NASA GNSS Activities

WG-B—Enhancement of GNSS Performance, New Services & Capabilities

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Session 2

*Review of the Progress on recent ICG-12 WG-B Recommendations*
ICG-12 (Kyoto) Recommendation:  
Use of GNSS for Exploration Activities in Cislunar Space and Beyond

Background/Brief Description of the Issue:  
During the WG-B GNSS SSV Working Group activities associated with the generation of the GNSS SSV Booklet, it became clear that the use of GNSS signals in support of missions within and beyond cis-Lunar space is possible and could contribute to improved on-board navigation capabilities.

Discussion/Analyses:  
It is essential to understand the user needs for missions to cis-Lunar space and beyond, and to perform detailed analyses of the GNSS SSV capabilities and potential augmentations related to the support of missions to cis-Lunar space and beyond.

Recommendation of Committee Action:  
WG-B will lead and Service providers, Space Agencies and Research Institutions are invited to contribute to investigations/developments related to use of the full potential of the GNSS SSV, also considering the support of exploration activities in cis-Lunar space and beyond.
Recent Results: Lunar GPS

• NASA has recently published two studies looking at the feasibility of GPS navigation at lunar distances:
  • **ION GNSS+ 2017: Winternitz, et al**¹
    • Published MMS Phase 2 results using GPS to 25 RE
    • Projected MMS performance to lunar distance
  • **AAS GN&C 2018: Ashman, et al**²
    • Looked broadly at GPS visibility for different antennas and C/N0 receiver threshold values
    • Validated results vs. MMS and GOES-16 flight data

• These studies represent early GPS-only analyses that could be used as basis for WG-B in-depth analysis.


NASA’s Magnetospheric MultiScale (MMS) Mission

- Discover the fundamental plasma physics process of reconnection in the Earth’s magnetosphere.
- Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 10km
- Flying in two highly elliptic orbits in two mission phases
  - Phase 1 1.2x12 \( R_E \) (magnetopause) Mar ‘14-Feb ‘17
  - Phase 2B 1.2x25 \( R_E \) (magnetotail) May ‘17-present
MMS study: Concept Lunar mission

- Study: How will MMS receiver perform if used on a conceptual Lunar mission with 14dBi high-gain antenna?
- Concept lunar trajectory similar to EM-1: LEO -> translunar -> Lunar (libration) orbit -> return
- GPS measurements simulated & processed using GEONS filter.
- Visibility similar to MMS2B, as high-gain makes up for additional path loss
  - Avg visibility: ~3 SVs; C/N0 peaks > 40dB-Hz (main lobes) or > 30 dB-Hz (side lobes)
- Range/clock-bias errors dominate – order of 1-2 km; lateral errors 100-200 m
  - With atomic clock, or, e.g., periodic 2-way range/Doppler, could reduce range errors to meas. noise level

Top: Signals tracked and radial dist to Earth (red) and Moon (cyan); Bottom: C/N₀

Filter position formal (3σ) and actual errors
Lunar GPS Visibility Simulation

- US plans to return to human exploration of the Moon and cislunar space with EM-1 and EM-2; one long-term objective is the Deep Space Gateway, an international, permanent way-station in the vicinity of the moon
- Near Rectilinear Halo Orbit (NRHO) is one proposed orbit; this is used here for the lunar simulation with only the outbound cruise
- **Three mission configurations:**
  - **Validation** – same antenna gain (7 dB peak), pointing, and receiver acq/trk thresholds as MMS (22 dB-Hz)
  - **High gain antenna** – 10 and 14 dB peak gain, same 22 dB-Hz receiver acq/trk thresholds
  - **Receiver design baseline** – 10 dB peak gain antenna, but 1 dB-Hz receiver thresholds
Lunar GPS Visibility Simulation

Lunar trajectory: number of SVs visible by altitude

Number of satellites visible by altitude for different antenna gains
Lunar GPS Visibility Simulation

- Outbound lunar NRHO visibility with 22 dB-Hz acq/trk threshold:

<table>
<thead>
<tr>
<th>Peak Antenna Gain</th>
<th>1+</th>
<th>4+</th>
<th>Maximum Outage</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 dB</td>
<td>63%</td>
<td>8%</td>
<td>140 min</td>
</tr>
<tr>
<td>10 dB</td>
<td>82%</td>
<td>17%</td>
<td>84 min</td>
</tr>
<tr>
<td>14 dB</td>
<td>99 %</td>
<td>65%</td>
<td>11 min</td>
</tr>
</tbody>
</table>

- A modest amount of additional gain or sensitivity increases coverage significantly

Number of satellites visible by altitude and receiver threshold
Conclusions: Lunar GPS

• MMS results show useful onboard GPS navigation at lunar distances is achievable now using currently-available signals and flight-proven receiver technology.

• A modest increase in gain or receiver sensitivity increases visibility significantly.

• Future work must extend these specific studies to full navigation analysis of cis-lunar spacecraft, and utilizing the full capability of multi-GNSS signals.

