
*Keeping the universe connected.*

# GNSS Space Service Volume Update

# Providers' Forum

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www.nasa.gov

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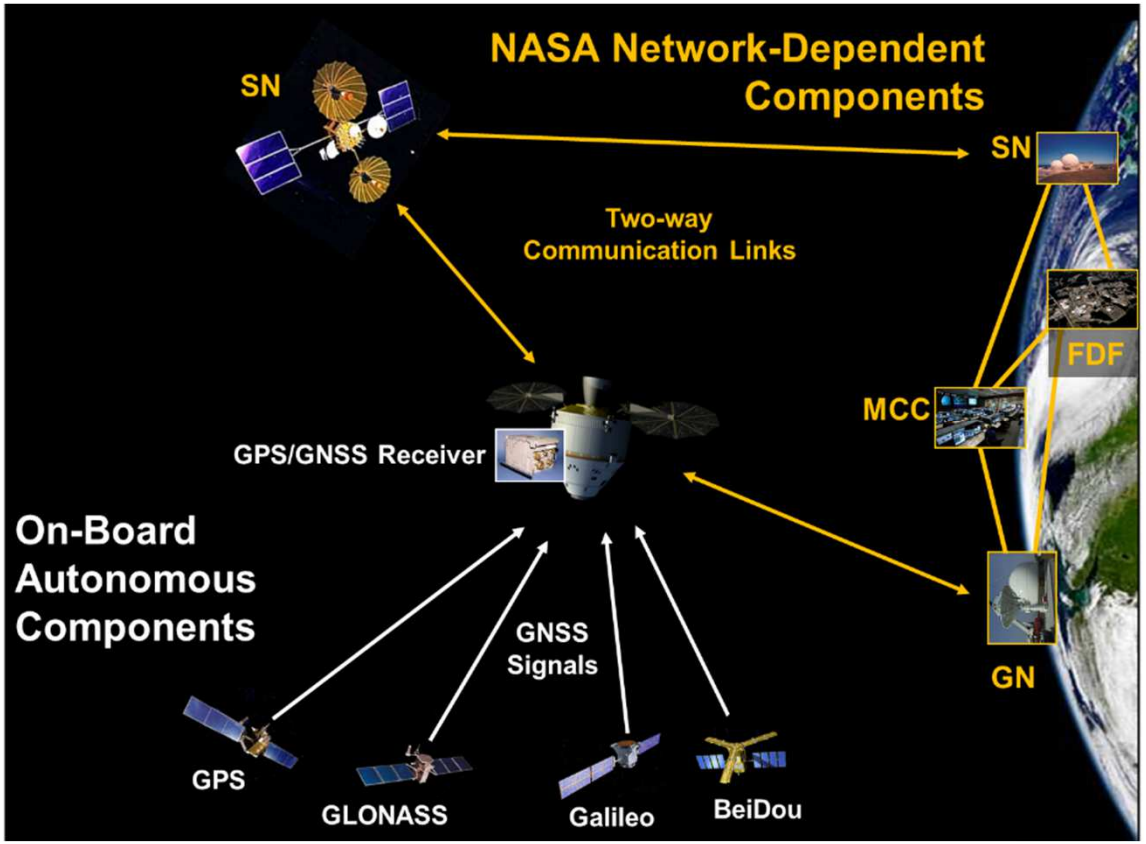
# Benefits of GPS/GNSS to NASA

**Real-time On-Board Navigation:** Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, GEO satellite servicing

**Earth Sciences:** GPS/GNSS used as a remote sensing tool supports atmospheric and ionospheric sciences, geodesy, and geodynamics -- from monitoring sea levels & ice melt to measuring the gravity field

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



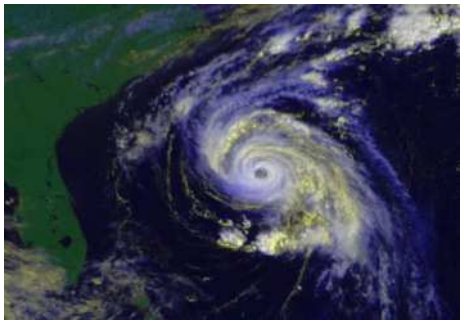

**NASA is investing approximately $130M** over the next 5 years on GPS/GNSS R&D and its implementation in support of space operations and science applications

