NASA

Navigating in Space
Taking GNSS to New Heights

The emergence of modernized and new GNSS systems has made possible the use of GPS signals combined with those from other constellations to support positioning and navigation applications above the orbits of GNSS satellites.

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Spacecraft in low Earth orbit (LEO), at altitudes below 3,000 kilometers, remain within the main Global Positioning System (GPS) signals' Earth coverage. Spacecraft employing GPS at these altitudes enjoy signal availability and navigation and timing performance emulating that of terrestrial users.

Until recently, the use of GPS on spacecraft that traverse above LEO and beyond the orbit of the GPS constellations was unproven and considered risky by spacecraft managers. The big question at the time was: would the power levels, availability, and accuracy of GPS signals at these altitudes facilitate navigation solutions and enhance mission objectives?

Flight experiments conducted around the turn of the new millennium demonstrated the viability of using GPS for navigation and time sensing in these high orbits by exploiting the full (aggregate) signal. In other words, employing the residual side-lobe signals in addition to the higher power, narrow, main Earth coverage signal.

Through a concerted effort by NASA, private industry, and others, specially designed weak signal GPS receivers were developed to support space missions at these high altitudes. New, exciting missions were proposed to make use of these navigation signals in space. Today, operational space missions are employing GPS above LEO and many other missions are in development.

Spacecraft using GPS in these orbits support a myriad of applications that protect Earth's inhabitants, through Earth and space weather detection and prediction, and revolutionize space missions through space vehicle formation flying, as examples. The emergence of modernized and new Global Navigation Satellite Systems (GNSS) affords spacecraft project managers a richer, more robust navigation sensing capability as the use of GPS signals combined with those from other GNSS constellations to support positioning and navigation applications above the orbits of GNSS satellites.

The expansion of the number of GNSS constellations, such as the European Union's Galileo, and China's BeiDou, and upgrades of existing constellations — GPS and Russia's GLONASS system — are enabling much more robust navigation solutions. This is accomplished through the substantial increase in the number of available signals, improved signal diversity, which improves navigation resiliency, and improved signal geometry, all of which enable improved end-user navigation performance.

Space user enhancements, made possible with interoperable GNSS signals, require key performance parameters specified across the constellations. The constellation providers and such regional augmentation systems as Japan's Quasi Zenith Satellite System (QZSS) and India's NavIC (Navigation Indian Constellation), are working diligently to achieve space user interoperability through forums such as the United Nations (UN)-sponsored International Committee on GNSS (ICG). These initiatives will result in improved capabilities for on-board autonomous positioning, navigation, and timing (PNT) at high altitude and better resilience to potential disruptions to the signals broadcast by any individual GNSS constellation.

GPS Use in HEO/GEO

GPS consists of a core volume of satellites in medium Earth orbit (MEO) transmitting one-way radio signals that are used to calculate three-dimensional position in the terrestrial and near-Earth domain, plus time. To achieve this, at least four GPS satellites are needed to be within line-of-sight at any given time to enable on-board real-time autonomous navigation through the formation of a point solution.

Continuous availability of at least four signals has become a standard expectation for GPS users up to 3,000 kilometers altitude, a region of space also known as the GPS Terrestrial Service Volume (TSV). However, as we move up in altitude beyond 3,000 kilometers, the number of available GPS signals decreases and, because of poor geometry and blockage of main beam reception by the Earth, four GPS signals are rarely available to enable formation of a point solution. Modern on-board navigation filters can operate with as little as one signal available at any one time, but the solution is not as accurate and even this level of availability can become less than continuous.

At these higher altitudes, the "spill-over" energy radiating over the limb of the Earth has come to define the utility and access of GPS (**Figure 1**). This more challenging signal processing environment has been designated as the GPS Space Service Volume (SSV), defined as the region of space between 3,000 kilometers altitude and geosynchronous orbit (GEO) altitude of about 36,000 kilometers (**Figure 2**).

Since 2004, NASA has been working with the U.S. Air Force to characterize and specify the performance of GPS within the SSV, which is currently defined in terms of user range error, minimum received power, and minimum signal availability of the Earth coverage GPS signals. For the L1 frequency, at GEO altitude the GPS SSV specification for a minimal 27-satellite-vehicle (SV) constellation calls for ≥ 1 signal(s) to be visible 80 percent of the time, and ≥ 4 visible one percent of the time, which is consistent with the performance provided by the traditional "spill-over" Earth coverage signal only. However, more advanced analyses and actual on-orbit mission measurements are now demonstrating that, in practice, the true capability of services in the space domain is much greater when using the full aggregate GPS signal. In fact, missions at and beyond GEO have tracked more than four GPS aggregate signals 100 percent of the time.

