National Aeronautics and Space Administration

SCaN

SPACE COMMUNICATIONS AND NAVIGATION

Keeping the universe connected.

ICG: Achieving GNSS Interoperability and Robustness

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Interoperability & Spectrum Access are Key NASA/SCaN Requirement Drivers

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 technically and financially 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 on **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.

NASA's Evolving Comm & Nav Networks Extend the Reach of GPS/GNSS

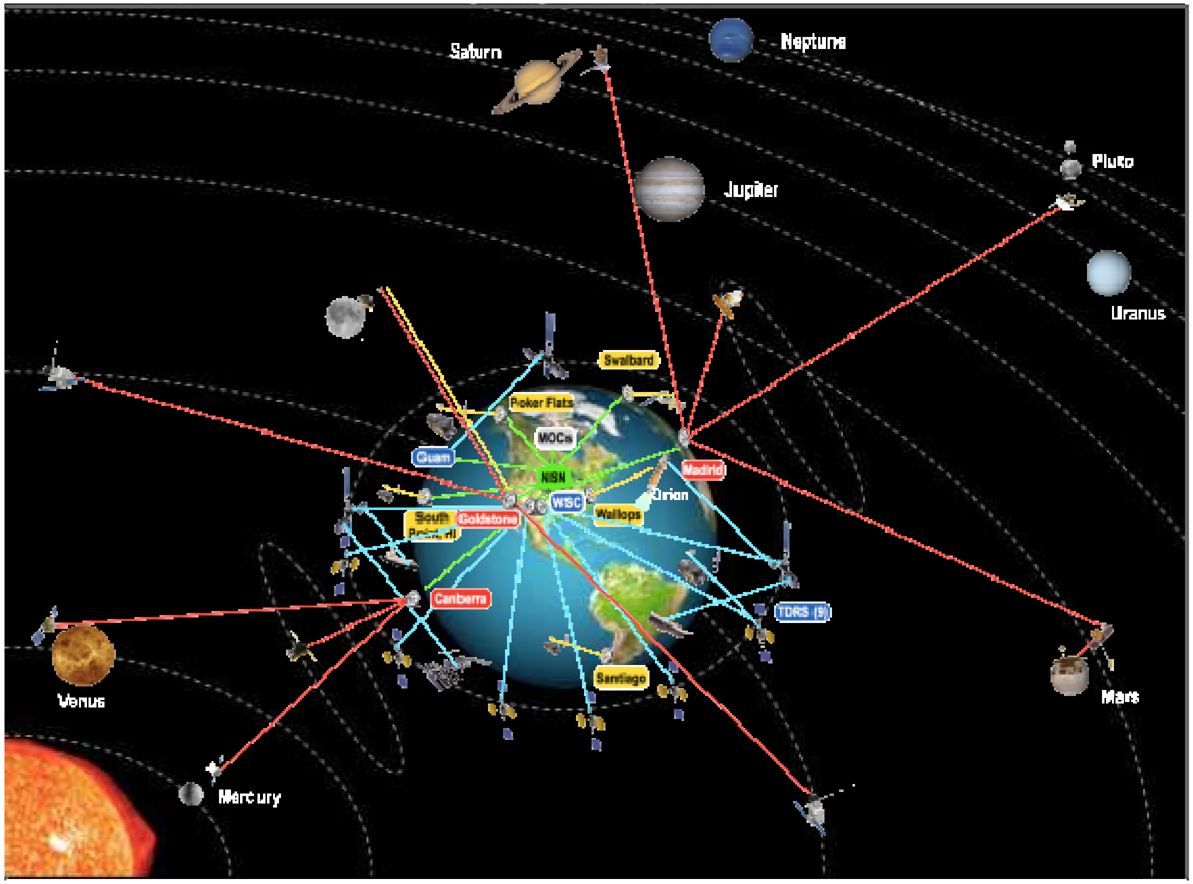
The current NASA space communications architecture embraces three operational networks that collectively provide communications services to supported missions using space-based and ground-based assets

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

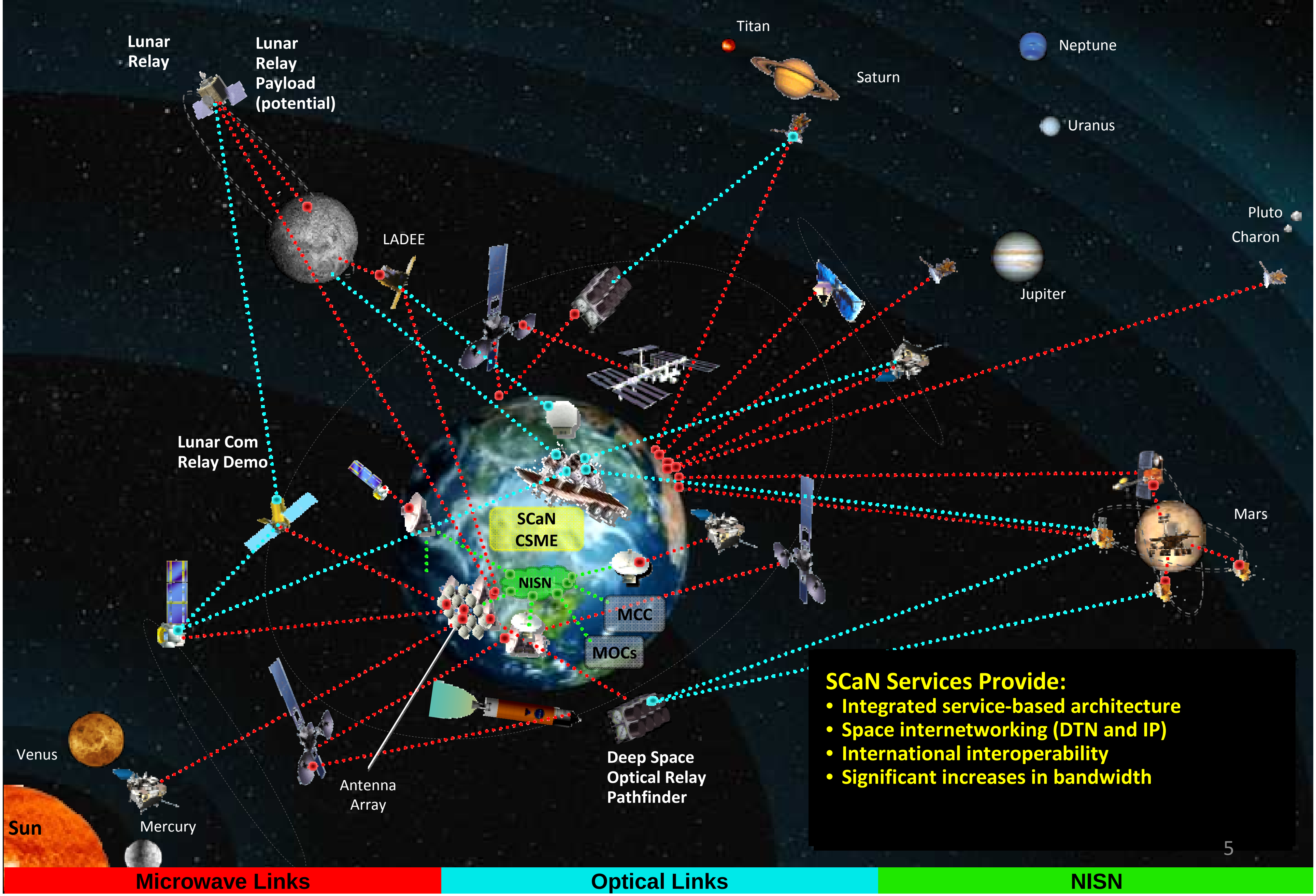
Deep Space Network - ground stations spaced around the world providing continuous coverage of satellites from Earth Orbit (GEO) to the edge of our solar system

