AMPERE AND GEOSCAN: UTILIZING COMMERCIAL SPACE INFRASTRUCTURE FOR DISASTER MITIGATION, PLANNING AND RESPONSE

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ABSTRACT

The past decade has seen a confluence of events that push geoscience into a new era enabling vast advances in space hazard characterization and monitoring. One primary direction for research of our Earth environment consists in taking a view of the Earth-atmosphere-geospace as a complete system. Without the global system perspective we cannot tackle many open questions and policy makers cannot make actionable decisions without real-time global coverage of key space measurements. A fundamental impediment to advance in this area is the paucity of observations, particularly in space. Fortunately, the dramatic increases in the number of commercial space platforms and technological advancements in commercial off the shelf (COTS) components and instrumentation enable the deployment of global arrays of instrumentation at a fraction of the historic cost enabling observational advances required to tackle system-level science questions. The cost reduction results from (a) using commercially developed instruments that are repurposed from their original consumer and industrial uses, such as GPS, inertial measurement, and magnetometers, and (b) new low cost access to space via commercially available hosted payloads, sub-orbital flights, and CubeSats. We will present recent research on this topic in general, and focus specifically on how the AMPERE program and GEOScan initiative can provide affordable breakthrough space weather data for communications, GIC's and the radiation environment. AMPERE is in final development and has already shown the capability to time resolve storm-time dynamics and substorm onset showing great promise for providing warning for and monitoring of geomagnetic storm hazards including GICs. GEOScan proposes to fly a full constellation of radiation dosimeters and GPS receivers for 3D imaging of the ionosphere and plasmasphere to 3 TECU accuracy and 2D imaging of radiation belt ions and electrons.

INTRODUCTION

The heartbeat of our Earth is set by the rising and setting of the sun. This influence, along with the inter-connected nature of geoscience subsystems, means that local dynamic processes on sub-diurnal scales do not act in isolation, but aggregate to influence other subsystems on global scales. The GEOScan facility is designed to meet these system science measurement challenges by expanding the frontier of our understanding about Earth and geospace as a complete and interconnected system.

The instrument suite designed to populate the Iridium NEXT constellation will address pressing questions about Earth's current state of energy balance and climate change, the current state of carbon balance, and nature's ability to sequester increasing CO_2. In addition, this constellation of hosted payloads can address how the large-scale transport of water and atmospheric mass affect, and respond to, changes in climate and water cycle on diurnal to annual timescales. The global response of the geospace environment to changes in solar activity can also be explored as well as the global response of the biosphere to the diurnal cycle.

HOSTED PAYLOADS ON THE IRIDIUM NEXT SATELLITE CONSTELLATION

In its new generation of satellites, Iridium has introduced a hosting concept for small scientific payloads of up to 5 kg. Each NEXT satellite is being developed with the ability to accommodate hosted payloads on its nadir and/or RAM facing surfaces. A standard interface between the hosted payload and Iridium NEXT satellite has been defined in the Secondary (Hosted) Payload Specification, which is part of the Iridium NEXT System Performance Specification.[1,2]

The 66-satellite main constellation (+6 in-orbit spares), configured in 6 orbital planes with 11 evenly spaced slots per plane, provides continuous global coverage as demonstrated by the RF footprints in Figure 1. This is achieved though cross-linked satellites operating as a fully meshed network that is supported by multiple in-orbit spares to provide real-time data downlink to the Iridium operated ground station network. The constellation has a design lifetime greater than 10 years in a polar orbit at 780 km with an inclination of 86.4°.

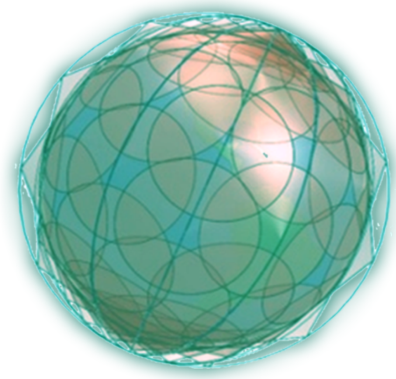

Figure 1. Iridium NEXT satellite constellation RF footprints.

Each Iridium NEXT satellite has a total hosted payload allocation of 50 kg in mass, 30 × 40 × 70 cm^3 in volume, and 50 W of average power. GEOScan is designed to fit into a hosted payload module, which has been allocated 5 kg in mass, 14 × 20 × 20 cm^3 in volume, and 5 W of average power. In addition to these resources, the Iridium satellite design provides for an unimpeded 75° half-angle nadir field of view, nadir pointing control to within 0.35° (pointing knowledge within 0.05°), spacecraft altitude control within 10 m, and spacecraft position control within 15 km (position knowledge within 2.2 km).

Table 1: Iridium NEXT hosted payload specifications and resource allocation for GEOScan

Iridium NEXT Hosted Payload Specifications		Iridium NEXT Resource Allocation for GEOScan
Weight	50 kg	5 kg
Payload Dimensions	30 × 40 × 70 cm^3	20 × 20 × 14 cm^3
Payload Power	50-W average (200-W peak)	5 W (average), 10 W (peak)
Payload Data Rate	<1 Mbps (orbit average) 100 kbps (peak)	10 kbps (orbit average), 100 kbps (peak)

GEOScan System Sensor Suite

The GEOScan system sensor suite is comprised of 6 instruments packaged to take advantage of the Iridium NEXT hosted payload allocation. This suite of instruments is designed to be batch manufactured to meet the cost and schedule constraints of the Iridium NEXT launch schedule and reduce costs through volume procurement, manufacture, integration, and test. The conceptual packaging of the suite of sensors is shown in Figure 2.

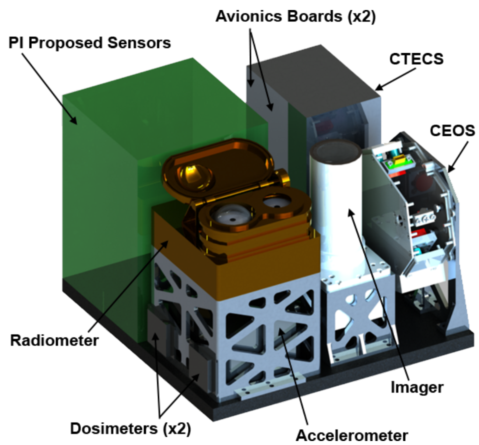

Figure 2. GEOScan's payload design uses a modular configuration for efficient assembly and testing. It also includes additional mass, power, data, and volume allocation for sensors proposed by scientific and government stakeholders.

