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GEOScan: A Geoscience Facility From Space

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ABSTRACT

GEOScan is a grassroots effort, proposed as globally networked orbiting observation facility utilizing the main Iridium NEXT 66-satellite constellation. This will create a revolutionary new capability of massively dense, global geoscience observations and targets elusive questions that scientists have not previously been able to answer, and will not answer, until simultaneous global measurements are made. This effort is enabled by Iridium as part of its Hosted Payload Program. By developing a common sensor suite the logistical and cost barriers for transmitting massive amounts of data from 66 satellites configured in 6 orbital planes with 11 evenly spaced slots per plane is removed. Each sensor suite of GEOScan's networked orbital observation facility consists of 6 system sensors: a **Radiometer** to measure Earth's total outgoing radiation; a **GPS Compact Total Electron Content Sensor** to image Earth's plasma environment and gravity field; a **MicroCam Multispectral Imager** to measure global cloud cover, vegetation, land use, and bright aurora, and also take the first uniform instantaneous image of the Earth; a **Radiation Belt Mapping System (dosimeters)** to measure energetic electron and proton distributions; a **Compact Earth Observing Spectrometer** to measure aerosol-atmospheric composition and vegetation; and **MEMS Accelerometers** to deduce non-conservative forces aiding gravity and neutral drag studies. Our analysis shows that the instrument suites evaluated in a constellation configuration onboard the Iridium NEXT satellites are poised to provide major breakthroughs in Earth and geospace science. GEOScan commercial-of-the-shelf instruments provide low-cost space situational awareness and intelligence, surveillance, and reconnaissance opportunities.

Keywords: Remote sensing, hosted payloads, radiometer, GPS, spectrometer, multi-spectral imager, dosimeter, accelerometer.

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 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.

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2. 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 through 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 of greater than 10 years in a polar orbit at 780 km with an inclination of 86.4°.

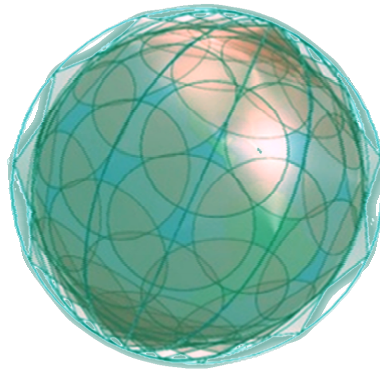


Figure 1. Iridium NEXT satellite constellation RF footprints.

Each Iridium NEXT satellite has a total hosted payload allocation of 50 kg in mass, $30 \times 40 \times 70 \text{ cm}^3$ 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, $14 \times 20 \times 20 \text{ cm}^3$ 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	$30 \times 40 \times 70 \text{ cm}^3$	$20 \times 20 \times 14 \text{ cm}^3$
Payload Power	50-W average (200-W peak)	5 W (avg), 10 W (peak)
Payload Data Rate	<1 Mbps (orbit average) 100 kbps (peak)	10 kbps (avg), 100 kbps (peak)

3. 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.

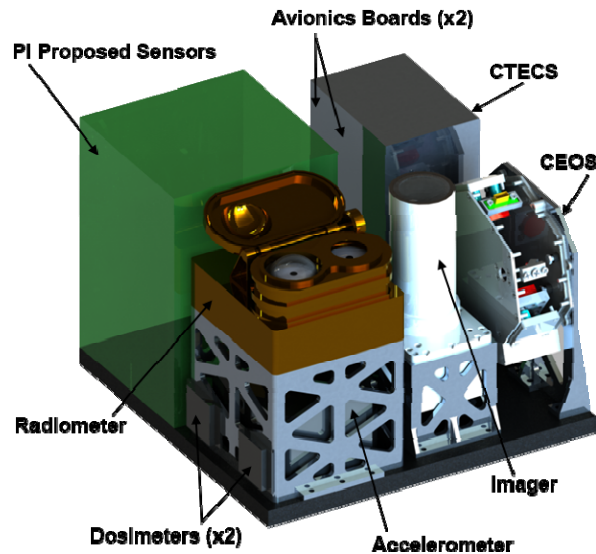


Figure 2. GEOScan's payload design uses a modular configuration for efficient assembly and testing. It also includes additional mass, power, data, and volume allocation for sensors proposed by scientific and government stakeholders.

3.1 GPS: The Compact Total Electron Content Sensors

The Compact Total Electron Content Sensors (CTECS) 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 GRACE satellites.

3.2 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 constellation, each with a 127 deg field-of-view radiometers will provide a global view of the Earth's 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 from differencing the two channels) is calibrated to a precision of 0.09 W/m² with an accuracy of 0.3 Wm⁻² using a NIST traceable calibration standard.

3.3 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.

3.4 Imager: Multi-Spectral MicroCam

The Multi-Spectral MicroCam Imager (MMI) 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 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° × 33° to provide global cover-age over a 2-h time interval. Each FOV footprint on the surface of the Earth is 465 × 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 min. In this 9-min time interval, the relative drift in longitude between a spot on the Earth and Iridium is 250 km.

3.5 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 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 to the most intense solar particle events and deep within the inner radiation belt.

