Update on NASA GPS Applications for Space Operations and Science

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55th Civil GPS Service Interface Committee Meeting
Tampa, Florida
15 September 2015
The Space Communications and Navigation (SCaN) program is responsible for providing worldwide communications & navigation services to enable and enhance robotic and human exploration and science missions.

SCaN leads in enabling NASA’s overall navigation capabilities through:
- standards development
- systems engineering
- architecture integration
- technology R&D
- spectrum coordination
- international interoperability
- national policy advocacy

Use of GPS/GNSS as another position and time source allows NASA to maximize the “autonomy” of spacecraft while reducing the burden on network operations and enabling countless science applications.
The 2004 U.S. Space-Based Positioning, Navigation, and Timing (PNT) Policy tasks the NASA Administrator, in coordination with the Secretary of Commerce, to develop and provide requirements for the use of the Global Positioning System (GPS) and its augmentations to support civil space systems.

The 2010 National Space Policy reaffirms PNT Policy commitments to GPS service provisions, international cooperation, and interference mitigation.

- Foreign PNT services may be used to augment and strengthen the resiliency of GPS.

Besides direct collaboration with interagency partners & foreign space agencies, NASA international engagement is conducted at:

- International Committee on Global Navigation Satellite Systems (ICG)
- International Telecommunications Union (ITU)
- Interoperability Plenary (IOP)
- Interagency Operations Advisory Group (IOAG)
- Space Frequency Coordination Group (SFCG)
- Consultative Committee for Space Data Systems (CCSDS)
2015-2017 PNT Board Membership: Focus is on Assured PNT through “PTA” (Protect, Toughen, Augment)

- **John Stenbit (Chair),** former DoD Chief Information Officer
- **Bradford Parkinson (Vice Chair),** Stanford University original GPS Program Director
- **James E. Geringer (2nd Vice Chair),** ESRI Former Governor of Wyoming
- **Thad Allen,** Booz Allen Hamilton retired Commandant of the Coast Guard
- **Penina Axelrad,** University of Colorado, Chair of Department of Aerospace Engineering
- **John Betz,** MITRE, Former Chair Air Force Scientific Advisory Board
- **Dean Brenner,** Vice President, Government Affairs Qualcomm
- **Scott Burgett,** Garmin International
- **Joseph D. Burns,** United Airlines, Former Chief Technical Pilot, United Airlines
- **Ann Ciganer,** VP Trimble Navigation, Director of GPS Innovation Alliance
- **Per K. Enge,** Stanford University, Head of Stanford Center for PNT
- **Martin C. Faga,** MITRE Retired CEO of Mitre
- **Dana A. Goward,** Resilient Navigation & Timing Foundation, Founder
- **Ronald R. Hatch,** consultant to John Deere, inventor of the GPS “Hatch” filter
- **Larry James,** Deputy Director, Jet Propulsion Laboratory
- **Peter Marquez,** Planetary Resources, Former White House National Security Space Policy
- **Terence J. McGurn,** private consultant, retired CIA analyst of Position, Navigation and Control
- **Timothy A. Murphy,** The Boeing Company, Technical Fellow with Boeing Commercial Airplane
- **Ruth Neilan,** Jet Propulsion Laboratory, vice chair, Global Geodetic Observing System
- **T. Russell Shields,** Ygomi, a founder of NavTeq

**International Members:**
- **Gerhard Beutler,** Professor of Astronomy and Director of the Astronomical Institute, U. of Bern.
- **Sergio Camacho-Lara,** Regional Centre for Space Science and Technology Education for Latin America and the Caribbean, Mexico
- **Arve Dimmen,** Division Director Maritime Safety Norwegian Coastal Administration (Norway)
- **Matt Higgins,** President International GNSS Society (Australia)
- **Rafaat M. Rashad,** Chairman Arab Institute of Navigation (Egypt)
• NASA’s policy sponsorship of PNT Board supplements technical contributions to GPS
  – Minutes, Recommendations, and Reports from taskings available at www.gps.gov
  – 15th meeting held Jun. 11-12, 2015, in Annapolis, MD
  – 16th meeting scheduled for Oct. 30-31, 2015 in Boulder, CO (in conjunction with the ICG 10th meeting)

