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A Submarine Based System for Radio Direction Finding and Communications Intelligence

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Abstract: This paper gives an overview of the recently completed development and production of an ultra-compact system for submarine applications. In particular it highlights some of the technical capabilities on the front-end side. The system consists of a compact direction finding (DF) and monitoring antenna with a high pressure radome and the respective onboard DF receivers and processing equipment. Despite being very compact, the system covers a wide frequency range from MF/HF to UHF. Some of the antenna design aspects are presented and constraints for the DF resulting from the small array aperture are discussed. The importance of having DF capabilities for communications intelligence is highlighted. The DF system features a number of advanced capabilities that are as yet non-standard in a wideband reconnaissance context. Chief among these are elevation angle of arrival estimation, simultaneous DF for vertical and horizontal polarizations as well as estimation of co-channel signals. These capabilities are motivated and examples are provided.

1 INTRODUCTION

Submarines are ideal reconnaissance platforms for radio communication traffic in open sea and coastal regions because in contrast to surface ships they can hide their presence. Hence potentially interesting radio activities will not be interrupted as is normally the case when sighting a surface ship whose technical capabilities for reconnaissance are easy to spot. The submarine can stay submerged and only a compact wideband antenna array enclosed in a ~0.5 m diameter radome needs to be deployed above the sea surface on top of a mast.

The system provides functionality for both tactical as well as strategic intelligence purposes. As such its main tasks are:

- Search and detection, interception, identification and DF of communications radio emissions
- Gather communications intelligence (COMINT) of radio transmissions
- Record communications signals and parameters for extraction and analysis.

Communication spectrum surveillance is most efficient when direction of arrival (DoA) information for each of the occupied radio frequencies is available. This helps particularly to discriminate different emitters in spectrally dense radio environments and to focus the surveillance on a certain angular sector of interest. More aspects are detailed in Sections 3.2 and 3.5. However, implementing the required DF antenna and DF system for a submarine is a special challenge due to the environmental and size restrictions. Antenna and radome design aspects are outlined in Section 2.

A submarine antenna is a low-altitude platform and because self protection purposes demand reliable DF of airborne communication emissions; the system must have extremely wide elevation coverage. In fact, joint estimation of azimuth and elevation DoA allows the system to discriminate between ground emissions and airborne emissions which capability is not typical of traditional COMINT DF systems. This dual DoA capability places high demands on the accuracy of phase measurements and requires precise and yet efficient calibration procedures for the DF arrays. The paper illustrates a suitable calibration setup in Section 3.3 and presents some sample results.

The system as implemented uses a five channel fully parallel DF receiver architecture. Section 3.4 outlines why this is favourable compared to solutions using antenna multiplexing. Primarily this enables direction finding of very short signal bursts, a higher sensitivity gain for a given averaging time and optimum signal dynamic range by adjusting the receiver AGC for each antenna individually.

Section 4 provides an overview and experimental results of some advanced system features. DF of multiple simultaneous emitters on the same frequency is proven in real-world scenarios by the MUSIC super resolution algorithm. Another feature is the extension of the DF for vertically polarized waves (which is the standard case for communications DF systems) to the joint DF of both vertically and horizontally polarized waves, thus preventing the estimation of "ghost directions".

2 ANTENNA DESIGN

2.1 Submarine environmental requirements

The DF and monitoring system described in this paper was designed for submarine applications. The requirement for a compact mast-mounted system greatly limits the antenna options but far greater mechanical complications are caused by the operating environment. During the development phase there had to be very close cooperation with the submarine supplier. The following environmental requirements (amongst others) were prescribed by the submarine main contractor:

- Operating temperature : -25°C to +60°C
- Humidity : 0 to 100%
- Operational shock : 90 g, half sine, 2 ms each axis
- Wave slap : 5 metric tons / m² (49 kPa)
- Vibration : MIL-STD-810F, method 515.5, Proc. 1
- Water pressure : 75 bar (7.5 MPa), max test pressure
  : 68 bar (6.8 MPa), no leakage pressure
  : 50 bar (5.0 MPa), nominal operating pressure
  Where Pa = Pascal = N/m².

During the development of the prototype antenna arrays and the radome these environmental requirements had to be taken into account. It is a relatively simple matter to design a radome that can survive the 75 bar of external pressure. Such a radome will be heavy and exceed the mass specifications of the submarine mast. The radome must not degrade the radio frequency (RF) performance up to 3 GHz. Because there is a very high elevation angle requirement for DF and monitoring this places particular requirements on the radome electrical design. In addition, the COMINT radome must support a 38 kg electronic intelligence (ELINT) system which attaches to the top of the main COMINT radome at a distance of about one metre above the interface to the mast on the submarine. The interfaces at the top of the COMINT radome and the main mast must be able to withstand the bending moments induced by the 90 g shock specification and the wave slap. Finally, the COMINT radome must not degrade the performance of the 2 to 18 GHz ELINT system mounted on top of the radome. The combination of the COMINT and ELINT sub-systems forms an ultra-compact signal intelligence (SIGINT) system covering MF/HF to 18 GHz.

The radome design was based on an interactive design process between the electromagnetic and structural requirements. Finite element method analysis tools (e.g. ANSYS) were used throughout for the structural analysis. Electromagnetic analysis was used to evaluate the transmission and reflection of the radome wall and ray tracing was used to evaluate the impact of the radome on the elevation performance of the ELINT antenna assembly.

2.2 Antenna sub-bands

The COMINT system covers the wide frequency range from MF/HF to 3 GHz. In order to optimize antenna array performance in this range, the frequency band is subdivided into MF/HF, VHF and UHF sub-bands. The MF/HF band is covered by a compact array of active ferrite antennas in a conventional Watson-Watt configuration. The VHF and UHF bands are covered with independent sub-arrays of five antenna elements disposed around a central mast. The central mast is hollow and must accommodate all the RF and control cables from the ELINT system, support the VHF and UHF arrays and carry their RF cables to the base of the assembly. In addition, the central mast also acts as the sense and monitoring antenna for the MF/HF ferrite array.

