National Aeronautics and Space Administration

# FY24 R&TD Innovative Spontaneous Concepts (ISC)

# Enabling Minimal Navigation Relay Architectures for the Moon and Mars

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**Strategic Focus Area:** Innovative Spontaneous Concepts

**Objectives: Our goal is to determine the benefits of a lunar surface station (SS) for position, navigation, timing, and communications (PNT+C) on the Moon and Mars.**

**Background:** Autonomous PNT+C for lunar users is an essential part of upcoming lunar missions. **We propose a SS deployed early during the development of a large lunar relay network at the lunar south pole (LSP) to significantly reduce the cost and timeline for PNT+C service deployment**. A LunaNet compatible SS located on the LSP utilizing the innovative Joint Doppler and Ranging (JDR) and JPL's high-performance clocks enables accurate and scalable PNT+C services to users with a small lunar constellation ranging from 1 – 4 orbiters (Figure 1)

**Approach and Results:**

- Developed minimum requirements and an architectural design for an SS-aided PNT+C system during the early deployment of LCRNS.
  - Designed orbits for constellation sizes ≤4: elliptical lunar frozen orbits were designed in SOAP then refined in MONTE and optimized for access to the LSP, stability under Earth and Sun perturbations, and navigation-based geometric diversity.
  - Determined an **SS location on the Connecting Ridge (-89.51°, 225°) that maximizes LOS coverage with permanently shadowed regions (PSR)** (Figure 2).
- Developed a high-fidelity navigation simulation in MATLAB to analyze the PNT performance of an SS-aided architecture for various user types over all constellation sizes.
  - With a three-orbiter constellation, this SS-aided PNT+C architecture achieved **real-time PNT accuracies of <20 m, <10 mm/s, and <100 ns (3σ) for surface users,** improving on traditional differential techniques by a factor of two and trilateration by orders of magnitude (Figure 3).
- Analyzed communications benefits of an SS relay for surface users
  - **User-to-SS relay link data rates are orders of magnitude larger (~300 Mbps when bandwidth limited) than the user-to-LNSP links, which are power limited (<5 Mbps).**
  - Funneling data from LSP users through a SS, rather than direct links to a relay, will simplify operations, enable lower SWaP designs for users, and enable higher overall data return.

