Lander-Aided Differential Doppler and One-Way Ranging for Lunar Rover Navigation with a Single Relay Satellite

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International space agencies and commercial companies are planning a range of lunar missions, from deploying lunar communications and navigation satellites in orbit (Giordano et al., 2023) to returning humans to the lunar surface (Watson-Morgan, 2023). In the near term, many efforts emphasize exploratory robotic missions in the lunar south polar region as precursors to sustained surface operations. These architectures frequently pair a landed element with one or more spacecraft in lunar orbit that provide communications relay and operational support for surface assets. For example, NASA's Artemis campaign pursues a Human Landing System that transfers to a lunar orbit prior to descent, and commercial providers including Blue Origin have been contracted to deliver crew and cargo landers for lunar surface operations (Watson-Morgan, 2023). This lander-and-orbit configuration motivates leveraging existing mission infrastructure for rover positioning and navigation. For early-stage rover missions, precise absolute localization is needed to support long-range traverses, science targeting, and safe operations in challenging terrain.

Many works have investigated vision-based lunar rover navigation, including crater-based map matching and factor graph methods (Daftry et al., 2023; Cauligi et al., 2023; Dai et al., 2025). However, long-range rovers operating across the lunar day-night cycle may experience extended periods of low illumination in addition to traverses near permanently shadowed regions, unless they explicitly avoid those areas. These constraints motivate navigation approaches that do not depend on continuous high-quality imagery. In this work, we consider navigation using radiometric measurements enabled by minimal lunar communications infrastructure together with onboard inertial odometry for positioning and navigation.

PROPOSED WORK

This work evaluates the rover localization performance under a minimal navigation infrastructure concept. The mission scenario assumes a single relay satellite operating in a Blue Moon Mark 1 pre-landing orbit described as a 10 km $\times$ 50 km low-altitude elliptical orbit, with its perigee placed over the rover operations region. The rover is deployed from a surface lander in the same region. We assume the lander position is known through human-in-the-loop map matching or pre-mission localization. Since the rover starts at the lander, the rover initial position error is modeled as near zero, set to 1 m 3D standard deviation.

The rover receives one-way Doppler measurements from the relay satellite downlink signal, where the satellite does not carry a dedicated navigation payload. The rover also receives one-way ranging measurements from the surface lander. The lander is equipped with a receiver that measures the Doppler shift of the relay downlink signal and broadcasts a Doppler measurement correction to the rover. The correction is intended to reduce the sensitivity of the rover's Doppler measurements to ephemeris errors and satellite clock effects without requiring the rover to estimate the full satellite state or requiring the lander to solve a standalone orbit determination problem. The rover uses only these two external measurement sources, together with onboard inertial odometry, to estimate its position over time. We evaluate performance across several mission cases that isolate the effects of the lander ranging link and of the lander broadcast Doppler corrections.

RELATED WORKS AND LIMITATIONS

Several studies have investigated rover or surface user positioning with limited lunar infrastructure. Tanaka et al. (2025) propose a minimalist system consisting of a single satellite, a known reference station, and a stationary user. They rely on differential dual one-way ranging for faster positioning convergence in comparison to Doppler measurements. Their study focuses on relative positioning for a stationary user and assumes dual one-way ranging capability, which is distinct from the one-way Doppler only signal considered in this work for the space segment.

Jun et al. (2024) introduce joint Doppler and ranging (JDR) and demonstrate real-time estimation of position, velocity, and timing for lunar surface users using one-way range and Doppler measurements from two orbiters along with a surface reference station. Their simulation study assumed that the reference station's clock was synchronized, which reduces emphasis on the network's clock noise. In contrast, the architecture considered in this work assumes only a single satellite and does not assume that the relay broadcasts a dedicated ranging code. We also explicitly study non-ideal clocks at the rover, lander, and satellite nodes, and we quantify how lander clock errors limit the effectiveness of the lander's broadcast Doppler corrections.

In prior work by the authors, we evaluated the localization performance of a rover using only the Doppler shift of a communication signal from a single relay satellite and demonstrated convergence to sub-10-m accuracy within two relay orbits (Coimbra et al., 2025). In the present work, we incorporate the measurements that are available from the surface lander that deploys the rover, and we introduce a lander-aided differential Doppler correction protocol. We also improve the error modeling fidelity relative to our prior study to better represent time-varying effects that arise in realistic operations.