There is no space inside the compact array for separate omni-directional monitoring antennas for the VHF and UHF sub-bands. The omni-directional antennas for these sub-bands are created by appropriate combination of the five individual antenna elements in amplitude and phase to create 'composite omnis'. The requirement for good omni-directional monitoring patterns not only close to the horizon but also up to high elevation angles impacted the design of the DF arrays. In the UHF sub-band improved DF can theoretically be achieved because there is sufficient space for a larger array aperture. However, the larger inter-element spacing in the circumferential array to reach it degrades the omni-directional ripple.

The frequency break points for the antenna sub-bands are selected to optimize the monitoring and DF performance. Because there are separate channels for monitoring and DF the frequency break points can be selected independently for monitoring and DF. This allows flexibility in the DF and monitoring processing.

2.3 System overview and dimensions

The COMINT system is mounted on top of a submarine mast with a 16 m long wet dip loop cable which runs from the COMINT/mast interface to the pressure hull of the submarine. Losses and phase changes through the dip loop cable will impact the DF system performance. For this reason there is a complete RF pre-conditioning assembly in the base of the radome below the Watson-Watt array. This RF assembly provides protection against high level signals from nearby emitters, RF pre-amplification, power combining for creating the omni-directional monitoring antennas and calibration ports for injecting calibration signals into the DF systems. The mass and space available for the RF assembly and its power supplies is extremely limited. For this reason the RF assemblies for each sub-band were implemented using microwave integrated circuit technologies. This design option greatly reduced the number of RF coaxial cables and connectors required to integrate all the required functions in the RF assembly. The compact nature of the RF pre-conditioning assembly is beneficial in that the entire unit is in a nearly constant thermal environment thereby reducing differential thermal drift between the RF channels.

The entire SIGINT system is about 510 mm in diameter and 1,400 mm high with the COMINT portion taking up 910 mm of this height. The total mass of the SIGINT antenna with all the stainless steel interfaces to the main mast is 220 kg. The radome encloses 0.3 m^3 of air which provides 300 kg of lift.

The ELINT portion of the SIGINT system is an existing sub-system which can also be mounted on another mast as an independent system. The ELINT antenna is installed on the top of the COMINT radome using blind-mate connectors for the RF lines. These RF lines as well as DC power and other signal interfaces pass down the centre of the COMINT antenna arrays without disturbing the COMINT system performance. The ELINT antenna uses amplitude comparison and phase interferometry for DF. The DF antenna elements are high pressure spiral antennas which take the external pressure directly on the spiral faces, i.e. there is no external radome over the spiral antennas. Omni-directional coverage is achieved with a 2 to 18 GHz slant 45 degree polarized antenna enclosed in a high pressure radome. The COMINT antenna can be operated without the ELINT antenna by installing a pressure-tight plate over the ELINT interface. This allows for flexibility and a system upgrade path – the COMINT can be fitted 'for but not with' the ELINT which can then be added at a future time.

The photograph in Figure 2.1 shows the complete SIGINT system. The ELINT system is on top and the dark grey spiral faces for the interferometer DF are visible. At the top of the ELINT system there is a L1/L2 GPS antenna. The COMINT system with all the RF front-end electronics is housed in the main radome below the ELINT.

Figure 2.1 Photograph of fully integrated SIGINT Assembly with ELINT sub-system on top and COMINT sub-system below.

2.4 Pressure testing of the COMINT radome

Clearly the radome is a critical part of the whole COMINT system both from a structural and an electromagnetic point of view. As stated earlier, the structural analysis was done using the ANSYS package. Many load cases were considered but the major loads are for the 7.5 MPa test pressure and the bending moments induced by the 90 g shock and the wave slap. The structural analysis and design were crucial steps in the final implementation of the radome. A key part of this process was the use of the measured mechanical properties of test samples of the radome wall configuration in the FEM analysis and not “typical parameters” from published literature. This gave a high level of confidence in the design before the first set of pressure tests of the prototype radome.

The pressure tests were conducted at a calibrated pressure test facility with a test dome capable of handling 9 MPa. The radome was sealed at the top with a dummy plate representing the interface to the ELINT antenna using the exact O-ring seal configuration. The base was attached to a dummy interface plate representing the submarine mast and using the exact O-ring seal and clamping mechanism as used on the mast. The test dome was sealed and filled with water. The pressure in the dome was recorded with a normal pressure dial gauge and a pressure transducer whose output voltage was monitored continuously on a laptop computer.

The dome was then pressurized in nominal steps of 0.5 MPa (5 bar) up to 5.5 MPa (55 bar). At each step the pressure stability was checked for at least one minute. At 55 bar the pressure was held for 2 minutes. Since there was no decrease in pressure, the pressure was then increased to 73.5 bar in two steps. At 73.5 bar the pressure was held for 5 minutes with no drop in pressure. Finally the pressure was increased to 80.8 bar and held there for 6 minutes – there was no loss of pressure. The taps to the pressure vessel were then opened and the water allowed to drain out of the dome.

At the completion of the structural integrity tests the antenna was removed from the mast interface base and the O-rings and base were visually inspected for moisture ingress beyond the O-rings - there was no ingress of moisture. A physical inspection was conducted of all the key mechanical parts of the radome – these being the radome wall itself and the interfaces between the radome wall and the upper and lower clamping rings which make the seals to the ELINT antenna and the mast interface. No hairline cracks or structural damage of any nature could be observed. The radome successfully passed the maximum test pressure requirement at a level of almost 6 bar above the 75 bar requirement.

In addition, the radome was subjected to repeated pressure load testing in the pressure dome. The structural analysis highlighted the areas of the radome with the highest stresses. The radome was instrumented with five strain gauges to establish whether major changes in stress occurred after repeated pressure cycling. Since the radome is a closed pressure tight system, the strain gauges and data recorder were enclosed inside the radome and powered by DC batteries. The radome was subjected to successive pressure cycles of 0 to 4 MPa, then to 0 to 4.5 MPa and then 0 to 5 MPa. This sequence of three pressure cycles was repeated 24 times giving a total of 72 pressure cycles to 40, 45 and 50 bar. Each pressure cycle was from 0 to the particular pressure value with each cycle from 0 to the desired value occurring in about three minutes per cycle.

