

Communication-Oriented Evaluation of Swarm Configurations for Lunar Radio Astronomy

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Abstract—Distributed lunar satellite swarms for low-frequency radio astronomy must satisfy interferometric and communication requirements. Designing such swarms is challenging because configurations that satisfy imaging requirements may exhibit very different communication behavior during mission operations. Swarm geometry determines the baseline distribution available for interferometric imaging. It also governs the time-varying inter-satellite communication topology required for data exchange outside the observation phase. This paper presents a communication-oriented evaluation of three lunar swarm initialization strategies under lunar orbital dynamics. The results show that configurations satisfying similar interferometric constraints can impose markedly different communication requirements. They further demonstrate that communication performance should be evaluated over the evolving network topology rather than from the initial swarm geometry alone. These findings indicate that communication characteristics and interferometric performance should be jointly considered during the early design of distributed lunar radio astronomy missions.

Index Terms—Satellite Swarm, Ultra-Low Frequency Radio Astronomy, Network Topology

I. INTRODUCTION

Distributed satellite swarms have emerged as a promising architecture for low-frequency radio astronomy, where nanosatellites cooperate to synthesize a sparse aperture in space. Concepts such as the Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) [1] require the swarm to satisfy scientific observation requirements and support reliable inter-satellite communication simultaneously [2].

Fig. 1 illustrates the mission workflow [3]. During the observation window on the lunar far side, the swarm performs radio-interferometric observations without Earth visibility. Afterwards, satellites enter the communication phase, during which data are exchanged, processed, and downlinked.

The scientific performance of an interferometric array is primarily determined by the distribution and temporal evolution of the baselines formed between satellite pairs. To achieve the desired angular resolution while maintaining sufficient spatial sampling, the maximum baseline length is constrained [1]. Understanding network dynamics is furthermore essential to efficiently sharing scientific data within the swarm, while optimizing energy consumption and maximizing the duration of the observation window, which represents the most scientifically valuable phase of the mission [4].

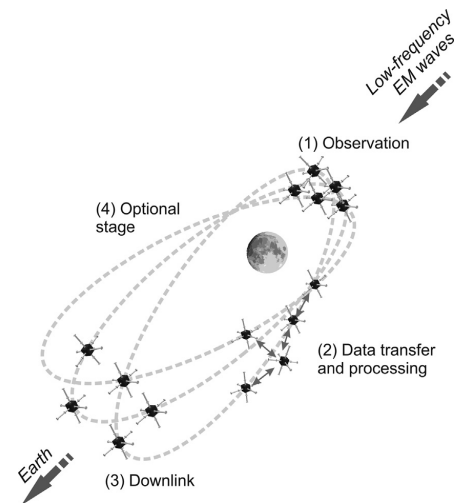


Fig. 1: Mission workflow of OLFAR [3]

Existing studies have primarily addressed orbit design and communication separately. Early OLFAR work adopted simplified mobility models to evaluate adaptive topologies [5], and Nagy *et al.* [6] proposed a communication protocol based on a static network topology. Akopyan *et al.* [4] introduced graph-based network characterization under orbital propagation, but limited the analysis to a single configuration. How different initialization strategies affect communication topology thus remains insufficiently explored.

This paper evaluates three lunar swarm initialization strategies with respect to interferometric and communication network performance. The objective is to determine how these aspects can be jointly considered when assessing candidate swarm configurations during early mission design.

II. METHODOLOGY

This section presents the methodology used to evaluate the interferometric and communication performance of dynamically evolving lunar satellite swarms. Three swarm initialization strategies are first defined and propagated under lunar orbital dynamics. All time-dependent interferometric and communication metrics are evaluated over the complete propagation interval. Their interferometric suitability is as-

sessed through the resulting characteristics during observation intervals, while their communication performance is evaluated during non-observation intervals using dynamic graph-based network metrics.

A. Swarm Initialization Strategies

Given the limited propulsion of nanosatellites, active formation maintenance is undesirable, so the swarm design instead aims to maximize natural orbital persistence while satisfying interferometric and communication requirements. We consider a swarm of N satellites evolving around a circular reference lunar orbit with radius a_0 aligned with the Earth–Moon orbital plane [7]. Since no nanosatellite swarm has yet been deployed in lunar orbit, we draw on several common initial configurations [8], [9] alongside one that we propose.

