International Committee on Global Navigation Satellite Systems

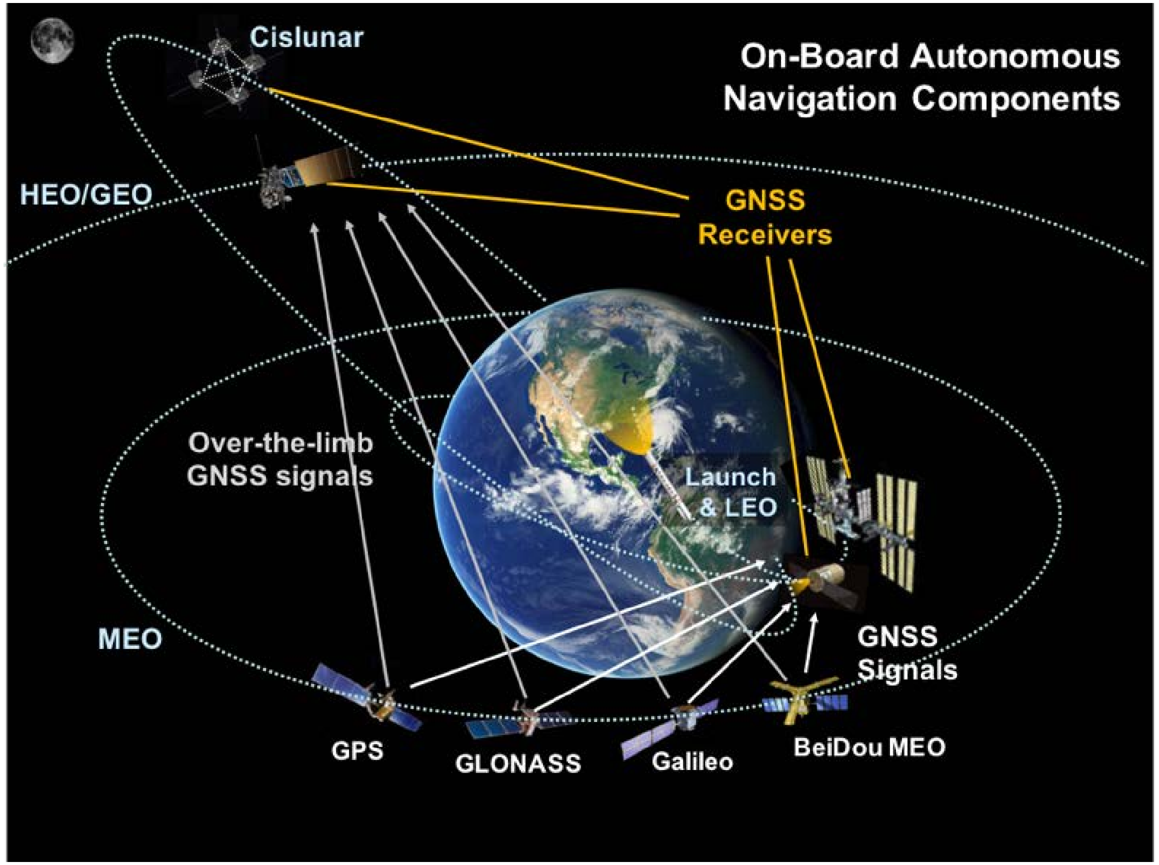
Development of an Interoperable GNSS Space Service Volume

Joel J. K. Parker, National Aeronautics and Space Administration (US)
Frank H. Bauer, FBauer Aerospace Consulting Services (US)
Benjamin W. Ashman, National Aeronautics and Space Administration (US)
James J. Miller, National Aeronautics and Space Administration (US)

Werner Enderle, European Space Agency (EU)
Daniel Blonski, European Space Agency (EU)

Space Uses of Global Navigation Satellite Systems (GNSS)

