JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Inter-satellite-link-aided Collaborative Navigation and Time Transfer of a Lunar PNT Constellation

Joint ICG-IOAG Multilateral Cislunar PNT Workshop 2026, Vienna, Austria

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Outline

- Background: Lunar PNT and the LunaNet
- A representative lunar PNT constellation
- Cislunar Collaborative Position, Navigation, and Timing (cPNT) with Inter-satellite Links (ISL)
- cPNT as a De-centralized Sensor fusion paradigm
- Navigation and Time Transfer Results
- Conclusions and future work

Lunar PNT Service Provider

Lunar Surface Assets

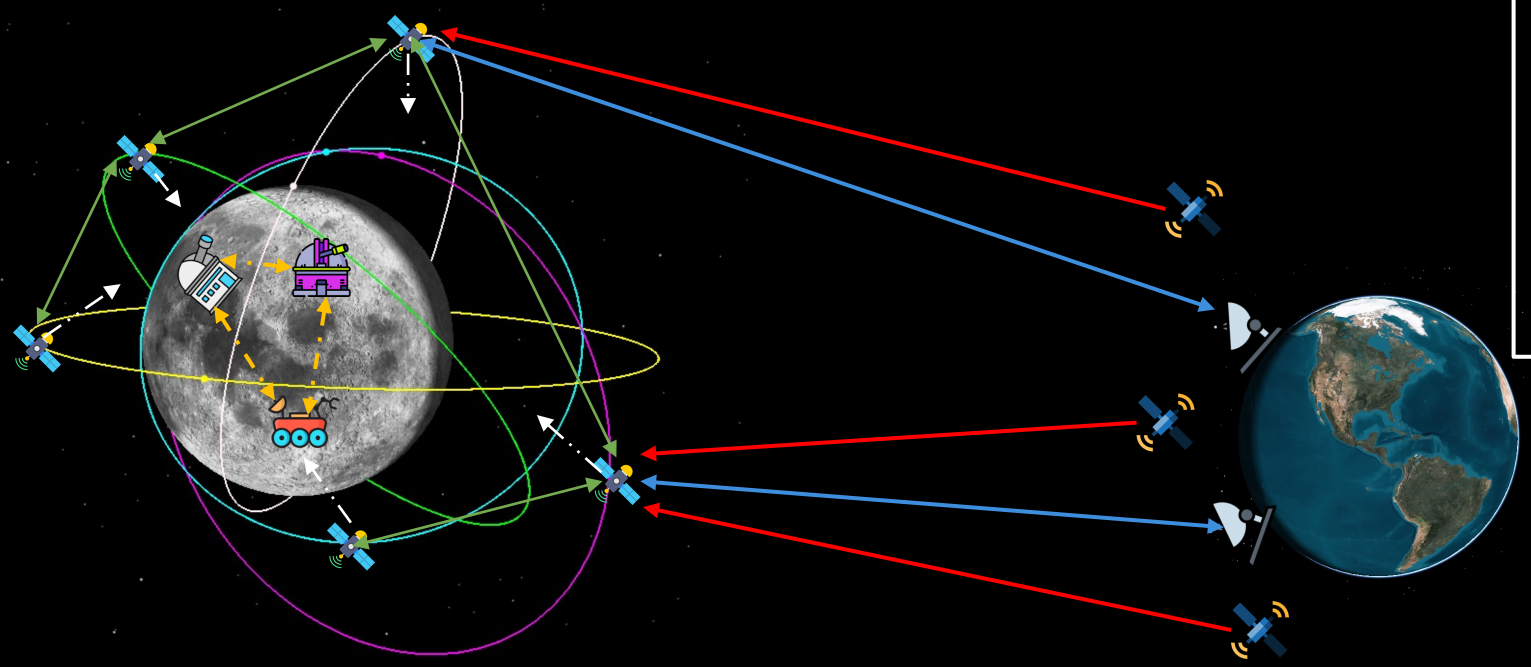
GPS SV

One-way PNT Signal

Inter-satellite Link (ISL): RF/Optical: Range/Data

Inter-asset Link (RF/Optical): TT&C, Data

Trunk Link (RF/Optical, GPS): Data, TT&C, Range, Time Transfer

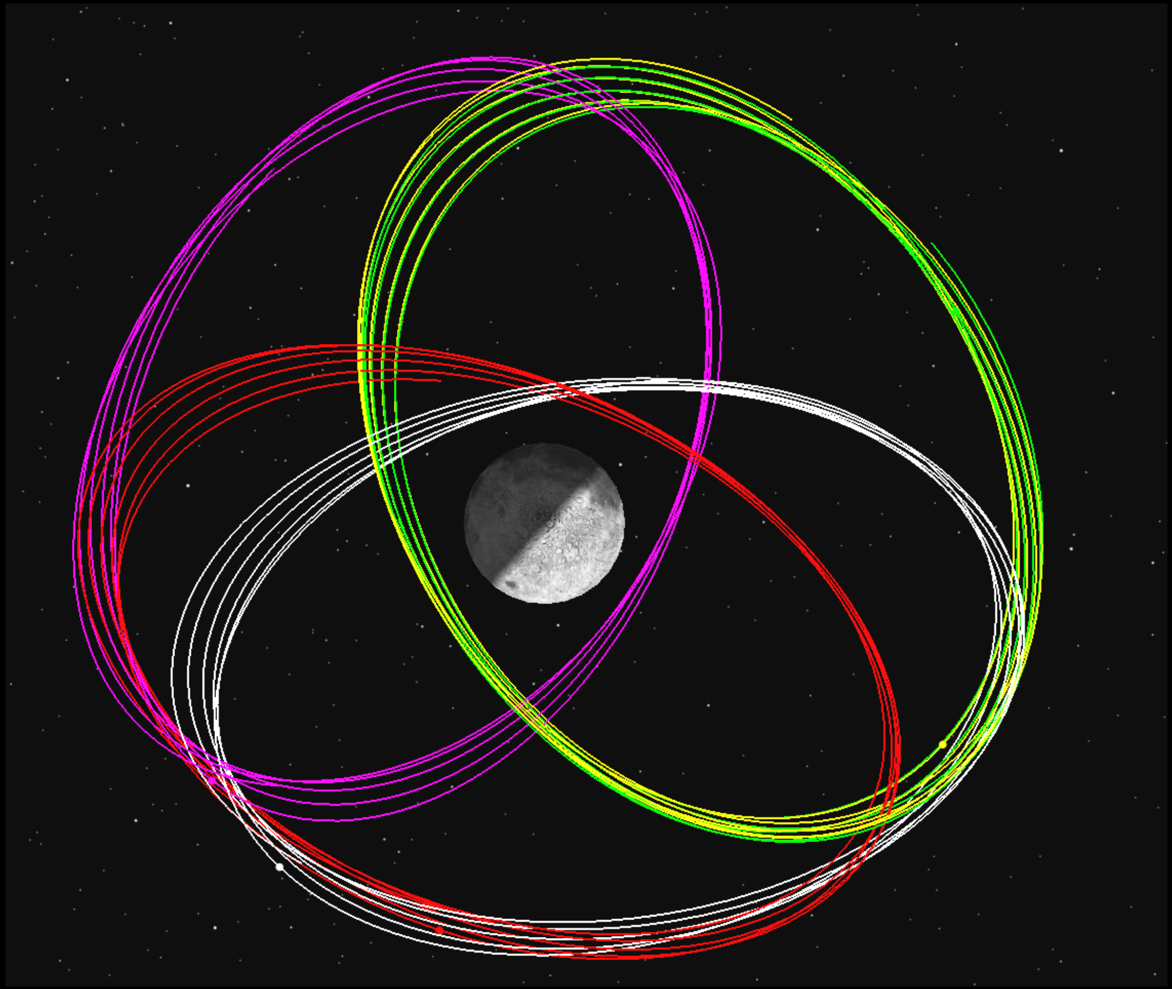


What is LunaNet?*

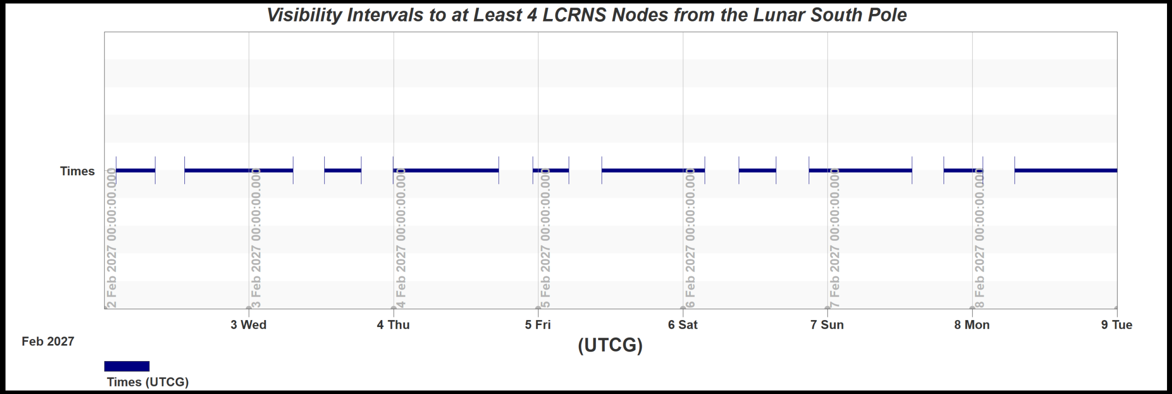
- *"A set of cooperating networks providing interoperable communications and position, navigation, and timing (PNT) services for users in transit to, around, and on the Moon"*
- *"… consists of a set of Earth Ground Stations, Lunar orbital relays, and surface assets"*
- *"A lunar analog to terrestrial GPS/GNSS with Associated benefits from broadcast signals and messages"*