1) *Perturbed Orbital-Element Initialization (POEI)*: In POEI, satellite parameters are generated by perturbing a common reference orbit: the semi-major axis a_0 is held fixed, while the remaining orbital elements are perturbed using zero-mean Gaussian noise [8].

$$\boldsymbol{\eta}_i = \boldsymbol{\eta}_0 + \boldsymbol{\epsilon}_i, \quad \boldsymbol{\epsilon}_i \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Sigma}), \quad (1)$$

where $\boldsymbol{\eta}_0$ is the reference set of orbital elements and $\boldsymbol{\Sigma}$ defines the perturbation variances.

2) *Uniform Orbital-Element Initialization (UOEI)*: In UOEI, each satellite is initialized by independently sampling orbital elements within predefined ranges around a reference orbit. The semi-major axis remains fixed at a_0 , whereas the remaining orbital elements are sampled from uniform distributions [9]:

$$\boldsymbol{\eta}_i \sim \mathcal{U}(\boldsymbol{\eta}_{\min}, \boldsymbol{\eta}_{\max}), \quad (2)$$

where $\boldsymbol{\eta}_i$ denotes the set of variable orbital elements for satellite i . The sampling bounds are selected such that the resulting swarm initially satisfies the mission baseline constraint D_{max} while allowing a dispersed orbital configuration.

3) *Lens-Based Initialization (LBI)*: Unlike POEI and UOEI, which apply random offsets to a reference orbit, LBI directly prescribes the initial geometry: satellites are sampled uniformly on a spherical cap of maximum extent $D_{max}/2$ centered on a reference satellite, forming a lens-shaped configuration that bounds the initial inter-satellite baselines to D_{max} . Each satellite is assigned the local circular-orbit velocity, directed tangentially with respect to the lunar north-pole axis. The swarm thus forms a three-dimensional spatial distribution while maintaining approximately circular orbital motion.

B. Interferometric Performance Metrics

1) *Observation Window*: Astronomical observations can only be conducted when the swarm is shielded from terrestrial radio-frequency interference by the Moon [3]. Accordingly, an observation window is defined as a continuous time interval during which all satellites in the swarm are simultaneously occulted from the Earth by the Moon. Longer observation windows are preferred, as they provide more uninterrupted time for interferometric measurements.

2) *Baseline-Length Characteristics*: The baseline lengths characterize the range of spatial scales sampled by the swarm. Shorter baselines provide sensitivity to larger angular structures, whereas longer baselines contribute to higher angular resolution. Their statistical characteristics are evaluated together with the baseline constraint D_{max} to compare the spatial sampling provided by the different initialization strategies.

C. Communication Performance Metrics

At each timestamp t , the swarm is represented as an undirected graph $\mathcal{G}(t)$. A communication link between satellites i and j is established when their separation is within a prescribed communication range R_C , which is treated as a scenario parameter. By varying R_C , the impact of communication range on network connectivity can be evaluated. The following graph-based metrics are considered [4]:

- The node degree is the number of direct communication neighbors of a satellite, and the k -vicinity extends this concept to nodes reachable within k hops.
- The number of connected components $C(t)$ quantifies network fragmentation, where $C(t) = 1$ indicates a fully connected network.
- For each satellite pair (i, j) , the Inter-Contact Time (ICT) is defined as the fraction of the analysis interval during which the corresponding communication link is unavailable. Two aggregate ICT metrics are considered. The first is the mean ICT over all theoretical pairs, reflecting the overall feasibility of direct communication across the swarm. The second is the mean ICT over existing links only, where an existing link is a pair that is connected at least once during the analysis interval. This metric reflects the temporal stability of communication links that actually occur. Satellite pairs with an ICT of zero form the persistent backbone of the network.

III. SIMULATION SETUP

The orbital evolution of the three configurations is propagated using TUDAT [11]. The gravitational attraction of the Moon, Earth, and Sun is included. For the lunar gravity field, the first six spherical harmonic coefficients are considered. Each configuration is propagated for 5 days, which is approximately 40 lunar orbits. The global parameters of the simulation are listed in Tab. I.

TABLE I: Simulation parameters

Notation	Definition	Value
N	Number of satellites	50 [1]
h	Altitude (km)	680 [10]
D_{max}	Maximum baseline length (km)	100 [1]
T_s	Simulation duration (orbit)	40
R_C	Communication range (km)	5–60 km (step: 5 km)
k	k -vicinity depth	[1; 2; 3]

IV. RESULTS AND DISCUSSION

A. Interferometric Performance

The three configurations provide comparable observation opportunities. The average observation windows are approx-

imately 2620 seconds for POEI and LBI, and 2510 seconds for UOEI. The slightly shorter windows obtained with UOEI are likely related to its larger orbital-element variations, which cause some satellites to traverse the lunar far side region more rapidly. A detailed investigation of the relation between orbital elements and the observation window is outside the scope of this work.

