Let's Take This Upstairs: Localizing Ground Transmitters With High-Altitude Balloons

Matthias Schäfer
SeRo Systems GmbH
Frankfurt am Main, Germany
schaefer@sero-systems.de

Yago Lizarribar and Gérôme Bovet
armasuisse Science + Technology
Thun, Switzerland
yago.lizarribarcarrillo/gerome.bovet@armasuisse.ch

Dieter Verbruggen
KU Leuven
Leuven, Belgium
dieter.verbruggen@kuleuven.be

***Abstract*—The ability to detect and locate Radio-Frequency (RF) transmissions on the ground is crucial for a wide range of applications, including radio spectrum protection, search and rescue missions, jammer localization, reconnaissance, and signals intelligence. Traditional methods using ground vehicles or aircraft equipped with specialized direction-finding equipment are reactive, expensive, logistically challenging, and often slow. This paper proposes a novel approach utilizing High-Altitude Balloons (HABs) to provide rapid and extensive coverage for RF signal detection and localization. Through extensive simulations incorporating real-world HAB flight paths, we demonstrate that transmissions with a power as low as 0.53 Watts can be detected over large areas within tens of minutes. Our results indicate that with proper setup, localization accuracies can be achieved that are sufficient to track down illegal or unwanted transmitters. The proposed method offers a cost-effective, minimally labor-intensive solution for effective large-scale RF transmission monitoring and localization.**

I. Introduction

The Radio-Frequency (RF) spectrum underpins modern wireless communication and navigation systems, with civilian applications like the Global Positioning System (GPS) and search and rescue missions. However, malicious actors can interfere with legitimate operations, posing significant risks to RF spectrum use. Detecting and locating these disruptions is critical to ensuring spectrum security. Traditional methods, such as using ground vehicles or reconnaissance aircraft equipped with specialized equipment, are reactive, costly, and logistically complex. Space-based platforms, like HawkEye 360, offer solutions but remain limited to select military users due to their high costs. Additionally, interference detection using ground or airborne assets is often too slow to capture short-term disruptions, especially when sources are in remote or inaccessible areas.

We propose a new method using High-Altitude Balloons (HABs). This platform promises easy and quick deployment combined with the coverage of very large regions. In this work, we investigate this option using real-world HAB flight paths combined with extensive radio signal propagation and hyperbolic localization simulations. Based on these simulations, we analyze the expected coverage from this approach, considering parameters such as the jammer's transmit power and the geometric constellation of the HABs and the transmitter. Our analysis found that with the right equipment and launch site geometry, detection of transmissions with a transmit power of just 0.53 Watts over distances of up to 1000 km is possible. This allows the detection and localization of transmissions and interference over very large areas within minutes after launch. Regarding localization accuracy, our simulations indicate that accuracies of a few tens to hundreds of meters can be achieved for single measurements, depending on the timestamp accuracy and the geometric conditions.

Utilizing aerial platforms to monitor the electromagnetic (EM) spectrum and localize specific targets has been explored to some extent. [1] set the groundwork for spectrum monitoring with HABs by collecting and analyzing different technologies at altitudes of tens of kilometers. However, this platform lacked the time synchronization and power sensitivity required for accurately localizing ground transmitters.

Most works on localization focus on remotely controllable Unmanned Aerial Vehicles (UAVs), or drones. In [2], a Direction of Arrival (DoA) localization is proposed using a single drone capturing data from multiple positions. [3] proposed a localization scheme based on Received Signal Strength (RSS) capable of localizing multiple transmitters simultaneously. [4] explores the optimal placement of aerial platforms to enhance localization performance in an RSS-based system. [5] analyzes the localization accuracy of a Time Difference of Arrival (TDoA) based approach, employing UAVs moving in circular or spiral patterns.

The systems proposed in the literature are predominantly based on simulations and would be challenging to implement in real-world scenarios. RSS-based methods suffer from decreased accuracy with distance and very high measurement noise due to small-scale fading, making them suitable only for small areas and deployments. Using drones for localization poses additional challenges, as battery life is a limiting factor, and the area that can be covered is relatively small due to the low altitudes supported by non-military drones. Moreover, DoA-based methods rely on more complex arrays of antennas, which might not be suitable for aerial platforms due to constraints in weight and size.