- *LunaNet Service Providers (LNSPs): NASA's LCRNS (**L**unar **C**omm. **R**elay & **N**avigation **S**ystem), ESA's Moonlight/LCNS (**L**unar **C**omm. & **N**avigation **S**ystem), and JAXA's LNSS (**L**unar **N**avigation **S**atellite **S**ystem)*

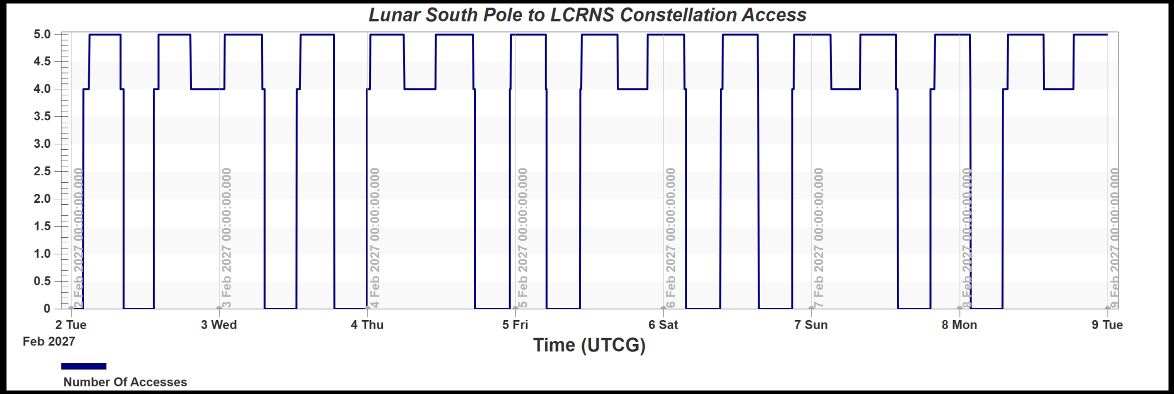
LNSP Constellation Navigation in Elliptic Lunar Frozen Orbits

- PNT satellites in ELFOs
  - Notional for Intuitive Machine's future five-satellite Lunar Data Network constellation (LDN)
  - Frozen orbits for nearly constant mean Eccentricity, Inclination, AoP
  - Apolune ~ 18, 500 km., Perilune~ 2100 km., Period ~ 32.80 h, Eccentricity ~ 0.678, Inclination, RAAN and AoP selected appropriately
  - Lower perilune to favor science, higher apolune favors longer access over Lunar SP
- Constellation navigation options
  - Ground stations (2-way X-band range and Doppler)
  - Weak-signal GPS (main + side lobes, autonomous)
  - Ground stations + GPS + OpNav
  - Add crosslinks



ELFO Constellation Access from Lunar SP

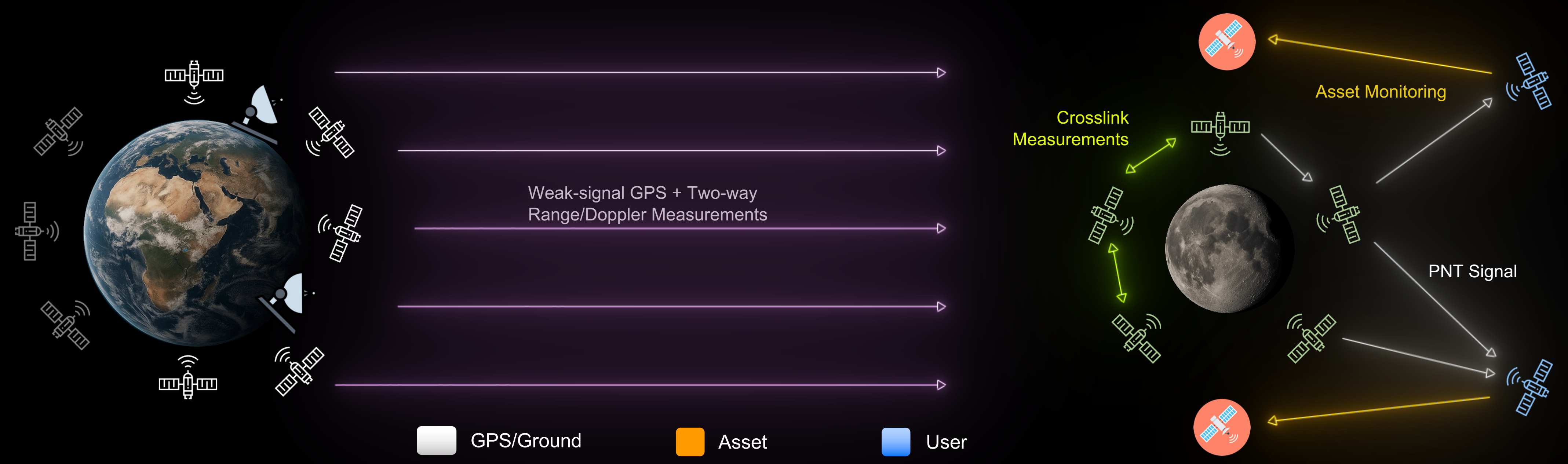




At least 4 SVs are visible from the Lunar SP ~ 70% of the interval, enabling instantaneous PVT estimation

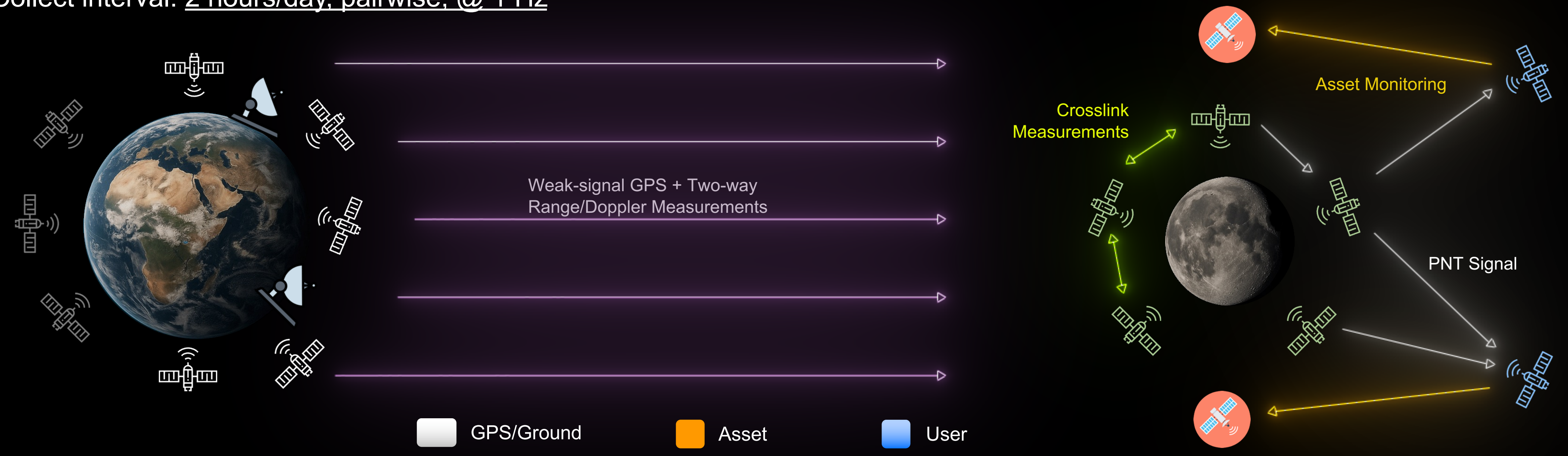
Weak-Signal GPS + Ground + ISL/Crosslinks