GPS: The Compact Total Electron Content Sensors

The Compact Total Electron Content Sensor (CTECS) is a GPS instrument that utilizes a Commercial-Off-The-Shelf (COTS) receiver, modified firmware, a custom designed antenna, and front-end filtering electronics to provide measurements of total electron content and ionospheric scintillation. Originally designed for a cubesat platform, CTECS has flown on the PicoSatellite Solar Cell Testbed 2 (PSSCT-2) mission in 2011. It is also manifested on the two-cubesat Space Environment NanoSat Experiment (SENSE) mission scheduled for launch in 2013. Noting that CTECS on PSSCT-2 successfully demonstrated for the first that a COTS receiver with modifications could perform as an occultation sensor on a spacecraft. In a 24-h period, a single GPS occultation sensor can provide several hundred occultations or total electron content (TEC) measurements distributed around the globe. Even with this number of occultations, latitude and longitude sectors still remain that are under-sampled at any given instant because of the geometry of the GPS constellation. GEOScan's 66 CTECS will provide an unprecedented continuous global snapshot of Earth's ionosphere and plasmasphere. The data will allow us for the first time to see the temporal and spatial evolution of the ionosphere/plasmasphere from 80-20,000 km with 5-min temporal resolution and 10 km height resolution with a measurement error < 3 TECU globally.

Furthermore, the gravity field will be derived using the satellites' trajectories determined from the onboard CTECS GPS receivers, as well as from ancillary data from the MEMS accelerometers and Iridium star cameras. In short, the positions and velocities determined from the CTECS receiver can be differentiated to reveal the accelerations caused by the various dynamic (mass transport) processes that occur at the surface and in the atmosphere. By accurately tracking the orbit of each Iridium NEXT satellite and removing non-gravitational influences, we can infer changes in Earth's gravity field and learn about the processes that create these changes (e.g., large-scale water mass movement). Global diurnal water motion maps at 1000 km resolution, accurate to 15 mm of equivalent water height can be created on sub-weekly time scales with a time-integrated monthly resolution that matches the Gravity Recovery and Climate Experiment (GRACE) satellites.

Radiometers

Climate change results from a less than 1% imbalance between incoming solar energy and energy reflected or re-radiated back into space. Currently, we measure incoming solar radiation to better than 0.03%; however, total outgoing radiation (TOR) has never been simultaneously, globally sampled and is accurate to just 1% – not enough to resolve this imbalance. Although these measurements are critically important to understanding and predicting changes in our climate, obtaining them was insurmountably impractical … until now.

Constellation measurements are now available at a fraction of the cost of a traditional satellite mission. From exploiting hosted payload opportunities on commercial satellites, like Iridium NEXT, to launching inexpensive cubesats, we can now affordably make global synoptic measurements of critical scientific and societal importance. This constellation, each with a 127° field-of-view radiometer, will provide a global view of the Earth's **total out-going radiation (TOR)** every 2 hours with better than 0.15% accuracy. The shortwave channel (0.2-5 micron) and total channel (0.2-200 micron) along with the longwave (determined form differencing the two channels) is calibrated to a precision of 0.09 Wm^{-2} with an accuracy of 0.3 Wm^{-2} using a NIST traceable calibration standard.

Each channel contains two bolometers: one looks outward, monitoring incoming radiation from the Earth, Sun, or space; the second looks inward, monitoring the radiance temperature of the instrument. Each bolometer pair forms the opposite arm of a resistive bridge circuit.

Both radiometer channels, total + shortwave, have a cavity absorber and a precision aperture that defines a wide field of view. The shortwave channel also has an IR-grade fused silica domed window defining the shortwave bandpass on the outward-looking bolometer. The spectral response of the Total channel is limited only by that of the absorbing cavity.

We currently baseline a black painted cavity absorber but are investigating the use of vertically aligned carbon nanotubes (VACNT) as a flat absorber to replace the cavity. APL has created a variety of VACNT forests for terrestrial and space-based instrument applications. VACNTs are the blackest, most spectrally flat substance known and would improve the responsivity of the radiometer by a factor of two.

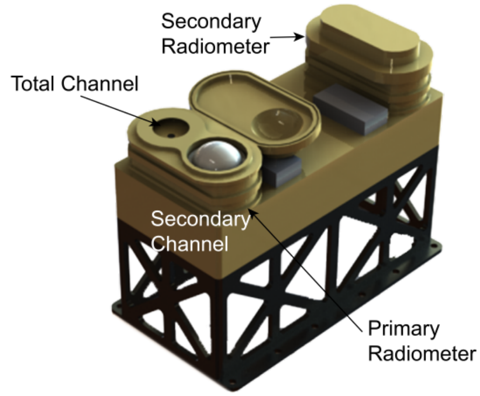

Figure 3. The radiometer's classic, simple design allows for a rapid development, yet accommodates 21st century technologies like carbon nanotubes.

Payload Specifications	
Instrument Mass	1.3 kg
Size	18 x 8 x 7 cm
Power	1 W
Data Rate	1 kbit/s per satellite
Two Spectral Bands per Radiometer:	
a. Total	0.2–200 μm
b. Shortwave	0.2–5 μm
Accuracy	0.3 W/m^2

Spectrometer: Compact Earth Observing Spectrometer

The Compact Earth Observing Spectrometer (CEOS) consists of an exceptionally small crossed Czerny-Turner spectrometer, a linear CCD array, and read-out electronics. Its modular design allows for easy substitution of optical elements, electronics, and optical sensors to rapidly and confidently customize the optical performance to meet a wide range of science goals. This design provides spectral measurements from 200 to 2000 nm with approximately 1 nm spectral resolution from 200 - 1000 nm and 3 nm from 1000 - 2000 nm. The foreoptics design provides a 1° field-of-view, which allows 14 km resolution.

