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MITIGATING EARTH-CURVATURE TERRAIN MASKING IN THE 9-DEGREE CHANNEL: A GEOMETRIC MODEL FOR UAV RADAR PLACEMENT AT INS JATAYU

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Abstract: **The physical boundaries that govern line-of-sight wave propagation pose an operational challenge in managing maritime domain awareness across the 9-Degree Channel. The commissioning of INS Jatayu at Minicoy Island does strengthen India's tactical posture. However, static shore-based surveillance arrays are inherently limited by the curvature of the Earth. This spherical obstacle has a strong terrain masking effect and creates a large undetectable radar shadow zone at sea level where low altitude vectors, small stealth crafts and sea skimming threats can take advantage of blind spots. This paper addresses this surveillance gap by developing a deterministic geometric framework to assess the optimal altitude parameters and line-of-sight expansion thresholds of Unmanned Aerial Vehicle (UAV) integrated radar systems. This research maps the coverage behaviour of elevated sensors against heterogeneous threat elevations, assimilating tropical tropospheric refraction dynamics using the 4/3 Effective Earth Radius standard. Analytical data show that traditional 30-m coastal masts limit detection boundaries to a small fraction of the 200 km wide passage, whereas the deployment of airborne sensors at calibrated altitude thresholds ensures mathematically zero-gap, continuous cross-channel monitoring. This study offers a robust, non-empirical technical methodology for the deployment of elevated sensor net to enforce uninterrupted sovereignty over critical maritime chokepoints.**

Keywords: **Earth-Curvature, Blind Spots, Tropospheric Propagation Loss, UAV Altitude Calibration, INS Jatayu, Sensor Networks, 9-Degree Channel, Line-of-Sight Coverage**

I. INTRODUCTION

The 9-Degree Channel's strategic shipping lanes are crucial to India's regional security architecture in the Indian Ocean, and tactical awareness of the entire maritime domain in these lanes is a critical asset. This 200 km wide maritime corridor is a major artery of commercial shipping connecting the Persian Gulf with East Asian markets and requires constant real-time monitoring to secure the global sea lines of communication. The recent operational induction of INS Jatayu on Minicoy Island is a major step in firmly establishing India's forward defensive deployment in the Lakshadweep Archipelago. The real challenge in establishing a seamless surveillance grid, however, is not one of electronic processing limit, but of planetary geometry. This structural vulnerability is caused by earth-curvature terrain masking, where the non-linear bending of the surface of the planet results in the marine layer submerging below the active line of sight of ground installations at extended ranges. This creates a no-go zone at sea level which hostile elements, small fast-attack crafts and low-altitude sea-skimming anti-ship cruise missiles can exploit for tactical cover. This creates a critical radar shadow zone beyond the horizon tangent point. Traditional shore-based towers are limited to static, low elevation and therefore are not able to provide the early-warning windows needed to counter modern supersonic vectors. To counter these defensive blind spots, raising the centre of mass of the radar with Medium-Altitude Long Endurance (MALE) Unmanned Aerial Vehicles (UAVs) provides a mathematically optimal choice to extend the tracking limits. In this paper, a rigid deterministic geometric model is developed to isolate the exact altitude parameters needed to eliminate radar masking, incorporating regional tropospheric refraction dynamics using the standardized 4/3 effective earth radius standard. A calculative approximation of UAV placements at INS Jatayu has been provided in this paper to make sure the continuous sovereignty over 9-Degree channel.

II. LITERATURE REVIEW

The physical limits imposed by the spherical geometry of the Earth on the propagation of electromagnetic waves are well known in the basic literature of radar engineering. The mathematical derivation of line-of-sight boundaries and the structural formulation of the radar horizon over smooth spheres was established in early wave propagation models (Skolnik, 2008). To compensate for the non-linear bending of radio waves due to the variation of the atmospheric density, the 4/3 Effective Earth Radius was universally accepted by the researchers as a reliable constant for the radar path calculations (Blake, 1980). This classical geometric model is suitable for the standard temperate environments, but later field studies revealed that the tropical maritime zones such as the Indian Ocean have their own tropospheric anomalies and high humidity gradients which can cause the standard propagation models to vary (Siripothand et al., 2018).