- Each LCRNS node is equipped with a weak-signal GPS receiver providing Pseudorange/Carrier Phase at L1 C/A
- Simultaneous, 2-way, X-band Range and Doppler coverage from a pair of ground stations on opposite hemispheres
  - 2 hours around ELFO apolune + 1 hour around perilune per Earth day
- RF Inter-satellite two-way links improve the accuracy of the broadcast ephemeris and clocks



ISL/Crosslinks + Weak-Signal GPS + Ground

- GPS reception is near-continuous
  - Reception C/No threshold is 20 dbHz, Antenna Gain ~ 15 dB
  - Clock parameters representative of USO, and estimated
  - Facilitates real-time, autonomous OD and time transfer with side lobe signal reception
- ISL
  - Additional measurements improve navigation accuracy, requiring fewer OD uploads by the Ground Segment
  - AutoNav capability: resilient to temporary GPS and/or Earth tracking outage
  - Collect interval: 2 hours/day, pairwise, @ 1 Hz

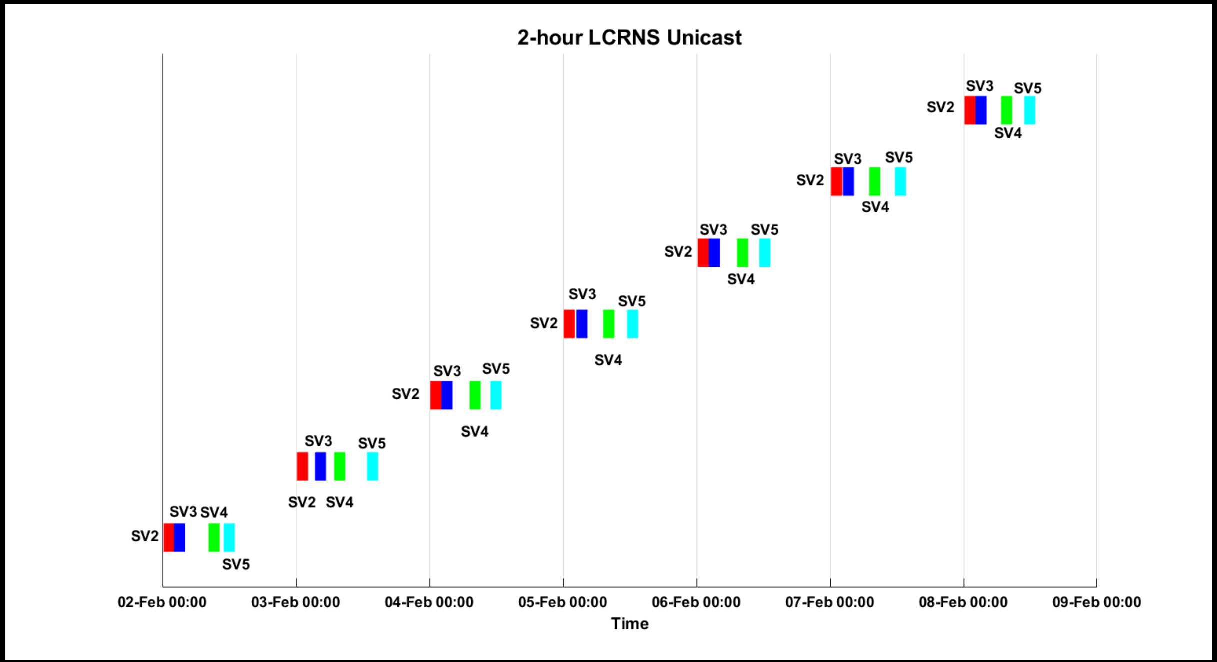


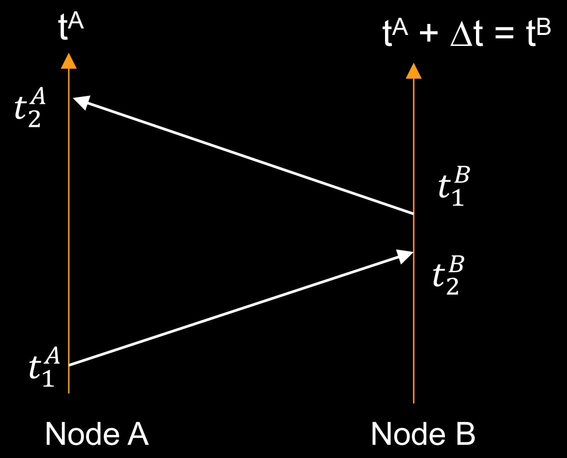
Modeling ISL Measurements

- ITU definition: *A radiocommunication service providing links between orbiting platforms*
  - Allows distribution of data, telemetry and range/doppler measurements between the satellites
- Steerable antennas establish links (Ka-band) between satellites according to ground-planned contact schedule
  - 2-hour daily, pairwise, sequential unicast @ 1Hz
- <u>Synchronous two-way ranging</u>
  - Node A transmits, node B receives, amplifies, re-transmits
  - Clock offset (Δt) is canceled out

$$\rho_{AB} = c.\frac{(t_2^A - t_1^A) + (t_2^B - t_1^B)}{2}$$

Transponder Delay

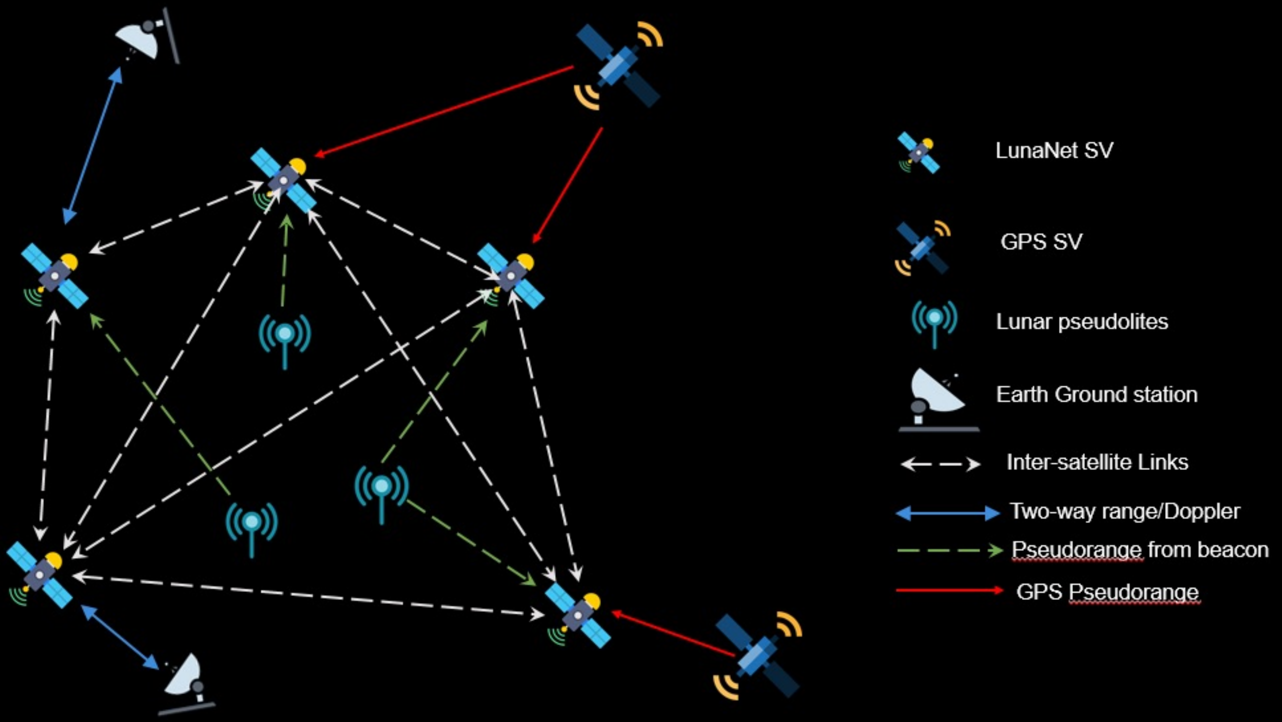




Defining Collaborative PNT

- *Collaborative PNT (cPNT) refers to a paradigm of navigation in which heterogeneous PNT data from multiple sources, such as GPS, ISL, and others from across the network are combined together in a sensor fusion algorithm such as the Kalman Filter to improve the self knowledge of the individual nodes*
- Sharing measurements between nodes naturally results in a correlation of their estimation errors, i.e., *<u>the joint covariance matrix is no longer block diagonal!</u>*

$$P_k = \begin{bmatrix} P_k^{11} & P_k^{12} & P_k^{13} & \cdots & P_k^{1N} \\ P_k^{21} & P_k^{22} & P_k^{23} & \cdots & P_k^{2N} \\ P_k^{31} & P_k^{32} & P_k^{33} & \cdots & P_k^{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_k^{N1} & P_k^{N2} & P_k^{N3} & \cdots & P_k^{NN} \end{bmatrix}$$



