National Aeronautics and Space Administration

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Title **Use of GNSS for Future Space Operations and Science Missions**

Name Frank van Graas, Ph.D.
Institute of Navigation S&T Policy Fellow

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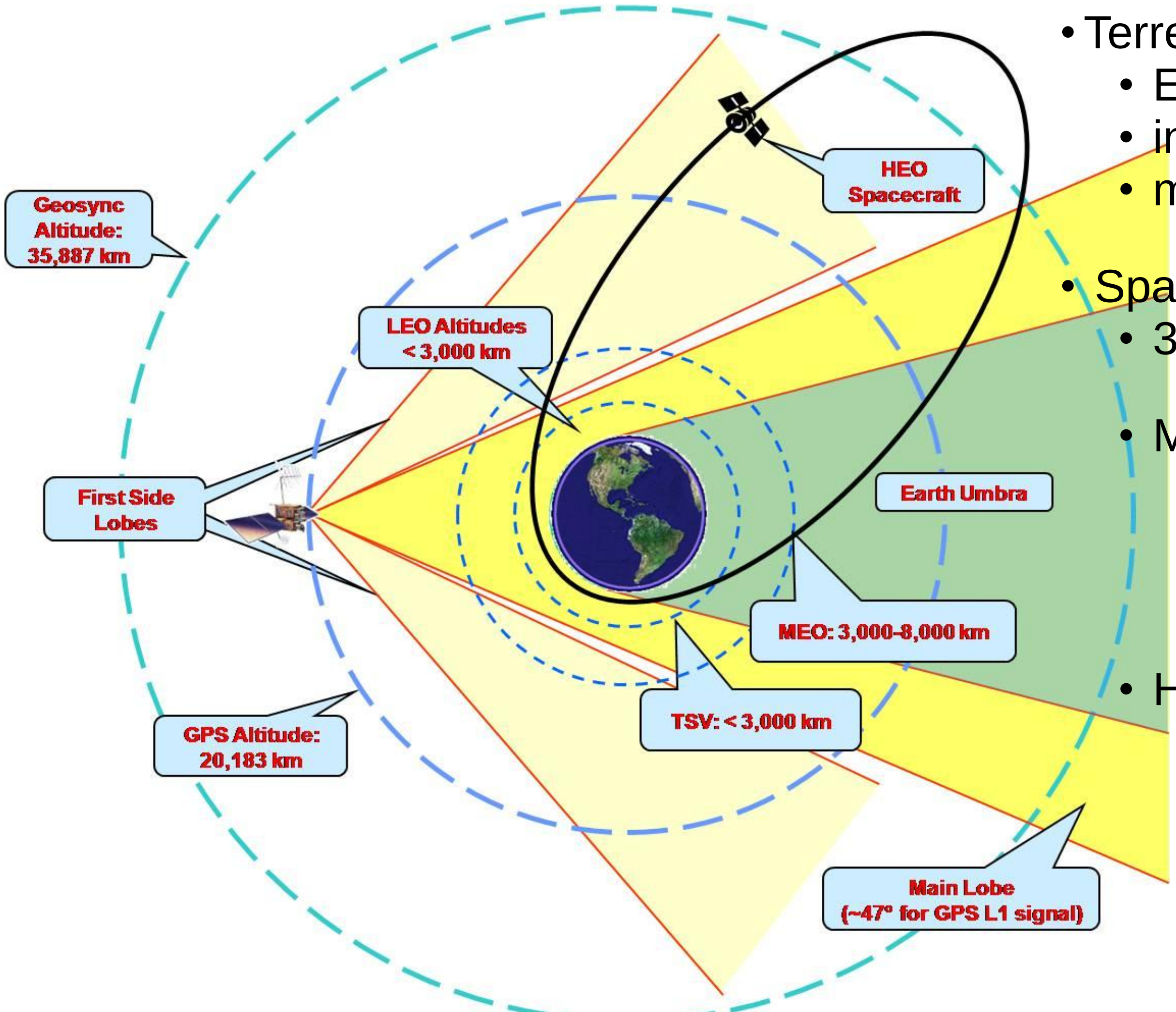
Executive Summary

- 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, DESDynl
- 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



