GEOScan: A Global, Real-Time Geoscience Facility

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Abstract*— *GEOScan is a proposed space-based facility of globally networked instruments that will provide revolutionary, massively dense global geosciences observations. Major scientific research projects are typically conducted using two approaches: community facilities, and investigator lead focused missions. While science from space is almost exclusively conducted within the mission model, GEOScan is a new concept designed as a constellation facility from space utilizing a suite of space-based sensors that optimizes the scientific value across the greatest number of scientific disciplines in the earth and geosciences, while constraining cost and accommodation related parameters. Our grassroots design processes target questions that have not, and will not be answered until simultaneous global measurements are made. The relatively small size, mass, and power of the GEOScan instruments make them an ideal candidate for a hosted payload aboard a global constellation of communication satellites, such as the Iridium NEXT's 66-satellite constellation. This paper will focus on the design and planning components of this new type of heterogeneous, multi-node facility concept, such as: costing, design for manufacture, science synergy, and operations of this non-traditional mission concept. We will demonstrate that this mission design concept has distinct advantages over traditional monolithic satellite missions for a number of scientific measurement priorities and data products due to the constellation configuration, scaled manufacturing and facility model.

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1. 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, but applicable to other hosted payload opportunities 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 CO2. 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.

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)

2. A CONSTELLATION OF HOSTED PAYLOADS

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°.

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).

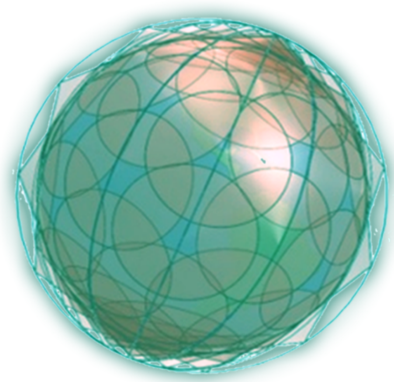

Figure 1 – Iridium NEXT satellite constellation RF footprints.

3. GEOSCAN SYSTEM SENSOR SUITE

The GEOScan system sensor suite is comprised of 6 instruments packaged to take advantage of the Iridium

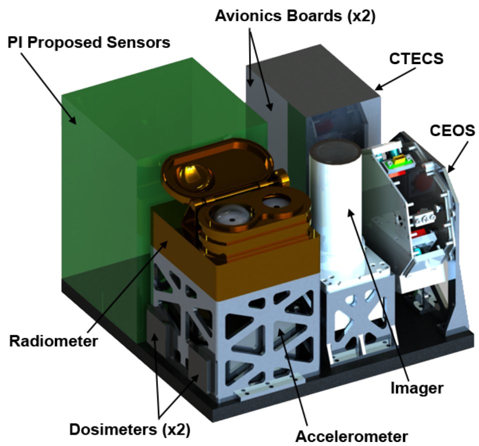

Figure 2 – GEOScan's payload design uses a modular configuration for efficient assembly and testing. It also includes additional mass, power, data, and volume allocation for sensors proposed by scientific and government stakeholders.

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.

GPS: The Compact Total Electron Content Sensors

The Compact Total Electron Content Sensors (CTECS) shown in Figure 3 are GPS instruments that utilize a commercial off-the-shelf (COTS) receiver, modified firmware, a custom-designed antenna, and front-end filtering electronics. 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

GEOScan will measure Earth's outgoing radiation simultaneously and globally with a constellation of heritage-driven, two-channel radiometers carried by the Iridium NEXT commercial constellation of satellites. This

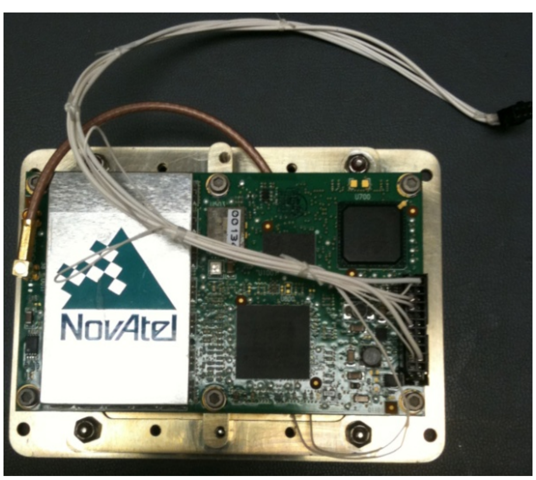

Figure 3 – CTECS from the PSSC2 uses the flight-proven NovAtel OEM628 receiver board and will be used in GEOScan's CTECS-O sensor.

