SSC08-X-2

Large Constellation Development Using Small Satellites

Bryan E. Bingham and Quinn E. Young
Space Dynamics Laboratory
1695 N. Research Park Way, North Logan, UT 84321; (435) 797-4433
bryan.bingham@sdl.usu.edu

Stephen A. Whitmore
Mechanical and Aerospace Engineering Department, Utah State University
4130 Old Main Hill, Logan, UT, 84322-4130; (435) 797-2951
swhitmore@engineering .usu.edu

ABSTRACT

Many natural phenomena of interest occur on a global scale. Accurately measuring and studying these phenomena require creating a network of globally spaced sensors a constellation of satellites allows for simultaneous global measurements, but has been traditionally viewed as cost prohibitive. Recent developments in small satellite technology have made it possible to create a global constellation while maintaining the cost at reasonable level. This paper describes the practical development of a global constellation of 90 pico-satellites that will be used for distributed ionospheric diagnostics. The constellation is created using one standard low-cost launch vehicle with an adept final insertion stage. The satellite design is based on the readily available and well-established pico-satellite technology developed by the Cubesat community. A single science sensor is highly integerated with the pico-satellite bus design. This "sensor-sat" design approach minimizes volume and mass, allowing for 90 sensor-sats to be launched and deployed from a single launch vehicle. The novel constellation design presented in this paper clearly identifies the platform upon which the next generation of space science and space weather needs can be effectively met using current small satellite technology.

NOMENCLATURE

a	=	semi-major axis of orbit, *km*
A_{sector}	=	sector area of earth's surface, km^2
e	=	eccentricity of orbit
h	=	mean orbital altitude, *km*
h	=	orbital angular momentum, km^2/sec
i	=	inclination of orbit, *deg.*
J_2	=	second order gravitational moment, 1.0826×10^{-2}
m	=	spacecraft mass, *kg*
N_{sat}	=	number of satellites in constellation
R_{earth}	=	mean Earth radius based on volume. 6371.08 *km*
R_{orbit}	=	orbital radius, *km*
$T_{revisit}$	=	E-Sat revisit time, *min*
t	=	generic time variable, *sec*
$\bar{v}$	=	orbital velocity vector, *km/sec*
V_{orbit}	=	orbital velocity, *km/sec*
Δi	=	difference in inclination angle between adjacent orbits, *deg*
Δh	=	difference in altitude between adjacent orbits, *km*
Δv	=	delta velocity, *m/sec*
v	=	circular orbital velocity, *m/sec*
v_1	=	orbit velocity after deployment, km/sec
v_r	=	velocity in local vertical, km/sec
v_v	=	velocity in local horizontal, km/sec
v_h	=	velocity in out of plane, km/sec
μ	=	planetary gravitational constant for Earth, $3{,}9860044 \times 10^5\ km^3/sec^2$
β	=	deployment elevation angle, degrees
α	=	deployment azimuth angle, degrees
$\dot{\Omega}$	=	rate of change of right ascension of ascending node (RAAN), deg/day
$\Delta[\dot{\Omega}]$	=	differential rate of change of RAAN between adjacent orbits, deg/day

INTRODUCTION

As the sun emits solar wind particles of electric and magnetic fields, the Earth's atmosphere is influenced and man-made technologies are effected. NASA has acknowledged this phenomenon as one of its major foci in the NASA Heliophysics Recommended Roadmap for Science and Technology 2005-2035.[1] The goal of this roadmap *is to understand the Sun, heliosphere and planetary environments as a single connected system and to apply this knowledge for the benefit of society and the exploration of the solar system.* To achieve this goal, NASA has initiated development and deployment of a fleet of satellites called the Heliospheric Great Observatory (HGO). This fleet will provide measurements that range from near solar space, across interplanetary space, and well into the Earth's magnetosphere.

The missing link in the Sun-Earth measurement chain is the Earth's high-latitude ionosphere, a critical region where the solar forcing of the Earth's upper atmosphere originates. At high latitudes, the ionosphere connects to the magnetosphere and solar wind–magnetopause interactions generate the Earth's electrical fields (E-field). The E-field represents the coupling agent between the magnetosphere and ionosphere and is the prime energy transport mechanism between the Earth's ionosphere-thermosphere system and the magnetosphere.[2]

While the general morphology of the E-field is known, its characteristics field during disturbed conditions and over a wide range of spatial and temporal scales are obscure. It is critical to obtain electric field measurements at high spatial and temporal resolution in the high-latitude aurora and polar-regions in both hemispheres to understand the effects of small-scale disturbances on the global evolution of the Earth thermosphere.[3,4]

To collect these critical data, a consortium of organizations including Clemson University (mission science lead) and the Space Dynamics Laboratory (SDL) at Utah State University (mission systems engineering, science payload) collaborated on a proposal for a flight experiment to fill in the gaps in the HGO measurement chain using *in situ*-sensors to map the Earth's high-latitude E-field simultaneously at many points. The proposed High-latitude Dynamic E-Field (HiDEF) Explorer program will deploy these *in situ*-sensors into multiple orbits to achieve the needed globally-dispersed data collection network.

