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A Methodological Framework for Effective GNSS RFI Localization Using LEO SDR Platforms

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Abstract—Global Navigation Satellite Systems (GNSS) are vulnerable to radio-frequency interference (RFI). Low Earth Orbit (LEO) satellites equipped with Software-Defined Radio (SDR) payloads offer a promising solution for wide-area RFI monitoring and localization. This paper proposes a methodological framework that integrates link budget validation, jammer impact assessment via carrier-to-noise density ratio degradation, and theoretical localization performance based on time-difference-of-arrival/frequency-difference-of-arrival (TDOA/FDOA) measurements. The framework introduces novel design metrics—namely the coverage and service areas—to jointly account for detection sensitivity and localization accuracy, and defines localization efficiency as a unifying benchmark. A case study demonstrates how realistic jammer transmit power, antenna patterns, and constellation geometry influence detectability and achievable accuracy. Results show localization errors on the order of 4–12 km for representative LEO constellations. The proposed framework provides a systematic benchmark for the design and evaluation of space-based GNSS RFI monitoring systems.

I. INTRODUCTION

The increasing reliance on Global Navigation Satellite System (GNSS) for a broad spectrum of civil and military applications has made them a critical infrastructure serving for a plethora of applications. However, GNSS signals remain inherently vulnerable to radio-frequency interference (RFI) [1], [2], due to their low power levels at reception and open broadcast nature. RFI can originate from both intentional and unintentional sources. Intentional interference includes deliberate jamming or spoofing designed to disrupt and deceive GNSS-based services, often associated with electronic warfare or illegal activities. In contrast, unintentional interference is typically due to radio frequency emissions produced by nearby communication systems operating in bands adjacent to the GNSS spectrum. Even minor spectral leakages beyond their allocated bandwidth can pose a significant threat to GNSS services [1].

Various approaches have been developed over time to address interference, particularly in the case of intentional threats. These include techniques for interference detection and classification, mitigation of its impact on receivers' operational capability, and localization of the interfering source, which can be either static or kinematic [3]–[5]. Furthermore, while spoofing has recently been counteracted at the system level through the introduction of signal encryption and authentication mechanisms, e.g., Galileo Open Service Navigation Message Authentication (OSNMA) [6], jamming attacks remain

highly detrimental despite the wide range of countermeasures implemented at the receiver level.

Interference monitoring techniques typically rely on a network of sensors designed to intercept and process data extracted from interfering signals [7]. The nature and configuration of the sensors used depend on the specific objectives of the RFI monitoring system. Among the various monitoring strategies, the deployment of dedicated receivers onboard low Earth orbit (LEO) satellites is gaining increasing attention in both industrial and academic domains. Besides, national and international institutions, space agencies, and military organizations are playing a key role in supporting this paradigm. This approach falls under the broader category of space electronic reconnaissance (SER), which refers to the process of detecting electromagnetic signals emitted by various sources using satellites, followed by signal processing and localization of the emitter's position [8]. Leveraging satellite constellations, especially in LEO, for GNSS interference monitoring offers several advantages, including the ability to simultaneously track authentic GNSS signals and sense potential RFI emitters on the ground [9]–[11]. Moreover, compared to terrestrial systems such as ground-based stations or UAVs, the broad spatial coverage provided by the LEO satellites makes them suitable for wide-area surveillance tasks. In this context, several studies have focused on optimizing the satellite constellation design with respect to geometric performance in support of specific localization techniques, e.g., time difference of arrival (TDOA), frequency difference of arrival (FDOA), and angle of arrival (AOA). In particular, given a fixed localization algorithm, the goal is to determine the optimal orbital parameters that maximize localization accuracy from a geometrical perspective [12], [13].