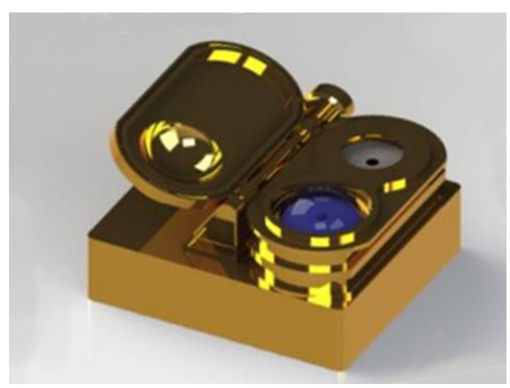

Figure 4 – Bolometer-based radiometers are a proven concept originating in the 19th century. They've flown on every Earth radiation budget mission since 1975. GEOScan's radiometer channels measure short (0.2-5 microns) and total (0.2-200) microns radiation.

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. The conceptual design of the radiometer is shown in Figure 4.

Spectrometer: Compact Earth Observing Spectrometer

The Compact Earth Observing Spectrometer (CEOS) shown in Figure 5 consists of an exceptionally small crossed Czerny-Turner spectrometer, linear CCD arrays, read-out electronics, and multiple optical paths to allow for a greater measurement range. 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 allows for 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

The Multi-Spectral MicroCam Imager (MMI) shown in Figure 6 is designed to provide multispectral images on both regional and global scales. The MMI provides multispectral imagery in the same footprint within a time of 30 s, each

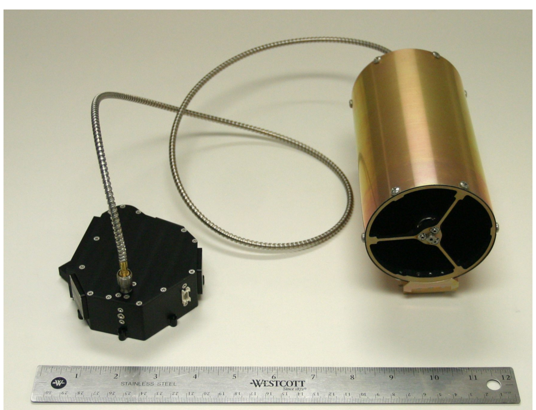

Figure 5 – The CEOS spectrometer, optical fiber and foreoptics will be derived from the current O/OREOS mission (pictured above).

with a spatial resolution of ~450 m (nadir). The spacing of the satellites in the constellation (11 satellites per orbital plane), and the fact that one MMI is placed on every satellite, will allow complete multispectral global imagery to be acquired every 2 hours.

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°

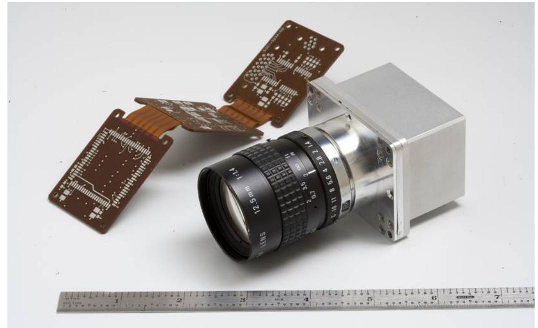

Figure 6 – GEOScan's MicroCam Multi-Spectral Imager (2.5×2×2 in) with a commercial C-mount lens developed under a JHU/APL Internal and Development Programs.