NASA Integrated Services Network (NISN) – no longer part of SCaN – managed by OCIO; provides terrestrial connectivity



International Interoperability Can Benefit from NASA's Worldwide Networks

Evolution of SCaN Integrated Comm & Nav Architecture

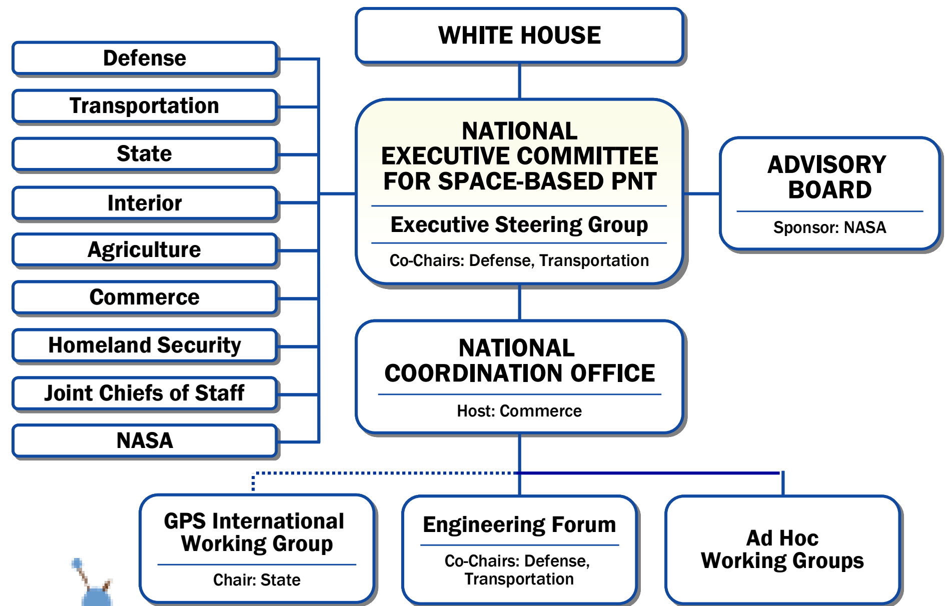


SCaN Services Provide:

- Integrated service-based architecture
- Space internetworking (DTN and IP)
- International interoperability
- Significant increases in bandwidth

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 ICG and IOAG to seek similar benefits from other PNT constellations to maximize performance, robustness, and interoperability for all

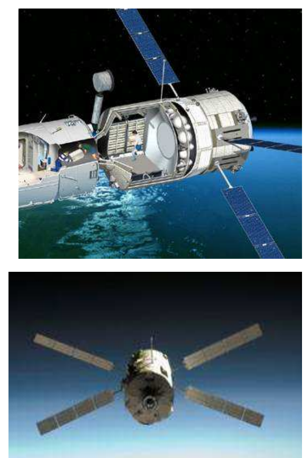


GPS/GNSS Enable Space Ops, Exploration, and Science Apps

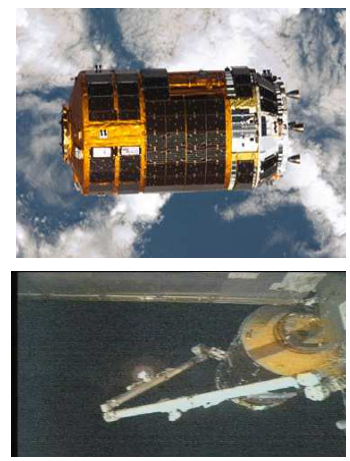
GPS PNT Services Enable:

- **Real-time On-Board Navigation:** Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, GEO satellite servicing
- **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 levels and ice melt to measuring the gravity field

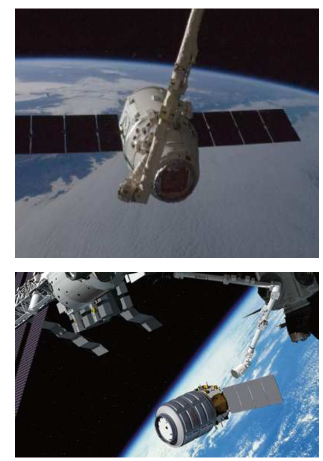
GPS Relative Navigation is used for rendezvous to ISS



