Accurate Hybrid HF Radio Direction Finder Approximation for Territorial Border Monitoring

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***Abstract*—Radio Direction Finding (RDF) is essential in Military or Law Enforcement using for identifying targets through electromagnetic spectrum emissions. The signal sources are crucial for strategic intelligence; real-time data collection and situational awareness related to communication networks and radar systems. RDF systems operate across multiple frequency bands including High Frequency (HF), Very High Frequency (VHF) and Ultra High Frequency (UHF) utilizing methodologies such as Angle of Arrival (AOA), Frequency Difference of Arrival (FDOA), and Time Difference of Arrival (TDOA). Attaining precise direction-finding accuracy in the High Frequency (HF) band is challenging due to ionospheres variations, multipath propagation, and interference. This study presents a hybrid High Frequency (HF) Radio Direction Finding (RDF) system that combines Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) techniques to enhance geolocation accuracy. The system employs three sensor stations to execute triangulation and enhance detection reliability in maritime settings. Simulations and field trials utilising Software Defined Radio (SDR) transceivers exhibit substantial enhancements in precision and audibility, elevating target localisation success from 80% to 95%. The proposed hybrid approach offers enhanced precision and stability, making it highly effective for maritime surveillance, enforcement operations, and traffic control along territorial borders. Furthermore, hybrid system Radio Direction Finder is more effectively for enforcement vessels and maritime traffic control is described in this paper.**

***Keywords*—radio direction finder, high frequency, radio emitter, operating system. angle of arrival, time difference of arrival, space weather forecast, optimum working frequency**

I. Introduction

High Frequency (HF) Radio Direction Finding (RDF) has long served as a foundational technology in Radio Surveillance, Signal Intelligence (SIGINT) and localization. Its ability to leverage ionospheres propagation for long-range communication makes it indispensable when satellite-based systems are unavailable or compromised. HF RDF is a critical asset for military and law enforcement agencies to monitor territorial borders. It enables precise detection, analysis, and geolocation of radio communications and electromagnetic signals, playing a crucial role in military and civilian applications. In an era where control over the electromagnetic spectrum is more contested than ever, advancements in HF RDF technology are essential for maintaining strategic superiority [1].

However, the inherent complexities of HF propagation and receiver limitations contribute to significant approximation errors in bearing estimations, posing an ongoing challenge for accurate source localization. Improvements in signal processing, antenna arrays, and computational techniques have driven the evolution of HF RDF. Traditional methods, such as Angle of Arrival (AOA) and Time Difference of Arrival (TDOA), continue to be refined by integrating artificial intelligence, machine learning and adaptive algorithms. These enhancements have improved accuracy, reduced latency, and expanded the operational capabilities of modern HF RDF systems [2]. A notable trend in recent developments is the integration of multiple localization techniques.

Therefore, this paper proposes a hybrid approximation approach of HF RDF by combining AOA and TDOA methods. A hybrid system could be created by combining TDOA with one or more geolocation systems. Specifically, at least one station should have both TDOA and AOA technologies coupled to create hybrid AOA/TDOA systems. Additionally, TDOA can be integrated with other geolocation technologies that provide a hybrid AOA/TDOA system, such as the AOA amplitude ratio technique. Hybrid AOA/TDOA systems have a minimum of two sites, with the remaining sites having TDOA measurement capabilities and at least one site having both AOA and TDOA measurement capabilities.

The rest of the paper is structured as follows: Section II presents the theoretical and recent works on HF RDF. Section III and Section IV provide the system model and results of the proposed hybrid HF RDF in a realistic use case of terrestrial border monitoring. Finally, Section V concludes the paper.

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II. Related Works

Radio Direction Finding (RDF) has progressed from early techniques such as Watson-Watt, Pseudo-Doppler, and Phase Interferometry to advanced hybrid systems. Traditional methods offered basic angular detection but were limited in precision and adaptability. Modern hybrid RDF integrates Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) techniques to enhance accuracy and signal stability. These systems use sensor stations and Software Defined Radios (SDRs) for real-time signal processing and triangulation. Key system considerations include antenna propagation, frequency band selection, receiver design, and spectral analysis. Hybrid RDF has demonstrated increased hearability and accuracy, making it highly effective for maritime surveillance and territorial border monitoring.

Table I shows the advantages and disadvantages of the interoperability aspects of Radio Direction Finder (RDF) methods from previous technologies, Angle of Arrival (AOA), Frequency Difference of Arrival (FDOA), Time Difference of Arrival (TDOA), Hybrid AOA and TDOA, and new RDF technologies, e.g., AI-enhanced systems, UAV-based RDF and Quantum RF/Sensing RDF systems. Previous work and new technology on hybrid radio direction finders can enhance precision in signal localization, resulting in more resilient systems capable of functioning effectively in complex environments. The new generation of HF RDF is shaping the future of electromagnetic spectrum operations [3].

TABLE I. Comparison Radio Direction Finder Technology Method

Methodology	Features				
	Year	Technology	Freq	Advantages	Disadvantage
TDOA with cloud backend	2021	TDOA over 5G Network	5G NR (Sub-6 GHz/mmWave	Wide area coverage, High timing precision	Dependent on network infra structure
Combination AOA and TDOA with fusion engine	2022	Hybrid AOA-TDOA systems	HF to UHF	Improved accuracy in NLOS environment, Resilient to interference	Complex system architecture, higher cos
Machine Learning on MIMO sensor arrays	2023	AI-Assisted RDF with MIMO	Wideband (HF to SHF)	Real Time, robust in dynamic scenarios	Requires high processing power, training data needed
AOA or hybrid methods mounted on drones	2024	UAV based RDF	VHF/UHF/SHF	Fast deployment, Mobile and flexible platform	Limited flight time, Environmental dependence
Quantum -enhanced AOA with entangled photon sensors	2025	Quantum RF/Sensing RDF (Emerging)	VHF to SHF (targeted)	Enhance Accuracy, Quantum Emerging Technology	Ultra precise, Immune to traditional jamming

