New Aspects of Progress in the Modernization of the Maritime Radio Direction Finders (RDF)

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This paper as an author contribution introduces the implementation of the new aspects in the modernization of the ships Radio Direction Finders (RDF) and their modern principles and applications for shipborne and coastal navigation surveillance systems. The origin RDF receivers with the antenna installed onboard ships or aircraft were designed to identify radio sources that provide bearing the Direction Finding (DF) signals. The radio DF system or sometimes simply known as the DF technique is de facto a basic principle of measuring the direction of signals for determination of the ship's position. The position of a particular ship in coastal navigation can be obtained by two or more measurements of certain radio sources received from different unspecified locations of transmitters on the coast. In the past, the RDF devices were widely used as a radio navigation system for aircraft, vehicles, and ships in particular. However, the newly developed RDF devices can be used today as an alternative to the Radio – Automatic Identification System (R-AIS), Satellite – Automatic Identification System (S-AIS), Long Range Identification and Tracking (LRIT), radars, GNSS receivers, and another current tracking and positioning systems of ships. The development of a modern shipborne RDF for new positioning and surveillance applications, such as Search and Rescue (SAR), Man over board (MOB), ships navigation and collision avoidance, offshore applications, detection of research buoys and for costal vessels traffic control and management is described in this paper.

KEY WORDS
~ RDF
~ AIS
~ SAR
~ MOB
~ Watson-Watt Antenna
~ Doppler RDF Antenna
~ HF
~ VHF
~ UHF

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1. INTRODUCTION

The idea for the development of Radio Direction Finding (RDF) was born, when in 1888 German inventor Heinrich Rudolf Hertz discovered the directional property of radio waves and when in 1889, the inventor of the radio Russian physics professor Alexander Stepanovich Popov carried out practical experiments according to Hertz's research successfully demonstrated the transmission of EM waves via a radio link. However, the special implementation of this important invention dedicated to find the direction of incidence of electromagnetic waves was set out in 1906 in a patent obtained by Scheller on the basis of the Direction Finding (DF) system.

The original invention of direction finders were polarizing DF devices that used rotating magnetic or electric dipoles, which axis coincided with the direction of the magnetic or electric field. This DF system was known as a first rotating-loop DF that reduces the direction of incidence from the direction of polarization. In 1907 two Italians, Ettore Bellini and Alessandro Tosi invented the DF system named after them and whose purpose was to determine the direction using a combination of two cross or loop antennas with movable coils. Excluding this invention, DF devices with a rotating loop were used very often during the First World War (WW1).

The famous British engineer Frank Adcock invented and antenna array with four equivalent vertical elements for transmitting and receiving directional radio waves. This DF enhanced the accuracy of the DF in relation to sky waves in the shortwave area, and in 1931 Adcock antennas were deployed in Germany and Great Britain.

In 1925/26, Scottish pioneer Sir Robert Watson-Watt realized that the outdated mechanically moved goniometer direction finder should be replaced with a new electronic visual direction finder. The first short-wave DF device that worked on the Doppler effects was introduced in 1941. Since 1943, the first dedicated DF devices have been used for special "radar observations" operating at 3000 MHz. Later, during the Second World War (WW2), the 3-channel cross-loops Watson-Watt DF devices for detecting German short-range submarines (huff-duff) were mounted onboard ships of the British Navy. At the same time, special wide-aperture DF devices with a circular array (Vullenweber) for remote DF operations were designed and deployed. On the other hand, the airborne VHF/UHF Doppler DF equipment for air traffic control was equipped at airport infrastructures around the world, while sometime later DF system became operational for vessel traffic control. The main improvement provided by pseudo-Doppler over Adcock was its ability to implement as a wide-aperture array capable of reducing errors due to multi-path interference.

Early in the 1970s, modern digital technology enabled greater advances in the development of DF and radar technology. Thus, the new generation of digital remote control and bearings were the main sources of this development, and since 1980, digital signal processing system has been increasingly used for the continuous development of the DF technique. It enables the use of interferometer DF devices and new possibilities for the development of multiwave DF devices with super-resolution. The first theoretical approach to advanced DF technology has been made and other significant outcomes for continuous innovation have been set in order to find a DF system for agile frequency emissions, such as signals and broad-spectrum frequencies. A significant outcome of this innovation was broadband DF technology, which was able to provide search and DF technique founded on digital filter banking theory, tipically using Fast Fourier Transform (FFT) (R&S, 2015; Ilcev, 2010; Ilcev, 2017; Skorik, 2014).

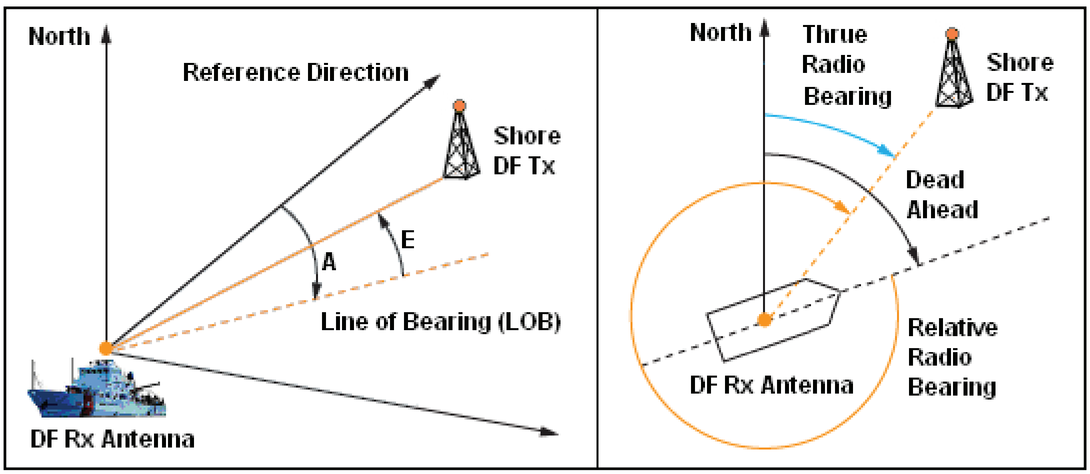

Figure 1.
Definition of Shore DF Tx and Reference Direction – Source: Rohde & Schwarz (2012).

2. OPERATING PRINCIPLES OF RDF SYSTEMS

The RDF systems for maritime applications are one of the oldest and most frequently used radio-navigation in the past time with many advantages and disadvantages of the use of the RDF in navigation, and positioning systems. The functions of RDF equipment can be divided into three integrated subsystems: sensor system, signal processor and display. The task of RDF equipment is to estimate the direction of the shore transmitter by estimating and measuring the parameters of the electromagnetic field. In practice, the deck officers during navigational operations on the ship's bridge turn the antenna of the RDF unit to find the direction of the radio beacon and take two or more beacon bearings off any DF transmitting station at the shore to indicate the ship's position on a chart. In fact, a radio bearing can be used to back up a visual bearing as well as any other type of navigational solution onboard oceangoing ships.

Practically, only by using azimuth (A) is it possible to get the direction, while the determination of elevation (E) is important for transmitters deployed on the shore around coastal waters, and especially for finding the direction of shortwave signals, which is the definition of shore DF Tx device depicted in Figure 1 (Left). During transmission, the RDF receiver takes timing and space samples from this frontal wave and ideally provides the estimated magnitudes for A and E as the most likely direction of the observed transmitter located on the shore. In Figure 1 (Right) is illustrated scenario of bearings that can be taken using the following reference directions: (1) Geographic or true North with the angle of true radio bearing; (2) Magnetic North and (3) Ship axis angle of relative or direct radio bearing.

