A LEO-SAR CONSTELLATION EQUIVALENT TO AN INTERFEROMETRIC GEOSYNCHRONOUS MISSION

Jalal Matar[1], *Marc Rodriguez-Cassola*[1], *Eduardo Rodrigues Silva Filho*[1], *Nida Sakar*[1], *Valeria Gracheva*[2], *Martin Suess*[2], *Gerhard Krieger*[1] *and Alberto Moreira*[1]

[1]German Aerospace Center (DLR), Microwaves and Radar Institute, Germany
[2]European Space Agency (ESA)

ABSTRACT

Geosynchronous synthetic aperture radar (SAR) missions offer the advantage of conducting multiple sub-daily interferometric acquisitions using a single platform. However, this comes at the expense of increased fuel and power budgets due to the significant distance to the Earth's surface. Consequently, such missions are suited for delivering SAR products with relatively lower spatial resolutions, typically hundreds of meters, over large localized areas spanning over one million square kilometers. Alternatively, a constellation of small SAR satellites operating in low Earth orbits (LEO) can also deliver similar interferometric products. In LEO, the reduced free-space propagation losses and simpler orbit insertion can be exploited to realize and operate a larger constellation of LEO-SAR satellites. This paper provides an equivalence framework between the two alternatives in terms of interferometric lags and coverage. It further outlines an example mission concept equivalent to Hydroterra, one of ESA's Earth Explorer 10 candidate missions.

Index Terms— Synthetic Aperture Radar (SAR), Constellations, Interferometry, Diurnal processes

1. INTRODUCTION

Geosynchronous synthetic aperture radar (SAR) missions allow for persistent monitoring of Earth processes on a continental scale. One notable example is Hydroterra, a candidate mission under ESA's Earth Explorer 10 program, which proposed placing a SAR system in a geosynchronous orbit to observe key processes in the diurnal water cycle [1]. The unique design of its orbit allows for multiple sub-daily repeat-pass interferometric and radiometric acquisitions, relevant for measuring integrated water vapor, snow water equivalent, landslides, surface soil moisture, and more, over target areas in Europe and Africa using a single platform [2].

Alternatively, an equivalent imaging capability can be achieved from low Earth orbits (LEO) by deploying formations of small SAR satellites to provide a similar number of sub-daily interferometric lags over target areas, such as the Mediterranean basin or the Sahel. This approach harnesses the enhanced efficiency offered by LEO, including the reduced free-space propagation losses (around 60 dB) and simplified orbit insertion to establish and operate a larger constellation of small LEO-SAR satellites. Fig. 5 illustrates the basic concept of the LEO-SAR constellation. It comprises multiple satellite clusters flying on one-day repeat orbits, typically sun-synchronous orbits (SSO). The different orbital planes, offset by their respective right ascension of the ascending node (RAAN), are utilized to achieve the required sub-daily interferometric lags using, making use of the Earth's rotation. Meanwhile, within each cluster, the satellites collaborate to ensure the coverage of the specific target areas. The collaborative coverage can be accomplished by deploying identical instruments (a favorable characteristic) on the same orbital plane separated by a time delay ΔT, or by placing them on adjacent orbital planes offset by their respective RAAN.

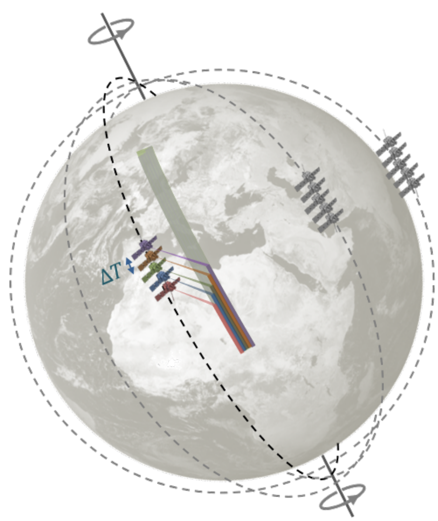

Fig. 1: A constellation of small LEO-SAR satellites capable of wide-swath coverage and sub-daily interferometric acquisitions.

In this paper, we investigate the equivalence between interferometric geosynchronous systems and LEO-SAR constellations in terms of sub-daily lags and coverage, and provide a mission example equivalent to Hydroterra with detailed specifications on the instrument, orbits, and cluster sizes.

2. EQUIVALENT LEO-SAR CONSTELLATIONS

The equivalence of SAR missions can be defined by their ability to deliver comparable end products that align with consistent mission objectives. Within this framework, key factors include the SAR mission's sub-daily interferometric capability and the coverage of predefined regions of interest with consistent imaging quality.