• NASA’s technical contributions focus on improving space operations & science for all
  – RNSS spectrum protection
  – GPS-based science applications (radio-occultation, geodesy, earthquake/tsunami warning, etc.)
  – GPS/GNSS civil signal monitoring (operational performance)
  – GPS MEOSAR (search and rescue)
  – Laser Retro-reflector Arrays (LRAs) on GPS III
  – Multi-GNSS space receivers (GSFC “Navigator” & JPL “TriG” families)
  – Interoperable GNSS Space Service Volume (SSV)

• NASA contributes towards fulfilling national policy goals through application of technology
  “The U.S. maintains space-based PNT services that -- (1) provide uninterrupted availability of PNT services; (2) meet growing national, homeland, economic security, civil requirements, and scientific and commercial demands; (3) remain the pre-eminent military space-based PNT service; (4) continue to provide civil services that exceed or are competitive with foreign civil space-based PNT services; (5) remain essential components of internationally accepted PNT services; and (6) promote U.S. technological leadership in applications involving space-based PNT services.”

• Enhancing GPS precision and availability enables “cutting edge” science, which in turn allows science to be applied towards improving GPS performance -- i.e., Satellite Laser Ranging (SLR)...
Satellite Laser Ranging (SLR) on GPS III

- Laser ranging to GNSS satellites enables the comparison of optical laser measurements with radiometric data, identifying systemic errors.
- Post-processing this data allows for refining station coordinates, satellite orbits, and timing epochs.
- The refined data enables improved models and reference frames.
- This results in higher PNT accuracies for all users, while enhancing interoperability amongst constellations.
- NASA Administrator Bolden collaborated with Air Force Gen Shelton & Gen Kehler to secure approval for Laser Reflector Arrays (LRAs) on GPS III.

**Diagram:**
- Satellite Orbit
- Laser Reflector Array on a Satellite
- Laser Pulse
- Laser Ranging Station

**Steps:**
- Laser pulse (start)
- Photon return (stop)
- Measurement of round trip time of laser pulse
- Station coordinate and satellite orbit determination relative to Earth’s center

**GPS Block II SVs 35 & 36**

**Image:**
- Space Geodesy provides positioning, navigation, and timing reference systems and Earth system observations.
Search and Rescue from Space: Distress Alerting Satellite System evolves into SAR/GPS
NASA strategic navigation requirements for science and space ops continue to grow, especially as higher precisions are needed for more complex operations in all space domains.

- Nearly 60%* of projected worldwide space missions over the next 20 years will operate in LEO
  - That is, inside the Terrestrial Service Volume (TSV)
- An additional 35%* of these space missions that will operate at higher altitudes will remain at or below GEO
  - That is, inside the GPS/GNSS Space Service Volume (SSV)
- In summary, approximately **95% of projected worldwide space missions over the next 20 years** will operate within the **GPS service envelope**

\( (*) \) Source: Aerospace America, American Institute of Aeronautics and Astronautics (AIAA), Dec. 2007

### 20-Year Worldwide Space Mission Projections by Orbit Type

<table>
<thead>
<tr>
<th>Orbit Type</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Low Earth Orbit</td>
<td>59%</td>
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<tr>
<td>Medium Earth Orbit</td>
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<td>GeoSynchronous Orbit</td>
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<tr>
<td>Highly Elliptical Orbit</td>
<td>5%</td>
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<tr>
<td>Cislunar / Interplanetary</td>
<td>1%</td>
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<tr>
<td>Orbital Transfers</td>
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</table>
- LEO-to-GSO, cislunar transfer orbit, transplanetary injection, etc.
- **Medium Earth Orbit:**
  - GNSS Constellations, etc.,
- **GeoSynchronous:**
  - Communication Satellites, etc.,
- **Highly Elliptical Orbits**: Example: NASA MMS 4-satellite constellation.