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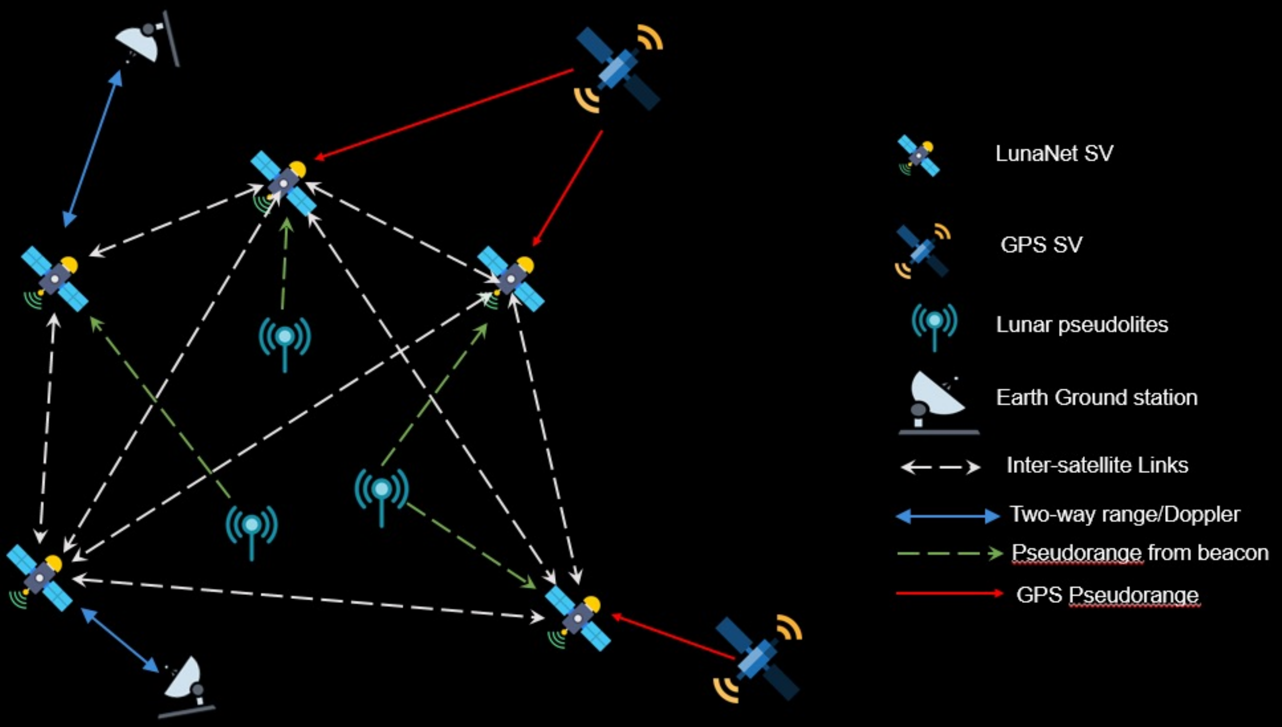
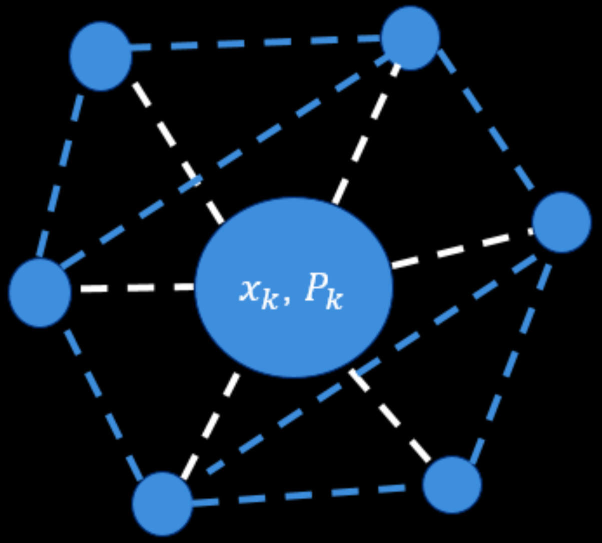
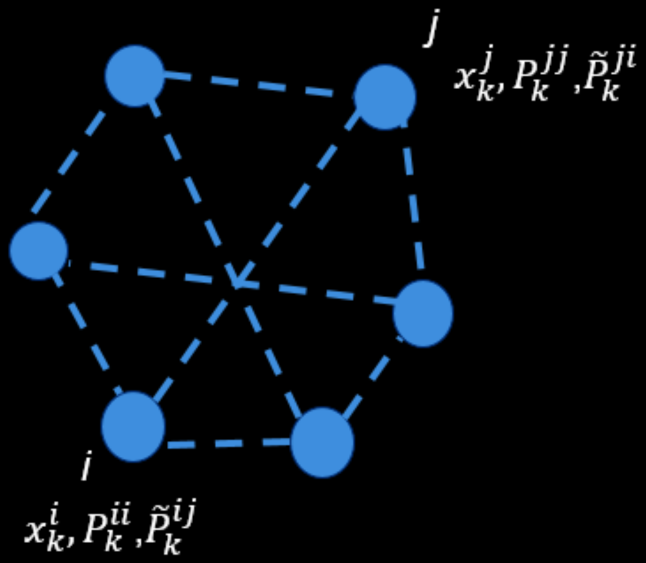


Collaborative PNT Paradigms





Centralized Architecture

- Filtering algorithm executed by a central processor
- Cross-correlations automatically accounted for
- Requires high data bandwidth
- Single point of failure

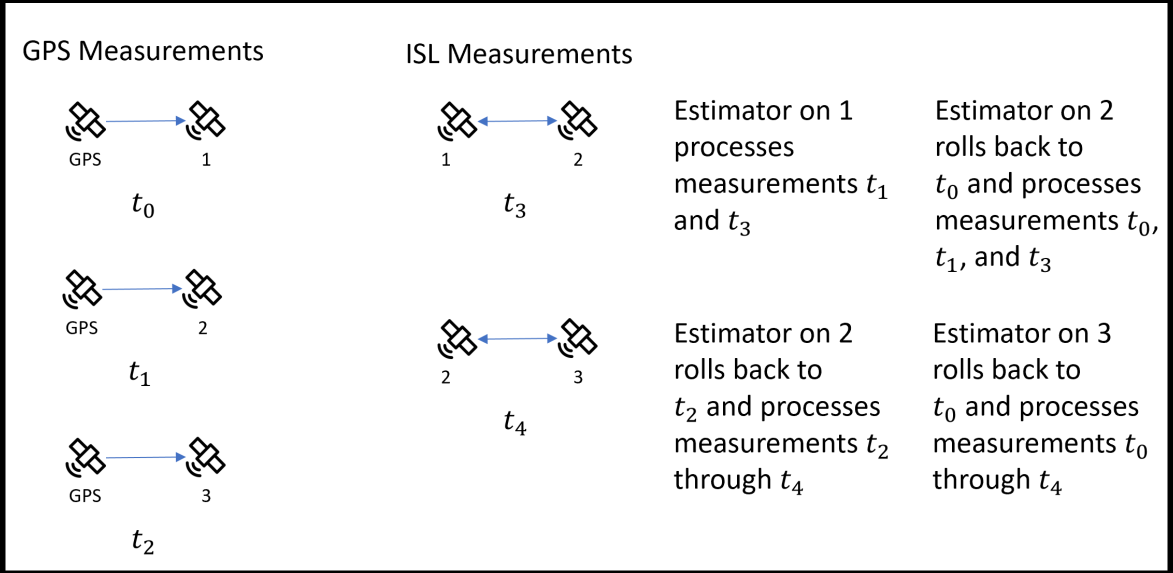
De-centralized Architecture

- Each node executes its own filter
- Communication occurs only during cross-linking
- Each node maintains an *estimate* of the cross-correlations
- Cross-correlation updates only after cross-linking
- Lower data needs; adds redundancy

Current analysis uses a custom, de-centralized cPNT architecture with real-time application heritage in land, air, and maritime applications

Collaborative PNT (cPNT) with Fused Measurements

- GPS and two-way range/Doppler measurements are fused with ISL range and range rate to estimate kinematic states and time (using an error state EKF)
- Each node (vehicle) maintains an estimate of its own state and time, as well as those of the other nodes
  - Nodes exchange stored measurements during ISL ranging
  - Measurements are transferrable by non-originating vehicles, e.g. 3 gets 1's measurements via 2
  - "Collective state" updated on contact when measurements are shared
  - Measurement (and other data) sharing can occur over a space-based, wireless Disruption Tolerant Network (DTN)



Results: Does adding crosslink improve accuracy?

