National Aeronautics and
Space Administration

LuGRE
LUNAR GNSS RECEIVER EXPERIMENT

Navigation Performance Trades and Analysis for the Lunar GNSS Receiver Experiment (LuGRE)

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Astrodynamics Specialist Conference

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Motivation

Artemis: we are going back to the moon!

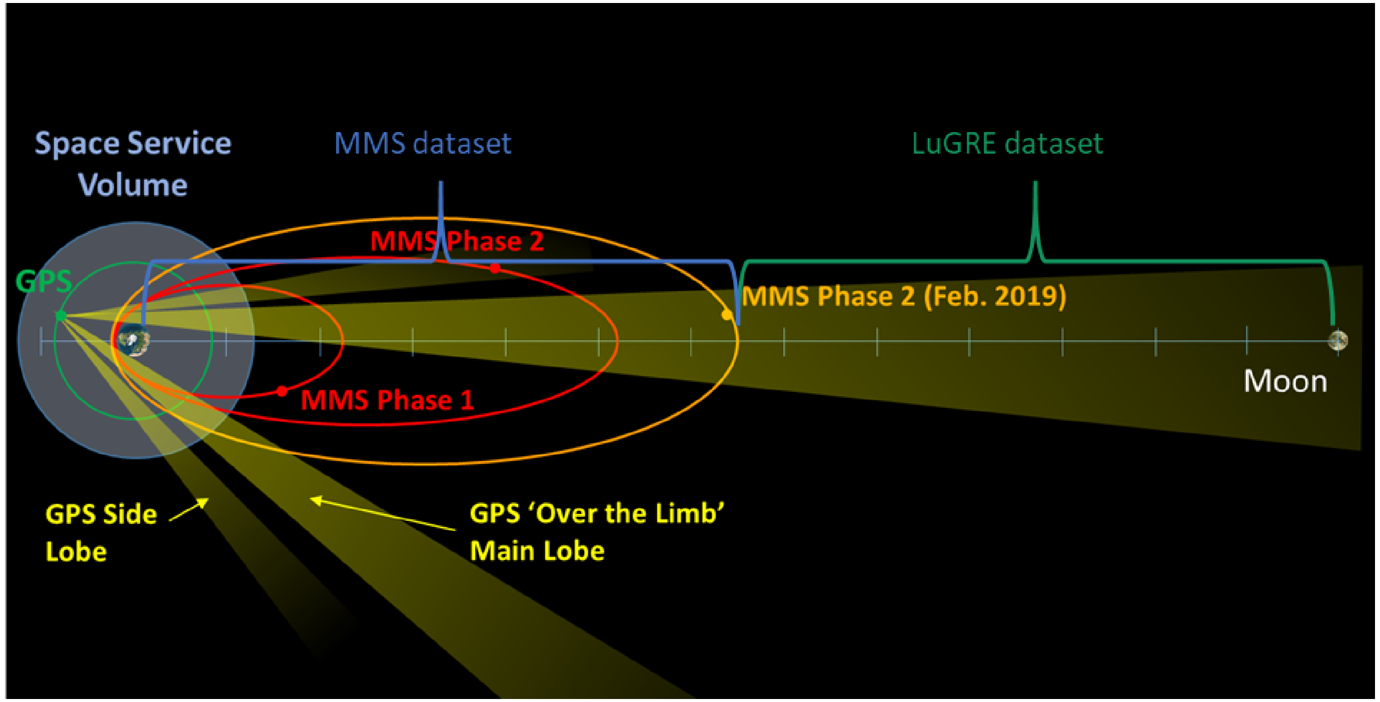
- It's been 50+ years, let's do it smarter now
- Navigation: key/enabling technology for a sustained lunar presence
  - History: massive ground station network made for Apollo
    - Today: ground stations are oversubscribed
  - Go back smarter: navigate autonomously, cheaply

Why is GNSS an answer?

- Architecture exists, could be used today
- Autonomous/onboard
- Well understood, widely used

Does GNSS work at the moon?

- Magnetospheric Multiscale (MMS), NASA helio mission
  - Received + used GPS signals ~50% of the way to the moon; necessary for navigation performance
  - Simulations: could be extended to lunar distances
- Need flight demonstrations to provide evidence
  - ***That's where LuGRE comes in!***



LuGRE Mission

LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI

Mission:

- NASA HEOMD payload for CLPS 19D flight
- Joint NASA/Italian Space Agency mission
- “Do No Harm” class
- Firefly Blue Ghost commercial lander

Payload Objectives:

1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

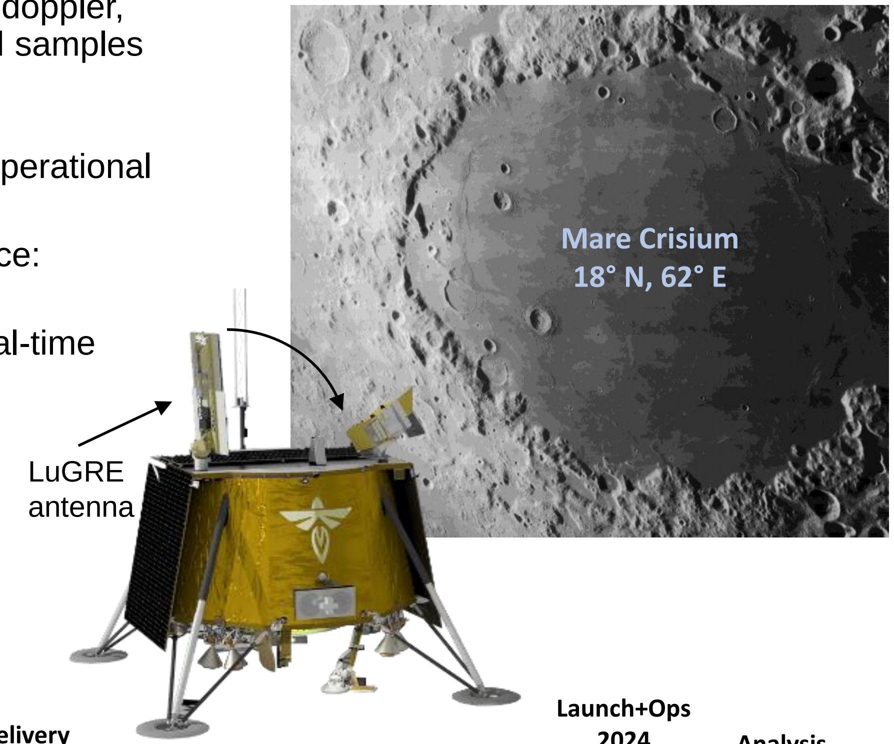
Measurements:

- GPS + Galileo, L1/E1 & L5/E5a bands
- Onboard products: multi-GNSS point solutions, onboard filter solutions, signal strength
- Observables: pseudorange, doppler, carrier phase, raw baseband samples

Utilization:

- Data + lessons learned for operational lunar receiver development
- Potential collaborative science: heliophysics, lunar geodesy
- Lunar human and robotic real-time onboard PNT

