

AoA Estimation Using Hybrid Phase-Amplitude Interferometry for LEO Spaceborne SDR Systems

Rafael S. S. Cruz¹, Valéria C. M. N. Leite¹, Felix D. Antreich¹, Olympio L. Coutinho¹

Abstract—This paper presents a two-dimensional Angle of Arrival (AoA) estimation system for compact Low Earth Orbit (LEO) platforms operating in the X-band. Severe size, weight, and power (SWaP) constraints restrict antenna dimensions, inducing phase-wrapping ambiguities. To overcome this, a Hybrid Ambiguity Processor (HAP) is applied, which deterministically fuses phase interferometry with amplitude comparison using a compact 2x2 orthogonal baseline array. Experimental validation using a software-defined radio (SDR) testbed under emulated orbital dynamics demonstrates the system's capability to successfully resolve ambiguities, accurately characterizing the spatial incident wavefront across the system's operational field of view.

Keywords—Angle of Arrival, Software Defined Radio, LEO Satellite.

I. INTRODUCTION

The rapid proliferation of Low Earth Orbit (LEO) constellations has transformed the space electromagnetic environment into a highly contested domain. As the deployment of LEO-based communication and remote sensing networks increases, so does their vulnerability to radio frequency (RF) interference, both intentional (jamming) and unintentional (multipath) [1], [2]. Consequently, there is a critical tactical and operational need for spaceborne Electronic Support (ES) systems capable of accurately detecting and geolocating ground-based terrestrial emitters from compact orbital platforms [3].

Geolocation from a single LEO satellite relies fundamentally on accurate Angle-of-Arrival (AoA) estimation. Determining the spatial look angles, more specifically the azimuth and elevation of the incident line-of-sight (LOS) vector, is the first essential step to translate RF wavefront measurements into terrestrial coordinates [5]. However, implementing high-precision direction-finding (DF) systems on LEO smallsats imposes severe Size, Weight, and Power (SWaP) constraints. These physical limitations restrict the number of receiver channels and the dimensions of the antenna arrays, forcing the design of compact interferometric configurations that inevitably face severe phase-wrapping ambiguities at the signal frequency [6].

For this work, the azimuth angle is the angular displacement from true North to the station, measured in a plane perpendicular to the nadir vector at the Sub-Vehicle Point (SVP), and elevation angle is measured between the SVP plane and the ground station as seen from the satellite.

¹Electronic Warfare Competence Center (CCGE), Aeronautics Institute of Technology (ITA), São José dos Campos - SP, Brazil, e-mail: {fean, olympio, rafaelcruz, valeriaileite}@ita.br. This work was partially supported by the Financier of Studies and Projects Agency (FINEP), Agreement No. 01.22.0581.00.

Based on Figure 1, the look angles are computed in two stages. First, a spherical triangle is formed on the Earth's surface, with vertices at the North Pole (A), the SVP (B), and the ground terminal (C) and the triangle elements are defined as: arc a , the great-circle distance from the SVP to the terminal; arc $b = 90^\circ$ (ground latitude); arc $c = 90^\circ$ (SVP latitude); and angle $A = \Delta\lambda$, the longitude difference between the SVP and the ground.

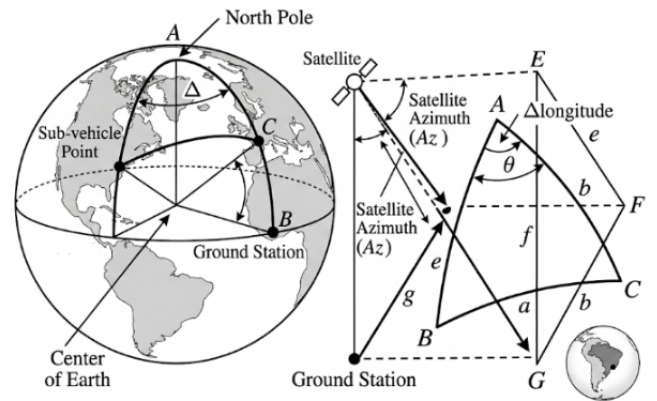


Fig. 1. Spherical geometry for satellite azimuth and elevation angles. Source: Adapted from [5].

Besides, satellite-based AoA methods can be classified according to the number of satellites involved: single-satellite, dual-satellite, and multi-satellite approaches. The single-satellite method relies on the line-of-sight (LOS) principle, and represents one of the most traditional and widely used techniques [3]. In this approach, the ground transmitter location is determined by the intersection of the oriented LOS vector, which is generated by a 2D AoA system onboard the satellite, and the Earth's surface. The advantage here is the possibility of performing instantaneous AoA estimation without requiring cooperation between multiple platforms. However, this approach generally demands a large number of antenna elements and receiver channels, imposing significant constraints on spacecraft size, mass, and cost [6]. These limitations motivate the investigation of compact array configurations capable of maintaining adequate AoA estimation accuracy with a reduced number of elements, as proposed.