ESA ATV 1st mission to ISS in 2008

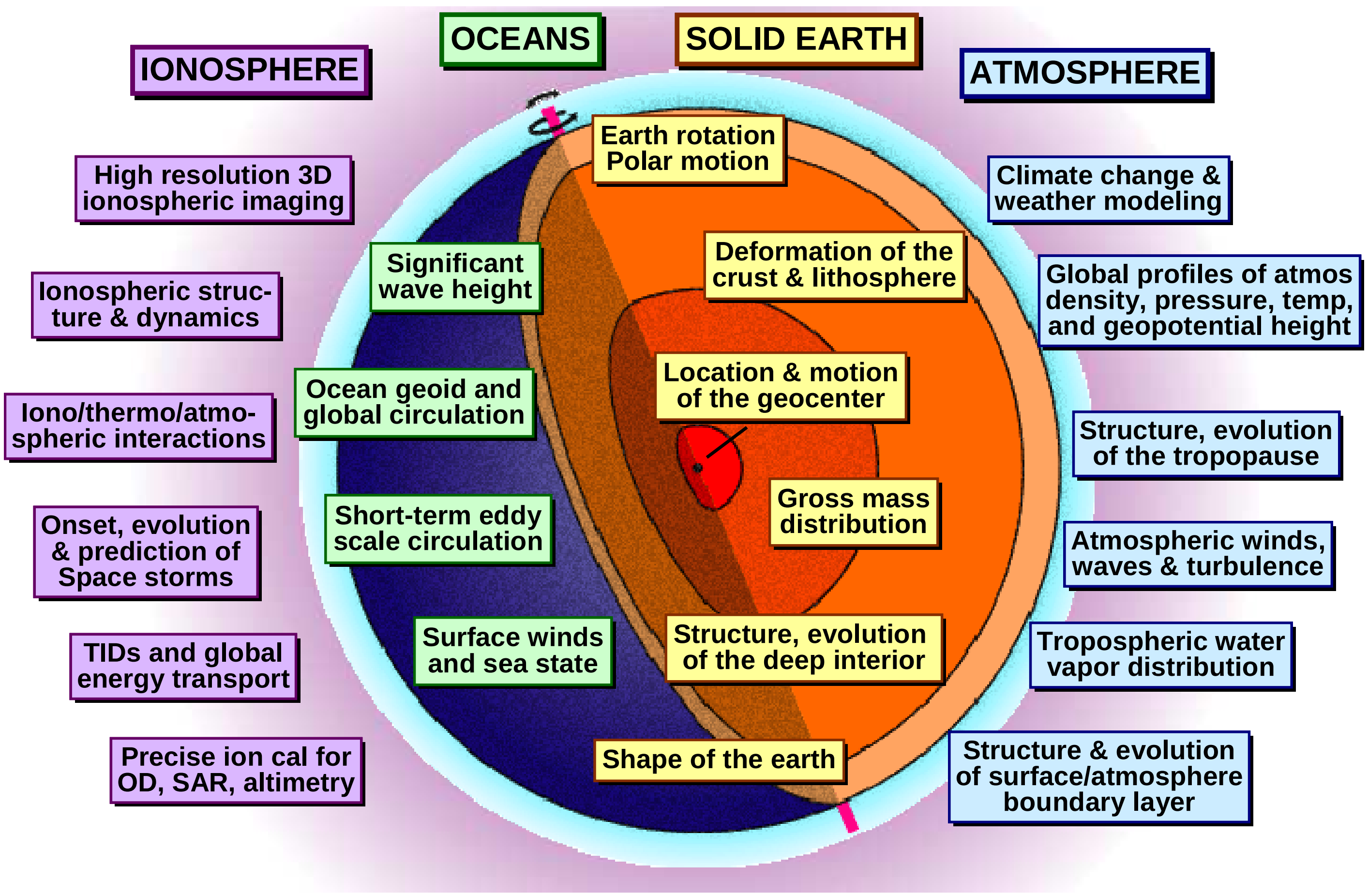


JAXA's HTV 1st mission to ISS in 2009

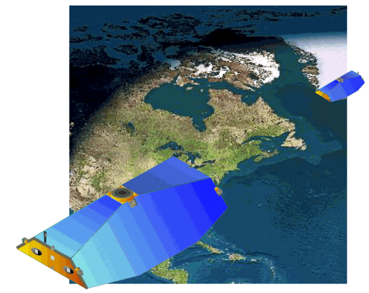


Commercial Cargo Resupply (Space-X & Cygnus), 2012+

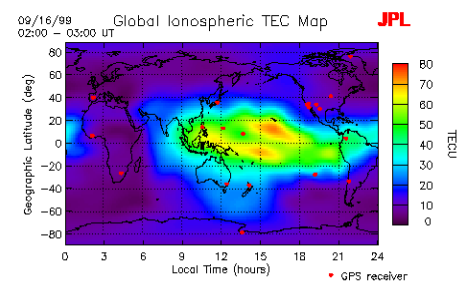
Unique Science Applications Enabled by GPS/GNSS – i.e., Radio Occultation, etc.,



Gravity Field Measurements (GRACE Mission)



Ionospheric Remote Sensing using GPS Occultation



Ocean Topography

NASA’s GNSS Perspective and Priorities

- GPS is a cornerstone to an evolving GNSS constellation enterprise that serves all humanity

- NASA is working with the U.S. Air Force and National Space-based PNT EXCOM to enhance GPS capabilities while making it more robust for all users, including:
  - Defining performance parameters for a GPS/GNSS Space Service Volume (SSV)
  - Implementing Laser Retro-reflector Arrays (LRAs) on GPS III to perform Satellite Laser Ranging (SLR)
  - Developing & fielding multi-GNSS receivers
  - Expanding the reach of GPS/GNSS signal monitoring networks
  - Protecting Radionavigation Satellite Service (RNSS) spectrum

- These collaborative efforts are strongly in sync with the goals and objectives of the ICG and its members to maximize GNSS benefits for all

Augmenting GPS in Space with TASS

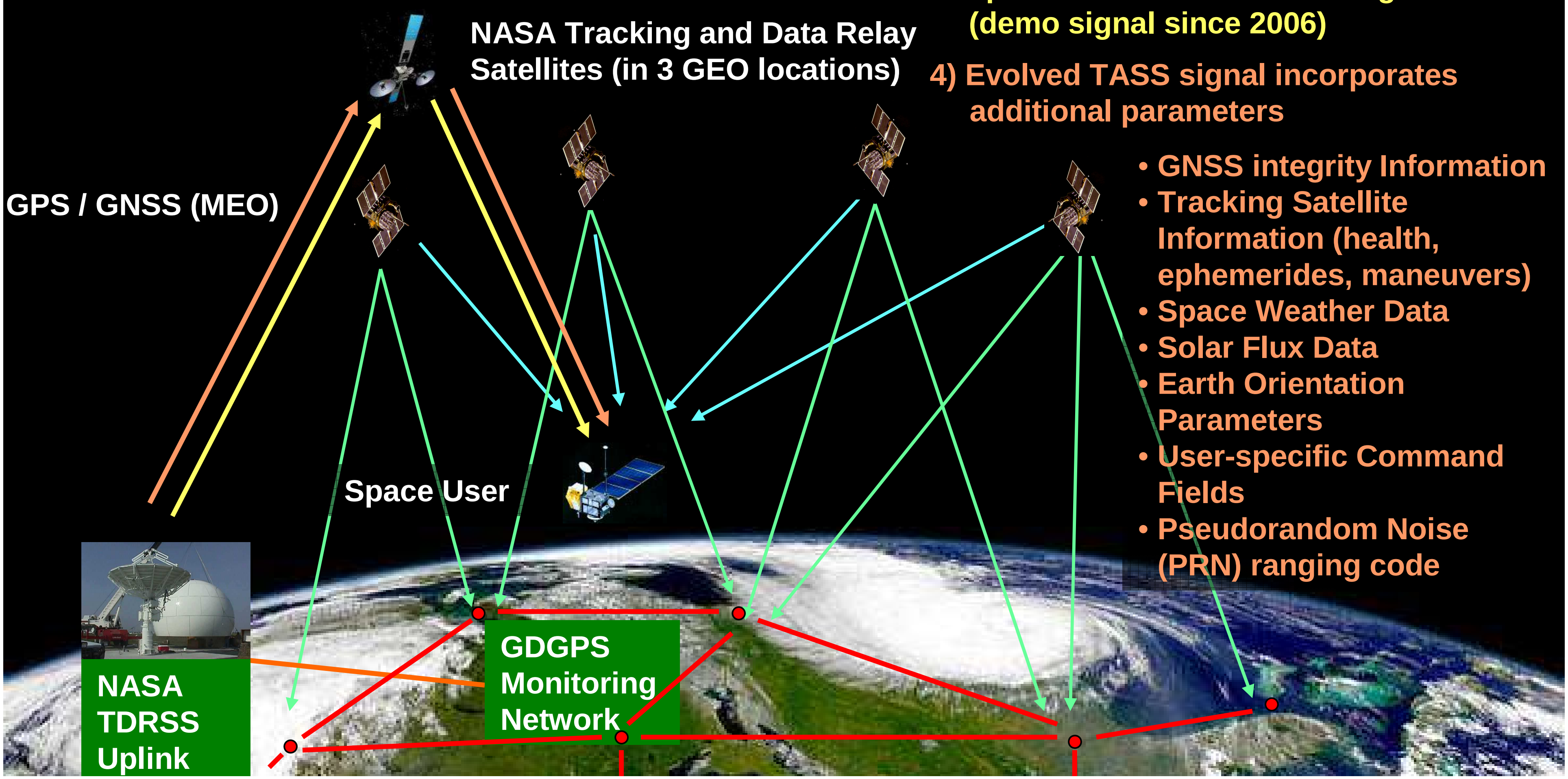
- **TDRSS Augmentation Service for Satellites (TASS)**
- **Supports all space users**
  - Communication channel tracking / ground-in-the-loop users
  - GNSS-based on-board autonomous navigation