NASA
CLPS
Commercial Lunar Payload Services



CLPS Draft RFP Jul 2020

CLPS Final RFP Oct 2020

CLPS Lander Award Feb 2021

LuGRE Checkpoint A Mar 2021

LuGRE Checkpoint B (SRR) Apr 2021

LuGRE Checkpoint C (CDR) Sep 2021

ETU Delivery Perf Test Start Oct 2021

EQM Delivery Mar 2022

We are here

FM Delivery Sep 2022

Payload Delivery Nov 1, 2022

Launch+Ops 2024

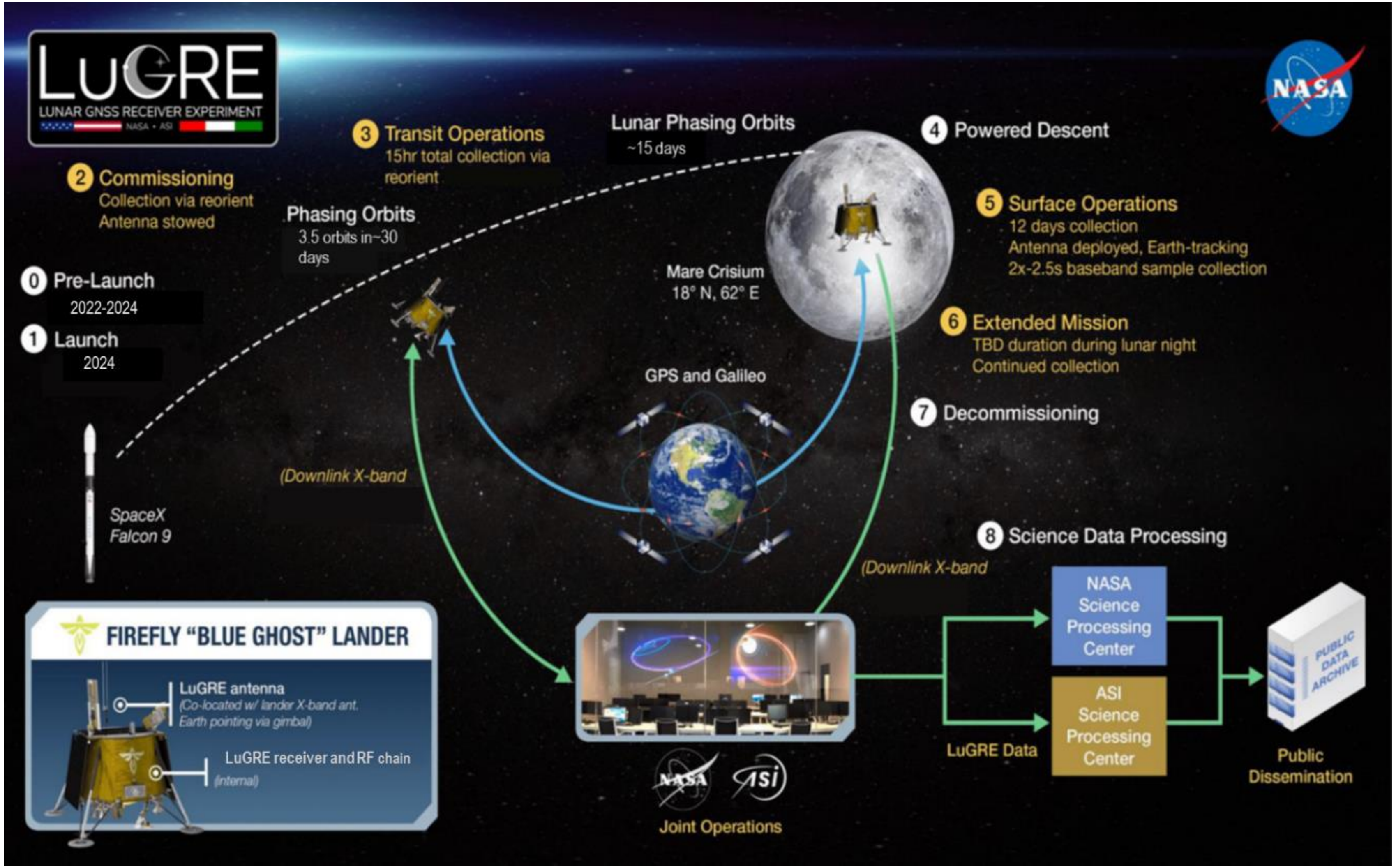
Analysis 2024-2025

Mission Overview

Launch:
- 2024, SpaceX Falcon 9

Transit
- 3.5 elliptical phasing orbits (~30 days)
- 15 days in lunar phasing orbits

Surface Ops
- 12 Earth days (1 lunar day)
  - Nearly-continuous operation
- Option to extend past nominal mission, after lunar night



Key Analysis Challenge:

- RX antenna is stowed in transit, but ***we must point to the Earth to get signals***
- Reorienting the lander requires propellant, which is limited

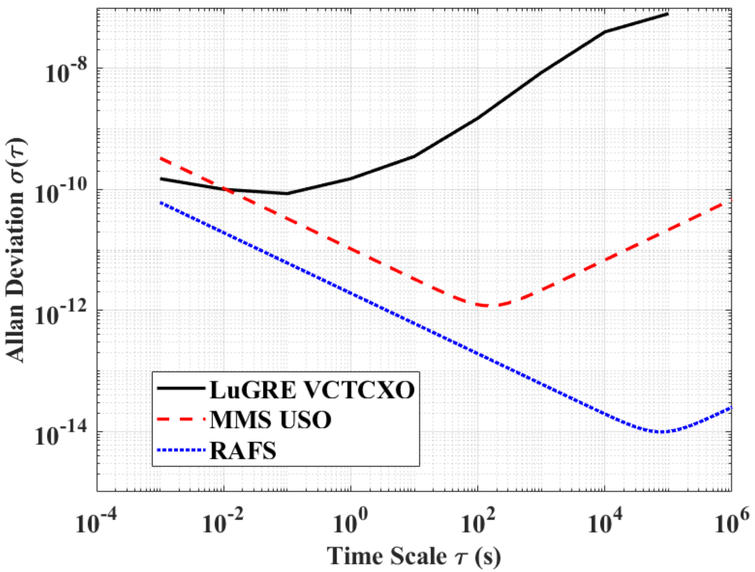
LuGRE is limited to 15 hours of operation time during transit
How do we best use this time?

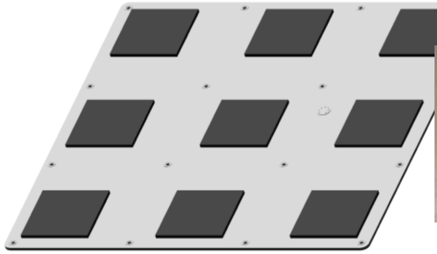
Payload Overview

How do these design decisions impact performance?
(ex. antenna gain, clock type)

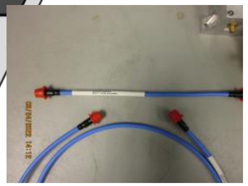
- Mass < 5 kg, Power <= 14 W
- Building off sub-orbital and LEO flight heritage:
  - Special receiver manufactured by Qascom
    - Weak signal acquisition/tracking algorithms
  - High gain antenna (16 dB peak gain; MMS was ~7 dB)
  - Low Noise Amplifier
    - 40 dB gain, <1 dB loss
- Timekeeping Onboard: Voltage Controlled Temperature Controlled Crystal Oscillator (VCTCXO)
  - GNSS measurement accuracy depends directly on clock stability
  - Past lunar navigation studies use much higher stability clocks (and get great results!)
    - MMS → Ultra Stable Oscillator (USO)
    - GPS, Galileo satellites → Rubidium Atomic Frequency Standard (RAFS)

Clock Stability Comparison

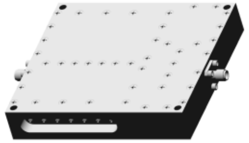




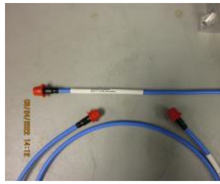
High Gain Antenna (HGA)



Coax

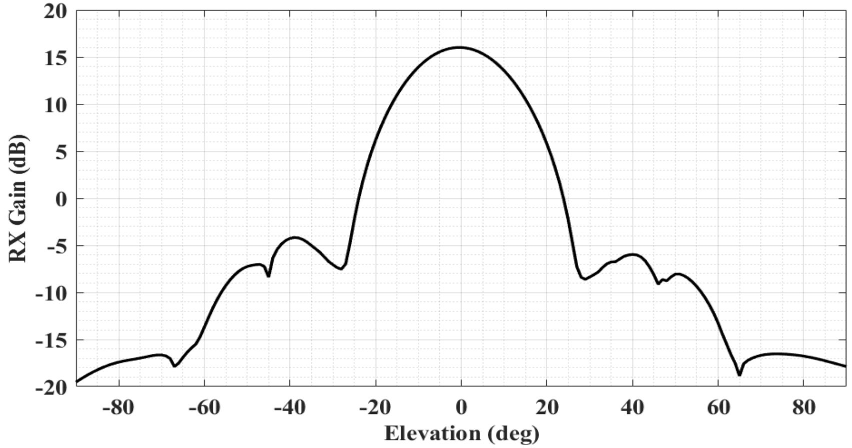


Low Noise Amplifier (LNA)



