GPS Based Autonomous Navigation Study for the Lunar Gateway

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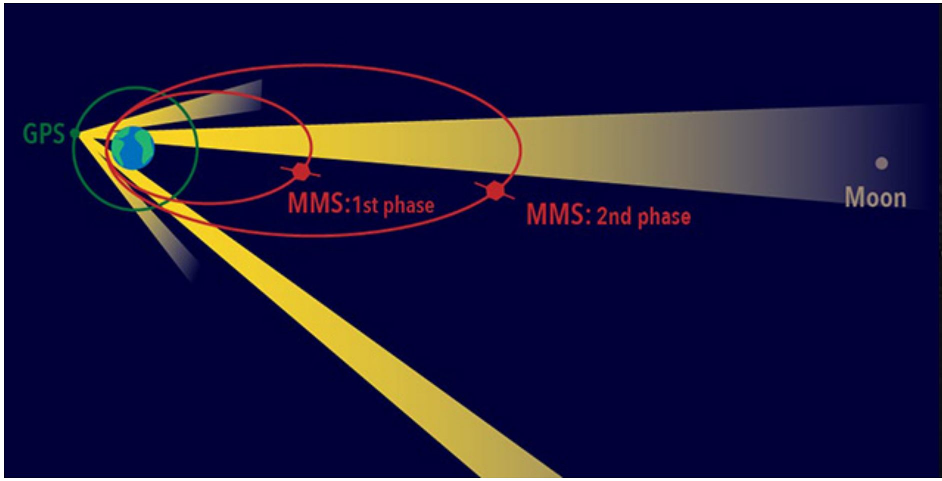
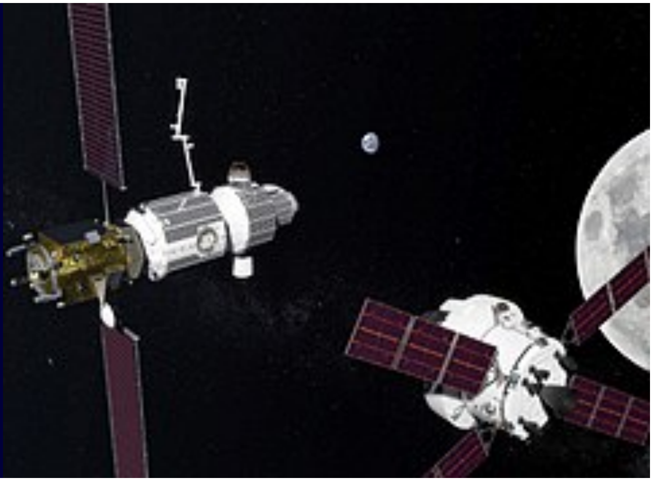
Outline

- Introduction
- Conceptual GPS system for Gateway
- Simulation description and calibration with Magnetospheric Multiscale Mission (MMS) flight data
- Gateway simulation setup
- Results
- Conclusion

Background on high-altitude (HEO) GPS

- **HEO GPS navigation offers performance and cost improvements, but poses challenges**
  - Sparse main-lobe availability, sidelobes weak/unspecified, poor geometry, potentially harsher radiation environment
- **Ongoing research in HEO GPS R&D since 1990’s. Recent missions have demonstrated great benefit of GPS onboard navigation at GEO and beyond**
  - Of particular note: MMS operating in orbit with 25 Earth radii (RE) apogee (40% lunar distance) soon to raise to 29RE is *highest operational use of GPS to our knowledge*. Excellent navigation results make strong case for GPS in lunar regime

