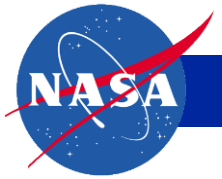

Use and Protection of GPS Sidelobe Signals for Enhanced Navigation Performance in High Earth Orbit

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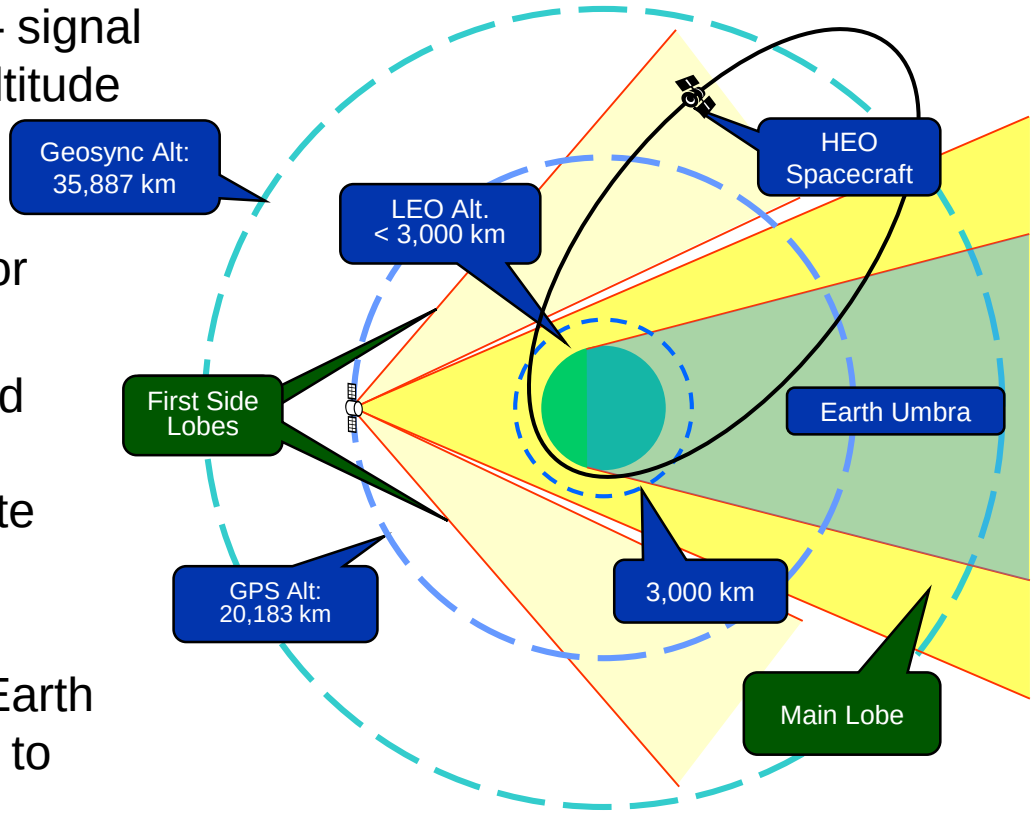
GPS Space Service Volume: Background

- **GPS Space Service Volume (SSV)** – signal environment from 3,000–36,000 km altitude
- Current SSV specifications only capture performance provided by signals transmitted within 23.5° (L1) or 26° (L2/L5) off-nadir angle.
- Recent on-orbit data & lessons learned show **significant PNT performance improvements** when the full aggregate signal is used.
- **Numerous** military & civil operational missions in High & Geosynchronous Earth Orbit (HEO/GEO) utilize the full signal to enhance vehicle PNT performance



GPS Development History:

1978	1989	1997	2005	2010	2017	2020s
First Block I launched	Block IIA (Boeing)	Block IIR (LM)	Block IIR-M (LM)	Block IIF (Boeing)	Block IIIA (LM)	Block IIIB

Current GPS III SSV Requirements

I. Availability

	HEO SSV (8,000–36,000 km alt.)		
	1+ Signals	4+ Signals	Max Outage (min)
L1	≥ 80%	≥ 1%	108
L2/L5	≥ 92%	≥ 6.5%	84