The term "Receiver front End" of the RDF Rx device is used to provide the initial stage of the receiver that convert the Radio Frequency (RF) signal into the Intermediate Frequency (IF), amplifies and forwards it via the bandpass filter. Besides, the filter bandwidth device controls the bandwidth of the receiver. The phase delays representing the components of the device are considered to be identical in all directions of the signal, which do not affect the operation of the DF operational system unless otherwise stated. Amplitude gains and losses are also assumed to be equal in all signal paths. The term "channel" is important to introduce the direction of a signal through a DF network. For instance, two radio signals may use the same channels and share the same circuits, but not necessarily the same frequency band. Moreover, in this case, all values of the angles are shown in degrees, where the real dimension from −180o to +180o has also been adopted. The appropriate values of the radians and the magnitude of the arctangent can be considered using the following relation:

$$\phi = \arctan(Y/X) \qquad (1)$$

where ϕ = true signal-bearing in azimuth referreed to true North in radians, Y = "–" and X = "+", which both signals are used to represent the quadrant of ϕ. In mathematical derivations, the RF signal is considered to generate a voltage in an adequate dipole antenna represented in the following form:

$$\int(t)\, V_d \sin(\omega t + \gamma) \qquad [v] \qquad (2)$$

where value t = Time in seconds (s), V_d = Maximum voltage induced in an adequate dipole antenna in Volts (V), ω = Signal frequency in rad/s and γ = Signal phase in radians. In addition, the other parameters are: λ = Signal wavelength in meters, ϕC = Bearing computed by the direction-finding system in radians, and value d = Distance between a pair of antennas in meters (m) (R&S, 2012; Ilcev, 2017; Gething, 1991; Pine et al., 2004; Nisar, 2016).

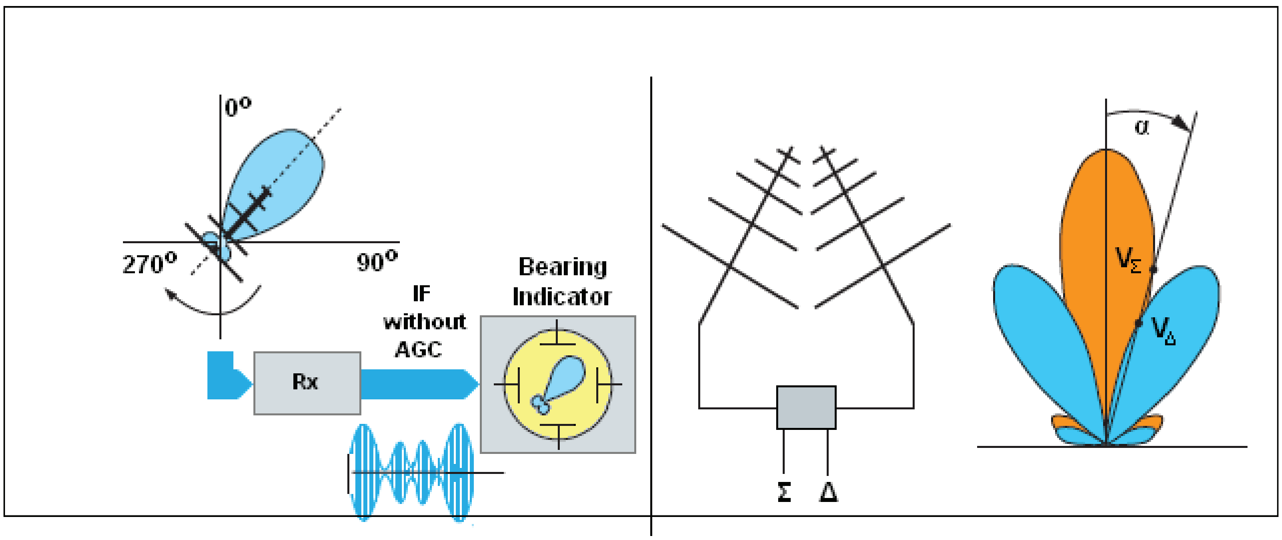

Figure 2.
Directional DF Antenna and Sum-difference DF Antenna – Source: Nisar (2016).

3. TYPES OF RDF SENSORS AND COMPONENTS

The RDF system onboard oceangoing ships may consist of the following main components: (1) Antenna system, (2) DF converter, (3) Evaluation unit, and (4) Display unit. Electromagnetic (EM) waves are caused by charging and discharging processes on electrical conductors and represented in the form of alternating currents.

The sensor components of the RD device couples transmission signals from the wave propagation environment. It consists of two or more antennas composed of an array, which detects the corresponding radio signals by the signal processor. There are basically two different modes of DF array antennas implemented in a sensor system: phase measurement and direction measurement antennas.

In the RDFtechnique, a special vertical dipole antenna array is designed to measure phases. As for the azimuth determination, the vertical dipole antenna shows that its ideal pattern of voltage amplification is in the omnidirectional direction, which is why this type of antenna is equally sensitive to all radio signals coming from any direction. Phase measurements are performed indirectly so that the dipole antenna measures the current signal amplitude at a certain point in space. The voltage obtained in the RD antenna can be calculated by:

$$V(t) = V_d \sin(\omega t + \gamma) \qquad [v] \tag{3}$$

The relative phase angle between the two array antennas can be achieved by comparing the voltage of the RDF antenna with the voltage of the second dipole antenna. In fact, when one antenna as a part of the RDF antenna array is dedicated for use as a source for phase comparison, this antenna is also known as a "sense" antenna. The ideal pattern of voltage gain (G) in the azimuth of the directional antenna as a function of the maximum antenna gain (Gmak) used for the Watson-Watt system can be determined using the following relation:

$$G = G_{max} \cos(\phi) \tag{4}$$

Due to the cosine form of the gain equation, this voltage gain pattern is often called the cosine pattern. In particular, the voltage of the multipurpose antenna arrays increases greatly, which is mainly depending on the direction of signal arrival. In such a way, real antennas for a direction-finding purpose are made of two or more dipole elements. For this reason, the actual voltage gain patterns are not real circumferential patterns, but their approximations. Thus, the projection of a new antenna array attempts to reduce cosine deviations, since deviations from the true cosine pattern result in bearing measurement errors.

3.1. Directional RDF Antenna Systems

The simplest way of DF is to use a mechanically rotated direction antenna, which rotates along the complete azimuth and the received voltage is evaluated. The bearing is estimated from the received voltage as a function of azimuth rotation of the antenna, while the position of receiving pattern in relation to the angle of rotation is provided by the bearing. Thus, this special method of DF is known as phase RDF as the directivity is obtained

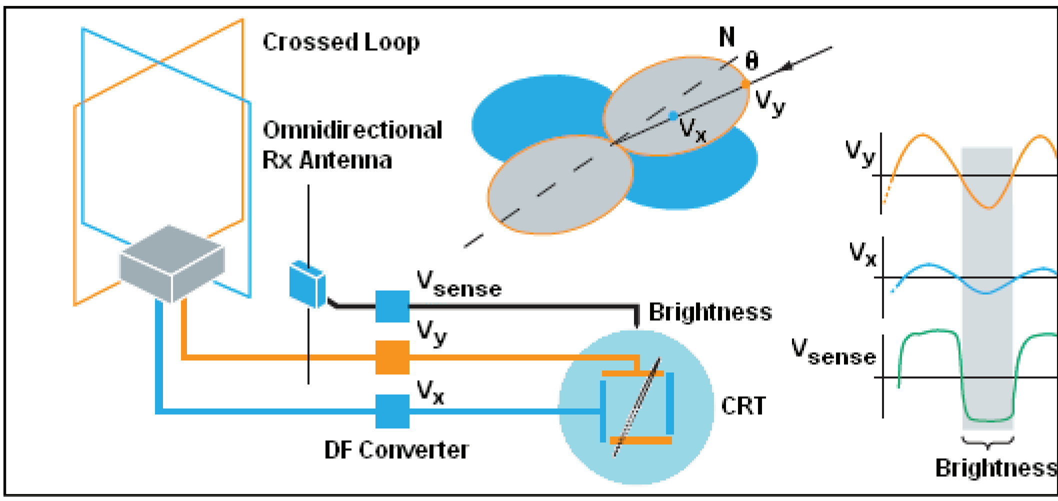

Figure 3.
Watson-Watt DF with Crossed-loop Antenna – Source: Rohde & Schwarz (2012).

by superimposing the waves with their phase depending on the angle of arrival. In its simplest form, an operator rotates the antenna and check the receive voltage level. When an assumed maximum receive voltage is obtained the direction is measured from a calibrated scale attached with the antenna. In a fully automatic direction finder based on this principle, the antenna is permanently rotated with a motor to form a rotating direction finder, which schematic diagram is illustrated in Figure 2 (Left).