The Promise and Benefits of GNSS to High Altitude Space Users

Based on current demonstrated performance of GPS in space, many future high Earth orbit (HEO) missions are poised to benefit from improved navigation, timing, and on-board autonomy. **Figure 3** summarizes space mission applications enabled by precision GNSS navigation in HEO. These include remote sensing from GEO requiring precise geolocation (e.g., Earth and space weather operational satellite constellations), space science missions, highly maneuverable spacecraft that need real-time orbit knowledge during maneuvers, formation flying missions, and others.

Like their LEO cousins, missions in the SSV segment benefit from current GNSS capabilities, including fast

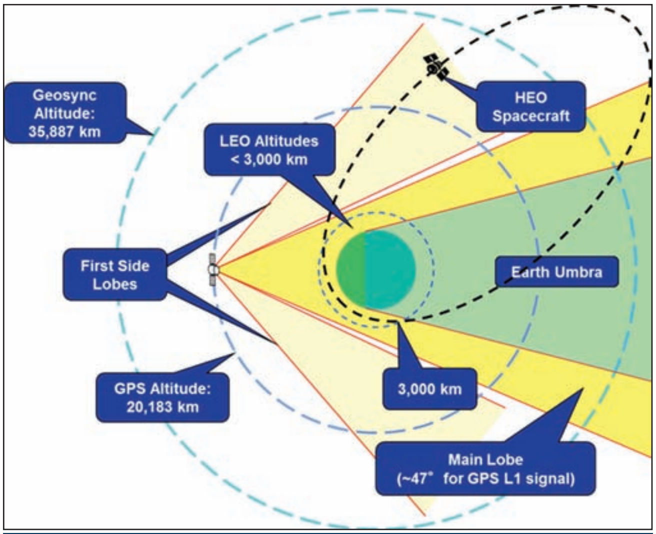

FIGURE 1 GNSS visibility limitations at higher altitude

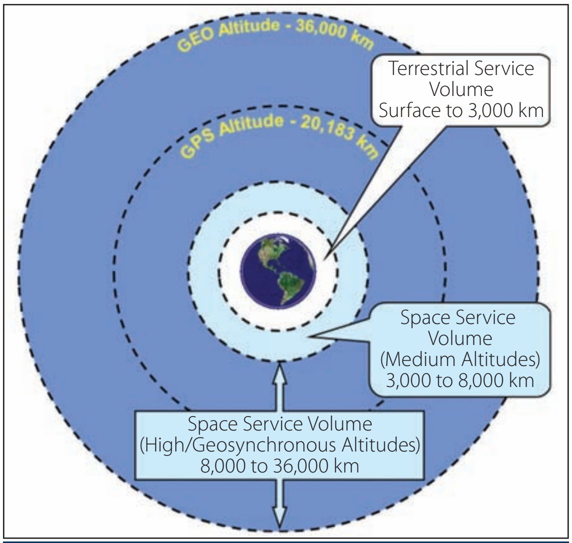

FIGURE 2 GPS Terrestrial Service Volume and Space Service Volume coverage

recovery from trajectory maneuvers, improved operations cadence, increased satellite autonomy, improved navigation performance, and precise timing reducing the need for expensive on-board clocks. These capabilities enhance mission data return and enable many benef ts to society.

A case example of the societal benefits is the joint NASA/National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) mission set. GOES is used by the National Weather Service (NWS) and others to enable weather predictions, severe storm warnings, and public safety information that saves lives and protects property. The next generation spacecraft series, GOES-R (GOES-R, S, T & U), which plans to be operational from 2016 to 2035, will employ GPS to substantially improve navigation as compared to previous generations. GOES-R's two key innovations—an improved imaging instrument coupled with GPS PNT — provide game-changing science products to substantially improved weather prediction capabilities and public-safety situational awareness of fast-moving events.

GOES-R illustrates the class of applications in which navigation performance must be maintained during, and subsequent to, propulsive maneuvers. On the legacy GOES satellites without GPS, station-keeping maneuvers mandated relaxing requirements for up to six hours post-maneuver, directly affecting the geolocation accuracy for tracking time-critical events such as tornadoes, flash floods, and forest f res.