The maximum nominal operating pressure is 50 bar. The radome was subjected to a very high fatigue scenario in a very short time with each cycle being from 0 to the desired value, i.e. the pressure was not adjusted gradually but increased at the maximum pump rate of the pressure test dome. The recorded strain gauge resistance values remained remarkably constant for successive pressure cycles. After completion of the pressure cycling the radome was opened and inspected as before. No mechanical changes or damage occurred during the repeated pressure cycling.

The ELINT antenna was mounted on top of the main radome and the COMINT system with all the internal antennas and the RF components were subjected to environmental qualification (shock, vibration, temperature, etc.). During these qualification tests the calibration injection function was used to monitor all the RF lines in the system to detect any changes in RF performance from the start of the environmental qualification to its completion. No significant changes were observed.

The COMINT radome has sufficiently high structural margins and successfully passed all pressure and environmental qualification tests. The electromagnetic performance is excellent and the entire COMINT antenna assembly, radome and RF front ends are ready for the implementation of the DF and monitoring functions as described in the next section.

3 DIRECTION FINDING SYSTEM

3.1 Hardware

The DF system is based on a five channel fully parallel DF receiver bank. The receivers are water-cooled to meet the low acoustic emission requirements for submarine use and mechanically ruggedized [2]. Clock and local oscillator signals are synchronized in order to ensure the required phase measurement accuracy for the full frequency range from MF/HF to 3 GHz. Moreover, calibration signal injection circuitry is included for automatic calibration of all RF paths. This is needed to compensate for differences in the frequency response of filters and cables as well as thermal drift. The DF receivers are internally equipped with an ADC sampling the down-converted IF signal, followed by a digital down-converter and an FFT processor. The complex FFT samples are output via LAN interface and finally reach high performance PC hardware for real-time DF processing. The tuners are usually operated in a frequency scanning mode in order to cover the desired very large observation bandwidth of the communications spectrum. The maximum coherent bandwidth at one center frequency is 16 MHz resulting in a frequency resolution of 4.9 kHz.

The complete COMINT system also contains a bank of 8 receivers for monitoring purposes that operate independently from the DF system. The complete equipment is fitted into a single 19" rack inside the submarine. For a block diagram of the complete system as well as the operational capabilities beyond direction finding and signal detection see the companion paper [1].

3.2 DF method

The DF system of the submarine relies on the correlative interferometer principle which in turn is based on a direct measurement of amplitude and phase of the signals at the output of an array of spatially distributed antennas. The left part of Figure 3.1 depicts some basic relations: An incoming signal x is supposed to reach the array as a plane wave front with wave number k describing the spatial period of the electrical field. The antenna elements perform a spatial sampling of the wave front, thus providing a characteristic amplitude and phase pattern, collected in the antenna steering vector $\mathbf{y}(\varphi)$, for each DoA φ of the incoming signal. The expected phase variation over the full DoA range depends on the ratio of the wave length $\lambda = c/f_C$ over the radius of the array r. For a wideband system this phase variation will necessarily vary significantly with the center frequency f_C of the signal. For the phase patterns to be unique over DoA, and consequently to avoid ambiguities in the DoA estimation procedure, a spatial sampling theorem applies: 'It is generally required that the element distance remains below half a wavelength at the upper frequency end'. This means in turn that the phase variation over the DoA at the lower frequency end can get very small.

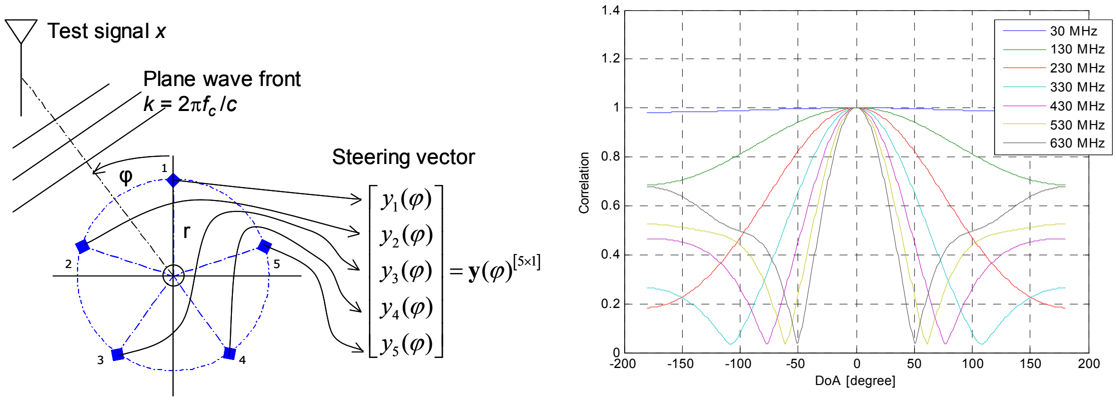

Figure 3.1 Left graph: Basic relationships for an interferometer DF system, Right graph: Shape of the correlation peak for various frequencies and fixed array radius as used in the submarine antenna.

The DF algorithm itself performs as a first step a vector correlation of the received signal vector $\mathbf{m}$ (the same structure as $\mathbf{y}$ above) with unknown DoA with the normalized steering vectors $\mathbf{a}(\varphi)$ of the array for all possible DoAs, also denoted as the array manifold. This results in a quantity $c(\varphi) = |\mathbf{m}^H \cdot \mathbf{a}(\varphi)|$ that can be termed a DoA spectrum[1], since it indicates the DoA dependent distribution of the received power. In the presence of only a single wave front at frequency f_C, the peak location of the DoA spectrum indicates the DoA of the incident signal. For a discussion on the presence of multiple wave fronts see Section 4.1.