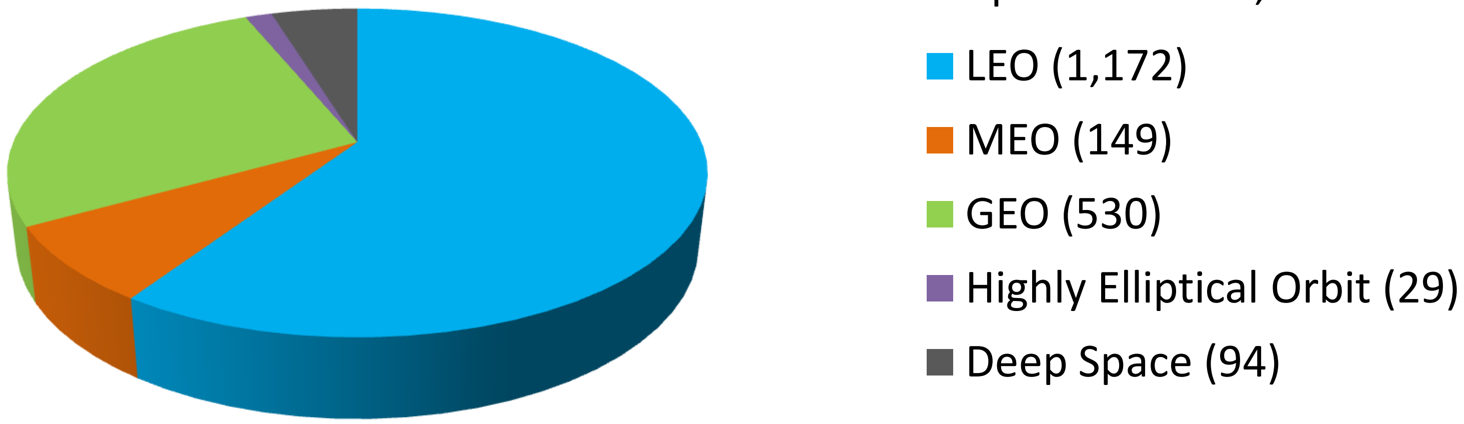
- Terrestrial Service Volume (TSV)
  - Earth surface to 3,000 km
  - instantaneous, 100% coverage
  - meter-level accuracy
- Space Service Volume (SSV)
  - 3,000 to 36,000 km (GEO)
  - Medium Earth Orbit
    - 3,000 to 8,000 km
    - typically instantaneous
    - meter-level accuracy
  - High Earth Orbit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

Based on: J. J. Miller, U.S.–E.U. GPS Galileo ICG WG-C Meeting, June 15-16, 2009

Projected Worldwide Space Missions

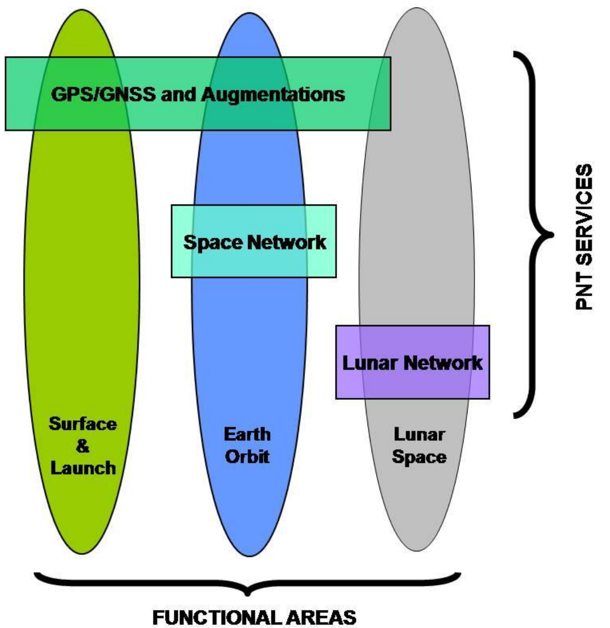
- Nearly 60% of projected worldwide space missions 2008-2027 will operate in LEO: inside the GPS Terrestrial Service Volume
- Nearly 35% of projected space missions will operate at MEO and GEO altitudes: inside the GPS Space Service Volume
- Combined, approximately 95% of projected worldwide space missions 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