A 2D AoA estimation can be effectively achieved through the combination of two independent antenna baselines. Orthogonal antenna pairs provide decoupled measurements of the incident wavefront, enabling independent estimation of angular components along each axis. These components can then be jointly processed to reconstruct the full direction of arrival.

This formulation is aligned with common interferometry methods, where multiple phase differences are jointly exploited for AoA estimation [5]. Additionally, it has been shown that the two-dimensional estimation problem can be decomposed into independent one-dimensional subproblems followed by an angular association step, supporting the use of orthogonal baseline configurations [3].

Thus, a 2D interferometric configuration can resolve the emitter's look angles simultaneously in the horizontal and vertical planes. For a 2×2 array with orthogonal baselines b_x and b_y the measured phase differences are given,

$$\varphi_A = \frac{2\pi d_A}{\lambda} \sin(\theta) \cos(\alpha), \quad (1)$$

$$\varphi_B = \frac{2\pi d_B}{\lambda} \cos(\theta) \cos(\alpha), \quad (2)$$

where φ_A and φ_B are the phase differences measured along the orthogonal baselines b_x and b_y with inter-element spacings d_A and d_B , respectively, λ is the operating wavelength, θ is the azimuth angle, and α is the elevation angle. Together, these two measurements provide the angular information required to fully characterize the satellite-to-ground geometry in both spatial dimensions. Thus, when the elevation angle $\alpha \neq 0$, approximating the emitter direction using a 1D interferometer introduces an error factor of $\cos \alpha$. For small elevation angles this factor is negligible; however, for the elevation angles typical of LEO satellites, it becomes significant and must be explicitly accounted for [3].

The azimuth and elevation angles are jointly estimated from the two measurements φ_A and φ_B as [3],

$$\hat{\theta} = \arctan\left(\frac{d_B \varphi_A}{d_A \varphi_B}\right), \quad (3)$$

$$\hat{\alpha} = \pm \arccos\left(\frac{\lambda}{2\pi} \sqrt{\left(\frac{\varphi_A}{d_A}\right)^2 + \left(\frac{\varphi_B}{d_B}\right)^2}\right), \quad (4)$$

where the $\pm$ sign reflects the inherent ambiguity between positive and negative elevation angles, which arises from the interferometer's inability to distinguish between signals arriving from above or below the array plane. As with 1D interferometers, the 2D configuration presents an inherent trade-off between unambiguous angular coverage and estimation accuracy [3].

In this context, this paper describes the development and experimental validation of a two-dimensional AoA estimation system operating in the X-band, implemented with a compact 2×2 interferometric array comprising two orthogonal spatial baselines. The proposed approach combines phase interferometry and amplitude comparison to resolve angular ambiguities that arise when the inter-element spacing exceeds half the operating wavelength ($d/\lambda > 0.5$), a condition commonly encountered in practical array designs. Compared to conventional multi-antenna direction-finding systems, the proposed architecture offers a significant reduction in implementation complexity and cost, while maintaining coherent AoA estimation across the system FOV.

Experimental validation was carried out using a dual-channel X-band front-end coupled to an Ettus USRP X310 Software Defined Radio (SDR) platform, under controlled conducted conditions emulating LEO satellite link geometries. The results demonstrate the effectiveness of the hybrid method in resolving phase ambiguity regions and accurately estimating AoA across a range of elevation and azimuth angles. This paper is organized as follows: Section II presents the hybrid AoA estimation proposed method. Section III details the SDR implementation and experimental setup. Section IV discusses the experimental results, and Section V concludes this work.

II. PROPOSED METHOD

The proposed method consists of 2 main steps: calibration, and Hybrid Ambiguity Processor, which will be summarized below.

A. Calibration

The accuracy of phase-based direction finding is fundamentally limited by the symmetry between the receiver channels. In practical implementation, hardware imbalances arise due to analog component tolerances, circuit variability, and cable length differences. To mitigate these effects, a software-injected closed-loop calibration methodology is employed. The process begins with the SDR generating a reference tone at the Intermediate Frequency (IF), which is upconverted to the X-band and symmetrically coupled into the inputs of both RF channels. Let $H_1(f_0)$ and $H_2(f_0)$ represent the complex transfer functions of Channel 1 and 2, respectively, at the operating frequency f_0 , characterizing the collective gain and phase shift of the analog front-end components. Because a common reference signal propagates through both paths, any discrepancies at the outputs are attributed strictly to internal hardware mismatches. A complex calibration factor, $K(f_0)$, is derived as the ratio between the reference channel phasor and the phasor of the channel under calibration [7].