Imager: Multi-Spectral MicroCam

GEOScan's MMI is a visible to near-infrared wide-field-of-view imager that uses a STAR-1000 CMOS imaging 1024 × 1024 array. MMI will use custom-designed strip filters oriented in the across-track direction. This will allow the imager to be used in a push-broom mode. The attitude of the Iridium NEXT constellation will be carefully controlled because each of the satellites has cross-linked communication receivers and transmitters. MMI uses refractive optics and will have a field of view (FOV) of 33° × 33° to provide global coverage over a 2-h time interval. Each FOV footprint on the surface of the Earth is 465 km × 465 km. Images will be acquired every 29 s to provide continuous imaging in the along-track direction of the satellite. The trailing satellite in a given orbital plane lags the leading satellite by ~9 minutes. In this time interval, the relative drift in longitude between a spot on the Earth and Iridium is 250 km.

Dosimeter: Radiation Belt Mapping System

The Earth's radiation belts comprise several components including relativistic electrons and highly penetrating energetic protons. During geomagnetic storms energetic particle fluxes across the belts can dramatically vary by orders of magnitude on the timescales from minutes to days. GEOScan's dosimeter payload will image radiation belt dynamics, including relativistic electron micro-bursts, global loss to the atmosphere, and variations in geomagnetic cutoffs of solar energetic particles. For example, using the 0.1 Hz electron dose rate, locally precipitating microbursts can be distinguished in the time domain from quasi-trapped flux. Microbursts, which are thought to be caused by whistler-mode chorus waves are estimated to be intense enough to remove all previously trapped

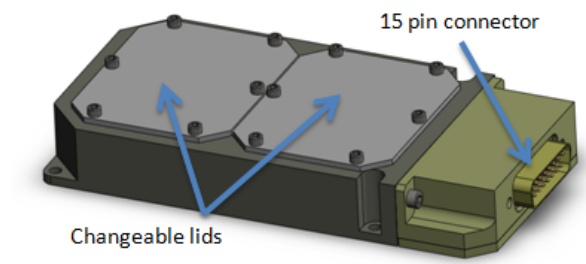

Figure 4. The GEOScan dosimeter payload Configuration.

Payload Specifications	
Geometric Factor	0.66 cm^2 sr
Resolution	14 μrad/count
Mass	300 g
Power	120 mW
Dimensions	05 × 2.5 ×.85 in

relativistic electrons from the radiation belts during a single day of magnetic storming. GEOScan dosimeters will provide first-of-a-kind quantification of the leading uncertainty in such loss calculations: the longitude extent of the precipitation. GEOScan dosimeters provide a significant broader impact for space weather by characterizing the geomagnetic storms that are a major contributor to spacecraft failure. For example, in 2003, 46 of the 70 spacecraft component failures were attributed to the October geomagnetic storm.

Each GEOScan payload will contain one pair of Teledyne micro dosimeters; one is an electron dosimeter with a 100-keV electronic threshold for registering a count, and the other is a proton dosimeter with a 3-MeV electronic threshold. A common thickness of shielding covers both dosimeters. Five unique lid-shielding choices will enable aggregating over multiple vehicles to obtain a dose-depth curve and electron and proton spectra. Shielding will be chosen to provide electron energy resolution from 0.3 to 5 MeV and proton resolution from 10 to 50 MeV. The dosimeter has more than sufficient dynamic range to measure the dose rate due to galactic cosmic rays at the geomagnetic equator for the most intense solar particle events and deep within the inner radiation belt.

Accelerometers: MEMS Accelerometer for Space Science

The MEMS Accelerometer for Space Science (MASS) is a micromechanical, silicon-based accelerometer with unprecedented sensitivity compared to current accelerometers of similar size and power that can be used for Earth science applications. Current space-based accelerometers on GRACE and Gravity field and steady-state Ocean Circulation Explorer (GOCE) require more power (tens of watts) and mass (+50 kg) than can be accommodated within the GEOScan payload allocation. GEOScan's approach utilizes a constellation of low-noise MEMS accelerometers, which would assist in aggregately measuring the variations in Earth's gravitational field as well as satellite drag for neutral density studies. Current commercial MEMS devices have demonstrated sensitivities in the 10 ng/rtHz range, with potential for 1 ng/rtHz – clearly suitable to compensate for the non-gravitational forces of 10^{-7} to 10^{-8} m/s^2. The performance of this class of MEMS accelerometers has shown a consistent white noise floor on the order of 10^{-11} g^2/Hz making the device ideal for gravimetric measurements.

CONSTELLATION SYSTEM SCIENCE

GEOScan employs a full constellation approach to answer outstanding system science questions about the Earth and remote sensing of space environment state variables. Equipping the full constellation provides homogeneity of observation, thus simplifying analyses and reducing error in inherently global calculations. This suitably dense, homogeneous network enables the use of modern reconstruction techniques to image state variables and persistent measurement of global change across a wide range of temporal and spatial scales.

GEOScan Climate Science-Measuring Earth's Energy Balance

GEOScan addresses Earth's current state of energy balance and climate change via a homogeneous constellation of satellites observing the Earth 24/7 with hourly temporal resolution and spatial resolution ranging from 500 km for the broadband radiometer to 450 m for the imager. This revolutionary coverage will enable discoveries concerning many open science questions critical to our ecosystems and our habitability -- notably how highly spatially and temporally variable phenomena aggregate to contribute to global change, and how global long-term changes affect smaller scales and surface processes where human beings live and work.