The shape of a potential correlation peak and therefore the spatial selectivity of the DF are strongly dependent on the element's phase variation over all DoAs, which directly relates to the actual carrier frequency as discussed above. The right part of Figure 3.1 shows for a few sample frequencies the shape of the correlation peak of an isotropic array with a radius as used within the submarine antenna. The very low phase variation at the lowest frequency leads to very poor spatial selectivity and thus

[1] $\cdot^H$ denotes the complex conjugate transpose of a vector.

reduces the DF accuracy at finite SNR. Moreover, it imposes the need for highly accurate phase measurements over the complete receive chain. At the higher frequencies the correlation starts forming a sidelobe at 180°, which can also impair the DF performance especially if there is no clean single wave scenario.

It is instructive to observe that the correlative interferometer approach is identical to beamforming, where an antenna beam is electronically steered to all possible DoAs, and the output power is recorded to yield the above mentioned DoA spectrum $c(\varphi)$. The only difference to a true beamforming setup is that the steering takes place in parallel and simultaneously into all directions. The (complex) weights of the beamformer are again the multitude of all normalized steering vectors $\mathbf{a}(\varphi)$ constituting the array manifold.

It is valuable to note that if the actual measurement vector $\mathbf{m}$ is likewise normalized to a unit L2 norm, the vector correlation measures actually the similarity of the currently received amplitude and phase pattern with the *a priori* known array manifold as a normalized quantity. If and only if the measurement vector is exactly identical to one of the steering vectors, the correlation peak reaches a value of 1. If the correlation peak in the DoA spectrum is smaller than 1, then there exists some sort of deviation in the measurement vector either due to limited SNR, the presence of interference or multipath effects, non-perfect compensation of the receiver RF chain, etc. Hence, the maximum correlation value provides a sensitive measure of the reliability of the calculated DoA estimate. In the submarine based system this is called the DF quality parameter, which is of high value from an operational point of view since it enables the system to filter out unreliable DoA values.

A further important property of the interferometric DF scheme is based on the fact that all receive channels operate phase-synchronized. This permits the use of coherent averaging of multiple temporal snapshots of the array measurement vector $\mathbf{m}$. This provides potentially a significant SNR gain for the received signals over the noise floor of the system that is uncorrelated between the different receive chains. Assuming sufficiently long integration time this enables detection and DoA estimation even for signals below the noise floor.

3.3 Antenna calibration

The description of the DF method reveals that it is of central importance to know the array manifold *a priori*. Whereas in the case of simple array geometries and idealized antenna elements it is possible to obtain the manifold from some Euclidean geometry, for a compact wideband array it is mandatory to actually *measure* the manifold in a rather time-consuming process, which is also called *antenna calibration*. The huge time consumption arises from the necessity to measure samples of the array response from all incident azimuth and elevation angles on a sufficiently dense frequency grid, resulting in N_azimuth x N_elevation x N_frequency total samples. In many DF systems for reconnaissance applications the dependency on the elevation angle of arrival is simply neglected as is also the case in many array processing research publications [5]. The argument behind this is that for low elevation angles the azimuth accuracy will only be degraded gradually. The higher elevation angles are excluded either per definition or per specification.

What in fact is often not discussed is what happens if in a practical scenario a signal does indeed arrive from a high elevation angle? The real answer is: 'Depending on the antenna properties almost anything can happen, from a rapid degradation of the azimuth accuracy to a completely wrong DoA estimate for higher elevations'. For the actual submarine-based DF system it is of great importance to preserve a good azimuth accuracy for a very wide range of up to 70 degrees of elevation, which is motivated by the fact that the submarine antenna will always be a low altitude platform (opposed to a land-based system, frequently deployed on a mountain top), where transmit sites on a coast will be higher, and that it is desirable to DF also signals emitted from air-borne platforms. Additionally, the DF system should tolerate a certain amount of roll and pitch that the submarine experiences due to the ocean waves and swells.

All this leads to the conclusion that a full 3D calibration of the submarine antenna is required, with the valuable side effect that the system also provides information on the elevation angle of arrival, which can be used to differentiate between air-borne and ship-borne emissions. An automated antenna calibration system has been setup with receiver hardware similar to that of the DF system. A test transmitter is controlled to transmit multi tone signals with appropriate frequency spacing and a 2 axis antenna positioner is controlled to turn and tilt the submarine antenna into all required orientations, as depicted on the left of Figure 3.2. In order to limit the total required measurement time it is advisable to select the azimuth and elevation grid spacing values as large as possible without compromising the DF accuracy. This can be managed by inspecting the so-called effective aperture distribution function (EADF) [4] of the antenna array, which essentially is a measure for the (spatial) frequency structure of the variations in the complex beam patterns over azimuth and elevation. It is not surprising that the required grid values are again frequency-dependent. The blue curve in Figure 3.2 right depicts for instance the required azimuth grid that starts somewhere at ~32° around 600 MHz and finally approaches ~15° at 3 GHz. This means in practice that measurements must be done in several sub-bands. This is also desirable because of the possible increase in the frequency grid for higher carrier frequencies. In addition there is also the need to change the source antenna set-ups according to their operating frequencies. Also, great care must be put into optimizing the source antenna set-ups to prevent undesired ground reflections. The actual antenna calibration measurements took place on a well-equipped antenna test range at Paardefontein north of Pretoria in South Africa [6] and [7].