This factor is then applied to the digitized complex baseband samples (I/Q) before processing by the HAP. This digital equalization ensures the system is hardware-independent, meaning the measured phase and amplitude variances are strictly functions of the incident signal's direction.

B. Hybrid Ambiguity Processor

The Hybrid Ambiguity Processor (HAP) was designed to overcome the physical limitations inherent to phase interferometry when the antenna spacing exceeds the spatial limit ($d > \lambda/2$) [8]. To resolve periodic phase ambiguities without degrading angular resolution, the algorithm fuses phase difference measurements with amplitude comparison. The core of this method relies on extracting the Delta-Sigma Ratio Function (DSRF), an amplitude-independent metric that correlates the envelopes of the complex signals received at each channel, such that,

$$DSRF(\theta) = \frac{|\tilde{u}_1(t)| - |\tilde{u}_2(t)|}{|\tilde{u}_1(t)| + |\tilde{u}_2(t)|} = \frac{G_{A1}(\theta + \theta_S)}{G_{A2}(\theta - \theta_S)}, \quad (5)$$

where $\tilde{u}_1(t)$ and $\tilde{u}_2(t)$ are the output phasors of each channel, and G_{A1} and G_{A2} represent the radiation patterns of the antennas subjected to a tilt angle of θ_S and $-\theta_S$, respectively. The function is strictly bounded within $[-1, 1]$ and its topology depends entirely on the radiation patterns.

The HAP utilizes the DSRF to isolate the ambiguity region in which the measured phase difference (wrapped within the $[-\pi, \pi]$ limit) operates. The algorithm evaluates the continuous DSRF value against a predefined array of thresholds. By employing a sequential logic structure that crosses the DSRF magnitude with the sign (positive or negative) of the ambiguous phase difference, the system determines the exact phase constant required to perform wavefront unwrapping. For spurious signal rejection, the HAP enforces a spatial filter by defining a Field of View (FOV) threshold, if the DSRF exceeds this limit, the unambiguous phase difference is forced to zero, ensuring that the system only processes the validated angular sector [8].

III. EXPERIMENTAL CONFIGURATION

A. System Parameters

This study considers a LEO satellite at a 450 km altitude as a platform for terrestrial emitter detection. The receiver system operates in X-band (9 GHz) using two antenna baselines of 4.5λ (15 cm). While these baselines improve angular resolution but intentionally induce severe phase ambiguities, establishing a stringent validation scenario for the HAP algorithm [8]. The generated state vectors and SVP coordinates seamlessly feed the RF signal emulator, guaranteeing that the synthesized waveforms reflect accurate spatial dynamics at an orbital velocity of 7.6 km/s. To isolate and validate the HAP methodology under controlled conditions, only Free Space Path Loss (FSPL) was considered; atmospheric attenuation and polarization mismatches were deliberately disregarded. A comprehensive link budget analysis incorporating complex atmospheric phenomena is deferred to future investigations.

B. Experimental Setup

This work considers a four-element (2×2) antenna array configuration comprising two orthogonal interferometric baselines, denoted as b_x and b_y , oriented along the x and y axes, respectively. The antenna elements are symmetrically arranged with respect to the array center, with the baseline b_x formed by elements located at $(+d_x/2, 0)$ and $(-d_x/2, 0)$, while the baseline b_y is formed by elements at $(0, +d_y/2)$ and $(0, -d_y/2)$ as shown in Figure 2.

Antenna radiation pattern, programmed into the signal generators, follows a sinc-shaped profile with a 30° beamwidth, 0 dBi main lobe gain, -30 dB sidelobe level, and a 7.5° antenna tilt. The local oscillator was tuned to 8.43 GHz. The RF signals were fed into a dual-channel Ettus X310 SDR with a TwinRX daughterboard, operating at an intermediate frequency (IF) of 570 MHz. An ADALM-PLUTO SDR provided the baseband calibration signal. Experimental setup is according to Figure 3.