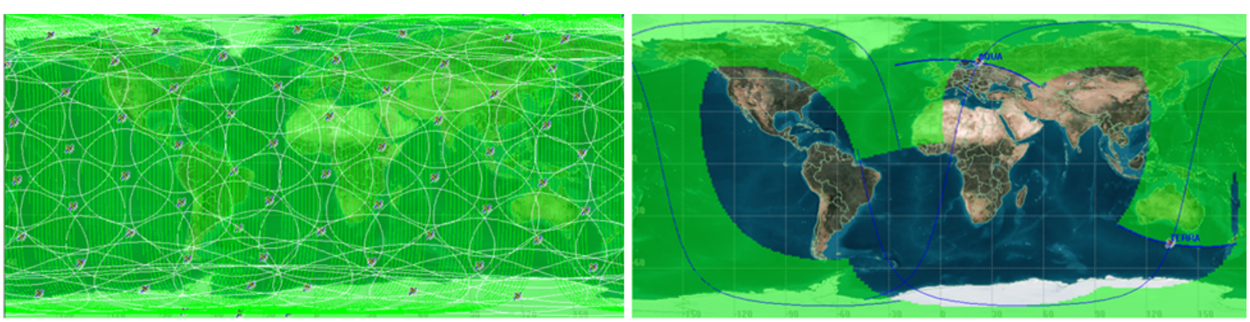

Figure 5. GEOScan achieves the science goals by providing superior spatial, temporal, angular, and local time coverage. Spatial coverage comparison between CERES on Terra and Aqua (right) and GEOScan's bolometer radiometer (left) for 1 hour. In a single hour, GEOScan will make 3600 global TOR samples, providing a statistical noise reduction factor of 60 every hour. After 2 hours the Iridium NEXT orbital planes completely intersect, providing 100% independent yet massively oversampled TOR, from all angles.

GEOScan's most central climate instruments are extremely well calibrated radiometers, which will measure, for the first time, the Earth radiation imbalance (ERI). ERI is the difference between incoming radiation from the Sun and the TOR. TOR is the sum of reflected solar radiation and emitted longwave radiation. How ERI and TOR change regionally and globally, and on timescales from hourly to annually, is critical for understanding climate change.

According to climate models, current climate change, including the dramatic melting of Arctic sea ice and Greenland glaciers, results from an ~0.1–0.2% imbalance between incoming solar energy and TOR. Currently, space instruments measure incoming solar radiation to >0.03%. However, TOR has never been simultaneously, globally sampled, and is accurate to no better than 1%—not good enough to resolve the imbalance predicted by climate models. GEOScan's global coverage of highly calibrated radiometers (0.3 Wm^{-2}) will measure TOR at the necessary 0.1% accuracy level. See Figure 5.[3,4,5]

GEOScan's time-variable gravity measurements focus on the large-scale, high-frequency spectrum of the gravity field that GRACE and other dedicated gravity field missions inherently cannot observe. These other missions cannot observe the high-frequency variations solely because of the limited sampling possible resulting from single satellite ground track (or satellite pair in the case of GRACE) measurements. The error caused by under sampling (independent of measurement accuracy) dominates any gravity solution at the daily to weekly timescales for a small number of satellites. This highlights the fact that with only one satellite pair, higher spatial resolution compromises temporal resolution and vice versa; the only way to improve both is to dramatically increase the number of satellites involved. GEOScan, with its 66-satellite constellation approach, addresses this short-coming in traditional gravity science investigations. The GPS measurements will track the orbits of the

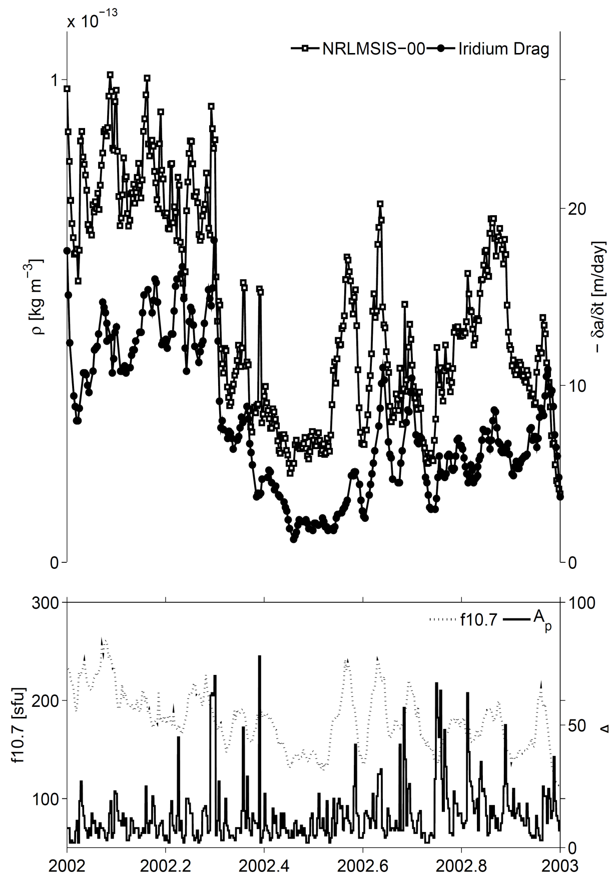

Figure 6: Drag sensed by an Iridium satellite compared with neutral density from an empirical model. The bottom panel shows the geomagnetic and solar radiation flux inputs that drive global thermospheric densities.

satellites to an accuracy of 2-3 cm, which, along with the data from the MEMS accelerometers, makes it possible to recover large-scale (>1000 km) gravity variations, which result mainly from the large scale movement of water mass.[6]

Measuring Total Atmospheric Densities with the IRIDIUM Constellation

Satellite drag is the predominant underspecified orbital perturbation in low-earth orbit. Changes in thermospheric density caused by geomagnetic storms can have a significant (up to >300%) impact on satellite drag even as high as 800 km altitude. Such high-latitude density perturbations have been reproduced successfully using assimilative mapping of ionospheric electrodynamics (AMIE), which are driven by data such as magnetometer perturbations provided by AMPERE on Iridium[7] as well as other ground and space-based data sources[8]. In addition to specifying high latitude energy inputs, the Iridium constellation of satellites also provides an unprecedented opportunity to simultaneously measure total thermospheric mass-densities in 12 equally distributed local solar-time sectors. This provides a way to validate and improve high latitude physics-based density specifications driven by AMPERE data, especially as these specifications are extended from 500 km into the exosphere.