Fig. 2 summarizes the baseline-length statistics over all observation windows. POEI primarily produces short baselines, indicating a compact swarm geometry. Although this supports dense short-baseline sampling, the limited number of long baselines may reduce the achievable angular resolution. UOEI exhibits the widest spread in baseline lengths, but a substantial fraction exceeds the 100 km mission constraint. LBI achieves an intermediate spread, providing considerably broader baseline coverage than POEI while effectively limiting the maximum baseline to the required range. These results indicate that LBI provides a strong compromise between baseline-length coverage and constraint compliance while avoiding orbit control for all 40 orbits.

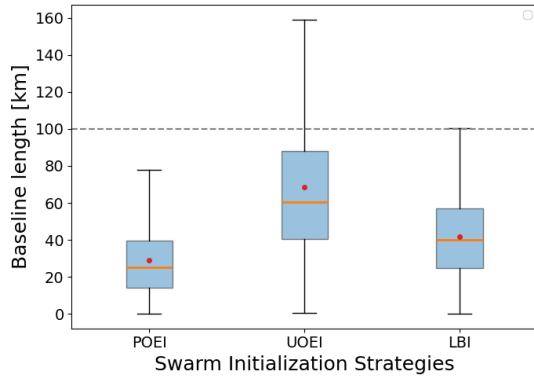


Fig. 2: Baseline distribution within observation windows. The orange line indicates the median, the red marker indicates the mean, and the dashed line denotes the 100 km maximum baseline constraint. Outliers are omitted for clarity due to the large sample size; the fractions of baseline samples exceeding 100 km are 0.2% for POEI, 18.2% for UOEI, and 0.0% for LBI.

B. Communication Network Performance

Fig. 3 illustrates the sensitivity of network connectivity to the communication range. While all three configurations eventually become fully connected as the communication range increases, the required communication range differs markedly among the initialization strategies. For POEI and LBI, at short communication ranges (5–10 km), small changes in pairwise distances during orbital evolution can cause links to appear or disappear, resulting in larger temporal variations in the number of connected components. In contrast, UOEI remains fragmented over a much wider range and requires a substantially larger communication range to achieve full connectivity. This behavior results from its broader spatial separation (Fig. 2), which produces more isolated clusters that cannot be bridged until the communication range is

sufficiently increased. These results indicate that UOEI places more demanding communication requirements on the swarm than POEI and LBI, potentially increasing transmission power requirements.

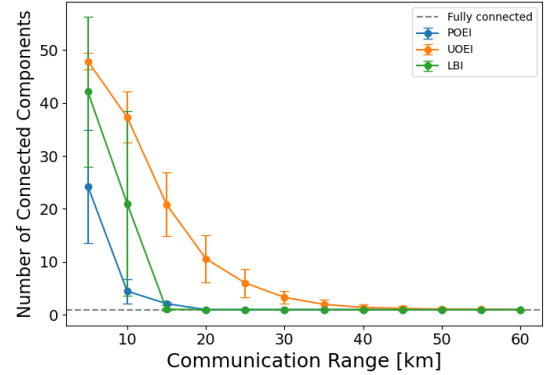


Fig. 3: Network fragmentation as a function of communication range, measured by the mean number of connected components. The dashed line indicates full network connectivity. Error bars denote the standard deviation across communication phase timestamps.

Based on this comparison, a communication range of 30 km is selected for the remaining network analysis. At this range, POEI and LBI are fully connected while UOEI remains partially fragmented. The selected range is not intended as a link-budget-derived design value, but serves as a discriminative operating point for comparing topology-induced connectivity differences.

The resulting graph-based metrics are summarized in Tab. II. Backbone-node statistics are computed only for nodes participating in at least one persistent backbone link. POEI achieves the strongest communication performance because its compact spatial distribution maintains more persistent communication links, resulting in the highest mean node degree, the lowest mean ICT, and the largest persistent backbone. LBI remains globally connected but exhibits fewer direct links and a less redundant backbone. In contrast, the broader spatial separation in UOEI produces a sparse topology with high ICT, a small persistent backbone, and recurrent fragmentation.

TABLE II: Network metrics at $R_C = 30$ km.

