Enhancing Navigation through NASA Initiatives

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International Association for Institutes of Navigation
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Seamless Navigation: Challenges and Opportunities

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Cairo, Egypt

SCaN Functions

- **Delineated in memorandum from NASA Associate Administrator (September 24, 2007).**
- SCaN serves as the **Program Office** for all of the Agency's space communications and navigation activities.
- SCaN manages and directs:
  - The ground-based facilities and user services provided by the Near Earth Network (Ground Network) and Deep Space Network;
  - The ground- and space-based facilities and user services provided by the geosynchronous Space Network and by a future Lunar Network and Mars Network.
- Activities include those that:
  - Integrate all existing NASA SCaN assets and build a single NASA-wide space communications and navigation architecture;
  - Represent NASA before associated national and international programs of spectrum management and space data systems standardization;
  - Represent and negotiate on behalf of NASA on all matters related to Space Telecommunications and navigation in coordination with the appropriate offices and flight mission directorates.

SCaN Key Driving Requirements

1. SCaN shall develop a **unified** space communications and navigation network infrastructure capable of meeting **both robotic and human** exploration mission needs

2. SCaN shall implement a **networked** communication and navigation infrastructure across space.

3. SCaN infrastructure shall provide the **highest data rates feasible** for both robotic and human exploration missions.

4. SCaN shall assure data communication protocols for Space Exploration missions are **internationally interoperable**.

5. SCaN shall **provide** the end space communication and navigation infrastructure for **Lunar and Mars surfaces**.

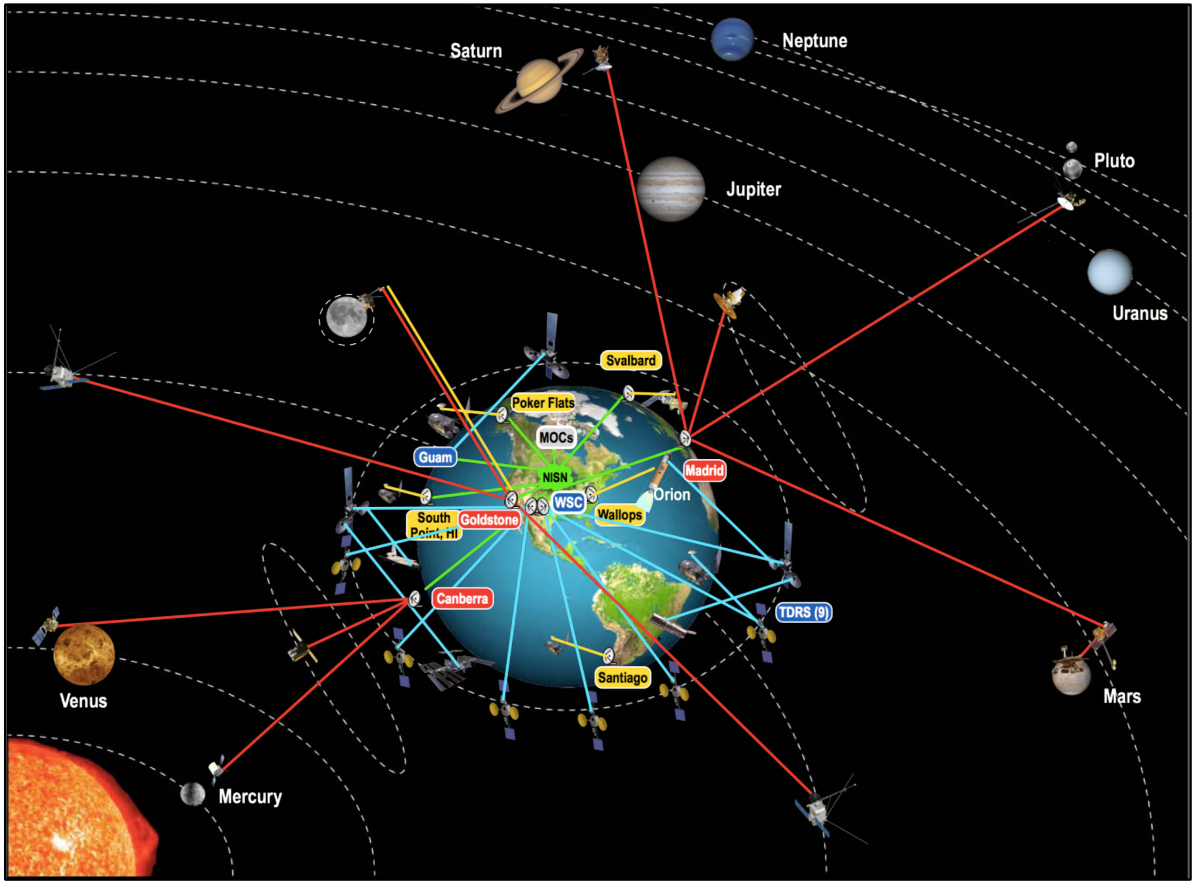
6. SCaN shall provide **anytime/anywhere** communication and navigation services **as needed** for Lunar and Mars human missions

7. SCaN shall continue to **meet its commitments** to provide space communications and navigation services to existing and planned missions.

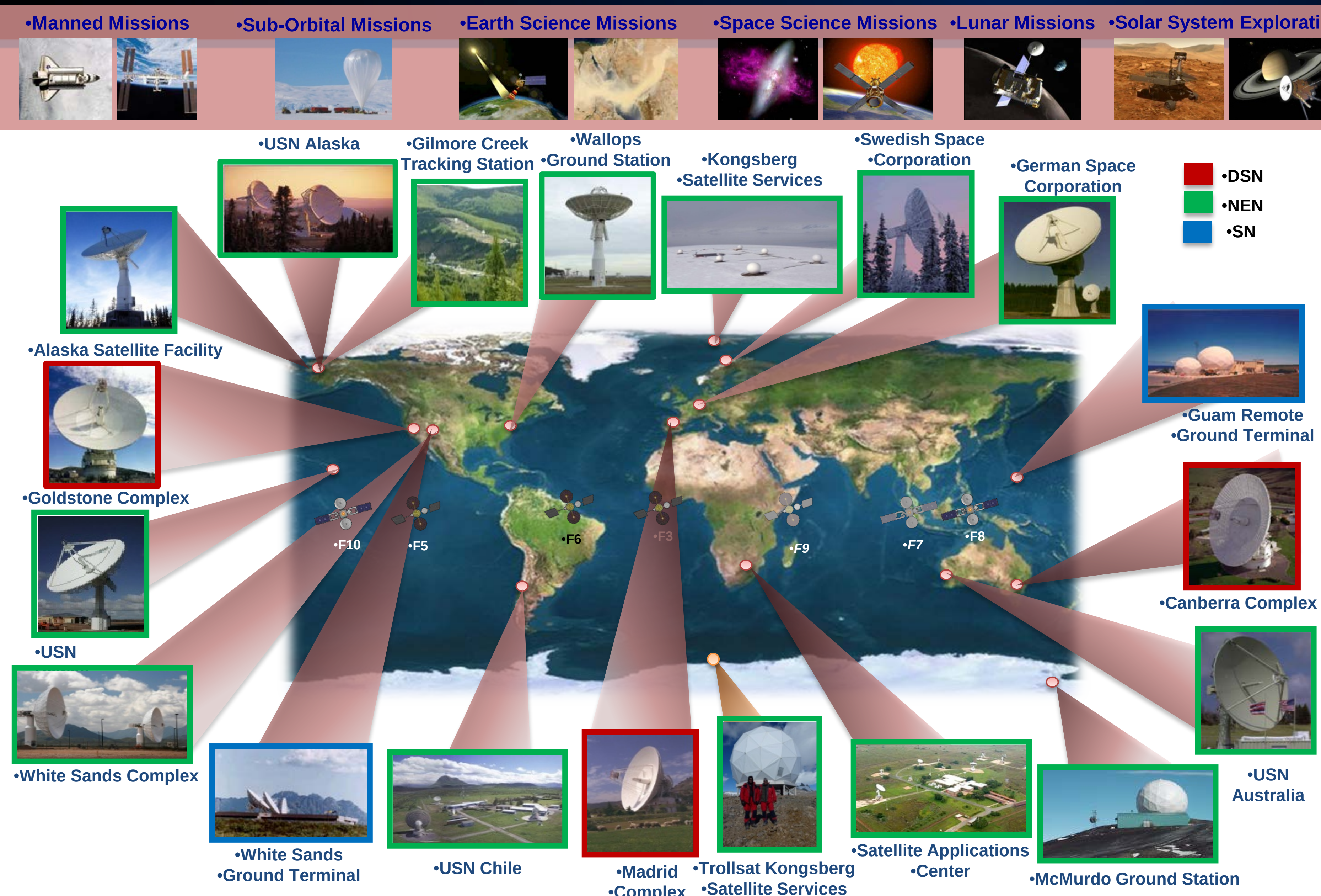
SCaN Current Networks

The current NASA space communications architecture embraces three operational networks that collectively provide communications services to supported missions using space-based and ground-based assets.