The Iridium measurements are made via observations of changes in orbital parameters of each satellite. One such parameter is the semi-major axis. Although it is not the optimal parameter for resolving neutral density information from orbits[9], it nevertheless provides a preliminary look at the atmospheric drag experienced by Iridium satellites. Figure 6 shows the semi-major-axis perturbation observed by one of the Iridium satellites compared with the modeled orbit-averaged density at the satellite location over the course of a year. The model used is the NRLMSISE-00 empirical thermosphere and the results correlate very well with observed Iridium orbital perturbations. Much of the temporal variability in the observed drag is caused by changes in the local-solar time of the satellite orbit as well as seasonal changes in thermospheric density. Solar-radiation pressure and changes in ballistic coefficient caused by changes in spacecraft orientation have not yet been removed and will be addressed as a part of future work. However, it is already apparent that sharp peaks in the F10.7 (solar EUV flux proxy) do correlate to spikes in Iridium drag as well. This provides the motivation for future work to derive neutral densities from the Iridium constellation.

Transformational Space Weather Nowcasting and Forecasting with the GEOScan Constellation

Significant progress has been made in the study of the Earth's geospace environment over the last few decades. We have a firmly established understanding of the system dynamics on a climatological basis along with a basic understanding of the universal physics of small-scale processes of waves, instabilities, magnetic reconnection, and energetic neutral atoms (ENAs). Yet accurate *nowcast*, much less forecast, of the details of individual space weather events remains elusive. We lack an understanding of the fundamental global properties of our system, such as determining what is the total energy input into the thermosphere, whether Hall or Pederson currents are primarily responsible for auroral current closure, and which mechanisms dominate radiation belt losses and their longitudinal extent.

Nowcasting and forecasting the global electron density field for space weather applications are difficult research operational challenges that have not yet been met. Operational requirements for electron density [Air Force, *IORD-II*] include profiles of electron density from ~80 – 1500 km altitude, with ~ 5 km vertical resolution, and ~ 50-100 km horizontal resolution with errors in electron density < 10%. That is a global 3D electron density field from 80-1500 km altitude with 5 km vertical resolution and 50-100 km horizontal resolution. First principle models cannot achieve such resolutions and accuracy. Data assimilative models can achieve all the above requirements, but *only with sufficient amounts of data.* In order to meet such stringent requirements over the entire globe, all the time, it is clearly necessary to have continuous global data coverage. This data coverage must be sufficient to sample the entire ionospheric profile with the required vertical resolution, and have the necessary horizontal resolutions. No existing data set, nor even combination of existing data sets, can meet this requirement. Thus, while in principle we have the theoretical understanding and numerical tools in place to provide required global nowcasts and forecasts of electron density, we do not have the necessary observational data. In addition to ionospheric nowcasting, there is a need for imaging the plasmasphere on a global, temporally updating scale. Plasmaspheric imaging is important since plasmaspheric densities impact the physics of the radiation belts. Plasmaspheric imaging to 20,000 km combined with radiation belt mapping of energetic electrons and protons will allow us to understand which loss processes dominate at different temporal and spatial scales. However, up until now there are almost no available direct measurements of plasmaspheric density.

GEOScan provides a transformative capability by providing the global data coverage necessary for the aforementioned investigations. GEOScan radio occultations will sample the ionosphere from 80 km altitude to the IRIDIUM satellite altitude of 780 km, Topside TEC observations provide information from the satellite altitude to the altitude of the GPS constellation (~ 20,000 km). Each GEOScan satellite will continuously monitor 10-15 topside TEC measurements to different GPS satellites, providing an almost overwhelming amount of topside and plasmaspheric data that can be used in tomographic imaging algorithms to obtain accurate, time evolving images of plasmaspheric density. For the radio occultations, each GPS receiver sees ~ 3 occultations at a time. Each occultation lasts ~ 1 minute. Over a 5 minute period we have a total of 66 × 3 × 5 = 990 occultations / 5

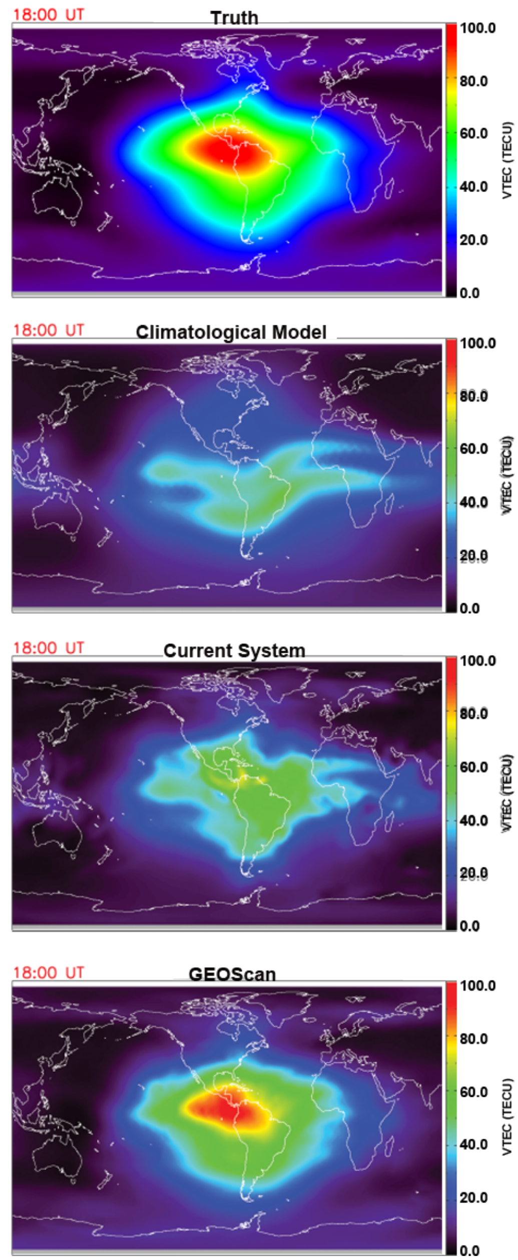

Figure 7. GEOScan tomographic imaging will fundamentally change our ability to understand geospace plasma dynamics. The top plot shows TIME-GCM simulated ionosphere for the geomagnetic super storm on 20 November 2003, treated as "truth" for simulating our observing system. This event is a strong "weather" departure from climatological predictions (IRI panel). The third panel shows that our existing ground-based GPS is grossly inadequate for imaging this event, whereas GEOScan observations alone (bottom panel) accurately capture the global dynamics of the geospace environment. The RMS TEC errors of the simulation shown are: IRI-16 TECU, ground-based GPS – 11 TECU, GEOScan only – 2.8 TECU.