ERROR MODELING

We utilize our existing simulation framework for measurement generation and error modeling (Coimbra et al., 2025; Coimbra and Gao, 2026). We model odometry error as a white noise term applied to the incremental distance traveled between consecutive rover states. For clock dynamics, we use a two-state stochastic clock model for all assets. Clock process noise parameters are selected based on the oscillator grade for the rover, lander, and satellite.

We apply a first order Gauss-Markov (FOGM) process on the ground truth relay acceleration, which induces time-correlated errors in relay position and velocity. Without correction, the expected ephemeris error growth is unbounded, which is not representative of plausible operations. We therefore assume that the relay periodically receives orbit determination and time synchronization (ODTS) updates at a 6-hour cadence, as assumed by some lunar relay specifications (SSTL, 2022). We model ODTS updates as discrete state corrections that reduce the relay ephemeris error states in position, velocity, and acceleration at the update time. We also reduce the broadcast ephemeris covariance at the update time to represent improved knowledge after correction. We assume the rover and lander are aware of the ODTS update times.

We account for relativistic effects by propagating each asset clock in proper time, including gravitational potential and velocity dependent rate terms, and we incorporate light-time delay in the radiometric measurement modeling. These effects are included to improve the physical consistency of the simulations and to ensure that deterministic rate terms are not incorrectly absorbed into the stochastic clock states in estimation.

For Doppler measurement noise, we apply thermal noise based on one-way Doppler error models using downlink carrier-to-noise density ratio and receiver tracking parameters (O'Dea et al., 2019). For one-way ranging measurements, we apply thermal noise consistent with receiver tracking loop performance. Although the focus or novelty of this paper is not in detailed signal modeling, these error sources are included to reinforce the fidelity of the results.

APPROACH

We use an Extended Kalman Filter (EKF) to estimate a 7-state vector consisting of the rover 3D position, a scalar relative clock drift between the rover and the relay that captures the clock contributions in one-way Doppler, a scalar bias term that captures residual time-correlated bias induced by ephemeris errors, and a 2-state lander-to-rover relative clock model consisting of relative clock bias and relative clock drift for the one-way ranging link.

We implement a lander-aided differential Doppler correction protocol. At each epoch when the relay is visible to the lander, the lander computes a predicted Doppler using nominal broadcast ephemeris and its known position, then forms a residual between the measured and predicted Doppler measurement. This residual is transmitted to the rover as a Doppler measurement correction. The rover subtracts the broadcast correction from its measured Doppler and processes the corrected measurement in the EKF. This approach reduces sensitivity to shared relay errors (e.g. ephemeris errors) and satellite clock effects without requiring the rover to estimate the full relay state and without requiring the lander to perform full orbit determination.

A practical limitation of the protocol is that the Doppler correction inherits lander clock errors, so differencing cannot perfectly remove relay-induced biases. We therefore model residual time-correlated Doppler bias and explicitly estimate the lander-to-rover clock offset terms required by one-way ranging, without assuming an independent lander clock filter.

We also incorporate the ODTS correction into estimation. At ODTS update times, we apply a correction to the bias state associated with relay ephemeris induced Doppler errors, and we reduce its covariance to represent improved ephemeris knowledge after the update. Between ODTS updates, the bias state evolves according FOGM dynamics, which is consistent with the truth ephemeris process.

The rover updates its state using corrected Doppler measurements at 1 Hz whenever the satellite is visible to the rover and continuously updates its state using one-way lander-to-rover ranging measurements at 1 Hz throughout the traverse. Odometry is used as a control input for state propagation. We perform Monte Carlo evaluations to quantify the performance across measurement configurations, geometries, and clock grades.

EVALUATION METHODOLOGY

We evaluate the localization performance using the proposed method for long-range rover traverses. The rover motion profile is modeled as an outward traverse along a straight line from the lander. Four primary mission cases are compared. In the first baseline, the rover uses only one-way lander-to-rover range and odometry. In the second baseline, the rover uses only one-way Doppler measurements from the satellite and odometry. In the third case, the rover uses both one-way range and one-way Doppler but does not receive the lander's broadcast Doppler corrections. In the fourth case, the rover uses one-way range, one-way Doppler, and broadcast Doppler corrections. The fully-aided scenario is illustrated in Figure 1. This set of cases isolates the contributions of lander ranging and lander-derived Doppler correction by selectively enabling each measurement source under otherwise identical conditions.