× 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

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. 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

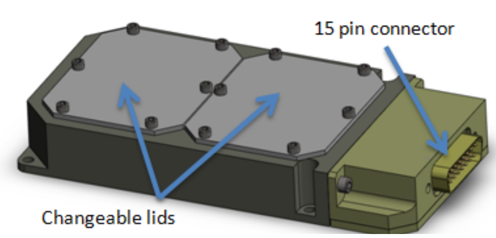

Figure 7 – GEOScan's dosimeter payload provides a compact instrument system for studying radiation belt dynamics based on Teledyne's micro dosimeter.

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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. The conceptual design is shown in Figure 7.

Accelerometers: MEMS Accelerometer for Space Science

The MEMS Accelerometer for Space Science (MASS) is a proposed 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.

4. 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.

AMPERE: Hosted Payload Constellation Patherfinder

AMPERE was the pathfinder in the application of commercial space partnership for breakthrough science. Development began in June 2008 and consisted of developing and uploading new flight software to each satellite of the Iridium constellation, and assembly of new ground data ingestion and processing systems.

The Iridium constellation configuration is ideal for measurement of the global electric currents that flow between the ionosphere and the high-altitude magnetosphere. AMPERE data are acquired continuously with >99.9% reliability, and APL has implemented a real-time science product stream, providing global maps of these currents with latencies demonstrated as short as 18 min. A key feature of the Iridium system is that these data are transmitted via the satellite system's communication links over the entire globe in true real time. Figure 8 shows reduced data acquired in a 10-min interval for 3 August 2010, 2200–2210 UT.

AMPERE measurements provide the first global and continuous measure of a fundamental physical quantity, allowing estimation of the distribution of electromagnetic energy deposition to the thermosphere and ionosphere. The AMPERE currents are acquired with a 9-min cadence, fast enough to follow the reconfigurations of the magnetosphere in response to solar wind forcing giving the first realistic inputs for atmospheric circulation models to understand the true thermosphere/ionosphere response to solar storms.

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, shown in Figure 9, 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

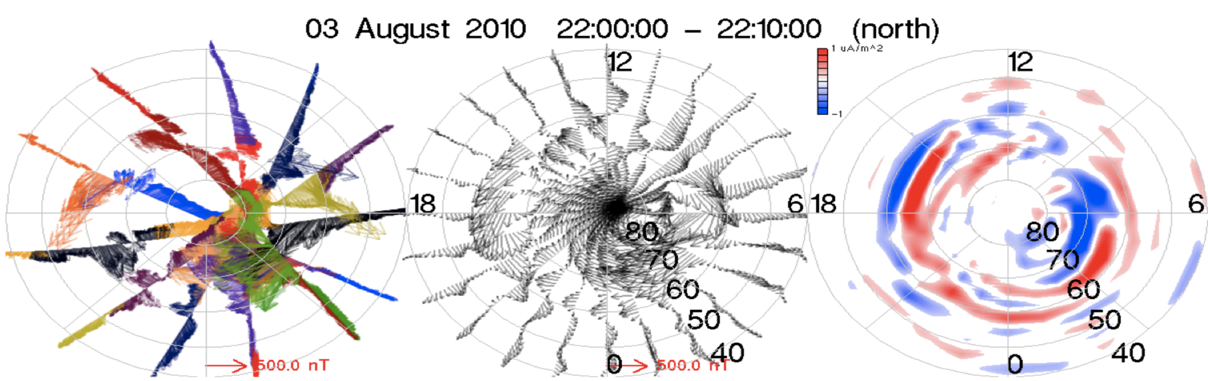

Figure 8 – AMPERE results for a 10-min interval during a geomagnetic storm on 3–4 August 2010. From left to right: magnetic perturbations from Iridium magnetometers showing signatures of currents; fit to the magnetic perturbations; radial current density obtained from Ampere's law to the fit.

contribute to global change, and how global long-term changes affect smaller scales and surface processes where human beings live and work.

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 3.[3,4,5]

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.