By effectively tracking the aggregate GPS signals already radiating over the Earth's limb, signal availability is vastly improved, leading directly to precise rapid recovery from station-keeping maneuvers and accelerated data collection and processing during potential disaster scenarios. The GPS SSV is enabling substantial improvements in GOES weather products that enhance weather prediction and provide timely natural disaster warnings to people located in the Western hemisphere including:

- improved cloud-tracked wind measurements to increase warning times for those in severe storm danger zones
- exact location and volume of downpours in mountainous areas to support accurate, timely flash flood warnings
- timely, precise location of remote wild f res to enable safe placement of f ref ghters and equipment near f re outbreaks
- more accurate prediction of early morning fog for aviation operations
- ability to better observe and predict weather in mountainous areas, where weather radar is ineffective
- high imager tempo and spatial/spectral improvements that enable reliable blending of GEO-observed (high temporal resolution) with LEO-observed (high spatial resolution) meteorology as well as blending with ground-based radars.

Without suf cient GPS signal availability in the SSV, such improved products would simply not be available. GOES data users include everyone in the Western Hemisphere as they are directly impacted by weather and natural catastrophic events. Societal benef ts derived from GOES-R, as enabled by GPS, will include lives saved, property protected, and aircraft optimally routed. Scientists expect that reliable extended forecasting will stretch from three to f ve days now to f ve to seven days with GOES-R data, enabled by the nearly-continuous availability of GPS at GEO.

Another example of the capabilities that the GPS provides to space users in HEO is NASA's Magnetospheric Multi-Scale (MMS) mission. MMS, launched in March 2015, is a formation flyer consisting of four GPS-equipped spacecraft operating in a highly eccentric orbit to measure the properties and effects of space weather. MMS's Navigator GPS receiver has enabled onboard (autonomous) navigation well beyond GPS altitude, and its measurements have greatly improved our understanding of GPS performance in the HEO environment well beyond GEO. MMS effortlessly tracks 8 to 12 GPS signals in an orbit with an apogee at 70,000 kilometers, or approximately double the altitude of GEO, the formal boundary of SSV coverage. Thus, MMS has demonstrated GPS satellites' full capacity to support space users.

Flight data shows that the signal availability provided by a minimal 27–space vehicle GPS constellation while using the full aggregate signal is 100 percent for ≥ 1 signal(s), and 98 percent for ≥ 4 signals as reported in the presentation by F. H. Bauer, "GNSS Space Service Volume and Space User Data

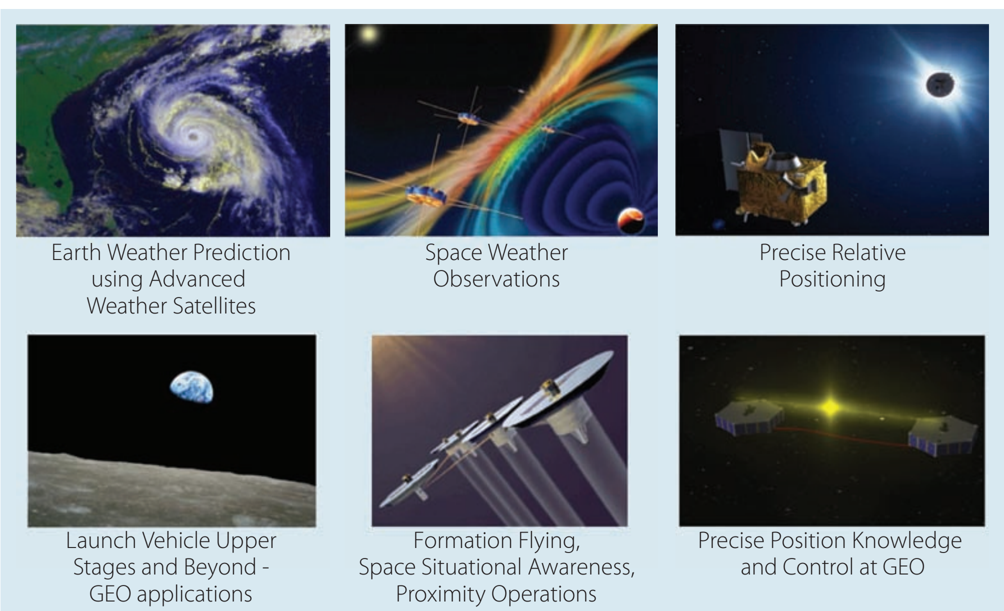

FIGURE 3 Current and future mission types in high Earth orbit benefiting from real-time GNSS navigation

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Update" at the 15th meeting of the GNSS Provider's Forum during the 10th meeting of the ICG (ICG-10) in November 2015. (See Addition Resources section near the end of this article for a full citation.)

