Title  Use of GNSS for Future Space Operations and Science Missions
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Executive Summary

• Current NASA use of GNSS: Autonomous navigation and experiment control, attitude determination, docking initial approach, timing, space shuttle orbit and re-entry, aeronautical, earth science

• Upcoming missions that rely on GNSS: Glory, LandSat, COSMIC IIA/IIB, Jason III, GPM, Orion Crew Vehicle, MMS, CLARREO, GOES-R, DESDynI

• GPS/GNSS supports/enables: Smart sensor webs, advanced climate studies, common docking system, conjunction analyses, redundancy for autonomous operations, GPS Metric Tracking, space weather monitoring, TDRS Augmentation Satellite System, accurate PNT

• Most missions also rely on ground-based correction networks for accuracy enhancements (Global Differential GPS)
Overview

• Background
  – GPS terrestrial and space service volumes
  – Current NASA use of GNSS
  – GPS-dependent missions/programs

• Opportunities/Risks
  – Technologies under development
  – Applications to upcoming missions
  – Emerging space use of GPS/GNSS
  – GPS/GNSS risk areas

• Investments
  – Existing and planned space GNSS receivers
  – Technology development areas
  – Standards/testing/monitoring
GPS Terrestrial & Space Service Volumes

- Terrestrial Service Volume (TSV)
  - Earth surface to 3,000 km
  - instantaneous, 100% coverage
  - meter-level accuracy

- Space Service Volume (SSV)
  - 3,000 to 36,000 km (GEO)
  - Medium Earth Orbit
    - 3,000 to 8,000 km
    - typically instantaneous
    - meter-level accuracy
  - High Earth Orbit / GEO
    - 8,000 to 36,000 km
    - over-earth-limb reception
    - lower power levels
    - mostly not instantaneous
    - 10-100 m accuracy

Nearly 60% of projected worldwide space missions 2008-2027 will operate in LEO: inside the GPS Terrestrial Service Volume.

Nearly 35% of projected space missions will operate at MEO and GEO altitudes: inside the GPS Space Service Volume.

Combined, approximately 95% of projected worldwide space missions over the next 20 years will operate within the GPS Service Volume.

Source: Aerospace America, Jan 2008
Current NASA Use of GPS/GNSS

- Autonomous navigation and experiment control (e.g. TIMED)
- Attitude determination (e.g. ISS)
- Docking initial approach (e.g. ISS)
- Timing
- Space shuttle orbit and re-entry
- Aeronautical
- Earth science
  - cm-level orbit determination
  - Relative navigation
  - Geodesy and geodynamics
  - Remote sensing
  - Ionospheric science
  - Climate studies
  - Occultation science

- Note: For operational use, applications are designed to rely on GPS performance standards only. Other GNSS may be used as long as the operation does not depend on the other GNSS.
- For scientific use, all GNSS may be used, which can be cost-effective (e.g. three GNSS are more cost-effective than tripling a LEO constellation for radio occultation measurements)