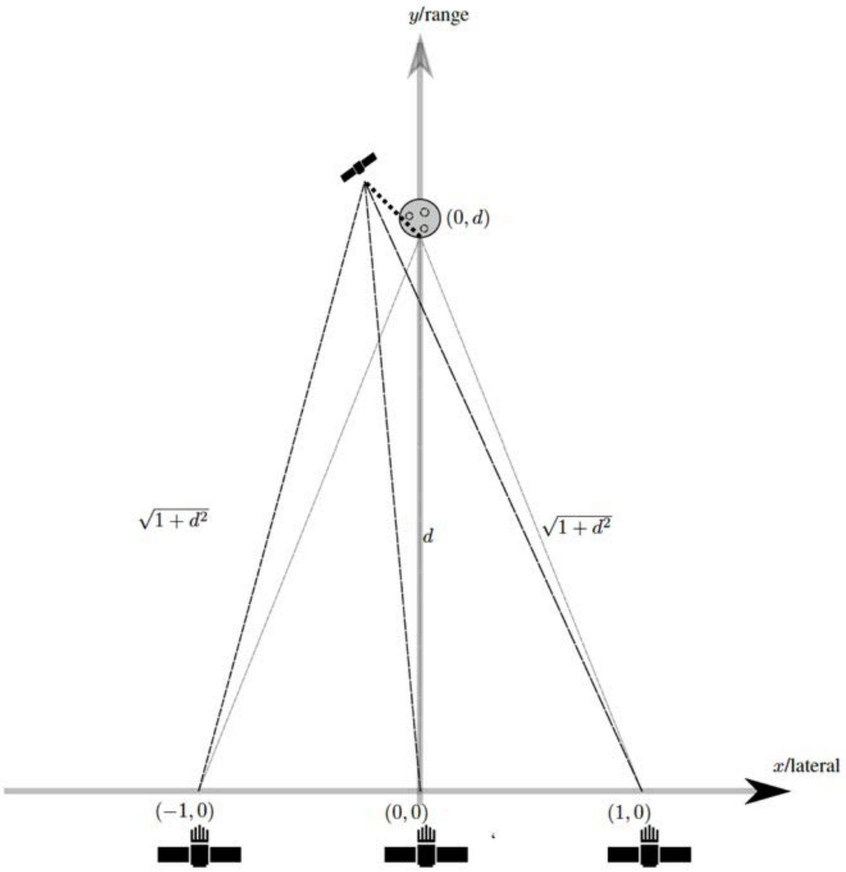




Note: in most cases GPS could/should be replaced by GNSS throughout this talk

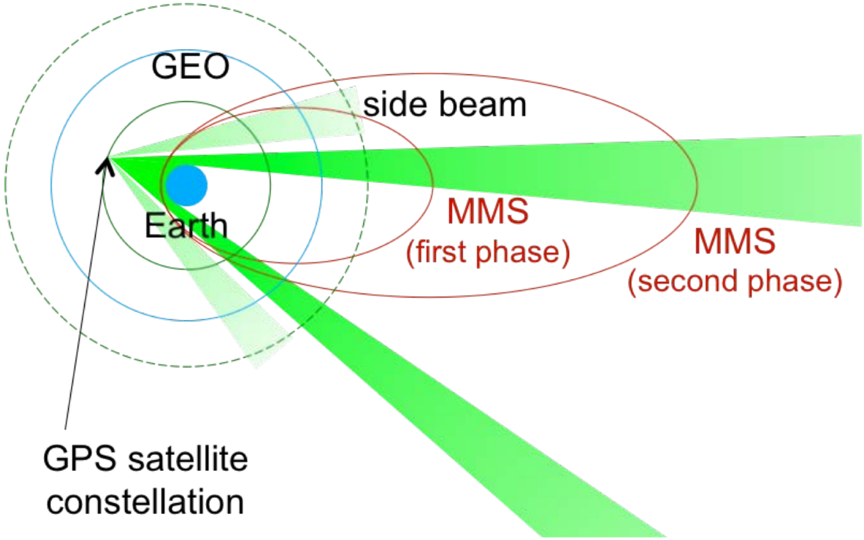
High altitude GPS error scaling

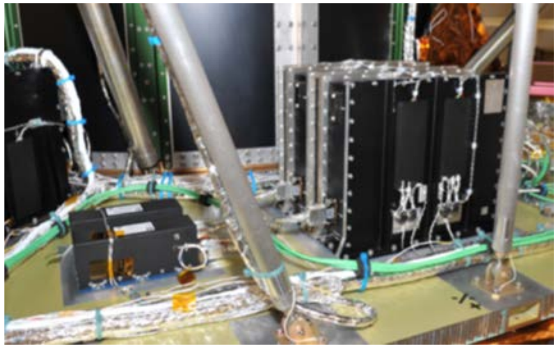
- **For high altitude GPS and ground tracking techniques, transmitter geometry degrades with increasing distance from the Earth**
- **For two-way ground tracking, lateral errors grow with distance, but range errors can be kept uniformly small**
- **For GPS one-way ranging, range and clock errors tend to dominate lateral errors and become very highly correlated**
- **In the paper, we show that for the simplified 2D *point positioning* problem**
  - lateral errors scale proportional to d
  - range and clock errors scale proportional to d^2
- **Can mitigate with use of a stable clock and navigation filter and/or augmentation with other measurements**
- **Nonetheless, GPS nav. performance can still be excellent at lunar distance**



MMS navigation system

- **MMS Navigation system consists of Navigator GPS receiver, with Ultra-stable crystal oscillator (USO) and Goddard Enhanced Onboard Navigation Software (GEONS)**
- **Navigator-GPS**
  - Product of NASA Goddard project to build high-altitude GPS receiver (~2001)
  - Rad-hard C/A code receiver, with fast unaided weak signal acq (<25dB-Hz)
  - Heritage on STS-125 Relative Navigation Sensor Experiment (2009), Global Precipitation Measurement Mission (GPM, 2014-), Tech incorporated into Honeywell Orion GPS - demo on EFT-1 of fast-acq for rapid recovery from blackout (Dec 2014)
- **GEONS**
  - UD-factorized Extended Kalman Filter, 4th/8th order RK integrator, realistic process noise models. High-fidelity dynamics and many measurement models available.
  - Development dates back to 1980’s on Cosmic Origins Background Explorer (COBE).
  - Flying on Terra, GPM, NICER, SEXTANT, MMS, planned on Restore-L

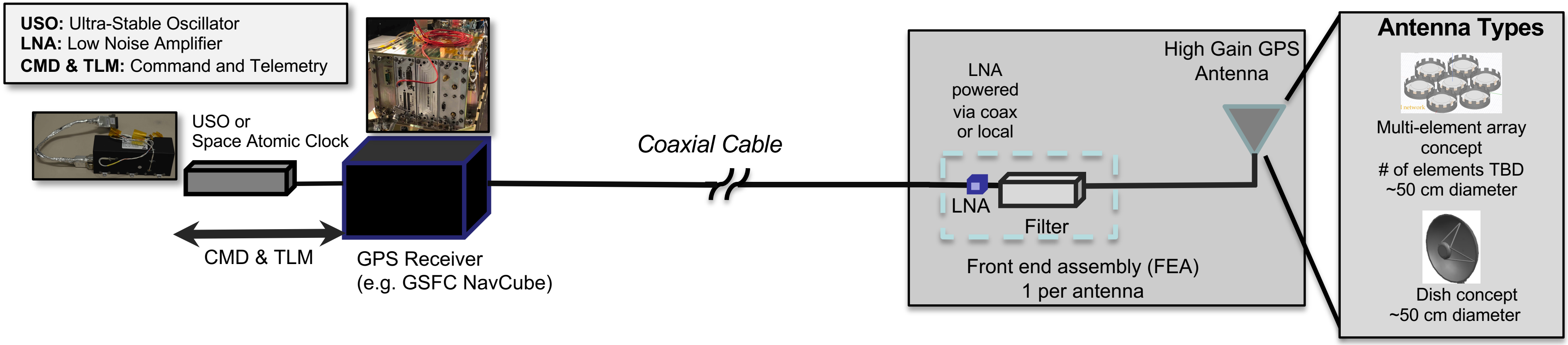




MMS Navigator GPS with USOs

A conceptual Gateway onboard GPS navigation system

- **Our study predicts that an MMS-like GPS navigation system, with an Earth pointed high-gain antenna (~14dBi) would provide strong onboard navigation for Gateway**



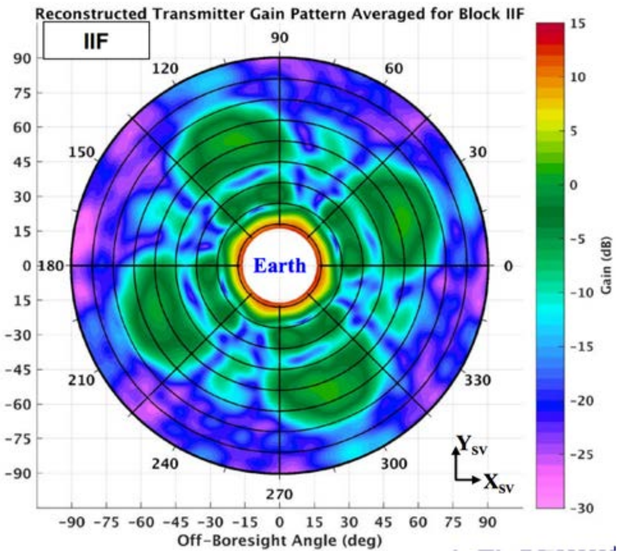
USO: Ultra-Stable Oscillator
LNA: Low Noise Amplifier
CMD & TLM: Command and Telemetry

- **Main electronics**
  - GSFC NavCube – Next Gen MMS Navigator GPS:
    - Reprogrammable Software Defined Receiver (SDR)
      - Upgradable to multi-GNSS, etc.
    - Updated MMS GPS baseband processor logic
    - GEONS navigation filter software tuned for NRHO
- **External oscillator**
  - MMS USO or
  - Space-rated atomic clock
    - Could significantly enhance performance