III. System Model

Understanding the principles of High Frequency (HF) communication is essential, as not all frequencies within the HF band are equally effective for long-distance propagation. System model for RDF architecture for basic requirement as Fig. 1. The process flow of the proposed hybrid RDF finder is divided into five phases below:

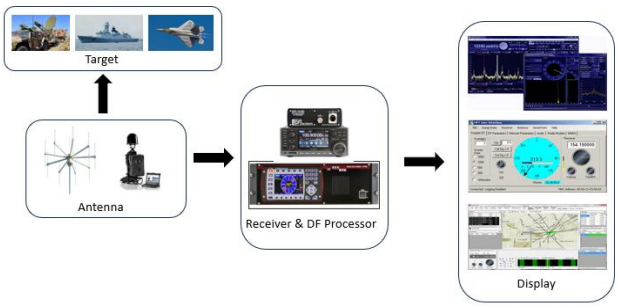

Fig. 1. Radio direction finder system design.

Phase 1: Analysis of AOA and TDOA method. Design antenna for a hybrid system in Radio Direction Finder (RDF) for coverage frequency and propagation, accuracy, and hearability, and compatible with sensor networks by Software Defined Radio (SDR) flexibility, integrating AOA and TDOA with gain operational locate from a narrowband source to a multipath environment.

Phase 2: Data collection and Real-Time Analysis by Spectro Analysis. Data Representation by collecting three sensor stations for analysis by 4 pathways in territorial water and shore to determine and analyze by frequency band from any ship in the maritime territorial area.

Phase 3: Compare and Test Using Simulation Model. From Phase 1 to Phase 3, the stages can be analyzed using MATLAB for simulation results and mathematical equations to determine the relevant format for the operational method using 3 sensors through the 4 pathways in maritime operations. Implementation of a hybrid High Frequency (HF) Radio Direction Finding (RDF) system requires the integration of various advanced technologies, including:

- Antenna Arrays: Operating within a frequency range of 9 kHz to 40 GHz, these arrays achieve an SNR of approximately 15−20 dB range and employ a combination of methods such as Power of Arrival (POA), Angle of Arrival (AOA), Time Difference of Arrival (TDOA) and Hybrid Direction Finding (DF) techniques.
- Multi-Point Ranging Method: A novel approach that enhances direction-finding accuracy by generating virtual target positions using direction-finding estimation information [4].

- Angle Accuracy: Ranging from approximately 0.5° to 2°, depending on the Signal-to-Noise Ratio (SNR) [5].
- Advancements in HF RDF technology: Recent research explores the latest developments in HF RDF, demonstrating how innovative techniques are revolutionizing direction-finding capabilities [6, 7].
- Multi-Channel Detector-Direction Finder: A method for detecting radio signals from radio emission sources [8, 9].

Phase 4: Sensor Data Analysis: Frequency selection plays a critical role in ensuring effective HF communication and depends on several factors [10], primarily:

- Communication Distance – A general rule in HF communication is that the greater the distance, the higher the frequency required [11]. For example, prediction software indicates that optimal frequencies for communication from Kuala Lumpur to surrounding areas range between 9 MHz and 18 MHz at 12:00H. As the distance increases, higher frequencies are needed. For instance, communication between Kuala Lumpur and Johor operates at 9 MHz, while communication with Sumatra requires 14 MHz. Similarly, for geolocation, we assume that all receivers and sensors for all HF RE signals consider the distance at which frequencies propagate from receivers along a curved path and the reflection height in the ionosphere [12]. The design of the model, which involves implementing multiple algorithms and then evaluating them using prediction software based on distance, suggests that it is possible to select the most suitable method for the current situational scenario in HF communication detection using a Radio Direction Finder based on accuracy and a reduced SNR ratio [13, 14]. Fig. 2 shows the Frequency Prediction on 17 Jan 2025 for Kuala Lumpur and nearby areas by data prediction using HTZ software for frequency prediction and planning spectrum management before setup radio direction finder sensor station. Multi-station passive localization algorithms based on hybrid Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) have been thoroughly the source and relies on the precise station position [15].
- Operational Time and Frequency Selection in HF Communication: The time of operation significantly impacts HF communication due to solar radiation effects. As the sun rises higher, solar radiation increases, leading to higher electron density in the ionosphere. Consequently, higher frequencies are required for effective communication. Fig. 3 shows the prediction data from the Australian Space Weather Forecast Center (SWF) for HF communication between Kuala Lumpur and nearby area on Jan 17, 2025, showing a T-Index (solar radiation level) of −2. The Optimum Working Frequency (OWF) increased in the afternoon and gradually decreased towards the evening, highlighting the dynamic nature of HF propagation influenced by solar activity. Planning and Analysis Spectrum Management for Hybrid System Radio Direction Finder can be use HTZ software as Fig. 3 and multi-step for derive configuration system as below:

```
GRAFEX INPUT DATA
Date: 17 4 2020
T index: -2
Tx name: Kuala Lumpur  Tx latitude: 3.15  Tx longitude: 101.72
Rx name: Arau  Rx latitude: 6.49  Rx longitude: 100.27
==================================================================

SWS GRAFEX HF FREQUENCY PREDICTIONS
==============================================================================
Circuit: Kuala LumpuArau                Date:  17 April, 2020      T-index:  -2
Bearings: 337 157                       Distance: 405 km
First Mode        |--------F r e q u e n c y  (MHz)---------|       Second Mode
1F 48-64 1E 23    1   5   10    15   20    25   30    35   40
UT  OWF EMUF  ALF |...|....| ....|....| ....|....| ....|....|  OWF EMUF  ALF UT
00  5.8  3.8  2.2   BFF%.                                                  00
01  7.4  4.9  2.7   ABFFF%.                                                01
02  7.4  5.6  3.0   ABBFF%..                                               02
03  7.7  6.1  3.1    BBBF%..                                               03
04  7.9  6.3  3.3    BBBF%..                                               04
05  8.2  6.4  3.3    BBBFF%.                                               05
06  8.3  6.4  3.3    BBBFF%.                                               06
07  8.3  6.2  3.2    BBBFF%. .                                             07
08  8.5  5.9  3.1    BBFFF%. .                                             08
09  9.1  5.3  2.9   ABBFFFF% ..                                            09
10  9.3  4.5  2.5   ABFFFFF% ..                                            10
11  8.4  2.8  1.8  AFFFFFF%% ..                                            11
12  7.6  0.6  0.0 FFFFFFF%%% ..                                            12
13  7.1  0.6  0.0 FFFFFFF%%. .                                             13
14  6.3  0.6  0.0 FFFFFF%%..                                               14
15  5.5  0.6  0.0 FFFFF%%..                                                15
16  5.2  0.6  0.0 FFFFF%%..                                                16
17  4.7  0.6  0.0 FFFF%%..                                                 17
18  4.4  0.6  0.0 FFFF%%.                                                  18
19  3.3  0.6  0.0 FFF%..                                                   19
20  2.5  0.6  0.0 FF%..                                                    20
21  1.7  0.6  0.0 F%..                                                     21
22  1.4  0.6  0.0 F%.                                                      22
23  2.7  0.6  0.0 FF%.                                                     23
UT  OWF EMUF  ALF |...|....| ....|....| ....|....| ....|....|  OWF EMUF  ALF UT