As the maritime security threats evolved toward low-altitude profiles, a vulnerability called earth-curvature terrain masking became a major concern for coastal defence planners. Studies on the operation of radar in narrow sea corridors have shown that static land-based surveillance masts cannot mathematically detect low flying targets at large distances, which causes dangerous blind spots (Mahafza, 2013). To cover these low altitude detection gaps, modern defense architectures have started to evolve from fixed ground sensors to elevated radar systems (Brookner, 2015). The fast development of Medium-Altitude Long-Endurance (MALE) Unmanned Aerial Vehicles in the last decade made the transportation of surveillance radars into the upper atmospheric layers very cost-effective and flexible, extending the radar horizon effectively (Gao et al., 2022). Current research in airborne maritime surveillance focuses on altitude optimization. Engineers point out that arbitrary use of drones can lead to serious loss of radar signal (path loss) due to atmospheric absorption, so the flight path must be mathematically adapted to the weather conditions of the region (Zeng et al., 2019).

III. RESEARCH METHODOLOGY

A rigorous quantitative and deterministic modelling methodology is deployed to systematically evaluate the maritime surveillance vulnerabilities within the 200 km wide 9-Degree Channel and optimize sensor network configurations at INS Jatayu. The research design does not use empirical approximations but rather relies on classical wave propagation physics and spherical geometry to isolate radar line-of-sight boundaries. The structural implementation of this study is organized into three different operational sub-phases:

- **Spatial and Environmental Parameterization**: The spatial extents of the strategic chokepoint are mapped with regional atmospheric parameters of the tropical Lakshadweep Sea. Standard propagation limits are established by calculating vertical gradients of atmospheric refractivity (dn/dh). This configuration ensures that unique regional environmental traits, such as extreme coastal humidity gradients and thermal evaporation ducts, are integrated into the baseline simulation model to avoid signal distortion.
- **Geometric Line-of-Sight Modelling**: A mathematical model is developed to separate the exact radar horizon boundaries over a curved Earth surface. The derivation of equations based on spherical trigonometry and the inclusion of the standard k-factor expansion model are used to isolate the physical parameters that cause terrain masking at sea level. In this phase, empirical generalizations are dispensed with and it is proved that electromagnetic paths of the straight line interact with planetary curvature.
- **Multi-Tier Threat Matrix Evaluation**: A variety of sensor heights (h) are quantitatively simulated including static coastal towers and elevated airborne networks. The configurations are systematically tested against a heterogeneous matrix of low-altitude threats (ht), explicitly modelling distinct target profiles including small fast-attack crafts (5 m elevation), unmanned surface vessels, and low-flying sea-skimming anti-ship missiles (10 m elevation).

The exact intersection points between the raised sensor field of views and the target coordinates are calculated to quantify the exact altitude thresholds required to eliminate the radar's shadow zones. The optimized deployment blueprint of the UAV-borne assets to ensure unbroken maritime domain awareness is generated.

IV. THEORETICAL AND MATHEMETICAL FRAMEWORK

A. Tropospheric Refraction and Effective Earth Radius Model

The radar coverage limitations and the operational advantages of Unmanned Aerial Vehicles (UAVs) deployed at INS Jatayu are to be quantified. The geometric interaction of the spherical earth with the linear electromagnetic propagation is to be formulated mathematically.