Coax

GNSS Receiver



High Gain Antenna Pattern
(Manufactured by Haigh-Farr)

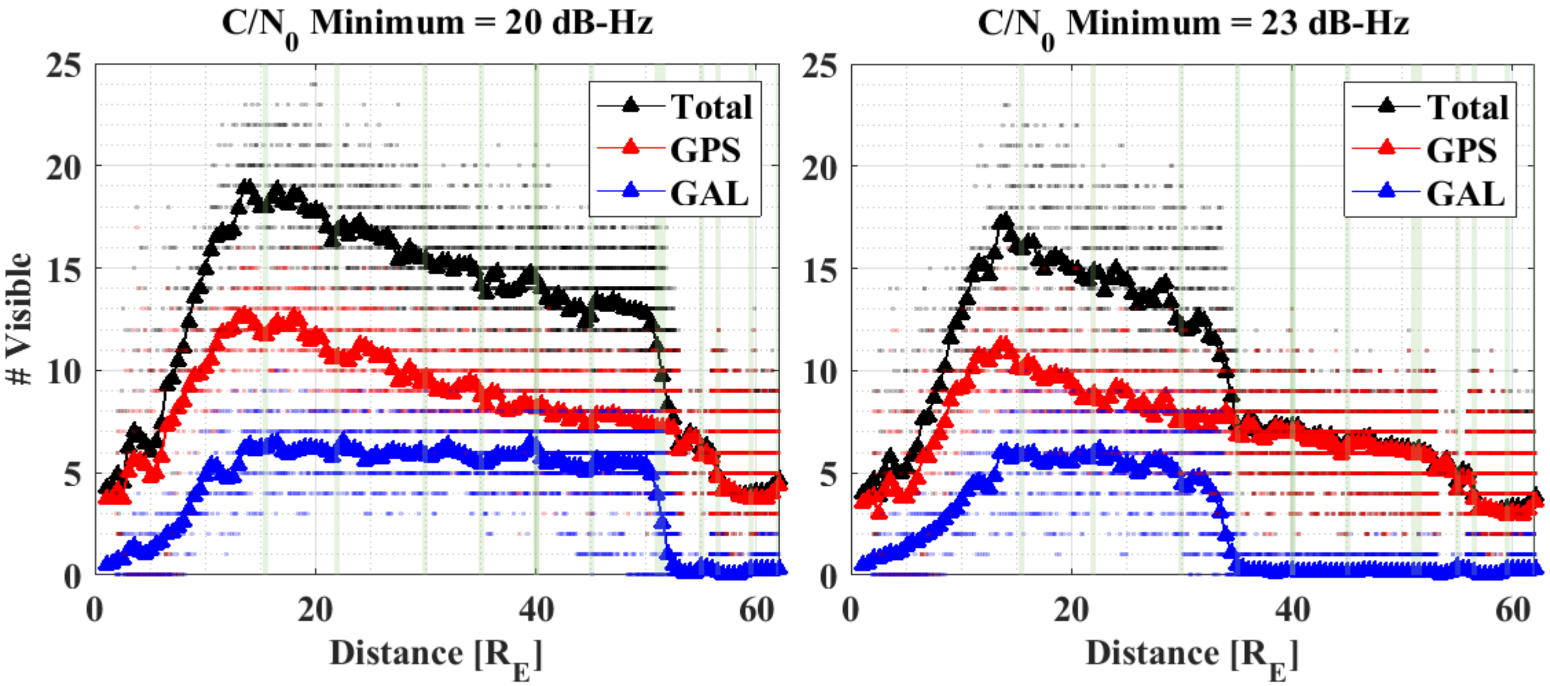
Simulation Setup

GEONS-Based Navigation Simulations:

- Goddard Enhanced Onboard Navigation System
  - UD-factorized extended Kalman filter
  - Flight software heritage: MMS Navigator system
  - Ground Simulation: MATLAB API to C library
- Multi-GNSS measurements (GPS, Galileo)
  - Applied measurement noise based on C/N0
  - Pseudorange (PR), Doppler
    - *Note: MMS didn't use Doppler*
- USO, VCTCXO bias from Allan Deviation data
- RF Link budget:
  - Target threshold C/N0 for acquisition = 20 dB-Hz
    - + 3dB for link margin → 23 dB-Hz
    - Flight data: will be somewhere in-between
  - Receiver: from lab characterization
  - GPS: best available calibration from flight data
  - Galileo: unknown, conservative assumption

Scenarios:

- Compare clocks, observables, C/N0 threshold
- 3 hour duration, 1 second time step measurements
- Truth states from Firefly planned trajectory
  - Filter dynamics: 100x100 Earth & Moon gravity