• ICG WG-B is a natural forum for these discussions and analyses, in keeping with the ICG-12 recommendation.
NASA Proposed Realization of Recommendation

- Conduct GNSS SSV Cislunar/Interplanetary Workshop
- Scoping:
  - How far is “beyond”?  
  - What does it include? Cislunar space? Lagrange points? Mars/Interplanetary?
- Workshop to be held prior to or immediately after ICG-13 meeting in X’ian, China
- Workshop will focus on trade study planning
- Trade study objectives:
  - Develop a PNT architecture, focusing on GNSS capabilities that will support missions within and around:
    - Cislunar space
    - Lagrange points
    - Mars orbit and Mars surface
  - As part of architecture trades, define minimal set of GNSS augmentations that will support these mission scenarios
  - Look at other PNT capabilities and augmentations that can support these mission scenarios in conjunction with GNSS; (e.g. X-ray Pulsar Navigation, Celestial Navigation, Deep Space Atomic Clock timing, Mars orbiter hosted payloads)
- Conduct regular meetings (once per month) to prepare for the workshop
Proposed Workshop on Future of SSV

• **Goal:** Collect international input on future directions for the Multi-GNSS SSV.
  – What are the major use cases?
  – What threshold performance is achievable?
  – What future SSV plans are in progress by the providers?

• **Time horizon:** 20–30 years

• **Participants:** Providers and Space Agencies

• **Venue (proposed):** Workshop alongside ICG-13, Xi’an, China.

• **Discussion:**
  – Is this agreeable path forward for ICG-12 Recommendation 2?
  – Interest by WG-B in participating in this discussion?
  – Comments on specific plan?
Status of the SSV booklet & Discussion of Future work, Status of Outreach Activities
SSV VIDEO
Objectives

• Develop a short but comprehensive video on the multi-GNSS Space Service Volume initiative

• Video should:
  – Define multi-GNSS and SSV concepts
  – Describe the importance and the benefit to humanity of an interoperable multi-GNSS SSV
Target Audience

• Video directed towards a general audience with some knowledge of spacecraft development and operations and some knowledge of GNSS

• Note that most aerospace engineers really don’t understand how GNSS works, so they fit into this audience

• US candidate audience includes:
  – US Congress
  – Senior executives in NASA and Other Government Agencies
  – Other decision makers

• International candidate audience includes:
  – UN COPUS
  – Senior Leaders in international space agencies
  – GNSS constellation providers
  – Space scientists
  – Space exploration experts
  – Satellite developers, especially spacecraft at GEO
Video Target Length

Research findings:
• Blog posting: How Long Should Your Next Video Be?  
  Ezra Fishman on July 5, 2016  
  https://wistia.com/blog/optimal-video-length

Blog Summary:
• Humans have short attention spans  
• Engagement decreases with video length  
• 2 minutes or less is best (70% engagement)  
• Every second beyond 2 minutes lowers engagement  
• Takeaway: Push for 2 minutes. Beyond 2 minutes focus entirely on the content—make it immersive and use video to eliminate words

Additional information:
• NASA video experts confirm findings; feel <3 minutes is best for SSV type videos

SSV Video Goal
• Work towards 3 minute goal
Individual Global Navigation Satellite System (GNSS) constellations in the Space Service Volume (SSV) have demonstrated outstanding operational and societal benefits but they supply insufficient available signals to fully support future missions.

An interoperable, specified Multi-GNSS constellation capability in the SSV is critical for the continuous coverage required to support future beyond-low-earth orbit missions that a single constellation cannot provide.
Video Script Content

• Major Topics:
  – GNSS Overview
  – SSV Overview
  – SSV applications
  – Conclusions (Including UN ICG collaborative efforts)
• When we first started to explore our Earth we innovated ways to improve our knowledge of navigation and time to guide us.

• Today, we rely on Global Navigation Satellite Systems, or GNSS, constellations, to safely navigate to our destinations and to support intelligent agriculture, power grids, financial commerce, Earthquake monitoring and many others.

• There are 4 navigation satellite constellations with global coverage—Russia’s GLONASS, United States’ GPS, Europe’s Galileo, China’s BDS, as well as regional systems—India’s NAVIC system and Japan’s QZSS.

• The term Multi-GNSS refers to the use of two or more of these interoperable constellations to achieve enhanced performance and increased robustness.
Many spacecraft use GNSS in low Earth orbit—those below 3000 km altitude--including the International Space Station. Space users in low Earth orbit enjoy GNSS performance similar to that of ground users. This is a great place to put your high definition video clips of your spacecraft!

More recently, space vehicles have started using GNSS in the more challenging Space Service Volume or SSV, which is that area of space beyond 3,000 km altitude and reaching up to 36,000 km
• Spacecraft in the SSV endure significant challenges when compared to spacecraft in low Earth orbit.