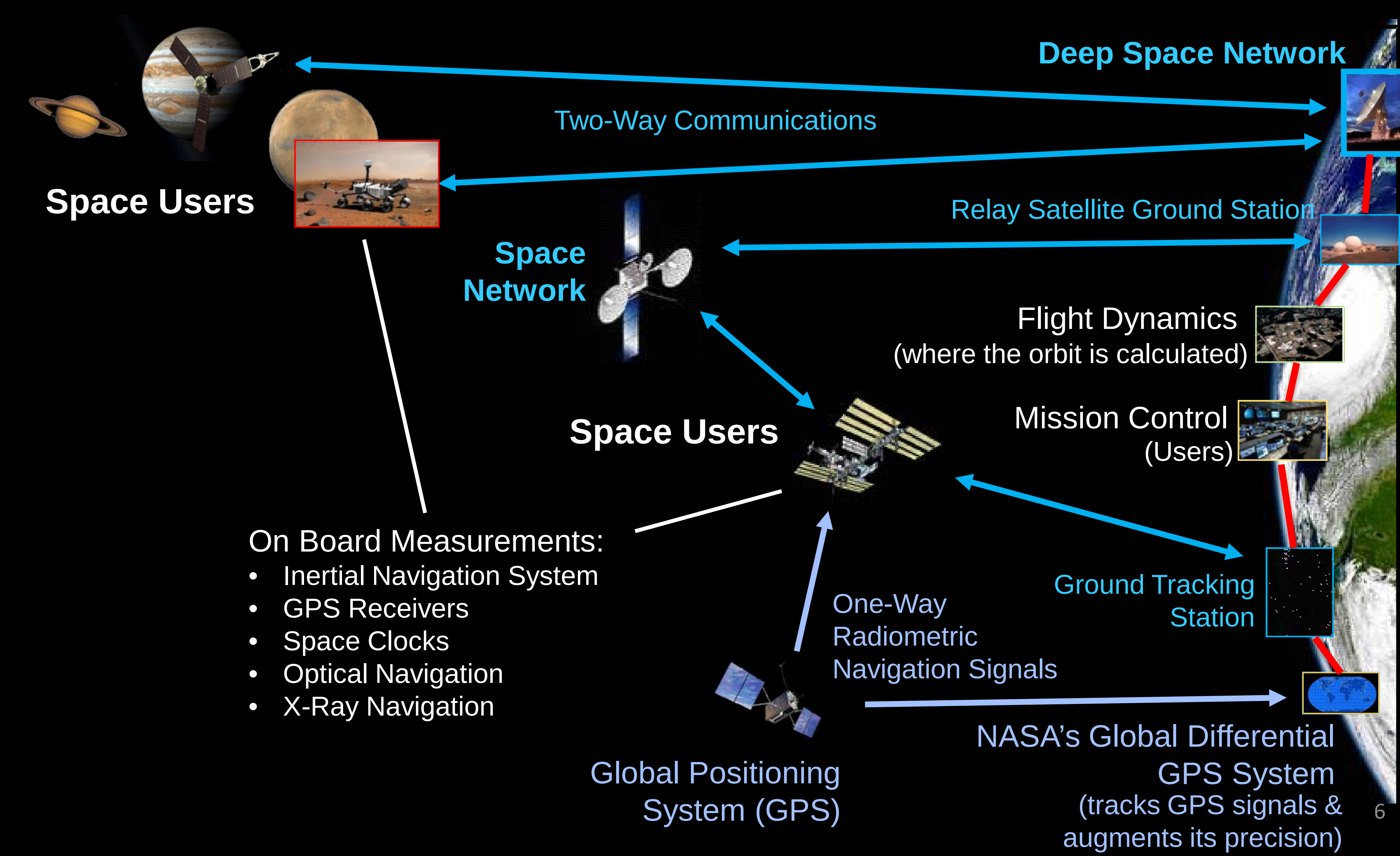
- **Near Earth Network** – NASA, commercial, and partner ground stations and integration systems providing space communications and tracking services to orbital and suborbital missions
- **Space Network** – constellation of geosynchronous relays (TDRSS) and associated ground systems
- **Deep Space Network** – ground stations spaced around the world providing continuous coverage of satellites from Earth Orbit (GEO) to the edge of our solar system



SCaN Network



SCaN Infrastructure Enables Mission Communications and Navigation

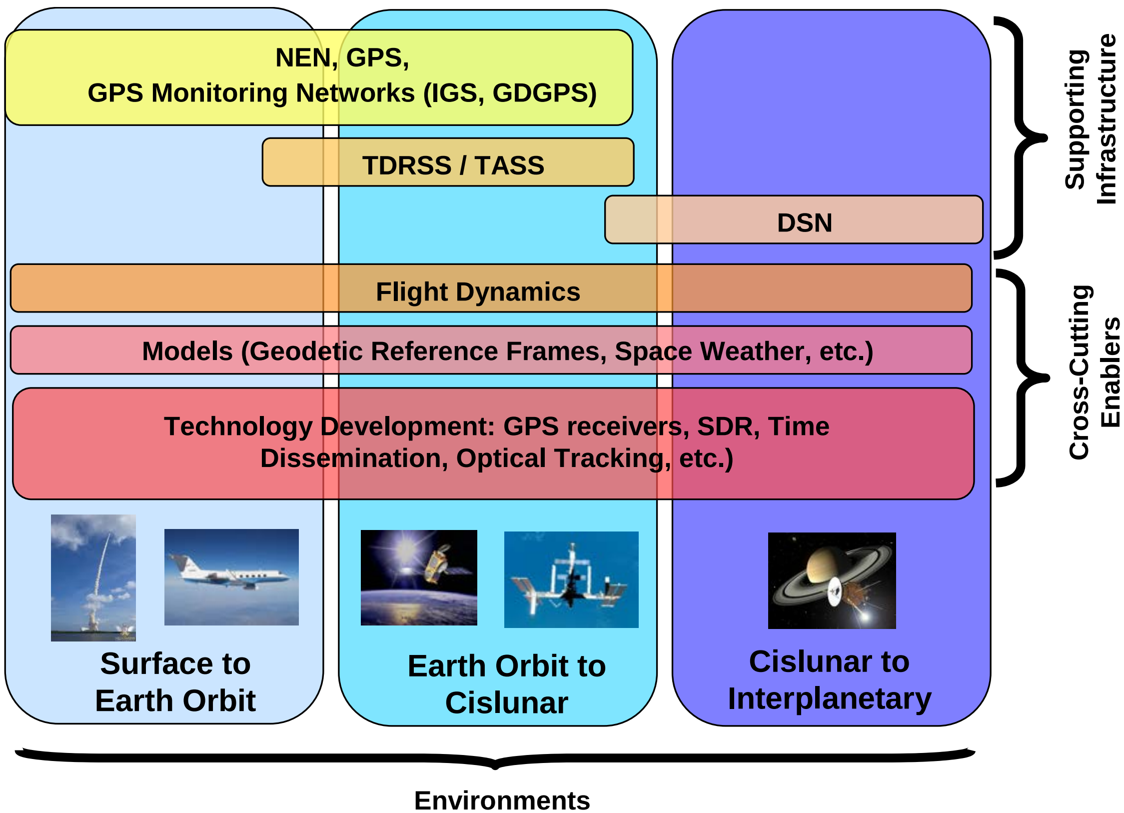


SCaN's Role in Navigation

Defining the 'N' in SCaN:

–In support of mission-defined requirements, SCaN provides navigation information ; as well as policy, systems engineering, architecture development, and technology development ; enabling three categories of services:

- **Communications** (enable user nav information to be forwarded/returned to & from space)
- **Metric Data Delivery** (e.g. measurements of spacecraft signals)
- **Reference Data Delivery** (including absolute time and geometric reference frames)



Objectives:

- Increase on-board autonomy, navigation precision, redundancy, and safety
- Optimize the use of the SCaN networks by reducing the communication/tracking burdens

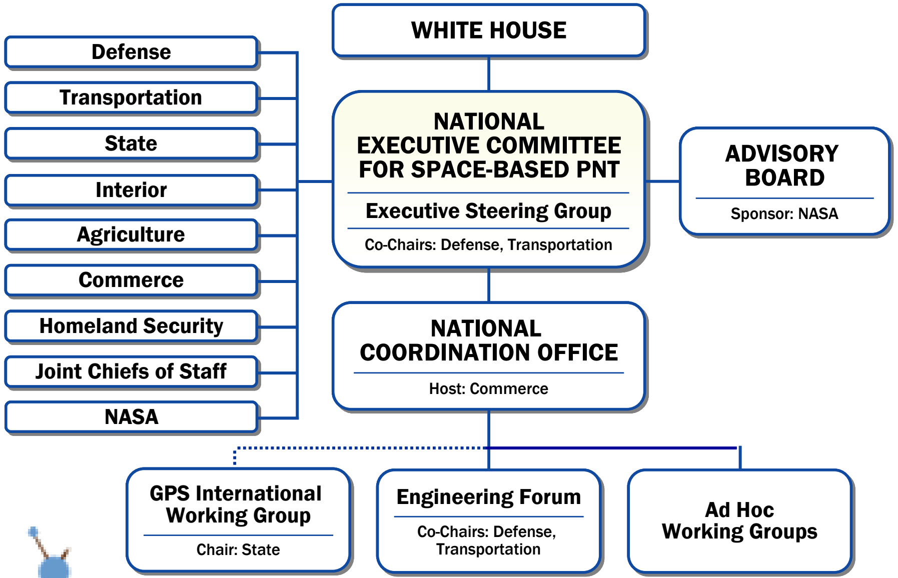
- **Cross-cutting enablers:**
  - –Technology Development (GPS receivers, optical comm/nav)
  - –Models (Geodetic Reference Frames/Satellite Laser Ranging, Space Weather, etc.)
  - –Flight Dynamics

NASA's Role:
U.S. PNT / Space Policy

- 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 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.