Our work proposes a system that addresses these shortcomings by utilizing a more cost-effective platform that offers reasonable accuracy with minimal manual operation, apart

This work was supported by armasuisse Science and Technology (S+T), Thun, Switzerland.

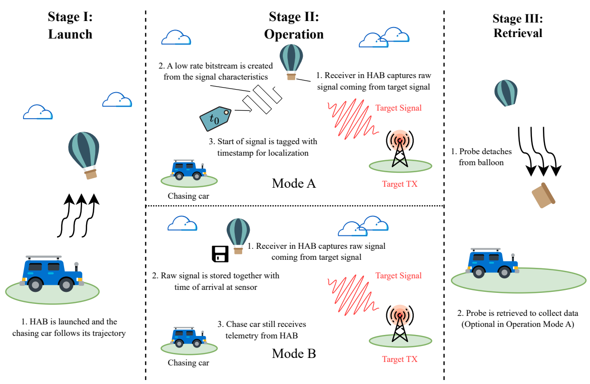


Fig. 1: The two different proposed concepts of operations. The first concept (Mode A) supports real-time detection and localization but provides lower sensitivity and accuracy compared to the second option (Mode B).

from the launch and retrieval of the payloads.

II. High-altitude Balloons

HABs are lightweight, gas-filled balloons specifically designed to reach stratospheric altitudes, typically ranging from 18 to 37 kilometers above the Earth's surface. These balloons serve a variety of purposes, from atmospheric research and weather monitoring to communication and surveillance. HABs lift payloads into the upper atmosphere using lighter-than-air gases, such as helium or hydrogen, which provide the necessary buoyancy. This allows HABs to reach considerable altitudes before stabilizing or bursting due to the expansion of the gas in the decreasing atmospheric pressure during the ascent.

Several parameters of HAB operations can be controlled to meet specific mission requirements. The type of gas used influences the lift and maximum attainable altitude. Helium is safer but provides slightly less lift compared to hydrogen. The ascent rate and maximum altitude are controlled through the volume of gas filled and the material and design of the balloon envelope. For the payload, size, weight, and power (SWaP) requirements are critical considerations. These requirements dictate the design and capabilities of the payload, including instruments, processing and communication capabilities. Weight also plays a critical factor when obtaining the necessary permissions to launch HABs. In Switzerland, for example, if the payload does not exceed 2 kg, there is no need to obtain a special license. Each country, however, implements their own regulations which must be carefully accounted for before launching a probe.

III. Concept of Operations

We propose a concept of operations designed to optimize both the deployment speed and the accuracy of our HAB system. These HABs, equipped with GPS-synchronized software-defined radios (SDR), are strategically positioned at various locations to ensure rapid deployment. The choice of launch sites is primarily influenced by geometric considerations related to the intended coverage area.

Our HABs can be deployed in two distinct modes: they can be launched periodically, similar to weather balloons, to scan for and localize unknown transmissions or interference, or they can be launched on demand, triggered by detections of RF disturbances reported by legitimate frequency users.

We propose two alternative operational modes for data collection, each with specific advantages and challenges. The first option involves onboard signal processing that automatically detects signals within the targeted frequency band and extracts information such as signal level, frequency of arrival, and precise GPS-synchronized timestamps. A signal signature is also generated to support cross-correlation and TDoA calculations. This information is then transmitted back to a ground receiver in real time, similar to the operation of typical radiosondes. This mode provides high system responsiveness by enabling real-time detection and localization of transmissions and interference. Furthermore, it eliminates the need for physical retrieval of the probe after landing, thus reducing the risks of payload loss, theft, or landing in inaccessible or hostile territories.