==============================================================================
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Fig. 2. Frequency prediction distance Kuala Lumpur nearby areas at 17 Jan. 2025.

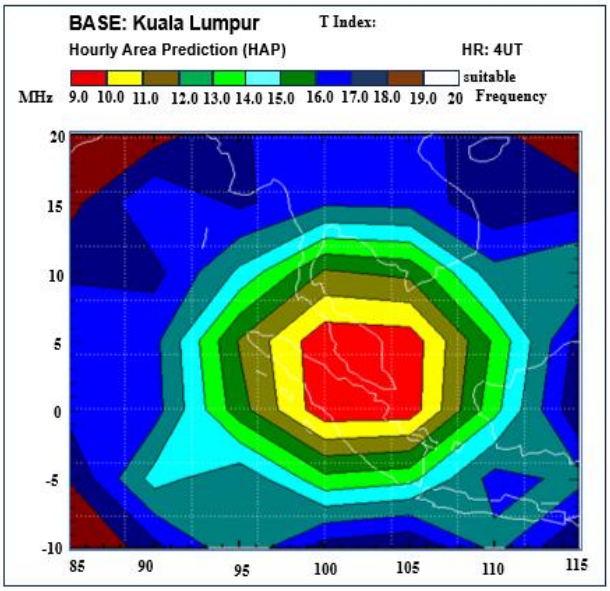

Fig. 3. Optimum high frequency communication for Kuala Lumpur and nearby area by HTZ software (change Fig. 3).

- Solar Activity and Its Impact on HF.
- Communication: Solar activity plays a crucial role in HF communication, as the release of electrons in the ionosphere is driven by solar radiation. This activity is measured by the **sunspot number**, which follows an **11-year cycle**. In **2024**, sunspot numbers were particularly low, indicating reduced ionospheres

density. As a result, many HF frequencies could not refract back to Earth and instead escaped into space. During such periods, frequency selection becomes even more critical, as the usable frequency range narrows significantly. Fig. 4 shows sunspot value number from 2020 to 2032.

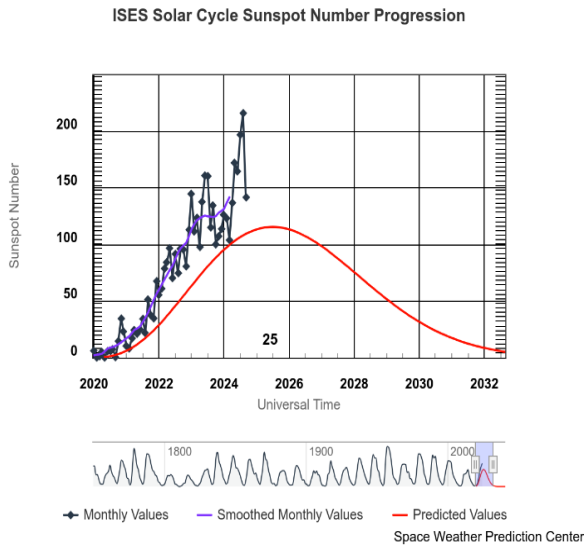

Fig. 4. Sunspot value number from 2020 to 2032 (change Fig. 4).

- Antenna Type and Height in HF Communication. The type and height of the antenna significantly influence the radiation pattern, which determines the propagation angle of radio waves from the Earth's surface. Short-distance communication requires a higher propagation angle, while long-distance communication benefits from lower angles for better ionospheres reflection. Additionally, factors such as transmission power and Voltage Standing Wave Ratio (VSWR) between the antenna and transmitter must be considered. Proper tuning ensures optimal wave propagation, maximizing signal efficiency and reliability. These antenna design significantly affect the accuracy and reliability of the bearing determination process and using the mathematical modelling method for the triangulation by two or more station direction finder [16]. The context of RDF systems, understanding HF propagation characteristics is essential for accurately determining signal sources. The system architecture integrates advanced algorithms, antenna arrays, and signal processing techniques to enhance direction-finding capabilities, ensuring precise geolocation of radio emissions across various distances and environments [17].

Phase 5: Radio Emitter Direction Estimation. The RDF system is designed to estimate the direction of a Radio Emitter (RE). Unlike radar systems, RDF operates passively, meaning it does not transmit any signals but only detects and determines the bearing of incoming radio waves without providing distance information [18, 19]. To determine the location of an RE, triangulation is used. This technique involves combining bearing data from two or more RDF stations positioned at different locations. The intersection point of these bearings indicates the possible location of the RE, as illustrated in Fig. 5. This method enables accurate geolocation of radio signals within the operational range of the RDF system.

Fig. 5. Visual representation of triangulation.

To obtain accuracy and precision in determining target location, several factors that need to be implemented in Hybrid RDF are as below:

- Triangulation and Optimal RDF Configuration: Triangulation occurs when two or more RDF stations, positioned at different locations, detect the same Radio Emitter (RE) and their bearing lines intersect, as shown in Fig. 5 [20]. While two RDF stations are sufficient for triangulation, challenges arise if the two stations and the RE are aligned in a straight line. In such cases, a third RDF station is necessary to establish a valid intersection point, as illustrated in Fig. 6. The addition of a third station enhances accuracy by reducing ambiguity and refining the estimated location of the RE [21]. Thus, an optimal RDF system configuration consists of three RDF stations arranged in a triangular formation. To enable triangulation, all three RDF stations must be interconnected through a communication system that facilitates real-time sharing of bearing data. This communication medium can include radio links, satellite connections, VPNs, or other secure networks [22]. Typically, one station is designated as the Master Station, responsible for collecting and processing bearing data to determine the precise location of the RE.

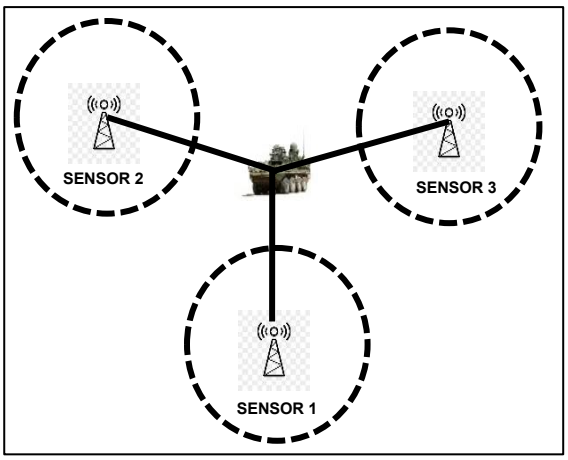

Fig. 6. Triangulation by RDF.

- RDF in the HF Frequency Range: The performance of an HF RDF system largely depends on the signal