• Among these are fewer signals in view due to the Earth obscuring most of the GNSS signals and the tight GNSS beamwidth.
Script Segment

- Spacecraft signals in the SSV are also much weaker signal strength due to the longer signal paths at these altitudes.
Engineers have developed special weak signal receivers to improve SSV reception and developed software to ensure robust performance with as little as one GNSS signal at a time.

But a single GNSS constellation cannot guarantee one signal in view at all times. And the availability of more signals further improves performance and robustness.
Analyses have shown that at low Earth Orbit, many signals are in view. But as the spacecraft approaches high altitudes in the SSV, a single GNSS system provides very few signals in view and signal outages can be over an hour.

However, when all GNSS constellations are employed, an average of 4–12 signals are in view, and at least 1 signal is always in view, resulting in substantially better performance.

Use tachometer to represent # signals in view—a key performance metric

- Tachometer goes from 0-12: 0-1 “red” 2-3 “yellow” & 4-12 “green”
- Spacecraft in GTO trajectory from LEO to GEO
- With 1 GNSS constellation at LEO, tachometer hits stops at 12
- As spacecraft traverses from LEO to GEO, tachometer drops precipitously from 12 (green) to 0-1 signals in view (red)
- As multiple constellations are added, tachometer goes from red to green; shows benefits of multi-GNSS

**GNSS Signals in View**
An interoperable Multi-GNSS SSV is a satellite gamechanger, supporting missions such as:

- Next generation weather satellites, such as EUMETSAT in Europe, GOES-R in the US, Himawari in Japan and Electro in Russia, substantially improving the quality of weather data collected and being a safety sentinel, warning people in danger of flash floods or wildfires.
- Human exploration out to the moon
- Space weather mission alerts to protect the world’s critical infrastructure against solar storms
- Missions to learn more about the Sun’s corona and
- Allows more accurate positioning of satellites in the dense geostationary belt
- Other benefits include reduced spacecraft operations costs through automation and autonomy and enabling new, exciting science through formation flying missions in the SSV

All for the benefit of society.

Need HD video clips of your SSV Applications Please!!
Conclusions

• Collaborative efforts, through the United Nations International Committee on GNSS, or ICG, are overcoming SSV technical hurdles through interoperability, common definitions and simulations and specifications.

• Individual GNSS constellations in the SSV have demonstrated superb operational and societal benefits but supply insufficient available signals to fully support future missions.

• An interoperable multi-GNSS constellation capability in the SSV is critical for the continuous coverage that a single system cannot provide.

• Once fully implemented, the ICG-led multi-GNSS space service volume initiative will be transformative for space missions. It ensures continuous GNSS navigation and timing and enables innovative space mission concepts as we continue to explore our universe for the good of humanity.
Forward Plan

• NASA solicits constellation video clips and high quality pictures from international community
  **Action to China, Europe, India, Japan Russia, USA**

• NASA will work with video producer, animators and production unit to develop polished SSV video final draft

• Present to WG-B for final comments around September

• Final video draft prior to November ICG meeting in China
Video Clip and Picture Guidance

• Make sure all video clips and pictures align with the script

• Items we would like to obtain include:
  – High resolution (HD) clips with detailed view of your satellite in orbit
  – Current and future prospective missions, like your GEO weather satellite, etc. In other words, satellite users in the SSV
  – Other ideas?

• We would really appreciate your inputs. These will be part of a polished video that we can all use to describe the SSV to many
Tentative Schedule

• Finalize script and action plan: This meeting
• Final video clips due from all parties: August 1
• Production version draft: ~ September 15
• WG-B review and comment: September 15-October 1
• Final Draft copy for review: ICG-13
• External release: Prior to Jan 1 2019
SSV OUTREACH
Status: SSV Outreach

- **SSV Booklet current outreach plan:**
  - (Publication of SSV Booklet + Video)
  - 24–28 Sep 2018: ION GNSS+, Miami, FL, USA [2 papers]
    - Paper 1: Development of Multi-GNSS SSV
    - Paper 2: Technical Results of Multi-GNSS SSV Analysis
  - 1–5 Oct 2018: IAC 2018, Bremen, Germany
    - Paper: The Multi-GNSS SSV
  - 4–8 Nov 2018: ICG-13, Xi’an, China
  - Mar 2019: Munich Satellite Navigation Summit

- **3x papers for Sep/Oct conferences must be developed very soon.**

- **Needs for this meeting:**
  - Approval of paper plan document, incl. titles, scope, outline
  - Approval of schedule and roles/responsibilities
  - Lead author commitments from each provider
Paper Roles/Responsibilities

• **Lead author:** Responsible for management of writing process and final drafts of manuscripts and presentations; *may not be the same as first author!*

• **Writing team:** Small (~5-person) team tasked with initial content authorship; meets often (~weekly) and responsive via email; does not necessarily involve all providers