Analysis: 30 RE Altitude

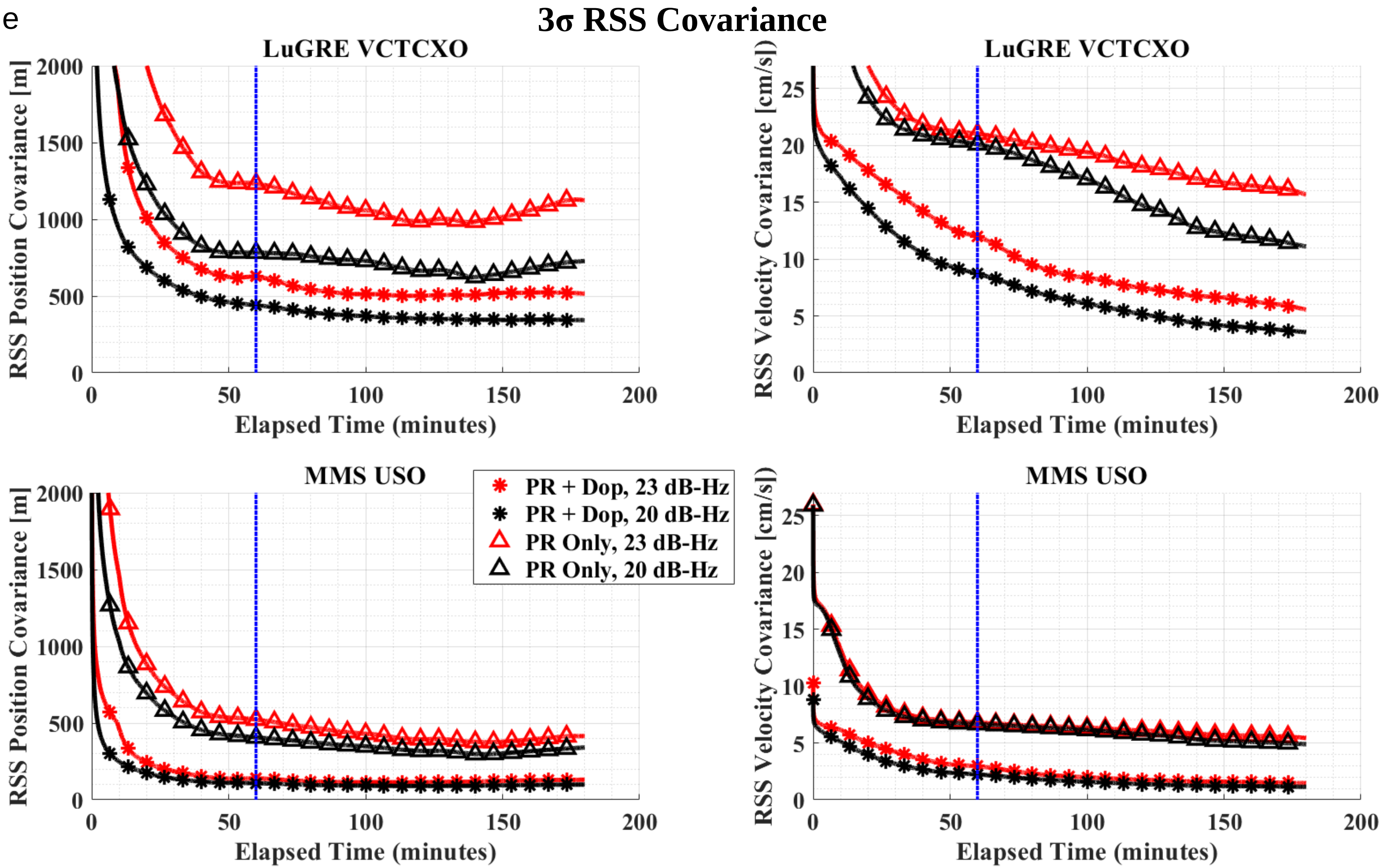
Initial 1σ: [5 km, 50 cm/s state; 10 km, 300 m/s clock bias and rate]

- Highest altitude from MMS; LuGRE collects new data
    - Average of 10-12 GNSS satellites visible

- Don't expect to converge in the traditional EKF sense
    - Do get convergence-like behavior
- PR only, with USO = results similar to MMS Flight Data

<u>Primary Design Takeaways:</u>

- Addition of Doppler as an observable helps significantly
    - Particularly true for higher stability clock
        - Due to lower Doppler noise
- Even with 3 dB margin, selecting operations period of 60 minutes is a good baseline (blue line)
    - Can get a good sense of the behavior in this time