Graphic based on: James J. Miller, "NASA Navigation Roadmap," SCaN Navigation Workshop – Washington D.C., January 23-24, 2008

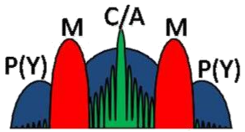
- Note: For operational use, applications are designed to rely on GPS performance standards only. Other GNSS may be used as long as the operation does not depend on the other GNSS.
- For scientific use, all GNSS may be used, which can be cost-effective (e.g. three GNSS are more cost-effective than tripling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

Current GPS-Dependent Missions/Programs

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

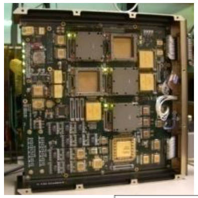
Technologies under Development

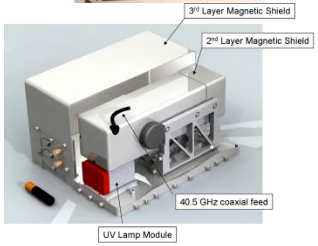
- GPS modernization: new signals (L5/L2C/L1C), retro-reflectors, well-defined Space Service Volume



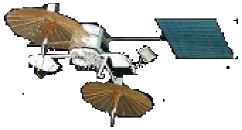
- GLONASS modernization, Galileo, Compass

- 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)



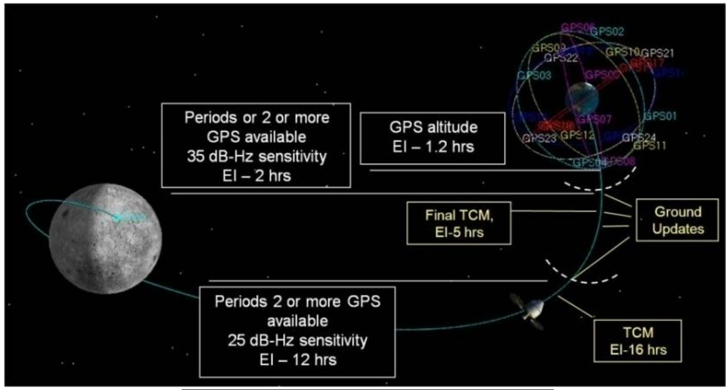


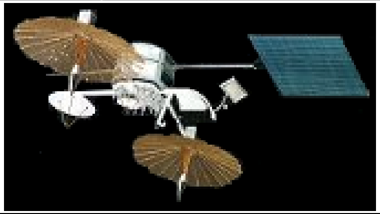
- Advanced space clock: Mercury-Ion (10^{-15})
  - Enables positioning and improved geometry with 3 GPS satellites
- TDRS Augmentation Satellite System (TASS)

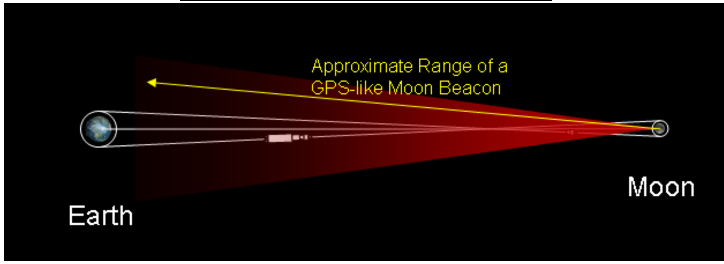


GPS concepts beyond the SSV

- 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





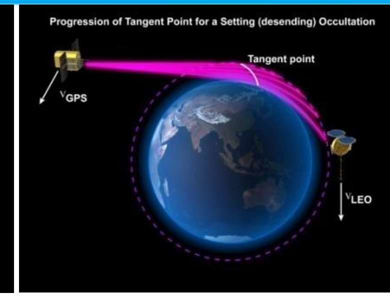


- Clock distribution
  - Time dissemination system with characteristics suitable for solar-system-wide operations
    - One-way navigation, VLBI, sensor webs, enhanced radio-science