- NASA is engaging with other space agencies at venues such as the International Committee for GNSS (ICG) and the Interagency Operations Advisory Group (IOAG) to seek similar benefits from other PNT constellations to maximize performance, robustness, and interoperability for all.



GPS Extends the Reach of NASA Networks to Enable New Space Ops, Science, and Exploration Apps

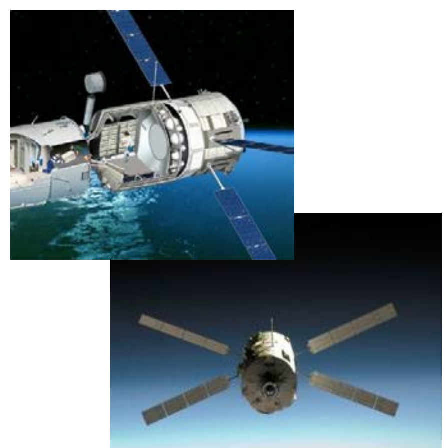
GPS services enable:

- **Real-time On-Board Autonomous Navigation:** Allows NASA to maximize the "autonomy" of spacecraft and reduces the burden and costs of network operations. It also enables new methods of spaceflight such as precision formation flying and station-keeping

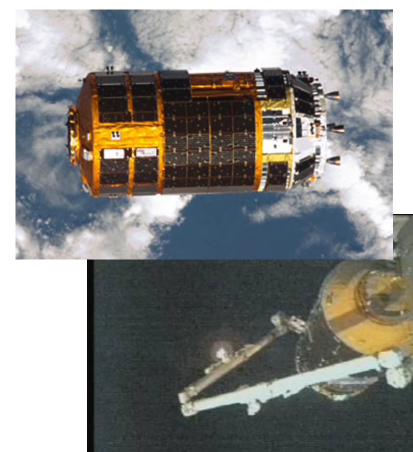
- **Attitude Determination:** Use of GPS enables some missions to meet their attitude determination requirements, such as ISS

- **Earth Sciences:** GPS used as a remote sensing tool supports atmospheric and ionospheric sciences, geodesy, and geodynamics -- from monitoring sea level heights and climate change to understanding the gravity field

GPS Relative Navigation used for Rendezvous to ISS



ESA ATV 1st mission to ISS in 2008

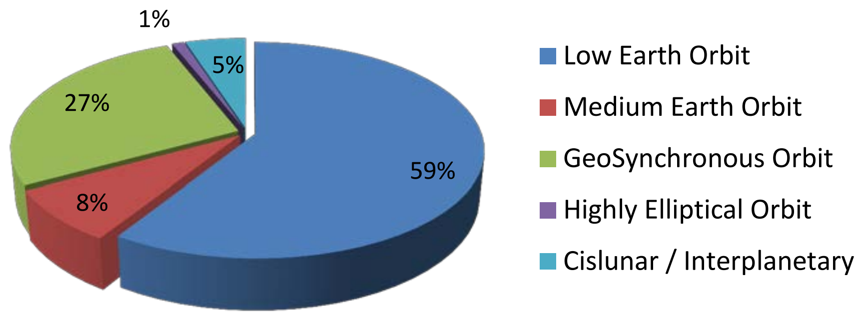


JAXA's HTV 1st mission to ISS in 2009

Growing GPS Uses in Space: Space Operations & Science

- Projections show that over the next 20 years:
  - Approximately 60% of space missions will operate in LEO (< 3,000 km)
  - Approximately 35% of space missions will operate at higher altitudes up to GSO (36,000 km).

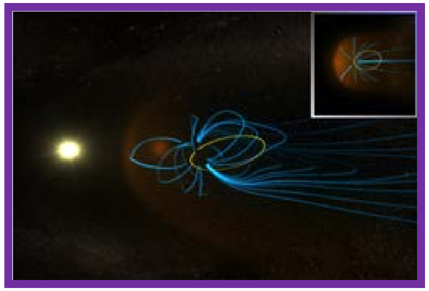
20-Year Worldwide Space Mission Projections by Orbit Type



Low Earth Orbit:
Earth Observation, LEO communication constellations, etc.

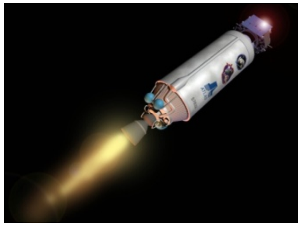
Medium Earth Orbit:
GNSS Constellations

GeoSynchronous:
Communication Satellites, Regional Navigation Satellite Systems



Highly Elliptical Orbits*:
Examples: NASA MMS 4-satellite constellation, communication satellites, etc.

(*) Apogee above GEO/GSO



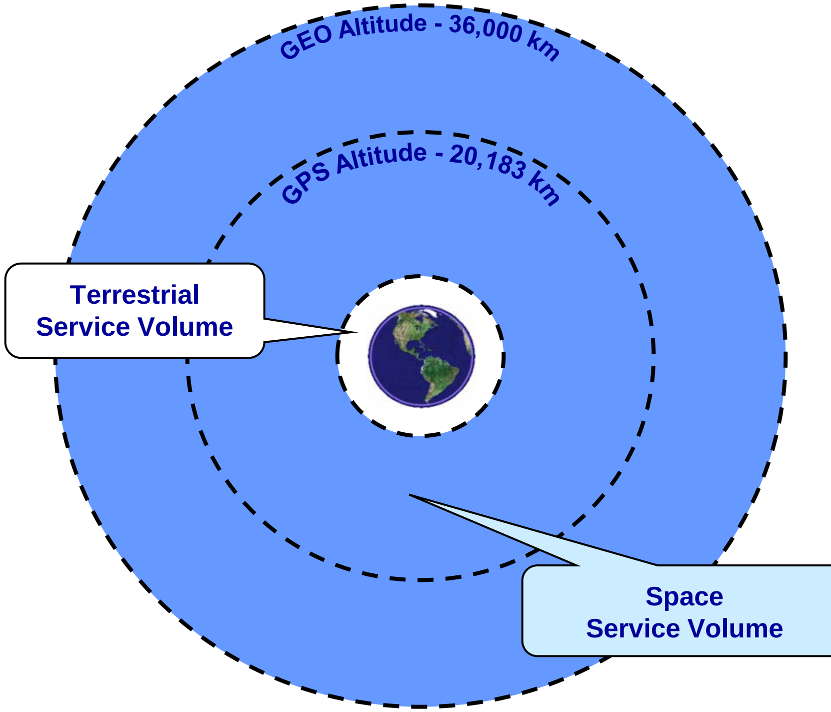
Orbital Transfers: LEO-to-GEO, cislunar transfer orbit (figure), transplanetary injection, etc.

GPS Performance in the Space Domain: An Interoperable GPS/GNSS Space Service Volume

- **Terrestrial Service Volume (TSV)**
  - The volume of space between the surface, and an altitude of 3,000 km (which includes much of LEO) is referred to as the Terrestrial Service Volume, or TSV
  - The performance characteristics of GPS within the Terrestrial Service Volume are described in the GPS Standard Positioning Service (SPS) Performance Standard: http://www.gps.gov/technical/ps/

- **Space Service Volume (SSV)**
  - Space user community was vulnerable to design changes because requirements were not explicitly stated
  - The volume of space between 3,000 km altitude and geosynchronous altitude (36,000 km) was defined as the Space Service Volume in GPS technical documents
  - Performance requirements for the GPS SSV were then developed to include satellite antenna patterns (side lobes) and group/phase delay variations
  - SSV therefore reflects a guaranteed level of performance within a service volume or sphere expanding out from the TSV to GEO

