer analysis is shown as the black trace in Figure 5. In comparison, the current density determined using the traditional single spacecraft data and with the stationary current sheet assumption is shown as red trace. The fluctuations in the red trace are mainly caused by temporal variations of small scale structures embedded within the large scale current sheet. However, these time-varying structures are treated as spatial variations when making the stationary current sheet assumption. Thus, these small scale fluctuations do not represent the true current density profile within the current sheet. The gradiometer method automatically removes temporal variations from the data since the two-point measurements are taken simultaneously. It also acts as a natural low-pass filter as any variations with spatial scales less than the spacecraft separation are filtered out. The gradiometer analysis result shows clearly two current sheet structures with currents flowing in opposite directions: the region 1 current (R1) flowing downward (positive current density J) and the region 2 current (R2) flowing upward (negative current density J). The current sheet thickness (in km) and the total integrated current intensity (in mA/m) are also shown in Figure 5 for each current sheet.

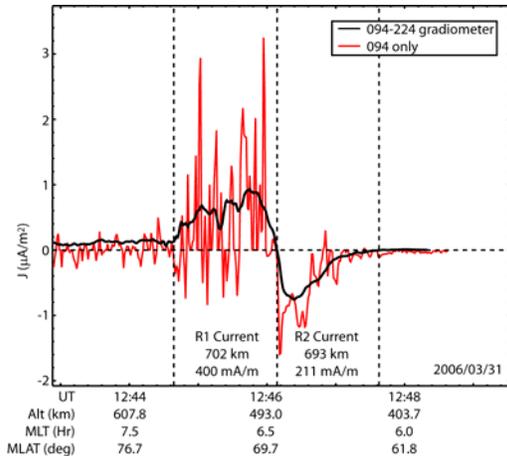


Figure 5. The current density determined by gradiometer analysis using simultaneous two-point magnetic field data from SC094-SC224 pair (black trace). In comparison, the current density determined using single spacecraft data (SC094 only) and by assuming stationary current sheet is shown in red.

Lithospheric Magnetic Field Gradients

When ST5 spacecraft were away from the auroral current sheet and over the continents, the magnetic field gradients are dominated by lithospheric magnetic fields (also called crustal magnetic fields due to the magnetization of Earth’s crust, or magnetic minerals). Using simultaneous two-point measurements in determining the magnetic field gradients effectively removes temporal effects by sampling the magnetic field at the same time. Figure 6 shows the low altitude (<400 km) magnetic field gradients (in nT/m) measured by ST-5 spacecraft SC094 and SC224 between March 28 and June 2, 2006 (Purucker et al., unpublished work). The gradients are calculated by first removing the Earth’s internal magnetic field (IGRF model) from the magnetic field strength measured by SC094 and SC224 individually, and then calculating the difference between the SC094 and SC224 measurements. Spacecraft separation averaged 400 km (Range: 100-600 km). The left panels show the gradient measurements made by SC094-SC224 pair. The right panels show the gradients predicted from the Comprehensive (CM4) field model, a model derived using data from satellite mapping missions (Orsted, CHAMP, Magsat, and POGO), and ground-based observatories⁴. The gradients from ST5 data exhibit correlations of between 0.5 and 0.94 with the CM4 model. ST5 provided the first simultaneous two-point measurements of lithospheric magnetic field gradients. The next such data set will be provided by ESA’s upcoming Swarm mission.

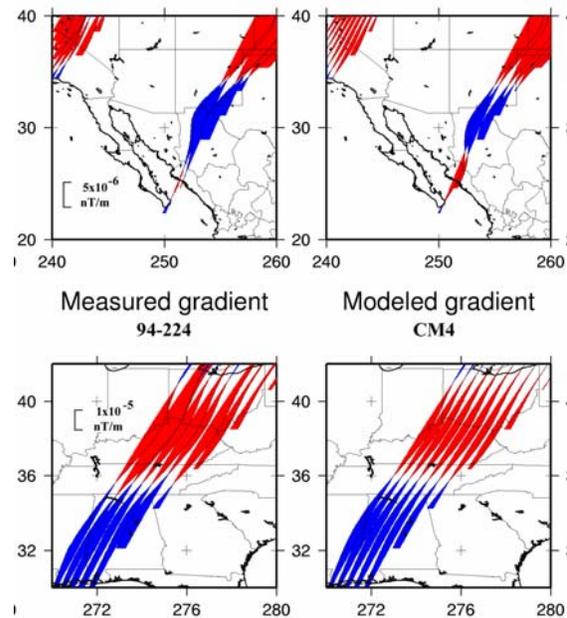


Figure 6. Stacked profile plots showing measured magnetic field gradients (left), compared with those predicted by the Comprehensive (CM4) field model (right) over portions of North America covered by ST-5 observations at altitudes of less than 350 km. Red colors indicate positive fields or gradients, blue are negative.