The alternative mode involves the continuous recording of the unprocessed output from the SDR's analog-digital converter, namely the in-phase and quadrature (I/Q) samples. This method, while retaining the highest level of detail and thereby providing higher sensitivity and accuracy, necessitates the physical retrieval of the payload after landing. Due to the large volume of raw I/Q data and the limited power onboard the HAB, it is not feasible to transmit I/Q data back to ground in real time. This limits the system's responsiveness and poses additional risks, such as the potential loss or theft of the payload, which can lead to mission failure if the remaining data is insufficient for localization.

Upon successful data collection—whether transmitted in real-time or retrieved post-mission—the data undergo centralized processing to calculate the TDOAs for the detected signals. If a signal is detected by three or more payloads, hyperbolic localization techniques are employed to accurately determine the source's location.

An overview of the concept of operations is shown in Figure 1.

IV. Link Budget

In this section, we analyze the power requirements for ground transmissions to be detected by our HAB platform. This analysis provides an initial indication of whether our approach can be sufficiently sensitive across a range of target frequencies and applications.

The link budget analysis considers different technologies and the distances observed in the HAB scenario. Given that we primarily deal with line-of-sight free space signals, we employ Friis transmission equation to model the signal power loss. This is expressed as:

$$P_r^{[\text{dBm}]} = P_t^{[\text{dBm}]} + G_t^{[\text{dBi}]} + G_r^{[\text{dBi}]} + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right) \quad (1)$$

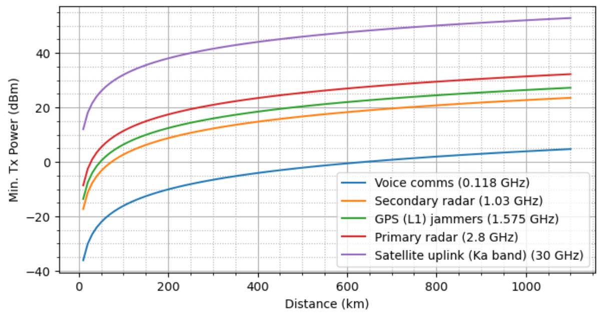


Fig. 2: Detection thresholds for transmissions of different technologies based on their frequency and distance between transmitter and the high-altitude balloon.

Here, P_r is the signal power observed by the HAB, P_t the transmit power from the signal source, $G_{r/t}$ the gains of the HAB and transmitter, λ the wavelength of the signal, and d the distance between the HAB and the transmitter.

To analyze the signal power constraints in our HAB-based ground transmitter localization scenario, we make certain assumptions about both the HAB platform and the ground transmitter. First, we assume the ground transmitter uses a perfectly isotropic antenna ($G_t = 0\,\mathrm{dBi}$), abstracting all transmitter properties into one variable, its transmit power (P_t), which hence becomes the effective radiated power (ERP) that includes both transmit power and antenna gain. We further assume the HAB platform employs a high-gain antenna directed towards the ground, with typical gains found in commercial high-gain antennas used for satellite navigation of around $40\,\mathrm{dB}$. Finally, the detection of transmissions requires a minimum signal-to-noise ratio (SNR) at the receiver. This detection threshold depends, among other things, on the bandwidth and modulation. Although these parameters are assumed to be unknown, typical values for SDRs are used where the noise floor is around $-100\,\mathrm{dBm}$ and the detection threshold is around $10\,\mathrm{dB}$.

Given these assumptions, we simplify the Friis equation to derive the following lower bound for transmissions to be detectable by our HAB probe:

$$P_t^{[\mathrm{dBm}]} \geq -130\,\mathrm{dBm} - 20\log_{10}\left(\frac{\lambda}{4\pi d}\right) \tag{2}$$

The remaining variables in Equation 2 are the frequency (expressed as wavelength λ) and the distance d between the transmitter and the HAB probe. Figure 2 shows the detection thresholds over distance for different technologies.

Considering that the longest line-of-sight distance between a HAB at an altitude of $35\,\mathrm{km}$ and a ground transmitter is approximately $1100\,\mathrm{km}$, the detection thresholds at this distance provide a benchmark for various technologies. For instance, under our assumptions, a GPS jammer on the ground would be detectable by our HAB probe if its transmit power is at least $27.2\,\mathrm{dBm}$ or $0.53\,\mathrm{W}$.