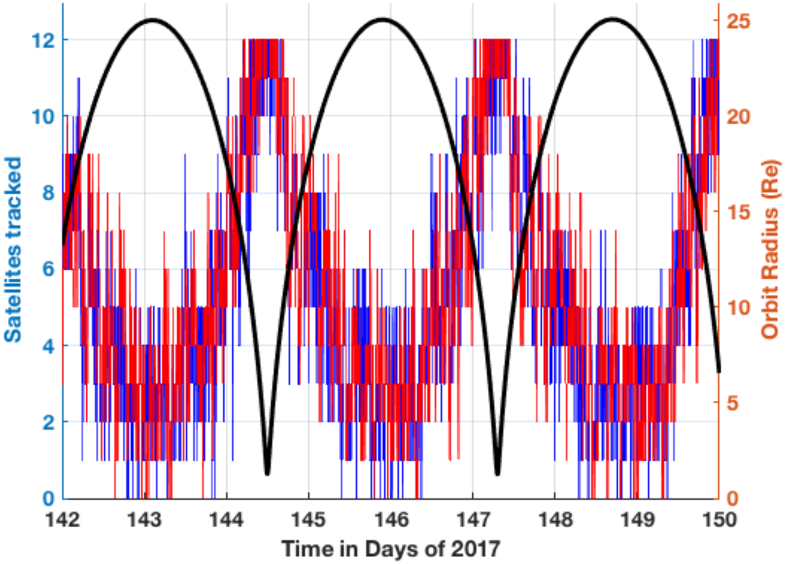
- **Antenna and Front End Assembly (FEA)**
  - 1 FEA with cables per antenna
  - 1 High gain GPS Antenna ~14dBi
    - *a small dish or multi-element array*
    - *Earth pointed, gimbal*

Sim calibration against MMS-2B flight data

- **Simulations performed using GEONS Ground Matlab Simulation (GGMS)**
  - *GEONS flight filter software* with MATLAB driver and measurement and clock simulation
  - Similar to system used for MMS preflight analysis
  - Includes high-fidelity GPS sidelobe link model using GPS Antenna Characterization Experiment (ACE) transmit antenna patterns [Donaldson, et al.]*, a GPS yaw model, and receiver noise model
- **To calibrate:**
  - Run sim from an initial state/epoch/GPS broadcast ephem obtained from MMS2B flight data
  - Compare sim vs. flight GPS C/N_0, adjust GPS transmit power and few receiver parameters to match
- **Obtained good match for all metrics (signals tracked, C/N_0 arcs, filter formal errors)**
  - Randomness in acquisition model prevents exact match in number of signals tracked



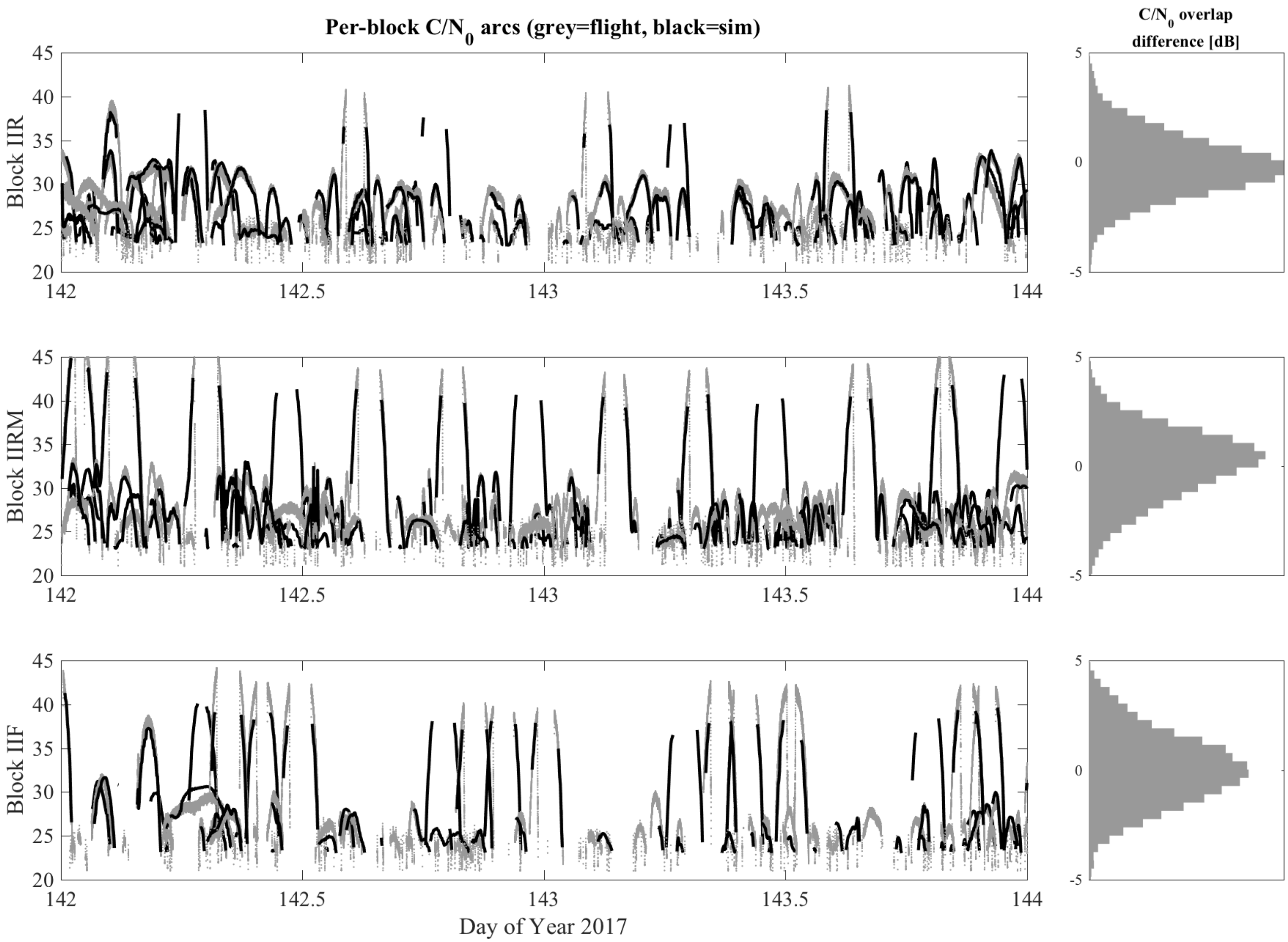
*ACE GPS IIF measured pattern [Donaldson, et al.]**



MMS2B Simulated (red) vs. on-orbit (blue) signals tracked

J. Donaldson et al., Characterization of On-Orbit GPS Transmit Antenna Patterns for Space Users, Proc. of ION GNSS+, 2018.