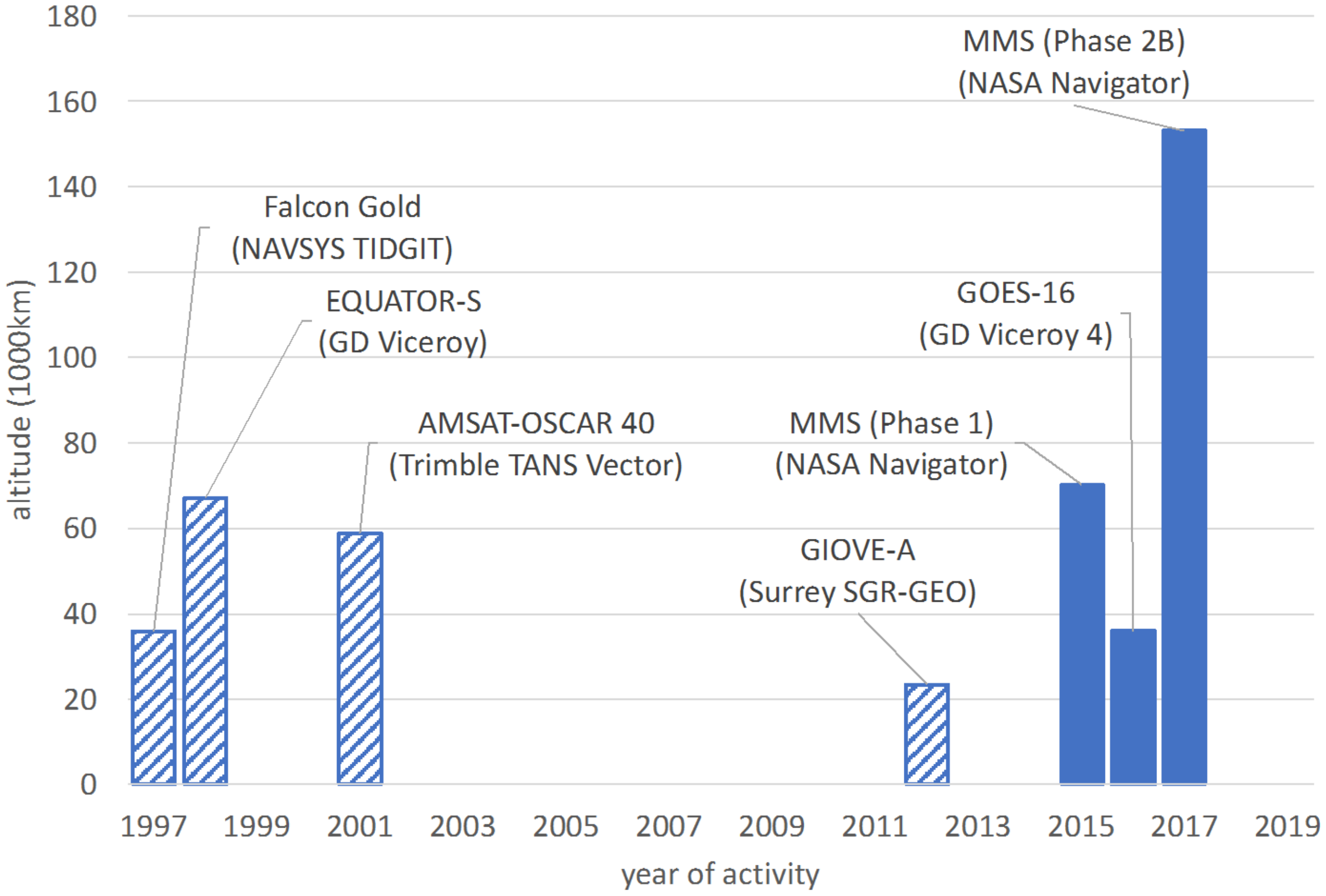
- **Real-time On-Board Navigation**: Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences**: Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements
- **Launch Vehicle Range Ops**: Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use
- **Attitude Determination**: Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements
- **Time Synchronization**: Support precise time-tagging of science observations and synchronization of on-board clocks



GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

High-Altitude GPS

- 1990s: Early flight experiments demonstrated basic feasibility – Equator-S, Falcon Gold
- 2000: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- 2001: AMSAT OSCAR-40 mapped GPS main and sidelobe signals (Davis et al. 2001)
- 2015: MMS employed GPS operationally at 76,000 km and recently 150,000 km
- 2016: GOES-16 employed GPS operationally at GEO



International Committee on GNSS (ICG)

- The UN International Committee on GNSS (ICG) brings together all six GNSS providers (China, Europe, India, Japan, Russia, & USA) and other voluntary participants to:
  - Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
  - Encourage compatibility and interoperability among global and regional systems
- Most recent meeting: ICG-12, Kyoto, Japan
- Next Meeting: ICG-13, X'ian, China

WG-S: Systems, Signals and Services

Major topics include:
- Spectrum compatibility
- Interference detection & mitigation
- Service interoperability
- Performance standards & monitoring

WG-B: Enhancement of GNSS Performance, New Services and Capabilities

Major topics include:
- Development of interoperable multi-GNSS SSV
- GNSS-hosted search-and-rescue payloads
- Space weather and ionosphere modeling