However, designing an effective RFI monitoring service requires careful consideration of the nature of the targeted interference sources. In fact, optimizing constellation geometry may not be sufficient to grant RFI detection and may not effectively support localization. One key aspect is that the power level received by the satellite constellation is not uniform across possible scenarios. It strongly depends on the relative geometry between the satellite and the RFI source, as well as the characteristics of the sensing payload and the antenna pattern of the RFI emitter. For example, an interfering source equipped with a directional antenna pattern aimed at the ground, designed for attacks against ground vehicles,

may not be easily detectable by satellites in orbit due to the low Effective Isotropic Radiated Power (EIRP) observed in orbit. Furthermore, when the goal of the monitoring system is to localize the interference source, it is essential that the localization accuracy reflects not only the absolute position of the transmitter, but also its impact on ground-based GNSS receivers. In other words, effective localization should be weighted by the degree to which interference affects operational GNSS services.

To the best of the authors' knowledge, current literature lacks a systematic framework to evaluate the performance of space-based GNSS interference monitoring systems with respect to these considerations. In this context, the present work proposes a methodology to design effective RFI localization systems based on LEO Software Defined Radio (SDR) payload, by analyzing key performance indicator (KPI), including transmitted and received interference power, C/N_0 degradation at the receiver level, and localization accuracy measured in terms of Root-Mean-Square Error (RMSE).

It is worth emphasizing that the methodological framework proposed herein serves as a theoretical design and evaluation tool for space-based RFI monitoring systems. Its primary purpose is to provide a systematic benchmark for the design phase and engineering trade-offs (e.g., selection of constellation architecture, calculation of receiver sensitivity requirements).

II. METHODOLOGY

The proposed methodology relies on a constellation of LEO satellites equipped with GNSS-disciplined SDR payloads capable of detecting, classifying, and localizing terrestrial RFI sources. The detection sensitivity of the payload is hereafter denoted as ξ . To ensure that the satellite system provides a significant advantage over terrestrial monitoring, whose performance is often limited by emitter-induced degradation and relies on techniques such as received signal strength (RSS) analysis or collaborative mapping networks, the localization algorithm must maintain high estimation accuracy across the majority of the coverage area defined by the constellation. In this study, the localization algorithm adopts a combination of TDOA and FDOA measurements as a representative case study [7], [14]. The methodological steps are summarized as follows:

- 1) **Link budget validation and C/N_0 degradation at nearby GNSS receivers:** The jammer-to-satellite link budget is first analyzed and validated to confirm that the received power on board is sufficient for reliable detection. The analysis accounts, among other parameters, for free-space path loss, antenna gains, atmospheric attenuation, and the minimum RFI power required by the detection algorithms. In parallel, it is essential to determine the impact area of the RFI source, as this sets an upper bound on the localization performance achievable for an effective monitoring system (see steps 2 and 4). The impact area is parametrically defined by the level of C/N_0 degradation experienced by a

terrestrial GNSS receiver as a function of its distance from the RFI source.

In the presence of an RFI source, the carrier-to-noise density ratio received at the GNSS receiver is assumed to degrade due to the additional noise power. The degraded C/N_0 is given by

$$\left(\frac{C}{N_0}\right)_{\text{jammer}} = \frac{C}{N_0 + I} \quad (1)$$

where C is the received carrier power, N_0 is the noise power spectral density, and I is the jammer Power Spectral Density (PSD).

We define the degradation factor (DF) as the ratio between the degraded and nominal C/N_0

$$\text{DF} = \frac{\left(\frac{C}{N_0}\right)}{\left(\frac{C}{N_0 + I}\right)} = 1 + \frac{I}{N_0}. \quad (2)$$

Assuming free-space propagation, the interference power spectral density I at the receiver is given by

$$I = \frac{P_T}{B} \left(\frac{\lambda}{4\pi d}\right)^2 \quad (3)$$

where P_T is the jammer's transmitted power, B is the receiver bandwidth, λ is the signal wavelength, and d is the distance between the jammer and the receiver. Substituting (3) into (2) yields the DF in decibels

$$\text{DF}_{\text{dB}} = 10 \log_{10} \left(1 + \frac{P_T}{BN_0} \left(\frac{\lambda}{4\pi d}\right)^2 \right). \quad (4)$$

Inverting the formula gives the maximum distance d_{RFI} at which the receiver experiences a degradation of DF_{dB}

$$d_{\text{RFI}} = \frac{\lambda}{4\pi} \sqrt{\frac{P_T/(BN_0)}{10^{\text{DF}_{\text{dB}}/10} - 1}}. \quad (5)$$

This value defines the impact radius, i.e., the distance from the jammer at which a receiver would experience a degradation factor equal to the specified DF_{dB} .