We conclude that utilizing a high-gain antenna enables the detection of even relatively weak transmissions over extensive distances when using HABs. This is sufficient in many real-world scenarios targeting transmitters like malicious jammers or military ground infrastructure, where transmitters often operate at much higher power levels. Moreover, our analysis presents a worst-case scenario by assuming that the transmitter is located at the edge of the HAB's viewshed. In realistic scenarios, transmitters are likely to be much closer than the maximum radio horizon of the HAB. Therefore, we anticipate that this approach will prove effective in most real-world applications, providing robust detection capabilities across a variety of operational contexts.

V. Coverage Estimation

The results from the previous section indicate that detecting comparatively weak transmissions over large areas using HABs is generally feasible. However, the link budget analysis was based solely on free space propagation and did not consider additional factors such as terrain and atmospheric effects. In this section, we adopt a more sophisticated propagation model to incorporate these elements, providing a more realistic assessment of the coverage achievable in real-world deployments and the challenges introduced by terrain.

To better understand the coverage obtained using HABs, we utilize the Longley-Rice or Irregular Terrain Model (ITM) [6]. The ITM combines electromagnetic wave propagation theory with empirical data and is tailored for predicting radio wave propagation across frequencies ranging from 20 MHz to 20 GHz.

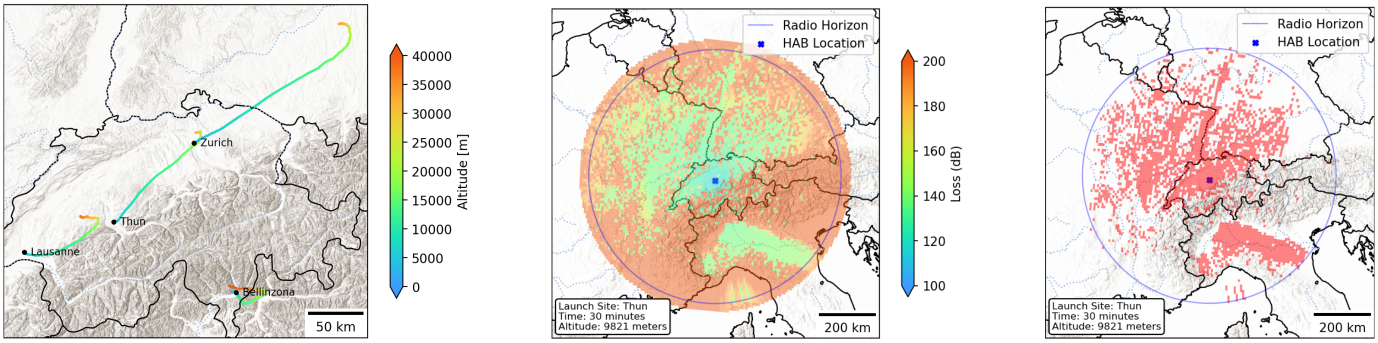
To accurately determine terrain profiles between a simulated sender and receiver location, we employ the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) provided by the United States Geological Survey [7]. This dataset offers an estimated global accuracy of $6\,\mathrm{m}$ at a resolution of 7.5 arc-seconds.

A. Model Assumptions

In our signal propagation simulations, we make assumptions similar to those used in the link budget calculations. Specifically, we assume an SNR of $10\,\mathrm{dB}$ is required for successful signal detection, the noise floor is at $-100\,\mathrm{dBm}$, and the transmit power of the ground transmitter to be localized is $27.2\,\mathrm{dBm}$, the theoretical minimum required for detection (see section IV).

Additionally, we assume that the target transmitters operate at a frequency of $1030\,\mathrm{MHz}$. This frequency is used by civil and military secondary surveillance radar (SSR) interrogators on the ground. This frequency is chosen due to its relevance in signals intelligence and spectrum monitoring, where locating military radar infrastructure and mobile interrogators (e.g., on ships) could be of interest. Furthermore, this frequency selection aligns with our mission planning for a subsequent real-world measurement campaign.