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



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

Goddard Space Flight Center

- Navigator GPS Receiver: GPS L1 C/A
  - Flew on Hubble Space Telescope SM4 (May 2009), planned for MMS, GOES, GPM, Orion (commercial version developed by Honeywell)
  - 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

- 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
- Tri GNSS Receiver (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: 2013

Key Space Agency International Collaboration

SCaN represents NASA at international fora related to space communications & navigation issues, including:

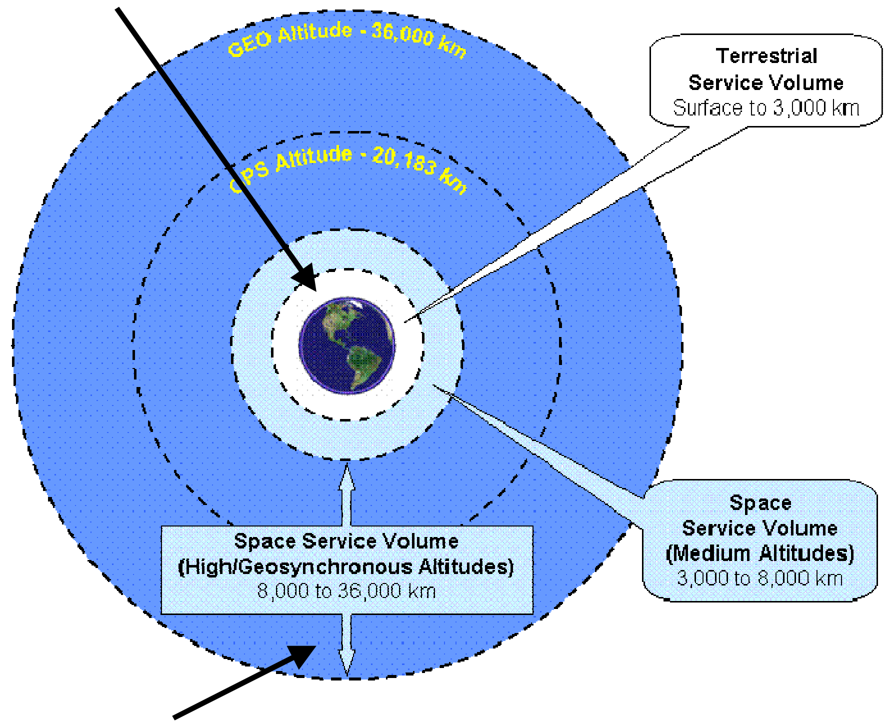
- Interoperability Plenary (IOP)
  https://interoperabilityplenary.org/home.aspx
  - Interagency Operations Advisory Group (IOAG)
    www.ioag.org
- Space Frequency Coordination Group (SFCG)
  https://www.sfcgonline.org/home.aspx
- Consultative Committee for Space Data Systems (CCSDS)
  http://public.ccsds.org/default.aspx
- International Telecommunications Union (ITU)
- International Committee on Global Navigation Satellite Systems (ICG)
  http://www.oosa.unvienna.org/oosa/index.html

GNSS Interoperability

Expanding the GPS Space Service Volume (SSV) into a multi-GNSS SSV

- At least <u>four</u> 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 <u>one</u> 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; <u>and</u>
  - 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, <u>if</u> interoperable, then GPS + Galileo + GLONASS + Beidou provide > 4 GNSS sats in line-of-sight at GSO.

Challenges & Issues for Emerging GNSS Services

- Challenged by global growth of all types of wireless devices
  - Unwanted emissions from adjacent bands can raise the RNSS noise floor
  - Excessive power in adjacent bands can overload RNSS receivers (or any other receiver)
  - In the past, incompatible mobile satellite services and low-powered devices have unsuccessfully sought to operate across restricted RNSS bands
  - Industry-level agreements (e.g., low-power digital TV, MSS ATC) can and have restrained unwanted emissions
- Protection of GNSS spectrum by just one country is inadequate if commercial devices that cause harmful emissions proliferate
  - Pressure for L-band spectrum to support mobile broadband and other innovations, e.g., unlicensed devices, cloud computing, software radios, etc.
  - International use of unlicensed repeaters and licensed in-band pseudolites, intentional and unintentional spoofers
  - Intergovernmental coordination of space-based L-band radars for EESS applications
  - Industry-level negotiations, interagency agreements, and international regulatory cooperation will be needed to sustain the RNSS bands

Options to Further Protect GNSS Spectrum

Protection from In-band Emissions

- Coordinate with other GNSS providers to limit the noise floor in the L-band
- Understand the operational performance parameters of all PNT systems & utilize multi-GNSS receivers
- Prevent increases in the noise floor due to EESS space-based L-band radars, future UWB devices
- Improve efforts to track down and eliminate intentional, small, commercial jamming devices
  - Plus in-band pseudolites