reception quality at the RDF station. A strong signal ensures stable and accurate bearing readings, whereas weak or unclear signals result in fluctuating readings with a higher margin of error [23]. Logically, closer proximity between the RDF station and the Radio Emitter (RE) should result in stronger signal reception, leading to more precise bearing calculations. However, this principle does not fully apply to HF RDF systems due to the nature of HF wave propagation. Most HF signals travel as sky waves, which reflect off the ionosphere rather than following a direct line-of-sight path. As a result, an RDF station located **too close** to the RE might fall within a skip zone − an area where no signals are received due to the wave's propagation pattern. Conversely, stations too far away might be outside the effective coverage range**.** Therefore, it is crucial to position HF RDF stations strategically within an optimal range to ensure reliable signal reception and accurate bearing estimation. If an HF RDF station **is** static and cannot be relocated, it presents an inherent limitation in signal reception [24]. This constraint can only be mitigated by deploying additional static HF RDF stations in strategic locations to improve coverage and accuracy. HF RDF operation is more challenging compared to other frequency ranges that rely on ground waves or direct waves [25]. This is because HF signals primarily propagate as sky waves, which are received at an elevation angle from the Earth's surface, as illustrated in Fig. 7. The elevation angle varies depending on the distance between the target Radio Emitter (RE) and the RDF station. Proper understanding and management of these elevation angles are crucial for optimizing HF RDF performance and ensuring accurate direction finding.

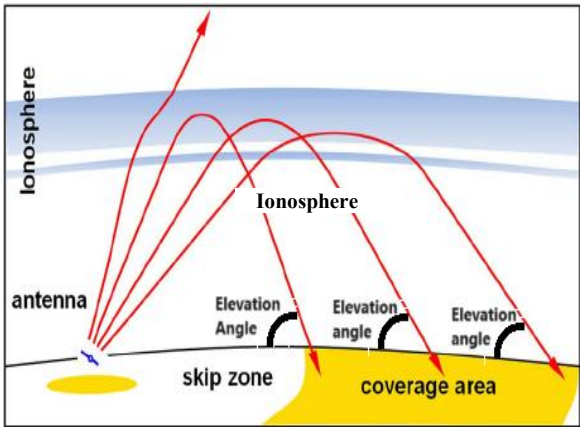

Fig. 7. Elevation angle.

When a Radio Emitter (RE) is located too close to an HF RDF station, the elevation angle of the received signal increases, approaching 90°**.** This situation is comparable to throwing a stone straight up into the air and having it fall vertically back down — It becomes difficult to determine the direction from which the stone was originally thrown. Similarly, in HF RDF, a high elevation angle makes it challenging to accurately determine the bearing, often leading to significant errors in direction estimation. Conversely, when the RE is farther away**,** the received signal arrives at a lower elevation angle, making it easier to identify the transmission direction accurately. This phenomenon is illustrated in Fig. 8, demonstrating how signal elevation impacts HF RDF performance.

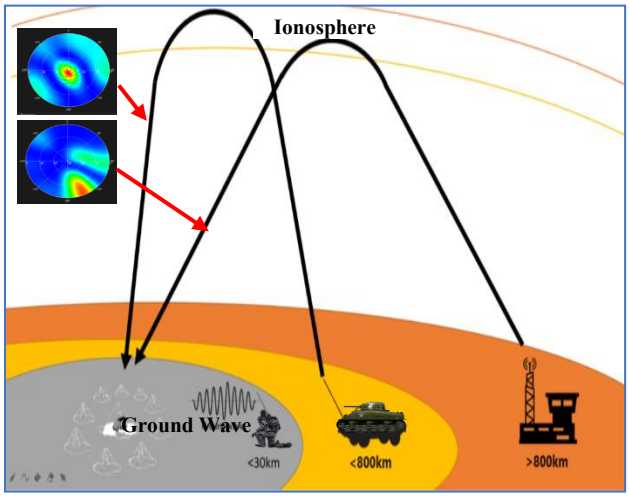

Fig. 8. Elevation angle effect.

The system automatically selects the appropriate antenna based on the operating frequency. The arrangement of these antenna arrays at each station is depicted in Fig. 9.

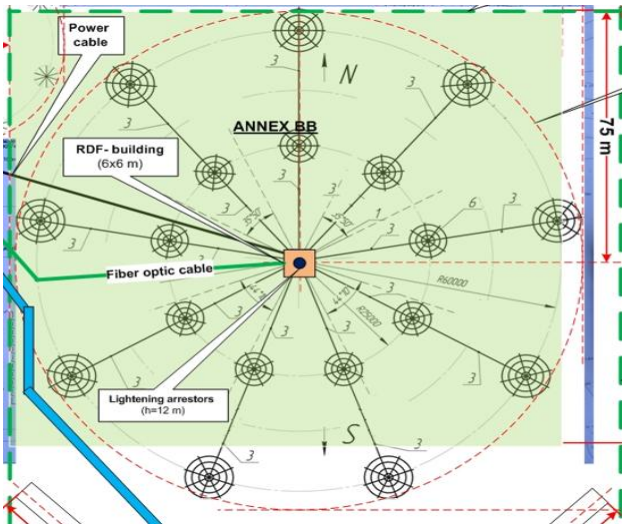

Fig. 9. Antenna array HF RDF layout.

- Bearing Acquisition Process in HF RDF — The bearing acquisition process, the obtained bearing readings fluctuate continuously. This result pattern is normal in any RDF system [26]. To manage these variations, most RDF systems collect all bearing readings and represent them in a histogram. The most frequent bearing value is selected, and the Root Mean Square (RMS) bearing is calculated based on the standard deviation of the histogram. RDF RP is the primary software used for obtaining bearing readings. Based on the Radio Direction Finder-Radio Parameter (RDF-RP) interface by HTZ Software Tools for

Planning and Analysis Spectrum shown in Fig. 10, the following steps should be followed to ensure accurate bearing acquisition:

1) Select an appropriate bandwidth: It should not be too narrow (excluding parts of the signal) or too wide (including noise or unwanted signals).
2) Observe bearing stability: This can be monitored through 2D and 3D bearing displays.
3) Consider the elevation angle: A lower elevation angle generally provides more stable bearing readings.
4) Identify the correct signal duration: Ensure the signal is active within the selected time window. Clear the histogram data before starting a new measurement. Play the selected signal to begin histogram formation. Obtain a histogram with the smallest standard deviation – If the result is unsatisfactory, repeat Step 4 with a different time window.
5) Finalize the bearing reading: Once satisfied with the histogram, click the 'Q max' button to extract the bearing reading based on the histogram analysis.

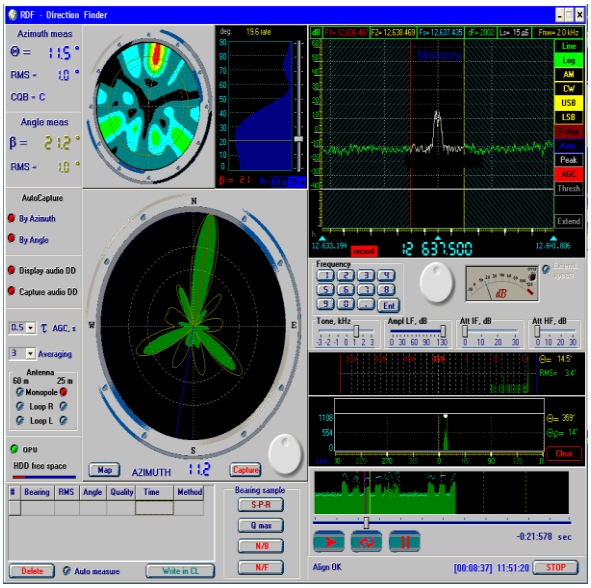

Fig. 10. RDF RP (radio parameters) interface by HTZ software tools.

The most critical part of the bearing acquisition process. If the selected time window does not match the actual signal transmission period, the obtained bearing will only reflect random environmental noise, leading to inaccurate results [27]. To ensure accuracy, Next step must be repeated until the operator is satisfied with the histogram. Fig. 11 illustrates three histogram examples, where the histogram with the smallest Standard Deviation (SD) provides the most stable bearing reading. In RDF systems, Standard Deviation (SD) represents the RMS value, serving as a key indicator of bearing accuracy and stability. A lower SD corresponds to higher precision, making it essential to select the correct signal duration for the most reliable results.

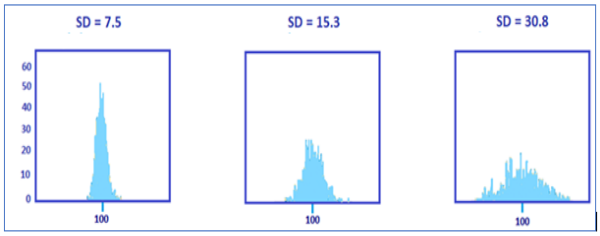

Fig. 11. Histogram data (Change Fig. 11).