GPS capabilities to support space users may be further improved by **pursuing compatibility and interoperability with GNSS** (Global Navigation Satellite Systems), such as the Russian GLONASS, European Galileo, and China's BDS

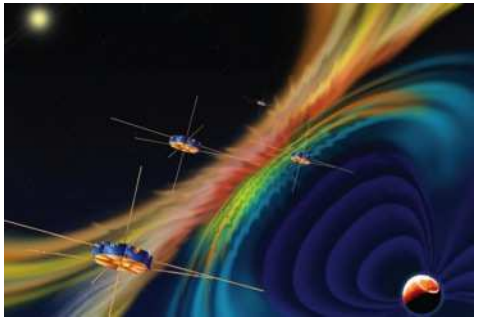
# The Promise of using GNSS for Real-Time Navigation in the Space Service Volume

## *Benefits of GNSS use in SSV:*

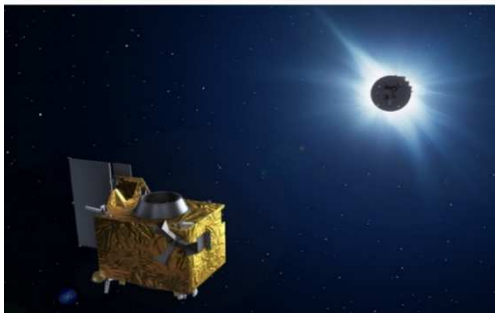
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- GNSS timing **reduces need for expensive on-board clocks** (from: $100sK-$1M to: $15K–$50K)
- Supports **increased satellite autonomy**, lowering mission operations costs (savings up to $500-750K/year)
- Enables new/enhanced capabilities and better performance for **HEO and GEO missions,** such as:



**Earth Weather Prediction using Advanced Weather Satellites**

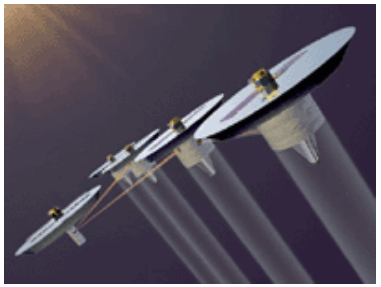


**Space Weather Observations**

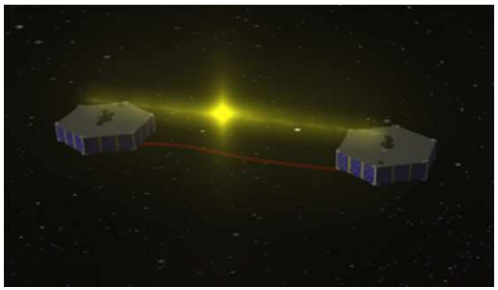


**Precise Relative Positioning**

**Launch Vehicle Upper Stages and Beyond-GEO applications**



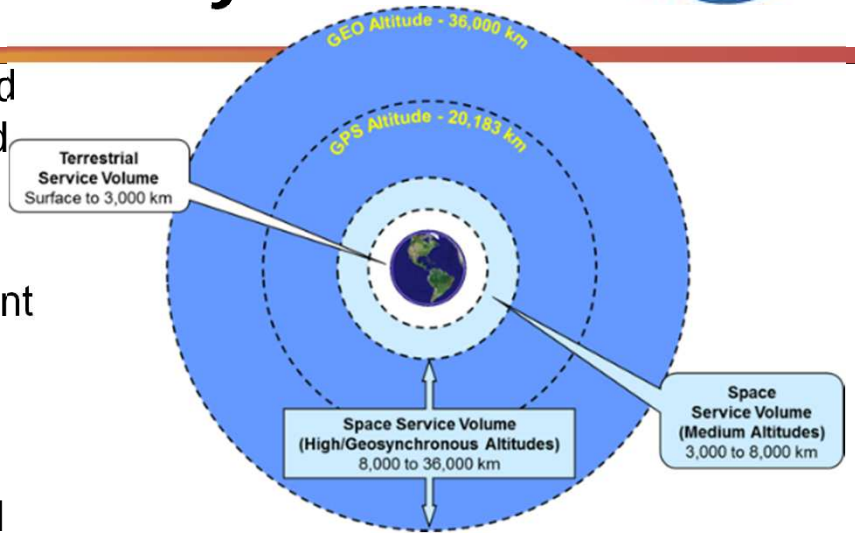
**Formation Flying, Space Situational Awareness, Proximity Operations**