2.1. Sub-daily Interferometric Lags

The nature of the sub-daily interferometric lags of a geosynchronous mission, such as Hydroterra, are highlighted in Fig. 2, where the elliptical trajectory of the spacecraft within a sidereal day is plotted on a longitude-latitude grid. The markers represent the centers of potential SAR acquisition intervals with one, three, or six-hour revisits. A cohesive sub-

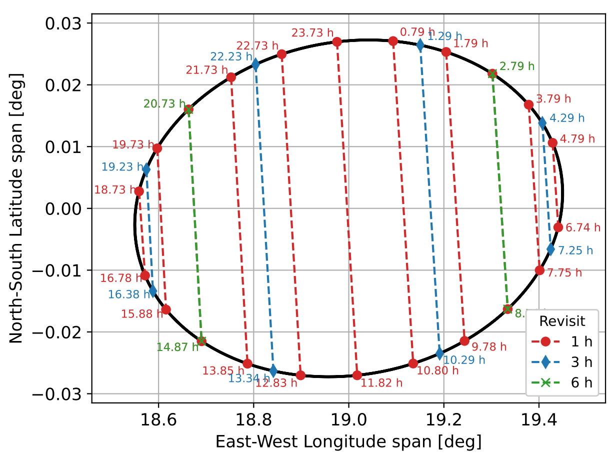

Fig. 2: Example of interferometric pairs obtained from Hydroterra, showcasing acquisitions with revisit intervals of 1 h, 3 h, and 6 h over a region in the Alps. The time is plotted relative to the time at the orbit's perigee.

daily interferogram can be formed by pairing an acquisition in the northern block with its traced counterpart in the southern block and vice versa. Hydroterra can offer seventeen, seven, or three sub-daily lags for the one, three, and six-hour revisit modes, respectively. On the other hand, an equivalent repeat-pass interferometric LEO-SAR mission can deploy C clusters on one-day repeat orbits, shifted in their RAAN, to achieve a similar number of sub-daily lags

$$L_{\mathrm{sub}} = C \cdot (C-1)\,. \tag{1}$$

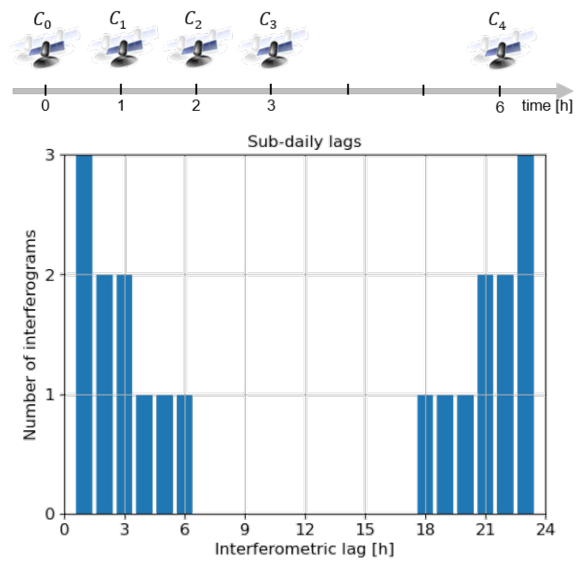

Fig. 3: Distribution of the twenty sub-daily interferometric lags from an example of five LEO-SAR clusters.

Fig. 3 shows the distribution of twenty sub-daily interferometric lags derived from an example of five clusters C_0 to C_4. The discrete time delays to the first cluster, plotted in hours at the top of the figure, enable the simultaneous fulfillment of the radiometric revisit requirement, with a one-hour shift corresponding to around 15 degrees offset in the RAAN. It is worth noting that a single differential interferogram requires four acquisitions from a geosynchronous SAR mission, whereas its LEO-constellation counterpart requires only three acquisitions. Fig. 2 illustrates the overlapping nature of the interferograms (with one being a subset of another), which might lead to an increase in the complexity of the inversion process. Considering this factor and the optimistic assumption of seventeen sub-daily lags for Hydroterra, a smaller LEO-SAR formation consisting of four clusters, providing the twelve sub-daily lags as depicted in Fig. 4, could yield similar information for the inversion process.