Critical to the validity of our simulations is the use of realistic trajectories for the simulated HAB flights. We utilize trajectory data obtained from several flights conducted for an independent study in 2019 [8]. These flights were launched



(a) Simulated trajectories.

(b) Path loss simulations.

(c) Areas of detection.

Fig. 3: (a) Simulated trajectories. (b) Example result of the ITM-based path loss simulations. A fixed upper limit of $200\,\mathrm{dB}$ was used for the color scale. (c) Area in which SSR interrogators can be detected by the HAB with a threshold of $153\,\mathrm{dB}$.

Site	Duration	Burst Altitude	Final Distance
Lausanne	2:46h	38.2 km	58.7 km
Thun	2:12h	31.2 km	106.2 km
Zurich	2:45h	33.4 km	162.4 km
Bellinzona	3:12h	40.3 km	8.3 km

TABLE I: Characteristics of the simulated HAB trajectories.

from a site near Frankfurt, Germany. To better match our concept of operations (section III) while retaining realistic features such as ascent rate and lateral movement due to winds, we remapped four trajectories to four virtual launch sites in Switzerland: Lausanne, Thun, Zurich, and Bellinzona. This selection provides insights into the effects of extreme terrain on localization coverage.

Figure 3a shows the four trajectories used in our simulations. The lateral similarity of the Lausanne, Thun, and Zurich flights indicates similar wind conditions during these three flights. Only the flight used for the Bellinzona site exhibited less wind, resulting in minimal lateral movement. For the three flights north of the Alps, the great circle distances between launch and landing sites ranged from approximately $60\,\mathrm{km}$ to $160\,\mathrm{km}$, whereas the flight used for the Bellinzona site had a distance of only about $8\,\mathrm{km}$. Table I summarizes the characteristics of the four selected trajectories.

B. Coverage Determination

To analyze the coverage obtained during the simulated ascent of the four virtual HABs described in the previous section, we implemented a discrete event simulation. This simulation models the coverage provided by each HAB at specific times during their ascent relative to the launch time. For this, we assume that all HABs are launched simultaneously (see also section III). At each simulated point in time, we use the last known position and altitude of each HAB to calculate its coverage. Using the ITM, we calculate the path loss experienced by a signal transmitted from ground locations on a grid with a resolution of approximately $9\,\mathrm{km}$. We use the radio horizon of the HAB plus a margin of $25\,\mathrm{km}$ for the grid size. As before, we require a SNR of $10\,\mathrm{dB}$ or higher and assume a noise floor of $-100\,\mathrm{dBm}$. The peak transmit power of a secondary surveillance radar is limited to $66\,\mathrm{dBm}$ [9]. However, in practice, transmit powers between $63\,\mathrm{dBm}$ and $65\,\mathrm{dBm}$ are more common. Given these parameters, we consider those locations p on the grid covered by the HAB where the ITM predicts a propagation loss of less than:

$$\mathrm{ITM}(p) \leq 63\,\mathrm{dBm} - (-100\,\mathrm{dBm}) - 10\,\mathrm{dB} = 153\,\mathrm{dB} \quad (3)$$

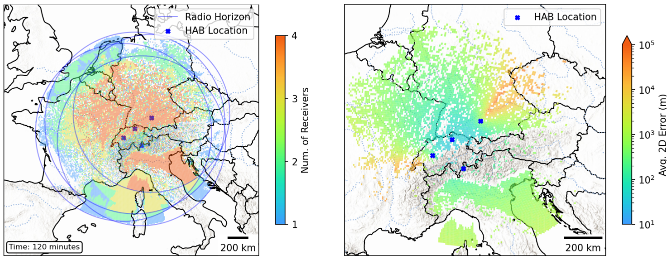
Figures 3b and 3c show the result of such a simulation. They depict the path loss and coverage for a simulated HAB 30 minutes after its launch from the Thun site. By this time, the HAB has ascended to an altitude of $9821\,\mathrm{m}$ above ground. Figure 3b shows the path loss for each point on the grid, estimated using the ITM. The ground coverage of the HAB at this point in the simulation is determined according to Equation 3 and shown in Figure 3c. The effect of the challenging terrain in Switzerland is evident, with the Alps casting a distinct shadow on the southern side, while coverage towards the north is more comprehensive. The coverage appears speckled because we simulate the ground view, assuming the transmitter is clamped to the ground. Consequently, even small elevations such as hills can cause shadows. As also visible in Figure 3c, this effect diminishes for grid points closer to the HAB as the elevation angle from the ground to the HAB increases, reducing the shadowing caused by terrain.