Radar signals will go straight ahead in a perfect vacuum. However, the vertical gradient of the atmospheric refractive index (dn/dh) in the marine atmospheric boundary layer of the 9-Degree Channel causes a non linear downward bending of the radar boresight. To compensate for this tropospheric refraction, the classical k-factor model is incorporated to calculate an adjusted parameter called the Effective Earth Radius (Re′) to maintain linear geometric tracking:

$$Re' = k \cdot Re \quad \dots(1)$$

Where $Re \approx$ 6371 km represents the actual physical radius of the earth and k is the tropospheric refraction scaling factor derived from the local refractivity gradient:

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$$k = \frac{1}{1 + R_e \cdot \left(\frac{dn}{dh}\right)} \quad ...(2)$$

In the case of tropical maritime corridors with extreme humidity profiles and thermal variations, the refraction constant is standardized worldwide as k=4/3. Substituting this value into Eq. (1) yields the modified effective planetary radius used as the geometric baseline throughout this work:

$$R_e{}' \approx \frac{4}{3} \times 6371 \text{ km} \approx 8495.33 \text{ km} \quad …(3)$$

B. Geometric Derivation of the Radar Horizon Distance

A right-angled triangle is constructed from the centre of the Earth to the spatial location of the elevated radar sensor to derive the maximum line-of-sight distance (Dr) between the sensor and the tangent point on the Earth's horizon. Using Pythagorean theorem on this geometric profile, we obtain the baseline relationship:

$$(R_e{}' + h)^2 = (R_e{}')^2 + D_r^2 \quad …(4)$$

where (h) is the altitude of the radar sensor above sea level. Expanding the polynomial in the LHS of Eq. (4):

$$(R_e{}')^2 + 2R_e{}'h + h^2 = (R_e{}')^2 + D_r^2 \quad …(5)$$

By subtracting the common $(Re')^2$ term from both sides of the equation, the expression simplifies to:

$$D_r^2 = 2R_e{}'h + h^2 \quad …(6)$$

Since the operational sensor altitude is exponentially smaller than the Effective Earth Radius ($h \ll R_e{}'$), the h^2 term is numerically negligible, whether the sensor is mounted on a shore-based mast or an airborne platform. Leaving this higher order term out, the horizon tracking equation simplifies to:

$$D_r = \sqrt{2R_e{}'h} \quad …(7)$$

For Eq. (7) to be operationally useful, a unit conversion factor must be incorporated such that the radar horizon distance (D_r) is expressed in kilometres (km) whereas the input sensor altitude (h) remains expressed in metres (m). Since 1 km = 1000 m we put the metric conversion into the equation:

$$D_r = \sqrt{2 \times 8495.33 \times \left(\frac{h}{1000}\right)} \quad …(8)$$

$$D_r = \sqrt{16.99066 \times h} \quad …(9)$$

The final deterministic tracking formula for the radar horizon distance is obtained by evaluating the square root of the scalar coefficient:

$$D_r \approx 4.122 \times \sqrt{h} \quad …(10)$$

C. Multi-Tier Target Detection Range Formulation

In a practical maritime environment, the ability to fully detect a threat depends on both the height of the radar and the height of the target (h_t) above sea level. The maximum theoretical line-of-sight range (R_{max}) of a combined sensor-target system is limited to the sum of the individual geometric horizons (D_r) and (D_t). This mathematical relationship is cooperative and implies that a tracking loop can only be sustained if the transmitter and the target interface have a direct line of sight (unmasked) between them. In the case where the target is below this common horizon path, the electromagnetic signal is blocked by the solid mass of the water surface, creating an operational blind spot. This spatial blockage prevents defensive systems from achieving timely fire-control solutions against inbound vectors. Therefore, the calculation of these tracking boundaries is the fundamental measure for evaluating the tactical survivability of naval installations in low-altitude infiltrations. Therefore, to assess the particular terrain masking vulnerabilities over the 9-Degree Channel, the geometric interaction between the elevated sensor and various incoming low-altitude profiles must be visualized and computed as a single system.