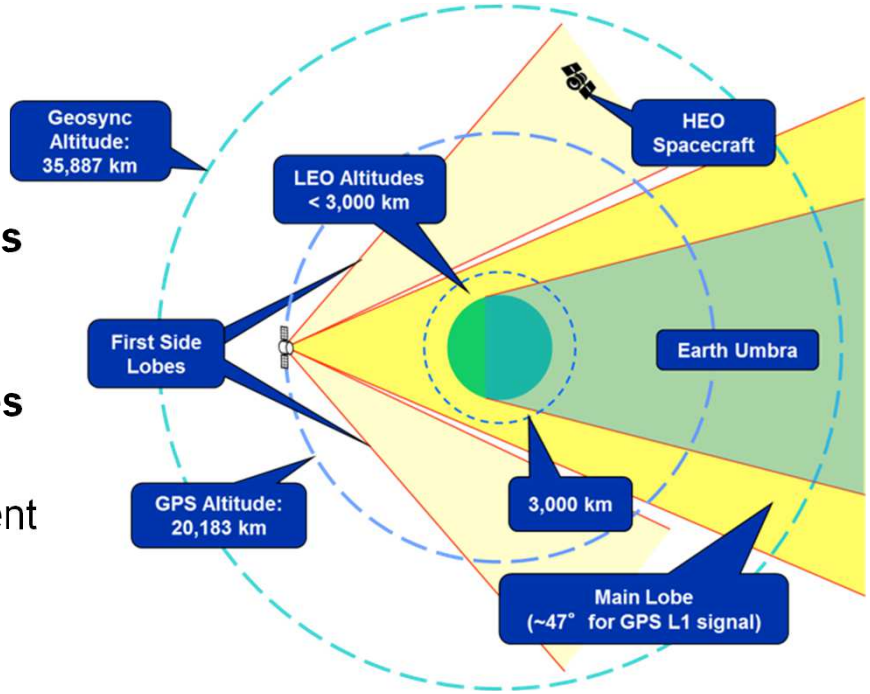


**Precise Position Knowledge and Control at GEO**

# GPS SSV Status and Lessons Learned: Executive Summary

- Current GPS SSV specifications, developed with limited on-orbit knowledge, only capture performance provided by signals transmitted within 23.5˚ (L1) or 26˚ (L2/L5) off-nadir angle (**Main Lobe Signal**).
- On-orbit data & lessons learned since spec development **show significant PNT performance improvements** when aggregate (**Main and Side Lobe**) signal is used.
- **Numerous** Civil operational missions in High & Geosynchronous Earth Orbit (HEO/GEO) utilize the full signal to enhance vehicle PNT performance
  - **Multiple** civil stakeholders **require** this enhanced PNT performance to meet mission requirements.
- **Failure to protect** aggregate signal performance in future GPS designs creates the risk **of significant loss of capability**, and **inability** to **further utilize performance** for civil space users in HEO/GEO
- Protecting GPS aggregate signal performance **ensures GNSS parity in the SSV**
- NASA-sponsored initiative underway to augment current SSV specification to ensure future signal availability of full, aggregate signal