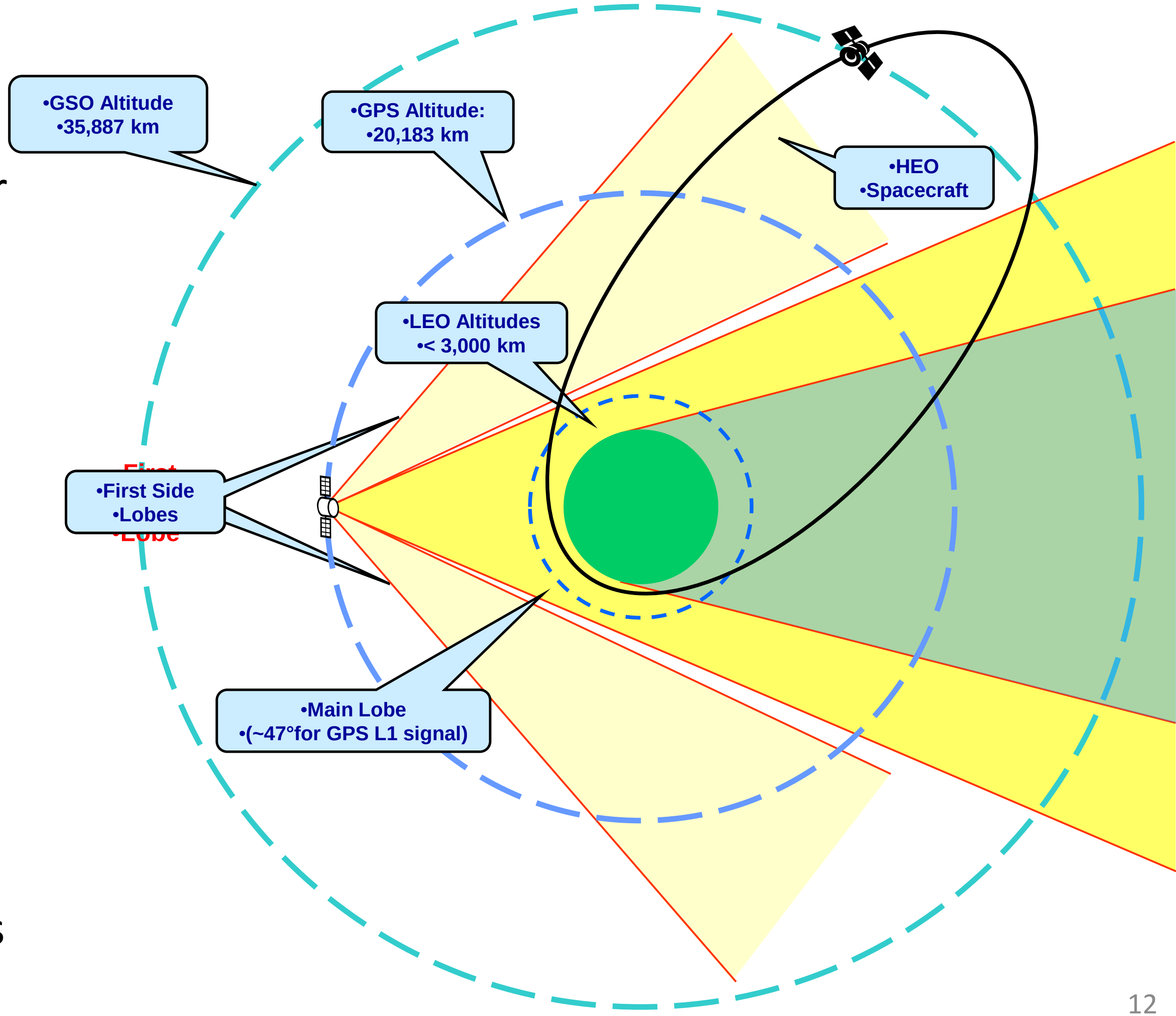
The volume of space where GPS provides PNT services is referred to as a *Service Volume*



"To scale" visualization of the terrestrial and space service volumes defined to specify space use of GPS

Using GPS Beyond LEO: Reception Geometry for GPS Signals

- When operating at higher orbits we are tracking the GPS signals broadcast “over the limb” of the Earth
- This is sometimes referred as ‘above the GPS constellation’ navigation
- Earth is blocking most of the GPS signals, so the availability is much smaller
- This is why the GPS transmitter ‘side lobes’ become vital to space users



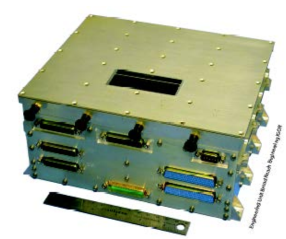
NASA GPS/GNSS Receiver Developments: Navigator and BlackJack "Family"

Goddard Space Flight Center (GSFC)

- Navigator GPS Receiver: GPS L1 C/A
  - Flew on Hubble Space Telescope SM4 (May 2009), planned for MMS, GOES, GPM (Honeywell commercial)
  - Onboard Kalman filter for orbit/trajectory estimation, fast acquisition, RAD hard, unaided acquisition at 25 dB-Hz
- Possible Future Capabilities
  - High-sensitivity Signal Acquisition and Tracking:
    - Acquisition thresholds down to 10-12 dB-Hz
    - Applicable to HEO, lunar, and cislunar orbits
  - Reception of New GPS Signals: L2C and L5
  - GPS-derived Ranging Crosslink Communications
    - Developed for MMS Interspacecraft Ranging and Alarm System (IRAS) to support formation flying
    - Features S-band communications link with code phase ranging, used in formation flying

Jet Propulsion Laboratory (JPL)

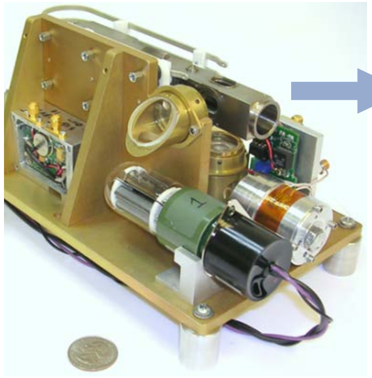
- BlackJack Flight GPS Receiver: GPS L1 C/A, P(Y) and L2 P(Y)
  - Precise orbit determination (JASON, ICESat, SRTM missions)
  - Occultation science (CHAMP, SAC-C, FedSat, 2 GRACE , 6 COSMIC)
  - Gravity field (CHAMP, GRACE)
  - Surface reflections (SAC-C, CHAMP)
  - 18 BlackJack receivers launched to-date
- IGOR GPS receiver: Commercial version from Broad Reach Engineering
- CoNNeCT Software Defined Radio: GPS L1 C/A, L2C, L5
- TriG GNSS Receiver under development: GPS L1, L2, L5, Galileo E1, E5a, GLONASS (CDMA and FDMA)
  - Features: open-loop tracking, steered array,
  - 2-16 antennas, RAD hard parts
  - Engineering models: 2011, production: 2013

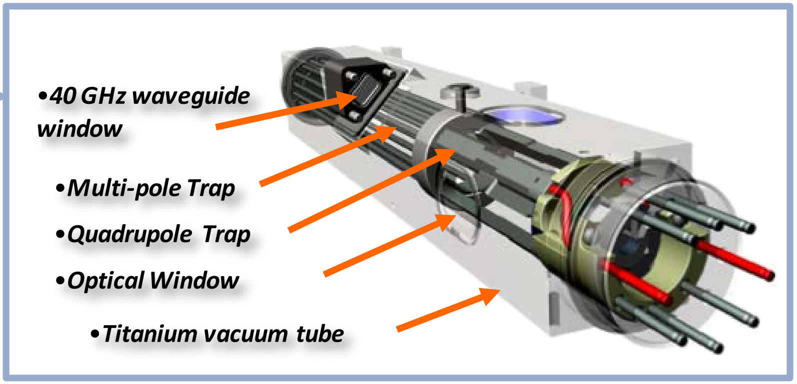


Deep Space Atomic Clock Technology Demonstration

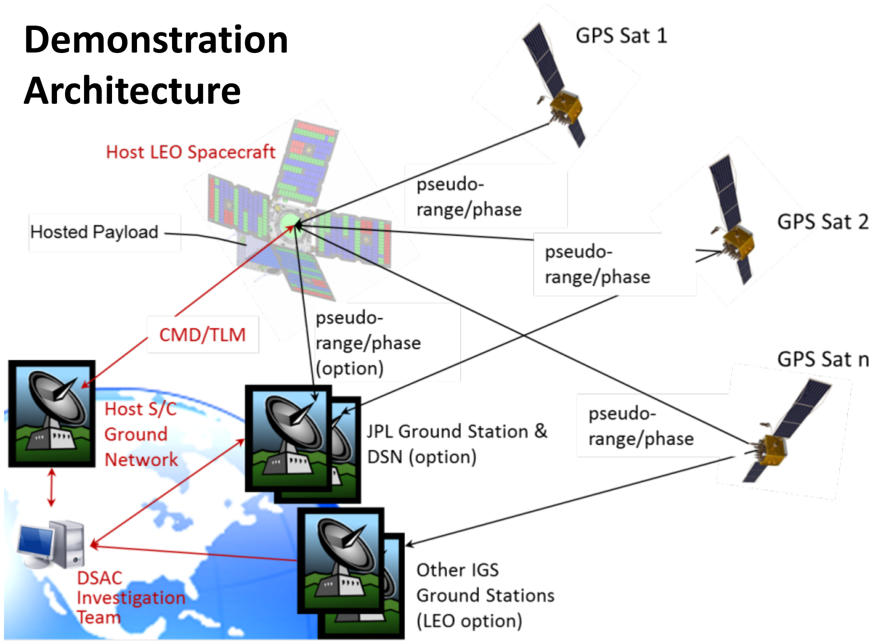
Objective

Develop an advanced prototype mercury-ion (Hg) atomic clock and demonstrate for a year in space, providing the unprecedented accuracy (Allan Deviation < 2.0E-14 at one day) needed for the next generation of deep space navigation and radio science. Identify steps needed to build 5 kg/20 W infusible flight version.