WG-D: Reference Frames, Timing and Applications

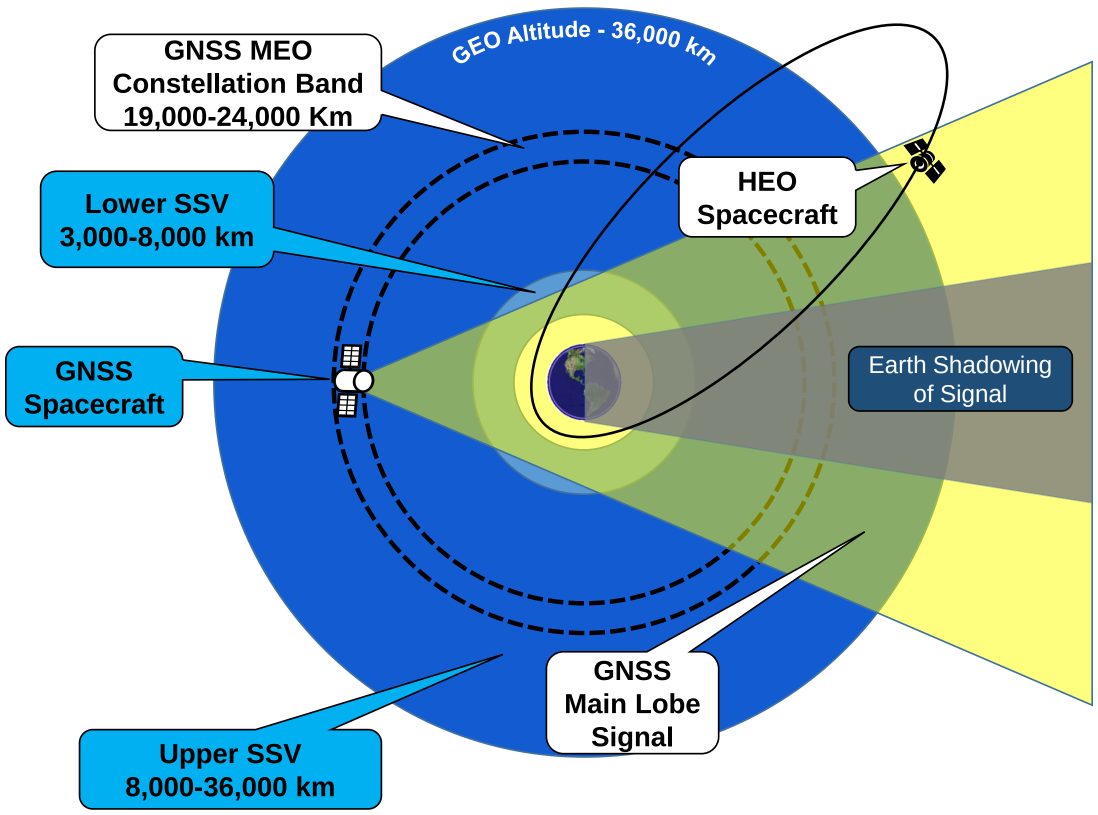
Major topics include:
- ITRF, geodetic reference frame interoperability
- Time standards & multi-constellation offsets
- Constellation orbit modeling & technical data

* Also: WG-C: Information Dissemination and Capacity Building

The Multi-GNSS Space Service Volume

- Two components:
  - Lower SSV (3,000 km–8,000 km)
  - Upper SSV (8,000 km–36,000 km)

- Three performance metrics:
  - Pseudorange Accuracy
  - Signal Availability
  - Received Signal Power



Constellation-Specific Support to SSV

Band	Constellation	Minimum Received Civilian Signal Power		Upper SSV Signal Availability (%)	
		0dBi RCP antenna at GEO (dBW)	**Reference off-boresight angle (°)**	**At least 1 signal**	**4 or more signals**
L1/E1/B1	GPS	-184 (C/A)[1] -182.5 (C)[2]	23.5	80	1
	GLONASS	-179	26	93.9	7.0
	Galileo	-182.5	20.5	64	0
	BDS	-184.2 (MEO)[3] -185.9 (I/G)[4]	25 19	97.40	24.10
	QZSS	-185.5	22	54	N/A
L5/L3/E5/B2	GPS	-182	26	92	6.5
	GLONASS	-178	34	99.9	60.3
	Galileo	-182.5 (E5b) -182.5 (E5a)	22.5 23.5	80 86	0 0
	BDS	-182.8 (MEO) -184.4 (I/G)	28 22	99.90	45.40
	QZSS	-180.7	24	54	N/A
	NavIC	-184.54	16	36.90	0.60