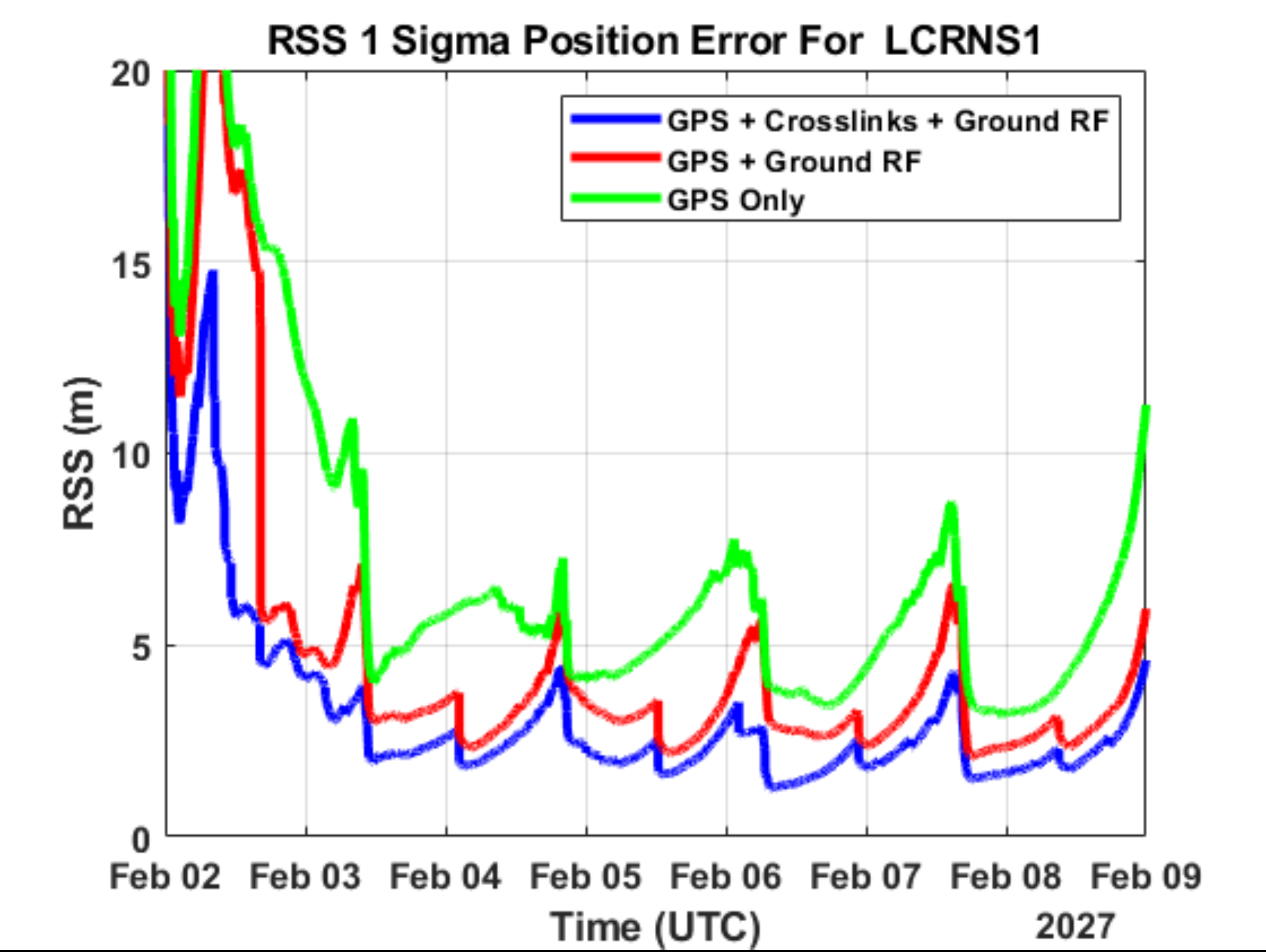
Analysis Settings

- Three scenarios were analyzed over 1 week in February 2027
  - GPS only: each LCRNS member navigates with a GPS receiver only. Overall covariance matrix is purely diagonal
  - GPS + 3 hours/day two-way range and Doppler from ground
  - GPS + two-way range/Doppler + ISL (2 hours daily)
- All scenarios use 48 by 48 LP150Q Lunar gravity model, Sun, Earth point mass, and Cannonball SRP
- Performance was analyzed in terms of RIC OD uncertainty, including RSS (root sum square) position

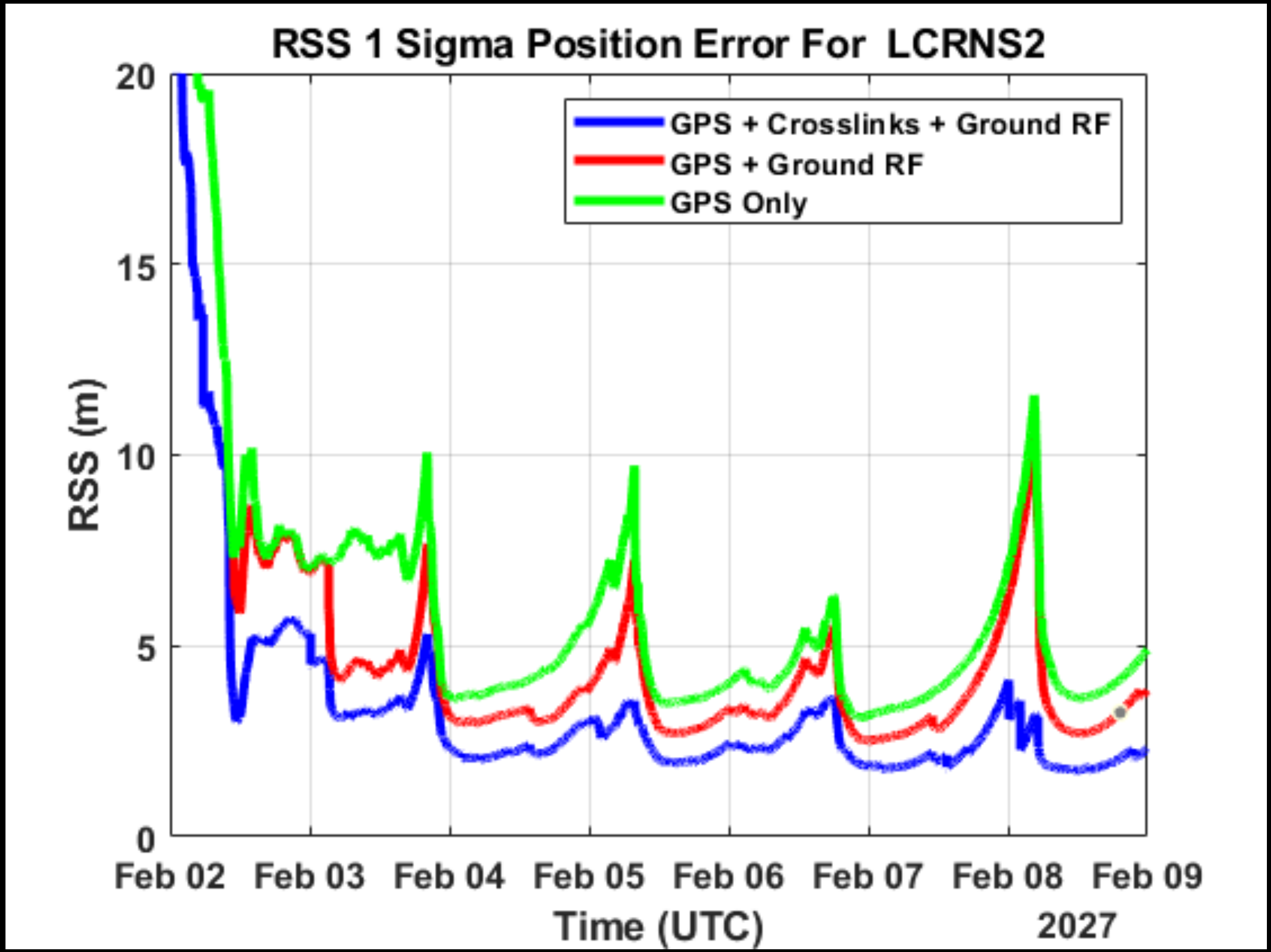
$$r_{RSS} := \sqrt{\sigma_R^2 + \sigma_I^2 + \sigma_C^2}$$