# Key Civil Stakeholder: GOES-R

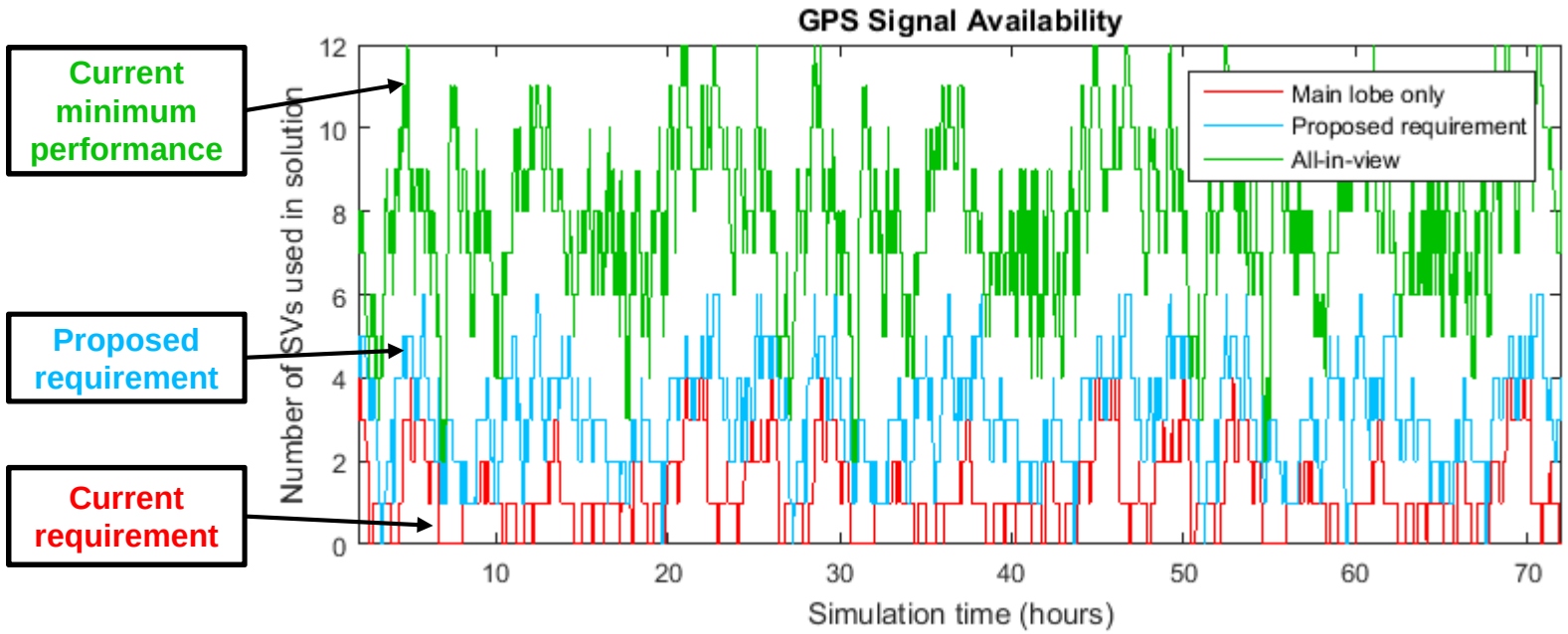
- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellite series
- 2016 Launch; Series operational through 2030s
- Improved Imager (ABI) combined with GPS PNT will be **societal game-changers** delivering data products to substantially improve public and property safety

- PNT driving requirements:
  - **Orbit position knowledge** requirement (right)
  - All performance requirements **applicable through maneuvers**, **<120 min/year** allowed exceedances
  - Stringent **navigation stability** requirements

| Parameter | Requirement (m, 1-sigma) |
|---|---|
| Radial | 33 |
| In-track | 25 |
| Cross-track | 25 |

- GOES-R series **cannot** meet stated mission requirements **with SSV coverage as currently documented**
- NASA-proposed requirement is minimum-impact solution to meet GOES-R performance needs
- NOAA also identifies **EUMETSAT (EU) and Japanese weather satellites** as reliant on increased GNSS signal availability in the SSV