• **Review team:** Larger team responsible for review of milestone drafts; involves all providers; may consist of all of WG-B SSV team
• **Title:** The Multi-GNSS Space Service Volume
• **Status:** Abstract accepted for presentation
• **Scope:**
  – Describes the concept, history, development, benefits, and use cases of the Multi-GNSS SSV.
  – Condensed and contextualized version of SSV Booklet.
  – Technical content describing high-altitude GNSS, SSV, and benefits, but limited analytical detail.
  – Written for a broad space audience – stresses what’s important, what’s new, and what the impacts will be.
  – Generally, more emphasis on international collaboration than the ION technical paper, but with more of a focus on the future than the ION programmatic paper.
  – Provide a future vision of international architecture development and use in cis-lunar space, in particular the lunar gateway.
Paper 2: ION (Development)

- **Title:** Development of an Interoperable, Multi-GNSS Space Service Volume
- **Status:** Accepted for presentation
- **Scope:**
  - Similar to the IAC paper.
  - Provide a discussion of the UN ICG process in facilitating an interoperable SSV.
  - This is more detailed in terms of what has already been done; content on development and trades.
  - Potentially more detailed results, benefits, use cases.
**Title:** Space User Visibility Benefits of the Multi-GNSS Space Service Volume: An Internationally-Coordinated, Global and Mission-Specific Analysis

**Status:** Accepted as alternate

**Scope:**
- Details the analysis used to calculate global and mission-specific visibility estimates.
- Covers constellation-specific configuration, simulation setup, assumptions, link budget, example missions, results analysis, verification.
- Visibility and DOP.
- Future work and technical refinements.
- Hope to swap this with the other ION paper so that paper is the alternate and this one is presented.
### Paper Schedule

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Description</th>
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<tbody>
<tr>
<td>Jun 21</td>
<td>ICG WG-B Meeting (approval of table of contents/plan for development/Roles and Responsibilities)</td>
</tr>
<tr>
<td>Aug 15</td>
<td>Final draft paper + presentation complete</td>
</tr>
<tr>
<td>Aug 16</td>
<td>Submit for review. For technical papers, only submission to space agencies is considered applicable. For policy or strategic papers, send to service providers for information, with deadline of Sept 10.</td>
</tr>
<tr>
<td>Aug 20</td>
<td>Space Agency/Institutional review submission deadline (final manuscript + presentation)</td>
</tr>
<tr>
<td>Sept 10</td>
<td>Provider feedback (if any)</td>
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<tr>
<td>Sept 10</td>
<td>Feedback from space agencies/institutions</td>
</tr>
<tr>
<td>Sep 17</td>
<td>IAC submission deadline (manuscript)</td>
</tr>
<tr>
<td>Sep 24</td>
<td>IAC/ION submission deadline (presentations)</td>
</tr>
<tr>
<td>Oct 5</td>
<td>ION submission deadline (manuscripts)</td>
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Session 7

Enhancement of GNSS signals and performance and required system enhancements
MISSION UPDATES
Magnetospheric Multi-Scale (MMS)

- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Phase 1: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - Phase 2B: Extends apogee to 25 Re (~150,000 km) **(40% of way to Moon)**

MMS Navigator System

- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set Guinness world record for the highest reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h
MMS on-orbit Phase 2B results: signal tracking

- Consider 8-day period early in Phase 2B
- Above GPS constellation, majority of signals are still sidelobes
- Long term trend shows average of \(~3\) signals tracked near apogee, with up to 8 observed.
- Visibility exceeds preflight expectations significantly
MMS on-orbit Phase 2B results: measurement and navigation performance

- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
  - Suggests sidelobe measurements are of high quality.

<table>
<thead>
<tr>
<th>Description</th>
<th>Requirement</th>
<th>Phase 1</th>
<th>Phase 2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis est. under 3 $R_E$ (99%)</td>
<td>50 m (Phase 1)</td>
<td>6 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Orbit position estimation (99%)</td>
<td>100 km RSS</td>
<td>65 m</td>
<td>55 m</td>
</tr>
</tbody>
</table>

Filter formal pos/vel errors (1σ root cov)

Pseudorange residuals
GOES-R Series Weather Satellites

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- GOES-R/GOES-16 Launch: 19 Nov 2016
- 15 year life, series operational through mid-2030s

- Features new CONOPS over previous generation:
  - Daily low-thrust station-keeping maneuvers, rather than annual high-thrust events
  - Continuous data collection through maneuvers, <120 min of outage per year
  - Tighter navigation accuracy requirements and faster cadence needed to support highly increased operational tempo

- Employs on-board GPS at GEO to meet stringent navigation requirements
- Utilizes GPS sidelobe signals to increase SSV performance and ensure continuous availability

GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico
GOES-R/GOES-16 Signal Reception

- GPS L1 C/A only
- Receive antenna designed for above-the-constellation use
- Max gain @20 deg off-nadir angle
- Tuned to process main lobe spillover + first side lobe

GOES-R/GOES-16 In-Flight Performance

GPS Visibility
- Minimum SVs visible: 7
- DOP: 5–15
- Major improvement over guaranteed performance spec (4+ SVs visible 1% of time)

