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Definition of a Small-Sats Constellation Geometry for the Detection and Localization of Radio-Frequency Interference Signals

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Abstract

Due to the proliferation of radio frequency interference (RFI), it is becoming critical for GPS users to be aware of local interferences, especially for safety and critical applications. This study proposes the mission design and the trajectory design and verification of a CubeSats constellation in Low Earth Orbit devoted to detect and localize GPS interferents on the ground surface. The ultimate goal of the study is to design the geometry of a constellation to maximize the probability of detecting and localizing RFI over Eastern and Southern Europe, with a focus on Mediterranean European countries.

The adopted approach foresees a first iteration of the design focused on a basic formation of three phased satellites to perform the detection of the RFI source and the related precise localization, guaranteeing that the three satellites cover contemporary the target area (where the RFI is located) and sense the interferent signals for at least one minute. The second iteration allows to moving on the definition of the constellation geometry that enables an improvement on the revisit time and a faster download of the information to the ground stations. This second step leads to the operational service where a revisit time of less than 6 hours and a latency on downloading information of few minutes are requirements to be satisfied.

Multiple analyses were conducted on both iterations, which showcased the effectiveness of the proposed solution. In both instances, the mission geometry satisfied the conditions set by the jammer for the communication link, along with the necessary revisit intervals for the area of interest. Furthermore, the simulations results show that the selected orbit geometry facilitate the complete downlink of data gathered on interference at the ground stations taken into account during the missions design process.

1. Introduction

Global Navigation Satellite Systems (GNSS), including GPS, GLONASS, Galileo, and BeiDou, provide essential services for navigation, timing, and synchronization across diverse sectors, ranging from aviation and maritime operations to telecommunications and financial markets. Despite their fundamental role, GNSS signals are inherently weak when received on Earth and thus highly vulnerable to intentional interference such as jamming, intended as a simple denial of the service through the overload of the receiver with noise, and spoofing, intended as deceiving the receiver into reporting false position, velocity and time information, potentially leading to hazardous misinterpretation [1]. Low-cost jamming devices are widely available and capable of disrupting GNSS receivers at ranges of several kilometers, posing severe risks to safety-critical applications [2] [3].

Several experimental studies have demonstrated the effectiveness of commercial jammers in real-world environments. As mentioned in [2] and [4], consumer-grade devices with output powers of only 1–2 W can disrupt GNSS receivers over distances exceeding 10–15 km in free-space conditions, with even greater impact on airborne users. Such results confirm the urgency of developing monitoring services capable of detecting and localizing interference events in near real-time. Beyond

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defense applications, jamming and spoofing of GNSS signals can have severe consequences on day-to-day activities, particularly in the aviation and satellite navigation domains, where intentional interference may critically compromise the safe operation of these platforms [3] [4].

One way to think about this service is to develop a constellation of satellites. In fact, small-sats constellation are gaining interest for a wide range of space missions, such as telecommunications [5], in-orbit servicing [6], [7], search and rescue, remote sensing [8], and defence. The presented work addresses this challenge by investigating the design of a small-sat constellation to detect and localize radiofrequency interference (RFI) sources over Europe, starting from the analysis of the possible features of a jammer and the technology available for small satellites in terms of receivers and antennas. The paper discusses the advantages and disadvantages of this constellation, highlighting its performance in terms of revisit time, coverage, and link strength.

This paper is organized as follows. Section 2 introduces the simulation setup and adopted methodology, including jammer definition, receiver assumptions, and constellation generation. Section 3 presents a numerical evaluation of the proposed approach, focusing on the single-triplet design and its extension to a full constellation; results are reported from simulation campaigns approximating real-world conditions. Finally, Section 4 concludes by summarizing the main findings and outlining directions for future research and implementation.

2. Simulation Setup and Methodology

In order to characterize the threat environment, representative classes of GNSS jamming sources [9] are considered. Portable and vehicle-mounted wideband chirp jammers are widely documented in the literature, with experimental campaigns that have shown that devices with output powers as low as 1–2 W can disrupt consumer-grade receivers over distances of 10–15 km in free-space conditions, with an even greater impact on airborne platforms [2] [4]. These results align with recent surveys confirming that *blanket interference*, particularly in the form of wideband noise signals, remains the most common and effective type of intentional interference, given its low cost and ease of implementation [10]. On this basis, two Effective Isotropic Radiated Power (EIRP) tiers are selected for the analysis: a low-power case of approximately $3.5\,\mathrm{dBW}$ ($\approx 2.2\,\mathrm{W}$) and a high-power case of $10\,\mathrm{dBW}$ ($\approx 10\,\mathrm{W}$). Expressing EIRP in dBW ensures that transmitter power, antenna gain, and feeder losses are consistently accounted for. These tiers bracket the range of values reported for commercial jammers and provide a realistic envelope for subsequent link budget evaluations. Moreover, two types of service are identified: detection of a source and localisation of a source. Through a literature review, it has been highlighted that the detection can be achieved by a single satellite while the localisation needs at least three satellites that must contemporaneously maintain the link with the jammer for at least one minute. From [9], the Goodness of Fit algorithm (GoF), considering a front end bandwidth of 20 MHz, needed a minimum received power of about -140 dBW. In order to keep a conservative link budget evaluation for the subsequent analyses, 1 dB margin is assumed, thus setting the worst case requirement of -139 dBW for the considered class of jammers - wideband chirp jammers - for which the sweep bandwidth is equal to the front-end bandwidth, set to 20 MHz. Table 1 summarises and integrates the above-described assumptions and considerations.