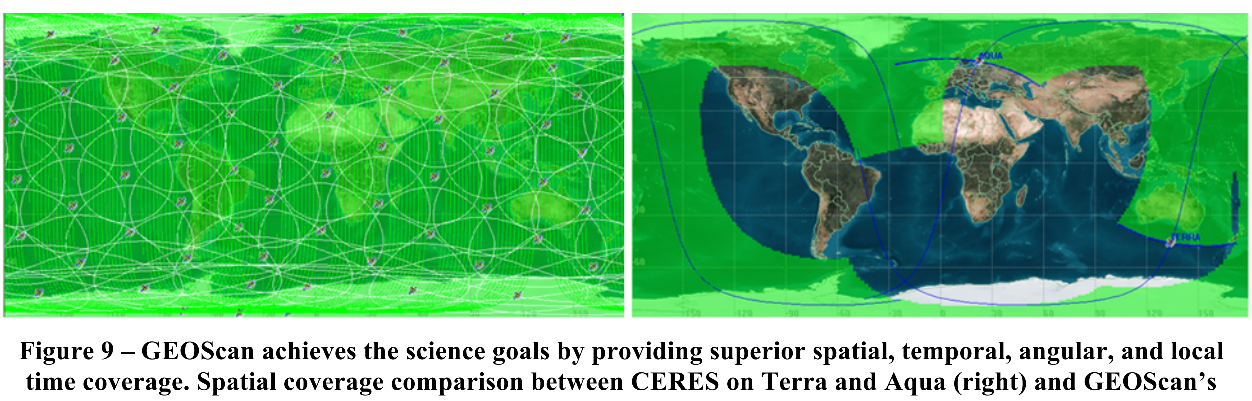

Figure 9 – GEOScan achieves the science goals by providing superior spatial, temporal, angular, and local time coverage. Spatial coverage comparison between CERES on Terra and Aqua (right) and GEOScan's bolometer radiometer (left) for 1 hour. In a single hour, GEOScan will make 3600 global TOR samples, 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.

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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 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 10 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.

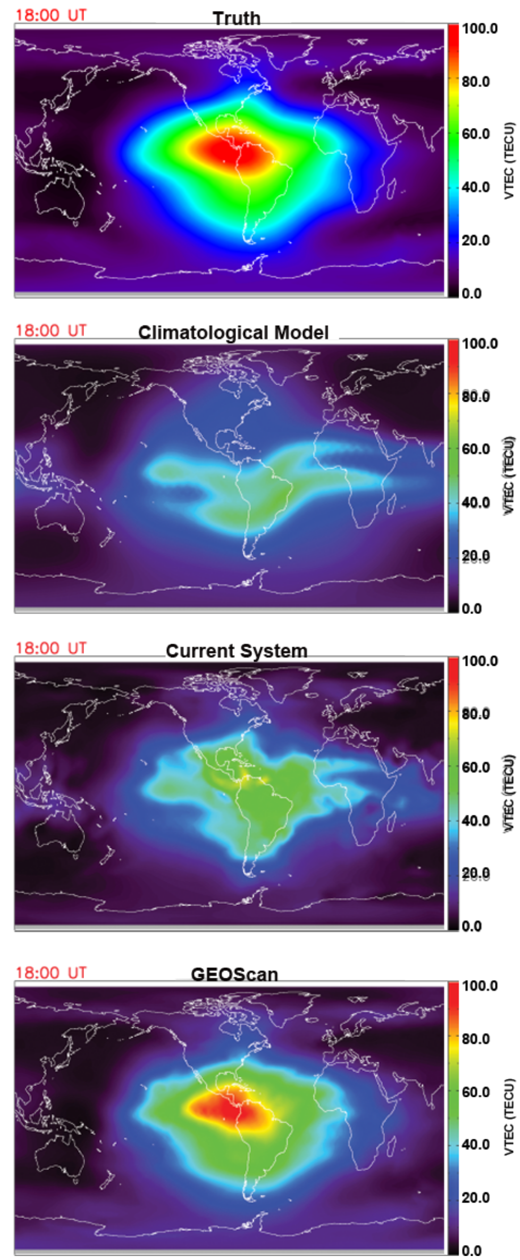

Figure 10 – GEOScan tomographic imaging will fundamentally change our ability to understand geospace plasma dynamics. The top plot shows TIME-GCM simulated ionosphere for the geomagnetic super storm on 20 November 2003, treated as “truth” for simulating our observing system. This event is a strong “weather” 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.