The HiDEF network will observe and return the key data needed to model and characterize the high latitude magnetosphere-ionosphere-thermosphere (MIT) global E-Field.[5] As magnetospheric processes evolve during a geomagnetic disturbance, the HiDEF E-field observations will provide a detailed map of the evolving magnetosphere dynamics. These data will provide for modeling of atmospheric forcing, coupled MIT dynamics, and of E-field evolution over a wide range of spatial and temporal scales.[6]

The HiDEF mission focuses on three principle areas of investigation: 1) defining the contribution of small-scale turbulent E-fields to the larger-scale electro-dynamical processes; 2) understanding how the high-latitude E-fields evolve during disturbed conditions; and 3) detecting high-latitude sources for mid- and low-latitude penetration E-fields.

The first investigation topic requires obtaining high-resolution *in situ* E-field measurements at small temporal and spatial scales. The second and third research areas deal with the larger-scale structures, and require the broader global-scale sensing of the high latitude E-field measurements. These sensing requirements are in direct conflict with each other. The first research topic requires a large number of measurements in a very small spatial region; while the latter two topics require a large number of measurements over a wide range of orbits and altitudes.

TOP-LEVEL HIDEF MISSION CONFIGURATION AND REQUIREMENTS ANALYSIS

SDL was tasked with defining a mission concept of operations (CONOPS) that allowed these disparate objectives to be achieved while minimizing cost and maximizing chances of mission success. This low-risk philosophy resulted in mission approach that replaces a single high-value, long-lead time sensor with a constellation of multiple low-cost, short development time sensors.

For this mission, this team used existing and proven technology for the sensors which lead to an innovative concept for deployment and orbit progression. The E-field sensors and their satellites are integrated into compact units. These units, or E-Sats, are based on well-established pico-satellite technologies. This approach allows rapid development and integration of multiple E-Sats. To determine the number of E-Sats needed to collect the required data, the HiDEF team took into consideration possible E-Sat failure rates and constellation achievement parameters.

By using simple satellite and science sensor implementations, the mission challenge is shifted from the development of the hardware to the lower risk logistics of the constellation tracking and communications management. This constellation of E-Sats will provide an unprecedented continuous stream of global *in-situ* ionosphere E-field data; and is analogous to a global network of ground-based weather stations.

Figure 1 depicts the proposed E-Sat and shows both the sensing (E-field) and communication booms. Each satellite is spin-stabilized at *1 Hz* about the vertical axis, and will have a volume of less than $0.0015\ m^3$, a mean frontal area of approximately $0.032\ m^2$, and have a mass of approximately *1.12 kilograms.*

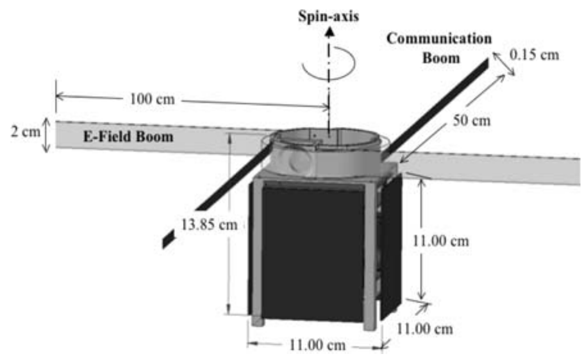

Figure 1: External View of Proposed E-Sat Configuration

Constellation Size

The science objective driving the quantity and configuration of E-Sats required is the revisit time between points on the globe. The high-latitude convection patterns change on time scales of approximately 10-20 minutes and at a maximum the revisit time needs to be between 5-10 minutes to properly resolve the E-field dynamics. A simple geometric analysis approximates the mean surface area swept-out by the orbiting satellites as a sphere, and then divides the surface area into equal sectors based on the number of satellites. The square root of the sector area calculates the length scale, and dividing by the mean satellite velocity approximates the mean revisit time.

$$T_{revisit} \approx \frac{\sqrt{A_{sector}}}{V_{orbit}} = \sqrt{\frac{4\pi \mathrm{R}_{orbit}^{\;2}/N_{sat}}{\mu/\mathrm{R}_{orbit}}} = \sqrt{\frac{4\pi\left[\mathrm{R}_{earth}+h\right]^3}{\mu\cdot N_{sat}}} \qquad (1)$$

The calculation method is shown in equation 1. Figure 2 plots the revisit time versus number of satellites for a 500-km mean altitude circular orbit. There are diminishing returns after approximately 75 satellites and this value selected for the HiDEF constellation. Allowing for a 20% contingency for satellites lost during deployment or failing within the mission lifetime, the program finally settled on 90 satellites for the HiDEF constellation. Latter sections of this paper will discuss the specific orbits and deployment logistics associated with the HiDEF constellation.