Analysis: 62 RE Altitude

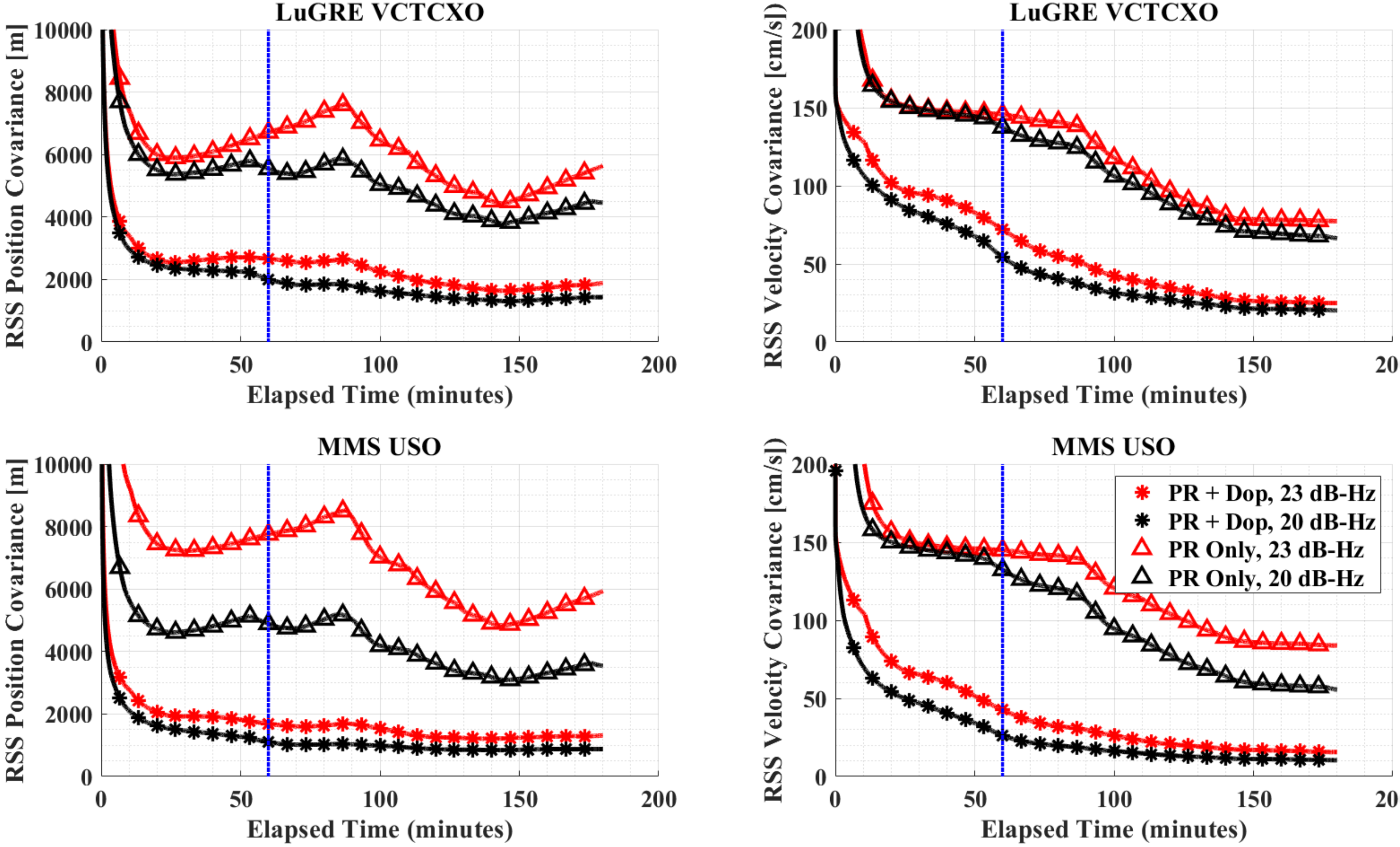
Initial 1σ: [5 km, 50 cm/s state; 10 km, 300 m/s clock bias and rate]

- 62 RE = highest altitude at which LuGRE will collect data (apogee of phasing orbit)
  - Average of 4-5 GNSS satellites visible
- Challenging observability
  - Dynamics change slowly relative to short observation period
  - Very little lateral motion relative to Earth

Primary Design Takeaways:

- Addition of Doppler as an observable matters *even more!*
  - Even more than clock stability
- Larger impact of C/N0 threshold at high altitudes
  - # of satellites visible is more variable