VI. Source Localization

The ultimate goal is not only to detect but also to localize the source of a transmission or interference. In this section, we evaluate the performance of a hyperbolic localization approach in the HAB scenario described above. Hyperbolic localization, also known as multilateration (MLAT), is a common approach to localization in wireless systems. In MLAT, three or more time-synchronized receivers are used to measure the TDoA of a radio signal at different locations. Given enough of these TDoA measurements, the location of the signal source can be estimated.

A. Hyperbolic Localization

In the general three-dimensional case, four receivers are required for localization (3D MLAT). However, if the height



(a) Coverage Distribution. (b) Localization error.

Fig. 4: (a) The coverage of all 4 HAB receivers $120\,\mathrm{min}$ after the launch. The blue lines indicate the theoretical radio horizon. (b) The distribution of the error across the region.

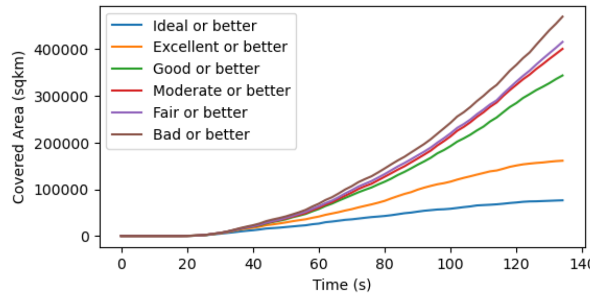


Fig. 5: MLAT coverage area increase during the simulated ascent of the HABs.

of the transmitter is known, three receivers are sufficient for localization (2D MLAT). Note that this is the case in our HAB scenario since we assume that the transmitter is ground-based, i.e., it has a height approximately equal to ground level. However, for the sake of simplicity, we use the 3D MLAT model for the remainder of this work.

Assume a transmitter emits a signal at a given point in time t within the coverage area of four HAB-based receivers. Let $\|p - p_i\|$ be the distance from the transmitter position p to the i-th receiver's position p_i, assuming that positions are represented by coordinates in a Cartesian reference frame (e.g., earth-centered, earth-fixed), i.e., $p = (x, y, z)$. The four receivers receive the signal at times $t_i = t + \|p - p_i\|/C$, where C is the signal propagation speed, approximately the speed of light. With four receivers ($i = 1, \ldots, 4$), we can now define the following relationships between the three independent TDOA measurements $\delta_{ij} = t_i - t_j$ with $i = 1$ being the reference receiver and $j = 2, 3, 4$:

$$\delta_{1,j} \cdot C = \|p - p_1\| - \|p - p_j\| \quad \forall j = 2, 3, 4$$

This means that the time differences of arrival are proportional to the unknown distance differences from the transmitter to the four receivers, scaled by the factor C. Since δ_{ij} are measured by the HAB receivers and $p_i = (x_i, y_i, z_i)$ ($i = 1, \ldots, 4$) are known, the only unknowns in this system of equations are the coordinates of the transmitter $p = (x, y, z)$. These equations can then be solved using various methods like Bancroft's or Least-Squares.

In the presence of measurement noise, the transmitter position estimates also become noisy. The propagation of this noise in the system of equations depends on the geometry of the receivers and the transmitter. The Dilution of Precision (DOP) is a factor that expresses how the measurement noise will affect the accuracy of the final position estimate based on the geometry of the receiver positions and the transmitter position. Measurement noise is amplified in constellations with a high DOP, whereas low DOP constellations yield a lower localization error variance.