Additional data and analyses of the GPS SSV, comparing predicted and measured performance, are described in other papers listed in the Additional Resources section as well. NASA has proposed an update to the GPS SSV specif cation to capture the needs of the emerging GPS SSV user base and to more accurately reflect the signal capabilities provided to high-altitude space users.

Other space missions in HEO/GEO that benefit from GPS/GNSS services range from science to space operations: space weather and heliospheric science, solar occultation, astrophysics, launch vehicle upper stages and interplanetary departure/return, space situational awareness, satellite servicing; formation flying, and optimizing GEO belt spacing for commercial spacecraft, i.e., higher precision station keeping that translates into enabling more spacecraft platforms to operate within the GEO belt. Thus, GPS truly becomes the cornerstone of an advanced space enterprise that is affordable and accessible to all, of great importance to the emerging commercial space sector in the United States.

Interoperable GNSS SSV through Multilateral Engagement at the ICG

The ICG is a UN forum, established in 2005, that meets annually to allow stakeholder organizations to coordinate on GNSS infrastructure and services. ICG benef ts people worldwide by promoting the use of GNSS, particularly in developing countries, by encouraging compatibility and interoperability amongst global and regional service providers.

The ICG consists of a Providers Forum and plenary supported by four working groups (WGs), namely: Global and Regional Navigation Satellite Systems, Signals and Services (WG-S, formerly WG-A for Radio Frequency Compatibility and Interoperability); Enhancement of Performance of GNSS Services (WG-B); Information Dissemination and Capacity Building (WG-C); and Reference Frames, Timing and

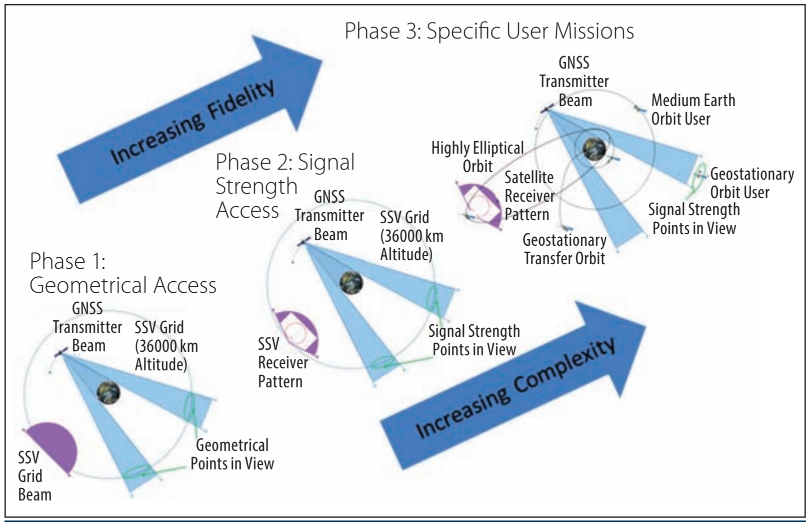

FIGURE 4 ICG WG-B assessment of Space Service Volume

Applications (WG-D). Most of the technical work to develop an interoperable Multi-GNSS Space Service Volume is done within ICG WG-B, which is then adopted by all attendees through ICG Plenary Joint Statements at the end of their work sessions. Work is conducted throughout the year in preparation for the annual meetings, usually held in November or December. (See ICG website, <http://www.unoosa.org/oosa/en/ourwork/icg/icg.html>.)

Four GNSS constellations are in operation or under deployment, along with a number of regional augmentations and regional navigation systems, some of which, such as QZSS and NavIC, also broadcast one-way ranging signals. As a result, a properly equipped user can access the signals from a combination of GNSS and regional constellations simultaneously to obtain improved performance and resiliency through enhanced signal availability, diversity, and geometry. The availability of this improved access is especially important at the higher altitudes of space missions due to the constraints noted earlier. However, this multi-constellation access requires constant coordination as the various systems come online and are modernized, specif cally: (1) interoperability among GNSS constellations, and (2) common definitions/specifications for use of GNSS signals within the SSV.

Once these core assumptions and requirements are agreed to and met by the PNT service providers, users will be able to optimize their spacecraft systems based on mission needs to enable continuous, real-time, on-board autonomous navigation for operations at the more challenging GEO/HEO altitudes. This is turn will lower mission operation costs, improve vehicle navigation performance, and allow for quick mission recovery after spacecraft trajectory maneuvers.

