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Small-Sat Science Constellations: Why and How

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ABSTRACT

Two thematic drivers are motivating the science community towards constellations of small satellites, the revelation that many next generation system science questions are uniquely addressed with sufficient numbers of simultaneous space based measurements, and the realization that space is historically expensive, and in an environment of constrained costs, we must innovate to "do more with less". We present analysis that answers many of the key questions surrounding constellations of scientific satellites, including research that resulted from the GEOScan community based effort originally intended as hosted payloads on Iridium NEXT. We present analysis that answers the question how many satellites does global system science require? Perhaps serendipitously, the analyses show that many of the key science questions independently converge towards similar results, i.e. that 20-40 satellites are needed for transformative, as opposed to incremental capability in system science. We focus on climate and gravity science as demonstrations of these findings. We also present analysis on the additional functional design elements of a science constellation such as launch and operations strategies, and new models for risk, mission costing, construction, and contracting that are adapted from the commercial satellite industry that enable significant cost savings. Data from actual recent design (such as the newly awarded RAVAN cube-sat mission) and build efforts are presented to support these assertions. We conclude with a discussion on implementation plans and the new paradigms for community and international cooperation enabled by small satellite constellations.

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 sensor suite 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 was initially designed to populate the Iridium NEXT constellation, but is applicable to other LEO hosted payload and small satellite constellation opportunities to 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 concept 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.

2. GEOSCAN SYSTEM SENSOR SUITE

The GEOScan system sensor suite is comprised of 6 instruments each designed to be less than 1W, 1Kg, $1M. The resource allocation for the GEOScan suite is shown in Table 1. This core sensor suite was designed with modularity in mind and to fit within the same volume constraints of approximately four (4) 1U CubeSats. Therefore, a subset of this sensor suite can be flown on potential CubeSats or other small satellite opportunities. This approach to the sensor suite design has been validated by ESTO's selection of a bolometer based radiometer originally developed for GEOScan for the InVEST CubeSat flight opportunity (http://www.nasa.gov/topics/technology/features/earth-cubesat_prt.htm). In addition, the Air Force continues to pursue the integration of dosimeters on the Iridium NEXT constellation with the HEALER program (https://www.fbo.gov/index?s=opportunity&mode=form&id=593b08fa065314c315c81e3f7ab2a7a4&tab=core&_cview=0).

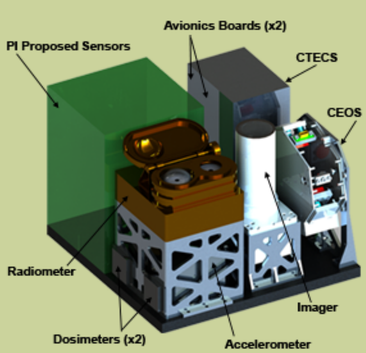
Table 1: GEOScan resource allocation

Weight	5 kg
Payload Dimensions	20 × 20 × 14 cm^3
Payload Power	5 W (average), 10 W (peak)
Payload Data Rate	10 kbps (min), 100 kbps (peak)

This suite of instruments is designed to be batch manufactured to reduce costs through volume procurement, manufacture, integration, and test. The

GEOScan's Sensor Suite

About the size of a shoebox, each system sensor suite has been designed for easy accommodation within a small-sat or hosted payload accomidation. GEOScan will consist of six sensors plus planned space for PI-Proposed Sensors (PIPS). Each sensor suite includes:



- A GPS **Compact Total Electron Content Sensor (CTECS)** to measure Earth's plasma environment and gravity field (Appendix D.1).
- A **Radiometer** to measure Earth's total outgoing radiation (Appendix D.2).
- A **Compact Earth Observing Spectrometer (CEOS)** to measure aerosol-atmospheric composition and vegetation (Appendix D.3).
- A **MicroCam Multi-spectral Imager (MMI)** to image a uniform global view of Earth-land, oceans, vegetation and aurora (Appendix D.4).
- A **Dosimeter** package to image the radiation belts (Appendix D.5).
- A **MEMS Accelerometer** package to measure non-gravitational forces and aid neutral density studies (Appendix D.6).
- **PIPS** – 1.4U NSF competed student/researcher experiments and instrument suites (Page D-16).

conceptual packaging of the suite of sensors is shown in Figure 1 and a description of each instrument is in Table 2 of instruments.