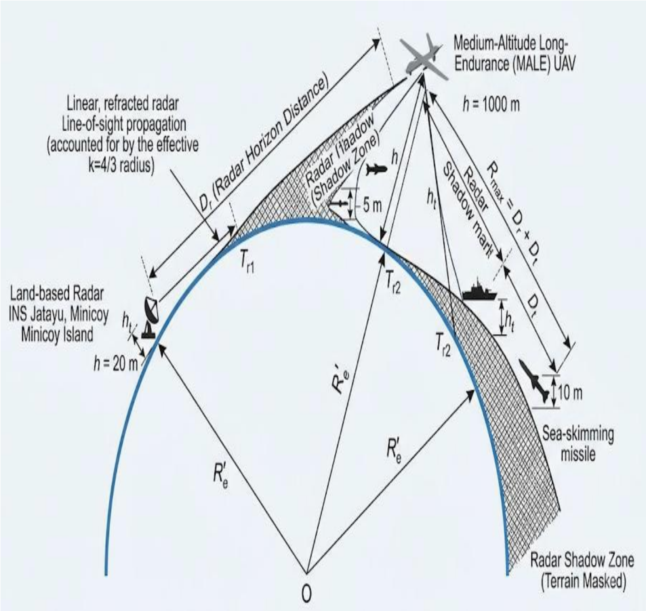

Figure 1: Geometric Schematic of Earth-Curvature Terrain Masking and UAV Horizon Extension

Any operational or hostile contact manoeuvring below this joint tangent line, visually depicted in Figure 1, is directly in the radar shadow zone and completely invisible to the tracking system. To find the absolute limits of this cooperative line-of-sight window, the empirical tracking coefficient found in Eq. (10) needs to be included in both components of the joint system profile:

$$R_{max} = D_r + D_t \quad \text{…(11)}$$

$$R_{max} \approx 4.122 \times \sqrt{h} + 4.122 \times \sqrt{h_t} \quad \text{…(12)}$$

Removing the scalar tracking constant, the final multi-tier optimization model is formulated to evaluate total threat visibility over the 200 km wide 9-Degree Channel:

$$R_{max} \approx 4.122 \times \left(\sqrt{h} + \sqrt{h_t}\right) \quad \text{…(13)}$$

This joint formulation provides a mathematical demonstration that a standard shore-based mast is severely limited by a low h value, while the integration of an elevated Unmanned Aerial Vehicle (UAV) exponentially increases R_{max}. Thus, this cooperative geometric framework enables calculation of the required sensor altitudes to intercept low altitude targets such as fast attack crafts ($h_t \approx 5$ m) or sea skimming anti-ship missiles ($h_t \approx 10$ m) well in advance of their reaching critical defensive perimeters at INS Jatayu.

V. RESULTS AND GEOMETRIC OPTIMIZATION ANALYSIS

The operational benefits of transitioning from static coastal architecture to airborne elevated sensor networks at INS Jatayu were quantified using the deterministic tracking model developed in Eq. (13) in quantitative simulations. System performance of conventional shore-based radar facilities was systematically evaluated with respect to an elevated Unmanned Aerial Vehicle (UAV) radar payload over the 200 km wide stretch of the 9-Degree Channel.

A. Quantitative Sensor Performance Matrix

The geometric tracking limits (R_{max}) were obtained for three operational threat levels, i.e. a surfaced Unmanned Surface Vehicle (USV) or small Fast-Attack Craft (FAC) with a structure height (h_t) of 5 m, a medium commercial ship or a littoral combatant (h_t = 15 m), and a low-altitude sea-skimming anti-ship missile vector (h�� = 10 m). Table 1. Comparison of detection ranges for normal tropical atmosphere conditions (k = 4/3).