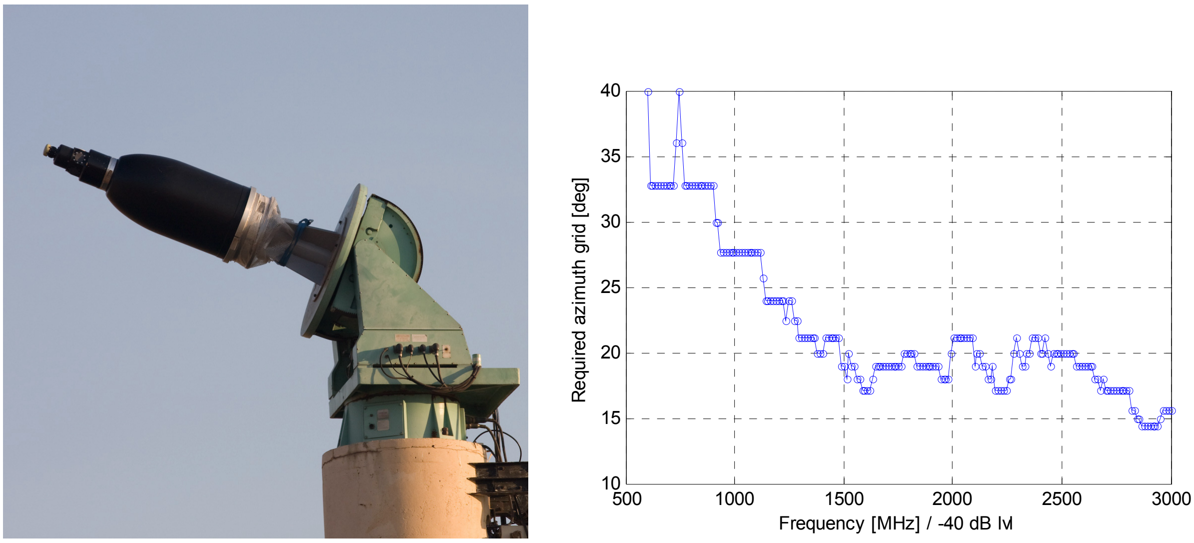

Figure 3.2 Left: Submarine antenna on the antenna positioner at a high elevation angle. Right: EADF based estimate of the required azimuth spacing for antenna calibration.

After calibration the same antenna test range was used to execute a comprehensive factory acceptance test (FAT) procedure for each COMINT antenna and DF system. During the FAT, a total number of more than 200,000 DoA samples distributed in a pseudo random pattern over the full azimuth and elevation range and all frequency bands were measured. Analysis of this data demonstrated excellent DF accuracy and system sensitivity well within the specified limits.

This holds true also for the DF in the MF/HF sub-band below 30 MHz. Instead of interferometer DF this sub-band uses the classical Watson-Watt DF algorithm on an array of ferrite loop antennas. Here, the antenna calibration is limited to a proper measurement of azimuth deviations and an optimization of the omni channel phase response to enable DF also for high elevation angles.

3.4 Advantages of the parallel receiver concept

The submarine-based DF system has been designed to feature five antenna elements per antenna group, connected to a fully parallel bank of five DF receivers. Aspects leading to this design decision and consequences of this design compared to alternative solutions are illuminated in the following paragraphs.

The number of antenna elements and parallel receivers

One of the most important issues in designing a DF system for COMINT applications is to find an acceptable trade-off between the system performance and the hardware complexity, which in turn translates into costs and required space for the equipment. Different application areas may lead to different solutions. In general it is known that for best DF accuracy and high immunity against multipath effects it is recommended to employ as many elements as possible for the array. For land-based systems a number of nine elements is frequently used. However, to draw the full advantage from the nine element solution it is required to place them on an array diameter that would be prohibitive for a submarine application.

A fundamental design decision is also whether each antenna element is fed to its own receiver or alternatively whether some antenna multiplexing scheme is used to reduce the total number of parallel receivers. The latter introduces a sequential measurement of the relative phases and amplitudes of at least some of the elements (e.g., seven elements connected to two receivers results in six multiplex cycles). This increases the total measurement time required to obtain one complete measurement vector for the array, which in turn means that the signal to be DF'd must constantly be present during the full array measurement cycle. Otherwise a valid DF result cannot be obtained. A fully parallel system has in contrast the *monopulse capability*, which means that a DF result is obtained even for very short signal bursts (a few microseconds with current receivers) as long as a signal of sufficient energy is received. A parallel system is thus ideally suited also for DF of frequency hopping signals.

The scan rate and the averaging gain

Another argument for a parallel receiver solution is that a DF system for COMINT purposes is most often operated in a frequency scanning mode. This is so because the coherent bandwidth of current receivers, typically up to 24 MHz, is much smaller than the desired observation bandwidth of the system, which is easily a few hundreds of MHz or even some GHz. Having antenna multiplexing cycles for each center frequency increases the so-called dwell time per frequency, thus reducing the scan rate of the system, indicated in GHz/sec, according to which the system provides DF results. A parallel system can potentially achieve higher scan rates and thus offers a higher probability of intercept for short time transmissions, which is an important system parameter for reconnaissance.

Alternatively, one can argue that the parallel system can exploit a longer dwell time more efficiently to collect a larger number of temporal snapshots of the complete measurement vector of the array. The obtainable averaging gain, resulting from the coherent averaging of the array output, translates directly into an improved DF sensitivity for weak signals. For a reconnaissance application this is a great advantage. For longer dwell times it is even possible to perform reliable DF for signals that are close to the noise floor of the receiving system or even somewhat below. The compromise setting between averaging gain and reduced scan rate is better achieved for a system using parallel receivers.

In addition, the scan rate of the DF system is affected by the settling time of the receiver for each new center frequency. The receiver must wait this time span before the actual signal capturing can start. The settling time is primarily needed for stabilizing the local oscillators and for adjusting the automatic gain control. For the parallel receiver system such as implemented for this submarine application, the AGC values are adjusted individually for each antenna element. This ensures maximum dynamic range for the array measurement vector. The settling time is needed only once per center frequency. A DF system with antenna multiplexing needs either an identical AGC for all antenna elements, which reduces the dynamic range, or an additional settling time for the AGC needs to be accommodated per multiplex setting. This results in an even higher dwell time per center frequency and consequently a reduced scan rate.

3.5 Emitter detection

The primary reconnaissance task of a COMINT system is to search in a wideband communication spectrum for transmitting activities. On the first level this is a classical detection problem that could be solved using only a single receive antenna for analyzing the power spectrum density (PSD). For a system with automated signal detection and also capable of operating in densely populated radio environments it turns out however that the use of DF information is almost essential for reliable emitter detection. This is because the detection is not only supposed to identify a spectral band with energy but also it is expected to identify individual emitters even if they have closely adjacent or even overlapping spectrum occupancy (co-channel signals). Moreover, for the initial identification of radio systems a reliable bandwidth estimation of an emitter is required and in dense scenarios this is hard to obtain from PSD data.