2.2. Localized Coverage

The coverage rate of LEO-SAR satellites is remarkably high; however, their accessibility, in terms of both spatial span and latitude reach, is closely linked to the orbital altitude and inclination. Fig. 5 shows the six observation scenarios for Hydroterra, each requiring exclusive coverage with varying spatial and temporal resolutions. Among these scenarios, E1 poses the most formidable challenge concerning coverage area, requiring a total swath width of 1,420 km from a single pass (ascending or descending) in a near-polar orbit. The total swath width can be notably reduced, e.g., to around 890 km, if the overlap region between ascending and descending passes can be aligned with the targeted region. For the

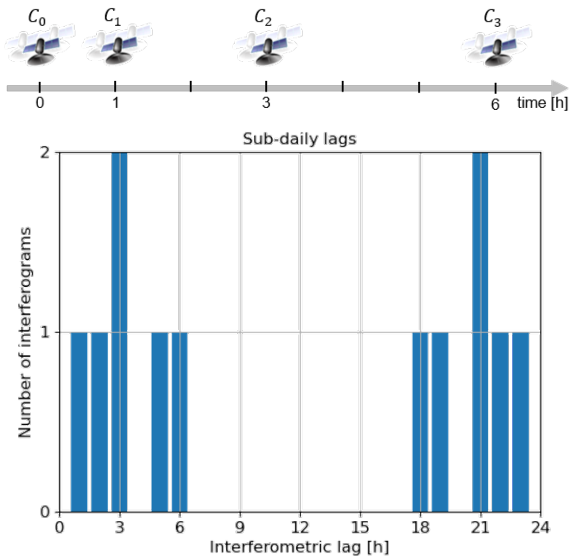

Fig. 4: Distribution of the twelve sub-daily interferometric lags from an example of four LEO-SAR clusters.

SSOs under consideration, the overlap is driven by the orbital altitude and observation geometry, i.e., incident angle range. Another approach is to adjust the orbital inclination to the latitude of the targeted region and the incident angle, which can reduce the single-pass swath width, e.g., to 1200 km. However, this will cause a loss in sun-synchronicity and introduce deviations in the local time of repeat passes.

3. EXAMPLE MISSION CONCEPT

This section introduces an example mission concept equivalent to Hydroterra, which helps illustrate the presented equivalence framework. The derivation of the various parameters builds upon the information provided in the preceding sections, specifically pertaining to the configuration of four to five satellite clusters and the overall swath width requirement. The design concept revolves around distributing the coverage of the wide swath among a cluster of identical spacecraft equipped with SAR.

When considering the orbit design, a limited number of one-day repeat SSOs are available at LEO altitudes. Examples of such orbits occur approximately at altitudes of 561 km, 888 km, and 1,257 km, resulting in 15, 14, and 13 revolutions within the one-day repeat cycle, respectively. The choice of the orbit impacts both the power budget and coverage. In LEO, the power budget is considerably more relaxed compared to a geosynchronous scenario. Therefore, the selection can prioritize the efficient coverage of the target region for the required SAR observation geometry, e.g., above 24-degree incidence. Table 1 presents the key parameters of the selected SSO at an altitude of 561 km tailored for the LEO-SAR formation. The orbit enables the full coverage of E1,

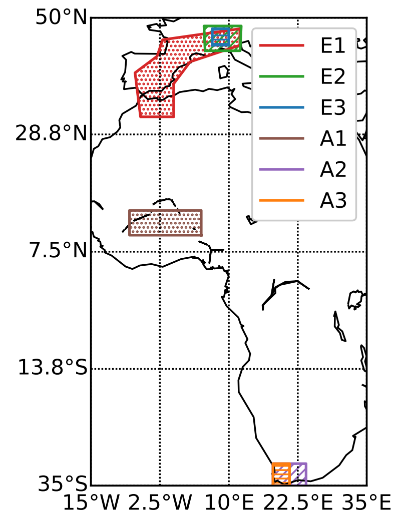

Fig. 5: Reference observation scenarios for the Hydroterra Mission over Europe and Africa.

Table 1: Parameters for a sun-synchronous orbit at 561 km altitude, suitable for the suggested LEO-SAR constellation.

Orbit parameter	Value
Type	1-day repeat SSO
Semi-major axis [km]	6939.128
Inclination [deg]	97.635
Eccentricity	0.001160
Argument of perigee [deg]	90
RAAN [deg]	342

shown in Fig. 5, by employing both ascending and descending passes, with a total swath width of 890 km.

Regarding the design of the SAR instrument for the individual spacecraft, the antenna dimensions are calculated based on several factors [3]. These factors include the swath portion targeted for coverage, the degree of ambiguity suppression required, the acquisition geometry, backscatter law [4], and the selected mode of operation [5]. In this example, the systems are operated in Stripmap mode to ensure simplicity and minimize the overall complexity of the instrument. The average transmit power of 17 W is calculated based on a target Noise Equivalent Sigma Naught (NESN) of -20 dB and a 2-D resolution of 2,500 m^2. The latter corresponds to the highest goal resolution of Hydroterra. In practice, Hydroterra targets a 1 km^2 resolution for larger regions such as E1 and A1, and enhanced resolutions in smaller regions such as 10,000 m^2, 40,000 m^2, and 250,000 m^2. Table 2 provides the main system parameters and performance metrics for a cluster of ten identical satellites. Each satellite is designed to cover a swath width of 90.6 km. The cumulative coverage capacity reaches the required 890 km, assuming a two-percent overlap between individual swaths. It is important to em-

Table 2: Relevant parameters and performance metrics for a formation of ten identical LEO-SAR satellites at 561 km.