## Current GPS-Dependent Missions/Programs

<table>
<thead>
<tr>
<th>Mission/Program</th>
<th>Application</th>
<th>Science/Notes</th>
<th>Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Shuttle</td>
<td>Orbit and re-entry</td>
<td>Operations</td>
<td>1993-present</td>
</tr>
<tr>
<td>CHAMP</td>
<td>Precise orbit (5 cm, 0.05 mm/s)</td>
<td>Occultation, gravity, surface reflections</td>
<td>2000-present</td>
</tr>
<tr>
<td>SAC-C (Argentina, US, Brazil, Denmark, France, Italy)</td>
<td>Precise orbit (7 cm, 0.07 mm/s)</td>
<td>Occultation, surface reflections</td>
<td>2000-present</td>
</tr>
<tr>
<td>Jason 1/2 (French/US)</td>
<td>Rapid orbit</td>
<td>Oceanography</td>
<td>2001-present</td>
</tr>
<tr>
<td>TIMED</td>
<td>Orbit, time</td>
<td>Autonomous experiment control</td>
<td>2001-present</td>
</tr>
<tr>
<td>Deep Space Network</td>
<td>GDGPS</td>
<td>Radio signal calibration, near real-time troposphere and ionosphere TEC maps</td>
<td>current</td>
</tr>
<tr>
<td>NASA CDDIS</td>
<td>Data services, GDGPS</td>
<td>Space geodesy, geodynamics</td>
<td>current</td>
</tr>
<tr>
<td>International Space Station</td>
<td>Orbit, time, attitude, docking</td>
<td>Numerous applications</td>
<td>current</td>
</tr>
<tr>
<td>ISS Service Module</td>
<td>Absolute and relative GPS</td>
<td>Approach to within 280 m to ISS</td>
<td>current</td>
</tr>
<tr>
<td>GRACE (US/Germany)</td>
<td>Precise orbit (2-4 mm baseline), 150 ps biased time transfer</td>
<td>Occultation, gravity</td>
<td>2002-present</td>
</tr>
<tr>
<td>ICESat</td>
<td>Precise orbit (5 cm)</td>
<td>Climate, remote sensing</td>
<td>2003-present</td>
</tr>
<tr>
<td>COSMIC</td>
<td>Precise orbit (7 cm, 0.07 mm/s)</td>
<td>Occultation</td>
<td>2006-present</td>
</tr>
<tr>
<td>CloudSat, CALIPSO (US/France)</td>
<td>Orbit determination</td>
<td>Earth science; GPS used for SINAHI collision avoidance</td>
<td>2006-present</td>
</tr>
<tr>
<td>TASS</td>
<td>Real-time orbit/clock corrections</td>
<td>With integrity</td>
<td>2006-present</td>
</tr>
<tr>
<td>FERMI (Fermi Gamma-Ray Space Telescope)</td>
<td>Orbit determination, time</td>
<td>Timing of Pulsars</td>
<td>2008-present</td>
</tr>
<tr>
<td>C/NOFS</td>
<td>Dual-frequency measurements</td>
<td>Detect/forecast ionosphere scintillation</td>
<td>2008-present</td>
</tr>
<tr>
<td>Ariane Transfer Vehicle (ATV)</td>
<td>Absolute and relative GPS</td>
<td>Approach to within 250 m to ISS</td>
<td>2008, 2010</td>
</tr>
<tr>
<td>H-II Transfer Vehicle, Japanese experiment module (JEM)</td>
<td>Absolute GPS and rendezvous with ISS</td>
<td>Approach to within 500 m to ISS</td>
<td>2009 and 1-2 per year</td>
</tr>
</tbody>
</table>
Technologies under Development

• GPS modernization: new signals (L5/L2C/L1C), retro-reflectors, well-defined Space Service Volume

• GLONASS modernization, Galileo, Compass

• Advanced space GNSS receivers
  – Software radios; multiple frequencies, multiple GNSS
  – High-sensitivity processing
  – Beam-forming/steering antennas
  – Onboard Kalman filter for accurate orbit/trajectory estimation
  – Acquisition and tracking algorithms for GEO/HEO dynamics
  – Onboard processing (requires accurate orbit/time)

• Advanced space clock: Mercury-Ion ($10^{-15}$)
  – Enables positioning and improved geometry with 3 GPS satellites

• TDRS Augmentation Satellite System (TASS)
GPS concepts beyond the SSV

- Use of GPS satellites
  - Trans-lunar navigation (Orion)
    - Trans-lunar injection and cruise
    - Out to Earth-Moon L1 libration point

- Use of GPS signal structure
  - TDRS broadcast of GPS signal structure
  - Moon/Mars Relay Satellites with a GPS signal structure
  - Moon/Mars beacons with a GPS signal structure
  - GRAIL lunar gravity mission will use the GPS signal structure to transfer time between the pair of spacecraft

- Clock distribution
  - Time dissemination system with characteristics suitable for solar-system-wide operations
    - One-way navigation, VLBI, sensor webs, enhanced radio-science