minute period. While this data alone only provides ~ 600 km horizontal resolution, when combined with the copious amounts of ground

GPS TEC data available (currently > 4000 sites and growing), we can easily achieve the required horizontal resolutions necessary to meet Air Force IORD-II requirements. A beautiful aspect of this constellation design is global continuous data that can be streamed to ground systems in near real-time. This allows, for the first time, global high-resolution, high accuracy nowcasts of electron density to be provided continuously in time. This is accomplished using global tomographic or data assimilation imaging methods such as Ionospheric Data Assimilation Four Dimensional (IDA4D).[7,8,9] When combined with first principle models, where the global density field is used to re-initialize the model, it becomes possible to provide accurate forecasts that are only limited by the accuracy of the forward model.

To illustrate the transformational ionospheric imaging capability of GEOScan, Figure 7 presents results from a GEOScan tomographic simulation experiment. As a data source, all 66 Iridium satellites were simulated for a full day, with only the GPS radio occultation data simulated. The actual GPS ephemeris for the satellites was used to assure accurate and realistic simulation scenarios. The day simulated was that of the November 20, 2003 geomagnetic super storm. The top plot shows first principle ionospheric model TIME-GCM treated as “truth” for simulating our observing system. This event is a strong “weather” departure from climatological predictions (second panel from top IRI climatological model). The third panel shows that our existing ground-based GPS is grossly inadequate for imaging this event, whereas GEOScan observations alone (bottom panel) accurately capture the global dynamics of the geospace environment. The RMS TEC errors of the simulation shown are: IRI-16 TECU, ground-based GPS – 11 TECU, GEOScan only – 2.8 TECU.

GEOScan Gravity Imaging

The time-variable gravity products created from GEOScan seek to provide new insights into the large-scale (>1000km), short-term (< 1month) mass transport processes governing the global water cycle. Any process that involves the transport of water, such as the melting of glaciers in the cryosphere, changes in continental hydrology (e.g., groundwater), or other processes in the oceans and atmosphere, creates a change in Earth’s gravity field. By precisely measuring the variations of Earth’s gravity over time, we can exploit this link and understand more about the behavior of these processes.

How the time-variable gravity field can be measured by GEOScan’s sensor suite is relatively straightforward, and is driven by the fact that changes in Earth’s gravity field, however small, will alter the trajectory of an orbiting satellite.[6] Using the CTECS GPS receiver, the absolute position of each Iridium NEXT satellite will be precisely determined, down to the cm level. These positions can then be differentiated to create a time series of satellite accelerations that represent both gravitational and non-gravitational forces. Those accelerations caused by non-gravitational forces, such as atmospheric drag and solar radiation pressure will be accounted for by the information provided by the onboard MEMS accelerometers, leaving as a final product only those accelerations due to Earth’s gravity.

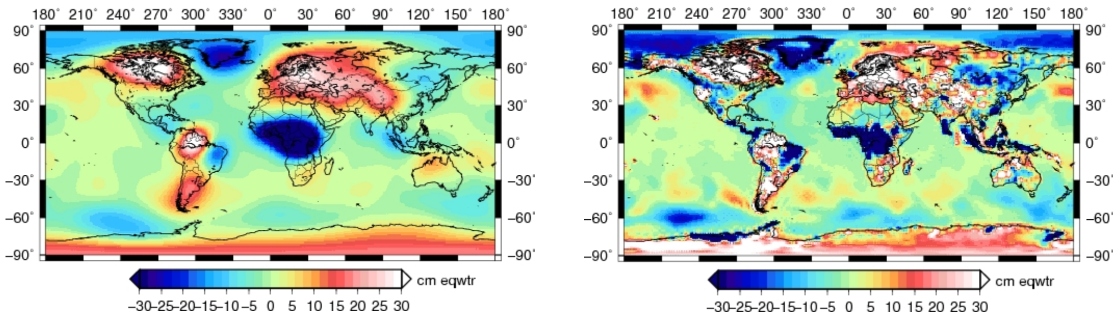

Figure 8. Illustration of the daily resolution expected from the GEOScan gravity products (right panel), as derived from a high-resolution coupled Earth system model (left panel). Units are in equivalent water height.

NASA's GRACE mission was the first to highlight the value of time-variable gravity data; however, despite its tremendous success, GRACE suffers from the measurement sampling limitations related to having only a single satellite pair. Since gravity observations are essentially point measurements, the spatial and temporal coverage of a single satellite will never permit the observation of high-frequency events, and this is why the temporal resolution for GRACE is approximately one month. While GEOScan will not be able to match the spatial resolution of GRACE, the time variable data collected from the full constellation of Iridium NEXT satellites will allow the monitoring of large-scale processes at the Earth's surface at time scales as short as one day. Global gravity data at this temporal resolution has never been collected before, and should be especially valuable to the ocean and atmosphere communities. Figure 5 demonstrates the potential quality of the GEOScan gravity products (right panel) from a single day's worth of measurements, compared to the full high-resolution signal (left panel) over the same timeframe, as derived from a recent coupled Earth system model.[10] As can be seen, a number of terrestrial and oceanic/atmospheric mass transport processes are clearly observed, with the spatial resolution corresponding to approximately 1000 km.