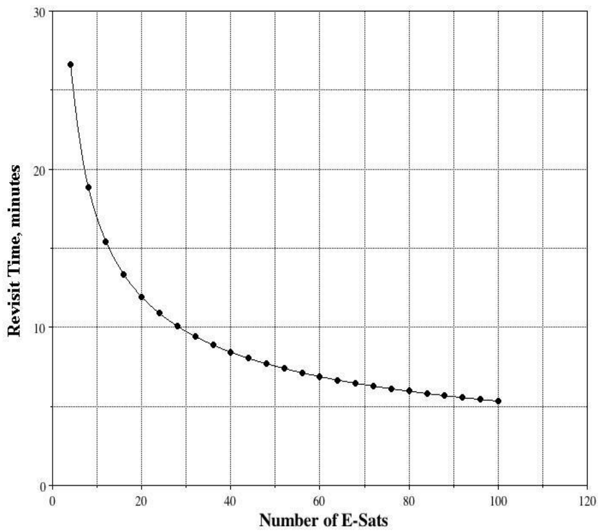

Figure 2: Revisit Time as a Function of HiDEF Constellation Size

Requirements for Initial Deployment Orbits

A prime mission requirement is for the initial constellation to be closely-aligned in high-inclination orbits with altitude and inclination differences that produce a precession difference. This will provide the constellation with momentum to naturally disperse and to provide global E-field coverage.

Eventually, the orbit precession will lead to more than 90º of separation between orbital ascending node longitudes. Mission operations will be divided into two phases. Phase 1 will disperse the satellite constellation into a "string of pearls" that tracks on a single high-inclination orbital plane. This densely packed string of E-Sats will provide data relevant to the first principal area of investigation described earlier: *the contribution of small-scale turbulent electric fields to the larger-scale electro-dynamical processes*.

Depending on the precise orbits selected, Phase 1 will last approximately 6 months. Phase 2 begins when the constellation has achieved a wide dispersal. The data returned will be relevant to the second and third research areas described in the introduction to this paper. The start of Phase 2 is somewhat arbitrary, since the constellation orbits are constantly changing after initial deployment.

The HiDEF science requirements mandated that global coverage be achieved within 6-months after launch and reach a maximum separation within 18 months after launch. The anticipated useful end-to-end lifetime of the constellation is approximately 24 months. Figure 3 shows the desired Phase 1 and Phase 2 satellite orbit configurations.

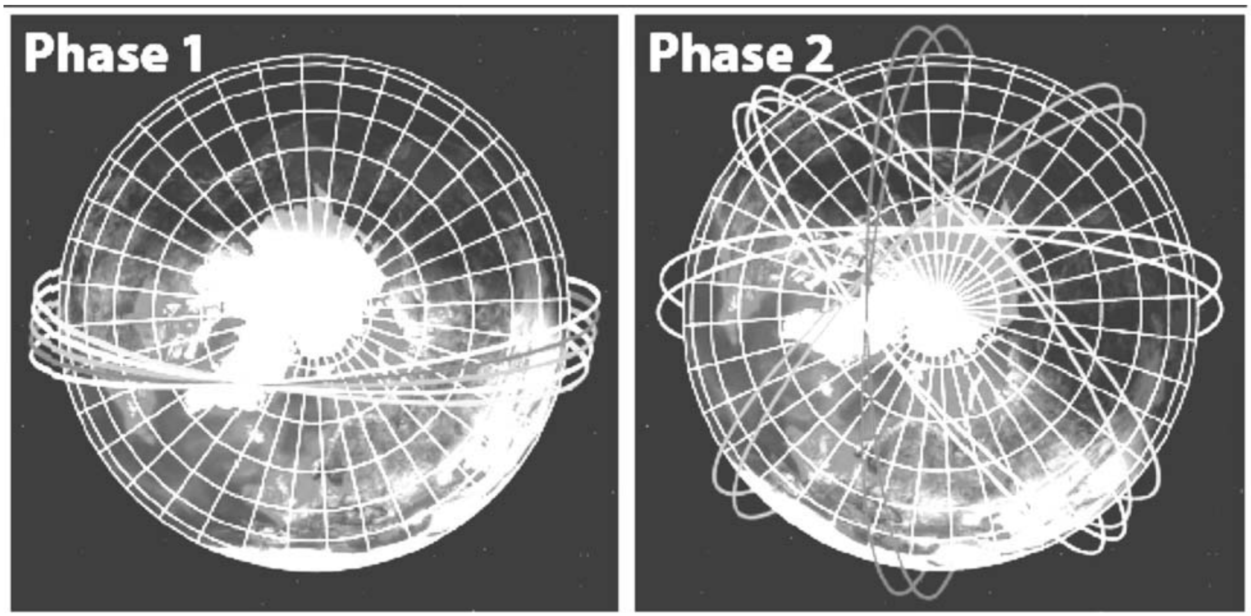

Figure 3: Phase 1 and Phase 2 HiDEF Orbit Configurations

Since the Earth's magnetic poles are predicted to be inclined at approximately 11.6° to the axis of rotation[7] during the HiDEF mission lifetime, the "nominal" or centered inclination of the orbits was selected at approximately 78.4°. In the upper ionosphere, magnetic field follows along lines of equi-potential, and can be measured along a wide range of altitudes varying between 250 and 800 km with a mean altitude of approximately 600 km.[8,9] This conditions prescribes the nominal initial deployment altitude for the HiDEF constellation. For the HiDEF mission, payloads will be deployed at varying conditions centered on about 78.4° inclination and 600 km altitude in order to achieve the constellation dispersion required for Phase 2 of the mission.