- Accuracy of RDF Systems: The accuracy of an RDF system is inherently variable due to the continuous changes in signal conditions. Even when measurements are taken at short intervals, such as every minute, the results fluctuate because they are dependent on real-time signal variations. If the received signal is sufficiently strong for RDF calculations, the deviation in readings remains minimal, and reliable data can be determined using a histogram display. Similarly, triangulation results also vary with each execution of the process. Therefore, the accuracy of an RDF system cannot be assessed based on a single reading. Instead, an averaged reading provides a more precise representation of the central bearing value derived from the HF RDF system. Bearing errors are typically influenced by several factors, including instrumental errors, signal strength, noise, and interference. Due to these factors, the bearing and location estimated by an RDF system are never 100% accurate. However, they are sufficient for approximating the region where the target Radio Emitter (RE) might be located. Post-analysis is crucial to refining RDF results before determining the exact position of the target RE. This post-analysis requires a significant amount of data and repeated RDF trials as input for evaluation. Notably, this process is typically conducted by RDF analysts rather than HF RDF operators. Fig. 11 illustrates the principles of triangulation error involving two RDF stations. This figure highlights the key factors affecting triangulation accuracy:

1) Bearing errors, $\Delta\theta 1$ and $\Delta\theta 2$.
2) Distance between RDF stations and the target, R1 & R2.
3) The angular position of both stations relative to the target, γ.

By considering these factors, post-analysis enhances the reliability of RDF measurements, leading to a more precise determination of the target's actual position.

Triangulation error as known Fig. 12 is referring of Radio Direction Finding (RDF) inaccuracies that arise when estimating the location of radio frequency source using two or more bearing sensor stations. This results from multipath signal differences between elevation angles and uncertainty's target location of the sensor RDF stations themselves. The formula for Circular Error (σr) in triangulation can be expressed as Eq. (1):

$$\sigma_\gamma = \frac{\pi}{180\sin\gamma}\sqrt{R_1^2\sigma_1^2 + R_1^2\sigma_2^2} \quad (1)$$

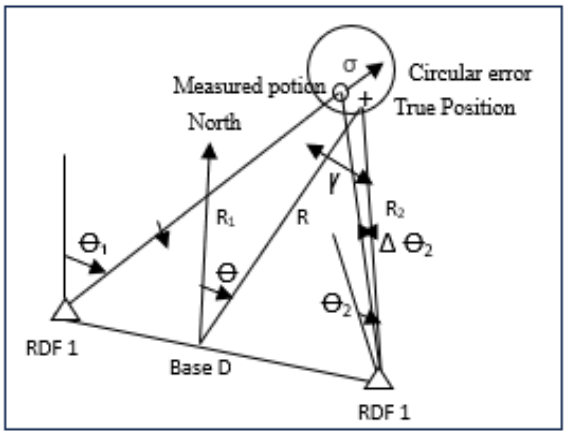

Fig. 12. Triangulation error between 2 RDF station.

where σ_r is the circular error (error radius), σ_2 is the average bearing error (**Δθ**) of RDF stations 1 & 2, R1 and *R*2 are the distances from RDF stations 1 & 2 to the target, while γ is the angle between the two bearing lines (RDF1 and RDF2) from the target in radians. Three stations, whose frequencies and locations have been identified, will be used as test targets. These points are listed in Table II.

TABLE II. LIST OF TARGET POINTS

No	Point	Freq (kHz)	Location
1	Point A	12.777	31.019444N/121.376667E
2	Point B	12.195	−6.214167N/106.850556E
3	Point C	13.285	23.183333N/113.266667E
4	Point D	6.676	13.733333N/100.5E

The measurement procedure is given by:

1) The target frequencies were monitored for two days (January 18 and 19, 2025) and the RDF and triangulation processes were conducted multiple times for each target.
2) Sensor 1 was designated as the Master Station.
3) To ensure operator capability at each station, the Master Station controlled the RDF operations at all stations via remote desktop.
4) All bearing and triangulation readings obtained were recorded in the designated test table.
5) The average bearing and triangulation readings for each station were taken and evaluated.
6) The bearing and triangulation readings for the same target were collected, and the circular error σr was determined.
7) The acceptability of the bearing accuracy was determined based on the circular error σr value.

Hybrid Radio Direction Finding (RDF) systems combine Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) techniques to improve target localization accuracy. AOA determines the direction of a signal using one or more mobile or fixed direction-finding stations, while TDOA calculates the target's position based on the time delay between signal arrivals at multiple fixed sensors. TDOA requires at least three synchronized sensors to provide real-time geolocation. In a hybrid system, AOA provides directional bearings, and TDOA offers precise position data. Together, they enable accurate triangulation and reduce ambiguity in target tracking, especially in maritime and border surveillance applications. Fig. 13 shows the diagram of Hybrid RDF using the AOA and TDOA method.

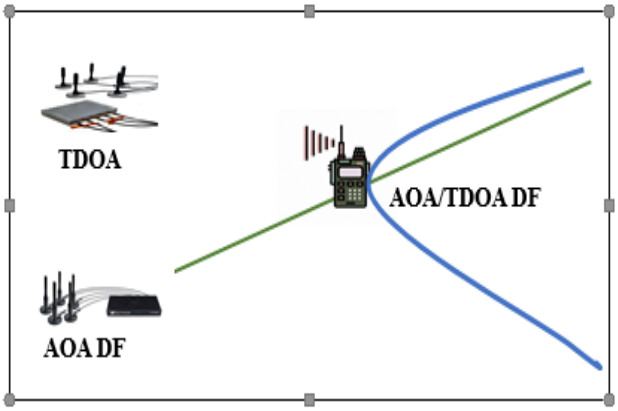

Fig. 13. Hybrid DF by AOA and TDOA method.

IV. RESULTS AND DISCUSSION

The monitoring of all captured frequencies was conducted over a two-day period, on January 18 and 19, 2025. Radio Direction Finding (RDF) and triangulation operations were carried out each time the target signal was transmitted. The results obtained are presented in Tables III and IV.