Parameter	Value
Antenna area [m^2]	3.1
Frequency [GHz]	5.405
Individual swath width [km]	90.6
Swath overlap [km]	1.8
Incident angle range [deg]	24 - 32.1
Pulse repetition frequency [Hz]	1595
Doppler bandwidth [Hz]	517.5
Transmit duty cycle [%]	10
Two-way losses [dB]	3
Noise figure [dB]	3
Average power [W]	17
2-D SLC resolution [m^2]	17.5×143
Ambiguity-to Signal Ratio [dB]	$<$ -22
NESN [dB]	$<$ -20

phasize that the average orbit duty cycle needed to cover the designated Hydroterra regions is only a few minutes per orbit, highlighting the potential to leverage available resources for extending the acquisitions toward near-global coverage. This expansion is facilitated by the numerous daily revolutions of a spacecraft in a LEO, such as the 15 revolutions in the suggested orbit at an altitude of 561 km. Fig. 6 demonstrates the full coverage of E1 by employing the proposed solution. The aggregation of the swath is enabled by either situating neighboring spacecraft on orbital planes offset by 1.06 degrees from the reference orbit detailed in Table 1, or by aligning them within a singular orbital plane, each with an incremental delay of 4.23 minutes. The latter configuration exploits the Earth's rotational movement to extend coverage.

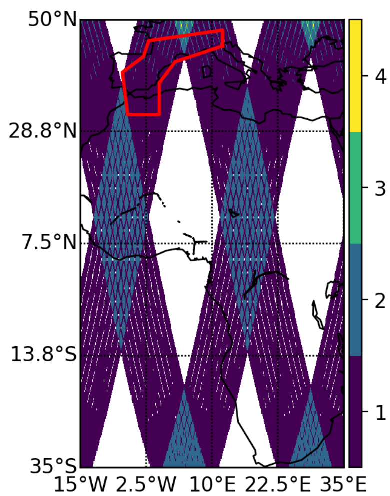

Fig. 6: Potential coverage of the E1 region with a total swath width of 890 km, achieved by deploying a cluster of 10 Satellites in a SSO at an altitude of 561 km.

In this example mission concept, the full formation comprises 40 or 50 satellites evenly distributed over four or five clusters, respectively. The configuration could be optimized at the cost of increased power demand or added instrument complexity. For instance, by adjusting the observation geometry to a steeper incident angle range, e.g., between 20 and 31.2 degrees, it becomes possible to cover wider sub-swaths of 121 km. This enables the reduction of the cluster size to seven satellites, resulting in a downsized formation with a total of 28 or 35 satellites. This adjustment also reduces the required antenna area to 2.1 m^2 but necessitates a 3.4 dB increase in average transmit power to maintain the target NESN. The required satellites for the proposed systems appear to belong to the 100 kg mass category. Additional optimizations to simplify the overall formation could involve employing multiple channels, different antenna topologies, and varying the operational mode. However, these considerations fall outside the scope of this paper.

4. CONCLUSIONS

This paper introduces the equivalence between a constellation of compact SARs in LEO and monostatic SAR systems strategically positioned in geosynchronous orbits to observe diurnal processes on Earth via sub-daily interferometric acquisitions. The work illustrates that a few satellite clusters deployed in rotated LEO planes can generate numerous sub-daily interferometric lags. Additionally, our results demonstrate that a group of highly-efficient LEO-SAR systems can enable the coverage of large regions of interest. These findings are supported by an example mission concept analogous to Hydroterra–an Earth Explorer 10 concept, providing detailed insights into formation size, key instrument parameters, and achievable SAR performance.

5. REFERENCES

[1] R. Haagmans et al., "Earth Explorer 10 Candidate Mission Hydroterra," *ESA Report Assessment*, 2020.

[2] V. Queiroz de Almeida et al., "Orbit, Performance and Observation Scenarios for ESA's Earth Explorer Mission Proposal Hydroterra," in *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*, 2021, pp. 7740–7743.

[3] A. Freeman et al., "The "Myth" of the minimum SAR antenna area constraint," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 38, no. 1, pp. 320–324, 2000.

[4] F. Ulaby, M. Dobson, and J. Álvarez-Pérez, *Handbook of Radar Scattering Statistics for Terrain*, 2019.

[5] J. Curlander and R. McDonough, *Synthetic Aperture Radar: Systems and Signal Processing*, vol. 11, Wiley, New York, 1991.