The received voltage is plotted as a function of the angle of DF antenna rotation, while the automatic receive voltage evaluation mechanism such as maximum detector, can be cascaded to form a fully automatic DF system. The benefits of this type of direction-finding system are as follow: (1) High sensitivity due to antenna directivity, (2) Easy and economical setup, (3) Multi-wavefronts can be resolved with the help of high directivity antennas, and (4) Direction-finding and monitoring can be done with the same antenna. This directional DF method results in some drawbacks which are due to the directivity characteristics of the antenna and due to limited its rotation speed, such as follows: (a) Directivity is reciprocal to the probability of intercept, and (b) Short duration signals can be processed effectively due to slow scanning speed.

Regardless of the drawbacks, direction-finding methods based on mechanically rotated antennas are still used as the advantages associated with them require very high cost and effort to attain with other methods. Thus, in high frequency range such as microwave, these types of systems are the only feasible option in terms of low noise, gain and cost. The antenna bearings can be obtained with a slowly rotating antenna if the directional pattern with a minimum in the direction of arrival is used along with a maximum. This antenna configuration will result in a monopulse DF systems that operate successfully as the incident waves are in the main receiving direction. In Figure 2 (Right) is illustrated the implementation of the concept using log-periodic dipole antennas that are connected by means of a 0/180o hybrid. The quotient of sum and difference signals produce a time-independent and dimensionless function known as DF function, which quotation is as follows:

$$PF(\alpha) = V\Delta(\alpha)/V\Sigma(\alpha) \tag{5}$$

In such a way, after forming the quotient of the two test voltage values, the DF function immediately delivers the bearing value α (R&S, 2012; Ilcev, 2017; Nisar, 2016; Schantz, 2011; R&D, 2018).

3.2. Watson-Watt RDF Antenna Systems

The Watson-Watt DF solution operates by measuring the value of the signal vector along two orthogonal axes. These values are then used as arguments to the arc function to calculate the bearing signals. A semantic drawing of the Watson-Watt DF antenna array is shown in Figure 3. The two components' values of the orthogonal signal are measured by implementing two vertically oriented directional antennas. In fact, the DF Adcock antennas are used at VHF and UHF-band, as they are required to have cosine gain patterns. Mathematically, using the maximum antenna output (Vα) the output signals produced by these antennas are realized as:

Watson-Watt

$$X(t) = V\alpha \cos(\varphi) \cos(\omega t) \qquad [V] \tag{6}$$

$$Y(t) = V\alpha \sin(\varphi) \cos(\omega t) \qquad [V] \tag{7}$$

If the signals received by the DF antenna are amplified and filtered with sinusoidal and cosine outputs in the directional pattern and applied to the x and y deflection plates of a Cathode-Ray Tube (CRT), in the ideal case is realized a line of the Lissajous image, whose slope θ corresponds to the angle of wave shows an ambiguity of 180°. The specified angle can be realized using the ratio of two signals with the following ratio:

$$\theta = \arctan\,(V_x / V_y) \tag{8}$$

The RF signals received by the DF antenna are converted to IF in the receiver and forwarded to the synchronous demodulator unit. The demodulated reference signal is then multiplied in the mixer using each of the two input signals X(t) and Y(t). Using a mathematical relation, the reference signal can be represented as:

$$R(t) = V_r \cos(\varphi t) \qquad [V] \tag{9}$$

were *Vr* = maximum value of the voltage [Volts], and here, any high-frequency components are removed with a low-pass filter, and including maximum voltage (Vo) the relation can be realized in the form of:

$$X = Vo \cos(\varphi) \text{ and } Y = Vo \sin(\varphi) \qquad [V] \tag{10}$$

The solution to value φc can only be specific if a reference is also obtained from a DF signal which phase is independent of the signal-bearing. The values and Y are then used to compute the bearing angle by:

$$\varphi_c = \arctan\,(Y/X) \tag{11}$$

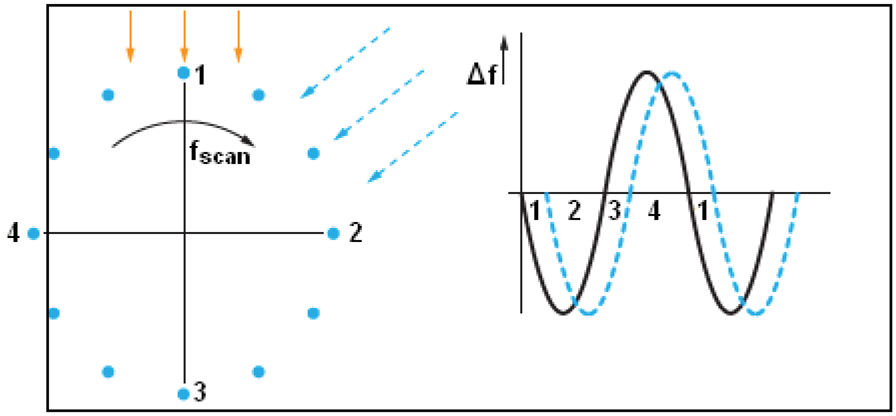

Figure 4.
Doppler DF Antenna Elements – Source: Rohde & Schwarz (2012).

As shown in Figure 3, an unambiguous bearing indication can be obtained if an additional signal is used in this DF method, which firstly was implemented by Watson-Watt in 1926. The distortion DF signal is taken from an omnidirectional receiving antenna with an unambiguous phase relationship. In fact, the Watson-Watt technique employs two pairs of Adcocks antenna to perform an amplitude comparison on the incoming signal. An Adcock antenna pair is a pair of monopole or dipole antennas that take the vector difference of the received signal on each antenna so that there is only one output from the antenna pair. Two of these pairs are located but vertically oriented to produce signals North-South (N-S) and East-West (E-W) which will then be forwarded to the receiver. The bearing angle can then be calculated in the receiver by taking the arctangent of the ratio of the N-S to E-W signal.

The principal advantage of this method is that the bearing is indicated without any delay, which means that it is able to find a monopulse direction in the range of entire azimuth angles. The special transverse loop antennas evaluated by the Watson-Watt method are suitable for maritime and other mobile applications due to their compact size and the following advantages: (a) Extremely short signal duration is sufficient, (b) Implementation is simple, and (c) Minimum space is required. The disadvantages are: (a) Small-aperture antenna ($D/\lambda < 0.2$) causing errors in case of multipath propagation, and (b) Large DF errors when receiving sky waves with steep elevation angles. However, the Adcock DF antenna is providing the following advantages over cross-loop array: (a) Overall error tolerance for receiving sky waves has improved, and (b) During multiple receptions, a wider aperture can be used to reduce the errors (e.g. $D/\lambda < 1$ for 8-fold Adcock) (R&S, 2012; Ilcev, 2017; Nisar, 2016; R&S, 2018; Denisowski, 2013; Moell & Curlee, 1967).

3.3. Doppler RDF Antenna Systems

The pseudo-Doppler system is a phase-based DF mode dedicated to provide an estimate of the bearing on the received signal by measuring the Doppler shift induced on the signal by sampling around the elements of the circular array. The basic system implemented in the DF technique was a single antenna designed to provide a circular motion, however, an advanced solution deploys a circular multi-antenna sampled successively, which sample is shown in Figure 4. In the case when the antenna part is circulating with a radius R, the received signal at frequency ωo is frequency modulated by the rotational frequency ωr of the antenna due to the Doppler effect. However, when the antenna part rotates towards the radiation source, the reception frequency increases, and if the antenna part moves away from the radiation source, the reception frequency decreases.