From the analysis of the test results in Table III and Table IV, the following observations were identified:

- A total of five RDF/triangulation attempts were conducted on the Point A target. In all five instances, the RDF bearing from Station 3 consistently indicated a direction opposite to the actual bearing, despite clear signal reception with no noise or interference present. No configuration errors were detected, and RDF operations on targets from other directions produced accurate results. This anomaly suggests a fault in one of the elements of the 25-meter antenna at Station 3, likely affecting the system's ability to resolve bearings within a specific angular sector (0° to 40°).
- The Point B signal was clearly received only at Station 1. At Station 2, the signal was very weak, while at Station 3 it was entirely undetectable. As a result, Station 2 produced a significantly deviated bearing, and Station 3 generated random bearings due to being outside the signal coverage area. Consequently, Point B was excluded from the target list on the first day of testing due to insufficient signal reliability for accurate triangulation.
- The average bearing readings for all targets are as shown in Table V.

TABLE III. MONITORING RESULT ON 18TH JAN. 2025

Time	Freq (kHz)	Station	Data			Coordination Target	
			Bearing	Distance (Km)	ΔBearing	Triangulation	ΔBearing
1051	12.663	Station 1	37.1	3504.1	15.1	33.106944	273.67
		Station 2	15.1	3077.3	1.2	122.364612	
		Station 3	212.5	3123.5	201.5		
1053	12.663	Station 1	37.1	3505.14	15.1	30.942779	15.23
		Station 2	14.7	3077.3	0.3	122.508881	
		Station 3	211.3	3123.5	203.4		
1107	12.663	Station 1	38.2	3505.14	14.5	32.3267811	48.70
		Station 2	14.5	3077.3	0.1	123.751390	
		Station 3	210.7	3123.5	202.3		
1138	12.663	Station 1	38.6	3505.14	14.5	30.7716111	31.76
		Station 2	14.5	3077.3	0.5	122.663584	
		Station 3	210.9	3123.5	204.5		
1207	12.663	Station 1	39.7	3505.14	14.7	31.9791681	43.88
		Station 2	14.7	3077.3	0.7	122.802322	
		Station 3	274.3	3123.5	206.7		
Average Stn 1	**0.6**	**Average Stn 2**	**0.7**	**Average Stn 3**	**207.3**	**Total Average**	**80.99**
		Legend:	> 0.0−1.9: High Accuracy				
			> 2.0−200: Medium Accuracy				
			> 201: Low Accuracy				

TABLE IV. MONITORING RESULT ON 19TH JAN. 2025

Time	Freq (kHz)	Station	Data			Coordination Target	
			Bearing	Distance (Km)	ΔBearing	Triangulation	ΔBearing
1051	12.338	Station 1	37.1	3504.1	1.3	33.106944	266.1
		Station 2	14.9	3513.2	1.2	122.364612	
		Station 3	212.7	2817.32	204.6		
1055	12.773	Station 1	35.2	2316.71	1.7	22.5833442	68.32
		Station 2	357.8	2388.42	0.2	114.456223	
		Station 3	345.2	1992.4	0.4		
1101	13.421	Station 1	36.7	2319.22	0.1	22.4765321	45.77
		Station 2	358.1	2410.33	0.7	114.532414	
		Station 3	346.3	1994.3	1.3		
1107	13.667	Station 1	150.1	3503.4	0.0	30.9437781	14.13
		Station 2	358.1	3582.22	0.3	121.506728	
		Station 3	210.6	2817.3	203.5		
1138	12.345	Station 1	4.3	1590.18	2.1	-6.4433333	100.32
		Station 2	14.3	1597.2	3.8	108.738890	
		Station 3	219.3	1893.4	3.7		
1150	6.675	Station 1	151.4	1933.2	2.3	12.0744321	190.24
		Station 2	210.77	2032.12	6.0	100.782067	
		Station 3	196.8	2111.3	99.4		
1158	12.775	Station 1	151.3	1590.22	1.5	-5.8803452	39.77
		Station 2	301.2	1600.22	0.4	106.978344	
		Station 3	219.8	1899.5	3.7		
1207	13.101	Station 1	35.6	1590.22	1.1	-6.3052311	39.62
		Station 2	214.55	1617.34	1.8	107.196345	
		Station 3	222.32	1899.3	0.7		
Average Stn 1	**1.4**	**Average Stn 2**	**1.7**	**Average Stn 3**	**66.32**	**Total Average**	**95.42**
		Legend:	> 0.0−1.9: High Accuracy				
			> 2.0−200: Medium Accuracy				
			> 201: Low Accuracy				

TABLE V. AVERAGE ERROR BEARING

RDF Station	Average Error Bearing (°)		
	18 Jan. 2025	19 Jan. 2025	Total
Station 1	1.3	1.2	1.21
Station 2	1.7	1.3	1.47
Station 3	64.6	68.7	66.78

If the bearing readings for Point B and Point A are excluded for the Station 1, the overall average bearing error is 1.25°. This indicates that the bearing accuracy of the Station 2 RDF station in sectors other than 0° to 40° is comparable to the other two RDF stations. The accuracy of the triangulation decision is considered acceptable if the actual location of the target falls within the circular error range, σr - Circular error. The following is the calculation of the circular error for each target. Table VI Shows all the RDF/triangulation test results for the Point B target.

TABLE VI. RDF/TRIANGULATION RESULTS FOR THE POINT B TARGET

Time	Freq (kHz)	Station	Data			Coordination Target	
			Bearing	Distance (Km)	ΔBearing	Triangulation	ΔBearing
0930	13.117	Station 1	37.1	2318.1	3.4	33.106944	154.32
		Station 2	356.8	2095.1	1.2	122.366412	
		Station 3	346.5	1991.4	0.4		
0945	13.225	Station 1	35.2	2386.2	2.3	22.5833442	120.33
		Station 2	355.4	2095.1	2.7	114.456223	
		Station 3	346.3	1991.3	0.6		
1030	12.375	Station 1	36.3	2319.6	0.6	23.4765321	42.11
		Station 2	358.3	2095.3	0.7	134.532414	
		Station 3	345.1	1991.3	0.2		
1051	12.773	Station 1	36.2	3502.2	0.5	30.9437781	47.12
		Station 2	14.7	3064.2	0.3	121.506728	