3.6 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 Gravity Recovery and Climate Experiment (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/s². The performance of this class of MEMS accelerometers has shown a consistent white noise floor on the order of 10⁻¹¹ g²/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 remotely sense the 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 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.

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 total out-going radiation (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 [3,4,5]. 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.

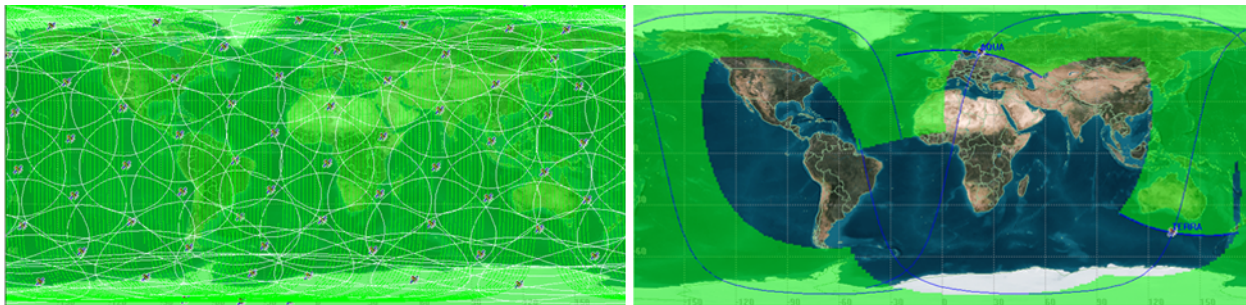


Figure 3. GEOScan achieves the science goals by providing superior spatial, temporal, angular, and local time coverage. Spatial coverage comparison between CERES on Terra and Aqua (right) and GEOScan's bolometer radiometer (left) for 1 h. In a single hour, GEOScan will make 3600 global TOR samples, providing a statistical noise reduction factor of 60 every hour. After 2 h the Iridium NEXT orbital planes completely intersect, providing 100% independent yet massively oversampled TOR, from all angles.

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 measurement sampling possible from a single satellite's ground track (or satellite pair in the case of GRACE). The error caused by undersampling (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 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 [6].

Significant progress has been made in the study of the Earth's geospace environment over the last few decades. 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. Answering these fundamental questions and reaching a predictive capability requires direct observations of key parameters. Global tomographic imaging [7] of the geospace electron density is GEOScan's central contribution. Height-resolved electron density will allow us to specify ionospheric conductivity and understand the physics of auroral current closure. In addition, 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 timescales of minutes to days. The GEOScan dosimeter payload will continuously and globally map this variability and will provide first-of-its-kind quantification of the leading uncertainty in loss calculations: the longitude extent of the precipitation.

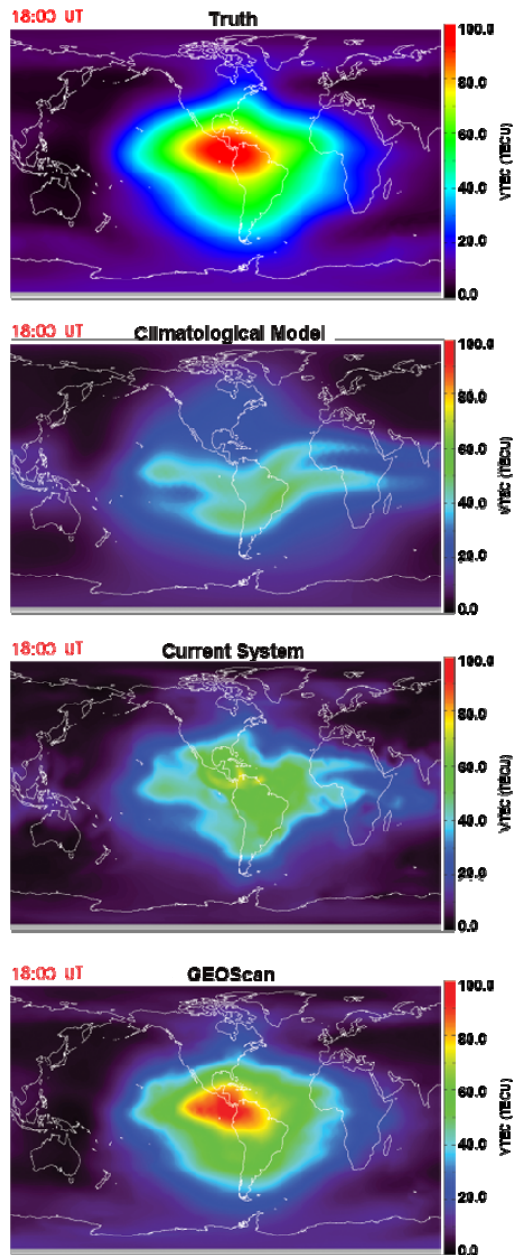


Figure 4. GEOScan tomographic imaging will fundamentally change our ability to understand geospace plasma dynamics. The top plot shows TIME-GCM simulated ionosphere for the geomagnetic super storm on 20 November 2003, treated as “truth” for simulating our observing system. This event is a strong “weather” 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.

5. 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 system 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+ 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 synergistic potential of public-private partnerships that leverage commercial space opportunities and scientific measurement goals.

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