2) Coverage area assessment for single satellites and satellite formations

The spatial coverage provided by a single satellite is evaluated by considering the geometric conditions required to meet the sensitivity threshold of the on-board detection, ξ , and the measurement extraction algorithms. The areas are defined as follows:

- $A_c^{(i)}$ denotes the coverage area of the i -th satellite, i.e., the region where the satellite has radiometric visibility and the sensitivity threshold ξ is satisfied.
- $A_s^{(i)}$ denotes the service area of the i -th satellite, i.e., the region where the localization accuracy is better than the jammer's impact radius, d_{RFI} .

The analysis is then extended to a satellite formation to define the corresponding combined areas:

- A_c denotes the combined coverage area of the satellite formation, i.e., the region where all satellites in the formation have simultaneous radiometric visibility satisfying ξ .
- A_s denotes the combined service area of the satellite formation, i.e., the region where the localization accuracy achieved by the formation is better than d_{RFI} .

Figure 1 provides a schematic representation of $A_c^{(i)}$, A_c , and A_s for a triplet of satellites in the presence of a jammer.

- 3) **Theoretical localization performance:** A parametric evaluation of the achievable localisation accuracy is carried out by computing the Cramér-Rao Lower Bound (CRLB) for the combined FDOA and TDOA observables, with the analysis performed as a function of the measurement noise covariance matrix $\bar{C}_0$. This allows the identification of geographical regions where the expected position uncertainty is below the maximum acceptable threshold, effectively defining the feasible service area for RFI localisation. To evaluate the effectiveness of the monitoring service, we define the localisation efficiency η as

$$\eta = \frac{A_s}{A_c}. \quad (6)$$

A localization efficiency of $\eta = 1$ indicates that the localization uncertainty meets the required bounds across the entire combined coverage area. This metric can be used to optimize the orbital parameters in formation flying.

- 4) **Design of observable estimation algorithm:** Finally, a cross-correlation based algorithm is considered to extract the required TDOA and FDOA measurements from the received signals. The algorithm is tailored to ensure that the estimation uncertainty remains within the bounds needed to obtain an uncertainty of the RFI source location that is at least lower than its area of influence defined at point 1.

Figure 2 provides a graphical representation of the methodology described above. This methodology provides an analytical and practical framework to assess meaningful RFI localisation from LEO, and its practical feasibility under realistic operational conditions, bridging the gap between theoretical performance limits and practical constraints about signal visibility at the observers.

III. RESULTS

The analyses that follow consider a jammer as a reference scenario for an RFI source, serving as a case study to assess signal degradation and to evaluate the achievable localization accuracy when a LEO-SDR localization system is deployed. Figure 3 shows the degradation factor in decibels (DF_{dB}) as a function of the distance of a hypothetical GNSS receiver from the jammer, for different jammer transmission power levels. The plot highlights three horizontal dashed lines indicating

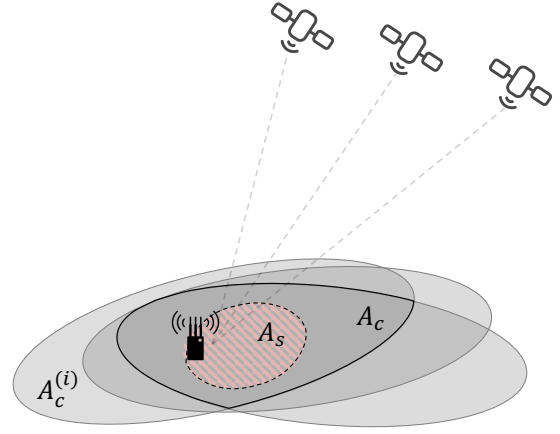


Fig. 1: Pictorial representation of $A_c^{(i)}$, A_c , and A_s for a triplet of satellites.

DF_{dB} levels of 3 dB, 10 dB, and 20 dB. Note that a degradation above 20 dB is typically considered sufficient to disrupt GNSS service at the receiver, as it causes strong GNSS signals to fall below the acquisition and tracking thresholds.