The key to achieving the proper constellation dispersion is selecting the deployment inclination and altitude perturbations to produce differential precession rates that globally disperse the constellation within the mission's 18-month time frame. To second order accuracy, the precession rate of the orbit right ascension of the ascending node (RAAN) is described by Eq. 2:

$$\dot{\Omega} = -\left[\frac{3}{2}\frac{\sqrt{\mu}\cdot\left(J_2 R_e^2\right)}{a^{7/2}\left[1-e^2\right]^2}\right]\cos(i) \qquad (2)$$

For two adjacent circular orbits with altitudes h and $h+\Delta h$ and inclinations i and $i+\Delta i$, the differential rate of RAAN precession can be approximated by:

$$\Delta\left[\dot{\Omega}\right] = \left[\frac{3\sqrt{\mu}}{2}\left(\frac{J_2 R_e^2}{\left(R_e+h\right)^{7/2}}\right)\right]\left[\sin(i)\cdot\Delta i + \frac{7}{2}\cdot\cos(i)\frac{\Delta h}{\left(R_e+h\right)}\right] \qquad (3)$$

Clearly, Eq. 3 shows that both orbit inclination and mean altitude can be used to control the differential rates of precession; but that at high inclinations, inclination angle is most effective. For the HiDEF mission, the inclination angle perturbation was the primary parameter used to control the precession rate. Altitude increments were selected to ensure that each orbit will be unique and will never cross the other orbits at the same altitude. This altitude restriction prevents the possibility of E-Sat collisions within the constellation.

Other restrictions on altitude were required to ensure that the lowest grouping of satellites would have sufficiently slow orbit decay to allow for a 24-month lifetime; the highest grouping of satellites would de-orbit within a 25-year time limit as mandated by internationally accepted NASA standards.[10,11]

A preliminary deployment orbit trade analysis determined that deploying 18 E-Sats at 5 different orbital altitudes and inclinations resulted in an orbit progression that was well suited for the HiDEF mission. Figure 4 shows a typical snapshot of the fully-mature Phase 2 constellation orbits and satellite orientations relative to the magnetic north pole. Superimposed on the graph are the principal science areas of interest (grey shading). The plot scale is in degrees from the north-pole in magnetic coordinates. The resulting deployment orbit inclinations and mean altitudes are listed in Table 1.

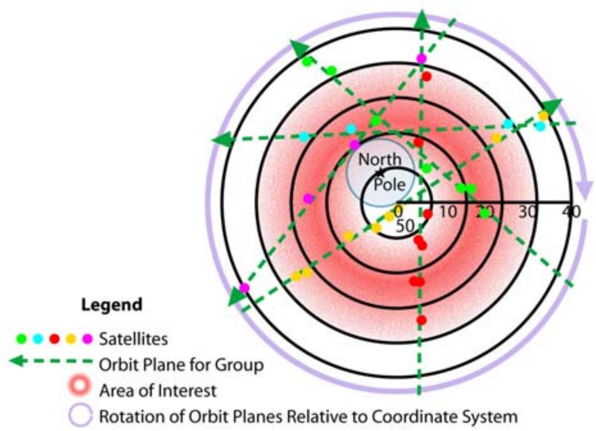

Figure 4: HiDEF Constellation Orientation Relative to Magnetic North Pole.

HiDEF Constellation Progression Predictions

Figure 5 shows the predicted orbit progression using these initial parameters. During the first month, the cluster stays tightly-packed and satisfies the requirements for the Phase 1 science mission. After the first month the constellation begins to spread. After 3 months, the cluster is still well-packed and is still capable of meeting the Phase 1 science objectives. After 6-months the constellation covers approximately 50 percent of the globe and the mission begins the transition from the Phase 1 to the Phase 2 science objectives. Full global distribution occurs approximately 12 months after deployment and lasts for an additional 6 months. In the 18-month configuration, approximately 25% of the constellation E-Sat members will be positioned at latitudes greater than 45 deg at any time.