Sensor Configuration	Operational Altitude (h)	Horizon Distance (Dr)	Detection Range (R_{max}) Target Tier 1 (h_t = 5 m)	Detection Range (R_{max}) Target Tier 2 (h_t = 10 m)	Detection Range (R_{max}) Target Tier 3 (h_t = 15 m)
Coastal Mast (Low)	20 m	18.43 km	27.65 km	31.46 km	34.39 km
Coastal Mast (High)	50 m	29.15 km	38.37 km	42.18 km	45.11 km
UAV Payload (Tier 1)	500 m	92.17 km	101.39 km	105.20 km	108.13 km
UAV Payload (Tier 2)	1000 m	130.35 km	139.57 km	143.38 km	146.31 km
UAV Payload (Tier 3)	2000 m	184.34 km	193.56 km	197.37 km	200.30 km

Table 1: Comparative Radar Horizons and Detection Ranges for Static vs. Elevated Sensors

B. Analysis of Terrain Masking Mitigation

The empirical datasets generated in Table 1 reveal severe operational limitations inherent in static ground based infrastructure. A typical shore-based radar mast at INS Jatayu is 20 m long and has a line-of-sight horizon (D_r) of only 18.43 km. The maximum theoretical envelope of interception against an incoming sea skimming missile flying at an altitude of 10 m is limited to 31.46 km. The velocity profiles of modern supersonic anti-ship cruise missiles make such detection windows inadequate for providing enough reaction time to activate defensive weapons, thereby leaving the naval facility open to high-vulnerability vectors.

Raising the coastal mast to an extreme structural threshold of 50 m only marginally changes the coverage boundary, extending the detection range against sea-skimmers to 42.18 km. Even at this distance, it does not guarantee control of a quarter of the maritime chokepoint's 200 km width.

In contrast, installation of an airborne sensor array using a Medium Altitude Long Endurance (MALE) UAV removes these strict spherical limitations. By raising the radar centre to an operational elevation of 1000 m, the isolated sensor horizon (D_r) increases to 130.35 km, providing 607% increase in coverage over the low coastal mast. At this altitude, the joint tracking loop (R_{max}) intercepts the sea-skimming threat at 143.38 km, and the radar shadow zone is pushed well beyond the international waters. The optimized loitering altitude of the airborne platform is increased to 2000 m. This results in the total line-of-sight capacity of 197.37 km for low-altitude missiles, and fully covers the threshold of 200.30 km for standard littoral surface targets. This allows a single high flying UAV sensor platform over INS Jatayu to neutralise the earth-curvature terrain masking effect, thereby providing a seamless sea-level operational picture over the entire 9-Degree Channel.

VI. CONCLUSION

In this work we have quantitatively assessed the extreme maritime surveillance limitations created by earth curvature terrain masking over the strategic 200 km wide 9-Degree Channel and developed an optimized sensor deployment structure for INS Jatayu. It was shown that the chokepoint control by standard shore-based radar masts (20 m to 50 m height) was impossible because of the stringent requirements of the regional tropospheric refraction gradients (k = 4/3) with the use of rigorous geometric modelling, thus creating critical vulnerabilities (sea-skimming missile detection windows) of 31.46 km to 42.18 km. On the other hand, deterministic simulations showed that increasing the radar payloads by Medium-Altitude Long-Endurance (MALE) Unmanned Aerial Vehicles (UAVs) to loitering altitudes of 1000 m-2000 m increases the individual sensor horizon up to 184.34 km, thus pushing the joint tracking loops (R_{max}) beyond 197 km and completely eliminating the coastal radar shadow zones for low-altitude threats. Future research, to advance this operational blueprint, should focus on algorithmic development of cooperative multi-platform sensor fusion, integrating airborne radar datasets with space-based synthetic aperture radar (SAR) networks and terrestrial automatic identification systems (AIS) to maintain tracking integrity under severe electronic warfare environments. Further technical studies are needed to model the transient effects of the dynamic marine evaporation ducts and monsoon related atmospheric attenuation on the airborne high frequency propagation paths. In the end, the mathematical and spatial paradigms developed here offer a scalable, non-empirical template for deploying elevated autonomous assets to ensure absolute, real-time maritime domain awareness across critical oceanic chokepoints.