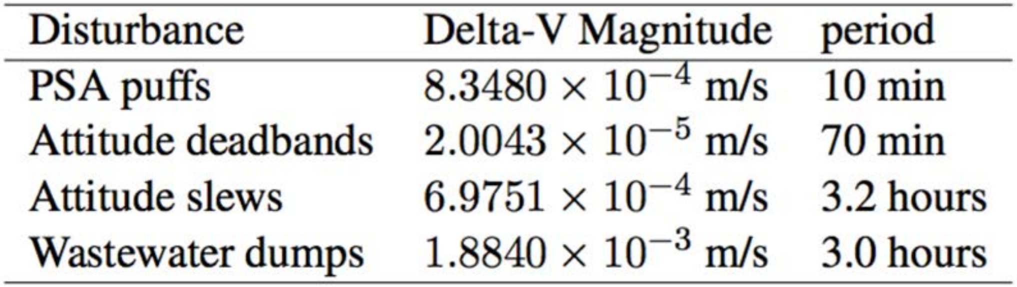
C/N_0 calibration results



Gateway trajectory

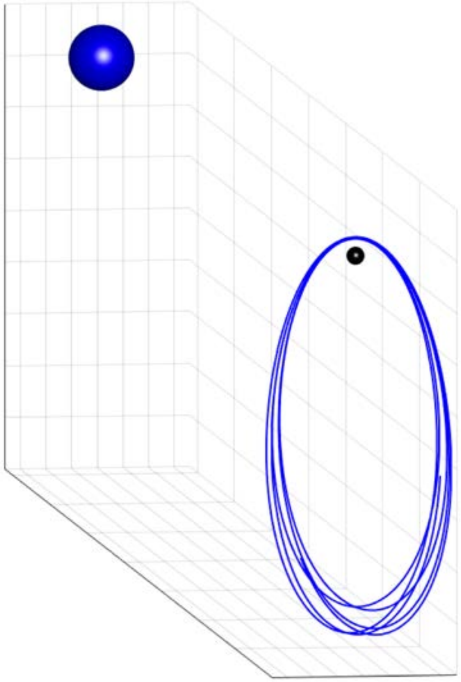
- The orbit studied for the Gateway: L2 Southern Near Rectilinear Halo Orbit (NRHO) with average periapsis altitude ~1800 km, apoapsis altitude of 68,000 km, 6.5 day period, in 9:2 resonance with the Moon's orbit
- Truth trajectories used in this study were generated using the high precision orbit propagator in FreeFlyer^{TM} as in [Volle and Davis]*
- *Uncrewed case* includes only (impulsive) orbit maintenance maneuvers executed (with 3% execution error) at each apoapsis to maintain the quasi-periodic orbit
- *Crewed case* includes additional disturbance delta-Vs as given in table below (as in [Volle and Davis]*)

Crewed case additional disturbances



Disturbance	Delta-V Magnitude	period
PSA puffs	8.3480×10^{-4} m/s	10 min
Attitude deadbands	2.0043×10^{-5} m/s	70 min
Attitude slews	6.9751×10^{-4} m/s	3.2 hours
Wastewater dumps	1.8840×10^{-3} m/s	3.0 hours

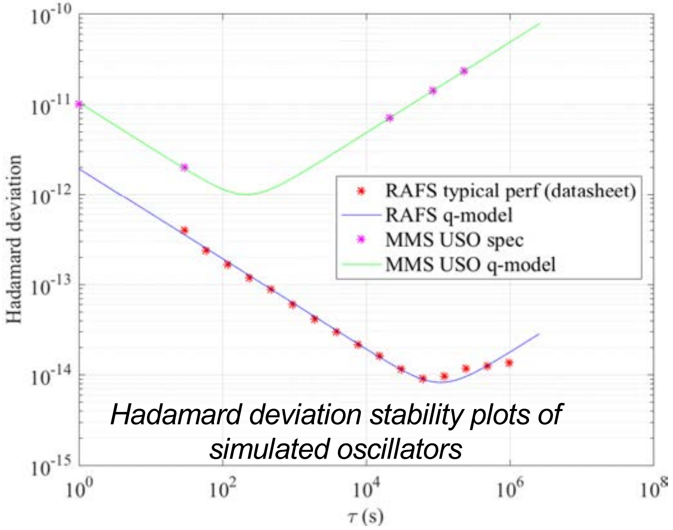
Note: PSA=Pressure Swing Adsorption (CO$_2$ capture system)



M. Volle and D. Davis, Examining the Feasibility of Relative-Only Navigation for Crewed Missions to Near Rectilinear Halo Orbits. Proc. of the AAS/AIAA Astrodynamics Specialist Conference, 2018

Gateway simulation cases

- **Ran 40-case Monte-Carlo simulations (varying initial state error, meas. noise/biases, maneuver disturbances, solar radiation pressure coeff. error, etc.), for three sensor configurations:**
  1. *Ground Station (GS) tracking baseline*
     - Two-way range and Doppler 8hr/day with ground stations alternating (Madrid, Canberra, Goldstone)
     - Used 30s meas rate/Doppler averaging and 4m range noise, 0.5m per-pass bias, 0.5cm/s Doppler noise and no bias (all 1σ)
     - This case modelled on setup in [Volle and Davis], and we obtained consistent results
  2. *GPS using MMS-USO*
     - Up to 12 Pseudoranges every 30s with random errors of 10m below and 4m above 40dB-Hz “strong signal” threshold (all 1σ)
  3. *GPS using space atomic clock*
     - Modelled Spectratime Rubidium Atomic Frequency Standard (RAFS)*, as example
- **Ran each sensor configuration for uncrewed and crewed disturbance models**