3σ RSS Covariance



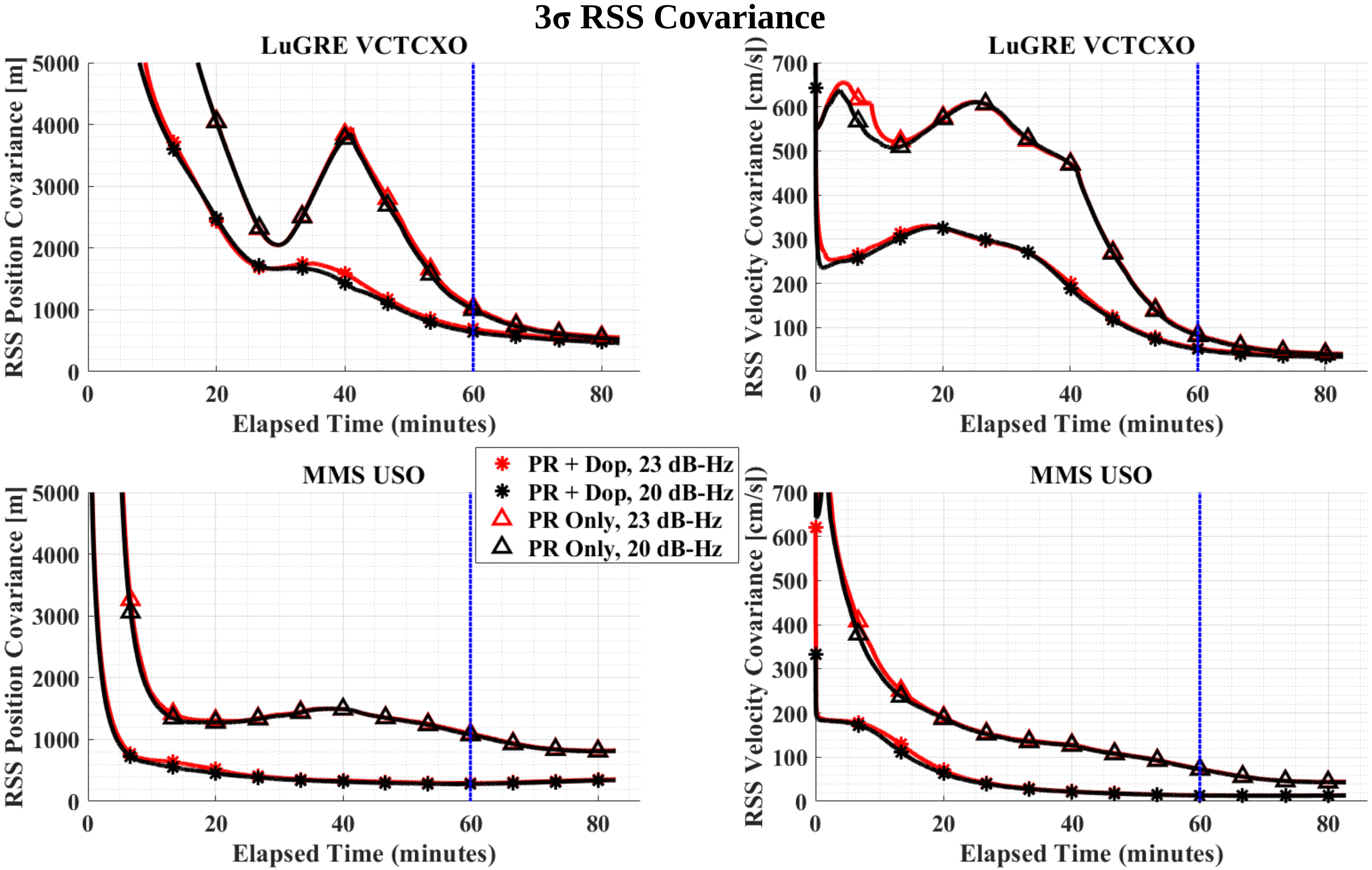
Analysis: Low Lunar Orbit

Initial 1σ: [5 km, 50 cm/s state; 10 km, 300 m/s clock bias and rate]

- 100 km altitude Low Lunar Orbit, period ~2 hours
  - Average of 5-6 GNSS satellites visible
  - ~Polar orbit, Earth is obscured for 30 minutes of orbit

Primary Design Takeaways:

- Clock stability matters much more
- Doppler continues to make performance much more robust
  - Interesting behavior without doppler as spacecraft moves towards/away from Earth in lunar orbit
- 60 minutes is a great choice for operation duration
  - Can see a much larger fraction of orbit period, closer to true EKF convergence



Analysis: Surface Measurement Frequency

Measurement Frequency Trade:

Higher data rate = better performance, more data to downlink

- Downlink volume is a finite shared commodity on the surface
- Options: receiver can process @ 1 Hz or 1/30 Hz (1 second, 30 second time steps)

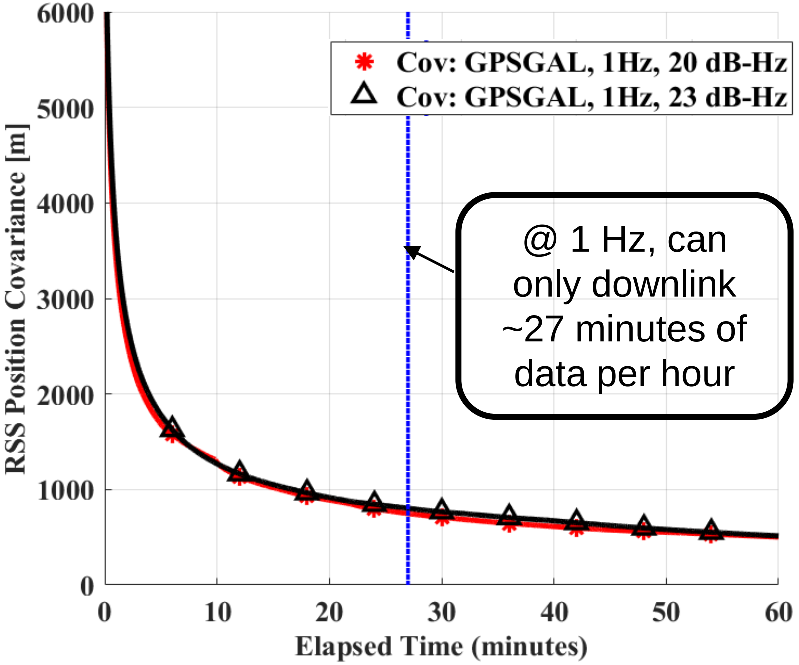
Simulations support:

1/30 Hz rate (30 second step) can be used on surface

- Reasonable long term performance can still be achieved
- Able to continuously measure *and* downlink all collected data