\( (*) \) Apogee above GEO/GSO
**GNSS Mission Areas (1):**
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

<table>
<thead>
<tr>
<th>No.</th>
<th>Agency</th>
<th>Mission</th>
<th>GNSS Systems Used</th>
<th>GNSS Signals Used</th>
<th>GNSS Application</th>
<th>Orbit</th>
<th>Launch (Actual or Target)</th>
<th>Notes</th>
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<td></td>
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<td>Es</td>
<td>2006</td>
<td>CNES controls the in flight satellite.</td>
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<td>El (El)</td>
<td>2006</td>
<td>CNES controls the in flight satellite in case of emergency on behalf of NAMURNAX or FUTUREMAT</td>
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<td>Launch via Nov 12, 2006, CNES controls the satellite in routine operations; ESA operates the mission.</td>
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<td>The system is with 4 satellites launched in Dec 2011. Receiver: MOSAIC</td>
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<td>CNES controls the in flight satellite in case of emergency on behalf of JASON-1/2 or in case of emergency on behalf of FUTUREMAT or MIMOSA</td>
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<td>Precise Orbit Determination (POD), Time</td>
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<td>One satellite to be launched in 2018 Receiver: SKYLOGC</td>
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GNSS Mission Areas (3):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

<table>
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<tr>
<th>№</th>
<th>Agency</th>
<th>Mission</th>
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<th>Launch (Actual or Target)</th>
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<tbody>
<tr>
<td>51</td>
<td>NASA</td>
<td>ISS</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Attitude Dynamics</td>
<td>LEO</td>
<td>Since 1998</td>
<td>Integrated SPS receiver</td>
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<td>GPS</td>
<td>L1 C/A, L1L2, L1L2, L1L2, L1L2, L1L2</td>
<td>Precise Orbit Determination, Orientation, surface reflections</td>
<td>LEO</td>
<td>2020</td>
<td>BlackJack II mission retired 11 August 2013</td>
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<td>GRACE (2 satellites)</td>
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<td>Precise Orbit Determination, Orientation</td>
<td>LEO</td>
<td>2002</td>
<td>BlackJack receiver, joint mission with GLI</td>
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<td>57</td>
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<td>L1 C/A</td>
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<td>LEO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>58</td>
<td>NASA</td>
<td>ISS Commercial Crew and Cargo Program - Dragon</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>LEO</td>
<td>2013</td>
<td>C2P C/B receiver</td>
</tr>
<tr>
<td>59</td>
<td>NASA</td>
<td>ISS Commercial Crew and Cargo Program - Cygnus</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>LEO</td>
<td>2013</td>
<td>C2P C/B receiver</td>
</tr>
<tr>
<td>60</td>
<td>NASA</td>
<td>CONCEPTS (South Pole-Ontario)</td>
<td>GPS</td>
<td>L1 C/A, L1L2, L1L2, L1L2, L1L2, L1L2, L1L2, L1L2</td>
<td>Radio occultation, precision orbit, time</td>
<td>LEO</td>
<td>2013</td>
<td>BlackJack-based C2P, monitoring of GPS/NAV radio occultation began in June 2013</td>
</tr>
<tr>
<td>61</td>
<td>NASA</td>
<td>GPS</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit, time</td>
<td>LEO</td>
<td>2014</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>62</td>
<td>NASA</td>
<td>CRISTAL-B</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>LEO</td>
<td>2014</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>63</td>
<td>NASA</td>
<td>COSMIC-1B (5 satellites)</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L2C, L2C, GLONASS</td>
<td>Orbit, time</td>
<td>LEO</td>
<td>2014</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>64</td>
<td>NASA</td>
<td>DSCO</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L2C, L2C, GLONASS</td>
<td>Time transfer</td>
<td>LEO</td>
<td>2016</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>65</td>