[1] L1 C/A signal

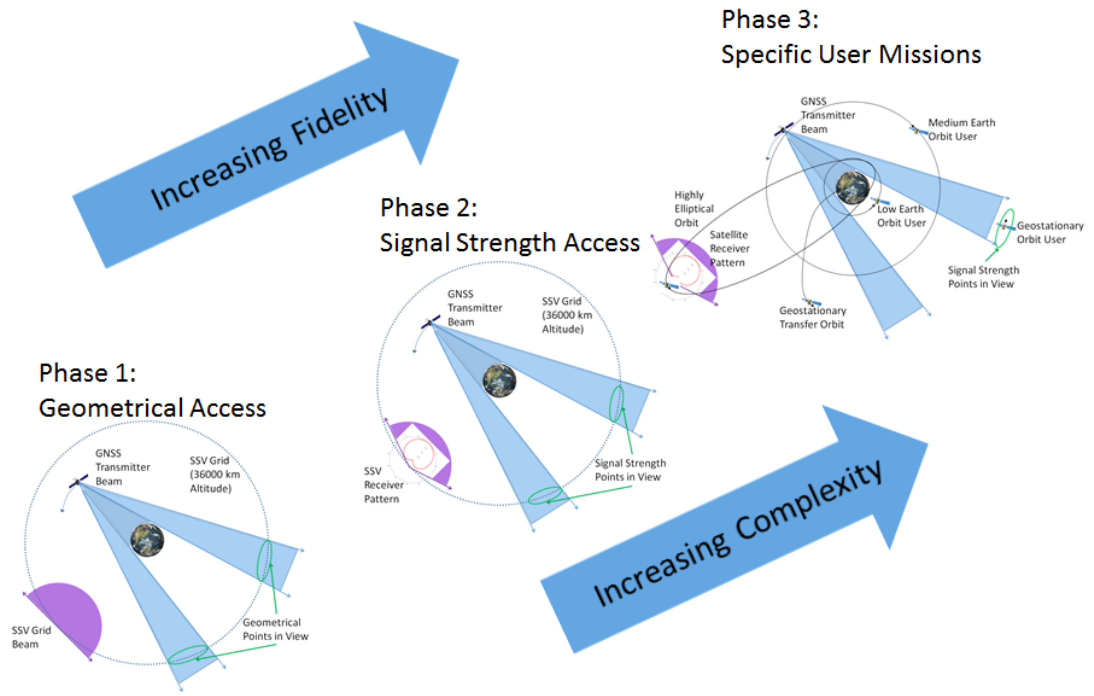
[2] L1C signal

[3] Medium Earth Orbit satellites

[4] Inclined geostationary (I) and geostationary (G) satellites

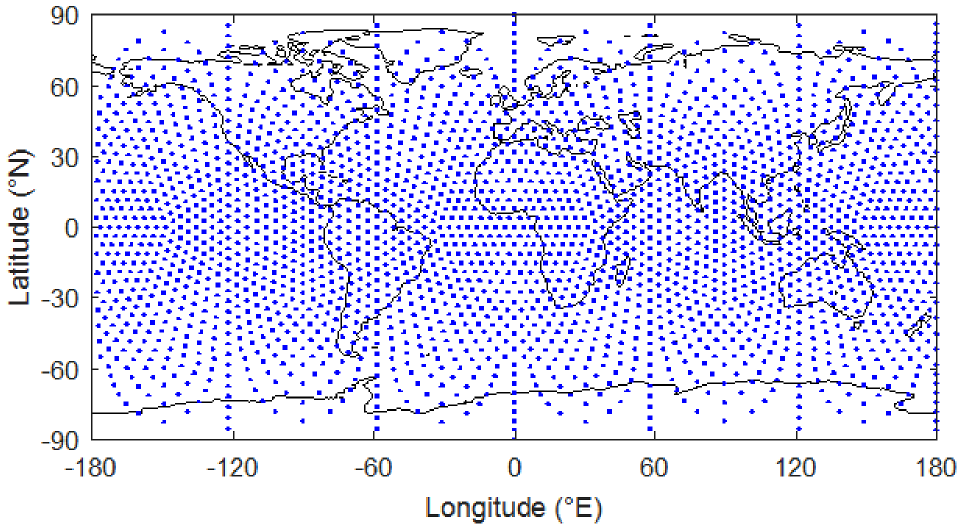
Performance Estimates

- Two types of analysis were performed over three phases:
    1. Global performance analysis
    2. Mission-specific performance analysis, consisting of:
        - GEO case
        - HEO case
        - Lunar case
- Phase 1 & 2 were focused on global analysis
- Phase 3 was mission-specific analysis



Global Performance

- Analysis performed to estimate signal availability on global grid of points (see right)
- Each grid point assumed to be stationary receiver with 0dBi antenna
- Results show improvement in Upper SSV:
  - 1+ signals: 94% -> 99.9%
  - 4+ signals: 7% -> 89.8%