Demonstration Architecture



Technology highlights

- State selection via UV optical pumping using Hg ions
- Extreme accuracy and stability via:
  - No buffer gases
  - No wall collisions
  - High Q microwave line from Hg
- Multi-pole trap yields insensitivity to disturbances

Key Features for reliable in-space use

- No lasers, cryogenics, or other consumables → long life
- Existing vacuum technology and no microwave cavities → easier manufacturability
- Radiation tolerant at levels similar to GPS Rb Clocks

Benefits of the Deep Space Atomic Clock

For NASA Deep Space Missions

Enable a shift to a more flexible/extensible 1-Way radio navigation architecture from the current 2-Way model

- For Example: Enables multiple spacecraft per aperture tracking at planets such as Mars or the Moon
- For Example: Europa Flyby Gravity Science can use any Ka-band reciever on Earth

Enable autonomous radio navigation

- For Example: Enables MSL-class doing pinpoint EDL (<100m) can save ~100kg of propellant
- For Example: Enables fully autonomous aerobraking operations

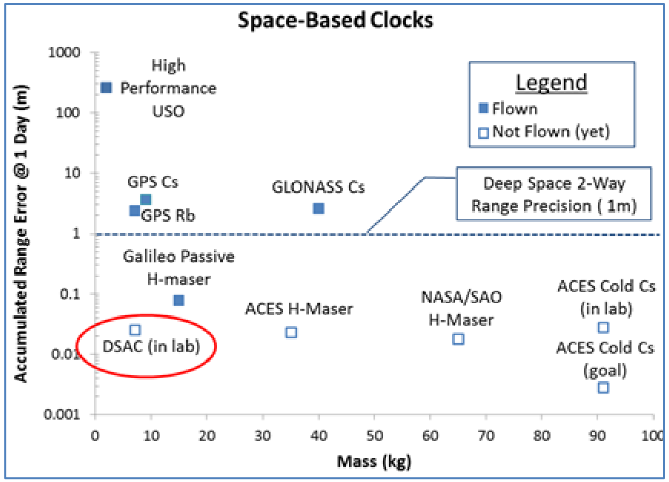
Increase navigation & radio science tracking data accuracy by 10 times and quantity by 2 times

- For Example: Mars Orbit Determination improves by a factor of 5
- For Example: Europa Flyby gravity science is collected in fewer flybys making the mission more robust

For GPS III

Performance of 1st-generation Hg ion trap clocks exceed current Rb clocks by a factor of 100

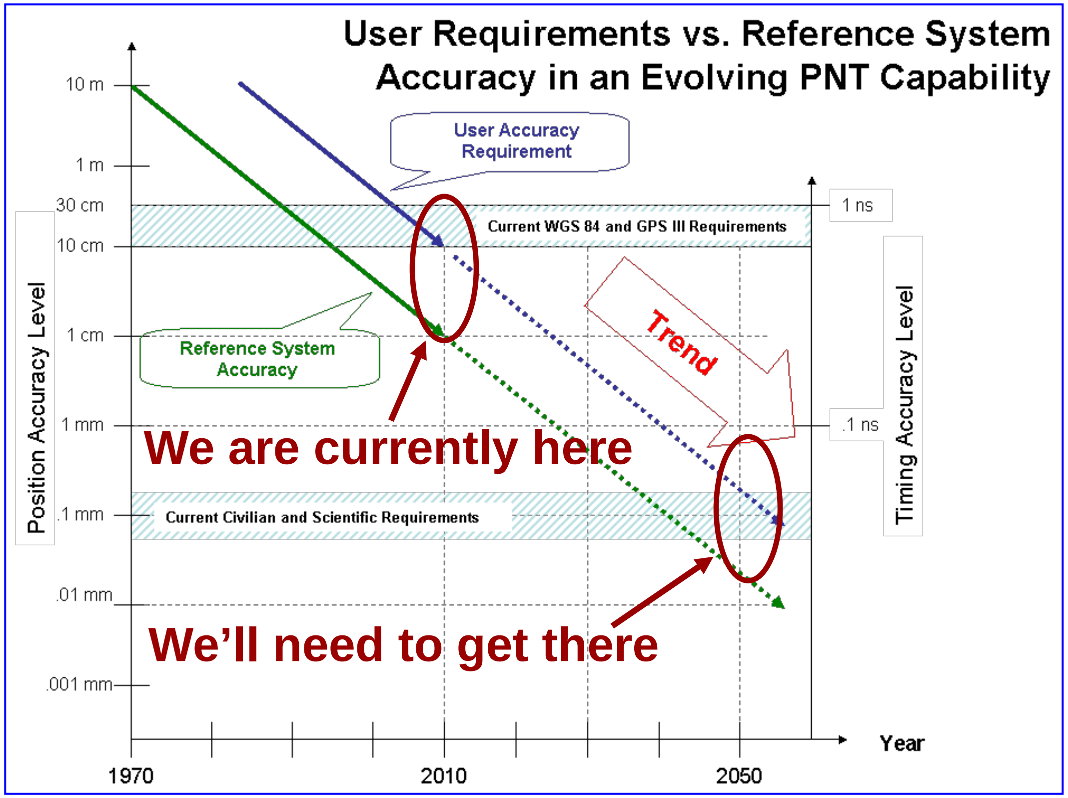
- Can reduce the number of uploads by the Control Segment SV clock correction parameter updates.
- Improves operational effectiveness in a long-term autonomous operational scenarios.

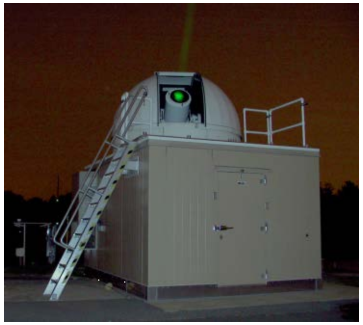


Satellite Laser Ranging to GPS

Laser Ranging to GNSS enables:

- Comparison of collocated radiometric and optical measurements used for model improvements
- Isolation of systematic errors in GNSS constellations and improves the reference frame accuracy
  - Variation of range and phase centers important for space users because they sample the signals far off the transmit boresight
- Improved models and reference frames necessary to support civilian and scientific requirements for higher PNT accuracy
  - Global sea height change measurement from space requires 1 mm/year precision, so reference frame needs to be constant to 0.1 mm/yr



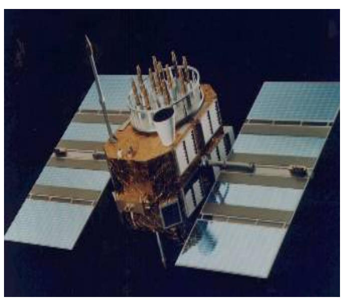


Recommended Standards for Laser Retro-reflectors Design

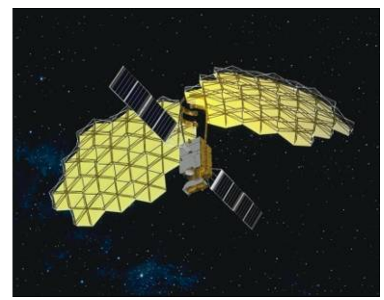
To ensure interoperability, ILRS recommends that:

- Retroreflector payloads on future GNSS satellites should have an “effective cross-section” of 100 million sq. meters (5 times that of GPS-35 and -36) for GNSS satellite
- The parameters necessary for the precise definition of the vectors between the effective reflection plane, the radiometric antenna phase center and the center of mass of the spacecraft be specified and maintained with an accuracy of a mm
- Retroreflector payloads for satellites such as Galileo in higher orbits should scale the “effective cross-section” to compensate for the R**4 reduction in signal strength

GPS 35/36 (US Air Force)



ETS-8 (JAXA)