Protection from Out-of-Band Emissions

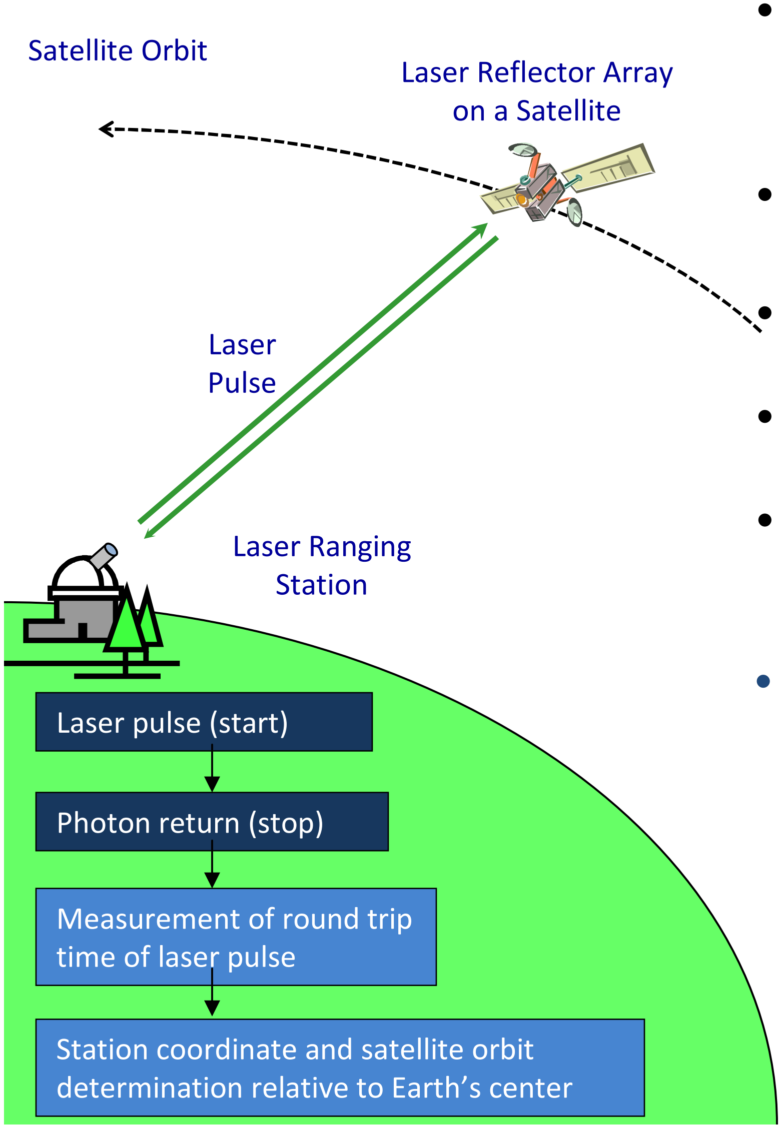
- Protect RNSS spectrum from out-of-band emissions in adjacent bands
  - Avoid “one-size-fits-all” solutions
  - Burden of evidence on proving safety, not causing harm, up to new entrants
  - Reflect industry best practices in improving out-of-band-emissions
- Protect RNSS applications from receiver overload resulting from excessive transmitted power in adjacent bands
  - Any application can suffer overload if the power differential is large enough

Summary

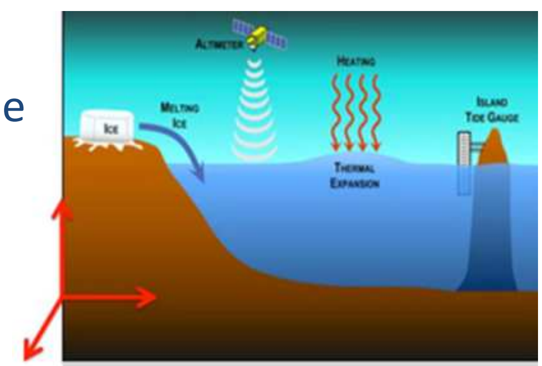
- Interoperability and robustness amongst the various GNSS constellations will benefit all users
- NASA is very active in national & international fora to enable service performance improvements and to preserve the spectrum environment
  - ICG, ITU, IOP, IOAG, SFCG, PNT EXCOM, numerous others…
- The NASA team on the U.S. Delegation looks forward to great collaboration at ICG-8, and welcomes productive technical exchanges with all participants on these issues.

BACK UP

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 worked with Air Force leaders Gen Shelton & Gen Kehler to approve Laser Reflector Arrays (LRAs) onboard GPS III
- Plans are now underway to deploy LRAs on GPS-III in the 2019 timeframe.



Space Geodesy provides positioning, navigation, and timing reference systems and Earth system observations

GPS SSV: Requirements / Performance Parameters

- Users in the SSV cannot always rely on conventional, instantaneous GPS solutions
- Thus, GPS performance requirements for the SSV are established via three parameters:
  - **Pseudorange Accuracy** (also known as User Range Error, or URE), currently set as 0.8 meters for GPS III
  - **Received Power**
  - **Signal Availability**

GPS III Minimum Received Civilian Signal Power (dBW) Requirement

Signal	Terrestrial Minimum Power (dBW)	SSV Minimum Power (dBW)	Reference Half-beamwidth
L1 C/A	-158.5	-184.0	23.5
L1C	-157.0	-182.5	23.5
L2 C/A or L2C	-158.5	-183.0	26
L5	-157.0	-182.0	26

GPS III Availability*

	MEO SSV		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	≥ 80% [1]	≥ 1%
L2, L5	100%	100%	≥ 92% [2]	≥ 6.5%