Table 1: Jammer emitter power specifications for high-power and low-power configurations.

Quantity	**High-power**	**Low-power**
Equivalent Isotropic Radiated Power	10 dBW	3.5 dBW
Atmospheric Loss	-0.2 dB	-0.2 dB
Maximum slant range	∼1230 km	∼740 km
Received isotropic power at max slant range	-149 dBW	-149 dBW
Satellite antenna gain	∼9 dBi	∼11 dBi
Received signal power	-139 dBW	-139 dBW
Jammer-to-Noise density ratio (J/No)	∼63 dB-Hz	∼63 dB-Hz

About the reception chain on the satellite, the actual state of the art technology [11] for small-sats has been considered. Reasonable features for the antenna are reported in Table 2.

Table 2: Antenna parameters and settings.

Parameter	**Value/settings**
Antenna type	Cosine aperture circular
Frequency	1.57 GHz
Gain	12 dB
Antenna HPBW	60 deg

The constellation design is driven by the following (perfor-

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mance) requirements:

- The Monitoring Area shall cover the East and Southern Europe, with a focus on Mediterranean European countries;
- The contemporary access duration between the satellite receiver and the jammer on ground in the Monitoring Area shall be at least 1 min;
- The revisit time over the Monitoring Area shall be less than 6 hours;
- The single formation shall be composed by at least three satellites as shown in Figure 1.



Fig. 1: Example of covered area

About the Monitoring Area, it is important to express the following:

- The satisfaction of the above requirements by all three satellites at the same time defines the coverage area of each triplet (concurrent observation of the jamming signals above the requirements).
  - Maximum delay for the signal snapshots < 1 ms, i.e., two snapshots collected by two different satellites have a non-null correlation and can be used for the TDOA and FDOA measurement estimation;
  - 1 minute of common visibility.
- RFI Source Localization Accuracy leads to the definition of the service area i.e., the geographic area in which localization can be reached within 2 km of horizontal error.

The simulation is performed using commercial System Tool Kit (STK) software, exploiting its ability to model a wide variety of systems and equipment, such as receivers, antennas, and transmitters. Four relevant scenarios are analyzed, based on the jammer's EIRP and the number of receiver satellites:

1. Localization of a high-power jammer using a single satellite triplet: a scenario involving three receiver-equipped satellites and a high-EIRP (10 dBW) jamming source;
2. Localization of a high-power jammer using a triplet constellation: a scenario involving multiple triplets and a high-EIRP jamming source;
3. Localization of a low-power (3.5 dBW) jammer using a single satellite triplet;
4. Localization of a low-power jammer using a triplet constellation.

2.1 Single Triplet Scenario Setup

A first set of analyses is conducted on a single triplet scenario, modeling the "train" configuration using three identical satellites. Orbital parameters are defined according to orbit-related mission requirements and a preliminary sensitivity analysis of the problem. A transmitter representing the characteristics of the jammer is randomly positioned in the target area, defined as the European region by four points; satellite receivers are also modeled to enable link budget simulations. Satellites are propagated using only perturbations up to J4, thus simulating and assuming active orbit maintenance. By adjusting the jammer's EIRP through STK's graphical interface, both high- and low-power scenarios can be easily investigated.

A constrained link budget analysis between the jammer and the receivers is performed to verify compliance with mission requirements. The built-in STK's ITU-R P676-9 model is used to evaluate atmospheric attenuation of the link. The link budgets of both first and last receivers are used to determine the time interval during which a simultaneous link with all the satellites is guaranteed, an essential parameter for assessing localization capabilities. Complete link budget and Azimuth-Elevation-Range (AER) data relative to the jammer are retrieved and analyzed to determine the maximum range at which the communication link remains closed at the boundaries of simultaneity. The range data is then used to model a virtual sensor object,

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attached to the middle satellite of the triplet, that represents the swath area where the communication link is instantaneously closed for the entire satellite triplet. The sensor swath rounds down the yellow area shown in Figure 1. A higher jammer EIRP is expected to result in a larger coverage area, due to the extended duration of links closure. Figure 2 illustrates the initial instance of simultaneous link closure between the satellite triplet and the jammer source. The red and green shaded regions denote the areas where a jammer achieves a closed link with all three satellites, with red representing the high-EIRP configuration and green the low-EIRP case. The increased transmission power in the high-EIRP scenario results in earlier link closure and a broader coverage area, enhancing the potential for successful localization. A reduced coverage area significantly complicates service, as it becomes more challenging to maintain a continuous link with the entire triplet while still satisfying mission requirements.