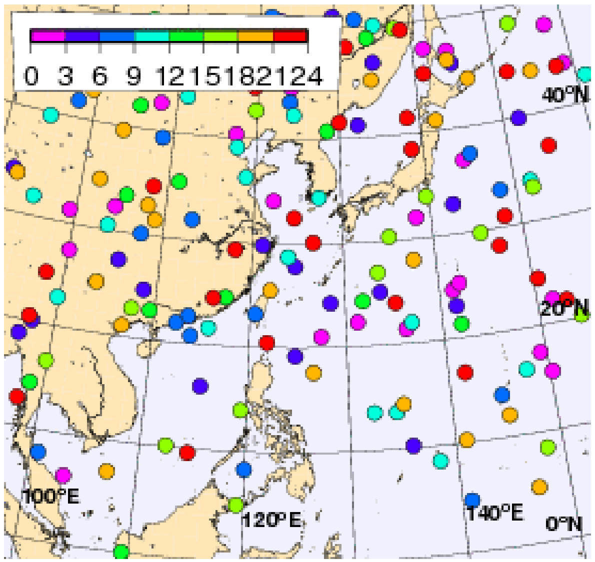
Applications to Upcoming Missions

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

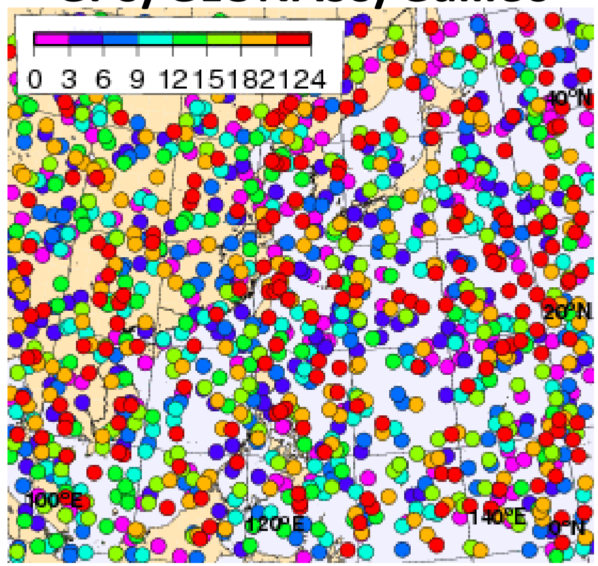
Occultation Example



FORMOSAT-3/COSMIC GPS



COSMIC-IIA GPS/GLONASS/Galileo

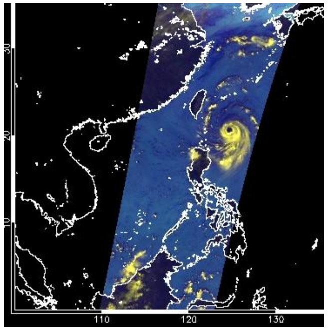


Different color shows availability of Radio Occultation (RO) soundings at different hours of the day.

Graphics from: Bill Kuo, et al., UCAR COSMIC Team

Key applications:

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



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)

GPS/GNSS Risk Areas

- 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)

TASS – TDRS Augmentation Satellite System

Existing and Planned Space GPS/GNSS Rx

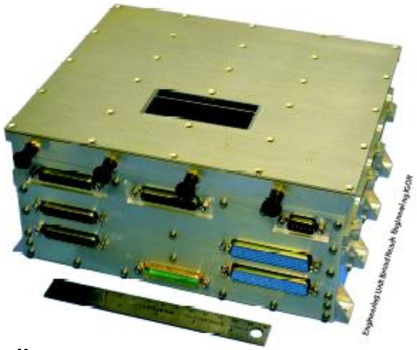
- Navigator GPS Receiver: GPS L1 C/A
  - Flew on Hubble Space Telescope SM4 (May 2009), planned for MMS, GOES, GPM, Orion/CEV
  - Onboard Kalman filter for orbit/trajectory estimation, fast acquisition, RAD hard, unaided acquisition at 25 dB-Hz
  - Honeywell is developing commercial version for Orion
- 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.

Information from: Dr. John Carl Adams, "Navigator Spaceflight GPS Receiver," January 23-24, 2008

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



Information from: Larry Young, JPL, "Navigation Developments in BlackJack Flight GPS Receiver," January 23-24, 2008 and "TriG Performance Capabilities," June 2009.

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

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