This analysis aims to establish a target localization accuracy for the jammer. Specifically, the goal is to ensure that the localization error remains smaller than the jammer's effective impact radius, defined as the distance within which GNSS receivers experience harmful signal degradation.

To complement this analysis, Figure 4 illustrates how the jammer's impact radius varies with its transmitted power. The three curves correspond to the degradation factor levels ($\text{DF}_{\text{dB}} = 3, 10, \text{ and } 20$ dB) previously shown in Figure 3.

Figure 4b provides a zoomed-in view of Figure 4a, allowing a clearer visualization of the behavior at low transmission power levels. The blue-shaded region in Figure 4 highlights the power levels of 3.5 W and 10 W, which, according to preliminary analyses, are the values that enabled successful localization using satellites in orbits of approximately 500 km altitude.

Figure 5 highlights that the transmission antenna of a jammer has a non-negligible impact on its localization. A ground-based jammer equipped with a toroidal antenna transmitting horizontally was considered. Specifically, Figure 5a depicts the variation of the TX antenna gain on the first y-axis and the corresponding free-space path loss on the second y-axis as a function of the elevation angle. Figure 5b, instead, shows the received power at a GNSS satellite (at 560 km altitude) as a function of the elevation angle. The elevation angle, on the x-axis, is defined with respect to the jammer's horizon, ranging from 0° (satellite at the horizon) to 90° (satellite at the zenith). The different curves in Figure 5b correspond to different transmission power levels of the jammer.

As shown in Figure ??, the free-space path loss progressively decreases with increasing elevation angle, as the satellite moves closer to the jammer, reducing the propagation distance. This would result in a monotonic increase of the received

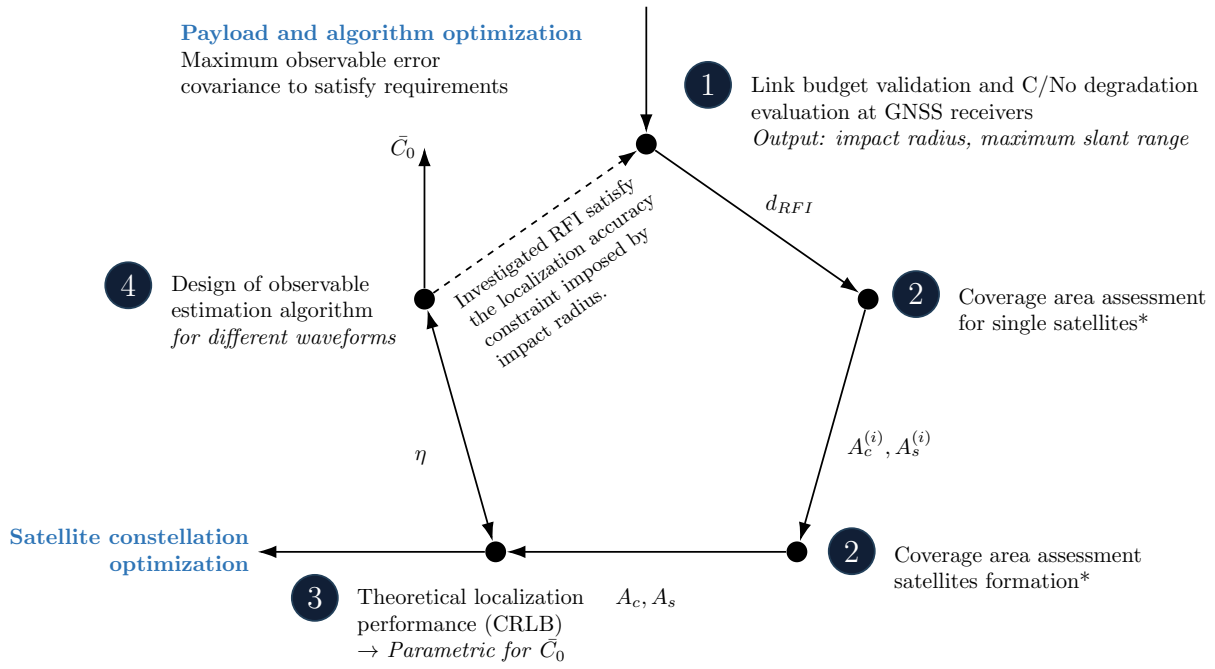


Fig. 2: Pictorial representation of the proposed methodology.