The submarine-based system derives all this emitter information by utilizing a multidimensional cluster identification scheme, operating jointly on the power spectrum and the angular domains. The basic idea behind this approach is that different emitters should be separable by their direction of arrival, and that their spectral extent can be easily obtained by the number of closely neighboring FFT bins with similar DoA. A representative signal example is depicted in Figure 3.3. Here, the PSD and the azimuth estimates for a digital trunk radio communication system are shown. The channel spacing and channel bandwidth is 25 kHz. For the human observer the channel structure and hence the potentially different emitters are probably already recognized from the PSD. However, for an automatic algorithm without prior knowledge it is hard to decide what spectral components belong to a single emitter. This task is greatly simplified if in addition the azimuth information is incorporated, since closely spaced channels are mostly received from different directions. The small overlapping regions of adjacent channels partly yield a degraded DF accuracy and would therefore increase the cluster extent in azimuth. This is automatically prevented by using a proper filtering rule that excludes DF estimates with a poor DF quality value and that are not shown in the figure. Thus, the clusters of one emitter can be kept compact, ensuring that the automatic clustering algorithm converges successfully.

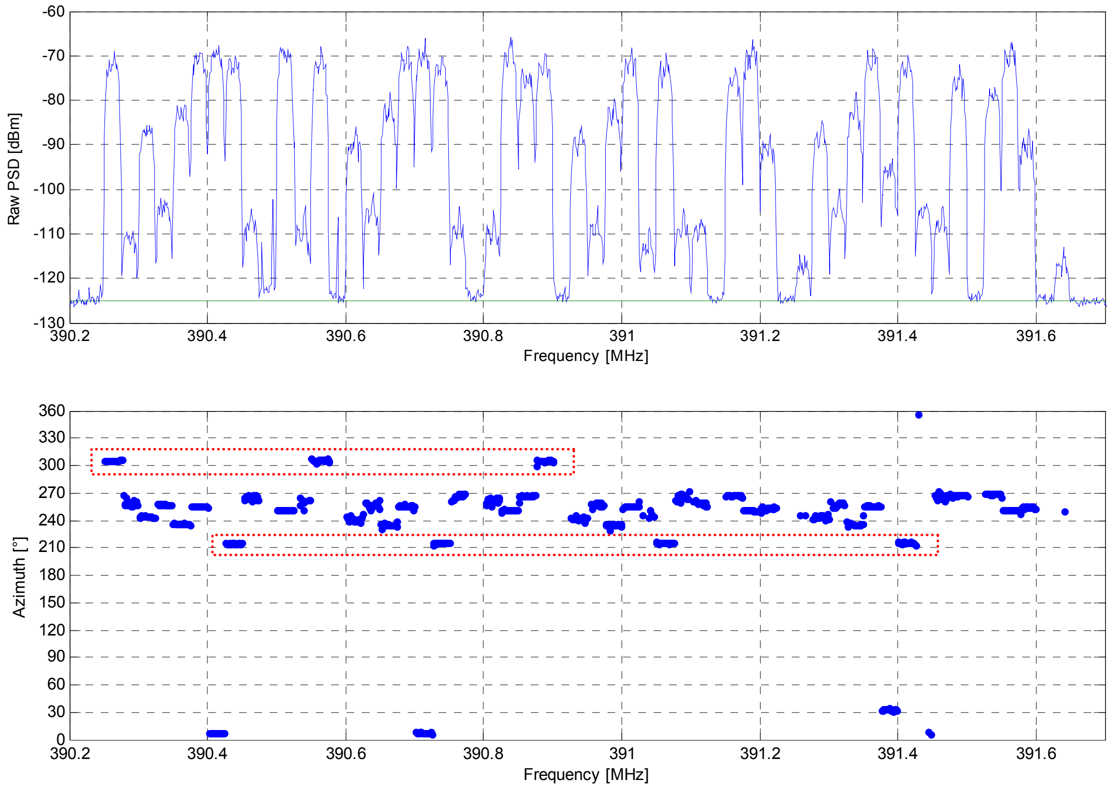

Figure 3.3 Power spectrum (top graph, the horizontal line indicates the noise floor) and azimuth information for a digital communication system (bottom graph, each blue dot indicates a DoA estimate, each of the red dotted rectangles denotes potentially co-sited emitters).

The described approach is also capable of resolving certain co-channel signal constellations. For instance it is possible to identify narrowband emitters that are hidden in wideband broadcast bands such as analog TV channels if they reach the DF system from a different DoA. Moreover, if the system operates with sufficient averaging time, the achievable SNR gain leads to the forming of clearly separable clusters in the DoA domains, as opposed to a pure variance reduction in the PSD. This enables the detection of very weak signals with only a few dB of SNR, and in the limit case even below the noise floor.

An additional main reconnaissance task requiring DF information is the identification of co-sited emitters. A special case of this task is the identification of emitters using frequency hopping. Here, the interrelationship of a rapid pseudo-random hop sequence can only be recognized if per burst DoA information is available. Consequently, the presence of more then one frequency hopping transmitter can only be detected with DoA discrimination. Similarly, the identification of individual emitters operating in a single frequency TDMA system is much easier because of the potential separation of the emitters in the DoA domain.

4 ADVANCED DF CAPABILITIES

4.1 DF of multiple co-channel signals

The standard correlative interferometer DF algorithm presumes that only a single source is active on each frequency. Moreover it is assumed that the incident signal arrives only via a single propagation path, i.e. that there are no secondary paths as a result of reflections. If these conditions are violated in practical scenarios, the DF accuracy of the correlative interferometer is either degraded or the DF results can get completely meaningless, which means that neither the DoA of the primary nor the DoA of a secondary source or path is estimated. What actually happens depends on the relative powers of the sources as well as their DoA separation and the antenna array characteristics.

The scientific field of array signal processing has generated a broad multitude of concepts and algorithms to deal with direction finding of multiple (co-channel) wave fronts at a receive array [8]. However, in the context of a wideband reconnaissance system, many of these approaches are not feasible. On the one hand this is due to the fact that the required optimality criteria for the array design cannot be met over the enormous relative bandwidths that are covered by traditional COMINT DF antenna arrays. On the other hand this relates to the prohibitively large numerical complexity of many of the schemes that rely finally on some sort of iterative search procedures to obtain a solution for a nonlinear maximum likelihood problem. For offline processing and the rather narrowband application of channel sounding, solutions such as RIMAX [4] are available, but not applicable for online computation.