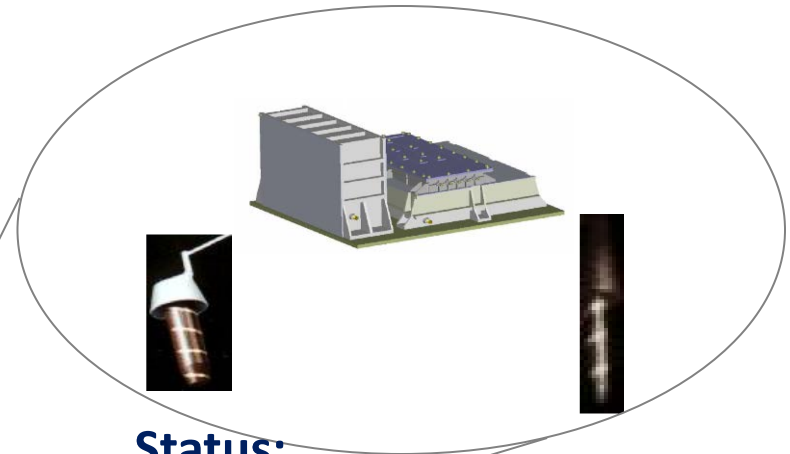


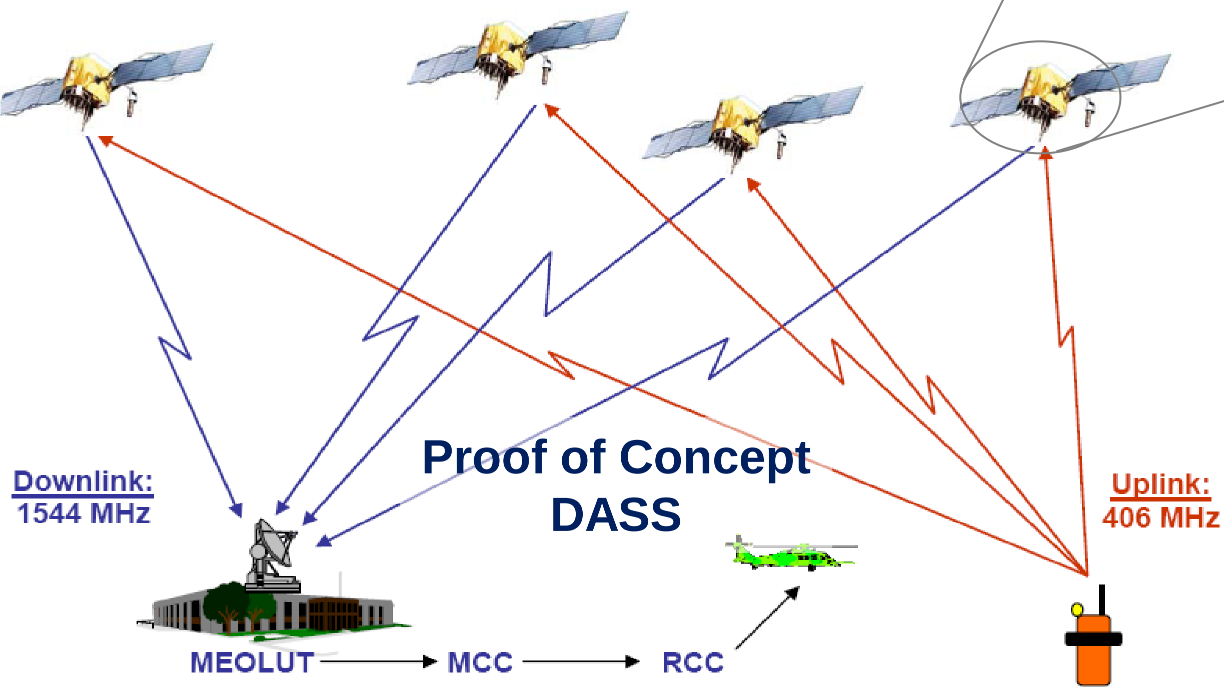
Required reflector cross section may be met by either: (1) Coated hollow cubes, in an array of 590 sq. cm compared to present 464 sq cm on GPS-35 and -36; or (2) ETS-8 (JAXA) style array with uncoated cubes.

Search and Rescue from Space with GPS: Distress Alerting Satellite System (DASS)

SARSAT Mission Need:

- More than 800,000 emergency beacons in use worldwide by the civil community – most mandated by regulatory bodies
- Expect to have more than 100,000 emergency beacons in use by U.S. military services
- Since the first launch in 1982, current system has contributed to saving over <u>*40,000*</u> lives worldwide





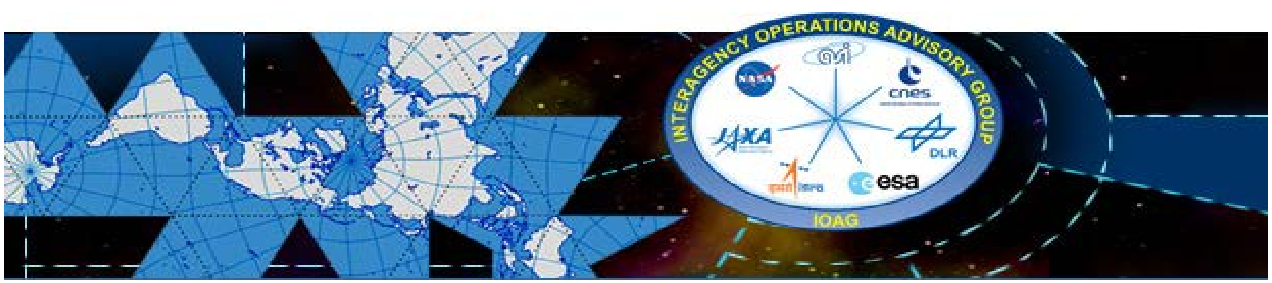
Status:

- SARSAT system to be discontinued as SAR payload implemented on Galileo
- NASA (with over $35M invested) and Air Force developed options for U.S. SAR system
- Successful NASA Proof-of-Concept DASS on GPS IIR(M) and IIF satellites
- Transition to GPS III transition underway

Enabling International Collaboration

•**SCaN represents NASA at international fora related to space communications and navigation issues. These include:**

- **Interoperability Plenary (IOP)**
- **Interagency Operations Advisory Group (IOAG)**
- **Space Frequency Coordination Group (SFCG)**
- **Consultative Committee for Space Data Systems (CCSDS)**
- **International Telecommunications Union (ITU)**
- **International Committee on Global Navigation Satellite Systems (ICG)**
- **Other Space Agencies**

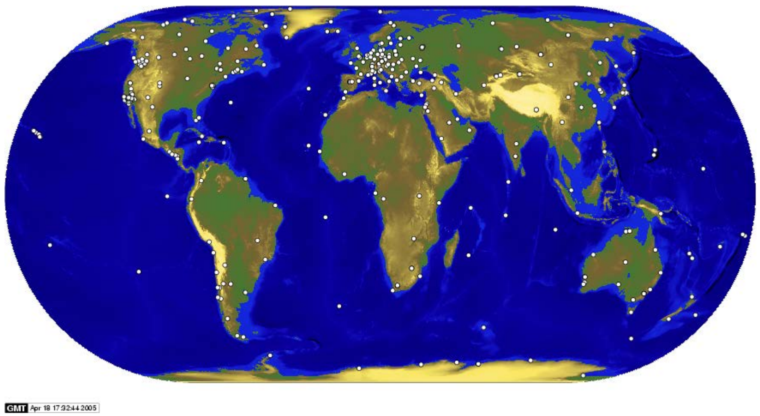


International GNSS Service (IGS)

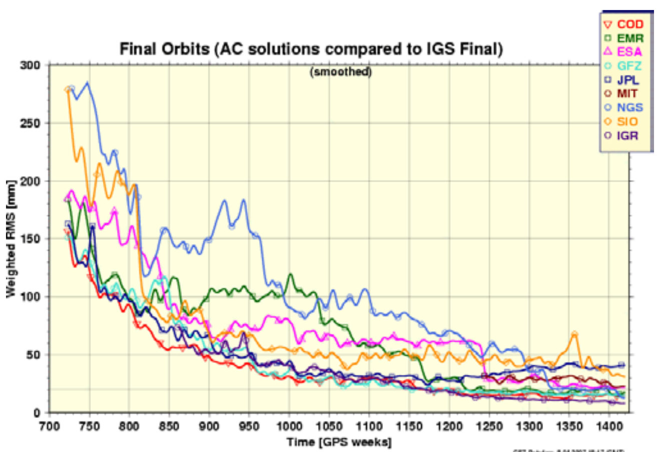
The IGS is a voluntary federation of more than 200 worldwide agencies in more than 90 countries that pool resources and permanent GPS station data to generate precise GPS products.

US agencies that contribute to the IGS include:
- *National Aeronautics and Space Administration (NASA),*
- *National Geospatial-Intelligence Agency (NGA),*
- *National Oceanic and Atmospheric Administration (NOAA)*
- *National Geodetic Survey (NGS),*
- *Naval Research Laboratory (NRL),*
- *National Science Foundation (NSF),*
- *US Naval Observatory (USNO), and*
- *US Geological Survey(USGS),*

… and numerous universities & research organizations.



Over 350 permanent tracking stations operated by more than 100 worldwide agencies comprise the IGS network. Currently the IGS supports two GNSS: GPS and the Russian GLONASS.



IGS products are formed by combining independent results from each of several Analysis Centers. Improvements in signals and computations have brought the centers' consistency in the Final GPS satellite orbit calculation to ~ 2cm