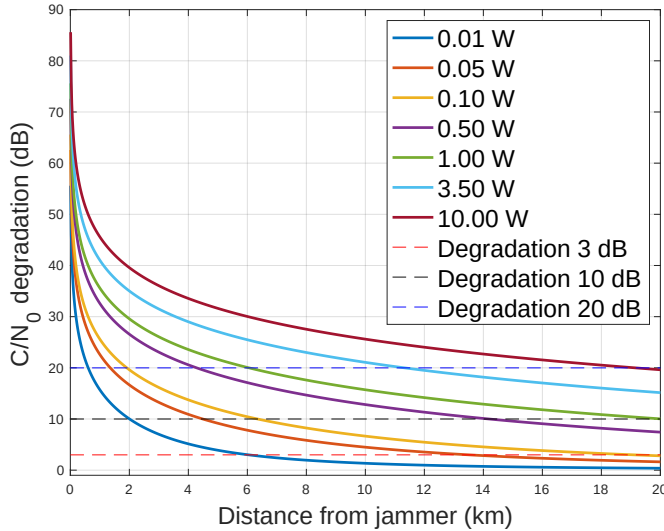


Fig. 3: C/No degradation as a function of the distance from the jammer. Degradation trends do not account for obstacles or specific attenuation effects.

power. However, in this scenario, the jammer employs a toroidal antenna whose radiation pattern exhibits maximum gain over the horizontal plane (towards low elevation angles) and minimal gain along the vertical axis (towards zenith). Specifically, at 90° elevation, the satellite being directly overhead, the antenna gain approaches zero due to the null of the toroidal radiation pattern in that direction. As a result, despite the minimal slant range, the received power at the satellite drops sharply.

Figure 5b highlights that, in this specific case with a toroidal antenna, the maximum received interference at the satellite occurs when it is near the horizon of the jammer. This observation emphasizes that the antenna radiation pattern plays a key role in shaping the jammer's effective impact region, and must therefore be carefully considered in both the design of monitoring systems and the constellation architectures that support them.

Regarding localization performance, Figure 6 presents two three-dimensional plots of the Horizontal Root-Mean-Square Error (H-RMSE), derived from the Cramér–Rao bound (CRB) matrix that consider both TDOA and FDOA measurements [14]. The standard deviations assumed for the measurement errors are 9.43×10^{-8} s for TDOA and 0.3 Hz for FDOA.

The analysis considers the passage of a lead-trail formation of three satellites in Sun-synchronous orbits at 560 km altitude over a 24-hour period. The x - and y -axes of the plots represent Earth latitude (-90° to 90°) and longitude (-180° to 180°), with a resolution of one degree in both directions, thus generating a dense grid of points covering the Earth's surface. For each grid point within the coverage area of the satellite formation, the localization performance was evaluated in terms of H-RMSE.

Specifically, Figure 6a shows the average H-RMSE values recorded at each grid point over the 24-hour period, while Figure 6b reports the minimum H-RMSE values achieved. The z -axis indicates the H-RMSE range, whereas the color scale is clipped between the 1st and 99th percentiles of the data for improved visibility. White regions correspond to areas outside the coverage of the three-satellite formation. The largest H-RMSE values appear around these uncovered regions, as