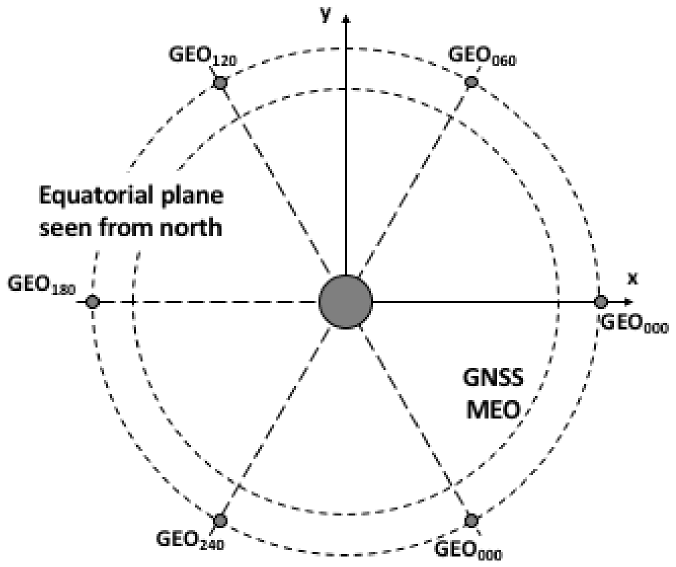


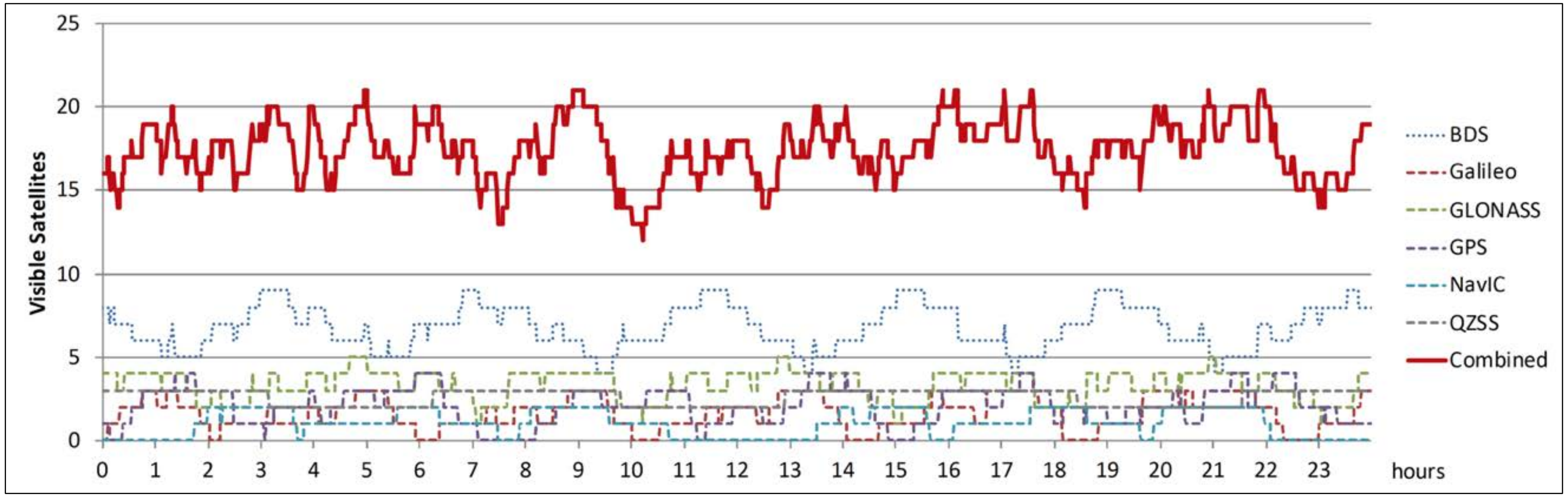
Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)[1]	**MOD (min)[2]**	**Avail. (%)[1]**	**MOD (min)[2]**
L1/E1/B1	Global systems	78.5–94	48–111	0.6–7	*
	QZSS	0	*[3]	0	*
	Combined	**99.9**	**33**	**89.8**	**117**
L5/L3/E5a/B2	Global systems	93.4-99.9	7–*	4.2–60.3	218–*
	Regional systems	1–30.5	*	0–1.5	*
	Combined	**100**	**0**	**99.9**	**15**

[1]average across all grid locations
[2]at worst-case grid location
[3]no signal observed for the worst-case grid location for full simulation duration