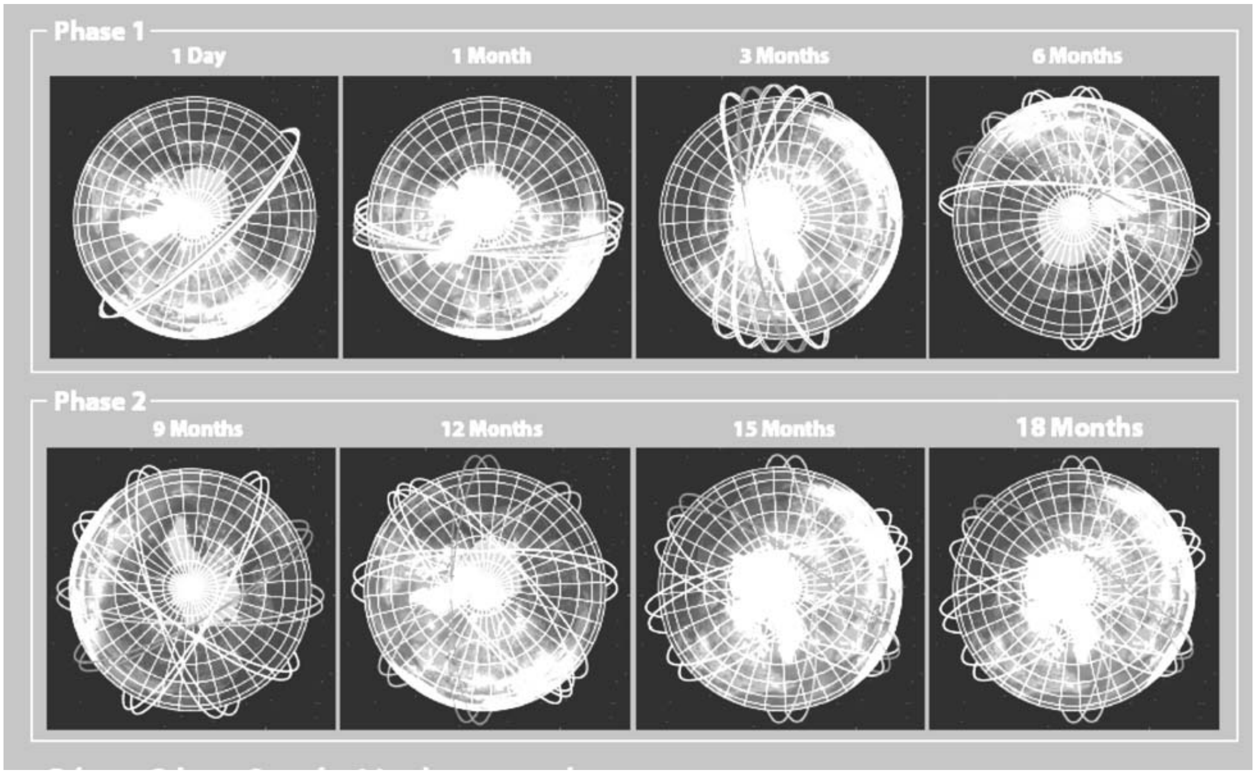

Figure 5: HiDEF Constellation Orbit Progression Prediction

Table 1: Deployment Orbit Parameters (July 2012 Launch)

Satellite Orbit Group	Release Altitude	Semi-Major Axis	Inclination	Initial RAAN Precession Rate
ID#	*km*	*km*	*degrees*	*degrees/day*
1	515	6884 – 6902	77.0°	1.70 to 1.72
2	555	6924 – 6942	77.7°	1.58 to 1.59
3	595	6964 – 6982	78.4°	1.46 to 1.47
4	635	7004 – 7022	79.1°	1.35 to 1.36
5	675	7044 – 7063	79.8°	1.24 to 1.25

Right Ascension of Ascending Node:	277.5°
True Anomaly:	Varies by Satellite
Argument of Perigee:	Varies by Satellite
Eccentricity:	0.0003 to 0.0013

HIDEF LAUNCH AND DEPLOYMENT ANALYSIS

The analyses presented in the previous section determined the proper number of constellation elements and initial deployment orbits required to meet the scientific objectives of the HiDEF mission. This section will analyze deployment and launch options required to achieve the initial constellation distribution. Payload mass distributions, on orbit *ΔV*, and launch-lift requirements will be addressed. A launch and deployment CONOPS will be presented. An approximate mission deployment will be developed.

Spacecraft Deployment System

The E-Sats will remain unpowered until ejection from the spacecraft deployment system (SDS). Following orbital insertion, each E-Sat will autonomously power on and perform a system checkout, including attitude determination operations and the initiation of science data collection. The SDS encloses and secures all 90 E-Sats for launch. It incorporates an enhanced design based on the flight-proven CubeSat Poly Pico-sat Orbital Deployer (P-POD).[12] The P-POD is a standard deployment system that ensures all CubeSat developers conform to common physical requirements. The P-POD plays a critical role as the interface between the launch vehicle and CubeSats. Figure 6 depicts the P-Pod locations within the stacked layers of the SDS.

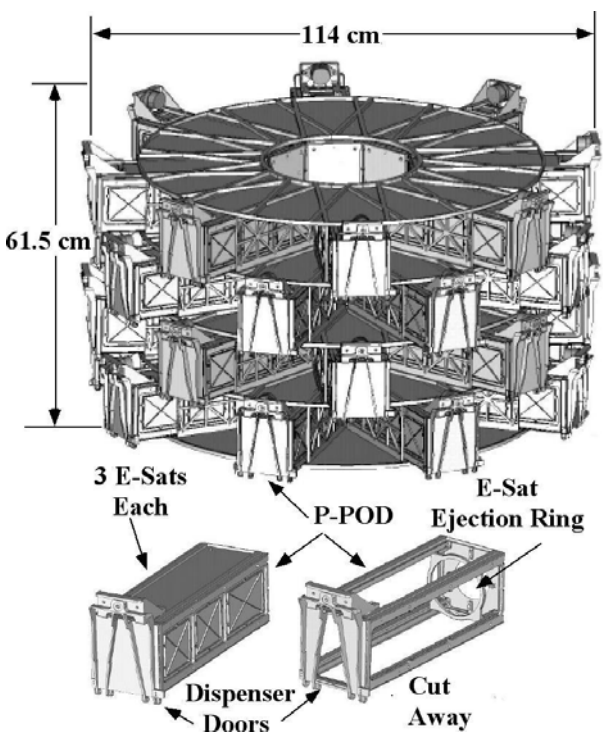

Figure 6: Satellite Deployment System

The SDS consists of 4 individual layers with each deck platforms containing up to 8 P-PODS. When fully populated, the SDS has a capacity for 96-E-Sats (24 P-Pods per deck). Each SDS layer is offset by 22.5 degrees from the adjacent layers. The modular avionics structure (MODAS), batteries, and wiring harness are mounted on the upper SDS deck. The HiDEF mission will use approximately 94% of the SDS payload capacity, using 30 P-POD dispensers, and 90 E-Sats. With appropriate mass contingencies, the estimated payload mass is 200 kg. Table 2 details the estimated HiDEF payload mass distribution estimates.