Nevertheless, for a certain class of practically relevant multi-wave situations it is possible to implement DF schemes that are superior to the classical correlative interferometer. For the end-user it is important to understand that this class of multiple *uncorrelated* sources is not a rare special case, but that it needs to be distinguished from the more general class of *correlated* sources.

Uncorrelated sources

Uncorrelated sources occur naturally in geographic areas with a high user density and limited radio resources: The same frequency is re-used by different users, within the laws of radio propagation a joint coverage area exists, where the array is exposed to multiple wave fronts. CDMA based communications systems feature multiple users within the same frequency band by design. Adjacent-channel interference is another potential reason for the occurrence of multiple uncorrelated signals. This can be observed in many channelized communication systems, where the channel spacing is typically somewhat smaller then the signal bandwidth (e.g. GSM). The azimuth separation of two emitters within their overlapping band (important for a successful clustering) is undetermined if only single wave DF is employed. The situation of multiple correlated sources may even only arise in the DF system itself, namely if DF of TDMA communication signals is carried out. Here, the signals of multiple emitters are in fact orthogonal in time, but a DF system is typically not synchronized to the time frame structure of the system. Hence, during the signal capture period of the DF receivers more than one user's time slots are gathered consecutively. After integration over time, inherent to the FFT, this results in co-channel signals for different users. This is called pseudo interference.

Multipath propagation and correlated sources

Correlated sources are in contrast typically observed due to the presence of multiple propagation paths from the transmitter to the DF receive array. If the excess path length of a secondary reflected path is less than the reciprocal of the signal bandwidth, the reflecting area virtually acts as a correlated second signal source with potentially differing DoA. Moreover, a reflection frequently has the side effect of tilting the polarization plane of an incident wave. An appropriate receive array would consequently need dual-polarized antenna elements, which is a further difficulty hindering the DF of individual multipath reflections in a general reconnaissance background. Another receive situation for correlated sources occurs with the advent of the modern digital broadcast networks such as DVB-T. Multiple transmit towers form a single frequency network (SFN) transmitting identical signals. DVB signals are rarely a reconnaissance target but due to their eye catching spectrum, the DF system behavior is always under particular scrutiny here.

DF system implementation

A number of DF schemes for the class of uncorrelated sources can be implemented in terms of numerical complexity using today's technology. Mostly they are inspired by spectral estimation algorithms in order to improve either the angular resolution or to improve the estimation efficiency, or both, over the conventional beamforming approach. Prominent examples are the Capon beamformer and the MUSIC super resolution algorithm [3]. For the submarine-based DF system a series of experiments has been carried out on the antenna test range with multiple uncorrelated sources to verify the operation of the MUSIC scheme. Here, the basis is the eigenvalue decomposition of the averaged array covariance matrix. The number of incoming waves is estimated by analyzing the power distribution of the eigenvalues. A significant step in magnitude separates the signal eigenvalues from the noise eigenvalues. The eigenvectors corresponding to the noise eigenvalues are used to compute the so-called MUSIC pseudo spectrum, whose peak locations mark the DoAs of the incoming wave fronts. The total number of separable sources by MUSIC is strictly limited by the number of antenna elements minus one. For the submarine based system this means that maximally four co-channel emitters can be resolved. Figure 4.1 shows a measured example of the MUSIC pseudo spectrum for a three sources setup.

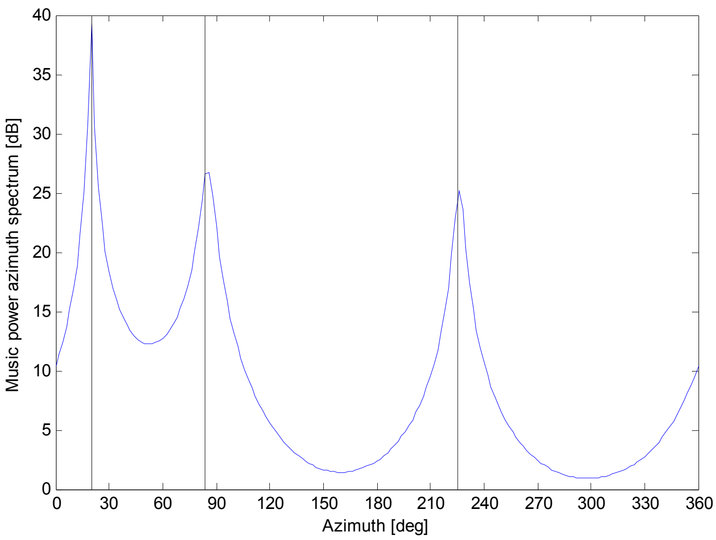

Figure 4.1 Music pseudo azimuth spectrum for a 3 sources setup. The black vertical lines denote the known DoAs.

4.2 DF for vertical and horizontal polarizations

Traditionally, a DF system for reconnaissance purposes operates per definition only for vertically polarized waves. The background behind this assumption is that many portable transceivers are equipped with monopole antennas that are vertically oriented. Air-borne platforms typically use aerodynamically shaped blade antennas which are mostly vertically polarized. This holds also for vehicle mounted antennas or base station antennas (although many of these operate in dual slant 45 degree polarizations). Moreover, for communication beyond the horizon vertically polarized (V-Pol) waves are better suited than horizontally polarized (H-Pol) waves due to different ground interaction.

At first sight the restriction of a DF system for V-Pol means that the array elements are designed for vertical polarization and that all calibration and test procedures are carried out with vertically polarized source antennas. What is frequently not so obvious is what happens when the DF system designed for vertical polarization experiences horizontally polarized reception? This case can easily occur in practical scenarios, since broadcast stations are often high power H-Pol transmitters. The cross-polarization attenuation in electrically rather small antenna elements and the mutual coupling in a compact array configuration are typically only in the range of 10 to 20 dB. This means that a high SNR signal can quite easily be available at the DF receivers for H-Pol waves.