B. Performance Analysis

In this section, we analyze the accuracy that can be expected in the HAB-based ground receiver localization scenario. To this end, we extend our simulations from the previous section. For a given point in time after the launch of the four virtual HABs, the coverage of each balloon is calculated according to the procedure described in section V. We then filter the grid points to retain the points covered by all four receivers, indicating potential 3D MLAT coverage. An example of these points for our simulated flights is shown in Figure 4a.

In order to evaluate the accuracy of the method in the next step, we generate measurements for each grid point by calculating the propagation delay from the grid point to each balloon and then adding a zero-mean Gaussian distributed measurement error to each propagation delay with a standard deviation of $100\,\mathrm{ns}$. Finally, we use these simulated measurements to estimate the transmitter location using SciPy's `optimize.least_squares` solver[1]. This is repeated 30 times for each grid point. Since we are only interested in the horizontal component of the 2D position, we use the great circle (haversine) distance between the estimated location and the respective grid point as our primary error metric.

The results of these simulations are summarized in Table II. We categorized the individual position estimations into six groups based on their DOP. The effect of DOP is evident: for low DOP values, the average position error is $130\,\mathrm{m}$, but this value increases rapidly with higher DOP values.

We note that the DOP in the simulated scenario was generally high, given that three of the four receivers were roughly aligned on an axis and geographically close to each other. The geographic distribution of the errors is shown in Figure 4b. As expected, areas exhibiting high errors are those along the extension of the axis formed by the three northern receivers, where the DOP is highest.

Figure 5 shows the increase of the MLAT coverage area during the simulated ascent of the four HABs, categorized by the same DOP classification used in Table II. For approximately the first $20\,\mathrm{min}$ after the launch, no MLAT coverage was achieved. This was due to the HAB launched from the Bellinzona site being separated from the others by the Alps. Consequently, the four HABs first had to ascend high enough (approximately $4\,\mathrm{km}$ altitude) to achieve overlapping ground views. After reaching this altitude, the MLAT coverage increased rapidly.

[1] https://scipy.org

DOP Category	DOP Range	% of Data	Average	Median	90-percentile	95-percentile	Max
Ideal	<10	19%	130 m	90 m	292 m	377 m	1144 m
Excellent	10-20	22%	361 m	294 m	742 m	907 m	2307 m
Good	20-50	39%	777 m	621 m	1630 m	2024 m	5106 m
Moderate	50-100	11%	1492 m	1231 m	3106 m	3739 m	9895 m
Fair	100-150	2%	2927 m	2458 m	6012 m	7220 m	13 907 m
Poor	>150	7%	11 810 m	7305 m	23 603 m	32 632 m	1 360 590 m

TABLE II: The localization errors in meters observed in the transmitter localization simulations separated by DOP category.

Despite the suboptimal geometry and the significant shadowing effect of the Alps, the area with a good or better DOP exceeded $100.000\,\mathrm{km}^2$ within about $75\,\mathrm{min}$ after the launch. This demonstrates that even with challenging terrain and less-than-ideal receiver placement, significant coverage with acceptable DOP can be achieved relatively quickly.

VII. Discussion

Our evaluation of localization performance in this work was conservative, assuming only four receivers, the minimum required for 3D localization, and individual measurements only. The results can be significantly improved if multiple transmissions from the same source are captured or if more receivers are used. Additionally, the geometry of the HAB launch sites used in this study was not optimized for area or accuracy. The results presented here represent a specific real-world scenario with pessimistic assumptions regarding geometry and terrain.

The approach also has its limitations. During the initial phase of the HAB ascent, coverage may be limited due to terrain until the balloons reach sufficient altitudes for overlapping ground views. Additionally, the reliance on a minimum of four receivers for 3D localization can be a constraint, particularly in scenarios where HABs cannot maintain ideal geometric configurations.

Despite these limitations, the altitudes achieved by HABs allow them to overcome terrain obstacles that typically hinder lower-altitude platforms like drones. This capability ensures that good coverage can still be achieved even in challenging terrains.