II. Received Signal Power

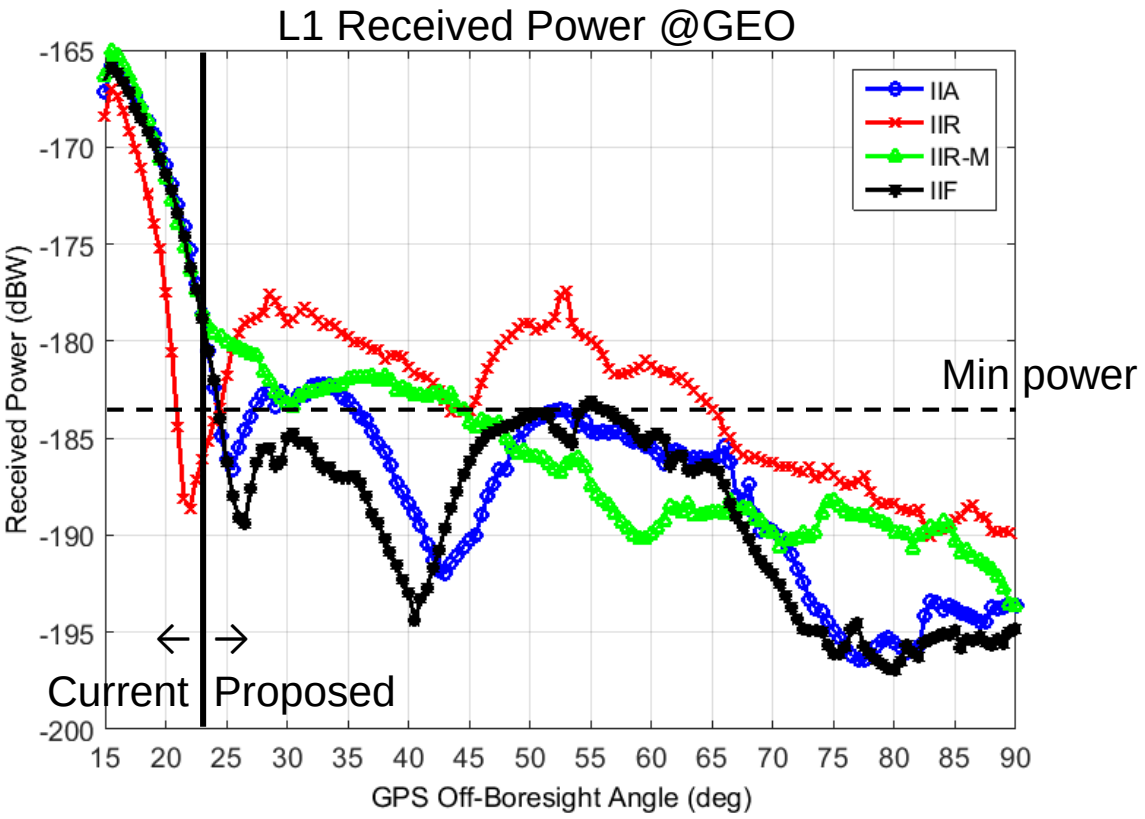
Signal	SSV Min. Received Power (dBW)	Reference off-nadir angle (deg)
L1 C/A	-184.0	23.5
L1 P(Y)	-187.0	23.5
L1C	-182.5	23.5
L1 M	-183.5	23.5
L2C	-183.0	26
L2 P(Y)	-186.0	26
L2M	-182.5	26
L5 (I/Q)	-182.0	26

III. Pseudorange Accuracy

Accuracy ≤ 0.8 m (rms)

Protection of Aggregate Signal Availability

- By utilizing sidelobes, missions are benefiting from significantly enhanced on-orbit performance
  - At nearly 2x GEO altitude, MMS sees nearly 100% availability of 4 GPS signals
- Average received power at GEO shows significant variations in sidelobes between Block II designs



- Because full signal isn't specified, future GPS blocks could suppress sidelobes and severely impact future HEO/GEO mission performance.
- To address this risk, NASA is proposing a modification to the current SSV requirements to capture user-required availability

Data from GPS ACE project

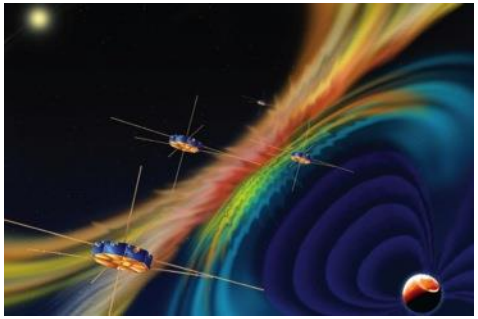
Current and Potential Future Missions Employing GPS in SSV HEO/GEO Segment

Rationale for GPS use in SSV:

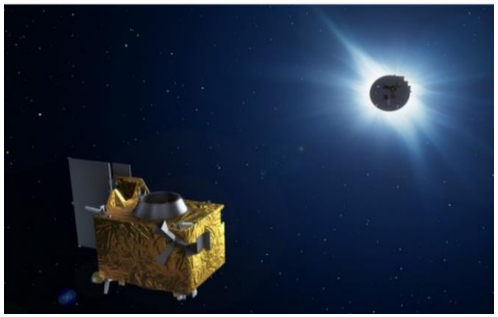
- Significantly **improves vehicle navigation performance** (from: km-class to: meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- GPS timing **reduces need for expensive on-board clocks** (from: $1M-500K to: $50K)
- Supports **increased satellite autonomy**, lowering mission operations costs (savings from: $0 to: $500-750K/year)

Mission Types include:

Earth Weather Prediction using Advanced Weather Satellites

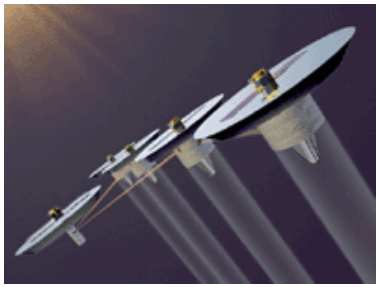


Space Weather Observations

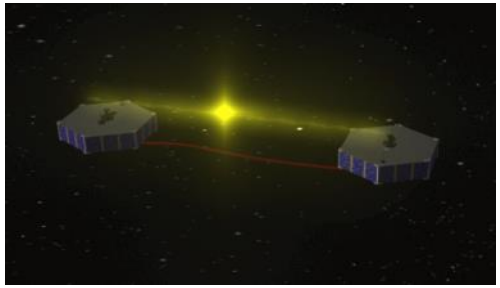


Solar Occultation Observations

Direct Injection Launch Vehicle Upper stages & Deep Space Enroute & Return



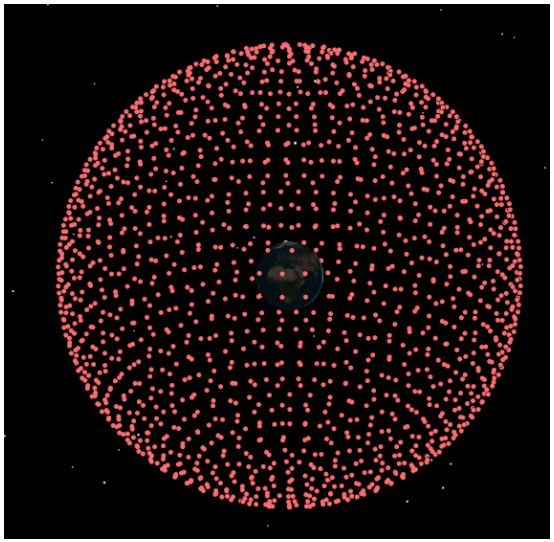
Formation Flying & Constellation Missions



Closer Spacing of Satellites in Geostationary Arc

GPS Performance Margin Analysis

- **Goal:** Determine on-orbit minimum performance margin over current requirement, considering full signal
- **Assumptions:**
  - 27-satellite constellation, Block IIR-M GPS satellites
    - GPS IIR-M consistently lower-performing than IIR
    - High-fidelity data unavailable for IIA, IIF
  - Minimum GPS transmit power (derived from edge-of-Earth spec)
  - Minimum received power threshold equal to current requirement
- **Analysis approach:**
  - Global coverage analysis using STK 10
  - 5° equatorial grid spacing (1652 points)
  - Availability evaluated at 95% of points
  - Availability analysis independent of pseudorange accuracy



STK Coverage Grid

Publicly-available GPS IIR/R-M antenna patterns: http://www.lockheedmartin.com/us/products/gps/gps-publications.html

GPS Performance Margin Analysis

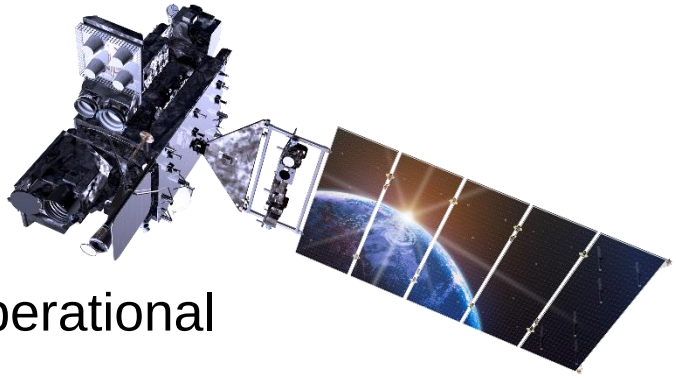
Minimum constellation performance, 27 IIR-M SVs, full signal:

	Signal	1+ SV	4+ SV	Max outage
Minimum IIR-M Performance	L1	100%	92.6%	0 min
	L2	99.2%	77.4%	9 min
	L5	99.2%	78.6%	8 min
Current Requirement	L1	80%	1%	108 min
	L2	92%	6.5%	84 min
	L5	92%	6.5%	84 min
Performance Margin	L1	20%	91.6%	108 min
	L2	7.2%	70.9%	75 min
	L5	7.2%	72.1%	76 min

- Specification designed so all codes within each signal (C/A, P(Y), etc.) result in identical minimum availability
- Actual on-orbit performance of current constellation greatly exceeds minimums.
- 4+ SV availability shows greatest increase over CDD levels.

GOES-R User Needs Analysis

- **Goals:**
  - Updated SSV requirement must be based on user needs, not current performance
  - Derive SSV capabilities required by GOES-R, as representative HEO SSV user
- **GOES-R**
  - NOAA/NASA Geostationary Operational Environmental Satellite
  - GOES-R, -S, -T, -U: 4th generation operational weather satellites
  - Launch: 2016, 20-year service life
  - First series to use GPS for navigation
    - General Dynamics Viceroy-4 receiver
  - Requirement: <120 min outage/year



GOES-R User Needs Analysis

- **GOES-R Requirements**
  - Orbit position knowledge requirement (right)
  - All performance requirements are applicable during and after maneuvers.

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

  - Error between 1 PPS & GPS time ≤ 85 nanoseconds (1-sigma).
  - Requirements unchanged for GOES-S, -T, -U
- **Analysis Approach**
  - GPS measurements to representative GOES-R orbit simulated using ODTBX
  - Three types of maneuvers were simulated, placed at worst-case GPS availability times:

Simulation Time	Maneuver Type	Direction	Duration (mins)	Thrust (N)
Day 1: 06:45:00	N/S Station Keeping	Cross-Track	45	0.5
Day 2: 07:30:00	Momentum Management	In-Track	5	0.24
Day 3: 07:00:00	E/W Station Keeping	In-Track	15	0.22

  - Measurements processed using GEONS EKF with varying levels of GPS signal availability (controlled via level of sidelobe contribution)