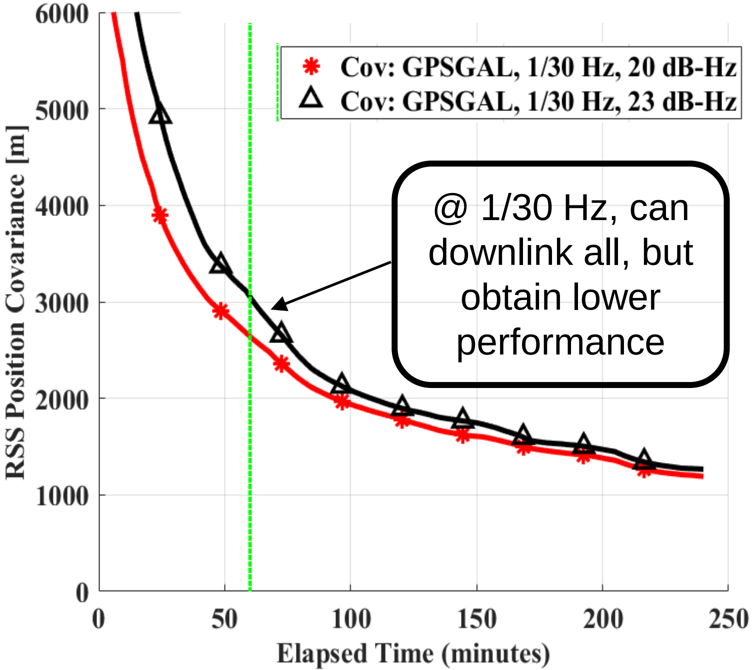
Initial 1σ: [2.5 km, 50 cm/s state; 10 km, 300 m/s clock bias and rate]

Short Term
1s Measurement Rate



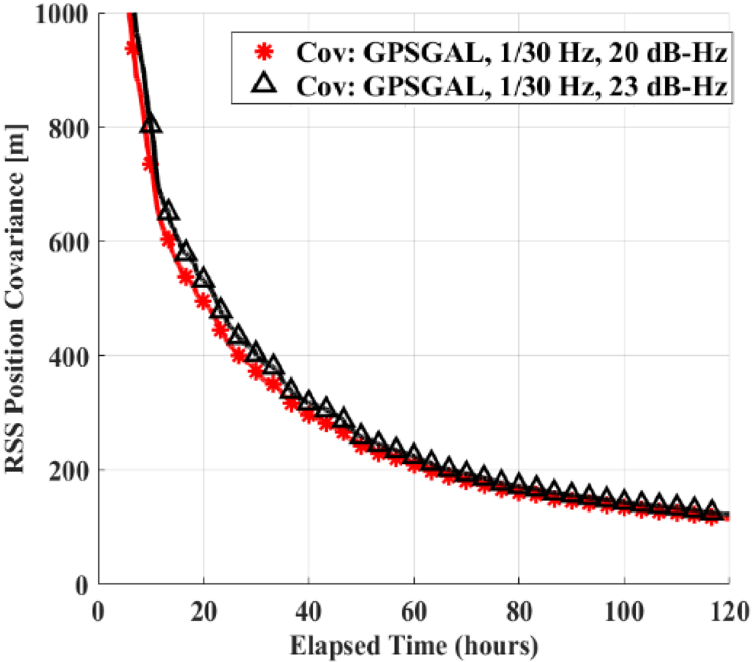
@ 1 Hz, can only downlink ~27 minutes of data per hour

Short Term
30s Measurement Rate



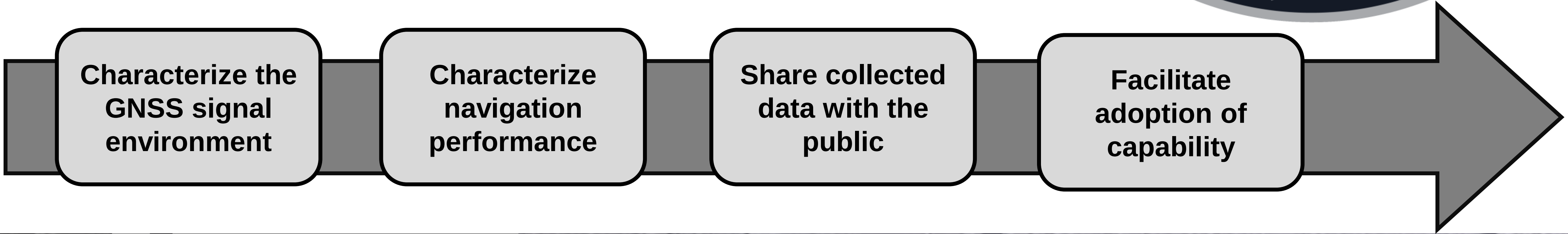
@ 1/30 Hz, can downlink all, but obtain lower performance

Long Term
30 s Measurement Rate



Conclusions

- Existing GNSS architecture: key navigation enabler in support of NASA's lunar activities
- LuGRE will demonstrate the technology and pave the way for future development
  - Prove what sort of visibility can be expected
  - Demonstrate what sort of navigation performance you can get from that visibility
- Intentional design choices can maximize performance and make GNSS a feasible choice for future lunar visitors



Characterize the GNSS signal environment

Characterize navigation performance

Share collected data with the public

Facilitate adoption of capability

Thanks for listening!

Email: lauren.schlenker@nasa.gov

Many thanks to the rest of the LuGRE team:

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Qascom: Samuele Fantinato, Efer Miotti, Oscar Pozzobon

and many others!