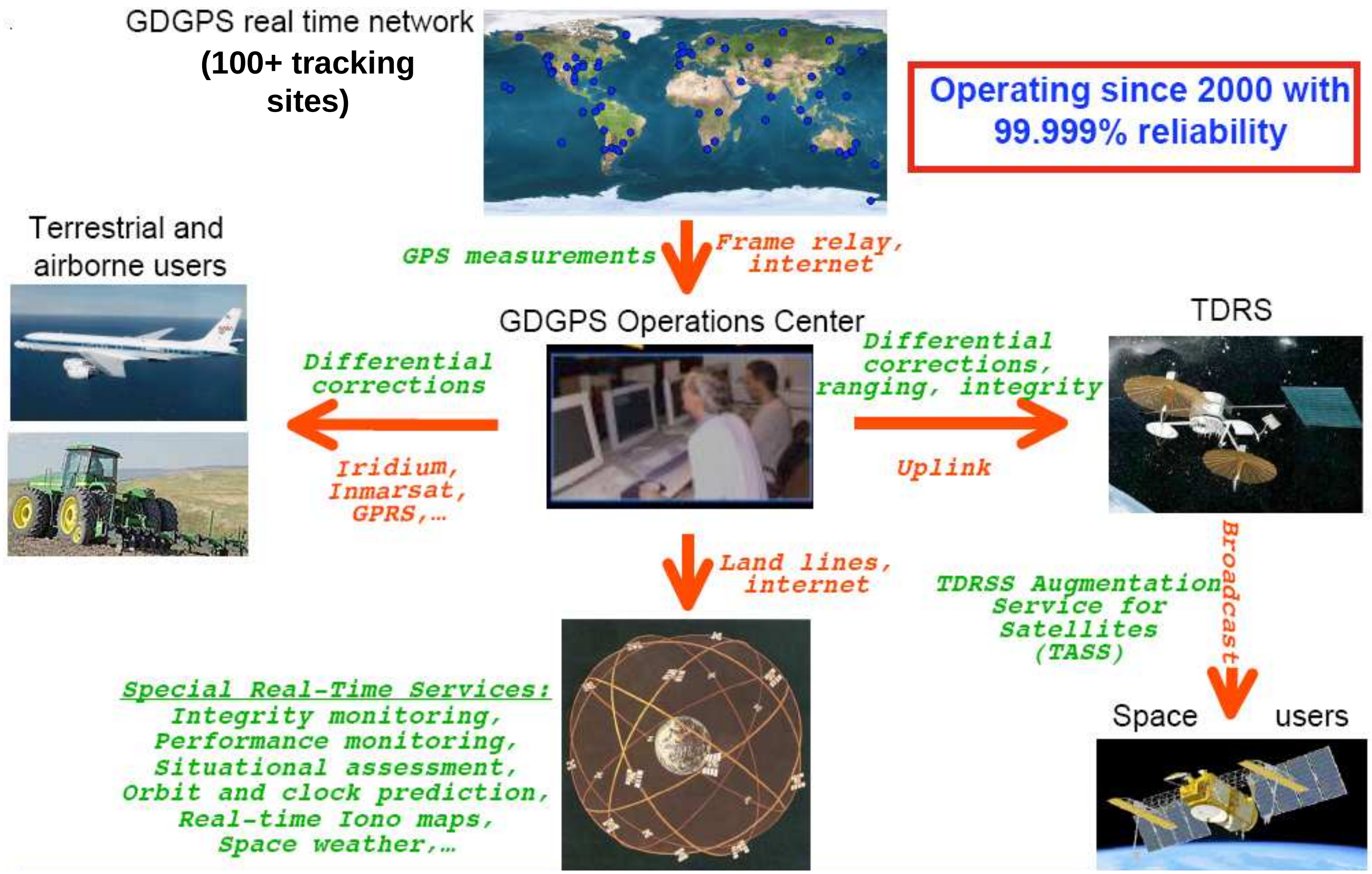
1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

(*) Assumes a nominal, optimized GPS III constellation and no GPS spacecraft failures. Signal availability at 95% of the areas within the specific altitude.

- 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

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



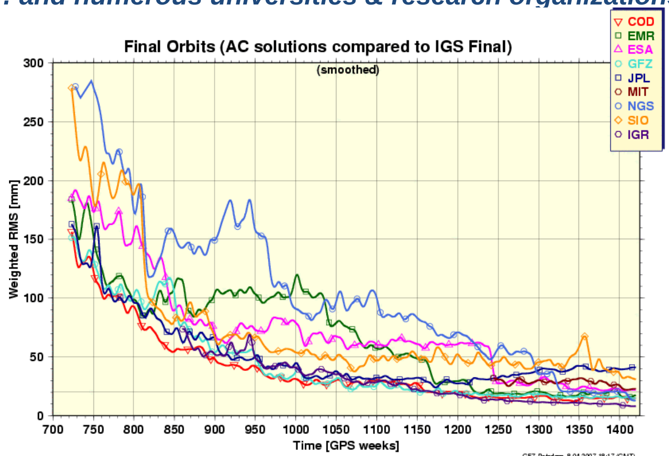
International GNSS Service (IGS)

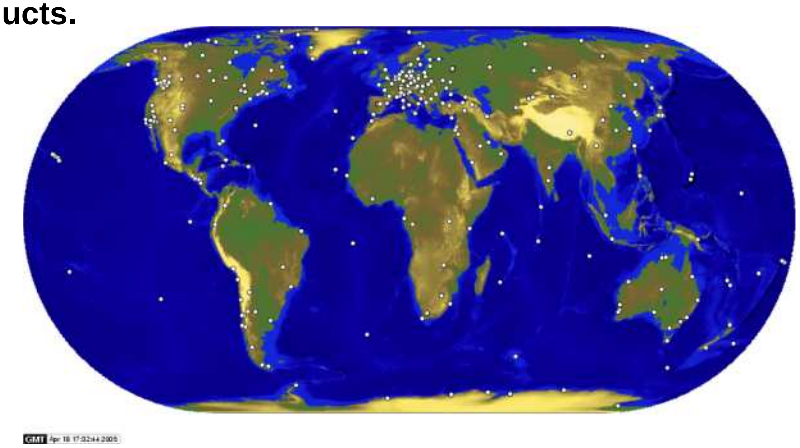
The IGS is a voluntary federation of more than 200 worldwide agencies in more than 90 countries that pool resources and permanent GPS station data to generate precise GPS products.

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.

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

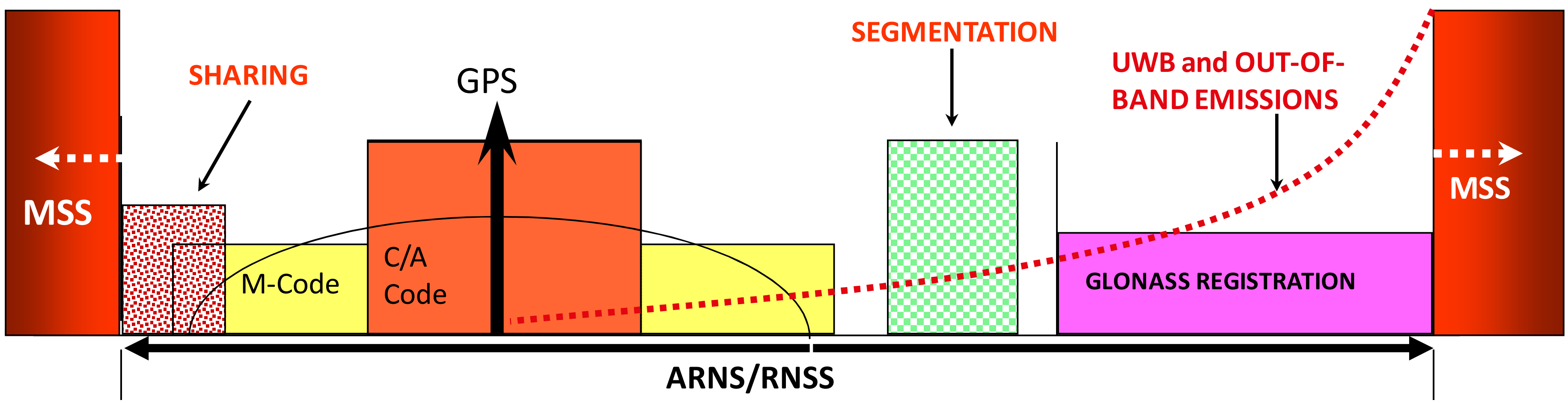
IGS products are formed by combining independent results from each of several Analysis Centers. Improvements in signals and computations have brought the centers' consistency in the Final GPS satellite orbit calculation to ~ 2cm