# NASA Proposed SSV Requirement Language (In-work)




**Signal Availability of GOES-R-class GEO Mission**

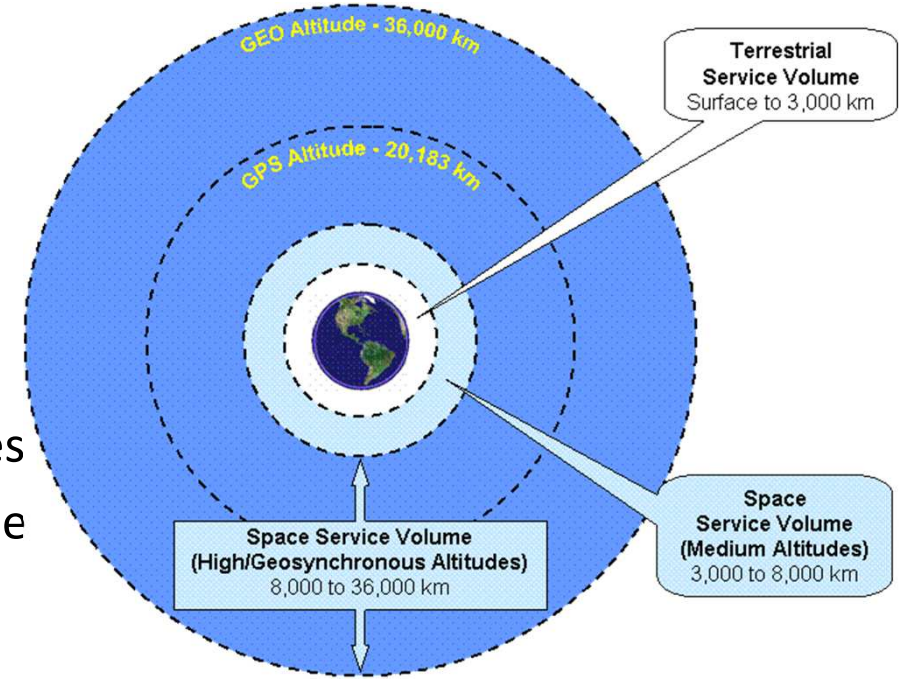
- Current requirement is a "triad" of three interrelated components:
  - Signal availability (% of time that 1 or 4 GPS signals are available; max outage time)
  - Minimum received signal power at GEO
  - Maximum pseudorange accuracy (equivalent to user range error)
- Proposed requirement adds second tier of capability specifically for HEO/GEO users
  - Increased signal availability to nearly continuous for at least 1 signal
  - Relaxed pseudorange accuracy from 0.8m RMS to 4m RMS
  - No change to minimum received signal power
  - Applies to all signals (L1/L2/L5), all codes

| PR acc. (rms) | 0.8 m | 4m |
|---|---|---|
| 1+ signal | ≥ 80% | ≥ 99% |
| 4+ signals | ≥ 1% | ≥ 33% |
| Max outage | 108 min | 10 min |

**SSV L1 HEO/GEO availability**

# More Resilient PNT Solutions In-Space through an Interoperable Multi-GNSS SSV

- At least four GNSS satellites in line-of-sight are needed for on-board real-time autonomous navigation
  - GPS guarantees this up to 3,000 km altitude
  - Meter-class real-time position accuracy
- At GEO altitude, an average of 1-2 GPS satellites will be available using only GPS main lobe signal with some long data outages
- GPS-only positioning possible using main lobe signal-only with on-board filtering, but very limited and with long waits for navigation recovery after trajectory maneuvers
- **GPS** + **Galileo** + **GLONASS** + **BDS** + **IRNSS** + **QZSS** would enable near-continuous visibility of four main-lobe GNSS signals on L1 frequency band or continuous visibility using L5 frequency band with 10 meter-class real-time position accuracy




To accomplish this requires:

- GNSS interoperability; and
- Common definitions & specifications for use of GNSS signals within the SSV
- Further improvements could be realized if GNSS systems specify aggregate (Main and Side lobe) signal availability