		Station 3	209.2	2817.3	201.3		
1057	13.411	Station 1	37.1	3611.3	0.4	−6.4433333	46.53
		Station 2	14.7	3062.2	3.8	108.782067	
		Station 3	209.2	2817.5	201.5		
1232	12.110	Station 1	154.2	3672.3	0.3	12.0744321	33.42
		Station 2	358.6	3071.5	6.0	100.782067	
		Station 3	345.3	1991.5	0.1		
1243	13.457	Station 1	161.3	1590.4	2.7	−5.8803452	40.81
		Station 2	14.8	1416.5	0.4	107.978344	
		Station 3	214.2	2816.4	268.3		
1407	13.992	Station 1	31.5	1537.2	0.5	−6.3052311	92.23
		Station 2	211.3	1416.5	1.8	105.196345	
		Station 3	220.1	1814.3	0.1		
Average Stn 1	**1.4**	**Average Stn 2**	**1.7**	**Average Stn 3**	**66.32**	**Total Average**	**95.42**
		Legend:	> 0.0−1.9: High Accuracy				
			> 2.0−200: Medium Accuracy				
			> 201: Low Accuracy				

Due to antenna error in the 0° to 40° sector at Station 1, triangulation for the Point A target was conducted using only two stations: Station 2 and Station 3. The angle between Stations 2 and 3 from the target is ϒ = 22.4°. The accuracy of the RDF result for this target can be determined by calculating the Circular Error, σr. Circular error represents the maximum acceptable distance deviation for a given target. If the maximum allowable error is 2°, the circular error for this target is calculated as follows Eqs. (2−3):

$$R_1 = 1416Km$$
$$R_2 = 1833.4\ Km$$
$$\sigma_1 = 2^{\circ}$$
$$\sigma_2 = 2^{\circ}$$
$$\gamma = 35.7^{\circ} \tag{2}$$

Average Error triangulation $= 65.23KM$, Circular error:

$$\sigma_\gamma = \frac{\pi}{180\sin\gamma}\sqrt{R_1^2\sigma_1^2 + R_1^2\sigma_2^2}$$

$$\frac{\pi}{180\sin 35.7}\sqrt{(1416.5^2 \times 2^2) + (1833.42 \times 2^2}$$

$$= 145.18\ km \tag{3}$$

It was found that the circular error value is 145.18 km. The average distance difference between the triangulation and the actual location of the Point B target is 65.23 km. This indicates that the triangulation between Stations 1 and 2 for this target is accurate and acceptable. When all sensor stations operate effectively, the Radio Frequency emitter can be utilized. However, one of the sensor stations experienced bad performance in the 0° to 40° sector due to an antenna issue. To precisely determine the emitter's location using an independent technique, at least two Angle of Arrival (AOA) sensors or three Time Difference of Arrival (TDOA) sensors are necessary. Nonetheless, elements such as multipath propagation, obstructions, and weak signals may hinder the identification of the emitter's signal over an adequate number of sensors, thereby affecting localisation efficacy. Triangulation remains reliable for target localization, as the system can compensate using the two unaffected stations. The antenna issue does not compromise overall RDF functionality, allowing users to proceed with operational deployment of the sensor HF RDF system.

V. CONCLUSION

This paper presents a hybrid Radio Direction Finding (RDF) system that integrates Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) techniques to improve signal localization accuracy and reduce noise and detection errors in High Frequency (HF) communication environments. Designed for applications such as maritime and border surveillance, the system demonstrates strong potential for real-time emitter tracking using fixed and mobile sensor networks. The hybrid approach enhances resilience against multipath interference and signal

distortion while minimizing infrastructure and cost requirements. Field test results confirm that combining AOA bearings with TDOA timing significantly improves geolocation precision in complex operational scenarios. Furthermore, enhancing RDF performance requires optimization of antenna layouts, implementation of advanced signal processing techniques, and the integration of hybrid methodologies, as proposed in this study. As research continues, the integration of artificial intelligence and advanced signal processing is expected to further enhance the precision and reliability of radio direction-finding systems for various applications. The application of a Genetic Algorithm (GA) further optimized the accuracy of hybrid Communication and Radio (CAR) geolocation across varying operational scenarios. Results confirm that the GA enhanced hybrid system provides improved positioning reliability and robustness, making it suitable for real-time monitoring and enforcement applications in complex HF communication environments.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Abdul Hadi Ramli, Nor Fadzilah Abdullah, and Asma Abu-Sama: Conceptualization; Abdul Hadi Ramli and Nor Fadzilah Abdullah: methodology, software, and validation; Abdul Hadi Ramli, Nor Fadzilah Abdullah, and Asma Abu-Sama: formal analysis; Abdul Hadi Ramli: investigation; Abdul Hadi Ramli, Nor Fadzilah Abdullah, and Asma Abu-Sama: writing-original draft preparation; Abdul Hadi Ramli: writing-review and editing; Abdul Hadi Ramli and Nor Fadzilah Abdullah: supervision; all authors have read and agreed to the published version of the manuscript.

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