- Time transfer is automatically achieved from GPS receiver clock estimation

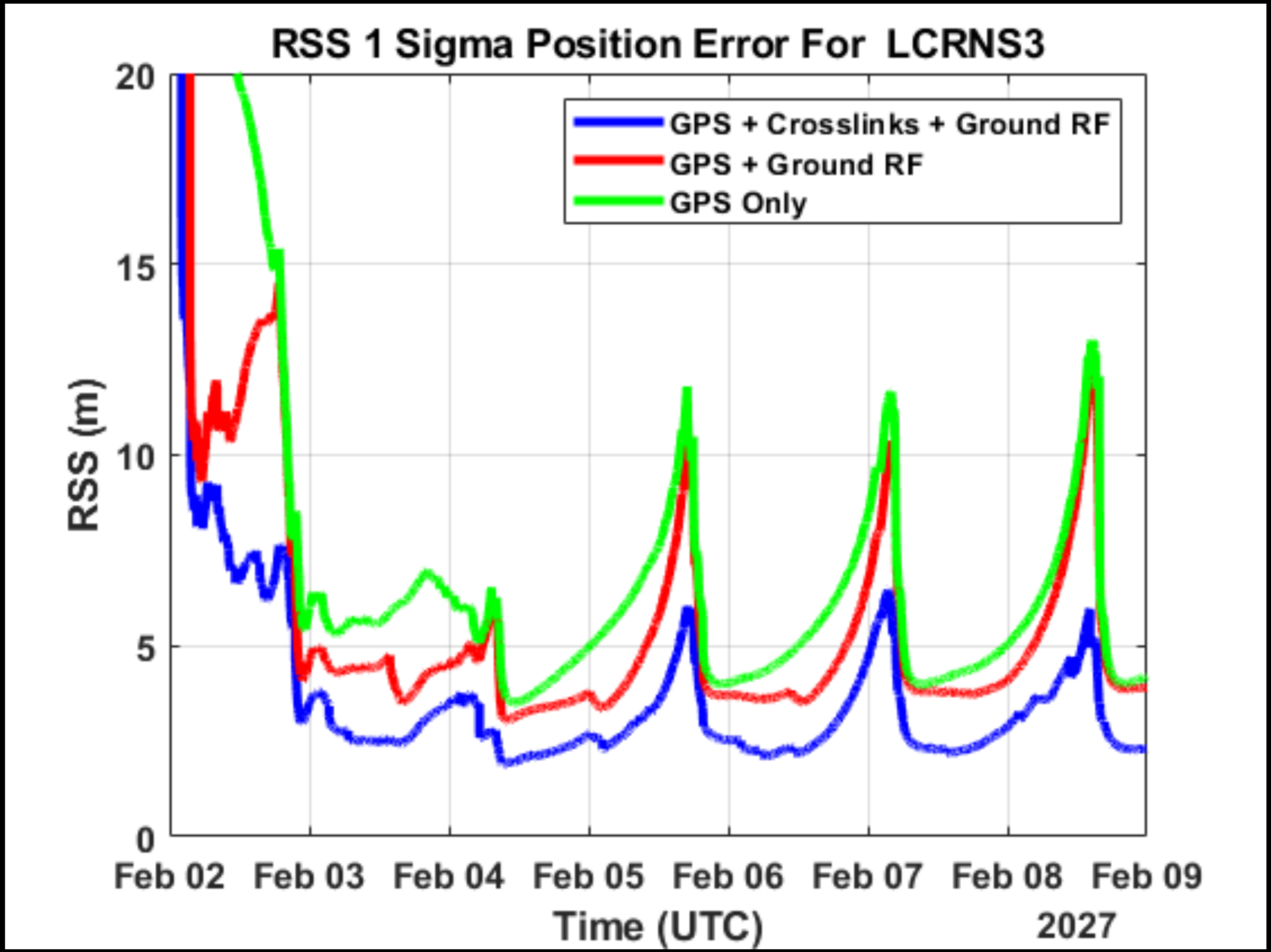
Node-1 RSS Position Estimation Error



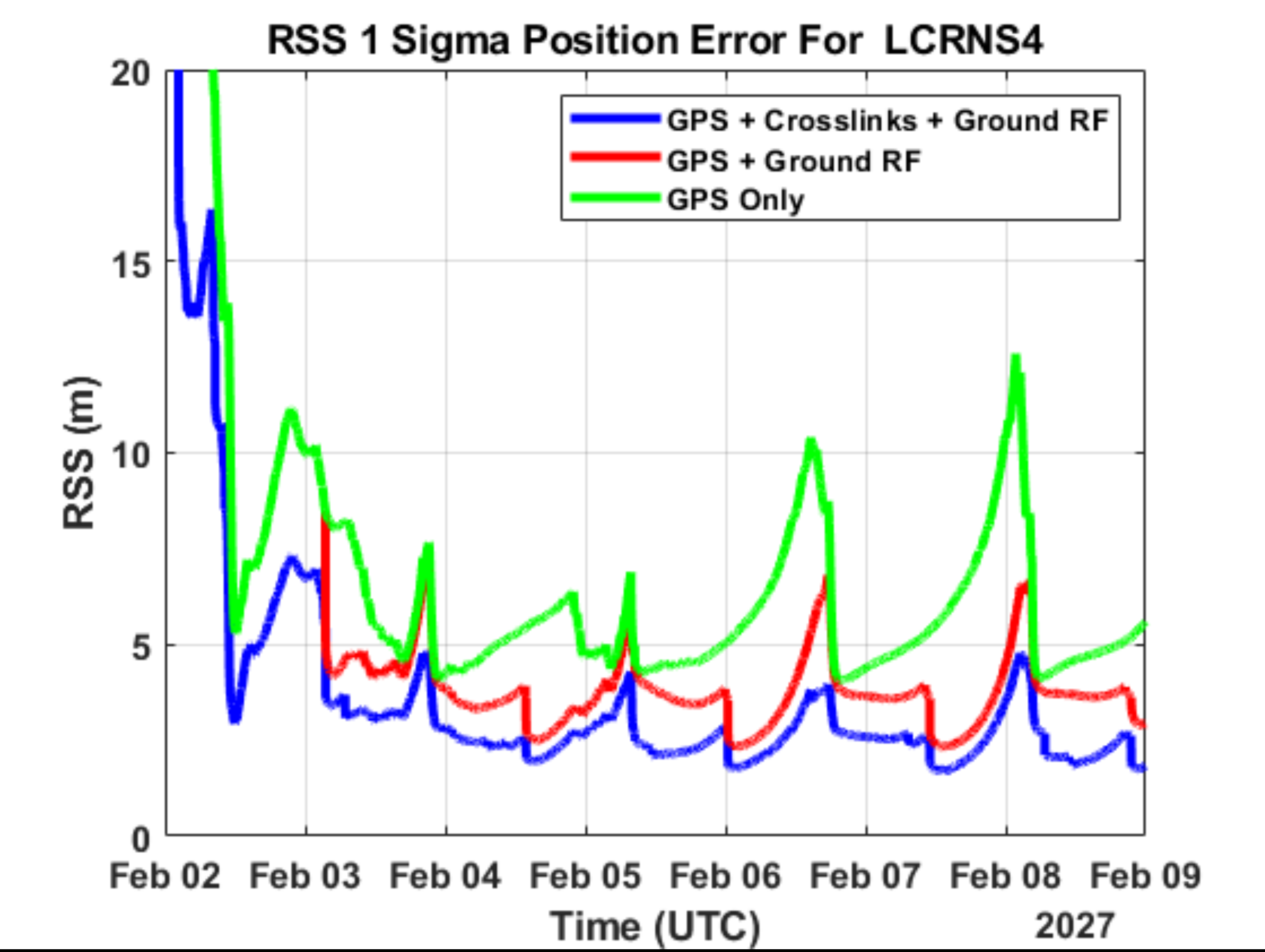
Node-2 RSS Position Estimation Error



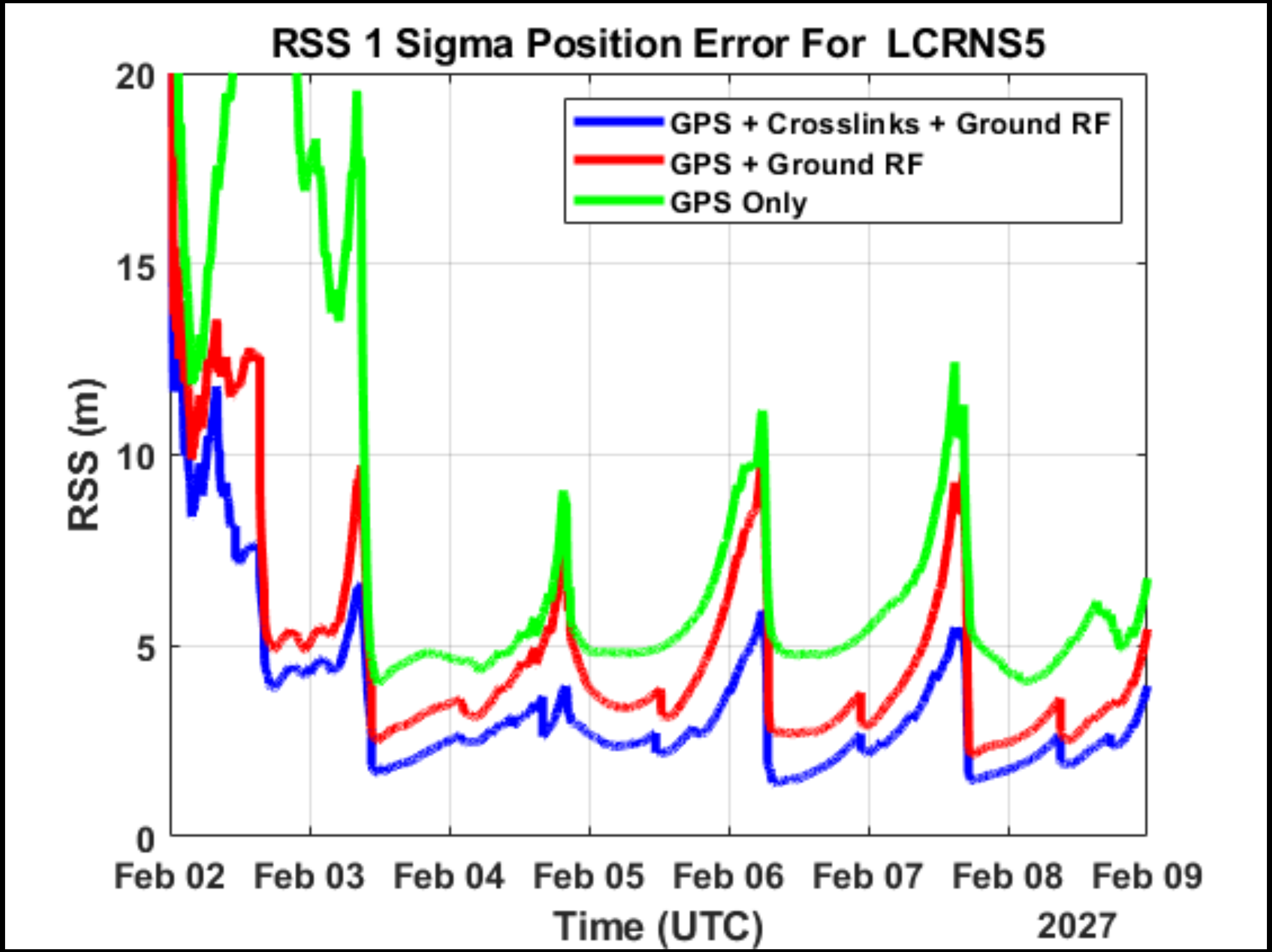
Node-3 RSS Position Estimation Error



Node-4 RSS Position Estimation Error

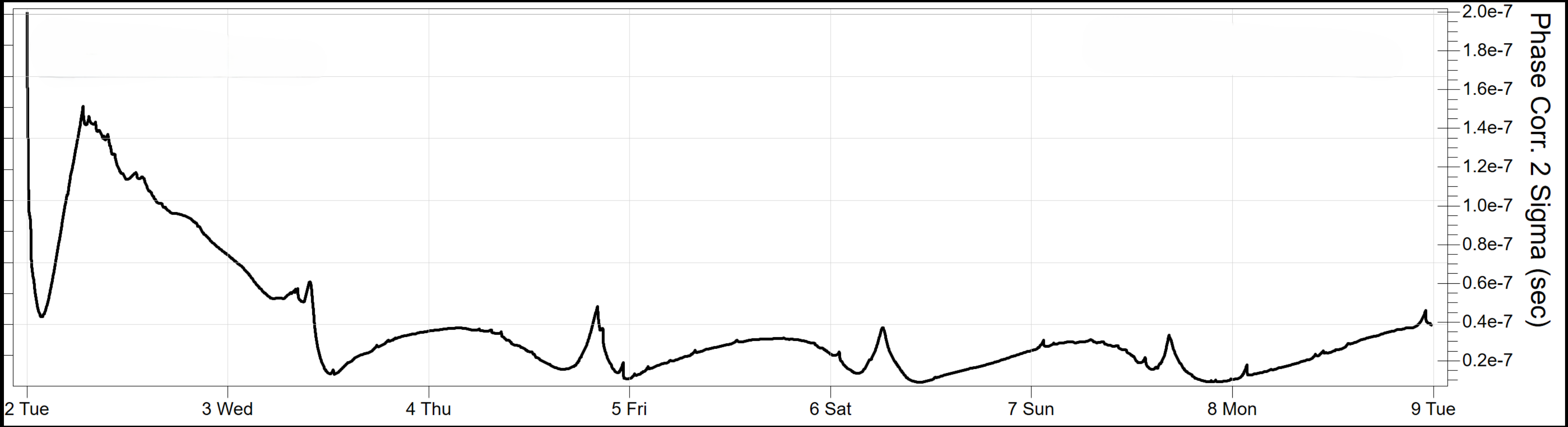


Node-5 RSS Position Estimation Error



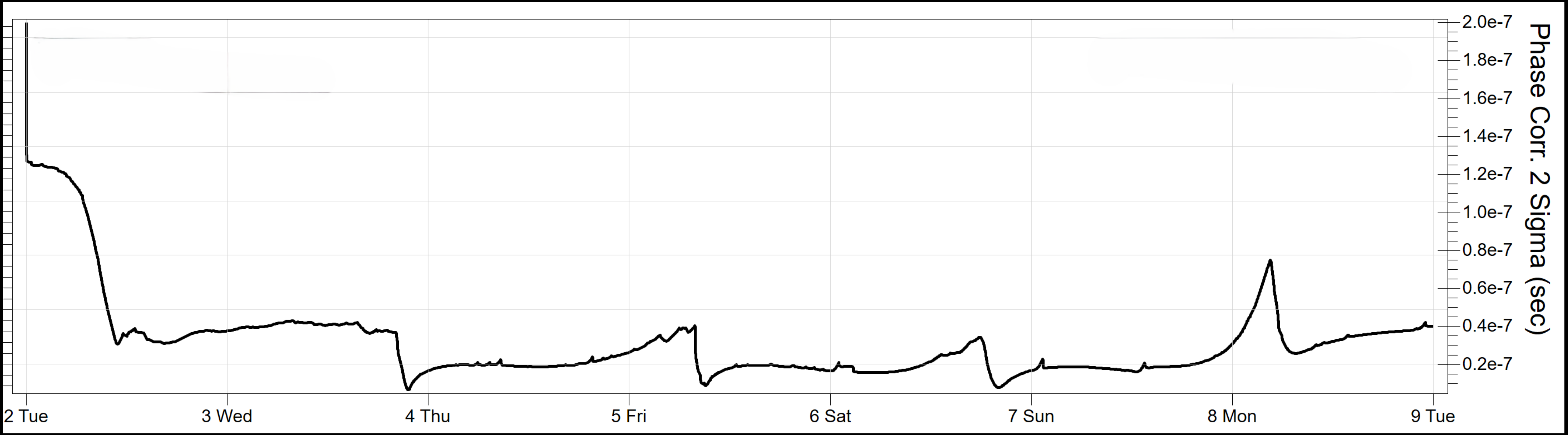
Node-1 Clock Estimation Error

1 –sigma ~ 6 meters or 20 nanoseconds

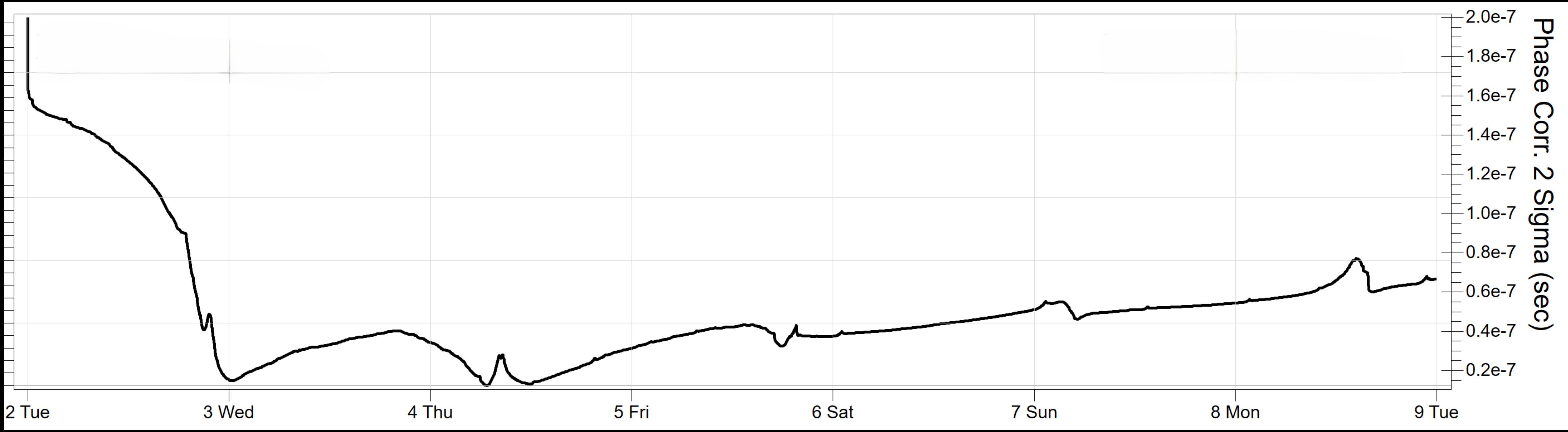


Constellation-wide Time Transfer Accuracy: 6-10 meters 1-sigma (~20-35 ns)

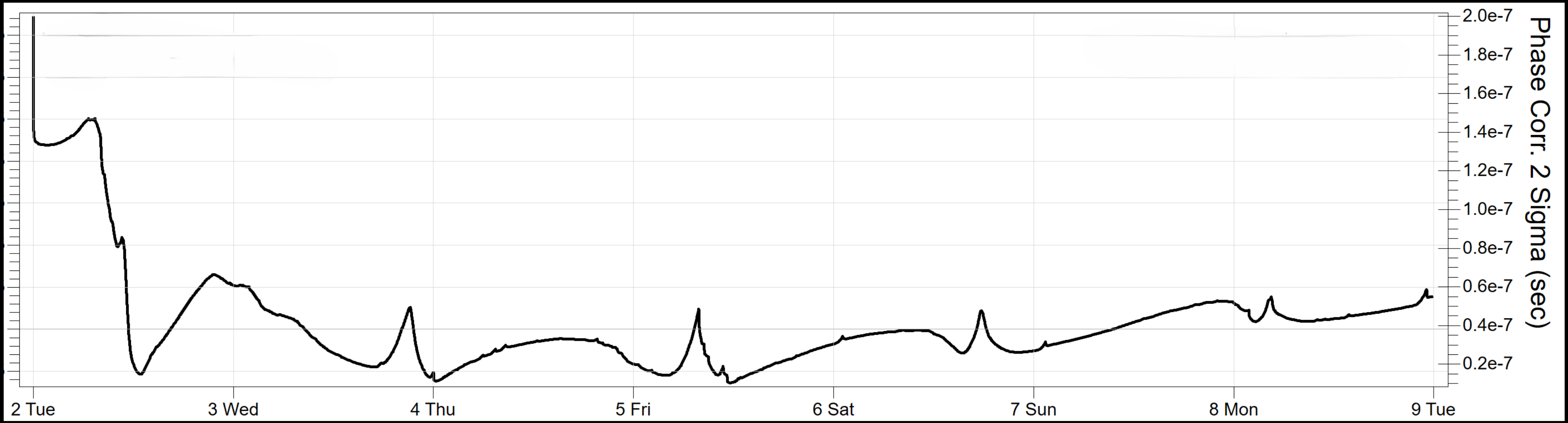
Node-2 Clock Estimation Error



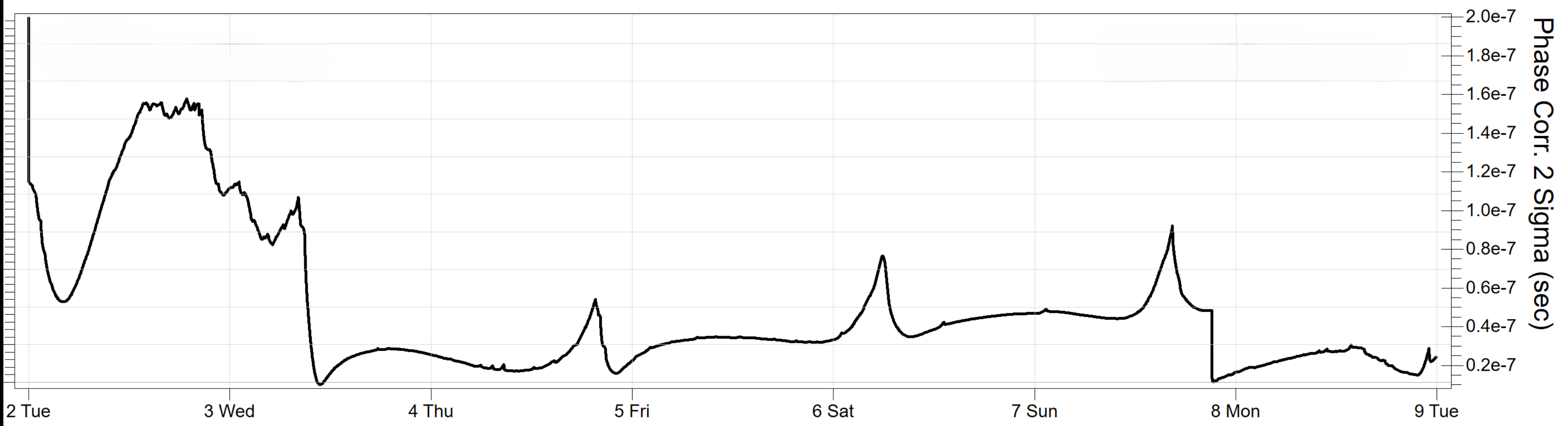