3. Constellation System Science

The GEOScan concept employs a constellation approach to answer outstanding system science questions about the Earth and remote sensing of space environment state variables. GEOScan science goals can be achieved with either a homogeneous or ad-hoc heterogeneous constellation.

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.

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 2 shows reduced data acquired in a 10-min interval for 3 August 2010, 2200–2210 UT.

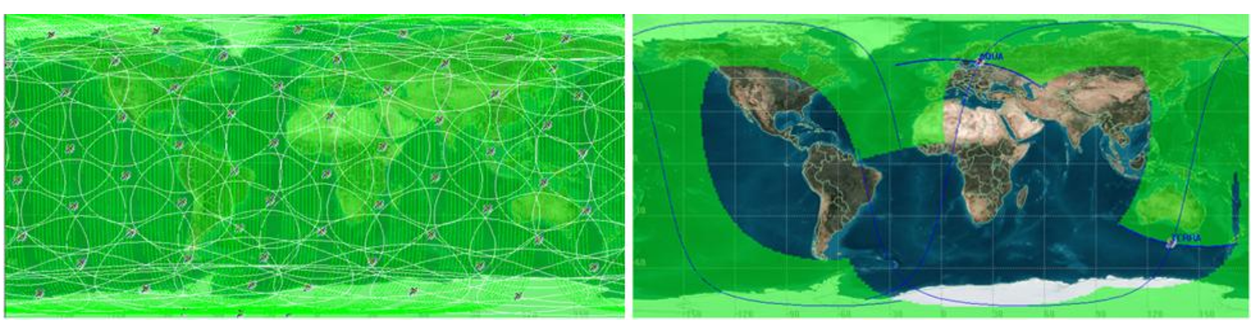


Figure 2: GEOScan achieves the science goals by providing superior spatial, temporal, angular, and local time coverage. Spatial coverage comparison between CERES on Terra and Aqua (right) and GEOScan's bolometer radiometer (left) for 1 hour. In a single hour, <60 GEOScan satellites will make 3600 global TOR samples, providing a statistical noise reduction factor of 60 every hour.

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 and the RAVAN CubeSat demonstration address Earth's current state of energy balance and climate change via a 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 imagers. This revolutionary coverage, shown in Figure 3, 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 (the RAVAN sensor) 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 Outgoing 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