# U.S. Initiatives & Contributions to Ensure an Interoperable, Sustained, Quantified GNSS Capability for Space Users

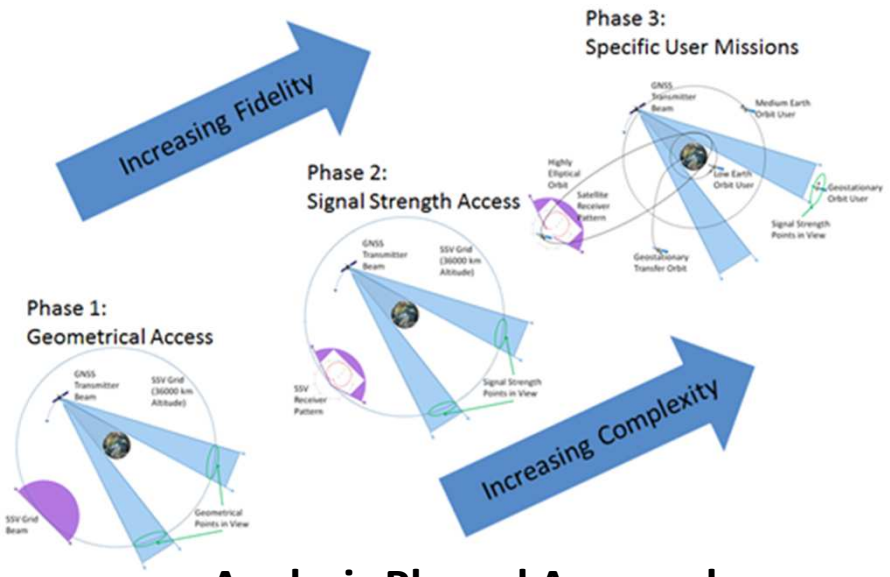
- Performing additional flight experiments above the constellation to characterize signals in cis-Lunar space
- Developing new weak signal GPS/GNSS receivers for spacecraft in cis-Lunar space through government technology developments (e.g. NASA Goddard Navigator, NavCube) and commercial procurements
- Working with the GPS Directorate and DoD community to formally document GPS requirements and antenna patterns for space users
- Developing missions and systems to utilize GNSS signals in the SSV (e.g. MMS, GOES, Orion)
- Supporting ICG WG-B SSV initiative through sustained technical guidance, SSV booklet development & leadership of SSV analysis
- Encouraging international coordination with other GNSS constellations (e,g, Galileo, GLONASS, BDS) to specify interoperable SSV capabilities

# ICG WG-B Observations

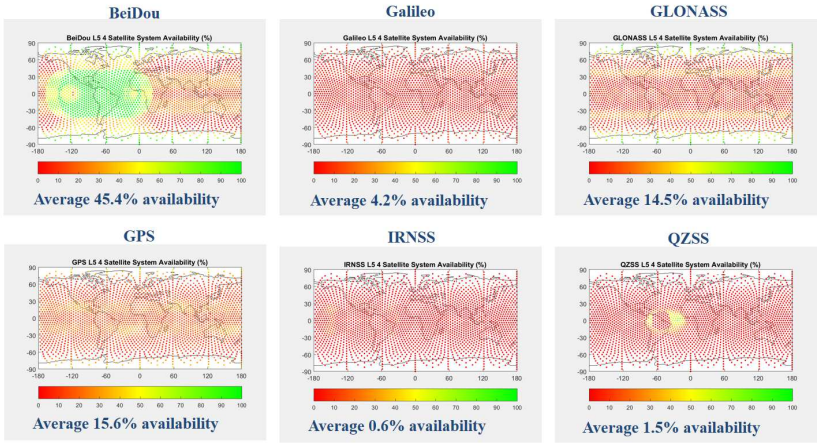
- WG-B is making significant progress in establishing an interoperable Global Navigation Satellite System (GNSS) Space Service Volume (SSV) through pre-work, analyses and regularly held teleconferences
- Co-chair leadership has kept the WG-B team at a high momentum
- WG-B Analyses underway to solidify understanding of expected HEO/GEO user performance using all provider's SSV signals (BDS, Galileo, GLONASS, GPS, IRNSS, QZSS)
- Not all providers are supporting current WG-B initiatives, particularly the current analysis effort. This is impeding the "full SSV interoperability" effort
- Recent ICG WG-B initiatives have led some providers (e.g. EU) to perform government studies to investigate best approaches for development and specification of SSV within their constellations

# On-Going Efforts:
# ICG WG-B Three-Phase Analysis Approach

- NASA is providing leadership in WG-B analysis effort to conduct an **independent assessment of the SSV using a multi-GNSS solution**
- Analysis effort builds capabilities across all providers to demonstrate the benefits of an interoperable GNSS SSV
- 3 phases of analysis with increasing complexity and fidelity:
- **Phase 1** is a geometrical analysis of GNSS signal visibility at MEO & GEO altitudes
  - Completed in May 2016
- **Phase 2** builds on Phase 1 results by incorporating signal strength constraints to the geometrical analysis at GEO altitude
  - Completed in September 2016
- **Phase 3** extends the signal strength analytical capabilities to realistic user missions, such as those in MEO, Geostationary Transfer, Highly Elliptical and Lunar trajectories