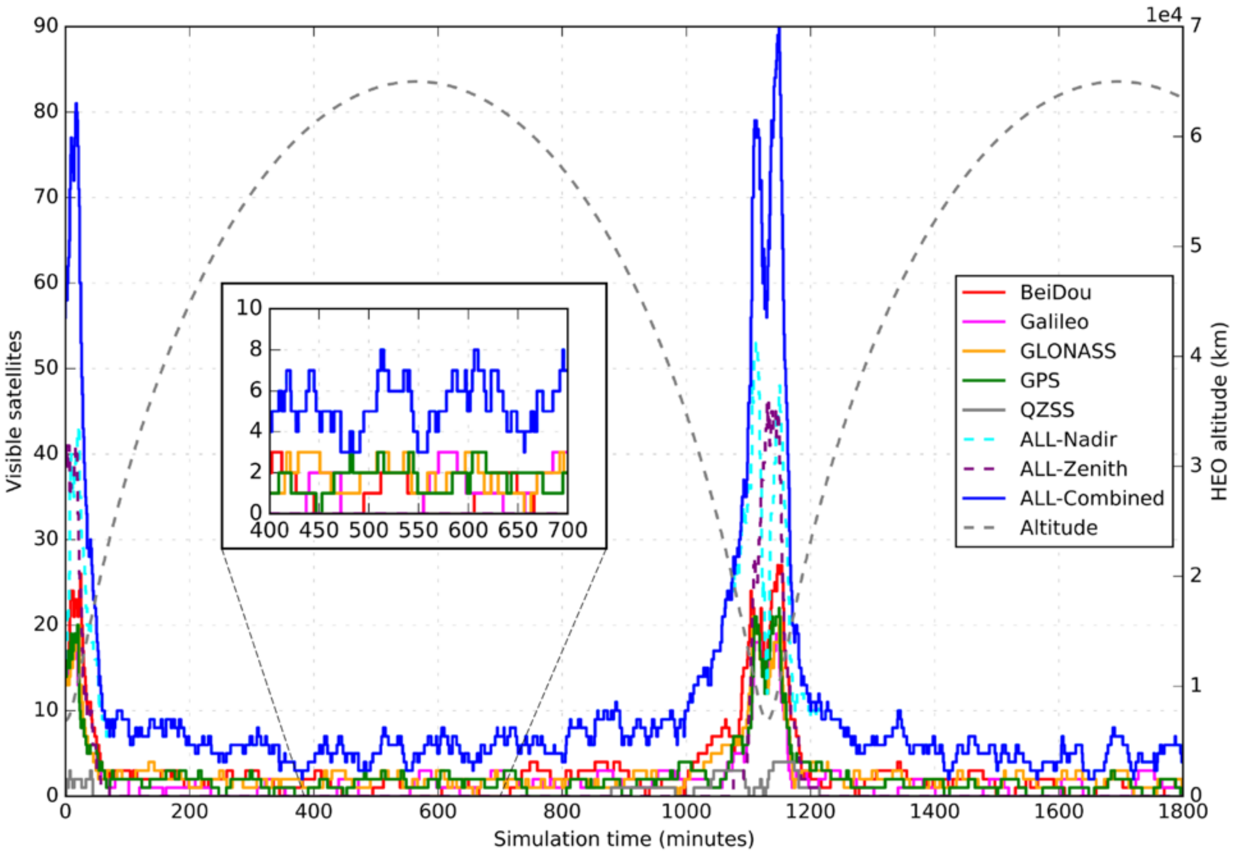
GEO Performance

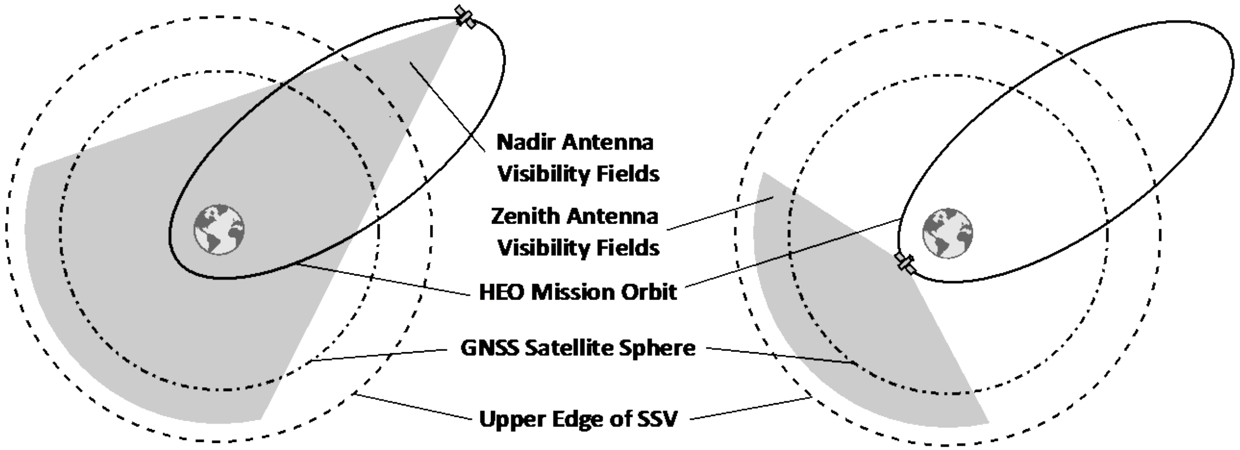
- Mission-specific analysis at six GEO locations (see right)
- Each satellite simulated with realistic high-gain nadir-pointed antenna
- Results (below) show drastic improvement from any individual constellation to all combined
- Visibility variable with location around GEO belt