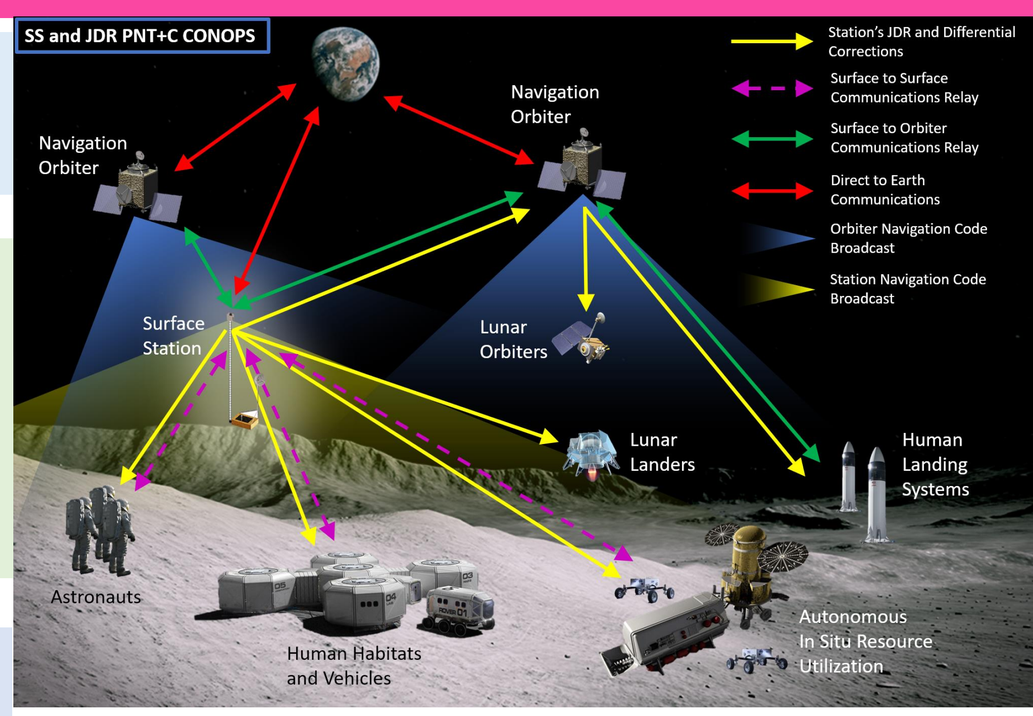


**Figure 1: CONOPS of an SS-aided JDR PNT+C architecture.**

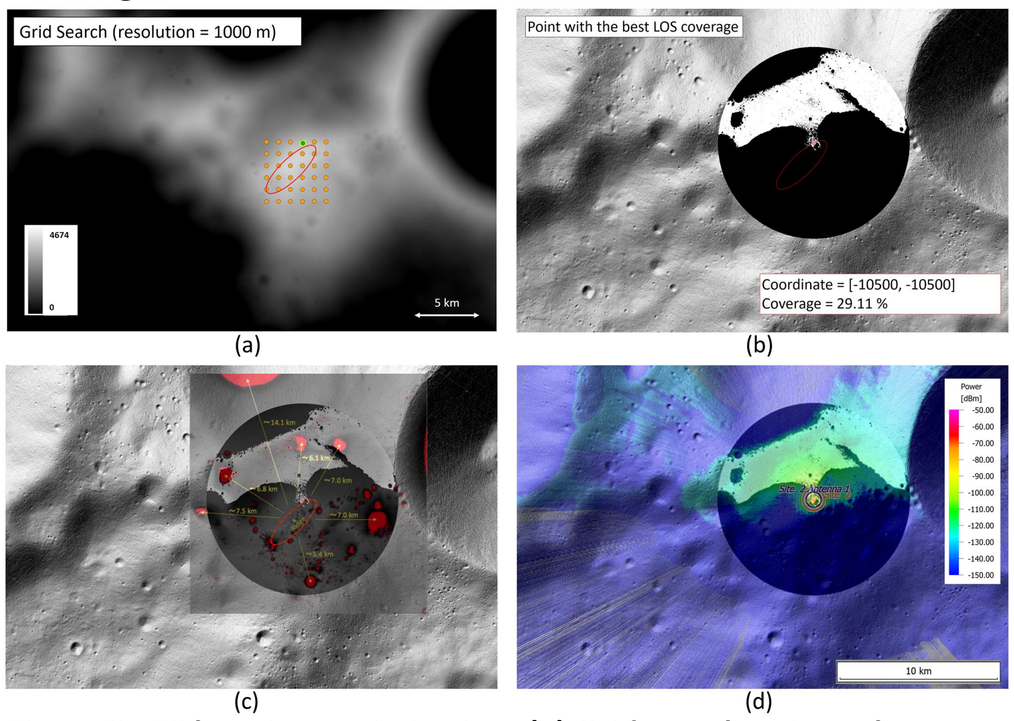


**Figure 2: SS location optimization. (a) Grid search points; the green point produced the best overall LOS coverage area shown in (b). (c) LOS coverage overlaid with a map of LSP PSRs in red. (d) FEKO radio frequency propagation simulation overlaid with LOS map.**

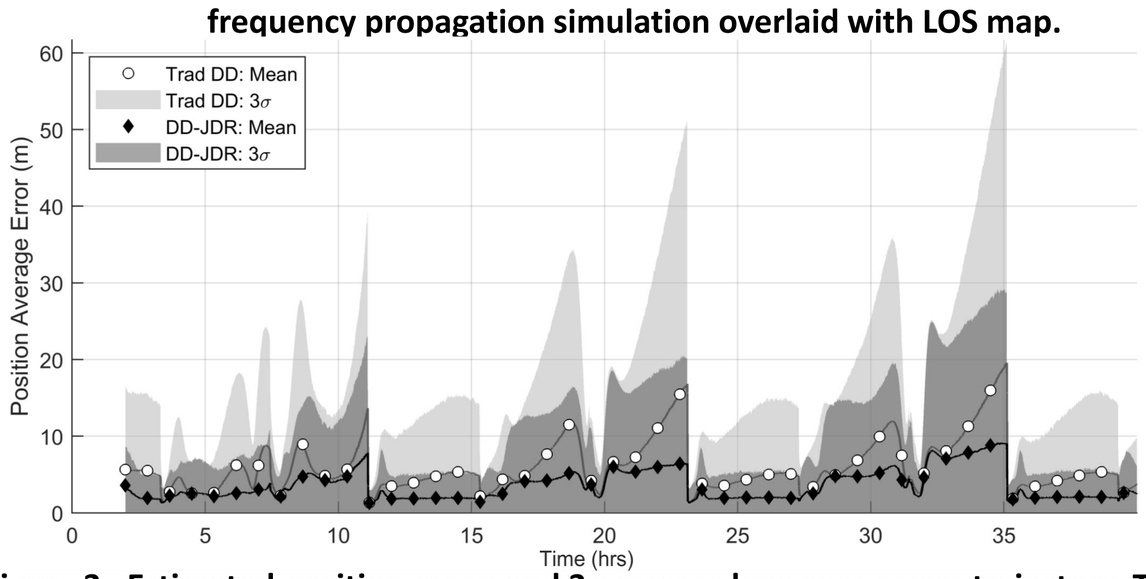


**Figure 3. Estimated position mean and 3σ error values over a user trajectory. The simulated user is a crewed vehicle circling a PSR located 6 km away from the SS. This analysis assumes a three orbiter constellation with at least two orbiters in view to the user continuously.**

**Significance/Benefits to JPL and NASA:**

- SS-aided PNT+C architectures **significantly reduce the required timeline and overall infrastructure cost for lunar PNT+C**. This system can provide critical services for near-term Cislunar missions with stringent PNT+C requirements, such as Artemis.
- **Long-term benefits include lunar timekeeping and orbit determination services**. JPL's clocks deployed on the SS will likely be the best timing and frequency references on the lunar surface, thus leading the lunar coordinated time and further strengthening JPL's leadership in deep space communications and navigation. SS-aided communication relay and in-situ orbit determination services would relieve pressure on the DSN.
- **SS-aided PNT+C is also extensible to Mars and other bodies** (Europa, outer planets, etc.), thus being relevant to planetary exploration endeavors for JPL.

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**Publications:**

"A Rapid, Low-Cost Path to Lunar Communication and Navigation with a Lunar Surface Station," submitted to IEEE Aerospace Conference, Big Sky, MT. March 8, 2025.

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