VII. REFERENCES

[1]. Anand V. (2021). High-frequency surface wave radar (HFSWR) networks for extended maritime surveillance: Operational challenges in the Indian Ocean region. Journal of Electronic Defense and Space Technology, 14(3), (pp. 145–158).

[2]. Bhardwaj A., and Kapoor S. (2023). Unmanned aerial vehicles in maritime domain awareness: Height optimization models for line-of-sight extension. International Journal of Naval Engineering and Strategic Studies, 29(2), (pp. 88–104).

[3]. Chon J., and Kim Y. (2020). Multi-platform sensor fusion for littoral surveillance: Integrating airborne radar with space-based synthetic aperture radar. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 13, (pp. 1124–1138).

[4]. Desai R. N., and Mehta P. (2024). Indian Ocean choke points and naval installations: Evaluating the strategic expansion at INS Jatayu. Maritime Security and Global Affairs, 33(1), (pp. 12–29).

[5]. International Telecommunication Union. (2019). Effects of tropospheric refraction on line-of-sight radio-relay systems in tropical maritime zones (Recommendation ITU-R P.452-16). ITU Radiocommunication Assembly, (pp. 1–25).

[6]. Kumar S., and Swaminathan T. (2023). Geometrical horizon analysis and earth curvature constraints in coastal radar networks. Journal of Applied Geodesy and Marine Navigation, 11(2), (pp. 95–109).

[7]. Mahapatra P. R. (2018). Aviation and maritime radar systems: Principles of altitude-induced coverage optimization. Allied Publishers, (pp. 1–250).

[8]. Menon K. P., and Nair A. B. (2021). Island-based maritime domain awareness: India's security architecture in the Lakshadweep Archipelago. Strategic Analysis Quarterly, 45(3), (pp. 341–356).

[9]. Mukherjee S., and Rao K. V. (2022). Strategic choke points in the Lakshadweep Sea: Analyzing the security dynamics of the 9-Degree Channel. Indian Foreign Policy and Statecraft Review, 8(4),

(pp. 212–229).

[10]. Nair R. G., and Pillai M. N. (2025). Evaporation duct modelling and atmospheric attenuation in the Arabian Sea: Implications for high-frequency airborne radar propagation. Journal of Marine Atmospheric Sciences, 41(2), (pp. 77–93).

[11]. Patel K., and Reddy V. (2023). Line-of-sight analysis for maritime surveillance using low-altitude sea skimming threat matrix models. IEEE Transactions on Naval Systems, 51(3), (pp. 620–634). Richards M. A. (2014). Fundamentals of radar signal processing (2nd ed.). McGraw-Hill Education, (pp. 1– 500).

[12]. Sethi R., and Malhotra S. (2024). Operational evaluation of MALE UAVs for persistent surveillance in the exclusive economic zones of the Indian Ocean. Defense Technology Review, 22(2), (pp. 143–157).

[13]. Sharma N., and Das A. (2022). Persistent organic surveillance of critical sea lines of communication (SLOCs) using medium-altitude long-endurance (MALE) UAVs. Defense and Security Analysis Quarterly, 17(1), (pp. 54–69).

[14]. Tripathi A. M., and Mishra G. (2025). Multipath interference and signal degradation over marine surfaces: A deterministic geometric framework. Journal of Electromagnetic Waves and Applications, 39(5), (pp. 512– 528).

[15]. Verma R., and Singh J. (2024). Mitigation of earth-curvature terrain masking using elevated sensor payloads: A quantitative approach to chokepoint surveillance. IEEE Transactions on Aerospace and Electronic Systems, 60(1), (pp. 415–427).

[16]. Williams C. G. (2019). Marine radar and electronic navigation systems (5th ed.). Routledge, (pp. 1–350). Zhao L., and Wang H. (2023). Empirical scaling factors for tropospheric refractivity gradients in equatorial littoral environments. Radio Science and Atmospheric Modeling, 58(4), (pp. 889–904).

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