The basic Doppler DF system uses a single receive antenna placed on the edge of a fast-moving turntable and its rotation speed is accurately adjusted by servo-controlled by a low-frequency rotating tone generated in direction finding processor. With the antenna moving towards the transmitter, the apparent receive frequency increased and when it is moving away from the transmitter this frequency decreased. At this point, the received signal becomes frequency-modulated at a rate of rotational frequency. This signal is fed to an FM receiver, which recovers the rotational frequency signal through demodulation. This rotational frequency is exactly equal to the rotational frequency of the turntable but its phase would be offset from the rotational frequency. It can be understood that the phase difference between the recovered frequency and original rotational frequency relates to the bearing of the received signal, so the instantaneous amplitude provides the following quotation:

$$u(t) = a\cos[\varphi(t)] = a\cos[\omega o t + (2\pi R/\lambda o)\cos(\omega r t - \alpha) + \varphi] \quad (12)$$

The instantaneous frequency is obtained by differentiating the phase such as:

$$\omega(t) = d\varphi(t)/dt = \omega o - (2\pi R/\lambda o)\,\omega r\,\sin(\omega r t - \alpha) \quad (13)$$

After filtering out the DC component ωo the demodulated Doppler signal is obtained as:

$$SD = (2\pi R/\lambda o)\,\omega r\,\sin(\omega r t - \alpha) \quad (14)$$

This demodulated signal is phase compared with a reference voltage of the same centre frequency as the one generated from antenna rotation to check their phase. The result of this comparison provides the bearing α by:

$$Sr = -\sin\omega r t \quad (15)$$

Since rotating an antenna element mechanically is neither practically possible nor desirable, several elements (dipoles, monopoles, crossed loops) are arranged on a circle, see Figure 4, and electronically sampled by means of diode switches (cyclic scanning) (R&S, 2012; Ilcev, 2017; Nisar, 2016; Denisowski, 2013; Moell & Curlee, 1967; Keen, 2018).

3.4. Basic Signal Processors

Signal processing is an important component of the RDF system but will be briefly described here on its basis. It can be concerned as the following process with 3 steps: down-frequency conversion, demodulation, and calculation of bearing. Therefore, the receiver is providing down conversion and amplification of the RF signal into a fixed IF. The demodulator, as a component of the receiver, or composed as a separate device, is providing conversion of the signal from the IF into a form suitable for the bearing processor that calculates the bearing.

In some systems, the demodulated input signal to the bearing processor is not suitable for audio purposes (i.e., the operator of direction-finding cannot use it to listen to the intercepted signal). If the demodulator used for the bearing processor is separate from the receiver, the receiver demodulator can be used to convert the signal to audio; otherwise, a special receiver may be required for this purpose (R&S, 2012; Nisar, 2016).

4. CONVENTIONAL RDF SYSTEMS

The traditional RDF system for navigation purposes lost importance due to the availability of Automatic Radar Plotting Aids (ARPA), Global Navigation Satellite Systems (GNSS), and other navigation systems onboard ships. However, today's requirements need modern RDF systems for determining the location of transmitters for enhanced SAR, traffic control at sea, and other solutions. The RDF mode is a navigation device for finding the direction to a fixed or recently mobile radio source known as bearings of transmitters. Due to low-frequency propagation characteristic to travel very long distances and "over the horizon", it makes a particularly good navigation system for ships, small boats, and aircraft that might be some distance from their destination. The operation procedure for determining the bearing of radio signals at a receiving point of the source can be realized by observing the direction of arrival of the wavefront.

The RDF unit consists of an antenna-feeder system, which is used to receive the radio waves propagating from the object on which a bearing is being taken and detected on a receiving indicator. Thus, the DF system refers to the establishment of the direction from which a received signal was transmitted. This can refer to radio or other forms of wireless communication. By combining the direction information from two or more suitably spaced receivers (or a single mobile receiver), the source of a transmission may be located in space via triangulation. Radio direction-finding is used in the ship's navigation, to locate emergency transmitters for SAR forces, for tracking Man over Board (MOB), and to locate illegal or interfering transmitters.

When, in 2002, the International Conference on maritime security decided with the implementation of AIS, it seemed as though the combination of GPS and AIS would offer total reliability for the assignment of a ship's position in Vessel Traffic Service (VTS) areas. However, this is frequently turning out not to be the case. Therefore, AIS is certainly an appropriate means of conveying a large and varied amount of information about shipping movements to all users onshore, but during navigation, master mariners need very precise aids in determining the ship's location at a certain point in time. This study reports on a solution to this that involves the aid of a modern RDF and other radio and satellite systems to provide some more reliable solutions for ships collision avoidance and tracking systems. In the following context will be introduced traditional multiband and multifunctional RDF devices (Ilcev, 2017; Skorik, 2014; Gething, 1991; Pine, 2004; Denisowski, 2013).

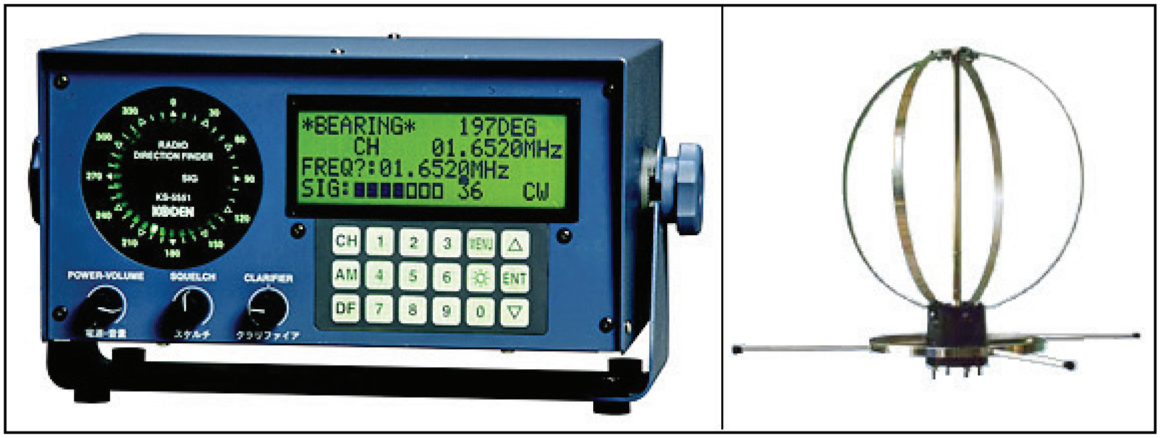

Figure 5.
Radio MF/HF/VHF DF KS-5551with Double-crossed RDF Antenna – Source: Koden.

4.1. Koden Shipborne Multiband MF/HF/VHF KS-5551 RDF System

The Koden KS-5551 RDF is an omni-directional automatic DF with intermediate wave 1 to 8 band and frequencies of 1 to 54 MHz band providing high accuracy coverage from 50 miles for MF/VHF and minimum 150 miles for HF-band. It provides digital and analog bearings to radio transmission and a loudspeaker is also included, shown in Figure 5 (Left). Up to 100 channels memory for spot receptions are helpful and users are free from repeating input operation of spot channels. Thus, measuring the receiving frequency range is the same as stated in the receiving band. It consists of a 600 mm diameter lightweight loop antenna with 15 m of cable and power rectifier, shown in Figure 5 (Right). Its bearing display panel uses a brilliant Light Emitting Diode (LED) for high visibility. Thus, the 3 digits numerical unit display on the liquid crystal panel indicates bearing by one-degree step. The LED lamps arranged in a circular pattern by 10-degree step provide a visual indication of bearing. This equipment has comfortable operability with rotary knobs for fine adjustment, the numerical keypad for number input, and dedicated keys for the functional setting. True heading can be input via National Marine Electronics Association (NMEA) to allow the KS-5551 device to display true bearings to transmissions, so at this point, the heading data can also be output on NMEA (Skorik, 2014; Denisowski, 2013; Koden, 2009).

4.2. Taiyo Shipborne VHF TD-L1630 RDF System

When, in 2002, the International Conference on maritime security decided on the implementation of AIS, it seemed as though the combination of GPS and AIS would offer total reliability for the assignment of a ship's position in Vessel Traffic Service (VTS) areas. However, this is frequently turning out not to be the case. Therefore, AIS is certainly an appropriate means of conveying a large and varied amount of information about shipping movements to all users onshore, but during navigation, master mariners need very precise aids in determining the ship's location at a certain point in time. This study reports on a solution to this that involves the aid of a radio direction finder and other radio and satellite systems to provide some more reliable solutions for ships collision avoidance and tracking systems.