NANOSATELLITE PATHFINDER

Advances over the past decade in highly reliable commercial electronics, miniaturization techniques, and materials have enabled a new class of small "nanosatellites," loosely defined as satellites having a total mass of 50 kg or less[14], that now afford the capability to execute a broad array of meaningful science, technology, and national security missions. A subset of this system-class, CubeSats, are canonically defined as single unit (1U) spacecraft with nominal stowed volume of 10x10x10 cm and mass of about one kilogram[15]. Capitalizing on significant, otherwise unused launch vehicle (LV) volume and lift mass capability, the first CubeSats were launched as opportunistic rideshares in 2000. Through repeated manifest successes, confidence was established such that they could be safely and readily incorporated into the LV and mission plan without impact to the primary payload[16]. Catalyzed by the emerging means by which to dramatically lower the cost and programmatic barriers to space access, there is growing global interest to find further ways to increase nanosatellite launch accommodation to form-factors larger than 3U CubeSat that offer greater mission capability[17], and in quantities well in excess of 10 free-flyer deployments per mission[18] that now permit fielding operational constellations (on a per plane basis).

Responding to the diverse needs of US Government sponsors for smaller spacecraft to more effectively utilize access to space, JHU/APL has created a flexible and modular, Multi-Mission Nanosatellite (MMN) spacecraft architecture for low-cost execution of critical missions spanning civil and national security applications. Among the many enabled applications, JHU/APL has been conceptually exploring the means by which key space weather phenomena could be observed with greater spatial and temporal distribution using nanosatellites[19]. To support this broad endeavor, JHU/APL has developed an initial triple (3U) CubeSat hardware prototype under a pathfinder effort, with two flight units scheduled for launch in the spring of 2013.[16,20]

As shown in Figure 9, the Multi-Mission Bus Demonstration (MBD) was designed to be an opportunistic satellite, capable of operating across a broad envelop of orbits that might be served by rideshare opportunities, with a modular payload interface to readily accommodate alternate instruments/sensors. Given the inherent packaging challenges of the CubeSat form-factor, MBD employs a highly-integrated design approach to incorporate all the critical subsystems found within a typical large mission satellite, with the requisite functionality to support a wide variety of missions. Several of these elements can and/or will be leveraged for GEOScan, including:

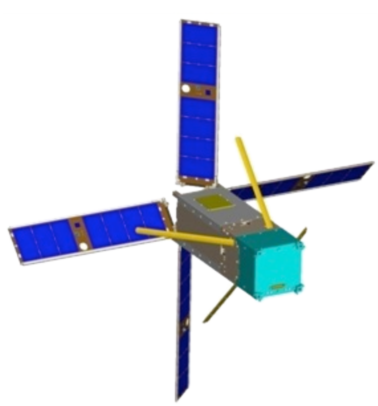

Figure 9. The JHU/APL Multi-Mission Bus Demonstration program, scheduled to launch in mid-2013, has a modular payload interface (blue), and will be a pathfinder for several key GEOScan technologies.

Global Positioning Subsystem (GPS)

An integrated NovAtel OEMV-1G GPS receiver is utilized onboard to supply periodic measurement of position and velocity data necessary for deriving an ephemeris solution, as well as provide an accurate time reference for calibrating precision clocks and other payload electronics as required. In addition to these functions, for GEOScan, the physically equivalent OEMV-1DF would be considered as a means to conduct radio occultation experiments.

LEON3FT Processor

A high reliability 32-bit LEON3FT processor with fault tolerant technology, was chosen for its combination of performance, low power quiescent state, and ability to operate in the harsh space environment.

Real-Time Operation System & Flight Software

Free, open-source Real-Time Executive for Multi- processor Systems (RTEMS) was selected for the real-time operating system (RTOS) and compatibility with the LEON3FT processor. An Operating System Abstraction Layer (OSAL) was able to facilitate the development process through compatibility with existing tools, as well as leverage some heritage code previously developed at

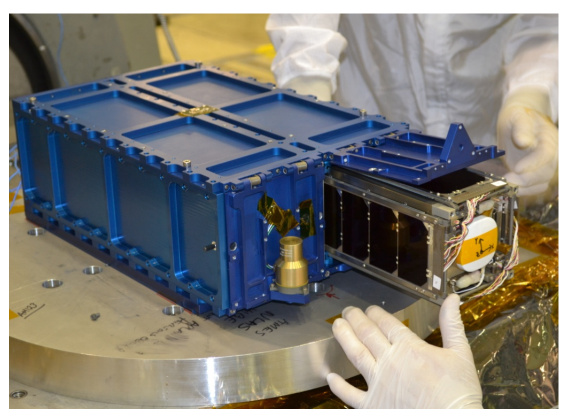

Figure 10. One of the two MBD satellites being stowed into the NASA NLAS dispenser.

JHU/APL for the NASA Solar TErestrial RElations Observatory (STEREO) mission.

MBD is designed to be compatible with the P-POD or other 3U dispenser systems, such as the NASA Nanosatellite Launch Adapter System (Figure 10), which can accommodate two 3Us or a single 6U spacecraft. As shown in Figure 8, a complete testing campaign for the program, including thermal balance, was conducted in the summer of 2011; the two spacecraft are presently in storage awaiting their planned launch next year.

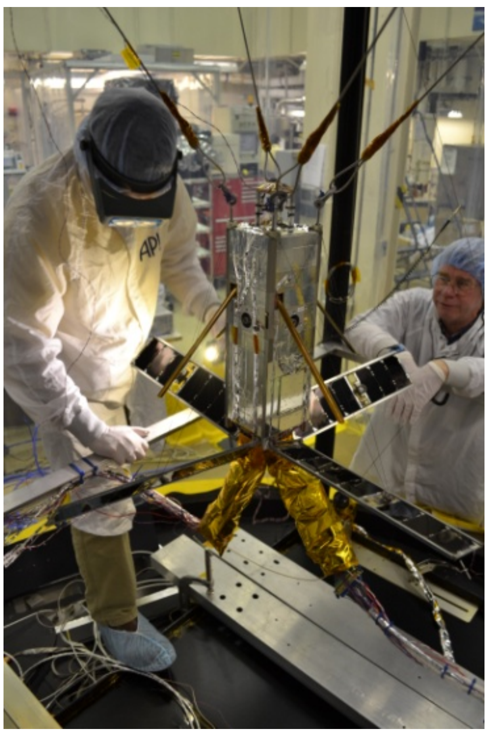

Figure 11. MBD being prepared for thermal balance testing at JHU/APL. The design was exercised over a broad thermal environment envelop to guarantee its suitability across a variety of orbit conditions.