We then perform a geometry sensitivity study in the fully-aided case. We compare traverses that are aligned with the relay ground track, traverses that are cross-track, and traverses that include both components. These scenarios expose the directionality that arises in single-satellite Doppler navigation and quantify when the lander ranging link and the correction protocol reduce that directionality dependence.

Clock quality is a central factor for one-way radiometric navigation. We repeat the fully-aided case across oscillator grades and perform a trade study on the performance impact when the rover and lander are equipped with chip-scale atomic clocks (CSACs) versus higher grade clocks such as a Rubidium atomic frequency standard (RAFS). This analysis quantifies regimes in which a higher grade lander clock improves the net value of differential Doppler corrections and compensates for lower grade rover clocks. Together, the mission case study, geometry study, and clock trade study inform payload selection and operational concepts for near-term lunar rover missions.

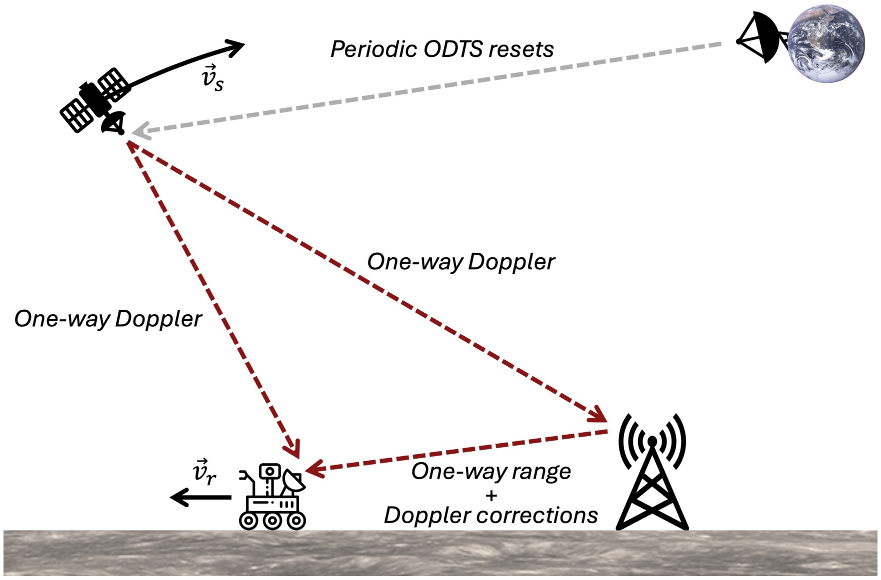

Figure 1: In the fully-aided scenario, the rover receives one-way Doppler measurements from the satellite and one-way range measurements from the lander, which acts as a reference station. When the satellite is visible, the lander also receives the satellite downlink Doppler and broadcasts a Doppler correction to the rover. In simulation, we model periodic ODTS updates from Earth that reset the ephemeris errors, shown in gray. We include only the resulting reset effects, since modeling Earth-Moon link operations is outside the scope of this work.

DESCRIPTION OF NEW AND INNOVATIVE ASPECTS

The novel contributions presented in this work are as follows.

- **Lander-aided differential Doppler using minimal infrastructure:** We evaluate a lander-aided differential Doppler framework that fuses corrected one-way relay Doppler measurements, one-way lander-to-rover range, and rover odometry in a three-node architecture that does not assume a dedicated navigation payload onboard the relay satellite.
- **Mission-driven evaluation across measurement configurations and geometries:** We provide a performance study for a 10 km × 50 km pre-landing orbit motivated by Blue Moon Mark 1 operations, including (1) ablations that isolate the value of lander ranging and the lander's broadcast Doppler corrections, and (2) traverse geometries that reveal directionality limitations in single-satellite Doppler navigation.

- **Trade study on clock quality for correction-based navigation:** We quantify sensitivity to the rover and lander oscillator grade and identify conditions under which the lander's broadcast Doppler corrections remain beneficial relative to uncorrected one-way Doppler measurements.

We acknowledge the Blue Origin team for communications and for providing information on mission scenario assumptions.

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