Hadamard deviation stability plots of simulated oscillators

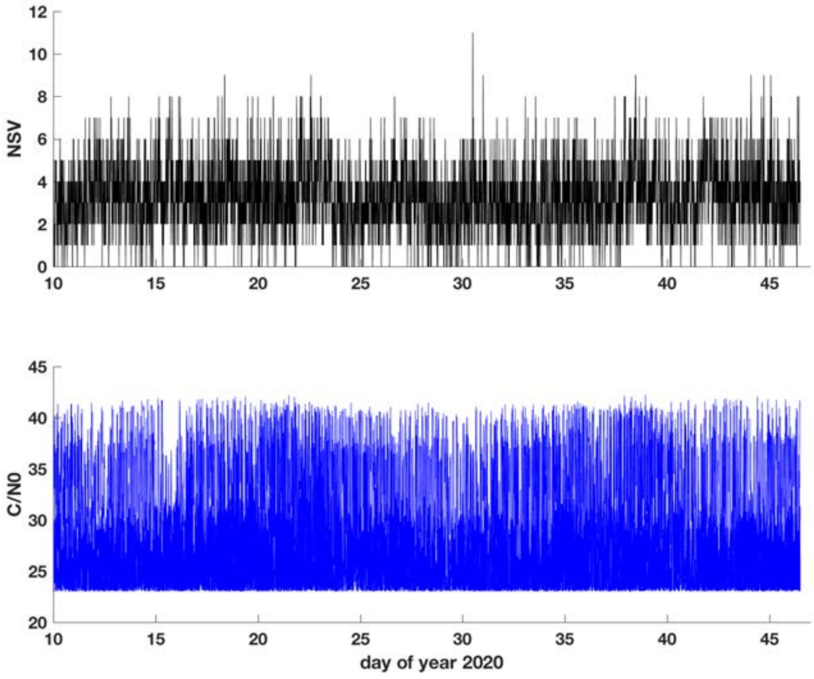
Dynamic Models Used in Simulation

	Truth Trajectory Simulation	GEONS Filter Propagation
Planetary Ephemeris	JPL DE 430	JPL DE421
Pont Mass Gravity	Sun, Earth, Venus, Mars, Jupiter, Saturn	Sun, Earth, Venus, Mars, Jupiter, Saturn
Lunar Gravity Model	30x30 GRAIL PRIM660	30x30 LP100K
Solar Radiation Pressure	Spherical 24000 kg, $80m^2$, CR= 2.0	Spherical 24000 kg, $80m^2$, CR= $2.0 + 0.2\ (1\sigma)$
Orbit Maintenance	Delta-Vs at apoapsis Planned	Planned + $3\%(1\sigma)$ Maneuver execution error

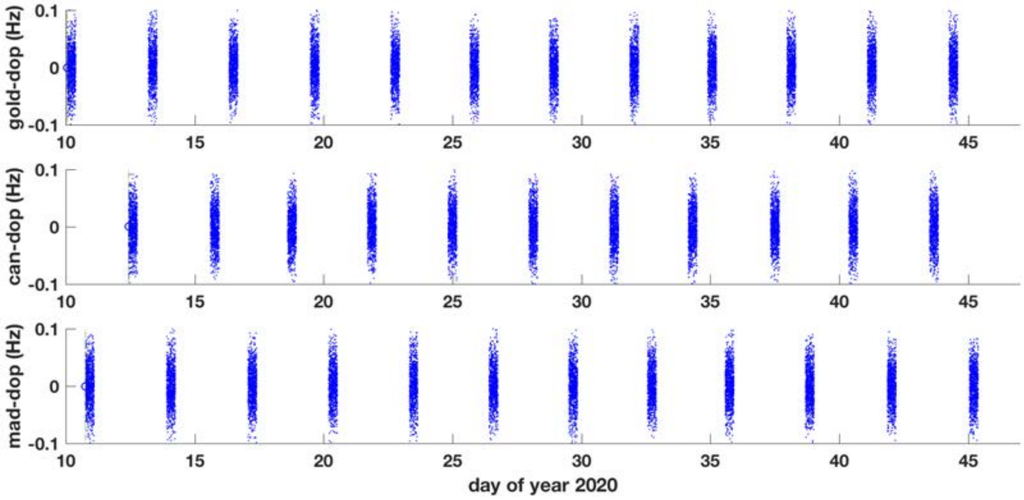
https://www.spectratime.com/uploads/documents/ispace/iSpace_RAFS_Spec.pdf

Measurement availability

- Simulation shows average of about three (3) GPS signals tracked in NRHO
- Far fewer Ground Station (GS) tracking measurements available and much larger tracking gaps than with GPS tracking



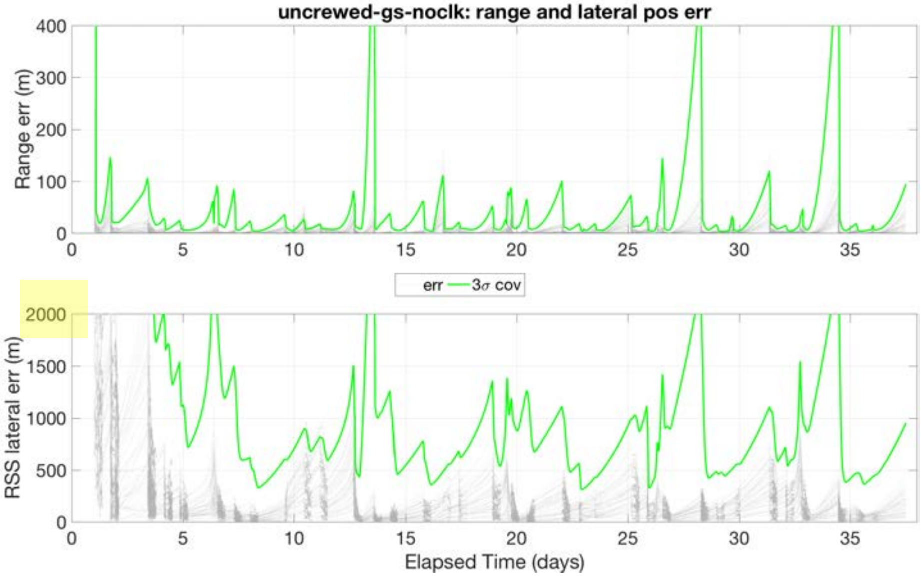
GPS signals tracked for one orbit period for one case from the simulation



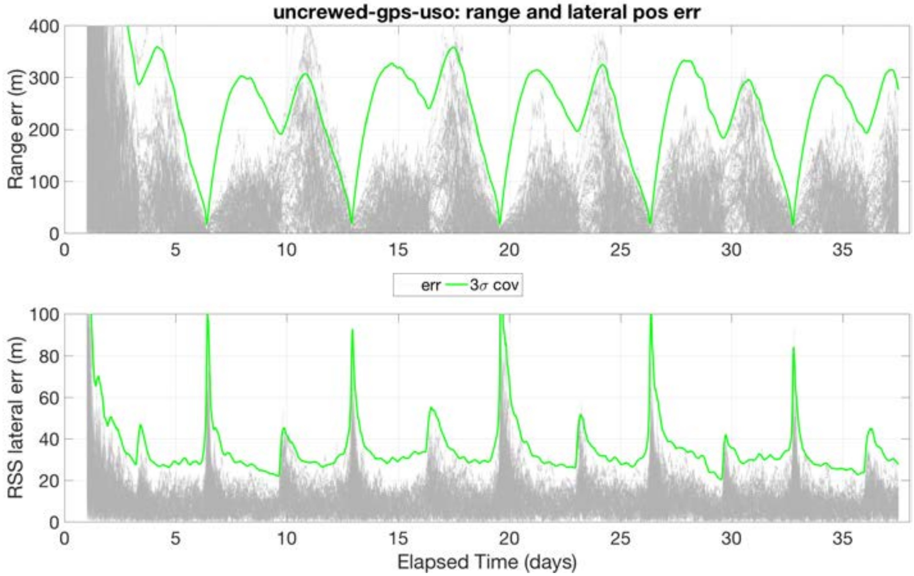
Doppler residuals for one case of the ground station tracking simulation