The VHF shipborne RDF is of inestimable value for making shipping lanes safer, especially when monitoring vessels representing a particularly high risk. It provides precise directional information about the origin of the VHF transmission at the time of the inquiry. The RDF unit offers additional assistance when putting pilots aboard via helicopter. In this

Figure 6.
Radio VHF DF TD-L1630 with 4-element Adcock Antenna – Source: Taiyo.

case, the helicopter can be guided with the aid of a land-based VHF direction finder to the ship lying on the roads, which is of great assistance particularly in poor visibility. In the other words, this is an automatic RDF, designed for reception and direction measurement of radio waves in International VHF-band and the US weather channels or Scandinavian fishing channels including SAR distress frequency 121.5 MHz and it has the following major features:

1. Manual, spot, and scan reception are selectable and all operations are commanded by the keyboard layout on its front panel;
2. The channel number with the type of station, ship and coast or weather can be stored in 100 addresses with a two-digit number, named Address No, from 00 to 99;
3. The direction of incoming radio signal with respect to bow direction of own ship is simply indicated with 2 types, a linear indicator for quick recognition and a numeric display;
4. H type Adcock antenna allows precise direction measurement with high sensitivity; and
5. Power source, 10V - 16V DC is provided and a suitable adapter is available for AC power source on option.

The VHF automatic digital RDF TD-L1630 has a user convenient operation panel with single purpose switches that are applied for function keys, shown in Figure 6 (Left). It has a frequency range of 110 to 170 MHz in 5 kHz step with one-touch reception of 121.5 MHz distress frequency and CH16 (156.8 MHz) by individual push button and it also provides output port for NMEA 0183 bearing data. It is provided with a computer-controlled synthesizer with a triple super-heterodyne circuit that provides high sensitivity, accuracy, and stability.

The unit is suitable for standby reception and a new tracking technique is adopted to give high stability, even receiving a weak signal with a low S/N ratio. The holding function is provided to maintain the last bearing data while receiving no signal. The bearing data is updated when receiving a new signal regardless of the holding function is on or off. When finding a radio transmitter for location purposes, it is important to use an antenna that permits good all-round reception. The 4-element Taiyo Adcock VHF-ADDF shipborne antenna is designed for installation on light masts in an environment that has a high salt content, which shape is shown in Figure 6 (Right). This antenna has to installed at the highest point on the mast, away from reflected fields, so that only the signal that spreads out on the direct path between the transmitter and the receiving antenna is tracked. Any residual errors are to be kept stable so that they can be easily compensated for by the computer at the receiver. The shape of the coastline and the topography of the hinterland play a role here, as does the presence of conducting obstacles e.g. antennas, bridges or silos, etc. In fact, for the direction-finding or location of vessels under-way, the location of one or more radio direction-finding stations in relation to one another and to the primary direction of shipping movements also plays a crucial role (Ilcev, 2017; Skorik, 2014; Schantz, 2011; Jakpar et al., 2016; Taiyo, 2007).

4.3. Plath Shipborne VHF/UHF DFP 2410 RDF System

The VHF/UHF DFP 2410 RDF unit is a large dynamic coherent bandwidth of 20 MHz with high scan-speed operating at a frequency range from 30 to 3000 MHz (VHF-UHF-bands). The receiver unit provides a 7-channel correlative interferometer principle and parallel processing of all channels and it permits the interception of frequency-stationary and frequency-agile emissions. Due to the correlative interferometer principle, this RDF unit is characterized by high bearing accuracy and immunity to interference. The true parallel processing of all channels performs the bearing of short-time signals even with a very small signal duration below the FFT time resolution from 500 Hz to

Figure 7.
Radio VHF/UHF DFP 2410 RDF and DFA 2450 Antenna – Source: Plath.

32 kHz features the optimal adjustment of the sensor system. Thanks to large dynamic range, high scan-speed as well as small noise figures the probability of signal detecting is very high. Thus, both narrow-band and short time signals can be intercepted.

This RDF device with its significant computing ability provides good accuracy and processing speed. Unlike similar systems, this RDF has 7 channels for continuous processing, so no blind spots occur when overlapping channels. In this way, its unmatched good accuracy allows to obtain reliable location using just 2 systems. So, thanks to a good design, high Spurious Free Dynamic Range (SFDR), high sensitivity, and significant Intercept Point (IP) - IP2/IP3 values, this device is able to detect weak or Low Probability Intercept (LPI) signals even when the system is disturbed with adjunct strong emitters or in motion. The specific method of hopper detection allows the identification of frequencies for jumping frequencies at speeds up to 2000 hops/s.

The DFP 2410 RDF shown in Figure 7 (Left) integrates a constant coherent bandwidth with variable frequency resolution and high sensitivity of -137 at the same time. The coherent bandwidth is remaining at 9.99 MHz even if it is using a frequency resolution of 500 Hz. The outstanding dynamic range sensitivity and low noise figure allow intercepting weak signals from great distances. Thus, it is able to calculate DF-results even in scanning mode with 20 GHz/s. The high processing capability of 10 Mio channels makes sure, that DF-results are calculated to all signals, even in high-density radio bands like tactical radio. The 7-channel interferometer principle is realized from the antennas to the receivers so that no signal is lost due to antenna switching or summarizing of several processed samples. In a non-scanning mode, it can detect all common hopping communication signals. The extremely high accuracy allows the location of emitters even with two DF-sets. Optionally this RDF unit can provide SCAN mode, reselection, and frequency range extension to 6 GHz.

The old model of Plath DFP 2055 RDF is designed to bear uplinks data of Inmarsat ground satellite terminals in the L-band and to be utilized in mobile Inmarsat intelligence systems. The evaluation of the detecting Inmarsat signals will be done on a PC or Laptop, so it can be also traced to the suspected ship doing smuggling of narcotics or captured by pirates. Except for bearing of Inmarsat up-link signals this unit is providing high RDF sensitivity and is optimized for mobile applications, especially for ships.

The passive DFA 2450 Adcock maritime antenna situated in radome has been specially developed for shipborne applications for installations on the highest position onboard small vessels, which is shown in Figure 7 (Right). This shipborne antenna has a high bearing accuracy and allows installations on any kind of ship mast. It is a lightweight passive 7-element direction-finding antenna and uses the correlative interferometer DF method. The antenna sensor system is particularly resistant to multi-path scattering and widely insensitive to polarization. The chassis is made of UV-resistant plastics (ABS laminate). Normally, this antenna is covering the frequency range from 30 to 3000 MHz and optionally provides frequency extension up to 6000 MHz. It also can be extended with HF radio direction finding capabilities. In this case, an additional HF antenna subsystem for the frequency range from 1 to 30 MHz is integrated into the pipe below the DFA 2450 V / UHF subsystem. The dipole antenna is vertically polarized, works consistently with the correlative interferometer method, and can be used in all climates (Ilcev, 2010; Skorik, 2014; R&S, 2018; Keen, 2018; Plath, 2010).

5. SPECIFIC RDF SYSTEMS

The operation on the sea requires high demands on the navigation and other purposes of equipment. Salty water, high humidity, mechanical load, and vibration as well as effective ultraviolet (UV) radiant exposure have a non-stop impact on electronic hardware, so the modern radio and navigation equipment is specially designed for this application. It supplies the highest reliability, very compact, and even under rough conditions. However, what is more important this equipment has to provide specific RDF solutions, such as Search and Rescue (SAR) and ships surveillance, universal navigation, Man over Board (MOB), Vessel Traffic Service (VTS), etc.

5.1. Rhotheta Shipborne and Coastal SAR VHF/UHF 4-band RT-500-M RDF System

The RT-500-M is a complete direction-finding solution for professional SAR applications at sea. This universal 4-band RDF operates and automatically monitors not only civilian bands at 121.5 MHz and CH16 (156.8 MHz) but also military emergency frequencies at 243 MHz and detection of research buoys. It

Figure 8.
Radio SAR VHF/UHF 4-band RT-500-M RDF with Antenna – Source: Rhotheta.

can also receive Cospas-Sarsat signals at 406 MHz of maritime Emergency Position Indicating Radio Beacons (EPIRB), land or personal Emergency Personal Locator (PLB) and aeronautical Emergency Locator Transmitter (ELT), provide the bearing of the source and display the content. However, this unit and Rhotheta RT-202 Crew Finder can serve as emergency receivers for SAR as Man Over Board (MOB), which monitors international emergency frequency 121.500 MHz and trigger an alarm of distress signals.