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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.

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 11 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.

5. Scaled Manufacture and GEOScan Cost Savings

An APL led cost estimating process using internal costing processes consistent with NASA's Cost Estimating handbook and NM 7120-81 was used to help determine cost constraints for GEOScan instrumentation and mission costs.

For APL, the Control Account Managers (CAMs), including the Project Systems Engineer (PSE), generated the bottom-up cost estimates (BUEs) for the mission, which were reviewed by the Project Manager (PM) for appropriateness and adequacy. These costs were validated by comparisons with initial top-down estimates made on the basis of institutional experience, as well as with parametric estimates performed by an independent team of experts. During the cost estimating process, the following top-level requirements and assumptions were used:

- All feasibility risks will be retired by Preliminary Design Review (PDR).
- Spares are minimized as appropriate.
- Standard APL business practices and Quality Management System procedures, processes, and systems are used.
- A streamlined management approach with clear lines of authority is applied.

However, the majority of cost savings associated with hosted payload missions are firm fixed price hosting fees and NRE savings derived from locking in an instrument design and then applying standard design-for-manufacture methods to the engineering units to produce designs suitable for mid-scale production of a qualified venture outside of APL. For GEOScan mid-scale production will happen at

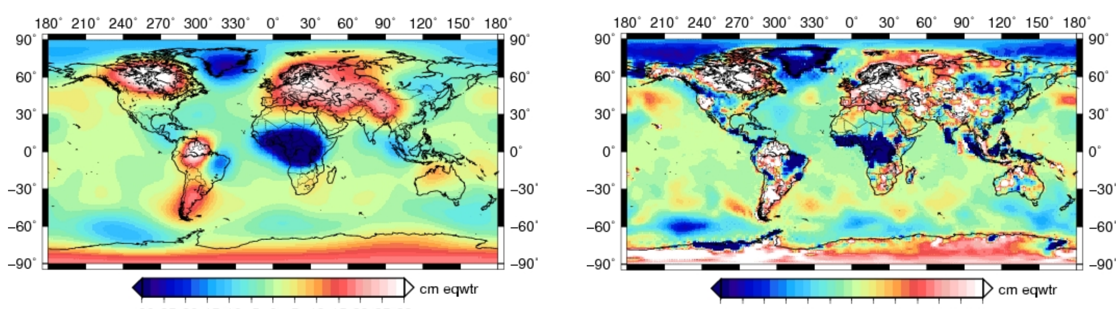

Figure 11 – Illustration of the daily resolution expected from the GEOScan gravity products (right panel), as derived from a high-resolution coupled Earth system model (left panel). Units are in equivalent water height.

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Draper Laboratory scaled-manufacturing facility. Draper has unique and extensive experience in multiple-unit production of high-tech space-qualified instruments and components for both military and civilian space applications. Draper will provide design oversight to ensure manufacturability based on more than 20 years of experience with manufacturing for programs such as the Trident Mk6LE Guidance Systems, Draper Multi-Chip Modules, and Compact Earth Observing Spectrometers.

The value of the GEOScan approach was demonstrated by Dr. Selva and Dr. Crowley at MIT using an optimization approach to the design of architectures for complex, reliable, and very large systems[18]. Leveraging ten years of research, they have applied scientific and societal measurement requirements from the Earth Science Decadal Survey, Committee on Earth Observing Satellites, Science & Technology advisory boards, and instrument capabilities to be expressed in the form of logical rules and data structures in this knowledge-based system. An efficient pattern-matching algorithm performs the comparison of the measurement requirements and the measurement capabilities based on 64 different measurement attributes. The associated costs for these approaches are then derived from the NASA Instrument Cost Model (NICM) IV (subsystem tool) for passive Earth-orbiting instruments. Overall, GEOScan is more cost effective by approximately ten times - it provides approximately 15-27% of the science for 1% of the associated decadal mission cost.