Navigation Performance
- $3\sigma$ position difference from smoothed ground solution (~3m variance):
  - Radial: 14.1 m
  - In-track: 7.4 m
  - Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m

GOES-16 & MMS SSV Lessons Learned

- Flight data presents real-world snapshot of current GPS SSV performance, especially the substantial enhancements afforded by side-lobe signals
- Side-lobe signals:
  - Shown to significantly improve availability and GDOP out to cis-Lunar space
  - Substantial enhancement of maneuver recovery for vehicles in SSV (graphic)
  - Integrity of signals sufficient enough to enable outstanding, real-time navigation out to cis-Lunar distances
- Operational use of side-lobe signals is an increasing area of interest & multiple operational examples are on-orbit and in development
- WG-B team should consider whether beyond main-lobe (aggregate) signals should be documented and protected to optimize the utility of the SSV

MMS response to apogee maneuvers with side-lobe signals (blue) and without (red)

Notes:
1) Blue—flight data
2) Red—simulated data based on flight signal availability
3) MMS Phase 1 (70,000 km apogee)
GARISS
**GAliileo Receivver for the ISS (GARISS)**

- **Objectives:**
  - Demonstrate combined GPS/Galileo (L5/E5a) navigation receiver for on-orbit operations
  - Analyze/validate navigation performance of dual-constellation receiver function

- **Approach:**
  - Adapt existing PNT code for software Galileo receiver for Software Defined Radio (SDR)
  - Operate waveform to conduct experiments and tests on-orbit

- **Benefits:**
  - Shows flexibility of SDR technology through development of Software/Firmware waveform for L-band SDR in SCAN Test-Bed
  - Illustrates efficiencies in development brought by use Space Telecommunications Radio System (STRS) operating environment

- **Timeline:**
  - Initial discussions at International meetings (mid-2014)
  - Project formulation/export license (mid-2016)
  - Design and development of the Galileo/GPS waveform for SCaN Test-bed (STB) (late 2016-mid 2017)
  - Qualification and test the Galileo/GPS waveform (mid 2017-late 2017)
  - On-orbit testing and experiments (2018)
NASA’s SCaN Testbed

S-band Antennas

Ka-band Antenna

L-Band (GPS/Galileo) Antenna

Space Communication and Navigation (SCaN) Testbed
Installed on the International Space Station (ISS) in July 2012
Fully reprogrammable Software Defined Radio capability at L-band
Operational/Experiment Concepts

- Support for multi-constellation GPS and Galileo
- Exclusive use of L5/E5a band
- Warm start acquisition aiding from ground via file upload
- Assess acquisition and tracking performance, pseudo-range errors, etc.
- Assess PVT performance
- Concept of operation
  - Transfer waveform from ground support equipment to STB
  - Operate waveform per STB schedule
  - Collect/process log data

Qascom + ESA/ESTEC

NASA Glenn ISS Payload Operations Center (GIPOC)

Waveform telemetry

Configuration + flight parameters

NASA Space communications networks

STB on ISS
GARISS: Status

**Status**
- Mild re-architecting of Interrupt Task made to accommodate include adaptive strategy for management to keep correlation peaks within processing interval
- Successful acquisition, track and PVT with STB Ground Integration Unit (GIU) using roof antenna (March 2018)
- Moved integration and testing to on-orbit operations
- Successful on-orbit acquisition, track and PVT solution (April 2018)
- Full function for GPS and Galileo processing established at qualification review (May 2018):
  - Acquisition and Time to First Fix (TTFF) requirements are met for Galileo and for combined GPS/Galileo
  - GPS-only on-orbit PVT availability > 20%
  - Galileo-only on-orbit PVT availability > 40%
  - PVT performance issues remain.
Path Forward
• Investigation of errors in pseudo-range estimation and, possibly, inter-constellation bias is ongoing.
• [Pending] Experimentation objectives potentially include:
  • examination of multipath effects
  • validation of inter-constellation time bias models,
Conclusions
• GARISS leverages SCAN testbed, STRS development framework
• Demonstrated effectiveness of multi-constellation/GNSS solutions
• First-ever on-orbit direct acquisition or L5/E5a (no L1 aiding)
AFTS
Autonomous Flight Termination System (AFTS)

- Independent, self-contained subsystem mounted onboard a launch vehicle
- Flight termination / destruct decisions made autonomously via redundant Global Positioning System (GPS)/Inertial Measurement Unit (IMU) sensors
- Primary FTS for unmanned Range Safety Operations and being considered as Primary FTS for human space flight (Commercial Crew and SLS)
- Advantages:
  - Reduced cost—decreased need for ground-based assets
  - Global coverage (vehicle doesn’t have to be launched from a range)
  - Increased launch responsiveness
  - Boundary limits increase due to 3-5 second gain from not having Mission Flight Control Officer (MFCO)
  - Support multiple vehicles simultaneously (such as flyback boosters)