Node-3 Clock Estimation Error



Node-4 Clock Estimation Error



Node-5 Clock Estimation Error



Constellation-wide Average 1-Sigma Uncertainties After Filter Convergence

GPS-only

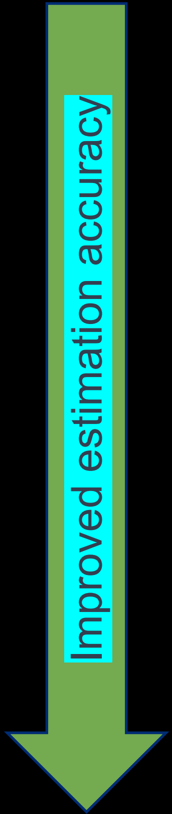
Radial (meters)	In-track (meters)	Cross-track (meters)	RSS Position (meters)
6.50	10.05	2.29	11.60

GPS + Ground

Radial (meters)	In-track (meters)	Cross-track (meters)	RSS Position (meters)
5.00	8.61	1.61	9.05

GPS + Ground+ ISL

Radial (meters)	In-track (meters)	Cross-track (meters)	RSS Position (meters)
3.56	4.20	1.17	4.83



Adding ISL improves position navigation accuracy by ~ 50% to 60%

Conclusions and Future Work

- A collaborative navigation method suited to AutoNav was analyzed for a representative LunaNet PNT constellation
  - Time transfer achieved as a by-product
  - Radio frequency inter-satellite links were modeled for two-way crosslink measurement generation
- Each LunaNet node is aware of every other node’s state, shareable via wireless network, adding redundancy against temporary navigation failure
- Crosslinks afford resilience against temporary GPS outage: detailed analysis is work in progress
- ISL collect interval and timing and its effect on navigation accuracy to be further explored
- Add Lunar pseudolites, OpNav, and other GNSS constellations to ISL observables
- Flatsat Lab demo planned with SBCs as Lunanet nodes, simulated GPS measurements (e.g. Spirent), and a wireless DTN implementation

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