E-Sat deployment is initiated by releasing a P-POD door. A large, captured spring within each P-POD generates a *ΔV* of approximately 5 m/sec for deployment of 3 E-Sats. Each P-POD houses 3 E-Sats. These 3 E-Sats are then individually separated by smaller *ΔV's* imposed by captured springs located on the E-Sat structure rails. Within each of the 5 orbit groupings a total of 18 E-Sats are deployed. The collected deployment *ΔV's* helps to maximize the spread of E-Sats within the individual orbit deployment groupings and results in non-overlapping orbits. This deployment procedure minimizes the chances of individual E-Sat collision.

Table 2: HiDEF Payload Mass Distribution

Item	Unit Mass, kg	Qty.	Mass Contingency	Total, kg
P-POD	1.17	30	10%	38.61
Structure	20.18	1	20%	24.22
MODAS, Batteries	4.60	1	20%	5.52
Harness	1.85	1	20%	2.22
E-Sat	1.075	90	0%	96.75
			Total	**167.32**

The deployment sequence from the SDS was chosen to maximize the precession between P-POD groups, and to balance the disturbance torques. The velocity imparted by the P-POD is of constant velocity, but can change in orientation based on the orientation of the SDS. The velocity can be in the local vertical, local horizontal, or out of plane direction as shown in Figure 7.

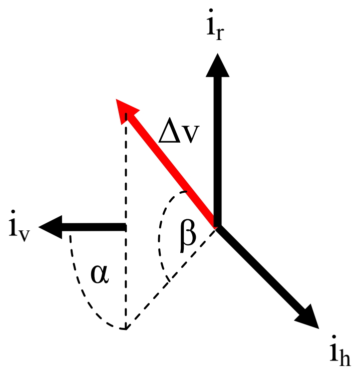

Figure 7: SDS Deployment Velocity

Assuming a circular orbit before PPOD deployment the velocity is given by equation 4:

$$v = \sqrt{\frac{\mu}{r}} \tag{4}$$

The velocity after PPOD deployment can be found from equation 5 where Δ*v* is the PPOD eject velocity:

$$\vec{v}_1 = \begin{bmatrix} \Delta v \sin\beta \\ v + \Delta v \cos\beta \cos\alpha \\ \Delta v \cos\beta \sin\alpha \end{bmatrix} = \begin{bmatrix} v_r \\ v_v \\ v_h \end{bmatrix} \tag{5}$$

Several of the classical orbital elements for the orbit after P-POD ejection can now be solved for using equations 6 through 9:

$$a = \frac{\mu r}{2\mu - v_1^2 r} \tag{6}$$

$$h = r\sqrt{v_v^2 + v_h^2} \tag{7}$$

$$p = \frac{h^2}{\mu} \tag{8}$$

$$e = \sqrt{1 - \frac{p}{a}} \tag{9}$$

These orbital elements can be substituted into equation 2 which is repeated below to calculate the precession rate of the new orbit:

$$\dot{\Omega} = -\left[\frac{3}{2}\frac{\sqrt{\mu}\cdot\left(J_2 R_e^{\,2}\right)}{a^{7/2}\left[1-e^2\right]^2}\right]\cos(i) \tag{2}$$

The precession rate is now a function of only 2 unknown parameters α and β which must be selected. A surface was created representing all possible values of α and β. This was generated for the 515 km altitude and 77° inclination orbit to obtain numerical values. Figure 8 shows that as β was varied from zero the differential precession rates between satellites decreases. The maximum and minimum precession rates are obtained when β is zero; therefore, it is desirable that the P-POD deployment velocity lie entirely in the horizontal and out-of-plane directions.

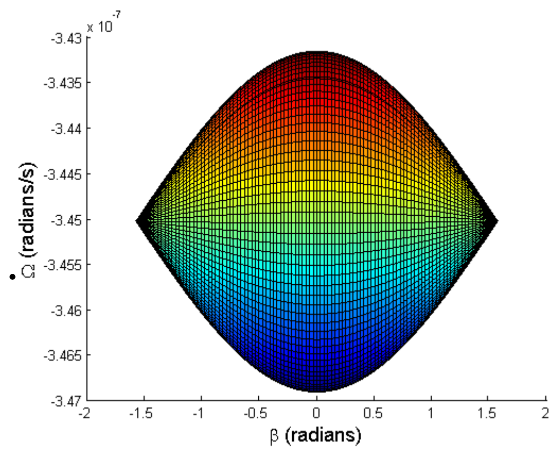

Figure 8: Surface of Precession Rates after Deployment

The angle the deployment velocity make with the local horizontal must be selected to coincide with the angles the PPODS are oriented in the SDS. As shown in Figure 9, the maximum rate of precession occurs when the deployment velocity is oriented at an angle near 35° to the local horizontal and the minimum occurs at an angle near 215°. The four remaining angles were selected to maintain equal precession rates and to minimize disturbances.