Graph courtesy Analysis Coordinator G. Gendt, GFZ Potsdam

http://igscb.jpl.nasa.gov

NASA funds the coordinating center the IGS Central Bureau

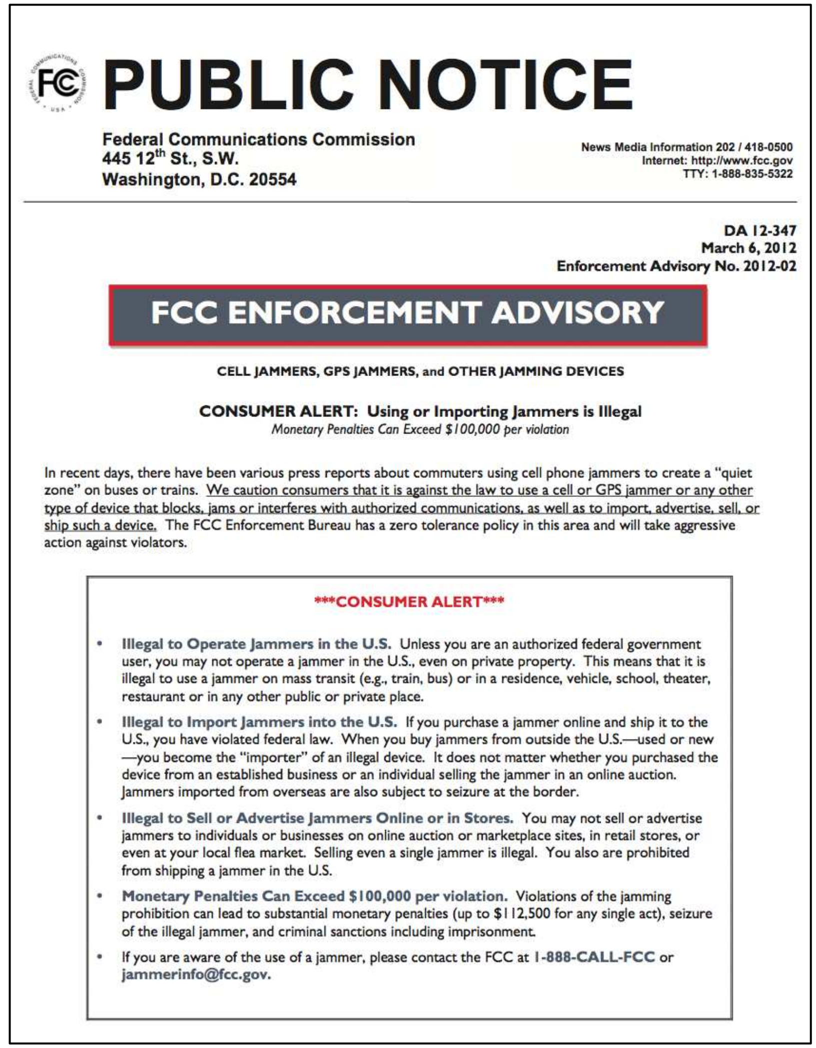
GPS/GNSS Services can be Harmed Several Ways



- The ARNS/RNSS spectrum is a unique resource
  - Sharing with higher power services jams weaker signals
  - Out-of-band and ultra wide-band emissions raise the noise floor
  - Segmentation prevents future evolution
- Spread spectrum GPS signals are unlike communication signals
  - 10^{-16} W received power, one-way
  - Any filter can be overwhelmed if exposed to enough power

Spectrum Protection at the National Level in U.S.

- In the U.S. Commercial GPS Jammers are Illegal
- The FCC Issues Cease and Desist orders to retailers, with penalties over $100,000 for each violation



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Washington, D.C. 20554

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Internet: http://www.fcc.gov
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DA 12-347
March 6, 2012
Enforcement Advisory No. 2012-02

FCC ENFORCEMENT ADVISORY

CELL JAMMERS, GPS JAMMERS, and OTHER JAMMING DEVICES

CONSUMER ALERT: Using or Importing Jammers is Illegal
Monetary Penalties Can Exceed $100,000 per violation

In recent days, there have been various press reports about commuters using cell phone jammers to create a "quiet zone" on buses or trains. We caution consumers that it is against the law to use a cell or GPS jammer or any other type of device that blocks, jams or interferes with authorized communications, as well as to import, advertise, sell, or ship such a device. The FCC Enforcement Bureau has a zero tolerance policy in this area and will take aggressive action against violators.

CONSUMER ALERT

- **Illegal to Operate Jammers in the U.S.** Unless you are an authorized federal government user, you may not operate a jammer in the U.S., even on private property. This means that it is illegal to use a jammer on mass transit (e.g., train, bus) or in a residence, vehicle, school, theater, restaurant or in any other public or private place.
- **Illegal to Import Jammers into the U.S.** If you purchase a jammer online and ship it to the U.S., you have violated federal law. When you buy jammers from outside the U.S.—used or new—you become the "importer" of an illegal device. It does not matter whether you purchased the device from an established business or an individual selling the jammer in an online auction. Jammers imported from overseas are also subject to seizure at the border.
- **Illegal to Sell or Advertise Jammers Online or in Stores.** You may not sell or advertise jammers to individuals or businesses on online auction or marketplace sites, in retail stores, or even at your local flea market. Selling even a single jammer is illegal. You also are prohibited from shipping a jammer in the U.S.
- **Monetary Penalties Can Exceed $100,000 per violation.** Violations of the jamming prohibition can lead to substantial monetary penalties (up to $112,500 for any single act), seizure of the illegal jammer, and criminal sanctions including imprisonment.
- If you are aware of the use of a jammer, please contact the FCC at **1-888-CALL-FCC** or **jammerinfo@fcc.gov.**