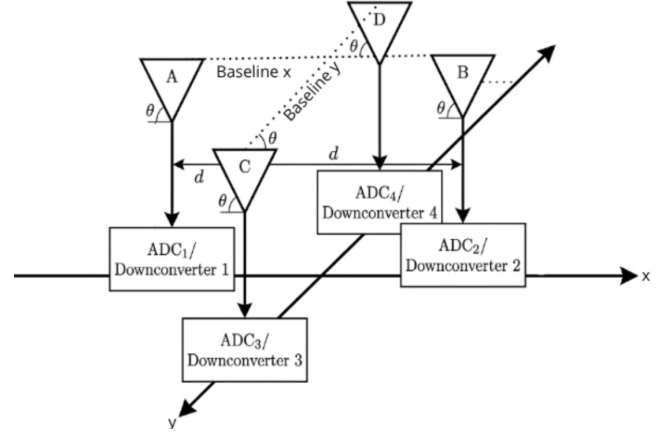


Fig. 2. Schematic of the 2×2 antenna array in double baseline configuration, detailing the signal flow and processing stages [3].

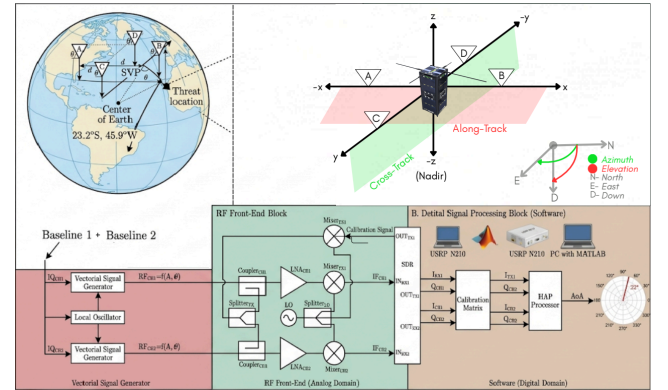


Fig. 3. Hardware and Software Architecture of the Experimental Setup for Hybrid AoA Estimation. Source: adapted from [8].

The satellite's local reference frame is defined by the along-track (b_x) axis, aligned with the velocity vector, and the cross-track (b_y) axis, perpendicular to the orbital trajectory, with the $-z$ axis pointing towards the Nadir. For translating the arrival angles to terrestrial regions, the NED (North-East-Down) reference frame is used. The azimuth (θ) is measured in the horizontal plane from geographic North, while the elevation (α) represents the angle between the LOS to the transmitter, which follows the direction to the horizontal plane. The experimental scenario was configured with a static transmitter located in Minas Gerais, Brazil (Lat: -20° , Lon: -43.7°). The satellite moves according to the latitude and longitude points specified in Table I, maintaining a stabilized attitude (fixed Roll, Pitch, and Yaw). This stabilization condition is critical because it ensures that the orientation of the 2×2 antenna array relative to the Nadir vector remains constant, allowing the variations observed in the estimated AoA to be due to orbital dynamics and not to platform oscillations.

To evaluate the direction-finding estimation accuracy across the diverse test geometries, the Root Mean Squared Error (RMSE) is applied as the primary performance metric. This statistical approach allows for a comprehensive quantification of the deviation between the AoA values estimated by the

HAP and the expected ground truth derived from the orbital simulation [4].

IV. RESULTS

The performance of the proposed method was evaluated under the following scenario: elevation and azimuth angles were varied across the operational range of interest, evaluating the method's angular resolution and ambiguity rejection capability in the horizontal and vertical planes.

For each test scenario, amplitude and phase measurements were obtained from 512 IQ samples per channel, acquired at a sampling rate of 20 MS/s and subsequently averaged.

Table I summarizes the experimental results, detailing the AoA estimation performance for both orthogonal baselines, to the specific azimuth and elevation of each test. Both spatial orientations have near-ideal accuracy, with b_y presenting a RMSE of 0.03° , and b_x achieving a statistically equivalent of 0.02° . These metrics confirm that the HAP algorithm successfully suppresses phase-wrapping ambiguities even at extreme oblique angles, confirming the consistent estimation accuracy of the proposed HAP implementation across the evaluated orbital geometries.

TABLE I

2D AoA ESTIMATION RESULTS FOR ORTHOGONAL BASELINES
(LATITUDE, LONGITUDE, AZIMUTH, ELEVATION, ANGLE OF ARRIVAL
EXPECTED AND ESTIMATED).

Lat./Lon.	Az./El.	Baseline x		Baseline y	
		Exp.	Est.	Exp.	Est.
-20/-43.7	Indef/-90	0	0.03	0	0.01
-19.5/-43.7	180/-82.96	0	0.04	7.04	7.03
-19/-43.7	180/-76.15	0	0.04	13.85	13.80
-19/-42.7	223.14/-71.32	12.65	12.64	13.51	13.48
-19.5/-42.7	241.85/-75.28	12.94	12.92	6.88	6.87
-20/-42.7	269.83/-76.95	13.04	13.05	0.03	0.05
-20/-43.2	269.91/-83.38	6.62	6.62	0.01	0.03

Note: Azimuth is geometrically undefined at nadir ($\alpha = -90^\circ$); AoA expected value set to 0° as reference.