HEO Performance

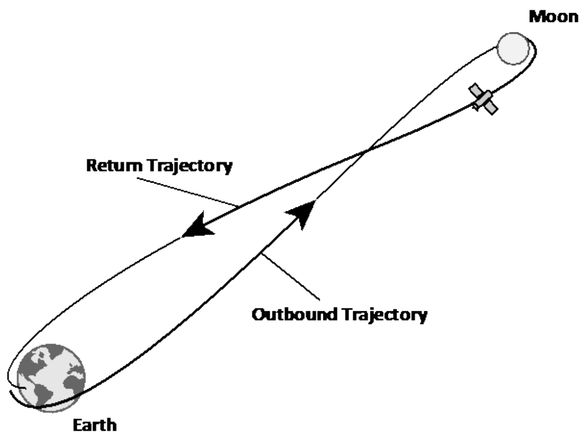


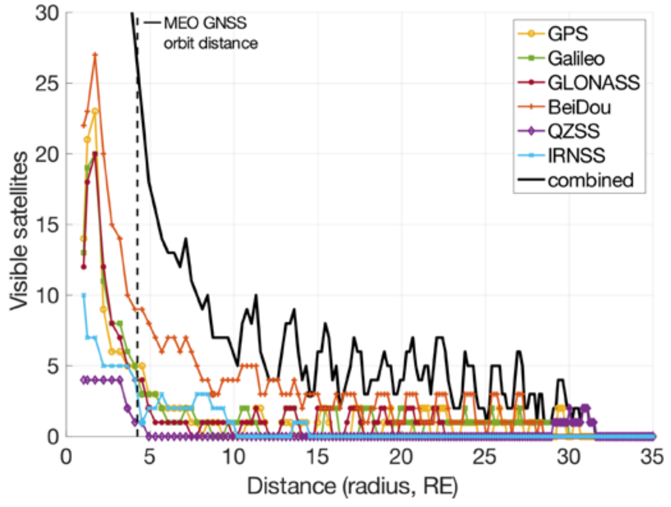


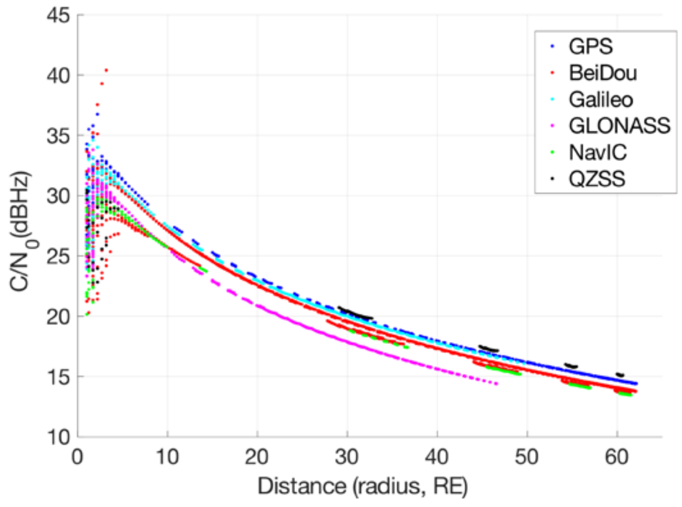
- Mission-specific analysis of example highly-elliptical science mission
- User satellite modeled with both nadir-pointed and zenith-pointed antennas (see figure above)
- Results (left) show improvement when all constellations are used together
- 100% coverage with multiple-satellite visibility is possible even at apogee with all constellations

Lunar Performance Simulations

- Mission-specific analysis of example lunar outbound trajectory
- User satellite modeled with both nadir-pointed and zenith-pointed antennas
- Results (below) show two key features:
  - Overall visibility is split into low-altitude regime with 100% 1+ visibility under approx. 30 RE, and zero-visibility high-altitude region
  - With moderate user equipment improvements, visibility can be achieved all the way to lunar distance





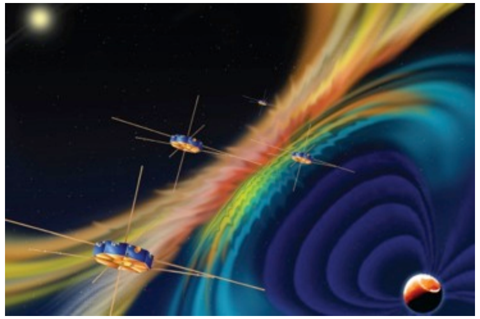


Benefits of Real-Time GPS Navigation in the SSV

Benefits of GPS use in SSV:

- Supports **fast trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- GPS 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 **High Earth Orbit (HEO) and Geosynchronous Earth Orbit (GEO) missions,** such as:

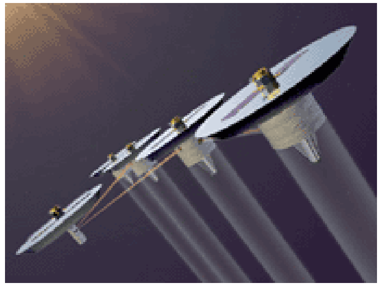
Earth Weather Prediction using Advanced Weather Satellites



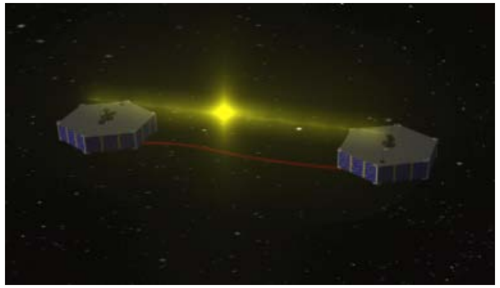
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