Metric	POEI	UOEI	LBI
Mean degree	27.6	10.86	17.69
Degree std.	9.07	6.60	4.12
Mean components	1.00	3.32	1.00
Mean ICT, all pairs	43.7%	77.8%	63.9%
Mean ICT, existing links only	12.1%	62.4%	35.1%
Backbone-pair ratio	46.3%	3.4%	23.1%
Mean backbone-node degree	22.68	2.21	11.32
Backbone-node degree range	2–37	1–7	6–16

Fig. 4 shows the temporal evolution of the mean k-vicinity at a 30 km connection range. The periodic oscillations observed in all configurations are caused by the time-varying relative geometry of the swarm during orbital propagation, which periodically modifies the underlying communication

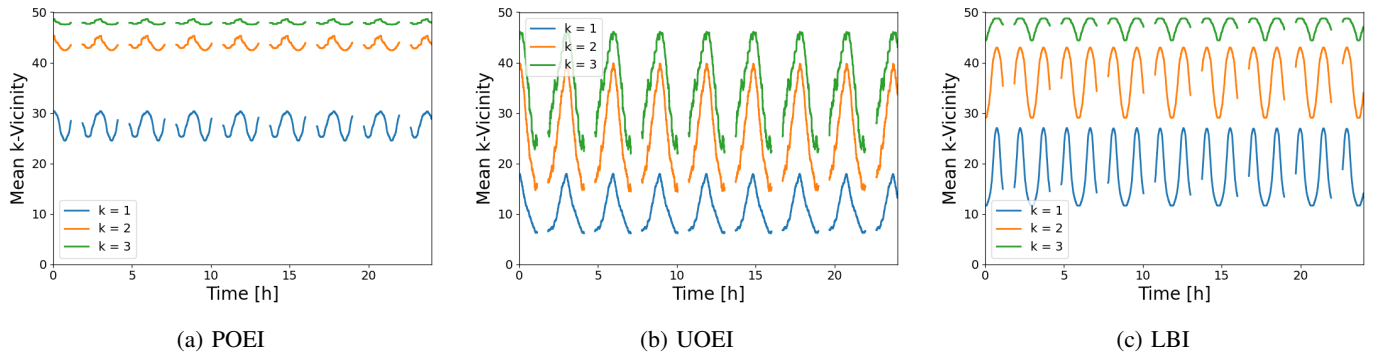


Fig. 4: k -vicinity over time at $R_C = 30$ km. The network behavior is periodic; therefore, one representative day of propagation, corresponding to approximately eight lunar orbits, is shown.

graph. POEI maintains high and stable reachability across all hop counts, with limited variation between orbits, indicating that its communication topology is less sensitive to orbital evolution and remains consistently connected over time. LBI experiences stronger oscillations in one- and two-hop vicinity, reflecting greater sensitivity of local neighborhoods to changes in pairwise distances. However, its three-hop vicinity remains relatively stable and close to the total swarm size, suggesting that alternative multi-hop paths compensate for temporary degradation of local connectivity and preserve large-scale reachability. In contrast, UOEI shows the largest oscillation amplitude and the lowest k -vicinity values across hop counts, consistent with its fragmented topology observed in Tab. II, and indicating that a substantial portion of the swarm periodically becomes unreachable even via multi-hop paths.

V. CONCLUSION

This paper presented a communication-oriented evaluation of three lunar swarm initialization strategies for radio interferometry: POEI, UOEI, and LBI, jointly assessed in terms of observation opportunities, baseline-length distribution, and time-varying communication performance under lunar orbital propagation.

While the three configurations offered comparable observation opportunities, their communication characteristics differed markedly. POEI forms a dense, persistent topology, but its compact baseline distribution limits long-baseline coverage. UOEI provides the broadest baseline coverage but frequently violates the maximum-baseline constraint and exhibits fragmented communication. LBI provides a favorable balance between interferometric and communication performance, offering a broader range of baseline lengths than POEI while respecting the baseline constraint and maintaining global multi-hop connectivity at a moderate communication range.

This work underscores the value of communication-aware evaluation in early-stage design of distributed radio astronomy missions. Complementing orbital and interferometric analysis with graph-based network characterization lays a foundation for future communication-aware swarm optimization, jointly designing formation geometry, network topology, and resource allocation.

Future work will incorporate repeated randomized realizations, detailed link-budget and energy models, and communication-aware formation optimization to translate network requirements into explicit swarm-design constraints.

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