Investigating Low-Altitude Constellations of Ad-Hoc Lunar PNT System for Distributed Spacecraft Autonomy

Yeji Kim[1]
Yonsei University, Seodaemun-gu, Seoul, 03722, South Korea

Brian C. Kempa[2], Caleb Adams[3], Richard J. Levinson[4], and Jeremy D. Frank[5]
NASA Ames Research Center, Moffett Field, California, 94035, USA

In this study, we examine a low-altitude Lunar Position, Navigation, and Timing (LPNT) constellations and the localization performance of Centralized Extended Kalman Filter (CEKF) and Decentralized Extended Kalman Filter (DEKF) algorithms. The primary investigation involves a 100-node swarm operating at a 100 km altitude, in contrast to previous studies that examined a 21-node asset in a frozen-orbit at 5,500 km. The autonomous operation of large-scale swarm is based on two-way Inter-Satellite Link (ISL) measurements, which involve pseudoranges and relative velocities among swarm nodes. We perform a numerical assessment of the two filtering approaches, utilizing 'fully sampled' measurements from all available assets as well as 'two ISL' measurements where each spacecraft is restricted to only two antennas. This research includes an analysis of CEKF under 2-ISL constraints and evaluates the performance of DEKF in a 100-node swarm, which has not been explored in previous studies. In addition, we examine the impact of increasing the sampling frequency for DEKF, showing that the update cycle can be shortened from a 10-minute interval. A novel approach for '2-ISL limited' DEKF will also be introduced, using a matching formulation that exhaustively enumerates all potential matches. This study provides valuable insights into large-scale distributed swarm operations, considering various filter configurations, sampling frequencies, matching strategies, and scalability of CEKF and DEKF for low-altitude LPNT applications.

The Lunar PNT technology plays a key role in providing reliable and robust navigation services on the Moon's surface and the South pole, where the primary Lunar missions are planned. To support upcoming Lunar missions, including small satellites from NASA's Commercial Lunar Payload Services program, the Lunar PNT system must be adaptable to smaller platforms like CubeSats. Driven by the growing involvement of public and private exploration partnerships, the traditional low Earth orbit missions are shifting to beyond geosynchronous orbit [1]. These upcoming missions aim to foster a sustainable and innovative exploration program, in collaboration with commercial and international partners, to facilitate human expansion throughout the solar system and return new knowledge and

---

[1] Master's Student, Department of Astronomy, AIAA Student Member.
[2] Computer Scientist, Intelligent Systems Division.
[3] Project Manager, Intelligent Systems Division.
[4] Computer Scientist, Intelligent Systems Division.
[5] Lead, Scheduling & Planning Group.

opportunities to Earth [2]. As part of this trend, there are increasing efforts to utilize science missions in Lunar orbit to develop a non-dedicated and ad-hoc PNT network system.

Two traditional approaches, the Deep Space Network (DSN) and the weak signal Global Positioning System (GPS), are established deep-space navigation technologies for missions beyond the geosynchronous orbit. Beginning in 1958, the DSN was developed to communicate with the Explorer 1 spacecraft based on the use of radiometric tracking in spacecraft navigation [3]. The DSN is capable of providing nearly unfettered coverage to spacecraft beyond low-Earth orbit (LEO), however, increased space mission volume has created concerns about future expectations of DSN usage for spacecraft navigation [4]. For cislunar mission applications, the position accuracy using DSN achieves 100 m (3σ) with at least three geometrically diverse ground stations when using radiometric tracking alone [5]. The DSN's dependence on Earth-based ground stations restricts its operational capabilities to periods of Earth visibility. This limitation, coupled with its poor localization performance, renders the DSN unsuitable for future lunar missions that demand continuous tracking and precise positioning. To satisfy the increasing requirements of DSN in Lunar applications, spacecraft are also required to improve their onboard antenna power and efficiency of the transmission. However, there is an important aggregate cost trade between adding capabilities to every spacecraft and adding to a capacity on the ground that serves multiple spacecraft [6].

A weak GPS system can provide PNT service while the user spacecraft is bound to the Moon, leveraging a single, steerable high gain antenna with the relatively narrow beam which includes all the sources in its field of view [7]. However, the higher the altitude the receiver is above the GPS constellations, the poorer and the weaker are the relative geometry and the received signal powers, respectively, leading to a significant navigation accuracy reduction [8]. The transmitted power becomes weaker with increasing distance from the Earth as well as signals tracked from one of the side lobes of the GPS antenna pattern. As a results, the number of visible satellites and relative geometric condition of the GPS satellites at very high altitude drops dramatically and reduces the navigation solution accuracy. Therefore, the weak GPS system is also not an ideal way to provide PNT service to upcoming Lunar missions when considering its limited geometric condition and the recued navigation accuracy.