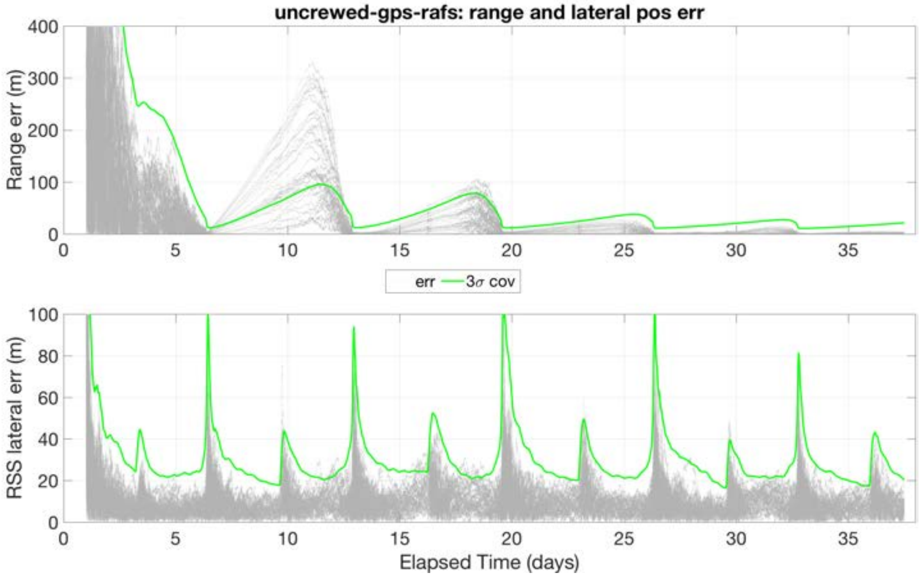
Uncrewed trajectory position errors

- **GPS gives better lateral performance**
- **GPS+USO has larger range error than GS baseline**
- **GPS+RAFS gives best range performance**
- ***Note: For GPS cases clock errors are essentially the same as range* errors**



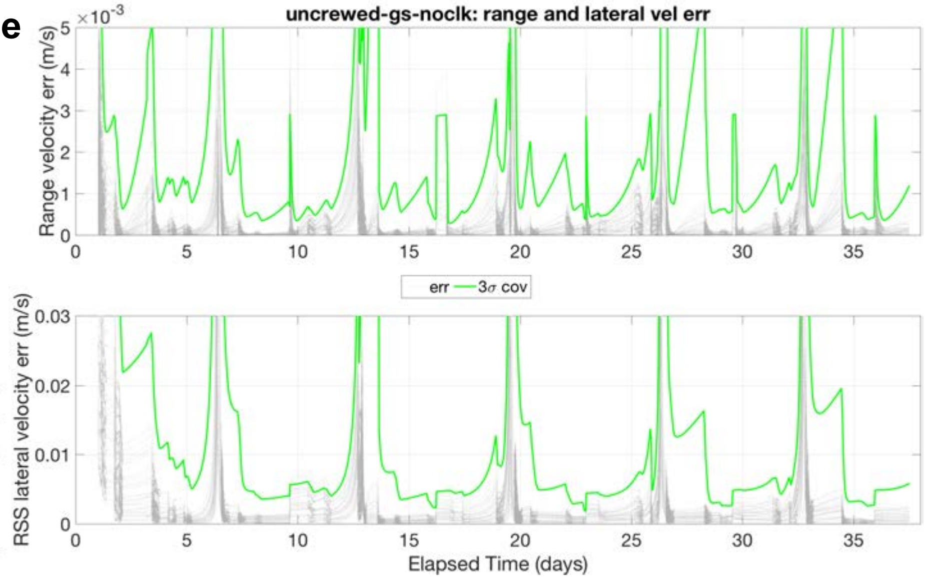
Uncrewed scenario - mean of 3-rms value over last orbit				
	Pos Range	Pos RSS Lateral	Vel Range	Vel RSS Lateral
Ground Tracking	32.9 m	467.4 m	1.0 mm/s	10.6 mm/s
GPS with USO	202.9 m	31.3 m	1.9 mm/s	1.4 mm/s
GPS with RAFS	8.5 m	30.5 m	0.2 mm/s	1.2 mm/s





Uncrewed trajectory velocity errors

- GPS gives better lateral velocity performance
- GPS+USO range velocity errors somewhat larger than GS baseline
- GPS+RAFS gives best range velocity performance



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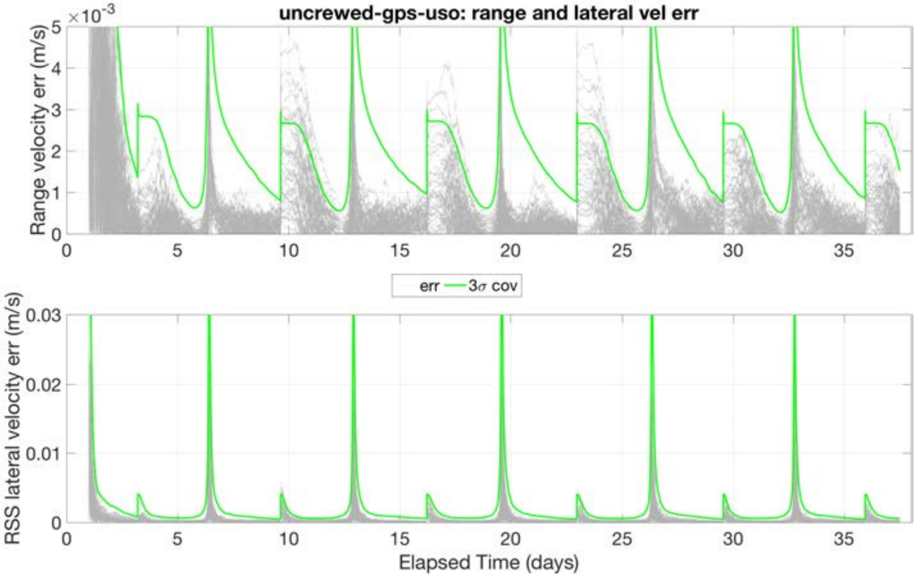
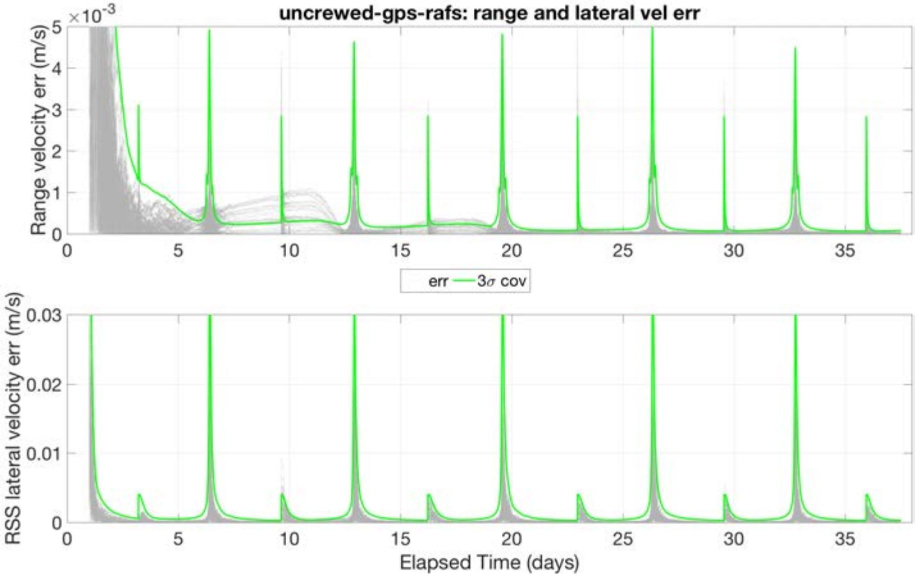
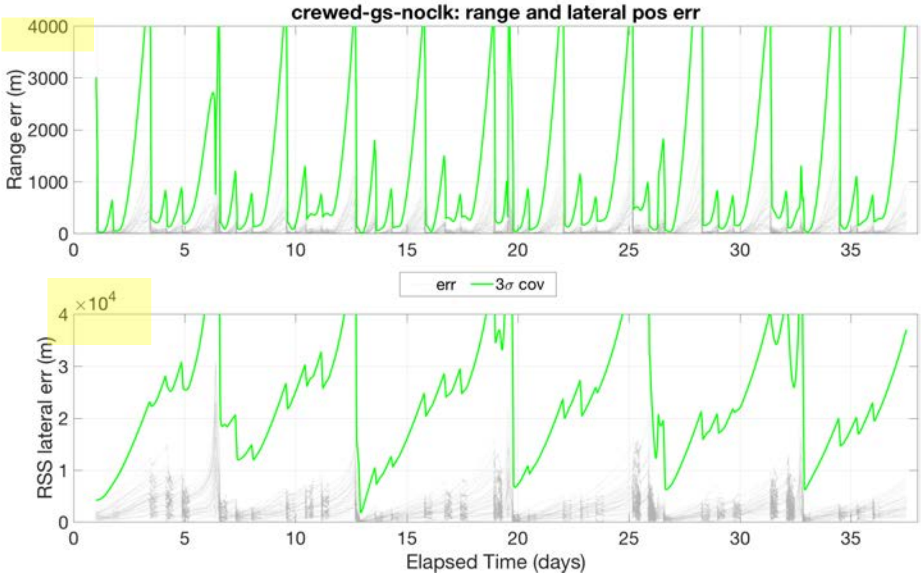