The RT-500 is the most professional direction finder for the VHF-marine band, VHF-air band, and 406 MHz Cospas-Sarsat emergency beacons for all mobile and personal applications, which Display Control Unit (DCU) is shown in Figure 8 (Left). It is best suited to the seagoing rescue, coastguard, guard, and other vessels. Thus, a ship gyro or GPS-compass can be NMEA coupled to maintain a true-heading radio bearing all times, and an NMEA data radio bearing output is foreseen for presentation in Electronic Chart Display and Information System (ECDIS). It has a dual or tri-watch overall bands fully remote controlled by Ethernet. The bright TFT unit display guarantees a visible reading in sunlight, a display-sleep function avoids dazzling at the bridge at night, and a clear overview of all direction finder information and operating parameters.

The bearing aerial is a dipole antenna with a housing containing all bearing electronics, which Antenna Unit (AU) is shown in Figure 8 (Right). The short bearing signal paths with low loss and also high insensitiveness to external disturbing fields are achieved. The bearing system is working with the Doppler principle by the high scanning frequency of 3 kHz and clockwise and counterclockwise rotation of the antenna to compensate running time errors highest precision of the system is achieved. Various interfaces (LAN, NMEA RS-422, and RS-232, etc) facilitate the integration of the direction finder system in legacy or planned system environments. Although the RT-500-M unit was optimized for use in high sea states, the same as RT-500 RDF, it is also suitable for stationary Vessel Traffic Service (VTS) applications at the shore. In Table 1 are presented all frequencies nominated for RT-500-M RDF (Ilcev, 2017; Skorik, 2014; Gething, 1991; Schantz, 2011; Rhotheta, 2010).

Table 1.
Frequency Bands for RT-500-M RDF.

Frequency Ranges:		**Emergency Frequency:**	
VHF air band	118.000 MHz	121.500 MHz	123.975 MHz
VHF marine band	155.000MHz	158.800 MHz	162.995 MHz
	Channel 00 Ship	Channel 16	Channel 88 Coast
UHF militari air band	240.000 MHz	243.000 MHz	245.975 MHz
Cospas - Sarsat	400.000 MHz	406.022 - 406.076 MHz	409.975 MHz

5.2. Rhotheta Coastal VHF/UHF 4-band RT-800 RDF System

The RT-800 VHF/UHF RDF is projected for stationary coastal surveillance and identification of ships that are transmitting on the VHF radio band. The bearing information from transmitters can be correlated with the corresponding radar target and AIS-position information at a Vessel Traffic Service (VTS) centres. Two or more RT-800 RDF systems on different locations can be used to locate a ship's exact position by triangulation, which can easily be integrated into a VTS environment.

The DF-system RT-800 combines the communication of Radio and SAR direction finders that provide bearing of all coastal and maritime radio stations. In such a way, equipped persons or vessels with EPIRB or PLB may be found quickly and safely saved. The RT-800 RDF is shown in Figure 9 (A - Left), which operates on different four frequency bands presented in Table 1. It provides decoding of transmissions on all 19 Cospas-Sarsat channels, fast frequency monitoring by scanning of up to 8 frequencies, effective remote operation via RS-232, Ethernet, and LAN interfaces. This unit is using an extremely compact, rugged and lightweight DF antenna for easy installation and use in harsh maritime weather conditions, which is illustrated in Figure 9 (A - Right). The bearing array is a dipole antenna, in which housing contains all bearing electronics. It is watertight (protection IP 67) and may be used under extreme and rough conditions. Thus short bearing signal paths with low loss, but also high insensitiveness to external disturbing fields are achieved.

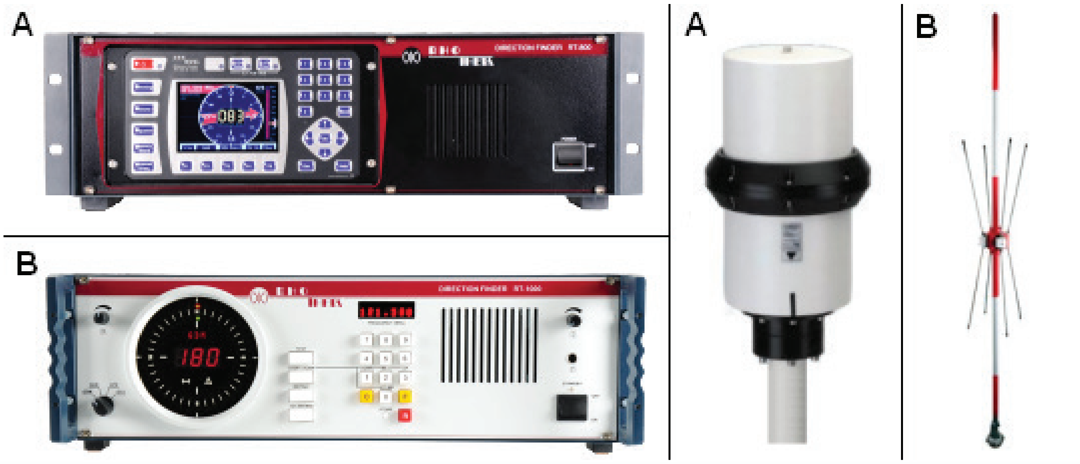

Figure 9.
Coastal Radio SAR RT-800 and RT-1000 Equipment – Source: Rhotheta.

The RDF coastal system is working with the Doppler principle and by the high rotation frequency of 3 kHz and clockwise and counterclockwise rotation of the antenna to compensate for running time errors, the highest precision of the system is achieved. The indicating and operating system represents bearing signals and allows operating and controlling of the bearing antenna. Additionally, external devices can be connected (speaker, audio, line out, PTT push to talk, and so on). Also data in and export is possible by various interfaces including remote control over IP and IP-based audio transmission. This RDF system is suitable for stationary surveillance of coastal ship traffic as well as for mobile use on big vessels (Ilcev, 2017; Skorik, 2014; Jakpar et al., 2016; Rhotheta, 2012).

5.3. Rhotheta Coastal VHF 2-band RT-1000 RDF System

The RT-1000 RDF system is designed specifically for aeronautical and maritime applications and complies with ICAO and DFS (Deutsche Flugsicherung) requirements, shown in Figure 9 (B – Left). The separate large and compact antenna system for simple installation is depicted in Figure 9 (B – Right), which location independent of controller workstation. More than 100 systems are currently in use worldwide for Air Traffic Control (ATC) or Ship Traffic Control (STC) and coast surveillance. The VTS network contributes to the safety of ships traffic by monitoring ships from information shore-based facilities. When a vessel enters the waters of a port or harbor, the responsible VTS station is informed accordingly by radiotelephony (VHF). The traffic control station then uses its radio RDF to determine the position of the vessel. Thus, the VHF coastal RDF contributes significantly to the safety of shipping traffic since the possibility of accidents caused by confusion is eliminated.

The RT-1000 is used as a navigation aid that allows controllers at the shore to transmit magnetic bearing to the navigation bridge or verify position reports received from ships. The radio bearing information can be also integrated into a radar

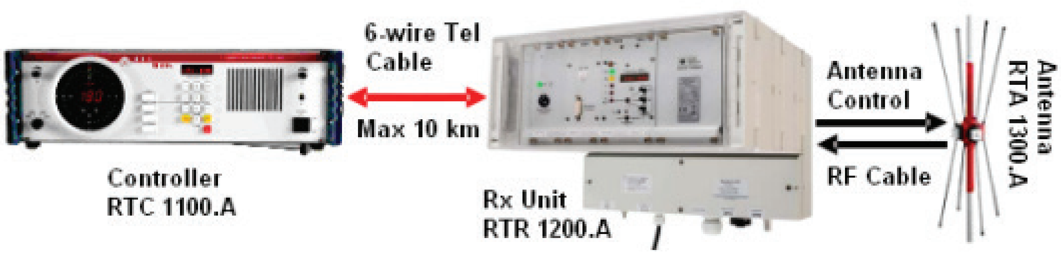

Figure 10.
Network Configuration of Coastal VTS – Source: Rhotheta.