Another navigation approach on the Moon is being developed, similar to the Global Navigation Satellite System (GNSS) on Earth, aiming to offer navigation service with continuous 24/7 coverage across the entire Lunar surface. For example, lunar communications relay and navigation systems (LCRNS) by NASA and Lunar navigation satellite systems (LNSS) by JAXA are designed to serve as dedicated Position, Navigation, and Timing (PNT) systems for the Moon. However, designing a dedicated LNSS and PNT service involves additional challenges, which are unique to the lunar environment, including limited payload capacity for the CubeSat platform, i.e., the size, weight, and power (SWaP) of the onboard clock, limited lunar ground monitoring stations, and limited financial investment as compared to the legacy Earth-GPS [9].

NASA's focus on utilizing CubeSat platforms on the Moon leads to an alternative Lunar navigation platform that leverages the existing Lunar science and exploration assets. The small satellites used in Lunar missions can be used to create a low-cost, autonomous, ad-hoc, and on-demand mission-centric Lunar PNT swarm capable of providing PNT services to these low-cost lunar missions [10]. As upcoming Lunar missions will often operate at low-altitude about 30 km to 100 km for scientific observations and mapping purposes, the low-altitude orbital constellations could be employed to create an ad-hoc Lunar PNT system. However, several issues must be addressed, such as the instability of these orbits, which often require maintenance or are only suitable for short-duration missions, operating for fewer than 90

days. Additionally, at an altitude of 100 km, the satellites have a limited period during which they are above the horizon and capable of providing PNT service to users.

The implementation of a non-dedicated, ad-hoc Lunar navigation constellation facilitates on-demand PNT services. A preliminary study of ad-hoc Lunar PNT system was conducted using 21 spacecraft in 5,5000 km altitude frozen orbits to test its feasibility and a basic performance of orbital asset localization among ad-hoc Lunar constellations in small satellites format [10]. These swarm assets are designed for autonomous localization with minimal Earth interaction, reducing dependency on bandwidth and ground resources. The design in [10] demonstrated the feasibility of a decentralized PNT approach, specifically employing a DEKF approach for state estimation, which helps minimize onboard operating costs. The DEKF method distributes computation across individual satellites, which lightens the computational load while maintaining accuracy in orbit ephemeris and clock offsets, similar to centralized systems [11]. In a follow-on study [12], each spacecraft was limited to 2 communications antennae, forcing the selection of measurements and scheduling spacecraft activities to perform the measurements. A matching algorithm is implemented to select the best measurements and schedule position estimation updates. The decentralized localization performance is also investigated with increasing levels of network degradation for swarm assets considering the impact of intermittent and permanent communication failure, to demonstrate the robustness and fidelity of the decentralized Lunar PNT service [13]. This study confirmed that the ad-hoc PNT constellations in frozen orbit are highly robust and resilient to communication failures. However, unlike frozen orbit swarm assets, the low-altitude satellites have a limited ground view at an altitude of 100 km, where the ad-hoc Lunar constellation consists of 98 low-altitude satellites, evenly distributed across seven circular polar orbital planes, alongside two satellites in a frozen orbit at an altitude of 5,500 km (Figure 1). Therefore, the number of satellites visible to ground users is significantly limited in low-altitude orbit constellations. As each visibility of a spacecraft remains intact for only a few ticks before it moves out of the field of view, the ground user encounters challenges in maintaining continuous navigation service, resulting in sparse availability and provision of Lunar PNT system. Consequently, service availability is primarily restricted to the Lunar South Pole region (Figure 2). Given these limitations and concerns, the localization performance of low-altitude swarm assets will be assessed in this study.

We focus on the investigation of the localization performance of low-altitude swarm assets and ground users near the Lunar South Pole. The overall flow of the Lunar PNT simulation incorporates the DEKF approach of asset localization and the weighted least-squares approach in user localization (Figure 3). The autonomous Lunar PNT simulation is primarily implemented in MATLAB, where the DEKF based on the matching scheduler is implemented with Google's OR-tools as a model builder and Gurobi optimization tool as a backend solver. The General Mission Analysis Tool (GMAT) is utilized to generate ephemeris data for swarm assets, and accounts for satellite orbital details, mass, and perturbations like solar radiation pressure and drag coefficients. Each ephemeris dataset is produced in the Moon International Celestial Reference Frame (ICRF) inertial coordinate system. For state estimation, the distributed swarm assets rely on two-way Inter-Satellite Link (ISL) measurements, which involve tracking pseudoranges and relative velocities between visible satellites and anchor nodes during each observation.