Enabling low cost, responsive, reliable access to space for all users

April 2006: WSMR Sounding Rocket
Mar 2007: SpaceX F1 Sounding Rocket
Sept 2010: WFF Sounding Rocket
Autonomous Flight Termination System - Operational Use

• In work over 18 years with many flight demonstrations
• Independent Verification and Validation (IV&V) completed June 2015
• Prototype AFTS units were flown on 13 SpaceX launches since April 2015
• First Operational Launch of AFTS on SpaceX CRS-10 launch, Feb 20, 2017
• 25 additional successful SpaceX operational launches to-date (as of June 2018)
• The successful SpaceX F9 Heavy launch demonstrated that without AFTS, such a launch system with 2 fly-back boosters, a 1st stage fly-back core, and a 2nd stage could not be supported by traditional range operations using a MFCO.

AFTS Fully Operational & Demonstrating its Critical Role of Protecting People & Property and Enabling Quicker Cadence of Launch Ranges
IGS UPDATE
Recent Significant IGS Events and Changes

- Ruth Neilan (IGS representative to ICG) retired from JPL in March 2018, and is no longer associated with JPL or NASA
- Allison Craddock appointed by JPL as Central Bureau Director and confirmed by the IGS Governing Board in April 2018
- New IGS Strategic Plan published in February 2018 and is available at: https://kb.igs.org/hc/en-us/articles/360001150012-2017-Strategic-Plan

International GNSS Service (IGS)

- A voluntary federation of over 200 international agencies
- Promotes and provides open and free access to high quality GNSS data and analysis products
- Providing high precision GNSS data, products and services, including: GPS + GLONASS combined orbits, GPS clocks, GLONASS clocks
- Supports realization of the International Terrestrial Reference Frame
IGS

GNSS Performance Monitoring
ICG-IGS Joint Trial Project (IGS-IGMA)

• Background and Objective
  • Trial project of the ICG Monitoring and Assessment Task Force (IGMA), coordinated in partnership with the IGS
  • Monitoring of GNSS constellation status and the quality of navigation signals enables numerous applications, including worldwide time and frequency transfer, and GPS meteorology.
  • High-precision GNSS monitoring of the earth is not possible without GNSS performance monitoring
    • Orbit accuracies of a few centimeters for any point in time are a requirement, and determination of this is only possible if the properties of all GNSS are known to the best extent possible—or—can be determined in orbit determination processes.
    • Many parameters have to be determined by monitoring:
      • Broadcast Ephemeris Accuracy (Orbits and Clocks)
      • SIS User Range Error
      • SIS UTS Offset Error
      • PDOP for GNSSs
  • Long term objectives:
    • Make all performance standard entries for each GNSS openly available
    • Provide a multi-GNSS service performance standard
GNSS Performance Monitoring
ICG-IGS Joint Trial Project (IGS-IGMA)

• Current Status
  • 12 Groups have responded positively to Call for Particaption
  • Initial results have been gathered and a standard methodology is in development
  • IGS-IGMA recommends to the service providers to make the following info available:
    • the antenna phase center values of all the GNSS systems
    • Know for which signal(s) the clocks are given/valid
    • the attitude law of the satellites, in particular during eclipse, that is used for the broadcast ephemerides

• Future work includes:
  • Review and enhance comparison of broadcast ephemerides
  • Start converting orbit and clocks to common location and compare
  • Develop and implement clock comparison strategy
  • SISURE and UTC to follow after orbit and clock comparison is resolved
Multi-GNSS Extension (MGEX) Pilot Project

- MGEX work focuses on integration of the evolving global and regional satellite navigation systems Galileo, BeiDou, QZSS, and NavIC (IRNSS) into the IGS data archives and operational products.
- Integration of the multi-GNSS observation data was completed in 2016, but improving the product quality of the emerging GNSS to achieve the same quality as for the legacy GPS and GLONASS is still an ongoing process.
- The IGS Multi-GNSS Working Group, led by Oliver Montenbruck, released a White Paper, titled “Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products.”
  - The paper discusses the parameters needed to ensure the highest possible performance of IGS products for all constellations and motivates the need for provision of satellite and operations information by the GNSS providers.
  - All information requested by the IGS is considered to be sufficiently abstract such as to neither interfere with the GNSS providers’ safety and security interests nor with intellectual property rights.
MGEX Achievements, Prospects, and Challenges

- MGEX has recently published a comprehensive paper detailing its achievements in the last five years, future prospects, and challenges.
- “The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges,” published in Advances in Space Research, Volume 59, Issue 7, 1 April 2017, Pages 1671–1697, discusses:
  - Multi-GNSS products derived from the IGS monitoring station network
  - Work towards full integration of new constellations into routine GNSS processing
  - Progress made within the MGEX project including BeiDou, Galileo, and QZSS for precise point positioning, atmospheric research, and other applications.
  - Biases; standards and conventions
- Due to copyright restrictions, a pre-print previous version of the article is available here: [http://bit.ly/MGEXasr](http://bit.ly/MGEXasr)
NGBS
Proposed System Under Development: Next Generation Broadcast Service (NGBS)