Figure 10 depicts the resulting initial deployments orbits relative to the payload dispenser in the local vertical/local horizontal (LVLH) coordinate system.

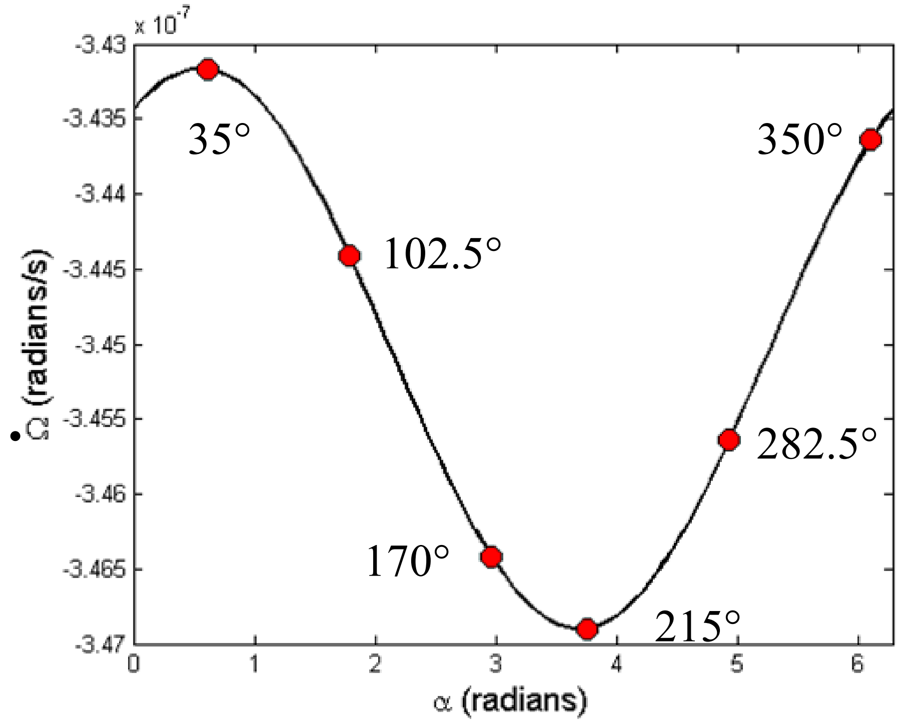

Figure 9: Surface of Precession Rates after Deployment

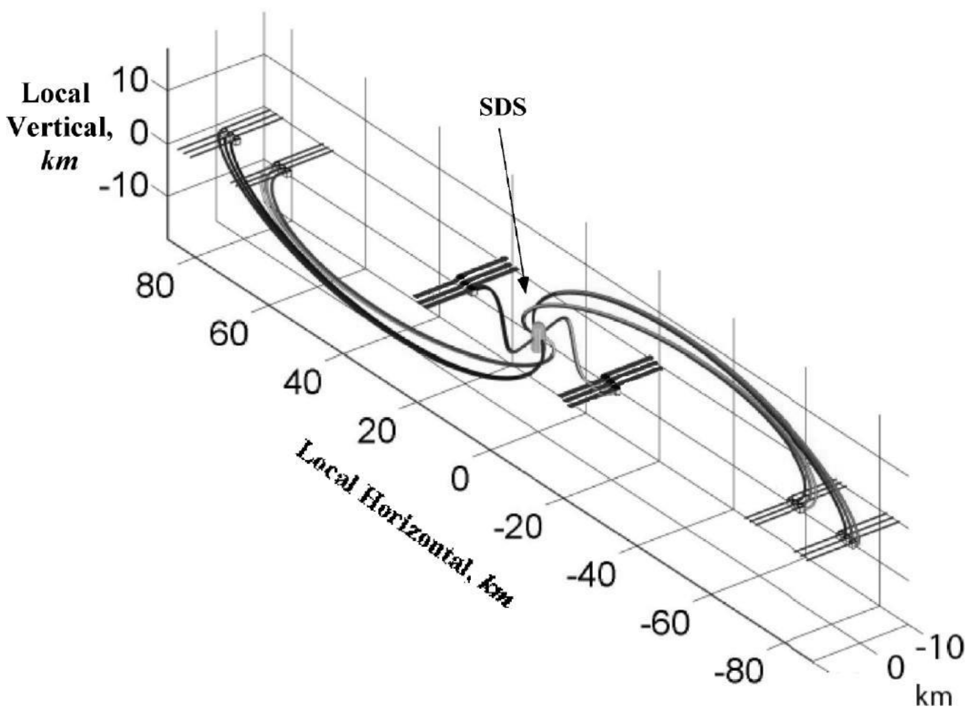

Figure 10: Trace of Initial E-Sat Deployment Orbits - 18 Total (LVLH Coordinates)

SUMMARY AND CONCLUDING REMARKS

Obtaining electric field measurements at high spatial and temporal resolution in the high-latitude aurora and polar-regions in both hemispheres is critical to understanding the effects of small-scale disturbances on the global evolution of the Earth thermosphere. To collect these critical data, a consortium of organizations collaborated on a proposal to create a globally dispersed network of sensors that would map Earth's high-latitude global electric field. The High-latitude Dynamic E-Field (HiDEF) Explorer will observe poorly understood high-latitude magnetosphere-ionosphere-thermosphere phenomena. The mission seeks to address 3 critical science areas: 1) defining the contribution of small-scale turbulent E-fields to the larger-scale electro-dynamical processes; 2) understanding how the high-latitude E-fields evolve during disturbed conditions; and 3) detecting high-latitude sources for mid- and low-latitude penetration E-fields.