•Graph courtesy Analysis Coordinator

•G. Gendt, GFZ Potsdam

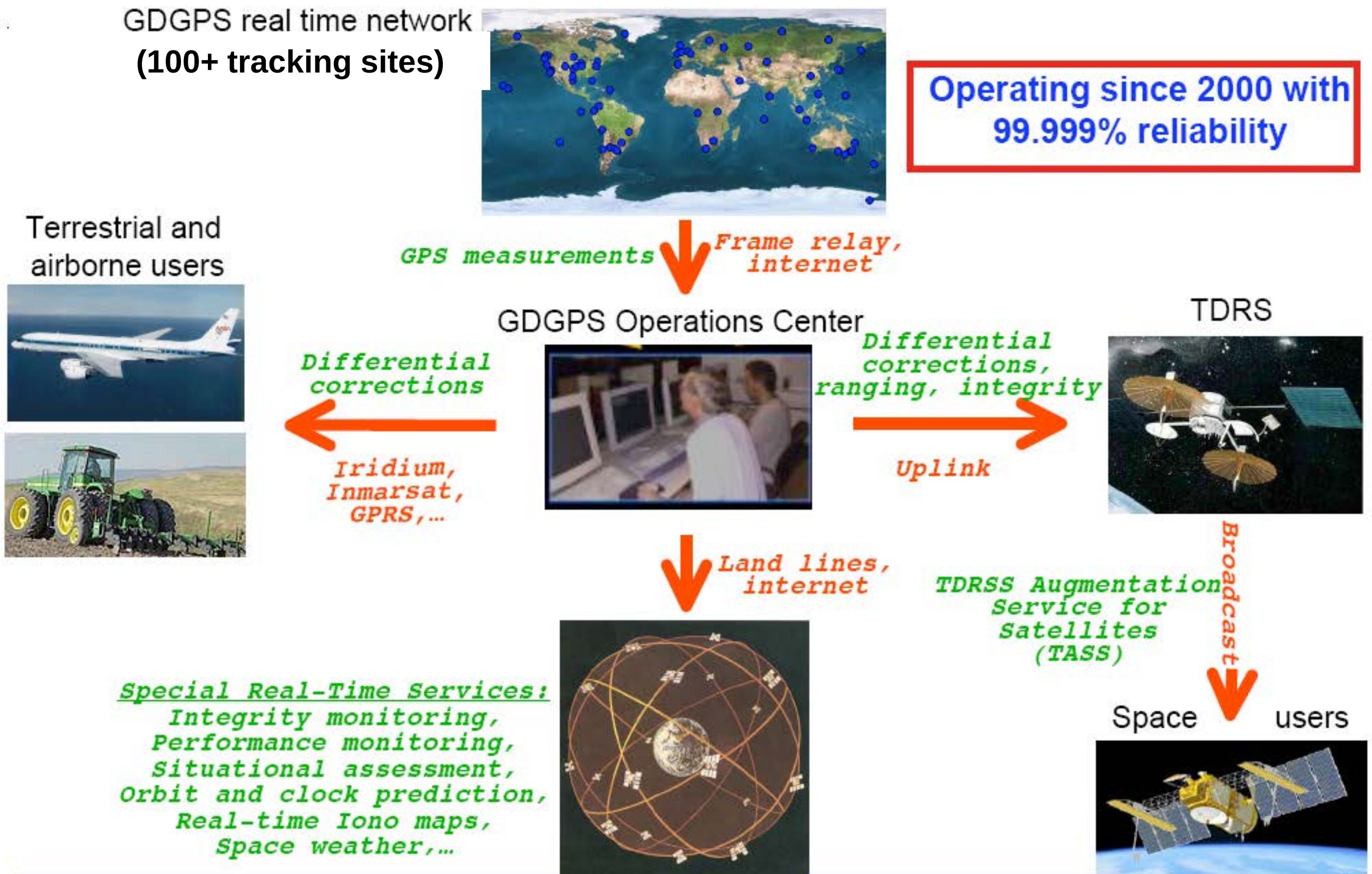
GPS Applications in IGS Projects & Working Groups
- IGS Reference Frame
- Supporting AREF - African Reference Frames
- Precise Time & Frequency Transfer
- GLONASS Pilot Service Project, now routine within IGS processes
- Low Earth Orbiters Project
- Ionosphere WG
- Atmosphere WG
- Sea Level - TIGA Project
- Real-Time Project
- Data Center WG
- GNSS WG

http://igscb.jpl.nasa.gov

NASA funds the coordinating center the IGS Central Bureau

Global Differential GPS System (GDGPS)

- Global, seamless, GPS augmentation system developed and operated by NASA's Jet Propulsion Laboratory
  - Supports real-time positioning, timing, and environmental monitoring for agency science missions. Provides advanced real-time performance monitoring
  - Provides timely products for GPS situational assessment, natural hazard monitoring, emergency geolocation, and other applications.
  - Operational since 2000, has more than 100 dual-frequency GPS reference stations



Augmenting GPS in Space with TASS

- **TDRSS Augmentation Service for Satellites (TASS)**
- **Supports all space users**
  - Communication channel tracking / ground-in-the-loop users
  - GNSS-based on-board autonomous navigation

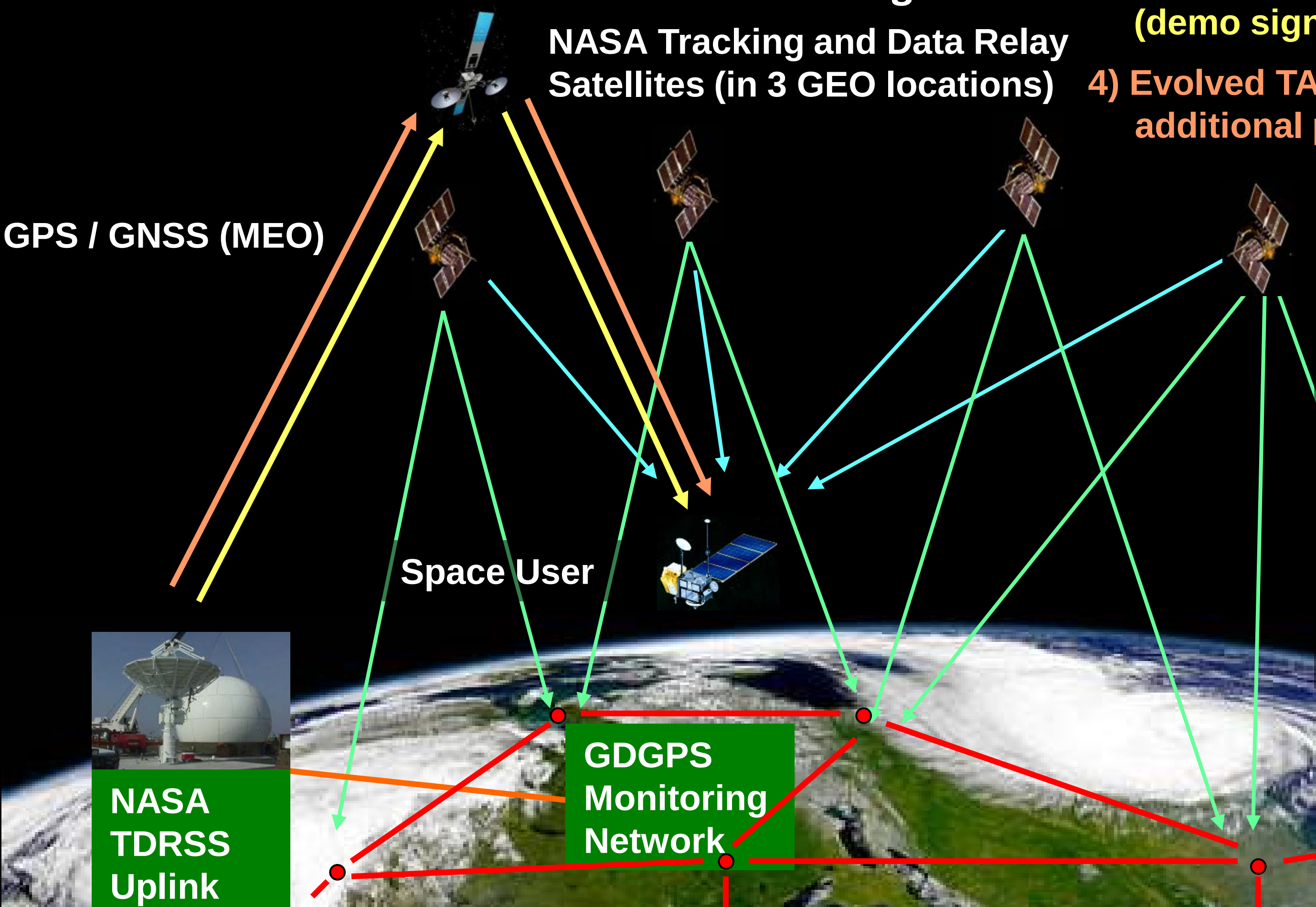
1) User spacecraft acquires GNSS signals

2) A ground network monitors GNSS satellites

3) GEO Space Network satellites relay GNSS differential corrections to space users on an S-band signal (demo signal since 2006)

4) Evolved TASS signal incorporates additional parameters

- GNSS integrity Information
- Tracking Satellite Information (health, ephemerides, maneuvers)
- Space Weather Data
- Solar Flux Data
- Earth Orientation Parameters
- User-specific Command Fields
- Pseudorandom Noise (PRN) ranging code



Closing Remarks

- 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 United States Air Force 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=_zM79vSnD2M