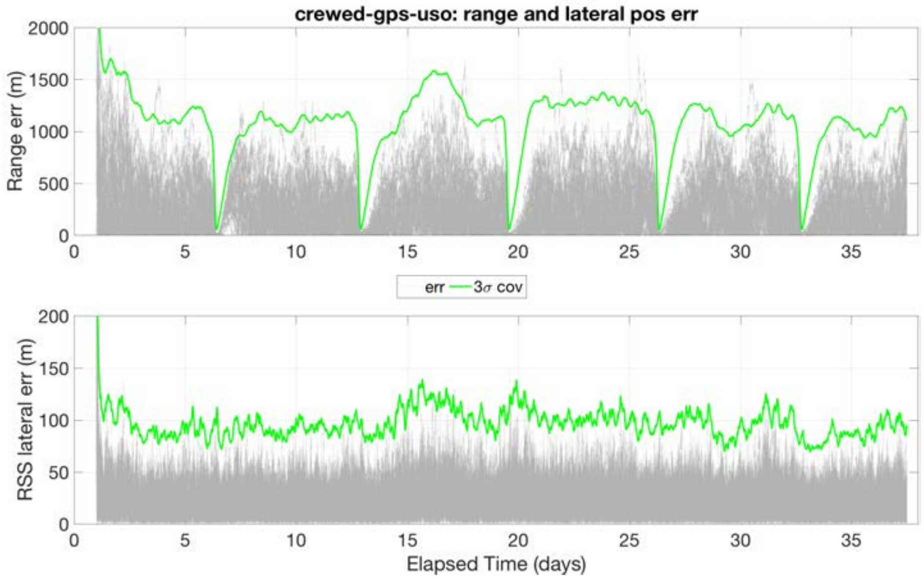
Crewed trajectory position errors

- GPS benefit greater for crewed case
- GPS+USO has larger range error than Ground Station (GS) baseline
- GPS+RAFS gives best range performance

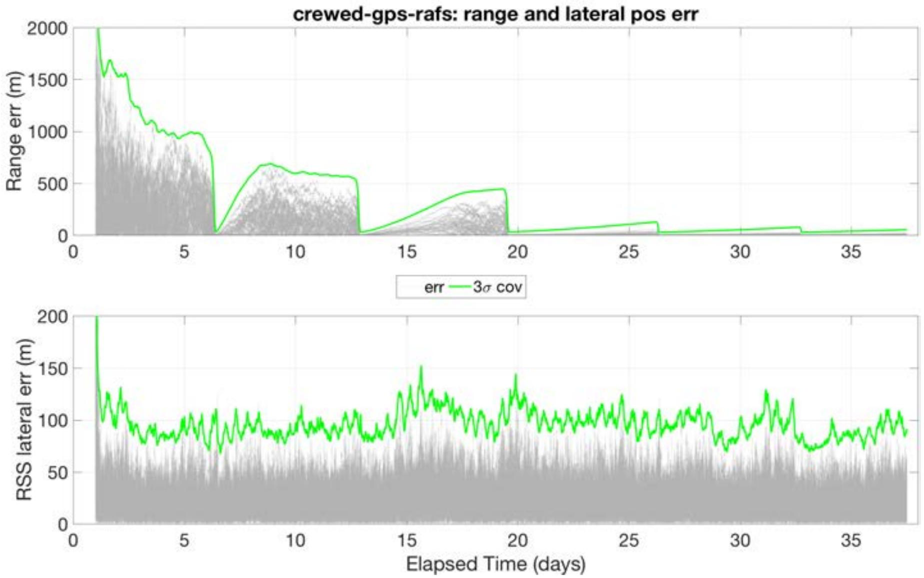


crewed-gs-noclk: range and lateral pos err

Crewed scenario - mean of 3-rms value over last orbit				
	Pos Range	Pos RSS Lateral	Vel Range	Vel RSS Lateral
Ground Tracking	450.5 m	8143.8 m	18.3 mm/s	155.3 mm/s
GPS with USO	909.7 m	79.0 m	18.9 mm/s	12.3 mm/s
GPS with RAFS	21.4 m	76.9 m	3.5 mm/s	11.9 mm/s