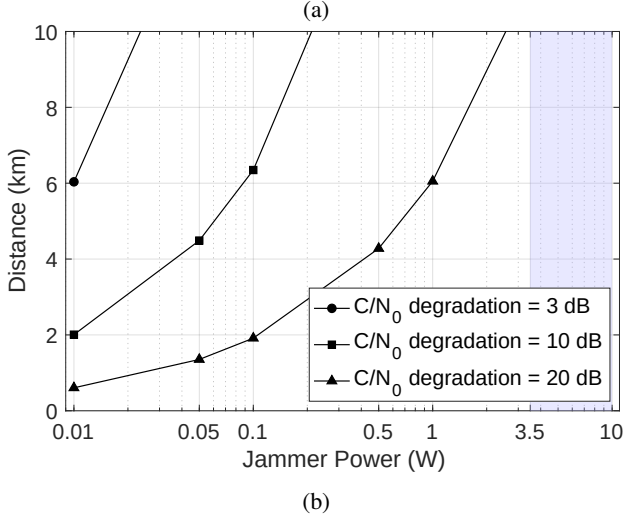
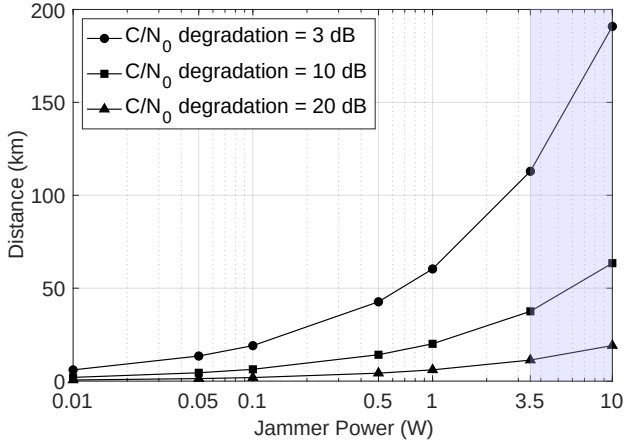


Fig. 4: Impact radius as a function of the jammer transmitted power. Shaded areas highlight powerful jamming emitters of interest for practical localization from LEO satellites.

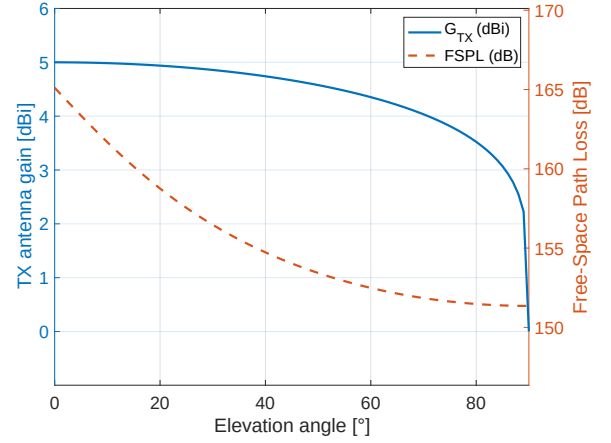
the unfavorable satellite geometry there significantly degrades localization performance. Conversely, the lowest H-RMSE values are observed in areas near the zenith of the satellite formation's ground track.

Given the assumed measurement error standard deviations, the minimum H-RMSE values are approximately between 4 km and 12 km.

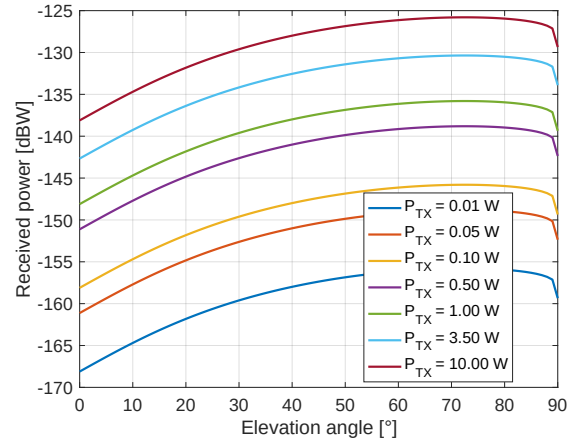
IV. CONCLUSION

This study presents a methodology for the design of an RFI monitoring system based on a formation of LEO satellites capable of detecting and localizing terrestrial interferers. The methodological steps, summarized in Figure 2, start from the jammer-to-satellite link budget and the definition of degradation factor (DF), a key metric to characterize the jammer's impact region. These metrics provide a performance-oriented framework to relate RFI detectability with localization requirements.