**Analysis Phased Approach**




**Phase 1 Analysis Results**

# US Team Recommendations to GNSS Providers

- Continue to evolve GNSS systems to support interoperability within the SSV
- Baseline SSV specifications as part of all future constellation developments with definitions and parameters that are common across all provider constellations
  - Specification should strive to capture near-continuous availability such as what may be provided by the aggregate GNSS signal (main & side lobes)
- Providers should perform a comprehensive series of antenna tests and power output measurements, pre-flight, to:
  - Characterize constellation gain and pseudorange accuracy for the full antenna pattern and to facilitate understanding of SSV specification margins
  - Enable mission designers to derive mission PNT performance of spacecraft in the SSV through mathematical models developed from antenna/power data
- Perform on-orbit characterization & testing of SSV specified signal parameters through dedicated flight experiments and mission data evaluation
- Encourage development of spacecraft and formation flying missions in the SSV
- Encourage active and consistent participation in all ICG SSV activities and initiatives, including the current interoperable GNSS analyses

# Closing Remarks

- NASA and all other space users increasingly rely on GNSS over an expanding range of orbital applications to serve Earth's population in countless ways
- Current and future space missions in SSV orbits are becoming increasing reliant on near-continuous PNT sensing using GNSS
- To ensure stable, robust PNT in the SSV, providers should:
  - Baseline SSV specifications as part of all future constellation developments using ICG-developed common definitions & parameters
  - Specification should strive to capture near-continuous availability such as what may be provided by the aggregate GNSS signal (main & side lobes)
- WG-B is making significant progress in establishing an interoperable Global Navigation Satellite System (GNSS) Space Service Volume (SSV) through pre-work, analyses and regular meetings
- NASA and the USG is proud to work with the GNSS providers to contribute making GNSS services more accessible, interoperable, robust, and precise for all users, for the benefit of humanity

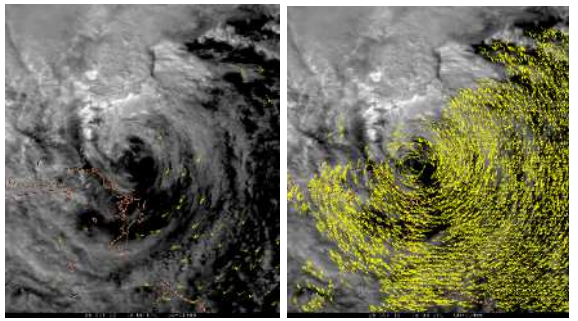
# Backup Charts

# Statement of Need:
# GOES-R Spacecraft Series Issue Summary

- GOES-R-U series operational weather satellites of national importance, protecting people and property through weather prediction and severe event warnings
- New, improved Imager (ABI) combined with near-continuous GPS PNT will have **game-changing** societal benefits with enhanced temporal, spatial, spectral & radiometric attributes
- GPS/GOES nav. stability & geolocation requirements critical to derive first & second derivative wind measurements, significantly improving wind velocity estimations
- Safety of people/property data products **requiring** the NASA-proposed (improved) SSV specification include:
  - Improved wind vector measurements—significantly enhancing convective (severe) storm prediction & danger zone warning time
  - Exact location & volume of mountain downpours—improves flash flood warnings
  - Timely, precise location of wild fires—enables safe placement of firefighters & equipment
  - More accurate prediction of early morning fog for aviation
  - Better prediction of mountain weather where radar is ineffective
  - Blending GEO-sat (high temporal resolution), LEO-sat (high spatial resolution) & ground-based radars for more accurate prediction
  - **Improved weather forecasting from 3-5 days (now) to 5-7 days (GOES-R)**

**Assembled GOES-R Spacecraft**


**Wind Vector Measurements Hurricane Sandy**



**Current** **GOES-R**

***Safety of People/Property Data Products Will Not Be Operationally Delivered if GPS Degrades Capability to Current GPS SSV Spec; Minimally Met Through Proposed SSV Spec***