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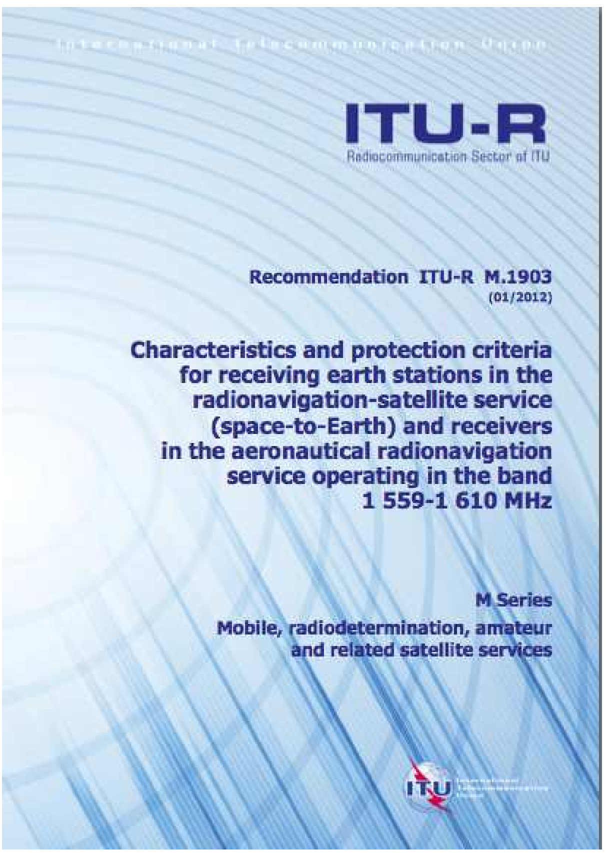
Spectrum Protection at the International Level

Approved ITU Recommendations on RNSS Protection Criteria Exist



RNSS definition from the ITU Radio Regulations (RR)

•No. 1.43 radionavigation-satellite service (RNSS): A radiodetermination-satellite service used for the purpose of radionavigation

•No. 1.59 safety service: Any radiocommunication service used permanently or temporarily for the safeguarding of human life and property

•No. 1.169 harmful interference: Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with the RR

•No. 5.28 Stations of a secondary service:

•No. 5.29 shall not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date

•No. 5.30 cannot claim protection from harmful interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date

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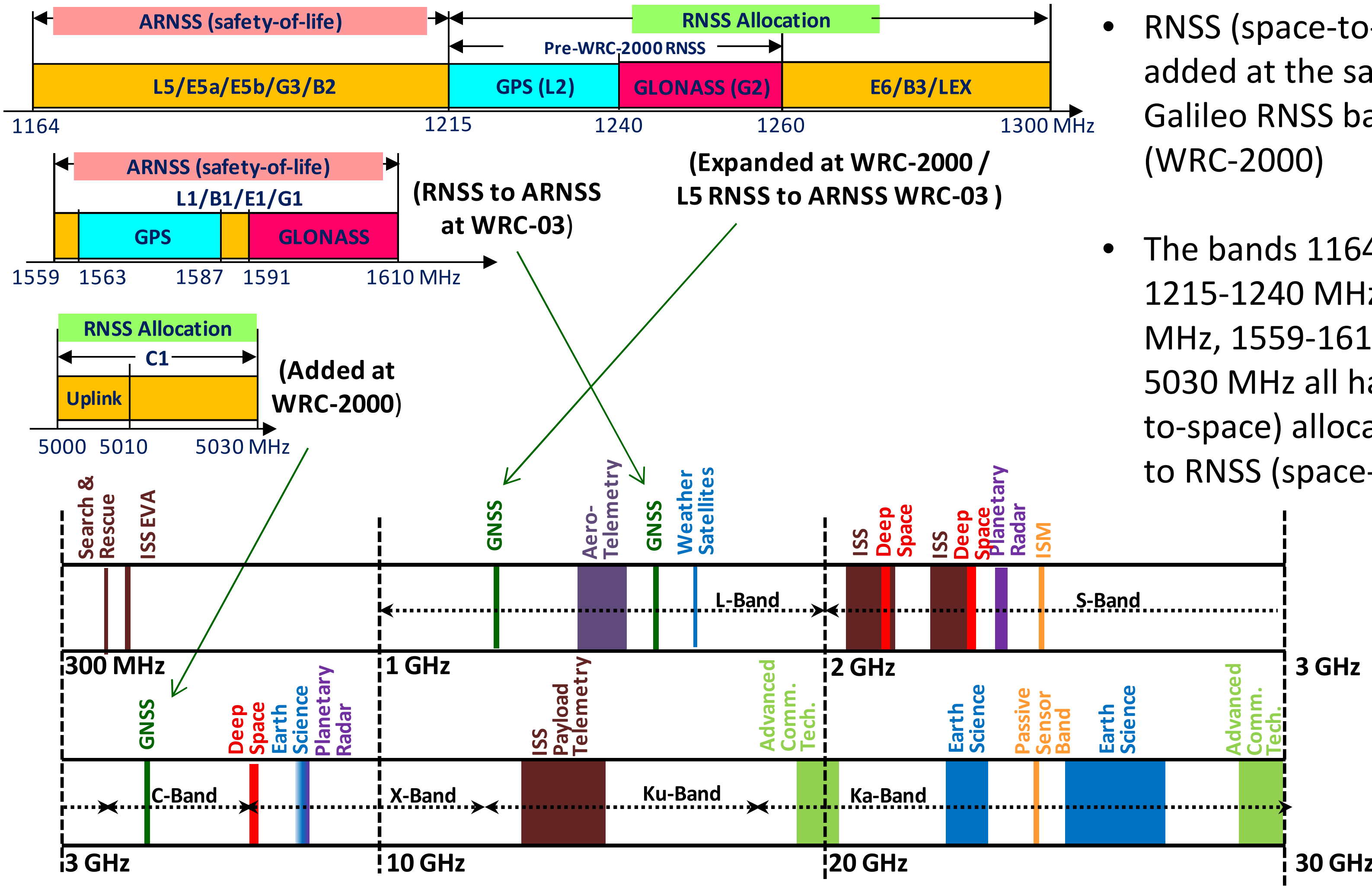
Evolving RNSS Spectrum



(NASA's Spectrum use 300 MHz – 30 GHz)

- RNSS (space-to-space) was added at the same time as the Galileo RNSS bands were added (WRC-2000)
- The bands 1164-1215 MHz, 1215-1240 MHz, 1240-1300 MHz, 1559-1610 MHz and 5010-5030 MHz all have RNSS (space-to-space) allocations in addition to RNSS (space-to-Earth)