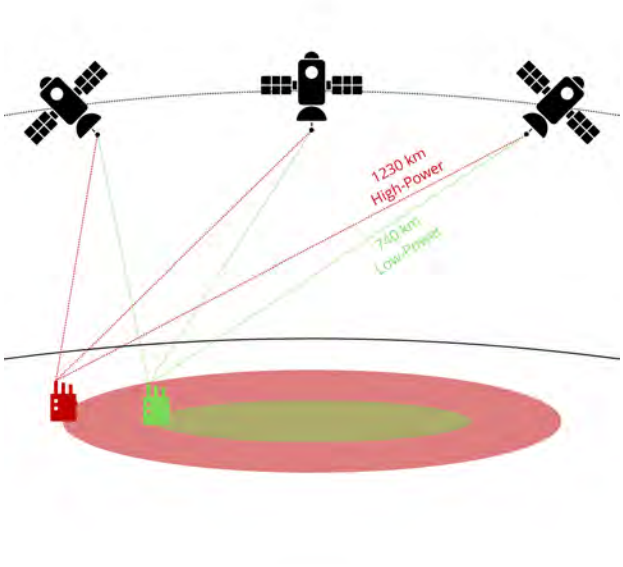

Fig. 2: High-power and low-power jammer scenarios

Virtual sensor objects are employed as assets in the coverage definition, enabling a coverage analysis based on link closure rather than optical access. Optical access analyses would include regions where the communication link is no longer available for one or more satellites, i.e. preventing localization capabilities. Once the simultaneity of the link is confirmed for a certain duration, a revisit time analysis is performed over the target area grid. This analysis aims to identify the maximum revisit time across the entire grid, thus verifying compliance with temporal requirements and ensuring full coverage of the target area. Minimum, average, and maximum revisit times are retrieved to identify critical grid points where simultaneous link availability is less frequent.

Ground stations are also included in the scenario. Multiple stations are considered and access analyzes are performed to determine the average daily number of accesses and their average duration, in order to meet the downlink requirements.

Finally, the propagator is switched to STK's High Precision Orbit Propagator (HPOP), and the satellite's physical parameters are modeled accordingly. The semimajor-axis decay and orbital lifetime are then computed to verify compliance with the minimum lifetime requirement.

2.2 Constellation Scenario Setup

This scenario extends the previous by employing STK's Walker tool to generate a complete satellite constellation, while retaining all previously defined parameters. Virtual sensors of all satellite triplets are assigned as assets in the coverage definition, allowing the evaluation of revisit time and coverage based on the link characteristics of the entire constellation. Revisit time and full coverage duration are expected to decrease significantly with the increasing number of satellites in the constellation, thereby providing an efficient service.

3. Results and Discussion

The results include the design of a satellite triplet and the overall constellation geometry, along with the corresponding revisit times and full coverage durations. Additionally, simultaneity coverage areas and ranges are reported.

3.1 Single Triplet Design

The final triplet design adopts a circular Sun-Synchronous Orbit (SSO), with a true anomaly offset of 1 degree between each satellite. An altitude of 560 km is selected to ensure a repeating ground track every 15 orbits, i.e. 24 hours. This characteristic guarantees that all covered points experience a maximum revisit time of 24 hours. The results of both low- and high-power simulations further confirm that this altitude enables a full simultaneous link coverage of the target area within a 24-hour period, thus ensuring a maximum grid revisit time of one day. The orbit is then selected to be circular in order to avoid altitude variations and to ensure a homogeneous

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service across the coverage area. Inclination is chosen to be sun synchronous to improve launch opportunities and high-latitude coverage. Table 3 recaps the triplet orbital parameters.

Table 3: Triplet orbital parameters.

Parameter	Value
Semi-major axis	6939.14 km
Eccentricity	0
Inclination	SSO
RAAN	291 deg
True anomalies	0-1-2 deg

Link closure is achieved by an individual satellite of the triplet at a maximum range of 1230 km in the high-power jammer scenario, while the low-power configuration limits the effective range to 740 km. As previously mentioned, these values influence the extent of the virtual swath area in which the jammer can be instantaneously detected and potentially localized, provided that the communication link remains simultaneously active for the triplet for at least one minute and communication constraints are satisfied. Given the Sun-synchronous nature of the orbit, polar ground stations are preferably considered, such as ESA Kiruna. They ensure an average link duration of approximately 9 minutes per pass and enable more than seven daily passes for downlink operations.