There is little formal guidance available for estimating the cost savings associated with producing multiple copies in small lots of a single design for space applications. Previous research demonstrated that the second copy of a unit has an expected cost of 35% of the cost of the original unit[19]. APL's experience producing multiple units of instruments and spacecraft is extensive; however, historical cost data are not available by unit. In order to estimate the cost savings for producing multiple units of a single design, historical cost data were analyzed for the JUNO JEDI instruments (3 units), The Van Allen Probes' RBSPICE instruments (2 units), STEREO spacecraft (2 units), and the Van Allen Probes spacecraft (2 units). Several methods yielded largely similar results.

The first approach was to analyze WBS-level cost information, which was applied to each of the four examples discussed above. At the WBS level, costs could not be assigned to individual units, but analysts were able to differentiate between recurring and nonrecurring engineering costs to generate an estimated copy-cost factor of 30-40%. This finding substantiated the research by Warfield and Roust.

Further analysis of available data also substantiated the cost-to-copy factor. The two RBSPICE units are exact copies of the three JEDI instruments flying on JUNO. Thus, cost information was consolidated for the five units. This allowed more insight into historical detailed costs by unit because JEDI instrument costs are kept separately from RBSPICE costs. The cost data was normalized for inflation and WBS differences to enable a cost-to-copy factor to be derived. This analysis assumed that material and labor costs for the two RBSPICE units were roughly equal to costs for the second two units produced for JEDI. This result also substantiated the average 35% cost-to-copy factor discovered by Warfield and Roust.

While this approach allows credible cost estimates to be developed for small lots of design units at APL, it does not apply a manufacturing learning curve, which would be required to understand total costs for a constellation of instrument units. To fulfill this requirement, NASA's Cost Estimating handbook[20] and NM 7120-81 NID, NASA Space Flight Program and Project Management Requirements (the interim directive for NPR 7120.5D) were consulted on the expected learning curve factor for aerospace production units. In addition, a secondary estimate was developed for validation (crosscheck) using the NASA Instrument Cost Model (NICM) IV. This provides a Learning Curve Slope of 85% for the unit cost learning curve:

$$\text{Cost}_{(2X)} = \text{Cost}_{(X)} * \text{Learning Curve Slope} \quad (1)$$

Where $\text{Cost}_{(X)}$ is the cost of the Xth unit and $\text{Cost}_{(2X)}$ is the cost of two times the Xth unit. For example, the 4th unit produced would be expected to cost 85% of the second unit and the 8th unit produced would be expected to cost 85% of the 4th unit.

These analyses demonstrate the substantial cost savings per unit for mission designs such as GEOScan when using an approach that locks in a qualified and tested flight unit design that considers design for manufacture principles and then produces multiple copies. This constrains NRE and reduces materials acquisition cost per unit (bulk supplier discount) as well as manufacturing cost (batch production and qualification/acceptance testing).

Thus, strong evidence already substantiates the Warfield and Roust cost-to-copy factor for APL's expected costs for producing multiple units. In addition, established theory utilizing learning curves, with a slope taken from NASA's cost estimating guidelines, provides a credible cost estimating technique for the production unit costs that can be applied to scaled manufacture for space applications.

6. 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

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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.

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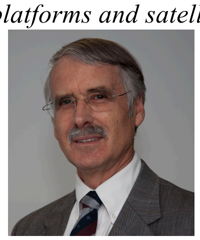

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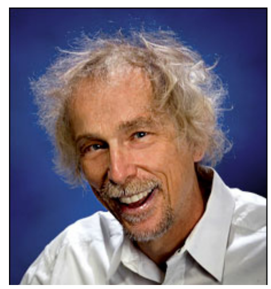

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