With these operational benefits in mind, in 2012 NASA introduced the SSV concept to the ICG, where it was adopted and has matured to a point in 2016 that all global and regional PNT service providers are in the process of characterizing the SSV performance of their own respective GNSS constellations in consultation with the world's space agencies. Several papers listed in the Additional Resources section address these efforts.

More recent contributions from NASA, and other space agencies within ICG WG-B, include conducting an independent assessment of the SSV using a multi-GNSS solution and developing GNSS flight experiments to validate signal performance. The independent assessment consists of three phases with increasing complexity and f delity (**Figure 4**).

Phase 1 of the assessment is a geometrical analysis of GNSS signal visibility at GEO altitude and was completed in May 2016. Phase 2 augments the Phase 1 geometrical accesses by constraining the solution via various minimum radio frequency (RF) signal level thresholds, and was completed in September 2016.

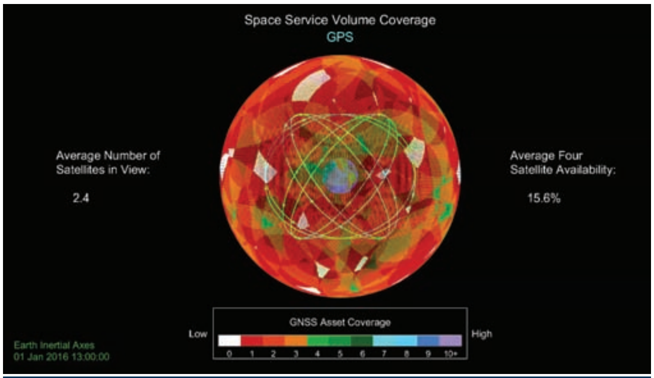

FIGURE 5 Geometric analysis showing L5 signal visibility at GEO of GPS-only

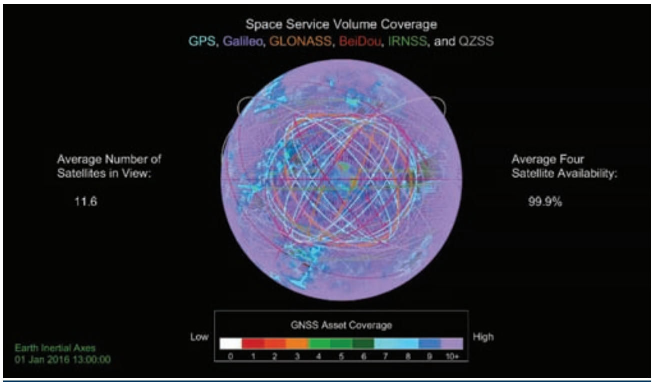

FIGURE 6 Geometric analysis showing L5 signal visibility at GEO of GPS, GLONASS, Galileo, BeiDou, NAVIC, and QZSS combined

Finally, Phase 3, which is currently under way, extends this analysis to specif c user missions including those in MEO, geostationary transfer orbits (GTO), and highly elliptical orbits. This assessment has demonstrated how the combination of the Earth coverage signal from multiple GNSS satellites can greatly improve navigation capabilities available to space users.

A preliminary geometric analysis using only mainbeam "spill-over" Earth coverage signals from each constellation shows that combining GPS and Galileo would enable an average of three satellites in view at GEO, with four satellites in view 30 percent of the time. By comparison, using all constellations (GPS, Galileo, GLONASS, BeiDou, QZSS, and NavIC) would enable four satellites visible at GEO approximately 95 percent of the time using the signals in the L1 frequency band. Further details are described in the paper by J. J. Miller *et alia* (2016B) listed in Additional Resources.

Detailed results for Phases 1 and 2 are described in articles by B. Welch listed in Additional Resources. The last two of those references are now fully published, dated November 2016. For example, **Figure 5** depicts the geometric analysis for L5 signal availability at GEO for GPS only, and **Figure 6** shows the results for all the GNSS constellations plus the QZSS and NavIC regional navigation systems.

The ICG has been key in the pursuit of a fully interoperable Multi-GNSS SSV, with discussions and recommendations encouraging other PNT service providers such as GLONASS, Galileo, BeiDou, QZSS, and NavIC to characterize the performance of GNSS services provided to space users and start developing formal specif cations. The ICG held its 11th annual meeting in Sochi, Russia, during the week of November 7–11, 2016. In preparation for this technical discussion, NASA has brought the latest flight data and analyses for discussion.