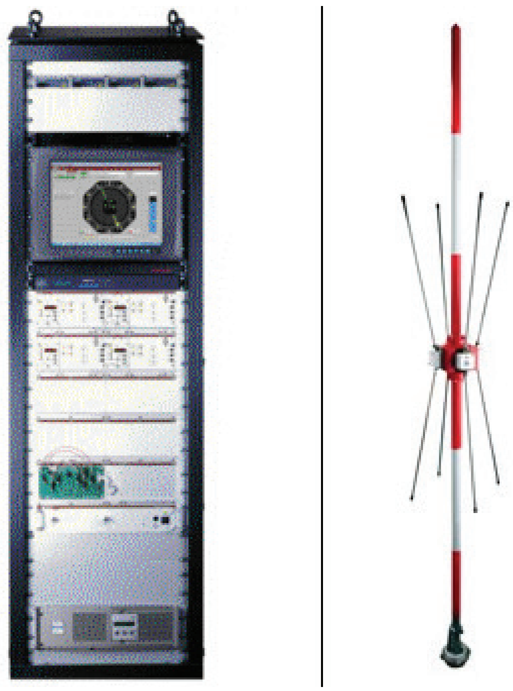

Figure 11.
Coast RDF RT-1000 MC and Ground Antenna – Source: Rhotheta.

screen, which makes it possible to immediately assign radio messages to the right vessel on the radar display. The system is using the following frequency range: Aviation band from 118.000 to 136.975 MHz and Marine band from 156.000 to 174.000 MHz. This unit is a high-precision Doppler direction finder with extremely high rotation frequency for fast signal processing and doesn't require an infrastructure for remote operation, which integrated modular RDF construction is depicted in Figure 10. Therefore, the receiver, demodulator, and antenna control module are integrated into the receiver unit located at the antenna position. The VTS network operates in "remote mode" and integrates the following components:

1. Massive direction-finding antenna system RTA 1300 installed remotely from the controller and connected to the receiver RTR 1200 by means of an RF cable; and
2. One remote RDF RTC 1100 coastal unit located up to 10 Km distance can be connected to the RTR receiver via a 6-wire telephone cable. Two RTC 1000 units can be connected in parallel.

The RT-1000 MC Multichannel RDF is designed for ATC and VTS systems, which station with the 4-elements antenna is shown in Figure 11 (Left and Right). It is a very cost-effective solution for applications where more than two simultaneous DF channels are required. The modular design makes the system adaptable for almost all modern DF applications up to 24 simultaneously DF-channels. Thus, the approved Doppler principle provides unrivaled system reliability. The compact antenna system is designed for very rough conditions and is easy to install. The RT-1000 VDF is used as an ATC navigation aid that allows controllers on the ground to transmit On-Demand Mobility (QDM) messages to the captain at the frequency of 156 and 174 MHZ using or verify position reports received from the ship. Bearing information can also be integrated into a radar screen, which makes it possible to immediately assign radio messages to the right targets on the radar display (Ilcev, 2010; Ilcev, 2017; Skorik, 2014; Moell & Curlee, 1967; Rhotheta, 2014).

5.4. Rohde & Schwarz (R&S) Determination of Vessel Bearings in Coastal Waters

The new R&S DDF04E digital RDF receiver is used in mobile traffic control systems to take the bearings of multiple aircraft or ships simultaneously using only one direction finder, which device is illustrated in Figure 12 (Left). The use of a wide-aperture DF ADD050SR shore array with nine antenna elements in combination with the correlative interferometer RDF method provides high accuracy, sensitivity, and outstanding immunity to reflections. This wide-aperture DF antenna covers the entire frequency range from 100 MHz to 450 MHz and with a diameter of three meters, which construction is illustrated in Figure 12 (Middle). The RDF antenna for mobile applications ADD153SR also covers the entire frequency range from 100 to 450 MHz.

Figure 12.
Coastal R&S DDF04E Maritime RDF with Shore and Ship Antenna – Source: R&S.

Due to its compact dimensions, this antenna is optimized for maritime applications and with radome protects the antenna elements against the effects of weather, which model is shown in Figure 12 (Right).

The DDF04E RDF system features wideband functionality for monitoring ships in coastal navigation, which DF method can, therefore, take place on as many as 32 channels (optional) simultaneously with the same high level of performance. The direction finder contains control software for the flexible management of the frequency channels. This device is also used at seaports and for monitoring and controlling maritime traffic. Using this type of RDF system option, the bearings of four ships, for example, can be taken quasi-simultaneously. Standard PC terminals provide monitoring, control data server, and display units via Ethernet. At the same time, all important VHF/UHF distress radio frequencies can be monitored: (1) Maritime radio distress frequency at 156.8 MHz, (2) International distress frequency at 121.5 MHz, (3) EPIRB distress frequency at 406 MHz, and (4) Military distress frequency at 243 MHz (Ilcev, 2010; Pine, 2004; R&S, 2018; R&S, 2018b; R&S, 2017).

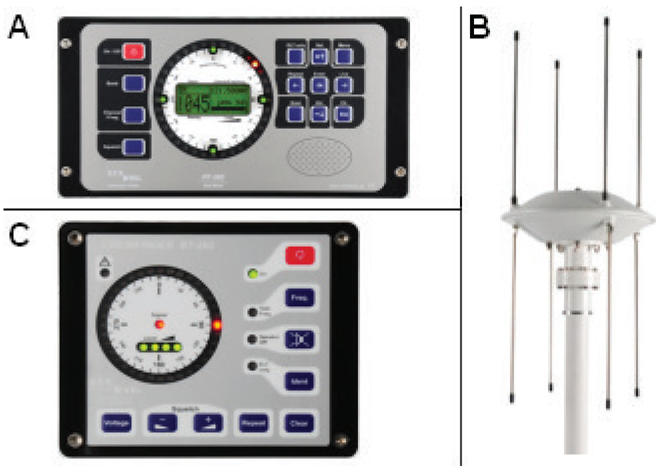

Figure 13.
Radio RDF RT-300 and RT-202 with Antenna –Source: Rhotheta.

5.5. Special Shipborne RDF Receivers and Transmitters

In this context will be introduced to the universal RDF receivers designed for Search and Rescue (SAR) forces operations, Man over Board (MOB) for the location of the crew, and monitoring radio communications. However, as list device will be a shortly described very small RDF transmitter used by the missing crew at sea.

5.5.1. Rhotheta RT-300 SAR/MOB VHF/UHF RDF System

The RT-300 is an all-purpose and universal RDF system is operating on VHF maritime and aviation bands and the VHF/UHF aviation bands, which is depicted in Figure 13 (A). Apart from universal use for ship navigation, this RDF system allows the bearing of radio signals in the radiotelephony maritime VHF band from 156,000 to 162,300 MHz as well as bearing of signals on the international VHF distress frequency at 121,500 MHz for mobile applications. Integrating a communication bearing system for coastal and maritime radio stations and a professional SAR-bearing operation system, the RT-300 RDF system allows quick bearing and detecting of EPIRB equipped persons or vessels for civilian and military applications. Specially designed for use under rough circumstances on sea vessels the system is extremely compact. The antenna and the display control unit are waterproof. The most sensitive receiving system allows the bearing of extremely weak or distant signals.

The RT-300 sets new benchmarks in terms of precision and reception sensitivity. Special algorithms permit the fast, stable display of information. The RT-300 direction finder system is also designed for mobile use on land under adverse conditions and is equally suitable for shore-based VTS facilities of ship traffic control. As stated, this unit also provides automatic monitoring of distress and emergency frequency 121.500 MHz during work on marine radio bands. The RDF illuminated control unit displays bearings with reference directions as true North, magnetic North, or relative direction. Thus, this RDF unit is optimizing signal processing for fast and stable direction-finding facilities with excellent localization precision. It provides the National Marine Electronics Association (NMEA), RS-485, and RS-232 interfaces for system integration and remote control capability and uses a special 4-element Adcock antenna mounted on top of the mast, see Figure 13 (B) (Ilcev, 2010; Skorik, 2014; Rhotheta, 2013).