The methodology further introduces the concepts of coverage and service areas, both at the single-satellite and con-



(a) TX antenna gain and Free-space path loss.



(b) Received power at a LEO satellite from a ground-based jammer equipped with a toroidal antenna pattern.

Fig. 5: Analysis toroidal antenna pattern.

stellation level, highlighting how joint radiometric visibility and localization accuracy constraints delimit the regions where effective monitoring is achievable.

The proposed framework is illustrated through representative results for steps 1 and 4 of the methodology, using a ground-based jammer as a case study. In particular, the analysis showed the behavior of the degradation factor and the corresponding impact radius as a function of the jammer's transmitted power. The influence of the jammer's antenna was also examined, demonstrating how a toroidal antenna strongly shapes the received power profile at a LEO satellite. Finally, localization performance was assessed using the H-RMSE metric derived from the CRB, considering both TDOA and FDOA measurements for a lead-trail formation of three satellites. Results highlighted that jammer positions near the satellites' zenith passages yield lower localization errors compared to regions with unfavorable geometry.

Overall, the proposed methodology provides a flexible and general framework to benchmark RFI monitoring systems. By linking interference impact metrics with achievable lo-

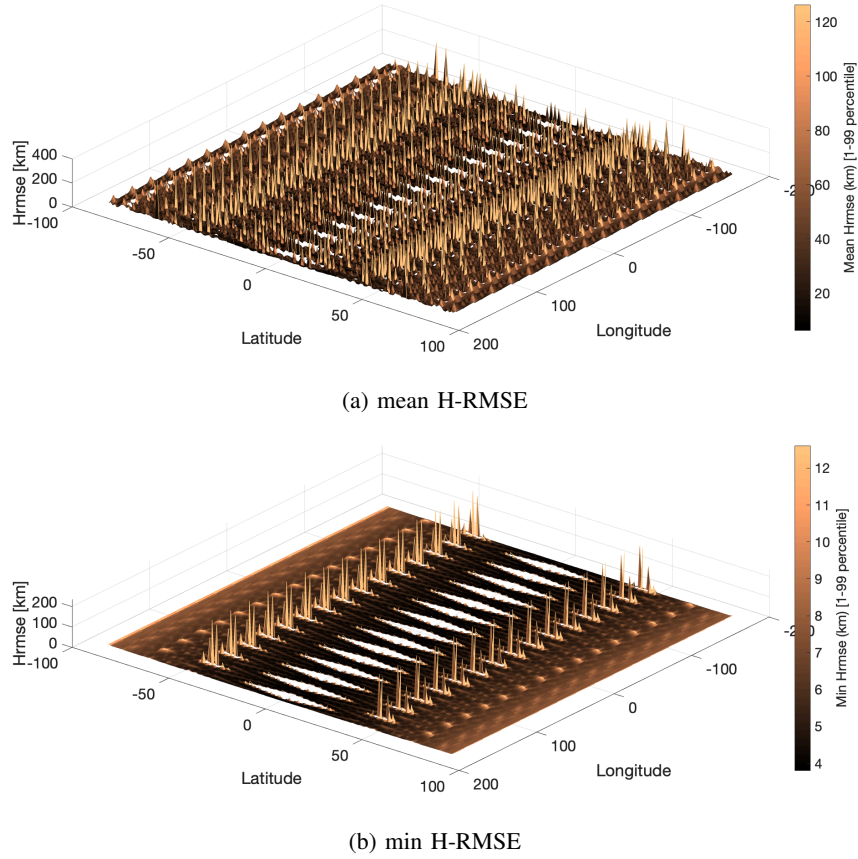


Fig. 6: Horizontal RMSE across latitudes (-90° – 90°) and longitudes (-180° – 180°). The color scale is clipped between the 1st and 99th percentiles. $\sigma_{\text{TDOA}} = 9.43 \times 10^{-8}$ s and $\sigma_{\text{FDOA}} = 0.3$ Hz.

calization accuracy, it enables a systematic evaluation of constellation designs, payload sensitivities, and measurement models. Future work will extend this framework to incorporate alternative localization techniques as well as additional KPIs that also account for the transmitted jammer signal levels.

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