SUMMARY

The GEOScan facility has been designed to meet the needs of a diverse user community and address measurement needs from the surface to geospace that enable transformative discovery. The Iridium NEXT satellite constellation provides real-time data with dense, frequent, and global measurements from the GEOScan sensor suites. This hosted payload consisting of 6 instruments is poised to address a wide array of outstanding science questions as well as compliment existing ground and space based assets for purposes of space weather nowcasting and space situational awareness. The Iridium NEXT constellation with its 10+ year lifetime will provide scientists and decision makers with valuable data at a fraction of the traditional cost of dedicated monolithic missions due to the use of COTS parts and a scientific hosted payload design that is mated to the Iridium business model and launch schedule. GEOScan and the Iridium NEXT hosted payload opportunity demonstrate the synergetic potential of public-private partnerships that leverage commercial space opportunities and scientific measurement goals.

REFERENCES

1. Iridium Communications, "Hosted Payloads," http://www.iridium.com/about/IridiumNEXT/HostedPayloads.aspx (2011).
2. Space Dynamics Laboratory, "Iridium NEXT Secondary Payload Sensor Pod Interface Control Document, Document No. SDL/10-352," http://www.iridium.com/DownloadAttachment.aspx?attachmentID=1223, 2010.
3. Church, J.A., N.J. White, L.F. Konikow, C.M. Domingues, J.G. Cogley, E. Rignot, J.M. Gregory, M.R. van den Broeke, A.J. Monaghan, and I. Velicogna, "Revisiting the Earth's sea-level and energy budgets from 1961 to 2008," Geophys. Res. Lett., 38 (L18601), 2011.
4. Loeb, N.G. , J.M. Lyman, G.C. Johnson, R.P. Allan, D.R. Doelling, T. Wong, B. Soden, and G. Stephens, "Observed changes in top-of-the-atmosphere

radiation and upper-ocean heating consistent within uncertainty," Nat. Geosci., 5:110-113, doi:10.1038/NGEO1375, 2012.

5. Trenberth, K.E. and J.T. Fasullo, "Climate Change: Tracking Earth's Energy," Science Perspectives, 328: 316-317, doi:10.1126/science.1187272, 2010.

6. Gunter, B.C., J.G. Encarnaçao, P.G. Ditmar, and R. Klees, "Using satellite constellations for improved determination of Earth's time-variable gravity," J. Spacecr. Rockets, 48(2):368-377, 2011.

7. Wilder, F.D, G. Crowley, B. J. Anderson, A. D. Richmond, Intense Dayside Joule Heating During the April 5, 2010 Geomagnetic Storm Recovery Phase Observed by AMIE and AMPERE, J. Geophys. Res., doi:10.1029/2011JA017262, 2012.

8. Crowley, G., D. J. Knipp, K. A. Drake, J. Lei, E. Sutton, and H. Luhr (2010), Thermospheric density enhancements in the dayside cusp region during strong BY conditions, Geophys. Res. Lett., 37, L07110, doi:10.1029/2009GL042143.

9. J. M. Picone, J. T. Emmert, and J. L. Lean. Thermospheric densities derived from spacecraft orbits: Accurate processing of two-line element sets. Journal of Geophysical Research, 110(A03301), 2002.

10. Bust, G.S., D. Coco, and J.J. Makela, "Combined iono- spheric campaign: 1. Ionospheric tomography and GPS total electron count (TEC) depletions," Geophys. Res. Lett., 27, 2849 – 2852, 2000.

11. Bust, G.S., T.W. Garner, and T.L. Gaussiran II, "Ionospheric Data Assimilation Three-Dimensional (IDA3D): A global, multisensor, electron density specification algorithm, J. Geophys. Res., 109, A11312, doi:10.1029/2003JA010234, 2004.

12. Bust, G.S. and C.N. Mitchell, "History, current state, and future directions of ionospheric imaging," Rev. Geophys., 46:RG1003, doi:10.1029/2006RG000212, 2008.

13. Gruber, T.H., J.L. Bamber, M.F.P. Bierkens, H. Dobslaw, M. Murböck., M. Thomas, L.P.H. van Beek, T. van Dam, L.L.A. Vermeersen, and P.N.A. M. Visser, "Simulation of the time-variable gravity field by means of coupled geophysical models." Earth Syst. Sci. Data, 3 :19–35, doi:10.5194/essd-19-2011, 2011.

14. University Nanosat Program (UNP) Nanosat-5 User's Guide, UN5-0001, Feb. 2007.

15. CubeSat Design Specification: http://cubesat.atl.calpoly.edu/images/developers/cds_rev12.pdf

16. Rogers, A.Q., and R.A. Summers, "Creating Capable Nanosatellites for Critical Space Missions," Johns Hopkins APL Technical Digest, Volume 29, Number 3, pp. 283-288, 2010.

17. Apland, T. Clint, A.Q. Rogers, D.F. Persons, S.R. Vernon, R.A. Summers, and L.A. Kee, "A Flexible Launch Vehicle Adapter System for 30-50 kg Nanosatellite Missions," IEEE Aerospace Conference, Big Sky, Montana, March 3-10, 2012.

18. Atchison, J.A., A.Q. Rogers, and S.J. Buckley, "An Operational Methodology for Large Scale Deployment of Nanosatellites into Low Earth Orbit," AAS 11-462, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, July 31 - August 4, 2011.

19. Rogers, A.Q., L.J. Paxton, and M.A. Darrin, "Small Satellite Constellations

for Measurements of the Near-Earth Space Environment.” In R. Sandau, H-P. Roser, A. Valenzuela (Eds.), Small Satellite Missions for Earth Observation: New Developments and Trends (pp. 113-121), Berlin: Springer, 2010

20. Knuth, A.A., P.M Huang, and A.Q. Rogers, “Multi Mission Bus Demonstration: A Unique Low-Cost Approach for End-to-End SensorSat Development,” Reinventing Space Conference, Los Angeles, CA, May 7-10th, 2012.