<td>NASA</td>
<td>GRACE-2</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L1L2, L1L2, L1L2, L1L2, L1L2, L1L2, L1L2</td>
<td>Precise Orbit Determination, Oceanography</td>
<td>LEO</td>
<td>2016</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>66</td>
<td>NASA</td>
<td>BNO</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Radio, range, orbit, time</td>
<td>up to 26 Earth radii</td>
<td>2016</td>
<td>Navigator receiver (3 receivers)</td>
</tr>
<tr>
<td>67</td>
<td>NASA</td>
<td>CRISTAL-C</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>LEO</td>
<td>2016</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>68</td>
<td>NASA</td>
<td>CRISTAL-D</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>LEO</td>
<td>2016</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>69</td>
<td>NASA</td>
<td>CYGNSS (5 satellites)</td>
<td>GPS</td>
<td>L1 C/A, L2C, L2C, GLONASS, Galileo</td>
<td>Orbit, time</td>
<td>LEO</td>
<td>2016</td>
<td>Delay Mapping Receiver (DRM)</td>
</tr>
<tr>
<td>70</td>
<td>NASA</td>
<td>COSMIC-1A (5 satellites)</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L2C, GLONASS, Galileo</td>
<td>Orbit, time</td>
<td>LEO</td>
<td>2017</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>71</td>
<td>NASA/GCR</td>
<td>GRADE-FO</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L2C, L2C, GLONASS</td>
<td>Orbit, time</td>
<td>LEO</td>
<td>2018</td>
<td>Navigator receiver, joint mission with GLI</td>
</tr>
<tr>
<td>72</td>
<td>NASA</td>
<td>Jason-3</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L2C, L2C, GLONASS</td>
<td>Precise Orbit Determination</td>
<td>LEO</td>
<td>2018</td>
<td>Navigator receiver proposed</td>
</tr>
<tr>
<td>73</td>
<td>NASA</td>
<td>GRASP</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L2C, L2C, GLONASS</td>
<td>Precise Orbit Determination</td>
<td>LEO</td>
<td>2017</td>
<td>Navigator receiver proposed</td>
</tr>
<tr>
<td>74</td>
<td>NASA</td>
<td>GRACE-2</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L2C, GLONASS</td>
<td>Orbit</td>
<td>LEO</td>
<td>2016</td>
<td>Navigator receiver</td>
</tr>
<tr>
<td>75</td>
<td>NASA</td>
<td>INECER (6S)</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>LEO</td>
<td>2016</td>
<td>Navigator receiver</td>
</tr>
</tbody>
</table>
These reference tables were initially prepared for the Interagency Operations Advisory Group (IOAG), and then updated for the International Committee on GNSS (IGS). The objective is to ensure the scope and needs of the emerging space user community are documented and to enable space agencies to collectively analyze potential requirements for space applications using GNSS. Space agencies are positioned to help GNSS service providers plan for provision of PNT signals to support space users out to GeoSynchronous Orbit altitudes. Space agency stakeholders will provide user requirements to GNSS/PNT service providers as knowledge is gained – as Performance Standards and Interface Specifications are updated. Space agencies have been defining their space user performance needs for their respective GNSS constellations, and strengthening collaboration with other international bodies such as ICG to ensure implementation of such capabilities. As a result of these efforts, the Joint Statement issued at the 8th meeting of the ICG (ICG-8) includes language on the GNSS Space Service Volume:

Challenges for GPS use in Space

- GPS availability and signal strength requirements for PNT services originally specified for users on or near surface of Earth
  - Primarily land, air, and maritime users
- Many emerging space users of GPS beyond Low Earth Orbit
  - Not just Geostationary Orbit
- Space users above the terrestrial service volume (>3,000 km altitude) share unique GPS signal challenges
- GPS space flight experiments in high orbits have shown that existing signal availability becomes more limited due to:
  - Geometry between the SV and the space user
  - Vast signal strength changes due to signal path length variations (near/far problem)
- To formally stabilize GPS signals for high altitude space users, NASA worked with U.S. Air Force to create a new Space Service Volume (SSV) definition and specifications
What is a Space Service Volume (SSV)?