The first research area requires obtaining high-resolution *in situ* electric field measurements at small temporal and spatial scales. The second and third research areas require obtaining measurements of the high-latitude electrical field on broader global-scale. The proposed project used well-established pico-satellite technologies for deployment of a constellation of 90 satellites with integrated electrical field sensing booms. Each satellite (E-Sat) was designed to have mass of approximately 1.12 kilograms. The individual E-Sats would be deployed using a satellite deployment system based on the Cal Poly P-POD dispenser design. With appropriate mass contingencies, the estimated payload mass is 200 kg.

A key feature of this mission is the placement of the constellation in a set of closely-aligned, high-inclination orbits with altitude and inclination differences that produce a precession difference. This will provide the constellation with momentum to naturally disperse and to provide global E-field coverage. Eventually, the orbit precession will lead to more than 90º of separation between orbital ascending node longitudes.

For the HiDEF mission, a preliminary set of 5 deployment orbits were selected to de dispersed about 79 degrees inclination and 600 kilometers mean altitude. The preliminary orbit set starts at 515 km mean altitude and increments upward in 40 km increments. The inclination angles start at 77 degrees and increments upward in 0.7-degree increments. These orbits were selected to provide good coverage about the Earth's magnetic poles and to be centered with the mid layers of the ionosphere. Minimum and maximum altitudes were selected to insure a minimum constellation lifetime of 24 months, and allow de-orbit compliance with NASA orbital debris regulations. The deployment will occur from a single launch vehicle. The deployment method has been selected to ensure each satellite was delivered to a distinct non-overlapping orbit.

The feasibility of the HiDEF mission was established by the analyses presented in this paper. This constellation of E-Sats would provide an unprecedented continuous stream of global *in situ* ionosphere E-field data. These data will fill in the missing portions of the last critical link in the Earth-Sun connection. The HiDEF mission will provide a significant complement to NASA's Heliospheric Great Observatory mission.

References

1. Anon., Sun-Solar System Connection, Science and Technology Roadmap 2005-2035, National Aeronautics and Space Administration, http://sec.gsfc.nasa.gov/SSSC_2005Roadmap.pdf , [Retrieved 06 May, 2008].
2. Ridley, A. J., Deng, Y., and Toth, G., The Global Ionosphere-Thermosphere Model, Journal of Atmospheric and Solar-Terrestrial Physics, Vol. 68, No. 5, May 2006, pp. 839-864.
3. Idenden, D. W., Moffett, R. J., Quegan, S. and Fuller-Rowell, T. J., Time-Dependent Convection at High Latitudes, Annales Geophysicae, Vol. 14, No. 11, Feb. 1997, pp. 1159-1169.
4. Smith, R. W., The Global Effect of Small-Scale Thermospheric Disturbances, Journal of Atmospheric and Solar-Terrestrial Physics, Vol. 62, No. 11, Nov. 2000, pp. 1623-1628.
5. 5. Codrescu, M. V., Fuller-Rowell, T. J., and Foster, J. C., On the Importance of E-field Variability for Joule Heating in the High-Latitude Thermosphere, Geophysical Research Letters, Vol. 22, No. 17, September 1995, pp 2393-2396.
6. Lotko, W., The Magnetosphere-Ionosphere System from the Perspective of Plasma Circulation: A Tutorial, Journal of Atmospheric and Solar- Terrestrial Physics, Vol. 69, No. 3, March 2007, pp. 191-211.
7. Merrill, R T., and McElhinny, M. W., The Magnetic Field of the Earth, Paleomagnetism, the Core, and the Deep Mantle, 3rd ed. Academic Press, San Diego, CA, 1998, Chapt. 1.
8. Abe, T., Whalen, A.W. Yau, A. W., Watanabe, Sagawa, S. E., and Oyama, K. I., Altitude Profile of the Polar Wind Velocity and its Relationship

to Ionospheric Conditions, Geophysical Research Letters, Vol. 20, No. 24, pp 2825-2828, 1993.

9. Bordeau, R. E., Science, Vol. 148. No. 3670, April 1965, pp. 585-594.

10. Anon, Guidelines and Assessment Procedures for Limiting Orbital Debris, NASA Safety Standard NSS-1740.14, 1995.

11. Anon, Process for Limiting Orbital Debris, NASA Technical Standard NASA-STD-8719.14, 2007.

12. Nason, I., Puig-Suari, J., Twiggs, R., Development of a Family of Picosatellite Deployers Based on the CubeSat Standard, IEEE Xplore, 0-7803-7231-X/01, 2002,http://cubesat.atl.calpoly.edu/media/Documents/Papers/ppod_paper.pdf, [Retrieved 09 May 2008].