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## Applications to Upcoming Missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>GNSS</th>
<th>Application</th>
<th>Orbit</th>
<th>Receiver</th>
<th>Signals</th>
<th>Launch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glory</td>
<td>GPS</td>
<td>Orbit</td>
<td>LEO</td>
<td>BlackJack</td>
<td>L1</td>
<td>2010</td>
</tr>
<tr>
<td>LandSat</td>
<td>GPS</td>
<td>Orbit</td>
<td>LEO</td>
<td>GD Viceroy</td>
<td>L1</td>
<td>2012</td>
</tr>
<tr>
<td>COSMIC IIA</td>
<td>GPS, GLONASS, Galileo</td>
<td>Occultation</td>
<td>LEO</td>
<td>TriG (potential)</td>
<td>L1, L2, L5, Galileo, GLONASS</td>
<td>2013</td>
</tr>
<tr>
<td>Jason III</td>
<td>GPS, GLONASS, Galileo</td>
<td>Oceanography</td>
<td>LEO</td>
<td>TriG (potential)</td>
<td>L1, L2, L5, Galileo, GLONASS</td>
<td>2013</td>
</tr>
<tr>
<td>GPM</td>
<td>GPS</td>
<td>Orbit, time</td>
<td>GEO</td>
<td>Navigator</td>
<td>L1 C/A</td>
<td>2013</td>
</tr>
<tr>
<td>COSMIC IIB</td>
<td>GPS, GLONASS, Galileo</td>
<td>Occultation</td>
<td>LEO</td>
<td>TriG (potential)</td>
<td>L1, L2, L5, Galileo, GLONASS</td>
<td>2014</td>
</tr>
<tr>
<td>Orion Crew Vehicle</td>
<td>GPS</td>
<td>Orbit, trajectory</td>
<td>LEO, MEO, GEO, trans-lunar</td>
<td>2 HI (Navigator)</td>
<td>L1 C/A</td>
<td>2014</td>
</tr>
<tr>
<td>MMS</td>
<td>GPS</td>
<td>Rel. range, orbit, time</td>
<td>up to 30 Re</td>
<td>Navigator</td>
<td>L1 C/A</td>
<td>2014</td>
</tr>
<tr>
<td>CLARREO</td>
<td>GPS, GLONASS, Galileo</td>
<td>Occultation</td>
<td>LEO</td>
<td>TriG (potential)</td>
<td>L1, L2, L5, Galileo, GLONASS</td>
<td>2015</td>
</tr>
<tr>
<td>GOES-R</td>
<td>GPS</td>
<td>Orbit</td>
<td>GEO</td>
<td>Navigator</td>
<td>L1 C/A</td>
<td>2015</td>
</tr>
<tr>
<td>DESDynl</td>
<td>GPS</td>
<td>Precise orbit</td>
<td>LEO</td>
<td>TriG (potential)</td>
<td>L1, L2, L5, Galileo, GLONASS</td>
<td>2016</td>
</tr>
</tbody>
</table>
Occultation Example

Key applications:
- water vapor, temp profile
- tropopause altitude
- gravity waves
- ionosphere (nav, comm, physics)
- ocean height
- typhoon prediction

Different color shows availability of Radio Occultation (RO) soundings at different hours of the day.

Graphics from: Bill Kuo, et al., UCAR COSMIC Team
Emerging Space Use of GPS/GNSS

• Operational
  – GPS metric tracking (2010 GPS MT agreement)
  – Space weather (monitoring, modeling, and prediction)
  – Redundancy for autonomous operations (including return to Earth)
  – Common initial approach docking system (NASA FY09 appropriations)
  – Conjunction analysis (42USC16781, Sec. 16781 and NPR-8715.6A)

• Science
  – Onboard processing (implies enough aid from GP to obtain precise time, position: cm, and velocity: sub-mm/s)
  – Calibration tool (e.g. calibrate less focused sensors, trajectory control)
  – Smart sensor webs (sub-ns time, VLBI, formation flying)
• Technical/Policy/Standards
  – Pro-active involvement to mitigate risks
  – Modernization: new signals, new opportunities, new risks (e.g. GPS SVN49, phase anomalies, GLONASS frequencies)

• Space Service Volume
  – Satellite antenna patterns (sidelobes), group/phase delay variations
  – Guaranteed performance in the SSV: partly mitigated by TASS

• Ground monitoring (Global Differential GPS) upgrades (new signals, incorporate additional GNSS)
  – Essential for high accuracy and performance assurance