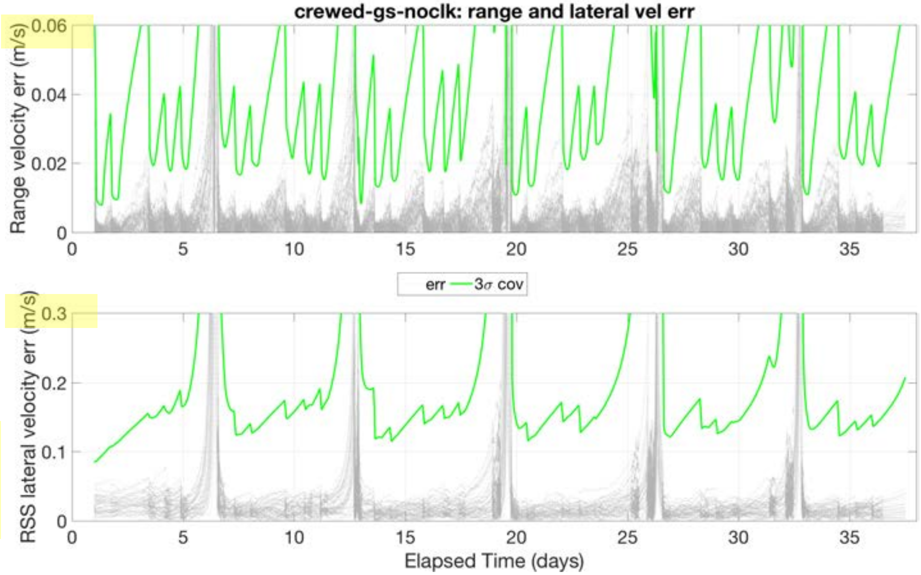
crewed-gps-uso: range and lateral pos err



crewed-gps-rafs: range and lateral pos err

Crewed trajectory velocity errors

- GPS gives better lateral velocity performance
- GPS+USO range velocity errors similar to GS baseline but more uniform
- GPS+RAFS gives best range velocity performance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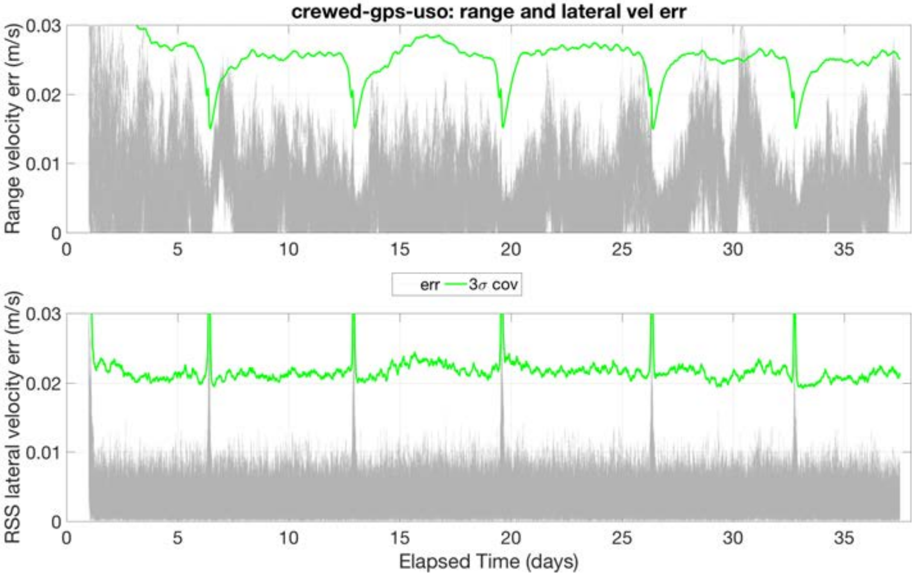
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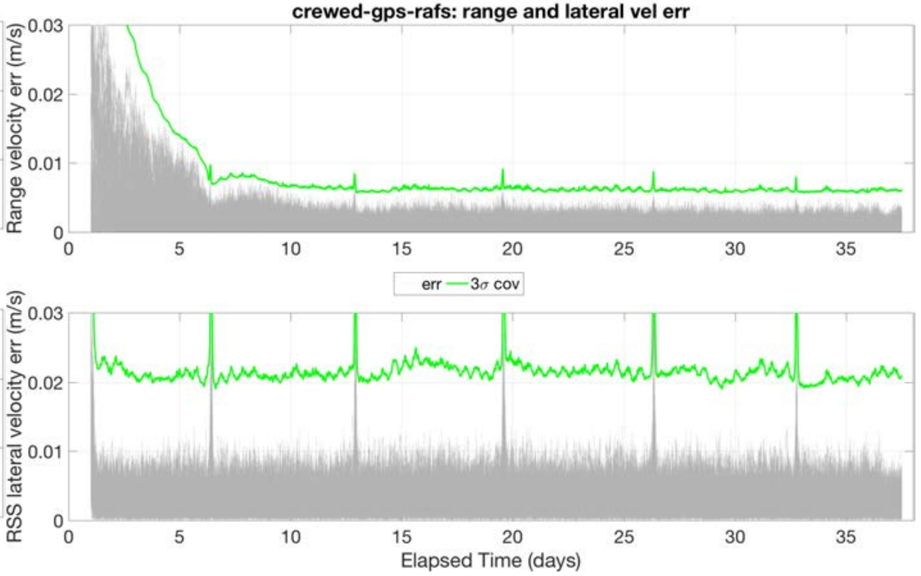
crewed-gps-rafs: range and lateral vel err

Conclusion

- **Developed simulations modeling performance of concept GPS system based on flight–proven MMS GPS navigation system with high-gain antenna and optional enhanced clock in Gateway NRHO with relevant disturbance models**
- **Carefully calibrated the simulation against on-orbit results from MMS Phase 2B and compared Ground tracking baseline to prior NRHO simulations**
- **Results indicate GPS can provide a simple, high-performance, on-board navigation solution for Gateway (and likely for other Lunar regime missions)**
- **Range/clock estimation is strongly enhanced by inclusion of atomic clock**
- **As compared to a conceptual ground-tracking baseline, the GPS solution offers:**
    - Improved performance in most cases, sometimes greatly improved
    - Real-time, on-board availability
    - A local clock solution
    - Reduced ground-tracking and operations costs/complexity
- **GPS/GNSS could be used standalone or as a complement to ground tracking or other sensors/measurements**

References

1. **[Volle and Davis]** M. Volle and D. Davis, *Examining the Feasibility of Relative-Only Navigation for Crewed Missions to Near Rectilinear Halo Orbits*. Proc. of the AAS/AIAA Astrodynamics Specialist Conference, 2018.
2. **[Donaldson et al.]** J. Donaldson, J. Parker, M. Moreau, D. Highsmith, and P. Martzen, *Characterization of On-Orbit GPS Transmit Antenna Patterns for Space Users*, Proc. of ION GNSS+, 2018.
3. **[Winternitz et al.]** L. Winternitz, W. Bamford, and S. Price, *New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances.* Proc. of ION GNSS+, 2017.
4. **Spectratime RAFS datasheet:** *https://www.spectratime.com/uploads/documents/ispace/iSpace_RAFS_Spec.pdf*