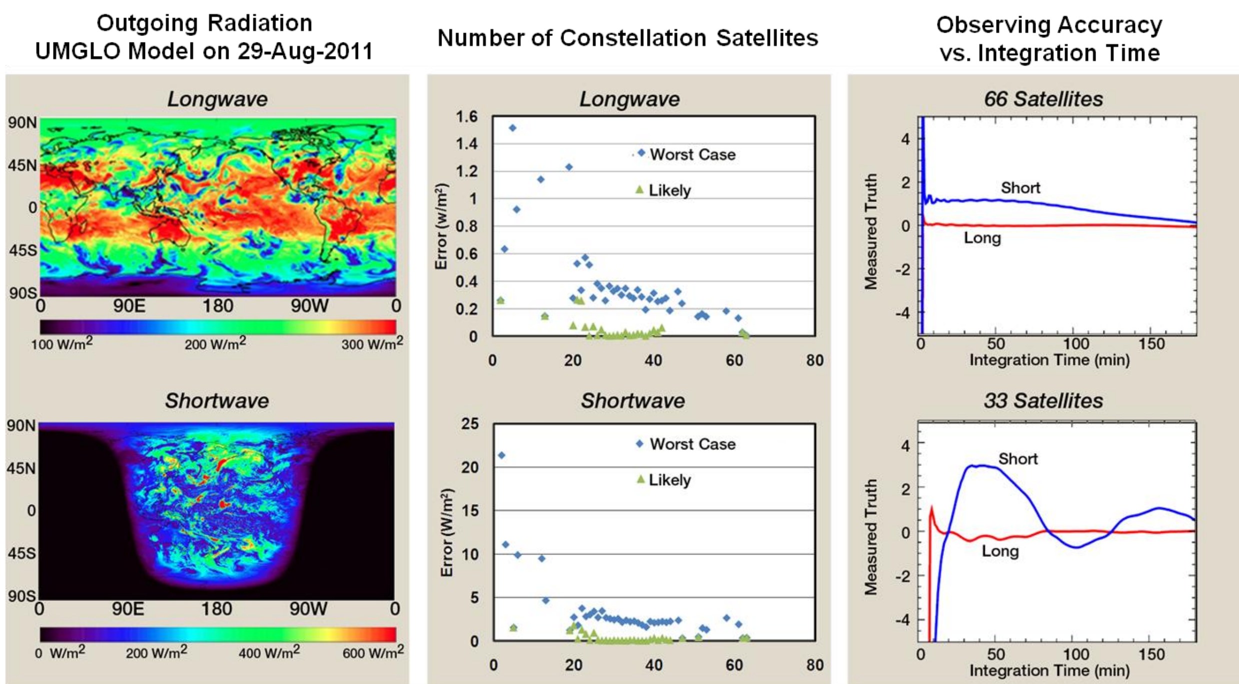


Figure 3: Simulated constellation observations showing that approximately 25-30 satellites are required for transformative Earth radiation measurements. Left: short- and longwave outgoing radiation from the UMGLO model used as "truth" for the simulations. Center: TOR accuracy for a 2-h integration time (plots show a statistical analysis of possible satellite configurations for 2 to 62 satellites). Bottom right: observing accuracy of 33 satellites an irregularly populated polar orbiting constellation resulting in the damped shortwave oscillations as a function of integration/averaging time. Top right: uniformly disturbed 66 satellites vs. integration/averaging time. The data processing scheme shown is simple averaging of the collected data; techniques such as tomographic and spherical harmonic fits for the actual TOR data would yield significant improvements.

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]

Figure 3 shows the results of numerous observing simulations based upon the UMGLO modeled radiative flux for an arbitrary day, 29 August 2010 [Allan et al., 2010]. Figure 3 summarizes the pertinent results from these simulations. The first plots on the left simply show the modeled short and long wave components of outgoing radiation. The middle plot shows TOR accuracy after 2 h integration as a function of satellite number for both likely and worst scenarios for an ad-hoc constellation. The next plots show that, using the 66 and 33 satellites, after 3h of data collection, a constellation network easily achieves both emitted and long-wave and reflected shortwave TOR accuracies. The middle and right plots were generated with simple averaging in order to make a straight-forward accuracy case. The more sophisticated techniques such a spherical harmonic representation achieves better than 0.1 W/m^2 over two hours. We are investigation a version of the tomographic algebraic reconstruction technique (ART) that optimally treats the overlapping observing geometry, which should also dramatically exceed this performance over shorter integration times [Dyrud and Murr, 2006].

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 present difficult research operational challenges that have not yet been met. Operational requirements for electron density [Air