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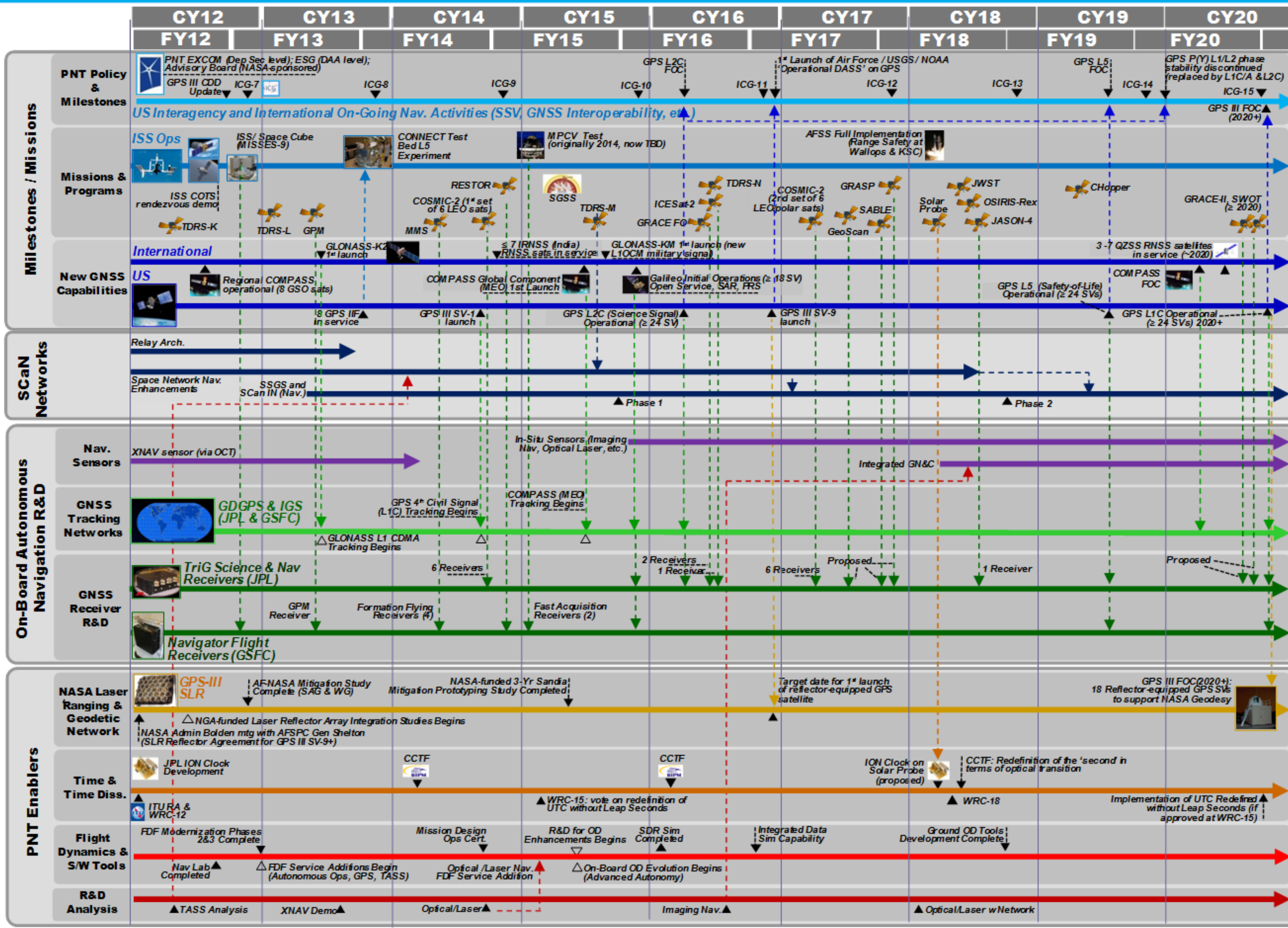
Backup Slides

“Near Earth” PNT Development Activities Timeline 2012-2020

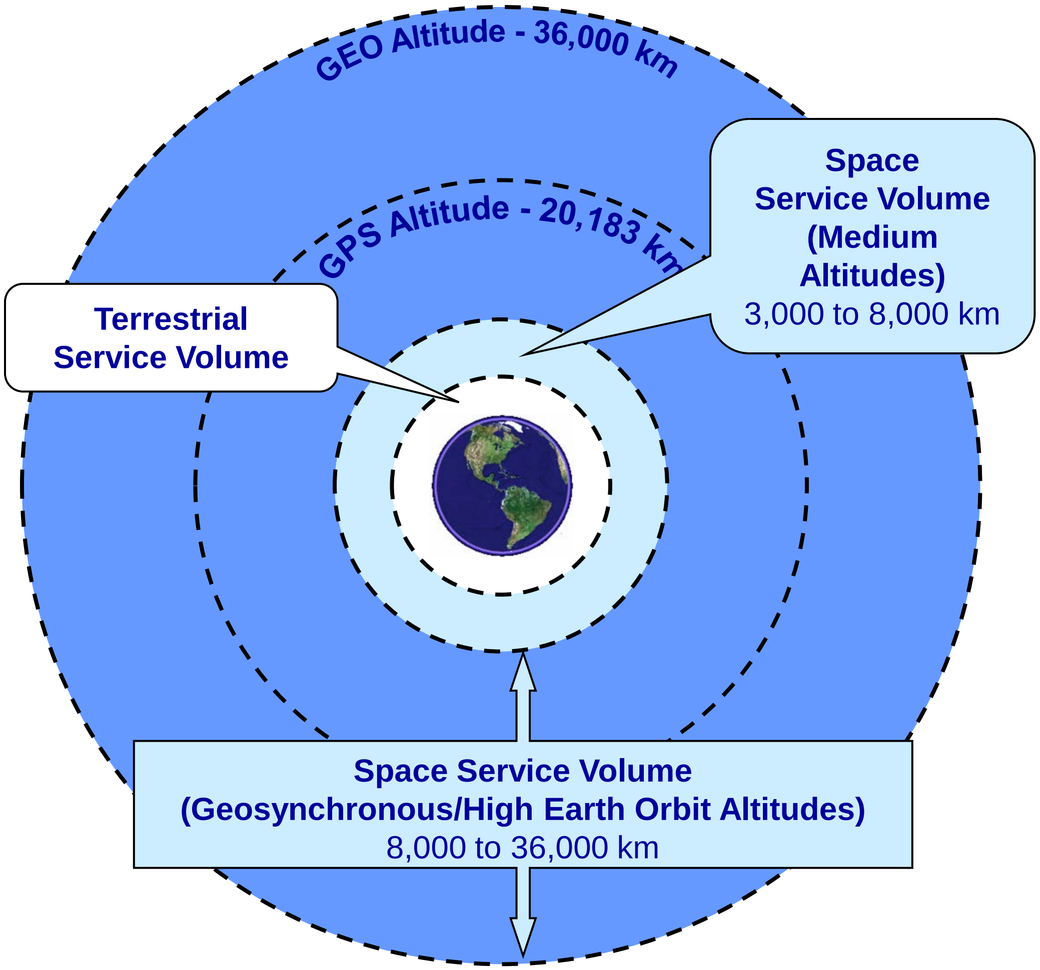


GNSS Mission Areas: Precise Orbit Determination, Timing, Relative Nav for Rendezvous, Formation Flying, & Science Applications

Mission	GNSS	Application	Orbit	Receiver	Signals	Launch
LandSat	GPS	Orbit	LEO	GD Viceroy	L1	2012
COSMIC IIA	GPS, GLONASS, Galileo	Occultation	LEO	TriG	L1, L2, L5, Galileo, GLONASS	2013
Jason III	GPS, GLONASS, Galileo	Oceanography	LEO	BlackJack/IGOR+	L1, L2, L5, Galileo, GLONASS	2013
GPM	GPS	Orbit, time	GEO	Navigator	L1 C/A	2013
COSMIC IIB	GPS, GLONASS, Galileo	Occultation	LEO	TriG	L1, L2, L5, Galileo, GLONASS	2014
MMS	GPS	Rel. range, orbit, time	up to 30 Re	Navigator	L1 C/A	2014
CLARREO	GPS, GLONASS, Galileo	Occultation	LEO	TriG	L1, L2, L5, Galileo, GLONASS	2015
GOES-R	GPS	Orbit	GEO	Navigator	L1 C/A	2015

Defining the Space Service Volume Beyond LEO

- Due to GPS performance variations based on altitude and geometry, the overall GPS SSV is in turn subdivided into two separate service domains:
- SSV for Medium Altitudes:
  - 3,000 to 8,000 km altitude
  - Visible GPS satellites can be present both above and below the user
- SSV for GSO/HEO Altitudes:
  - 8,000 to 36,000 km altitude
  - Visible GPS satellites are predominantly below the user



SSV Meant to Overcome "Traditional" GPS Constraints in Space Environment

- GPS availability and signal strength for Positioning, Navigation, and Timing (PNT) services originally specified for users on or near the Earth's surface
  - Primarily developed for land, air, and maritime users, however most LEO space users up to 3,000 km share similar operational benefits as more "traditional" Earth users
- Space users increasingly rely on GPS/GNSS for spacecraft navigation and science, however space remains a challenging operational environment at higher altitudes:
  - Rapidly changing geometry affects acquisition, tracking, time-tagging, navigation
  - Large dynamic ranges – "weak" and "strong" satellites with wide signal gain variability
  - High Doppler & Doppler Rates
  - Fewer satellite signals available
  - Mission antenna placement – visibility, multipath, radiation on very dynamic platforms
- To overcome these constraints, NASA has invested in:
  - Conducting flight experiments to characterize GPS signal performance beyond LEO
  - Developing new GPS/GNSS space-qualified receivers to support missions in geosynchronous orbit and highly elliptical orbits with apogees beyond GEO

Space Service Volume Characteristics

The characteristics that differentiate the SSV for Medium Altitudes & SSV for GSO/HEO Altitudes are as follows,

- **Medium Altitudes (3,000 – 8,000 km)**
  - Four GPS signals available simultaneously a majority of the time
  - Conventional space GPS receivers will have difficulty:
  - GPS signals over the limb of the Earth become increasingly important
  - Wide range of received GPS signal strength
  - One-meter orbit accuracies feasible

- **GSO/HEO Altitudes (8,000 – 36,000 km)**
  - Nearly all GPS signals received over the limb of the Earth
  - Users will experience periods when no GPS satellites are available
  - Received power levels will be weaker than those in TSV or Medium Altitudes SSV
  - A properly designed receiver should be capable of accuracies ranging between 10 and 100 meters depending on receiver sensitivity and local oscillator stability

Specifications to Support SSV Users

- Three parameters are used to determine the characteristics of GPS signals to support positioning, navigation, and timing (PNT) in the SSV
  - **Signal Availability:** the number of GPS/GNSS satellites in direct line-of-sight with the receiver at any given time
  - **Received Power:** the minimum power level required at the GPS/GNSS receiver at altitude
  - **Pseudorange Accuracy:** contribution of the GPS/GNSS system to the measurement of the distance between a GPS/GNSS satellite and a GPS/GNSS receiver