The expected AoA, obtained from the simulated orbital geometry, and the AoA estimated by the algorithm demonstrate strict linearity in both dimensions.

As evidenced in Figure 4, it provides visual evidence of the system's integrity, allowing for a direct analysis of the agreement between the obtained estimates and the reference values.

Rigorous monitoring of all experimental points along the ideal bisector ($y = x$) confirms the exceptional linearity of the HAP on both orthogonal baselines.

V. CONCLUSION AND FINAL COMMENTS

This work evaluated the joint application of HAP for AoA estimation in LEO satellite scenarios, using a compact 2×2 interferometric array and an Ettus USRP X310 software-defined radio (SDR) platform in a controlled conducted environment. Results confirm the effectiveness of the proposed methodology across all experiments. The experiment (orthogonal baselines $b_x = b_y = 4.5\lambda$), demonstrated consistent angular coherence across both spatial orientations under an emulated LEO geometry, with a maximum RMSE of 0.03° .

Overall, the findings establish the technical feasibility of AoA estimation in LEO scenarios using compact arrays

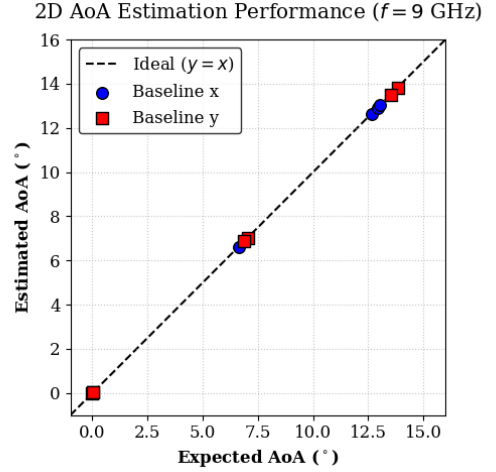


Fig. 4. Correlation between estimated and expected Angle of Arrival (AoA) for orthogonal baselines at 9 GHz.

and commercial SDR hardware, confirming that HAP is a promising strategy for resolving interferometric ambiguities in regimes where $d/\lambda = 4.5$ in this work. The next steps should address more realistic channel models and antenna configurations to further validate the proposed approach.

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REFERENCES

- [1] J. R. Wertz, D. F. Everett, and J. J. Puschell, *Space Mission Engineering: The New SMAD*. Hawthorne, CA, USA: Microcosm Press, 2011.
- [2] Bureau of Communications, Arts and Regional Research, "Analysis of Low Earth Orbit Satellites: Implications for Australia's agriculture and mining sectors," Australian Government, Sep. 2024.
- [3] F. Guo, Y. Fan, Y. Zhou, C. Zhou, and Q. Li, *Space Electronic Reconnaissance: Localization Theories and Methods*. Singapore: John Wiley & Sons Singapore Pte. Ltd., 2014.
- [4] Q. Zhang, J. Li, Y. Tang, W. Deng, X. Zhang and Q. Wu, "An Efficient 2-D DOA Estimation Method for Unfolded Coprime L-Shaped Array," in *IEEE Systems Journal*, vol. 17, no. 2, pp. 3328–3331, June 2023, doi: 10.1109/JSYST.2022.3203461.
- [5] D. L. Adamy, *Space Electronic Warfare*. Norwood, MA, USA: Artech House, 2021.
- [6] L. G. da Costa, R. Cruz, D. O. Silva, R. H. de Souza, and F. Antreich, "Robust passive DoA estimation for low-SWaP airborne platforms: A dual-antenna synthetic aperture approach," in *Proc. Simpósio de Aplicações Operacionais em Áreas de Defesa (SIGE)*, 2025.
- [7] J. A. S. Melo, L. C. Severo, and O. L. Coutinho, "Amplitude and phase imbalance calibration for space-based precision direction finding systems," in *12th Swedish Aerospace Technology Congress (FT2025)*, Stockholm, Sweden, 2025.
- [8] R. S. S. Cruz, J. A. S. Melo, V. C. M. N. Leite, L. C. Severo, F. D. Antreich, O. L. Coutinho, "Hybrid phase-amplitude angle of arrival (AoA) estimation combining a double channel X-band front-end with software defined radio," in *Asia-Pacific Microwave Conference (APMC)*, 2026 (under review).