Current SSV Geometry Definitions

**SSV (High/Geosynchronous Altitudes)**
8,000 to 36,000 km

- Main Lobe Availability: Never 4+ sats
- Power: Weak signal levels

**Space Service Volume (Medium Altitudes)**
3,000 to 8,000 km

- Main Lobe Availability: nearly continuous 4+ sats
- Power: Some reduced levels

**Terrestrial Service Volume**
Surface to 3,000 km

- Missions <3000 km
- Main Lobe Availability: 4+ sats

Specification of SSV Availability & Signal Strength is Crucial for Reliable Space User Mission Designs
GPS Space Service Volume
Requirements / Performance Parameters

• Users in the SSV cannot always rely on conventional, instantaneous GPS solutions

• Thus, GPS III performance requirements for the SSV are established via three parameters:
  – Signal Availability
  – Received Power
  – Pseudorange Accuracy (also known as User Range Error, or URE): GPS III requirement ≤ 0.8 meter (rms)

• Benefits of defining SSV requirements for other Global Navigation Satellite Systems (GNSS):
  – Provide additional GNSS signals in space for much greater signal availability at higher altitudes
  – Enable new interoperable capabilities as new PNT systems emerge
  – Protect legacy applications and RNSS radio frequency (RF) spectrum as GNSS services evolve
  – Secure mission economies of scale that extend network capabilities for all participating space users
  – Increase onboard and safety for spacecraft operations while reducing burdens on network tracking and communications for all participating space users

GPS III Minimum Received Civilian Signal Power (dBW) Requirement

<table>
<thead>
<tr>
<th>Signal</th>
<th>Terrestrial Minimum Power (dBW)</th>
<th>SSV Minimum Power (dBW)</th>
<th>Reference Half-beamwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 C/A</td>
<td>-158.5</td>
<td>-184.0</td>
<td>23.5</td>
</tr>
<tr>
<td>L1C</td>
<td>-157.0</td>
<td>-182.5</td>
<td>23.5</td>
</tr>
<tr>
<td>L2 C/A or L2C</td>
<td>-158.5</td>
<td>-183.0</td>
<td>26</td>
</tr>
<tr>
<td>L5</td>
<td>-157.0</td>
<td>-182.0</td>
<td>26</td>
</tr>
</tbody>
</table>

GPS III Availability*

<table>
<thead>
<tr>
<th></th>
<th>MEO SSV</th>
<th>HEO/GEO SSV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at least 1 signal</td>
<td>4 or more signals</td>
</tr>
<tr>
<td>L1</td>
<td>100%</td>
<td>≥ 97%</td>
</tr>
<tr>
<td>L2, L5</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

(*) Assumes a nominal, optimized GPS III constellation and no GPS spacecraft failures. Signal availability at 95% of the areas within the specific altitude.
Expanding the GPS Space Service Volume (SSV) into a multi-GNSS SSV

- At least four GNSS satellites in line-of-sight are needed for on-board real-time autonomous navigation
  - GPS currently provides this up to 3,000 km altitude
  - Enables better than 1-meter position accuracy in real-time
- At GSO altitude, only one GPS satellite will be available at any given time.
  - GPS-only positioning at GSO is still possible with on-board processing, but only up to approx. 100-meter absolute position accuracy.
  - GPS + Galileo combined would enable 2-3 GNSS sats in-view at all times.
  - GPS + Galileo + GLONASS would enable at least 4 GNSS sats in-view at all times.
  - GPS + Galileo + GLONASS + Beidou would enable > 4 GNSS sats in view at all times. This provides best accuracy and, also, on-board integrity.
- However, this requires:
  - Interoperability among these the GNSS constellations; and
  - Common definitions/specifications for the Space Service Volume (3,000 km to GSO altitude)

≥ 4 GPS satellites in line-of-sight here (surface to 3000 km)

Only 1-2 GPS satellites in line-of-sight here (GSO)… but, if interoperable, then GPS + Galileo + GLONASS + Beidou provide > 4 GNSS sats in line-of-sight at GSO.
GPS SSV Limitations & Knowledge Gained Since

- 2003-2006 CDD update performed despite limited understanding of GPS signal strength & availability in SSV
- At the time, on-orbit data limited to brief flight experiments above the constellation
  - Most comprehensive data from AMSAT-Oscar-40 flight experiment which spanned several weeks
- Over the past decade, significant SSV-relevant knowledge gained from:
  - Performance and capabilities of newly developed weak signal spaceborne receivers (e.g. Navigator)
  - Additional flight experiments (e.g. GIOVE)
  - Released GPS Antenna Pattern measurement data
  - On-orbit mission performance in HEO (e.g. GPS ACE & MMS)
Magnetospheric Multi-Scale (MMS)

- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Phase 1: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - Phase 2: Extends apogee to 25 Re (~150,000 km)

MMS Navigator System

- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set a record for the highest-ever reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set a record as the fastest operational GPS receiver in space, at velocities over 35,000 km/h
# Measured Performance with Side Lobe Signal Availability

## Signal Availability Contributed by Side Lobes
(Assumes 24 Satellite Constellation)

<table>
<thead>
<tr>
<th>L1 Signal Availability</th>
<th>Main Lobe Only</th>
<th>Main and Side Lobes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 or More SVs Visible</td>
<td>Never</td>
<td>99%</td>
</tr>
<tr>
<td>1 or More SVs Visible</td>
<td>59%</td>
<td>Always</td>
</tr>
<tr>
<td>No SVs Visible</td>
<td>41%</td>
<td>Never</td>
</tr>
</tbody>
</table>

**Current Spec:** L1 Signal Availability → 4 or more SVs visible: >1%

## Recent Flight Data From Magnetosphere Multi-Scale (MMS) Mission

**Current spec:** **Four** or more PRs shall be available more than or equal to 1% of the time

**MMS is seeing 100%**
Reception Geometry for GPS Signals in Space

- **Geosync Altitude:** 35,887 km
- **LEO Altitudes:** < 3,000 km
- **GPS Altitude:** 20,183 km
- **3,000 km
- **Main Lobe:** (~47° for GPS L1 signal)
- **HEO Spacecraft
- **Earth Umbra
Benefits of Aggregate (Main & Side Lobe) GPS Signal Use

• Would give “green light” for space Project Managers / Mission Planners to consider GPS for future space missions beyond LEO

• Would substantially enhance HEO/GEO missions and new mission types through:
  • Significantly improved signal availability
  • Improved navigation performance
  • Improved Position Dilution of Precision (PDOP)
  • Faster mission restoration after trajectory maneuvers, supporting...
    – Agile, maneuvering space vehicles
    – Improved science return
    – Formation/Cluster flight

Protection of Aggregate GPS Signals Minimizes Risk to Future HEO/GEO Missions and Allows Project Managers to Exploit all Signals in Space
SSV Development Acknowledgements

• Sincere thanks to all in the U.S. that have helped realize the Space Service Volume vision and continue working towards improving it:
  – USAF SMC GPS-Directorate
  – GSFC Antenna Characterization Experiment (ACE) Team
  – GSFC Magnetospheric Multi-Scale (MMS) Mission Team
  – Frank Bauer
  – E. Blair Carter
  – Stephan Esterhuizen
  – Dale Force
  – Arthur Hutchinson
  – Jim Johansen
  – Thomas Johnson
  – Jules McNeff
  – James Miller
  – Mike Moreau
  – A. J. Oria
  – Scott Pace
  – John Rush
  – Joel Parker
  – Park Temple
  – Jennifer Valdez
  – Larry Young

• Also acknowledging, in advance, all outside the U.S. that recognize the in-space advantages of the Space Service Volume specification and provide leadership in developing a Space Service Volume specification for their GNSS constellation
• NASA and other space users increasingly rely on GPS/GNSS over an expanding range of orbital applications to serve Earth populations in countless ways.

• The United States will continue to work towards maintaining GPS as the “gold standard” as other international PNT constellations come online.

• NASA is proud to work with the USAF to contribute making GPS services more accessible, interoperable, robust, and precise for all appropriate users.

• GPS precision enables incredible science, which in turn allows NASA to use this science to improve GPS performance.