Numerical evaluations of the decentralized localization process are conducted to demonstrate the feasibility of the low-altitude PNT system in providing reliable navigation services. The main approach involves using DEKF and CEKF to localize 100 satellites in low-altitude constellations, where the CEKF is implemented to serve as a baseline for comparing the performance of distributed algorithms. In both cases, we evaluate 'fully sampled' measurements from all available assets, and 'two ISL' measurements when spacecraft are

constrained to have only two antennas. We test four estimation techniques: CEKF fully sampled, CEKF two ISL, DEKF fully sampled, and DEKF two ISL filters. As the DEKF update cycle is comprised of network setup, communication, and computations, a global broadcast network and 2-way ISL network setup will take from 4 to 6 minutes as maximum [12]. In this simulation, the DEKF update cycle is set to 10 minutes, including a 4-minute latency for obtaining and computing the actual measurement updates. We experiment an increased update cycle to demonstrate the feasibility and evaluate the impact on localization performance using various tuning values for measurement noise covariances (Figures 4 and 5). By comparing centralized and decentralized approaches using a matching algorithm, we analyze the influence of cross-correlation factors in the covariance matrix, assuming 100% reliability of all assets and measurements. The increased frequency and the adjustments of tuning parameters reveal distinct error patterns between the two scenarios. The localization accuracy of the swarm assets and ground users is assessed by taking the median error across 100 assets and one ground user (84.9°S, 137.5°E) over 7-day simulation period (Table 1).

Since the user localization accuracy is significantly affected by the performance of the swarm assets, it is crucial to maintain high localization accuracy within the swarm. This study will continue to explore decentralized filtering for autonomous LPNT operations, with further investigation of an 'iterative' matching approach which enumerates every valid matching pair, planned for the following month.

A. Images, Figures, and Tables

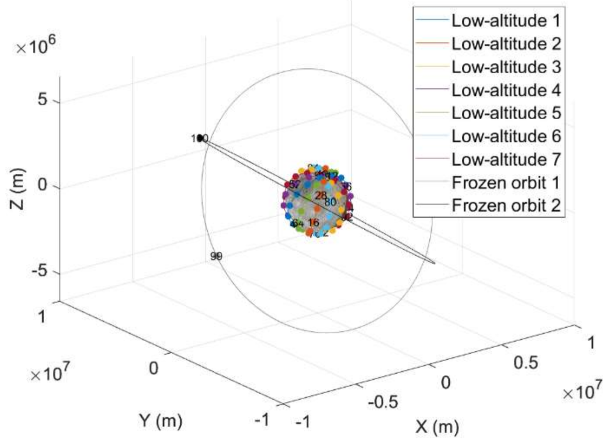

Fig. 1 Low-altitude constellations of Lunar PNT system

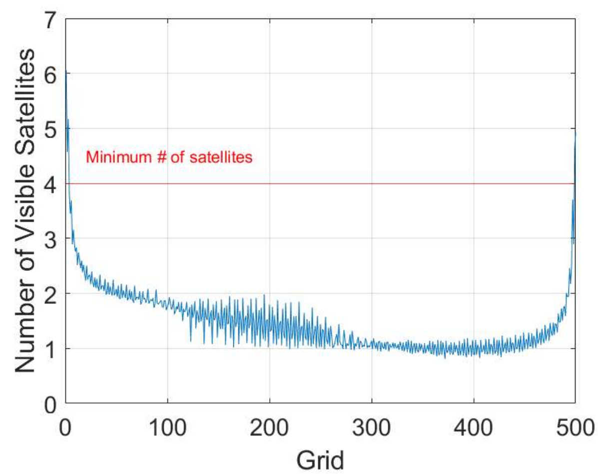

Fig. 2 Number of Visible Satellites (Grid ~ 1 (500) indicates near the South pole (North pole))