- NGBS would provide unique signals and data to enhance user operations and enable autonomous onboard navigation
- NGBS service may consist of:
  - Global coverage via TDRSS S-band multiple access forward (MAF) service
  - Unscheduled, on-demand user commanding
  - TDRS ephemerides and maneuver windows
  - Space environment/weather: ionosphere, Kp index for drag, alerts, effects of Solar Flares/CMEs
  - Earth orientation parameters
  - PN ranging code synchronized with GPS time for time transfer, one-way forward Doppler and ranging
  - Global differential GNSS corrections
  - GNSS integrity

NGBS could have direct benefits in the following areas:
- Science/payload missions
- SCaN/Network operations
- TDRSS performance
- GPS and TDRSS onboard navigation users
- Conjunction Assessment Risk Analysis
- Capabilities consistent with the modern GNSS architecture
Next Generation Broadcast Service

- NGBS 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) TDRSS satellites relay GDGPS differential corrections to space users via the Multiple Access Antenna (MAA)

4) Evolved NGBS signal could incorporate 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
NGBS: Benefits, Status, and Conclusions

• Benefits
  – Improves the level of autonomous operations for users
  – Improves coordination and responsiveness to transient scientific phenomena among multiple spacecraft (e.g. gamma-ray bursts, gravitational waves)
  – Provides alternative/additional navigation beacon to supplement GNSS, improving resiliency to users

• Conclusions
  – Enables user-initiated services (essential to science activities such as the study of transient astronomical events)
  – Provides user spacecraft with radiometrics and data to support autonomous, on-board navigation and operations
  – Makes space weather data available (of special interest to human spaceflight operations)

• Status
  – Requirements are being developed at NASA for the next generation TDRS relay

Engagement from the user community is critical. Seeking stakeholder feedback: what services would be beneficial?
FUTURE MISSIONS
Potential Future Application: Lunar Orbital Platform - Gateway

- NASA Exploration Campaign: Next step is deployment and operations of US-led Lunar Orbital Platform – Gateway (previously known as Deep Space Gateway)
- Step-off point for human cis-lunar operations, lunar surface access, missions to Mars
- Features include:
  - Power and propulsion element (PPE) – targeted for 2022
  - Human habitation capability
  - Docking/rendezvous capability
  - Extended uncrewed operations (not continuously crewed)
  - Lunar near-rectilinear halo orbit (NRHO)
- Gateway conceptual studies are continuing with ISS partners
  - Requirements to be baselined in 2018
  - To be followed by Broad Agency Announcement for partnerships
- **Gateway represents a potential application for on-board GNSS navigation**
- NASA will continue providing updates to WG-B as plans develop.

### GNSS Mission Areas (1):

Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

#### Table of Missions

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<tr>
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<th>Launch (Actual or Target)</th>
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<th>Updated By</th>
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<td>Launch avai. Nov 02, 2008; CNES controls the satellite in routine operation; ESA operates the mission</td>
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<td>Navigation (PVT) and Precise Orbit Determination (POD) plus one GNSS receiver for scientific use</td>
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<td>2020</td>
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<td>2021</td>
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<td>SAR</td>
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<td>Altimetry &amp; imager</td>
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### GNSS Mission Areas (1):

**Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography**

**Nov. 14, 2017 Version (Updated for ICG-12 & and IOAG-21)**

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<td>Navigation (PVT) and Precise Orbit Determination (POD) plus one GNSS receiver for scientific use - Radio Occultation</td>
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<td>2021</td>
<td>7 Instruments for Earth Observation, including Radio occultation</td>
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<td>LEO</td>
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<td>2016-Nov-17</td>
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<td>52</td>
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<td>ALOS-2</td>
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<td>L1</td>
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<td>LEO</td>
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<td>Unmanned ISS transportation</td>
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GNSS Mission Areas (1):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