VIII. Conclusion

In this study, we investigated the feasibility of using HABs for detecting and localizing RF transmissions on the ground. The results indicate that this approach provides significant coverage and reasonable localization accuracy, even in challenging terrains. Our simulations demonstrated that HABs could detect transmissions with a transmitting power as low as 0.53 Watts across large areas, with localization accuracies of a few tens to hundreds of meters.

The primary strength of the HAB-based approach lies in its rapid deployment and extensive coverage area. Compared to traditional methods using ground vehicles, aircraft, or drones, HABs offer a cost-effective solution with minimal manual operation, apart from the launch and retrieval of the payloads. The high altitudes achieved by HABs allow them to overcome terrain obstacles that would typically hinder lower-altitude platforms like drones.

Several factors emerge when comparing HABs to other platforms, such as drones and satellites. Drones offer flexibility and precise control over their positions, but their coverage area is limited by battery life along with low operating altitudes. Satellites provide extensive coverage and high-altitude advantages, but their high cost, restricted access, and long revisit periods limit their use to selected military actors and large organizations. HABs strike a balance between these platforms, offering extensive coverage and cost-effectiveness without the operational complexities of drones or the prohibitive costs of satellites.

In conclusion, while the HAB-based approach for RF transmission detection and localization shows great promise, further optimization and real-world testing are needed. Future work should explore the benefits of using more receivers, optimized launch site geometries, and the integration of multiple transmission data to enhance localization accuracy and coverage. Additionally, methods need to be developed to accurately timestamp and identify signals of unknown modulation to enable real-time data collection.

References

[1] B. Reynders, F. Minucci, E. Perenda, H. Sallouha, R. Calvo-Palomino, Y. Lizarribar, M. Fuchs, M. Schäfer, M. Engel, B. Van den Bergh, S. Pollin, D. Giustiniano, G. Bovet, and V. Lenders, "SkySense: Terrestrial and aerial spectrum use analysed using lightweight sensing technology with weather balloons," in *Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services*, MobiSys '20, (New York, NY, USA), pp. 352–363, Association for Computing Machinery, June 2020.

[2] M. A. A. Careem, J. Gomez, D. Saha, and A. Dutta, "RFEye in the Sky," *IEEE Transactions on Mobile Computing*, vol. 21, pp. 2566–2580, July 2022.

[3] Z. Li, A. Giorgetti, and S. Kandeepan, "Multiple Radio Transmitter Localization via UAV-Based Mapping," *IEEE Transactions on Vehicular Technology*, vol. 70, pp. 8811–8822, Sept. 2021.

[4] H. Sallouha, M. M. Azari, A. Chiumento, and S. Pollin, "Aerial Anchors Positioning for Reliable RSS-Based Outdoor Localization in Urban Environments," *IEEE Wireless Communications Letters*, vol. 7, pp. 376–379, June 2018.

[5] D.-H. Kim, K. Lee, M.-Y. Park, and J. Lim, "UAV-Based Localization Scheme for Battlefield Environments," in *MILCOM 2013 - 2013 IEEE Military Communications Conference*, pp. 562–567, Nov. 2013.

[6] A. Longley and P. Rice, "Prediction of tropospheric radio transmission loss over irregular terrain. a computer method," tech. rep., Institute for Telecommunication Sciences, 1968.

[7] J. J. Danielson and D. B. Gesch, "Global multi-resolution terrain elevation data 2010 (gmted2010)," tech. rep., U.S. Geological Survey, 2011.

[8] M. Schäfer, R. Calvo-Palomino, F. Minucci, B. Reynders, G. Bovet, and V. Lenders, "Higher than a kite: ADS-B communication analysis using a high-altitude balloon," in *Proceedings of the 7th OpenSky Workshop 2019*, pp. 117–104, 2019.

[9] European Telecommunications Standards Institute, "EN 303 363-1 V1.1.1 (2022-02): Air Traffic Control Surveillance Radar Sensors; Secondary Surveillance Radar (SSR); Harmonised Standard for access to radio spectrum; Part 1: SSR Interrogator," tech. rep., ETSI, 2022.