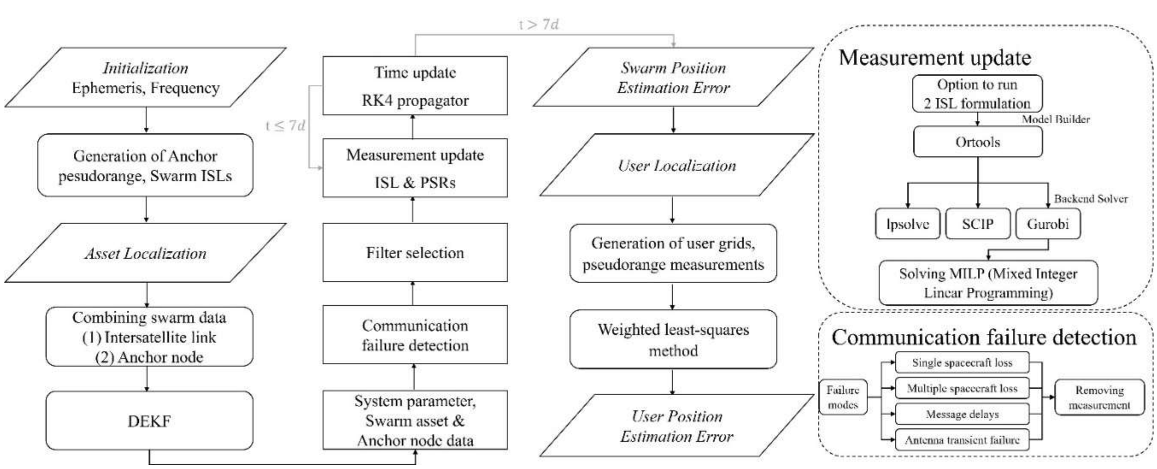

Fig. 3 Ad-hoc Lunar PNT simulation flowchart

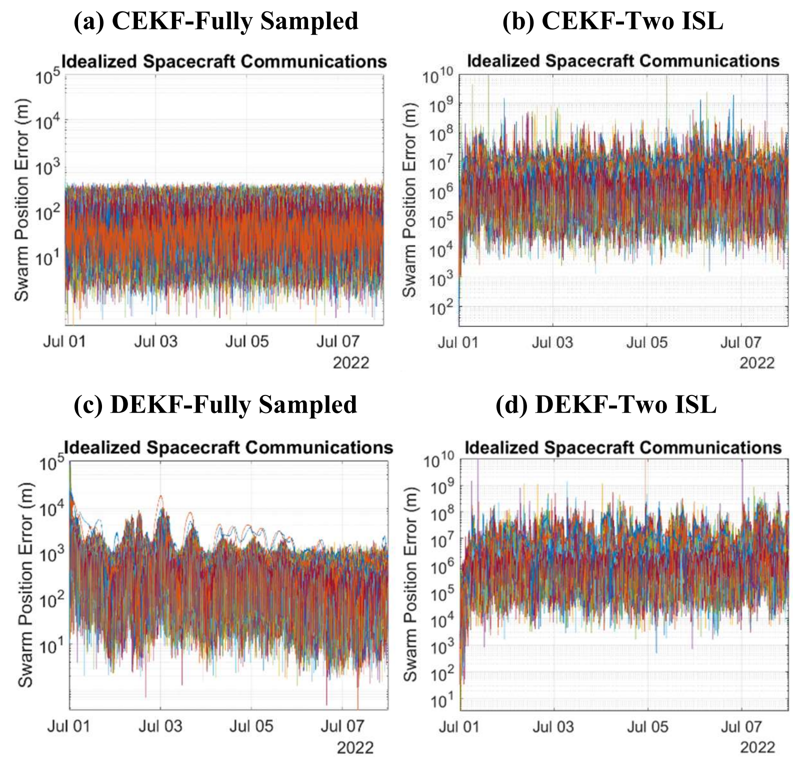

Fig. 4 Localization performance of 100 assets with 10-min frequency ($R = [200; 0.02]$)