5.5.2. Rhotheta RT-202 MOB VHF RDF System

The RDF shipborne system RT-202 is an MOB emergency receiver designed for detecting and locating emergency signals that are transmitted by a radio beacon on the international emergency VHF 121.500 MHz frequency, which is shown in Figure 13 (C). It triggers an alarm in the event a distress signal is received, so this unit can be used as a homing RDF-system to a beacon and support so rescue activities of crewmembers that fell into the sea. Otherwise, the direction of the emergency small RDF transmitter carries by fallen crewmembers overboard can be determined and indicated by a LED ring. This SAR unit features a selective squelch function that only triggers an alarm if a distress signal is actually identified and eliminates false alarms due to radio frequency interference or other radio signals. When the selective squelch function is deactivated, any radio signal can be received regardless of its modulation.

The RT-202 RDF receiver also features a second operating frequency at 121.650 MHz for training and testing purposes. In the event of a man overboard situation, the individual in distress can be found quickly and easily in any weather conditions. With its compact antenna, shown in Figure 13 (B), this SAR RDF unit is also suitable for installation onboard of smaller vessels and rescue craft as well as for rescue missions on land (Ilcev, 2010; Ilcev, 2017; Rhotheta, 2011).

Figure 14.
Radio RDF RT-600 Rx with Antenna and Orca TX-103 Radio Tx –Source: Rhotheta and BriarTek.

5.5.3. Rhotheta RT-600 Multiband RDF System

The RT-600 or SAR-DF 517 is RDF designed to receive and locate emergency signals and special application signals on the international distress and application-specific frequencies in the VHF/UHF frequency range for aeronautical and maritime applications, which receiver unit is illustrated in Figure 14 (Left). This RDF receiver is using the RT-600 antenna shown in Figure 14 (Middle). In particular, it is an advanced wideband RDF receiver capable of capturing and indicating directions to any source of an emergency signal on 406 MHz Cospas-Sarsat frequencies and many maritime channels. The system can be extended by additional frequency bands to cover a frequency range from 118 to 470 MHz at its full stage of extension. For the other mobile applications, this unit is used for a special law enforcement version that supports the stolen vehicle recovery, tracking the Electronic Tracking System (ETS) and other beacons. The sophisticated software provides significantly improved tracking capability over conventional tracing equipment.

The RDF receiver mode is generally used to display all valid information processed by the DF signals received from a target transmitter. The amount and kind of information displayed by the Display Control Unit (DCU) depends on the type and content of the signal received and processed by the RDF system. Simple signals such as the analog sweep-tone modulation received from a SAR beacon EPIRB, PLB, and ELT at 406 MHz and other emergency signals at 121.500 MHz and from 400.000 to 406.092 MHz, allow displaying only basic bearing information. However, digital signals received from Cospas-Sarsat and other mobile recovery systems allow displaying more information, such as the beacon Identification number (ID), GPS coordinates, codes, Vehicle Location Unit (VLU), and so on (Ilcev, 2010; R&S, 2018; Rhotheta, 2010b).

5.5.4. ORCA RT-600 TX-103 RDF Transmitter

The ORCA TX-103 transmitter is an innovative personal saltwater location and recovery system or MOB alarm system for maritime rescue applications developed by BriarTek Inc, which unit with antenna is illustrated in Figure 14 (Right). This system operates on 121.5 MHz and includes a transmitter, receiver, and direction finder. When the transmitter is activated, it emits a 121.5 MHz signal that is processed by the receiver rapid recovery of a sailor who has fallen overboard. In such a way, the receiver emits an audible alarm and displays the vessel identification and a serial number of the transmitter on the receiver LCD. The transmitter also emits a signal that is processed by the direction finder and other standard SAR equipment to locate the MOB.

This RDF system can be used to design a similar RTD transmitter for installation onboard ships and other objects at sea. These transmitters can provide constant emissions on a certain frequency that RDF receivers on other ships can receive and determine the position of adjacent ships for collision avoidance (Ilcev, 2010; Moell & Curlee, 1967; BriarTek, 2015).

6. CONCLUSION

The aim of this paper was to describe the author's contribution to new designs of ship RDF and its modern aids for positioning and tracking at sea. The RDF system was for a long time successfully used onboard ships as a navigation tool, however with the implementation of ARPA radars, GPS and GLONASS, AIS, and other navigation systems, its importance was drastically reduced and almost withdrawn from history. Over the last few decades, the merchant fleet has grown dramatically in the world, so that increasing demands have emerged for greater safety of navigation and for more successful means of collision avoidance. Although Americans and Russians have developed the GNSS technique to near perfection, no GPS or GLONASS receiver can provide the positions of other nearby ships. The navigation radar and VHF AIS in practice have reduced propagation during very bad weather conditions, while the L-band satellite communication and AIS systems can be used during heavy weather conditions. In such a way, new solutions need to be investigated and developed, such as the RDF system for the determination of adjacent ships and other tracking shipborne applications.

REFERENCES

Bauk, S., Schmeink, A. & Colomer, J., 2016. An RFID model for improving workers' safety at the seaport in transitional environment. Transport, 33(2), pp.353–363. Available at: http://dx.doi.org/10.3846/16484142.2016.1233512.

BriarTek, 2015. ORCA RT-600 TX-103 RDF Transmitter, BriarTec Inc., San Diego, USA.

Denisowski, P., 2013. A Comparison of Radio Direction Finding Technologies. Rhode & Schwarz, Munich, Germany.

Gething, P.J.D., 1991. Radio Direction Finding and Superresolution. Available at: http://dx.doi.org/10.1049/pbew033e.

Ilcev, D.S., 2010. Maritime Communication, Navigation and Surveillance (CNS) Systems. Space Science Centre (SSC), DUT, Durban, South Africa.

Ilcev, D.S., 2017. Shipborne Radio and Electronic Navigation Systems. Space Science Centre (SSC), DUT, Durban, South Africa.

Jakpar, M.J. et al., 2016. Exploitation of Radio Direction Finder in the design of a UHF Transmitter Locator System. Indian Journal of Science and Technology, 9(25). Available at: http://dx.doi.org/10.17485/ijst/2016/v9i25/96618.

Keen, R., 2018. Direction and Position Finding by Wireless. Franklin Classic Trade Press, West Bloomfield, USA.

Koden, 2009. Multiband MF/HF/VHF KS-5551 RDF System. Koden Electronic, Tokyo, Japan.

Moell, J.D. & Curlee, T.N.,1967. Transmitter Hunting – Radio Direction Finding Simplified. McGraw Hill, New York.

Nisar A., 2016. Radio Direction Finding, Theory and Practices. University of Engineering and Technology, Lahore, Pakistan.

Pine K. at al., 2004. Radio Direction Finding for Maritime Search and Rescue. Flinders University, Adelaide, Australia.

Plath, 2010. Shipborne VHF/UHF DFP 2410 RDF System. PLATH GmbH, Hamburg, Germany.

R&S, 2012. Introduction into Theory of Direction Finding. Rohde & Schwarz, Munich, Germany.

R&S, 2017. Digital Direction Finder for Traffic Control. Rohde & Schwarz, Munich, Germany.

R&S, 2018. ADD Multichannel DF Antennas. Rohde & Schwarz, Munich, Germany.

R&S, 2018b. Determination of Vessel Bearings in Coastal Waters", Rohde & Schwarz, Munich, Germany.

Rhotheta, 2010. Shipborne and Coastal SAR VHF/UHF 4-band RT-500-M RDF System. Rhotheta Elektronik GmbH, Murnau, Germany.

Rhotheta, 2010b. RT-600 Multiband RDF System. Rhotheta Elektronik GmbH, Murnau, Germany.

Rhotheta, 2011. RT-202 VHF RDF System. Rhotheta Elektronik GmbH, Murnau, Germany.

Rhotheta, 2012. Coastal 2-band RT-800 RDF System. Rhotheta Elektronik GmbH, Murnau, Germany.

Rhotheta, 2013. RT-300 VHF/UHF RDF System. Rhotheta Elektronik GmbH, Murnau, Germany.

Rhotheta, 2014. Coastal VHF RT-1000 RDF System. Rhotheta Elektronik GmbH, Murnau, Germany.

Schantz, H.G., 2011. On the Origins of RF-based Location. Q-Track Corporation, Huntsville, Alabama, USA.

Skorik, I., 2014. Radio and Satellite Tracking and Detecting Systems for Maritime Applications. DUT, Durban, South Africa.

Taiyo, 2007. Shipborne VHF TD-L1630 RDF System. Taiyo Musen Co. Ltd., Tokyo, Japan.