“On Target with GPS Video”
www.youtube.com/watch?v=_zM79vS nD2M
Backup
GPS-III LRA Implementation Update

- Systematic co-location in space through the precision orbit determination of GPS satellites via satellite laser ranging will contribute significantly towards improving the accuracy and stability of the International and WGS 84 Terrestrial Reference Frames
- NASA-DoD partnership to support laser ranging of next generation GPS satellites
  - Naval Research Lab supporting the development and testing of the flight arrays
  - National Geospatial-Intelligence Agency supporting the integration of the arrays with the satellite vehicles
- AFSPC-NASA-STRATCOM Memorandum of Understanding signed on August 22, 2013
- NASA has planned for the delivery of at least 27 arrays

- Successful LRA Preliminary Design Review (PDR) on April 25, 2013
- Sub-array successfully demonstrated spacecraft compatibility in September 2013
- Interface Control Document (ICD-GPS-824) approved by GPS Change Configuration Board on Jan 23, 2014
- Completed Engineering Qualification Model (EQM) assembly on Nov 7, 2014
- Draft joint NASA-DoD Concept of Operations developed and going through DoD approval cycle
- Development and Implementation is a collaboration between Goddard Space Flight Center, NGA, and NRL

LRA Engineering Qualification Model
7-Aperture Sub-Array


These and other NASA References:

http://www.emergentspace.com/related_works.html
Mid-1990s—Efforts started to develop a formal Space Service Volume
- Discussion/debate about requiring “backside” antennas for space users
- Use of main lobe/side-lobe signals entertained as a no cost alternative

1997-Present—Several space flight experiments, particularly the AMSAT-OSCAR-40 experiment demonstrated critical need to enhance space user requirements and SSV

February 2000—GPS Operational Requirements Document (ORD), released with first space user requirements and description of SSV

- Shortcomings
  - Did not cover mid-altitude users (above LEO but below GPS)
  - Did not cover users outside of the GEO equatorial plane
  - Only specified reqts on L1 signals (L2 and L5 have wider beam-width and therefore, better coverage)

2000-2006—NASA/DoD team coordinated updated Space User reqmts
- Worked with SMC/GPE, Aerospace support staff & AFSPC to assess impacts of proposed requirements to GPS-III
- Government System Spec (SS-SYS-800) includes threshold reqmnts
- Shortcomings:
  - Developed with limited on-orbit experiment data & minimal understanding of GPS satellite antenna patterns
  - Only specifies the main lobe signals, does not address side lobe signals
GPS and Human Space Flight: Past, Present, and Future

- **Space Shuttle Program**
  - Specialized MAGR GPS receivers were designed to accept Inertial Navigation System (INS) aiding
  - One GPS receiver (retaining TACAN as backup) was installed on Discovery and Atlantis
  - Three GPS receivers on Endeavour (TACAN was removed)

- **International Space Station (ISS)**
  - Combined GPS + INS receiver tested on shuttle flights in April 2002 (STS-110 / Atlantis)
  - Four GPS antennas on the ISS truss assembly
  - Used for attitude determination
  - Relative GPS navigation used for rendezvous of ISS unmanned resupply

- **Orion**
  - Two Honeywell GPS receivers integrated with INS
  - Highly sensitive RF radio can track weak signals from the GPS constellation half way to the moon
  - Orion Exploration Flight Test-1 (1st unmanned flight) launched on Delta-IV in Dec. 2014
Additional HEO/GEO GPS Enablers

• Weak signal spaceborne receivers, including NASA GSFC’s Navigator
  – HEO/GEO performance enabled through:
    • Weak signal acquisition and tracking (25 dB-Hz)
    • Integrated on-board navigation filter (GEONS)
    • Radiation hardness
  – Navigator innovations incorporated in commercial HEO/GEO receivers developed by Moog Broad Reach, Honeywell and General Dynamics

• U.S. Publication of GPS Block IIR & IIR(M) Antenna Patterns

• International Engagement in HEO/GEO GNSS Operations
  – GIOVE on-orbit antenna measurement experiment
  – HEO/GEO receiver development
### TriG Future Missions and Configurations