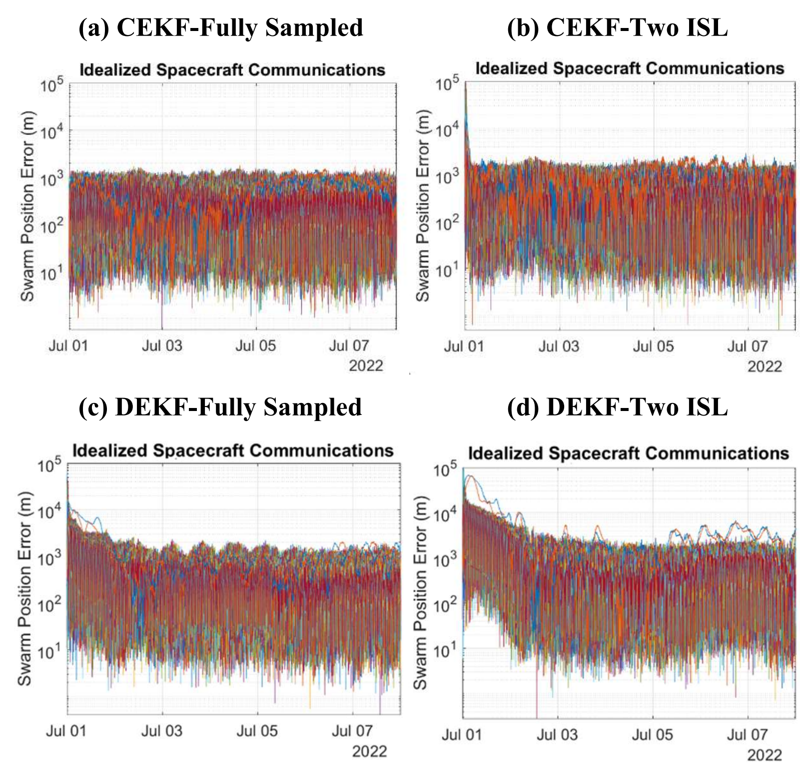

Fig. 5 Localization performance of 100 assets with 5-minute frequency ($R = [200000; 20]$)

Table. 1 Localization performance of swarm assets and ground user for 7 days

R	Sampling Rate	Localization	Median Position Estimation Error (m)			
			CEFK-Fully Sampled	CEKF-Two ISL	DEKF-Fully Sampled	DEKF-Two ISL
[200;0.02]	10 min	100 Swarm Assets	42.12 m	1974073.7 m	404.4 m	1856590.0 m
		South Pole User	15.01 m	1151407.2 m	16.33 m	187323.9 m
[200000;20]	5 min	100 Swarm Assets	262.4 m	371.2 m	347.2 m	586.8 m
		South Pole User	16.75 m	16.69 m	16.72 m	17.39 m

B. References

[1] Zucherman, A. P., Braun, B. M., and Sims, E. M., "Navigating the policy compliance roadmap for small satellites." Journal of Space Safety Engineering, Vol. 9, No. 4, 2022, pp. 582–599.

[2] Gill, T., "NASA's Lunar Orbital Platform-Gatway," Space Congress Proceedings of 45th the Next Great Steps, 2018.

[3] Mudgway, D. J., "Uplink-Downlink, A History of the Deep Space Network 1957–1997," National Aeronautics and Space Administration, Washington, DC, 2001.

[4] Steffes, S. R., Barton, G. H., Bhatt, S. A., Fritz, M. P., King, E. T., and Woffinden, D. C., "Deep Space Autonomous Navigation Options for Future NASA Crewed Missions," AIAA SPACE and Astronautics Forum and Exposition, February 2018, pp. 5369.

[5] Collicott, B. C., and Woffinden, D., "Lunar navigation performance using the deep space network and alternate solutions to support precision landing," In AIAA Scitech 2021 Forum, 2021, pp. 0375.

[6] Cesarone, R. J., Abraham, D. S., and Deutsch, L. J., "Prospects for a next-generation deep-space network," Proceedings of the IEEE, Vol. 95, No. 10, 2007, pp. 1902-1915.

[7] Witternigg, N., Obertaxer, G., Schönhuber, M., Palmerini, G. B., Rodriguez, F., Capponi, L., ..., and Floch, J. J., "Weak GNSS signal navigation for Lunar exploration missions," Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015), Tampa, Florida, September 2015, pp. 3928-3944.

[8] Capuano, V., Basile, F., Botteron, C., & Farine, P.-A., "GNSS-based Orbital Filter for Earth Moon Transfer Orbits," Journal of Navigation, Vol. 69, No. 4, 2-16, pp. 745-764.

[9] Bhamidipati S., Mina T., and Gao G., "Design Considerations of a Lunar Navigation Satellite System with Time-Transfer from Earth-GPS," Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), St. Louis, Missouri, September 2021, pp. 950-965.

[10] Hagenau, B., Peters, B., Burton, R., Hashemi, K., and Cramer, N., "Introducing the Lunar Autonomous PNT System (LAPS) Simulator," IEEE Aerospace Conference (AERO), March 2021, pp. 1-11.

[11] Wen, Y., Zhu, J., Gong, Y., Wang, Q., and He, X., "Distributed orbit determination for global navigation satellite system with inter-satellite link. Sensors," Vol. 19, No. 5, pp. 1031.

[12] Frank, J., Levinson, R., Hillsberg, E., Cramer, N., and Burton, R., "Distributed scheduling of position estimation updates in ad-hoc lunar constellations," AAAI Spring Symposium Series, 2022.

[13] Kim Y., Kempa, B., Adams, C., Levinson, R., Frank, J., "Localization of Ad-Hoc Lunar Constellations in Communication Failure Modes for Distributed Spacecraft Autonomy", Proceedings of the 2025 International Technical Meeting of The Institute of Navigation, January 2025.