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<th>GNSS System/s Used</th>
<th>GNSS Signals Used</th>
<th>GNSS Application</th>
<th>Orbit</th>
<th>Launch (Actual or Target)</th>
<th>Notes</th>
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<th>Updated By</th>
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<td>61</td>
<td>NASA</td>
<td>ISS GPS</td>
<td>L1 C/A</td>
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<td>Attitude Dynamics</td>
<td>LEO</td>
<td>Since 1998</td>
<td>Honeywell SIGI receiver</td>
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<td>62</td>
<td>NASA</td>
<td>COSMIC (6 satellites) GPS</td>
<td>L1 C/A, L1/L2 semi-codeless, L2C</td>
<td>Radio Occultation</td>
<td>LEO</td>
<td>2006</td>
<td>GOD (BlackJack) receiver; spacecraft nearing end of life</td>
<td>2016-Apr-28</td>
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<td>63</td>
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<td>L1 C/A, L1/L2 semi-codeless</td>
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<td>LEO</td>
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<td>BlackJack receiver; mission retired 14 August 2010</td>
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<td>Precise Orbit Determination, Occultation, precision time</td>
<td>LEO</td>
<td>2012</td>
<td>BlackJack receiver, joint mission with DLR</td>
<td>2016-Apr-28</td>
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<td>67</td>
<td>NASA</td>
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<td>Orbit</td>
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<td>68</td>
<td>NASA</td>
<td>ISS Commercial Crew and Cargo Program - Dragon GPS</td>
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<td>LEO</td>
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<td>Orbit / ISS rendezvous</td>
<td>LEO</td>
<td>2013+</td>
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<td>2016-Apr-4</td>
<td>JJ Miller</td>
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<td>70</td>
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<td>L1 C/A</td>
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<td>Orbit, time</td>
<td>LEO</td>
<td>2014</td>
<td>Navigator receiver</td>
<td>2016-Feb-4</td>
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<tr>
<td>72</td>
<td>NASA</td>
<td>COSMIC IV (6 satellites) GPS, GLONASS FDMA</td>
<td>L1 C/A, L1C, semi-codeless P2, L5</td>
<td>Occultation</td>
<td>LEO</td>
<td>2013</td>
<td>BDS receiver, 8 RF inputs, hardware all-GNSS capable, will track GPS + GLONASS at launch</td>
<td>2017-Nov-6</td>
<td>L. Young</td>
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<tr>
<td>73</td>
<td>NASA</td>
<td>DSAC GPS, GLONASS FDMA</td>
<td>L1 C/A, L1C, semi-codeless P2, L5</td>
<td>Time transfer</td>
<td>LEO</td>
<td>2013</td>
<td>BDS+ (BlackJack) receiver</td>
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<td>74</td>
<td>CNES/NASA</td>
<td>Jason 3 GPS, GLONASS FDMA</td>
<td>L1 C/A, L1/L2 semi-codeless, L2C</td>
<td>Precise Orbit Determination, Oceanography</td>
<td>LEO</td>
<td>2013</td>
<td></td>
<td>2016-Apr-28</td>
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<td>75</td>
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<td>MMS GPS</td>
<td>L1 C/A</td>
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<td>Rad, range, orbit, time up to 30 Earth radii</td>
<td>LEO</td>
<td>2013</td>
<td>Navigator receiver (8 receivers)</td>
<td>2016-Apr-28</td>
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<td>Orbiter</td>
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<td>LEO</td>
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<td>RUAG Space receiver</td>
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<td>GPS bio-scatterometry</td>
<td>LEO</td>
<td>2016</td>
<td>Delay Mapping Receiver (DMR), SSTL, UK</td>
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<td>80</td>
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<td>Sentinel 64 (Jason-CS), 2 Satellites GPS, GLONASS FDMA, Galileo</td>
<td>L1 C/A, L1C, semi-codeless P2, L5</td>
<td>Occultation, Precise Orbit Determination</td>
<td>LEO</td>
<td>2020 and 2025</td>
<td>BDS receiver with 2025</td>
<td>2017-Nov-6</td>
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<td>81</td>
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<td>GRASP GPS, GLONASS FDMA, Meteors, Galileo</td>
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### GNSS Mission Areas (1):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous,
Formation Flight, Radio Occultation, Oceanography

**Nov. 14, 2017 Version (Updated for ICG-12 & and IOAG-21)**

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<th>Launch (Actual or Target)</th>
<th>Notes</th>
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<th>Updated By</th>
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<tr>
<td>82</td>
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<td>NICER (ISS)</td>
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<td>Orbit</td>
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<td>L1 C/A</td>
<td>Navigation</td>
<td>Surface to LEO</td>
<td>Since 1990</td>
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<td>L1 C/A</td>
<td>Integrated inertial navigation system (INS) &amp; GPS</td>
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<td>Since 2010</td>
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<td>Falcon-9 Launcher</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Deploy to INS for additional orbit insertion accuracy</td>
<td>Surface to LEO</td>
<td>Since 2013</td>
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<td>Precise Orbit Determination, timing</td>
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<td>2020</td>
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<td>2015-Oct-6</td>
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<td>Orbit</td>
<td>LEO</td>
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**Notes:**
- **Orbit Type:** Ee = Equatorial Earth Orbiter; Ei = Inclined Earth Orbiter; Ep = Polar Earth Orbiter; Es = Sun Synchronous Earth Orbiter; G = Geostationary; H = High Elliptical Earth Orbit; R = Earth orbiter Relay; O = Other orbit type (specify in remarks)

**Organizations:**
- **ASI:** Agenzia Spaziale Italiana
- **CNES:** Centre national d’études spatiales
- **CSA:** Canadian Space Agency
- **DLR:** German Aerospace Center
- **ESA:** European Space Agency
- **JAXA:** Japan Aerospace Exploration Agency
- **NASA:** National Aeronautics and Space Administration