<table>
<thead>
<tr>
<th>TriG Payload Type</th>
<th>Description</th>
<th>Mission Phase</th>
<th>Launch</th>
<th>System Mass (kg) CBE</th>
<th>Power Est (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Space Atomic Clock</td>
<td>Precise Clock Validation Timing using Precise Orbit Determination</td>
<td>Phase C/D</td>
<td>Mid 2016</td>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>COSMIC 2 Equatorial</td>
<td>Radio Occultation and Space Weather Observations.</td>
<td>Phase C/D</td>
<td>Mid 2016</td>
<td>12</td>
<td>65</td>
</tr>
<tr>
<td>Grace FO IPU</td>
<td>Micron Ranging and Precise Orbit Determination Some RO</td>
<td>Phase C/D</td>
<td>August, 2017</td>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>SWOT</td>
<td>Precise Orbit Determination 1553 comm card</td>
<td>Phase A</td>
<td>2020</td>
<td>6</td>
<td>35</td>
</tr>
<tr>
<td>Ni-SAR</td>
<td>Precise Orbit Determination Cold Spare</td>
<td>Phase A</td>
<td>2021</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>JASON CS</td>
<td>Precise Orbit Determination Radio Occultation 1553 comm card</td>
<td>Pre Phase A</td>
<td>2020</td>
<td>22</td>
<td>65</td>
</tr>
</tbody>
</table>
GPS Antenna Characterization Experiment (ACE)

• GPS ACE project deployed advanced GPS receivers at the ground station of a Geostationary Earth Orbit (GEO) satellite
• Collection of side lobe data as seen at GEO in order to characterize the transmit antenna patterns
• On July 8, 2015 the GPS ACE NASA Team was awarded the Group Achievement Award by the NASA Administrator for contributions to an unprecedented intergovernmental collaboration to perform the first comprehensive, on-orbit characterization of GPS satellite side-lobe transmissions
• The project will contribute to the development of the GPS SSV

GPS ACE NASA Team

The current GPS spec only covers out to an angle of 23.5°

In-Flight Measurement Average from GPS IIF SVs

In-Flight Measurement Average from GPS IIR-M SVs
• In the first month after launch, the MMS team began turning on and testing each instrument and deploying booms and antennas.
  – During this time, the team compared the Navigator system with ground tracking systems and found it to be even more accurate than expected
  – At the farthest point in its orbit, some 76,000 km from Earth, Navigator can determine the position of each spacecraft with an uncertainty of better than 15 meters
  – The receivers on MMS have turned out to be strong enough that they consistently track transmissions from eight to 12 GPS satellites – excellent performance when compared to pre-flight predictions of frequent drop outs during each orbit
SSV specifications are crucial for space users, providing real-time GPS navigation solutions in High Earth Orbit

- Supports increased satellite autonomy for missions, lowering mission operations costs
- Significantly improves vehicle navigation performance in these orbits
- Supports quick mission recovery after spacecraft trajectory maneuvers
- Enables new/enhanced capabilities and better performance for HEO and GEO/GSO future missions, such as:

- Improved Weather Prediction using Advanced Weather Satellites
- Space Weather Observations
- En-route Lunar Navigation Support
- Formation Flying & Constellation Missions
- Military Applications
- Closer Spacing of Satellites in Geostationary Arc
Augmenting GPS in Space with TASS

1) User Acquires GPS signals
2) GDGPS Tracks GPS signals
3) GEO Satellite Relays Differential Corrections to User
4) Evolved TASS could incorporate:
   - GPS integrity information
   - Tracking satellite information (health, ephemerides, maneuvers)
   - Space weather data
   - Solar flux data
   - Earth orientation parameters
   - User-specific commands
   - PRN ranging code
A GNSS Augmentation to the Tsunami Early Warning System Requires International Cooperation and Data Sharing

- The Pacific Region is well populated with GNSS CORS Networks - many that stream data in real-time
- Several research groups have worked to advance GNSS-aided rapid earthquake magnitude assessment and tsunami wave prediction
- Several international teams have recommended the establishment of a GNSS-aided tsunami warning network.
- The UN General Assembly, IUGG, IGS have issued resolutions for the sharing of geodetic data to mitigate Natural Hazards.

Existing GNSS stations if streamed and analyzed in real-time will provide:
- Rapid and more accurate tsunami warnings
- Basin wide tracking of propagating tsunamis