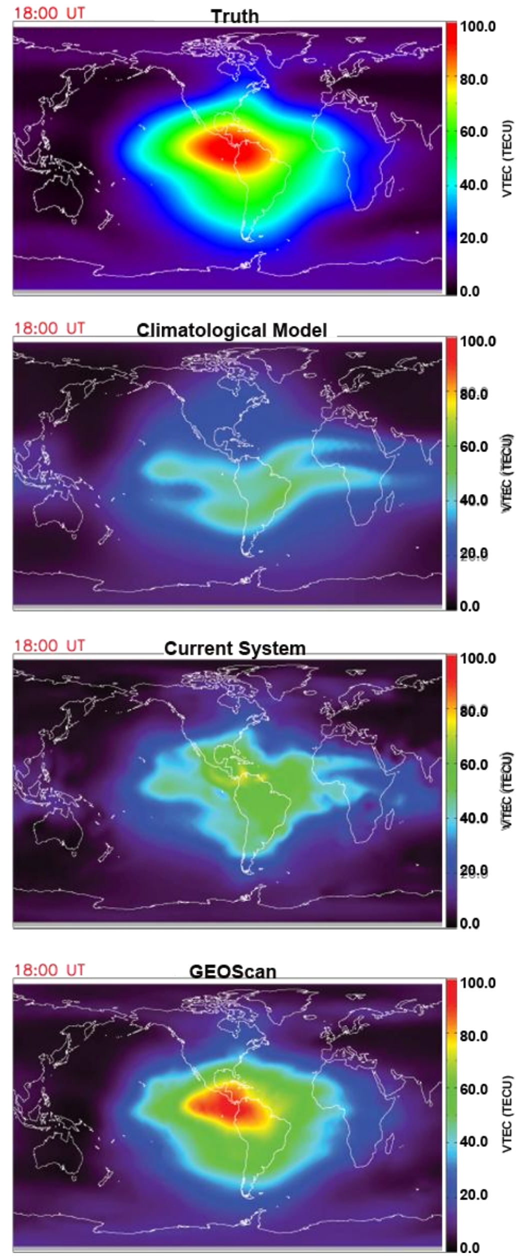


Figure 4: GEOScan tomographic imaging will fundamentally change our ability to understand geospace plasma dynamics. The top plot shows TIME-GCM simulated ionosphere for the geomagnetic super storm on 20 November 2003, treated as "truth" for simulating our observing system. This event is a strong "weather"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

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 achievable from 30 to 40 simultaneous measurements.* 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 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 4 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

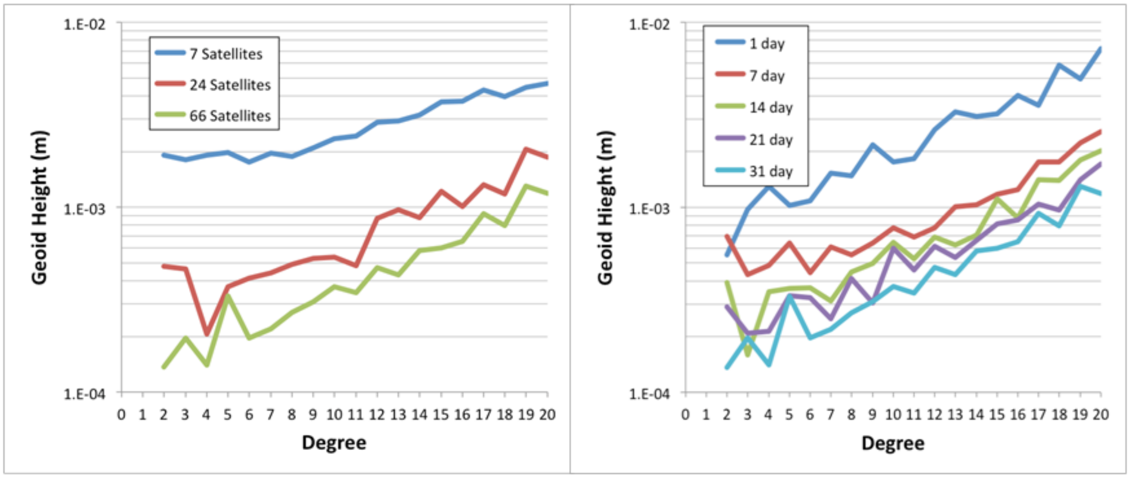


Figure 6: Simulations of constellation derived gravity accuracy represented in terms of geoid height uncertainty (m) versus spherical harmonic fit degree (1 global mode (divide 20,000 km by degree for approximate spatial resolution). The left hand side figure shows assumed a 31-day (similar to what GRACE produces) solution with realistic precise orbit determination noise assumptions (i.e., 2-3 cm GPS positioning error, similar to COSMIC). The right side of the figure shows these variations as a function of temporal resolution. All plots on the right hand are for a 66-satellite constellation, again with the same noise assumption.