• Data integrity
  – Clock/orbit/status anomalies: can be mitigated by TASS

• Timely space receiver development
  – Advanced receivers (multi-freq, multi-GNSS, high-accuracy/sensitivity)
• **Navigator GPS Receiver: GPS L1 C/A**
  - Flew on Hubble Space Telescope SM4 (May 2009), planned for MMS, GOES, GPM, Orion/CEV
  - Onboard Kalman filter for orbit/trajectory estimation, fast acquisition, RAD hard, unaided acquisition at 25 dB-Hz
  - Honeywell is developing commercial version for Orion

• **Possible Future Capabilities**
  - **High-sensitivity Signal Acquisition and Tracking**
    • Acquisition thresholds down to 10-12 dB-Hz
    • Applicable to HEO, lunar, and cislunar orbits for CxP
    • GPS is a near term, complementary navigation solution for CxP
  - **Reception of New GPS Signals: L2C and L5**
  - **GPS-derived Ranging Crosslink Communications (TRL 6)**
    • Developed for MMS Interspacecraft Ranging and Alarm System (IRAS)
    • S-band communications link with code phase ranging
    • Signal processing and RF down conversion integrated into receiver design
    • Applicable to future spacecraft formation flying missions and CxP automated rendezvous and docking sensing needs.

Existing and Planned Space GPS/GNSS Rx

- BlackJack Flight GPS Receiver: GPS L1 C/A, P(Y) and L2 P(Y)
  - Precise orbit determination (JASON, ICESat, SRTM missions)
  - Occultation science (CHAMP, SAC-C, FedSat, 2 GRACE, 6 COSMIC)
  - Gravity field (CHAMP, GRACE)
  - Surface reflections (SAC-C, CHAMP)
  - 18 BlackJack receivers launched

- IGOR: Commercial version from Broad Reach Engineering

- CoNNeCT SDR: GPS L1, L2, L5

- TriG is under development: GPS L1, L2(C), L5, Galileo E1, E5a, GLONASS (CDMA)
  - Features: open-loop tracking, beam-forming
    2-8 antennas, 36 channels, RAD hard
  - Engineering models: 2011
  - Production schedule: 2013

Technology/Development Areas

- Toolbox for GPS/GNSS analyses
  - Support standards development: coverage, accuracy, receiver requirements
- Enabling of smart sensor webs and advanced climate studies
  (sub-ns time, cm position, sub-mm/s velocity)
- Advanced space GPS/GNSS receivers
  - Software radios; multiple frequencies, multiple GNSS; high-sensitivity processing
  - Onboard Kalman filter for accurate orbit/trajectory estimation
  - Acquisition and tracking algorithms for GEO/HEO dynamics
  - Onboard processing (requires accurate orbit/time)
  - Ultra-stable clock integration
- Use of GPS and/or GPS signal structure beyond the SSV
- Time dissemination
- Common docking initial approach system using international GNSS signals (L1C)
- Maximize autonomous conjunction information (GNSS-based: improved space situational awareness, false alarm reduction, fast detection of spacecraft upset)
- Upgrade GPS/GNSS signal monitoring and corrections (GDGPS) for autonomous and safety operations; combine with receiver autonomous integrity monitoring
- Integration of international monitoring networks
- TASS orbit, clock & space weather dissemination

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Standards/Testing/Monitoring

• Standards to be maintained/developed
  – GPS Standard Positioning Service Performance Standard
  – GPS Interface Specifications
  – GNSS standards as they are developed
  – GNSS space receiver standards (new)
    • GNSS minimum performance standards to support conjunction analyses
    • GPS metric tracking implementation
    • GNSS performance standards for docking to within 250 m or better

• Testing/Monitoring
  – GPS/GNSS signal monitoring
  – Increased use of clock: one-way ranging, availability, improved position/velocity
Summary

• GPS/GNSS are important to NASA operations and science missions
  – PNT architecture is dependent on GPS and monitoring/correction networks (Global Differential GPS)
  – Essential area for NASA involvement
• Maintain current GNSS-supported capabilities
• Enable new applications: GPS Metric Tracking, space weather monitoring, TDRS Augmentation Satellite System, redundancy for autonomous operations, advanced climate studies, common docking system initial approach, conjunction analysis, accurate PNT, smart sensor webs