GOES-R User Needs Analysis

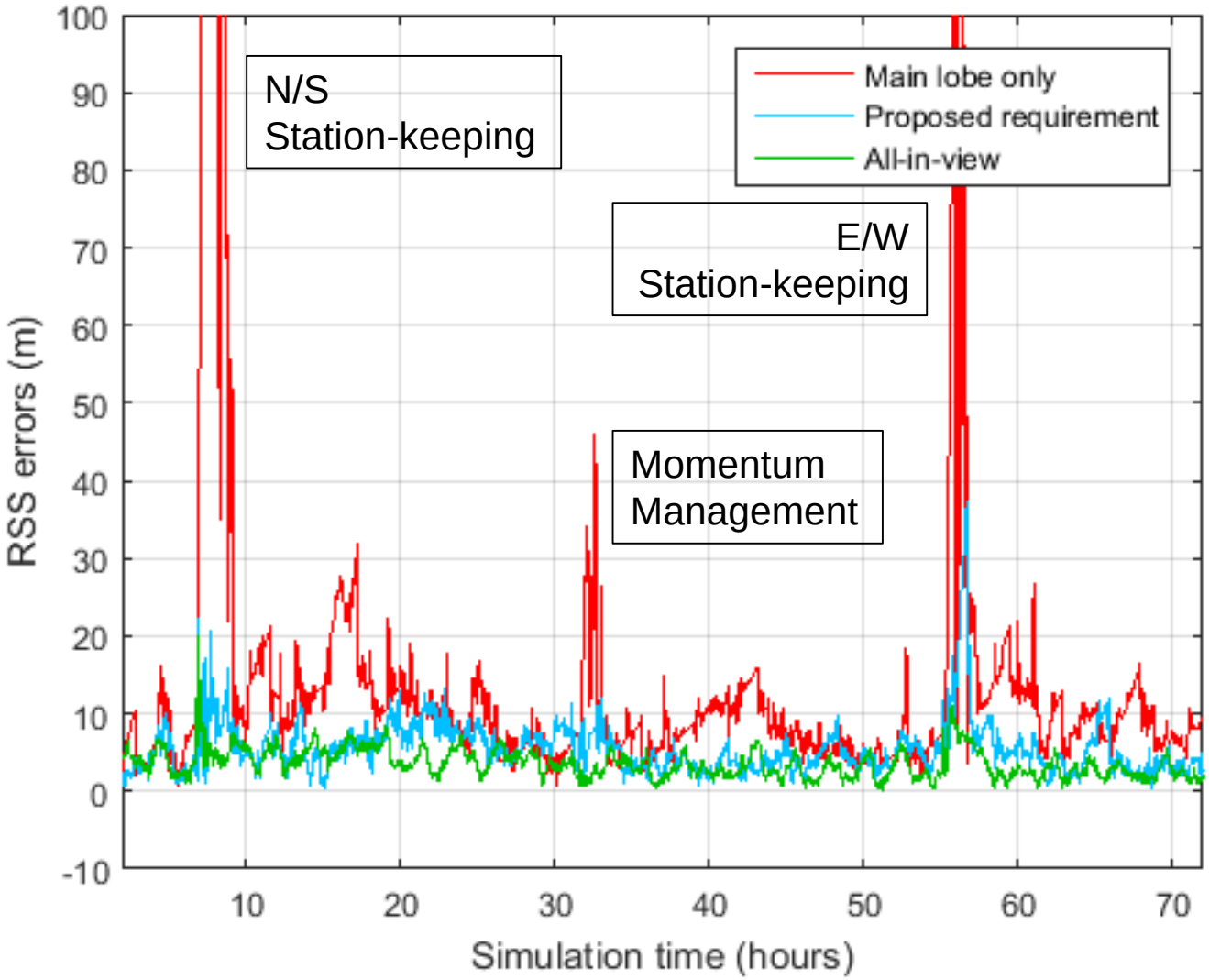
- **Availability Results Summary:**

Avail. [1+,4+]	Pass/Fail	Details
80%, 2.5%	Fail	Fails positioning and stability requirements for all maneuvers, outages of up to 80 min
96.75%, 20.5%	Fail	Fails positioning and stability requirements for all maneuvers
98.75%, 32.3%	**Pass**	**Passes with minimum required performance for N/S maneuver**
100%, 84.5%	Pass	Passes with very stable positioning during maneuvers

- **Additionally, at the 99% availability level, a pseudorange accuracy sensitivity analysis was performed**
  - Pseudorange errors were increased from 2m to 5m until requirements were violated
  - Errors were applied to full signal (mainlobe and sidelobes)
  - **4m** pseudorange accuracy caused nominal but acceptable requirements violations, given conservatism in analysis

GOES-R User Needs Analysis

- Only 1 SV in view necessary to recover solution
- At current required availability, post-maneuver errors exceed requirement in all cases, for up to 3 hours
- Proposed availability bounds errors within requirement



Errors with respect to simulation truth

Proposed SSV Requirement Modification

- Proposed requirement adds a second availability specification, applicable at a less stringent pseudorange accuracy.
- Updated availability requirement (4m added, **0.8m unchanged**):

	0.8m rms accuracy			**4m rms accuracy**		
	1+ Signals	4+ Signals	Max Outage (min)	1+ Signals	4+ Signals	Max Outage (min)
L1	≥ 80%	≥ 1%	108	≥ 99%	≥ 33%	10
L2/L5	≥ 92%	≥ 6.5%	84	≥ 99%	≥ 33%	10

- MEO specification unchanged.
- Requirement captures GOES-R minimum capability with no margin.
- Applies to all signals, all codes.
- There remains significant margin in current minimum constellation performance, esp. in 4+ signal availability.
- Separate analysis indicates that 4m accuracy is realistic in sidelobes.

Conclusions & Next Steps

- **Existing requirements** for GPS signal availability in the SSV **do not capture** significant performance improvements when the full aggregate signal (mainlobe and sidelobes) is used.
- Without a specification, this **performance is at risk** of being reduced in future GPS designs, beginning in the 2030s.
- NASA has demonstrated:
  - **significant existing availability margin** for existing GPS Block II spacecraft, and anticipates similar performance for current Block IIIA signals
  - **user requirements** (GOES-R) that drive an updated SSV specification for HEO/GEO users
- NASA is working through the **US Air Force Interagency Forum for Operational Requirements** (IFOR) process to adopt the proposed requirement.
  - Process includes formal requirement specification, statement of user needs, and analysis of alternative solutions
  - Target for completion is **March, 2016**
- If adopted, the proposed requirement will **protect capabilities** required by users today, and **enable enhanced usage** of GPS for navigation in HEO for the future.