Formation Flying, Space Situational Awareness, Proximity Operations



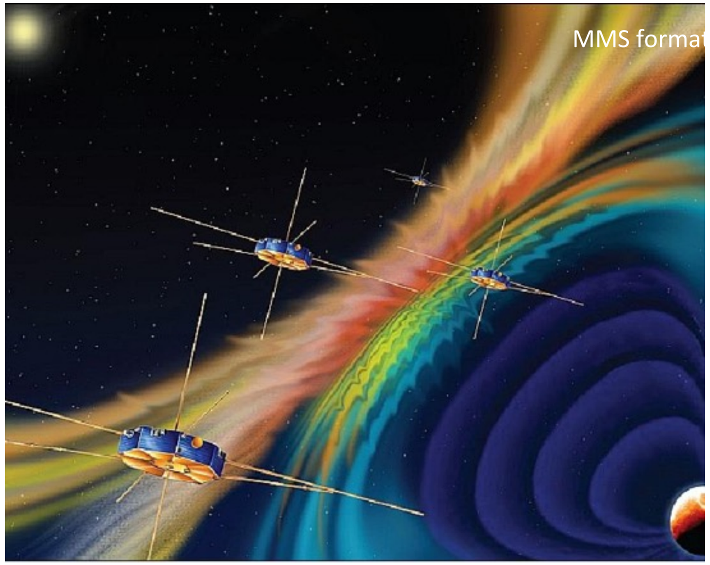
Precise Position Knowledge and Control at GEO

SSV: Future Civil Applications

- Earth Weather Missions
  - Objectives: Improve weather forecasting from 3-5 days to 5-7 days; protecting people and property through early warning of tornados, flash floods, and wildfires
  - Role of the SSV: Accurate orbit prediction (position and velocity), fast recovery from trajectory maneuvers, navigation stability to prevent internal image and image to image pixel, and timing
- Space Weather and Heliospheric Science Missions
  - Objectives: Enable High Earth Orbit and Cislunar observations of the magnetosphere to improve understanding of space weather and to potentially start space weather prediction.
  - Role of the SSV: Improved navigation performance (e.g. 10-meter to 1-meter class) and fast recovery from trajectory maneuvers (minute class) for accurate placement of space weather phenomenon; improved operations cadence and increased satellite autonomy to support constellation or formation flying missions; Precise timing enabling lower cost clock alternatives

SSV: Future Civil Applications (cont.)

- Satellite Servicing
  - Objectives: Extend the lives of satellites through upgrade, repair, refueling, and orbit adjustment; debris removal; in-orbit construction or installation
  - Role of the SSV:
    - Fast recovery from trajectory maneuvers required—on the order of minutes during critical rendezvous, proximity operations, and docking
    - Near-continuous GPS signal availability needed to support satellite responsiveness and autonomy
    - Highly accurate absolute orbit state (position and velocity) are necessary to support far-field rendezvous—as a general rule of thumb, position must be known to an accuracy of 10% the inter-vehicle range
- Formation Flying Missions
  - Objectives: Enable new classes of missions and new scientific viewpoints through formation flying; spans full spectrum of vehicle sizes (CubeSats to ISS class) and mission orbits (MEO, HEO, GEO, Cislunar)
  - Role of the SSV: Precise navigation and timing, fast recovery from trajectory maneuvers, enhanced operations cadence, and increased satellite autonomy. Requirements as low as meter-class navigation in real time, cm-level relative navigation and micro- to nanosecond timing synchronization



SSV: Future Civil Applications (cont.)

- Commercial GEO Missions
  - Objectives: Increase density of the most coveted real estate in space, benefiting commercial and civil space users
  - Role of the SSV: Accurate position and velocity measurements and near-continuous GPS signal availability needed to enable accurate, autonomous vehicle station keeping during near-continuous low thrust maneuvering
- Launch Vehicle Upper Stages & Deep Space Missions, En Route, and Return
  - Objectives: Improve real-time vehicle insertion and trajectory accuracy reducing fuel requirements and improving payload mass capacities
  - Role of the SSV: High accuracy, high cadence position, velocity, and time knowledge to minimize the trajectory propagation errors of the vehicle during flight

SSV: Future Civil Applications (cont.)

- Lunar Missions
  - Objectives: There is a renewed interest in the moon as a target for rovers, landers, and human exploration. The US plans to return to human exploration of the moon and cislunar space in the next few years with Exploration Missions (EM) 1 and 2. EM-3 may begin construction of a “gateway”—a permanent way-station in the vicinity of the moon for staging deep space activity
  - Role of the SSV:
    - GPS can provide measurements for mid-course correction burns during outbound and return cruise
    - Simulations have shown that GPS signal availability can be extended to lunar distances by augmenting existing high-altitude GPS navigation systems (such as MMS) with a high-gain antenna (Winternitz et al. 2017, Ashman et al., 2018)
    - Navigation backup for the crew capsule, Orion, if communications link is lost
    - Lunar platform like the gateway could use GPS for position, velocity, and attitude, as well as a stable and accurate timing source for hosted science and technology payloads

Conclusions

- Use of high-altitude GNSS has expanded significantly, and is now an enabling technology for future missions.
- Through the UN International Committee on GNSS (ICG), all GNSS and RNSS providers have agreed to the Multi-GNSS Space Service Volume, which documents performance expectations above 3,000 km altitude.
- Performance estimates (global and mission-specific) show significantly enhanced signal availability at all altitudes when multiple constellations are used.
- Full results are available in UN SSV Booklet.