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 a dual frequency GPS receiver, the absolute position of each satellite in the constellation 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

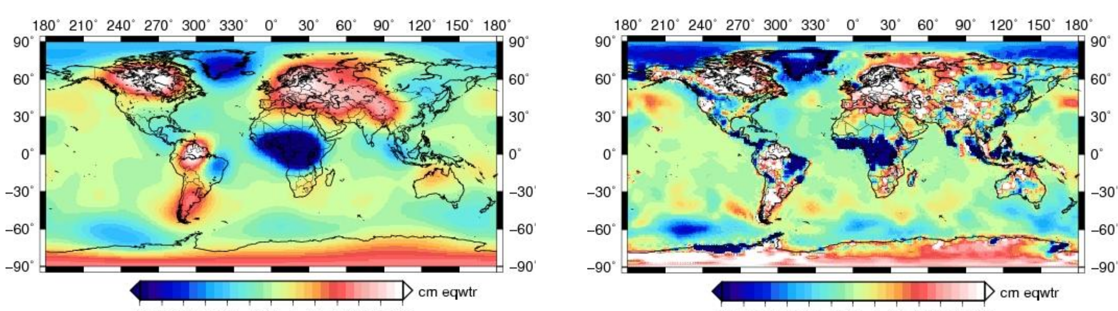


Figure 5: Illustration of the daily resolution expected from the GEOScan gravity products (right panel), as derived from a high-resolution coupled Earth system model (left panel). Units are in equivalent water height.

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 6 illustrates the type of time-variable gravity signals that would be detectable from a GEOScan deployment, in units of geoid height. For comparison sake, geoid variations induced by processes in the atmosphere, hydrology, ocean, cryosphere, are near 0.1 meter[6], as derived from a recently developed coupled Earth system model[10]. The variability of each process (in terms of square-root degree variances) at the daily and monthly time scales is shown in the two panels, with the simulated error curves of the GEOScan gravity products overlaid. For satellite numbers of 24-66 in a constellation can sense gravity measurements at sub-monthly time scales using only GPS, when aided with additional sensors such as inertial the sensitivity can be increased by an order of magnitude. Even with a 2-3 cm GPS positioning error, these sub-monthly measurements would complement the current high resolution, monthly GRACE measurements.

Figure 6 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.

4. 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 small-sat missions are firm fixed price commercial buses 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 (as planned for the Air Force's HEALER program). For GEOScan mid-scale production is planned at 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.

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.

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. This GEOScan 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, and Earth and Space Science. A 40-60 small-sat constellation with a 5-10 year lifetime will provide scientists and decision makers with transformative data at a fraction of the traditional cost of dedicated monolithic missions due to the use of COTS parts, low cost commercially available small satellites. A small-sat GEOScan can be built and launched for under $350M. GEOScan and the commercial small-sat industry demonstrate the synergetic potential of public-private partnerships that leverage commercial space capabilities and scientific measurement goals.

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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. 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.

8. 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.

9. 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.

10. 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.

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

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

13. 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.

14. 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.

15. 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.

16. 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

17. 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.

18. Selva, D., E. F. Crawley (2012) Modeling the Scientific Value of Earth Observing Missions. AIAA 2012

19. Warfield, K., and K. Roust, "The JPL Advance Projects Design Team's Spacecraft Instrument Cost Model: An objective, multivariate approach," First Annual Joint ISPA/SCEA Int. Conf., International Society of Parametric Analyists/Society of Cost Estimating and Analysis, Toronto, Ontario, Canada, 1998.

20. Stewart, Rodney, Richard M. Wyskida, and James D. Johannes. Cost Estimator's Reference Manual, 2nd Edition. Wiley-Interscience, 1995.