ENABLING FUTURE MICRO-SATELLITE CONSTELLATION MISSIONS – CONVEX MISSION CONCEPT

The ST5 mission has demonstrated the ST5 spacecraft’s capabilities as a platform for research grade science measurements; and thus, the spacecraft itself can be directly infused into future missions. One of NASA’s objectives (Objective #15) is to explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational systems. Attaining a mature understanding of how solar activity and variability affects the interplanetary medium, the magnetosphere, the ionosphere and the upper atmosphere of the Earth is a critical aspect for developing a predictive capability. Measurements from single spacecraft or tight clusters of spacecraft cannot provide a globally coherent picture for such a vast volume of the dynamical system. Because of this, and the requirement of cost-effectiveness, constellations of ten’s of small (i.e.

micro-) spacecraft have been proposed to provide basic magnetic fields and charged particles measurements with sufficiently dense spatial coverage to yield definitive observations of the system-level response to major solar-terrestrial events. Many such constellation missions have been envisioned by NASA's Sun-Solar System Connection (SSSC) Roadmaps and strategic roadmaps to answer critical meso- and macro-scale problems in solar-terrestrial physics. For example, the Magnetospheric Constellation (MagCon) is the most mature of the constellation mission in early development⁵. MagCon is a strategic mission, designated as Solar Terrestrial Probe Mission #6. It will deploy ~30–36 spacecraft of the ST5 class in the plasma sheet to provide magnetic field, plasma and energetic particles measurements needed to determine the temporal and spatial development of geomagnetic storms and substorms in the Earth's night-side magnetosphere.

Herein we describe a new concept for a micro-satellite constellation mission which is currently being developed by GSFC scientists and engineers. The mission is called Magnetospheric Convection Explorer (CONVEX). It is designed to be implemented within NASA's Medium Class Explorer (MEDEX) cost and schedule constraints. The main science objective of CONVEX is to answer the most important outstanding question in Geospace Science: How does magnetospheric convection respond to major solar eruptions (e.g., Coronal Mass Ejections) and internal plasma processes (e.g., reconnection) to accelerate and inject charged particles and electromagnetic energy into the radiation belts and the auroral ionosphere? Thus, the CONVEX mission answers high priority Heliophysics science questions defined by the National Academy of Sciences and the NASA Roadmaps. The measurement strategy is to map the time evolving magnetic field and plasma flow vectors in the Earth's plasma sheet. The multi-point measurements then will be used to generate the first global "images" of magnetospheric convection, which will allow definitive determinations of how major solar events lead to specific types of space weather in the near Earth environment.

The CONVEX mission concept is outlined as follows:

- Ten identically-instrumented micro-satellites based on the GSFC developed ST-5 spacecraft bus;
- Direct injection of all 10 spacecraft into a $6.67 R_E \times 25.75 R_E$ elliptical orbit with a string-of-pearls constellation configuration forming a ~ $20 R_E$ quasi-linear array of observatories

across the magnetotail in the east-west direction at intervals of 0.3 to $3 R_E$ (Figure 7);

- Two instruments, a miniature magnetometer (ST5 heritage) and a plasma velocity analyzer, making simultaneous measurements of the two basic MHD plasma state variables (magnetic fields and plasma flow fields) across the magnetotail at spatial and time resolution accessible to MHD models.
- Measurements feeding into MHD models to continuously generate global images of changes of the magnetospheric convection using the measurements as inputs.

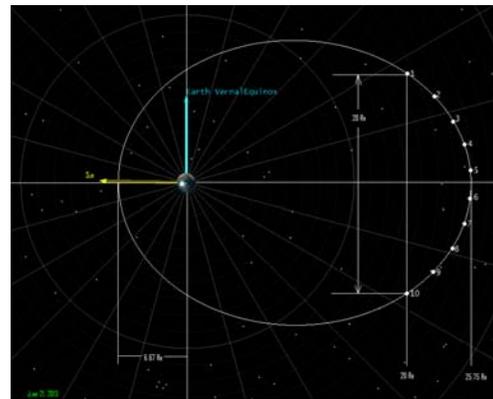


Figure 7. CONVEX orbit and constellation configuration during science data collection campaign. The Sun is to the left and the Earth's magnetotail is to the right.

The ST5's successful deployment and execution have enabled us to leverage the development of CONVEX on its unique flight heritage to optimize the performance and reduce the complexity and cost of the micro-satellite bus. The CONVEX mission design also takes advantages of new space weather modeling capabilities at GSFC to minimize the number and complexity of the micro-satellites in its constellation. First results of the concept study have indicated that the CONEX mission is feasible within the MIDEX constraints. We continue working on various trade studies to refine the mission design.

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and includes A. L. Jones, F. L. Markley, C. R. Mendelsohn, G. F. Meyers, and R. C. Mills.

References

1. Carlisle, C.C., G. Le, J.A. Slavin, J.T. VanSant, and E.H. Webb, Space Technology 5 - Technology Validation Update, IEEE Aerospace Conference Proceedings, 2006 IEEE Aerospace Conference, Vols 1-9 , 517-526, IEEE, New York, NY, USA, 2006.
2. Carlisle, C.C., and E. Webb, Space Technology 5 - A Successful Micro-Satellite Constellation Mission, Proceedings of 21st Annual AIAA/USU Conference on Small Satellites, Paper Number SSC07-VII-6, Logan, UT, August, 2007.
3. O'Donnell, J.R., M.A. Concha, J.R. Morrissey, S.J. Placanica, A.M. Russo, and D.C. Tsai, Space Technology 5 launch and operations, Proceedings of 30th Annual AAS Guidance and Control Conference, Paper Number AAS 07-091, AAS Publications Office, San Diego, California, 2007.
4. Sabaka, T., N. Olsen, and M. Purucker, Extending Comprehensive Models of the Earth's Magnetic Field with Oersted and CHAMP data, Geophys. J. Int., 159, 521-547, Nov., 2004.
5. Moore, T.E., et al., The Magnetospheric Constellation (MC): Global dynamics of the structured magnetotail, Updated Synopsis of the Report of the NASA Science and Technology Definition Team for the Magnetospheric Constellation Mission, October, 2004.