A key lesson learned is that GPS is still the "Gold Standard" for space-based PNT and, as such, NASA is proud to work with the U.S. Air Force to continue improving its capabilities. Missions such as NASA's MMS have set a world record for highest and fastest acquisition and tracking of the GPS signal thus far, and have set the stage for future enhancements. GPS capabilities in space have also set the goal high for other GNSS constellations seeking to provide similar services.

For space users, comparable availability and performance improvements will indeed become available as an interoperable GNSS SSV is incrementally realized by the work of the ICG. The ICG is making great strides in the coordination of interoperable signals and specif cations that enable space missions of the future to employ GNSS signals well beyond LEO, and all users will benef t.

Conclusion

A wide variety of space missions and applications stand to benef t from real-time on-board autonomous precision navigation in HEO either using GPS alone, or in combination with other GNSS signals. The ICG has become the world-wide forum where these benef ts and contributions come together into an evolving Multi-GNSS SSV.

In addition, recent operational missions have demonstrated that actual performance of GPS far exceeds the current SSV specif cations, which were developed over a decade ago when our understanding of the true performance of GPS in space was limited. It is now evident that once again GPS far exceeds all expectations, and for this NASA and our partner space agencies are grateful to the U.S. Air Force for providing this key infrastructure element.

The capabilities provided by the GPS aggregate signal structure (both main beam and side lobes) already serves critical public safety space missions such as the GOES-R satellite just launched, and even preserving a subset of these existing aggregate signal capabilities would be a vital enabler for the GPS of the future to operate as a stand-alone system to support critical U.S. missions even as new multi-GNSS service options become available.

Until then, comparable availability and performance improvements will be realized incrementally as an interoperable Multi-GNSS system becomes fully operational through the work of the ICG. The ICG is making great strides in the coordination of interoperable signals and specif cations that will enable all manner of space missions to employ GNSS signals well beyond LEO. NASA's looks forward to working with our partners to make this scenario a reality, with GPS as the cornerstone of the advancing U.S. space enterprise.

Additional Resources

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Authors

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A. J. Oria joined Overlook Systems Technologies, Inc. in 1998. Since 2003 he's provided GPS, navigation policy, and engineering subject matter expertise in support of PNT activities to the SCaN office at NASA Headquarters, and is currently program manager for NASA support. Prior to Overlook he worked in the United Kingdom, first as a research assistant at the College of Aeronautics in Cranfield University, and then research associate at the Institute of Engineering Surveying and Space Geodesy at the University of Nottingham. Oria received a Bachelor of Science in aerospace engineering (Magna Cum Laude) from Parks College of Saint Louis University, Missouri; a Master of Science in aeronautics and astronautics from Stanford University, California; and a Ph.D. in astronautics and space engineering from Cranfield University, United Kingdom. His doctoral dissertation was on "Spacecraft Operations in the Vicinity of an Active Comet."

Scott Pace is the director of the Space Policy Institute and a professor of practice in international affairs at George Washington University's Elliott School of International Affairs. His research interests include civil, commercial, and national security space policy, and the management of technical innovation. From 2005–2008, he served as the associate administrator for program analysis and evaluation at NASA. Prior to NASA, Pace was the assistant director for space and aeronautics in the White House Office of Science and Technology Policy. From 1993–2000, he worked for the RAND Corporation's Science and Technology Policy Institute (STPI). From 1990 to 1993, Pace served as the deputy director and acting director of the Office of Space Commerce, in the Office of the Deputy Secretary of the Department of Commerce. He received a Bachelor of Science degree in physics from Harvey Mudd College, Masters degrees in aeronautics & astronautics and technology & policy from the Massachusetts Institute of Technology, and a doctorate in policy analysis from the RAND Graduate School.

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Bryan W. Welch is an electronics engineer in the Advanced High Frequency Branch (Code LCF) at NASA Glenn Research Center (GRC) in Cleveland, Ohio. He contributes to several projects in the fields of communication and navigation system analysis. Welch currently supports the GRC SCENIC Project as the lead communications engineer and the GRC Cognitive Communications Project as the RF/communications lead of the SCAN Testbed payload, as well as having previously supported the GRC GPS/PNT Project as its technical lead and working with international partners of the International Committee on GNSS WG-B in its technical analysis development. Welch received a Bachelor of electrical engineering degree and Master of Science in electrical engineering from Cleveland State University. He is currently finalizing his dissertation research activities in support of an Engineering Ph.D. Welch joined NASA in 2002. IG

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