In conclusion, the proposed design successfully meets the fundamental requirements outlined in section 1, enabling the localization of a jammer within a defined area, which depends on its emitted power. Future improvements may focus on refining the configuration while preserving the train formation, particularly by optimizing the true anomaly separation between satellites. Increasing this separation could enhance localization accuracy and overall performance, albeit at the cost of reduced link simultaneity; thus, a trade-off between these aspects should be carefully investigated. Additionally, lowering the orbital altitude would extend the duration of the service link thanks to an earlier link closure, although this would come at the expense of reduced satellite lifetime and increased station-keeping demands.

3.2 Constellation Geometry

As discussed in section 2, the constellation scenario represents an extension of the triplet configuration. The triplet is used as a reference unit to generate a Walker Delta constellation composed of three orbital planes, evenly spaced by 120 deg in right ascension of the ascending node. Each orbital plane hosts two triplets, separated by 180 deg in true anomaly, while the internal configuration of each triplet maintains a 1 deg spacing in true anomaly between its three satellites (see Table 4 and Figure 3).

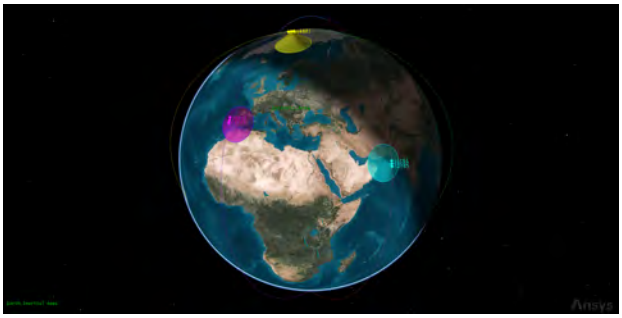

Fig. 3: Constellation implemented in STK

The Walker Delta constellation is widely recognized for its effectiveness in optimizing global coverage. Moreover, increasing the number of orbital planes reduces revisit time, thereby enhancing the probability of detecting and localizing a jammer. The constellation design here presented considers launch costs as a design driver, aiming to reduce the number of orbital planes required, and the production cost of the 18 satellites. While maintaining the current constellation architecture, increasing the number of orbital planes and satellites would lead to improved revisit times and enhanced detection capabilities. However, such improvements would come at the expense of significantly higher costs associated with launch, manufacturing, and long-term maintenance of the service. This trade-off must be carefully evaluated in future design iterations.

Since the individual triplet configurations remain unchanged, no variations are observed in the link budgets. Instead, when evaluating the full constellation, the service revisit time is significantly affected. In the high-power jammer scenario, the target area achieves complete coverage in less than 6 hours, with a maximum revisit time of approximately 4.7 hours. Conversely, in the low-power case, full coverage is obtained in about 21 hours, with a maximum revisit time of 20.9 hours. These results highlight that a low-power jammer may evade detection if active during the coverage gaps, underscoring the limitations of the current configuration in such scenarios. An increase in the number of orbital planes could be considered to further reduce the revisit time. However, such an enhancement must be carefully weighed against the substantial increase in

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Table 4: Orbital parameters per triplet (true anomaly refers to central satellite).

Triplet	Orbital Parameters
Triplet 1	RAAN: 291°, True anomalies: 0° ± 1°
Triplet 2	RAAN: 291°, True anomalies: 180° ± 1°
Triplet 3	RAAN: 51°, True anomalies: 60° ± 1°
Triplet 4	RAAN: 51°, True anomalies: 240° ± 1°
Triplet 5	RAAN: 171°, True anomalies: 120° ± 1°
Triplet 6	RAAN: 171°, True anomalies: 300° ± 1°

constellation-related costs, including launch, production, and operational expenses.

4. Conclusions

Given the broad scope of the problem, several simulation parameters remain unconstrained. This preliminary study therefore focuses on tailoring the orbital parameters to satisfy the fundamental requirements outlined in section 1. Future research should focus on a constellation optimization method to enhance localization and revisit time aspects, while meeting all the essential requirements. Although a systematic approach has been adopted, already accounting for launch constraints, propulsion system limitations, and cost considerations, further refinements in the constellation architecture are necessary to enable a comprehensive feasibility assessment of the service. Regarding the technical methodology, relying on just STK constrains the research to manual parameter adjustments and significantly slows down data post-processing. Therefore, future work should explore the integration of a Matlab/STK interface to enable automated analysis and improve workflow efficiency.

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