The small blue circles in Figure 4.2 provide an example of the DoAs that are estimated by the conventional V-Pol DF system if an H-Pol source is placed at a DoA of 148 degrees. Depending on frequency, almost any DoA but the true one is estimated. Only the quality parameter of the DF output (not shown in the graph) may indicate a poor reliability of the estimated DoA values, which can however have several reasons. This is exactly the situation if the operators of a reconnaissance target communication system decide to simply rotate their Yagi antennas from vertical into horizontal orientation. In fact, this simple manipulation breaks the DF capability of many high performance fully automated reconnaissance systems.

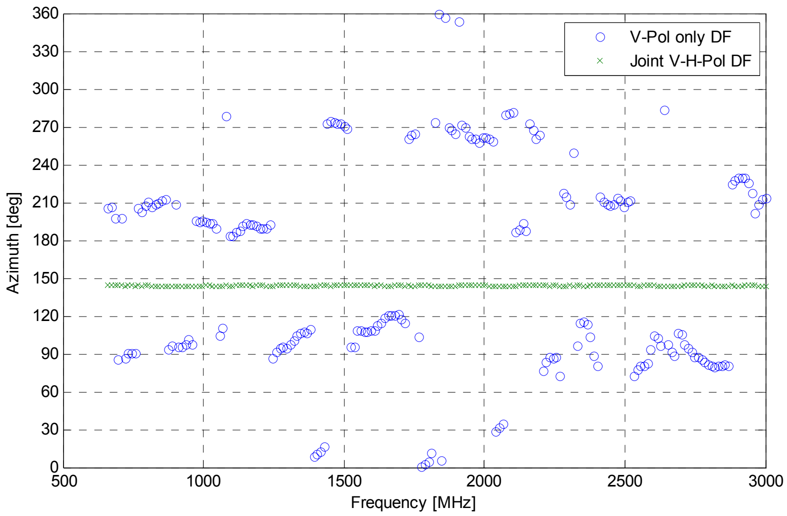

Figure 4.2 Blue circles denote DoA results for H-Pol signals received by a system designed for V-Pol DF only. Green crosses indicate DoA results for joint DF of V- and H-Pol signals.

Neglect of such fundamental practical aspects and limitations is unfortunately not uncommon in the array processing literature which is also revealed in a recent paper [5]. The optimum solution for the problem of direction finding of arbitrarily polarized signals is to measure V-pol and H-pol components separately, thus requiring both dual-ported elements (for example patch antennas in UHF), or requiring separate co-located V-Pol and H-Pol antenna elements. Only recently such a configuration has been commercially advocated by a well-known DF system supplier.

Due to the restrictive space requirements the submarine antenna could not be equipped with separate elements for dual polarization. However, as an intermediate solution the approach of dual polarized calibration and joint V-Pol and H-Pol DF has been demonstrated to be feasible. This is possible by extending the measured array manifold over azimuth and elevation by measuring calibration data obtained from a horizontal source. In this way, the DF algorithm not only provides information on azimuth and elevation of a source but can also discriminate between V-Pol and H-Pol sources and provides a meaningful DoA for H-Pol sources. The green crosses in the example in Figure 4.2 illustrates impressively that the estimated DoA is back to the true source DoA (148 degrees) over almost the full 2.5 GHz if this joint DF scheme is adopted.

Another more practical example is depicted in Figure 4.3, where the radio environment of a broadcast band is scanned. This graph shows the actual output of the online DF system, Matlab is only used for visualization. The left part of the spectrum is occupied by a strong analog TV station; probably some multipath effects lead partially to a second cluster in elevation but with identical azimuth. At 239 MHz a digital audio broadcast (DAB) station is observable with different azimuth and an elevation of 90° which is used by convention to indicate H-Pol in the graph. A second somewhat weaker analog TV station is observable around 247 MHz, likewise with horizontal polarization. All this information is provided by the system without user intervention.

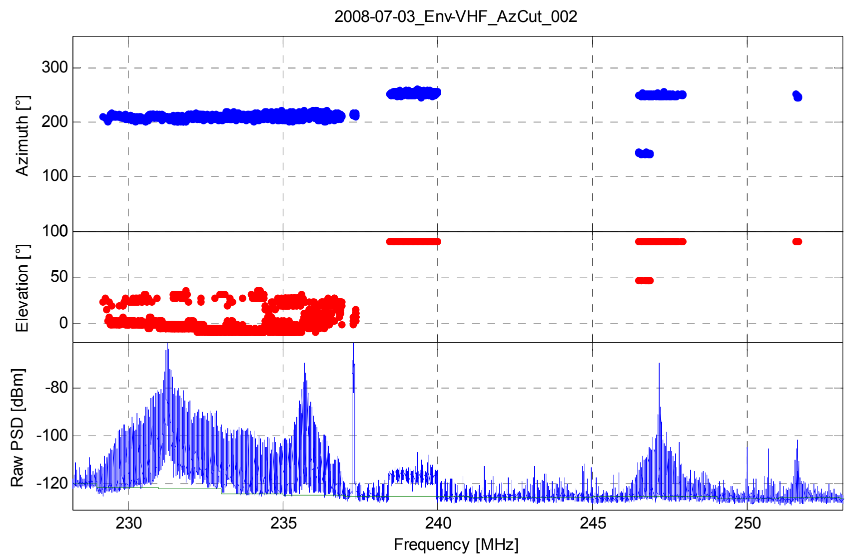

Figure 4.3 Example DF results of an environment scan with joint V/H polarized DF, strong analog TV V-Pol, DAB H-Pol, weak analog TV with H-Pol, H-Pol is indicated by 90° elevation.

5 CONCLUSIONS

This paper has described the requirements for a compact ultra wideband COMINT DF and monitoring system covering the MF/HF to UHF bands for submarine applications. The size and mass limitations force certain antenna array sub-band selections to optimize array performance not only on the horizon but also at high elevation angles. The COMINT radome which must accommodate a 2 to 18 GHz ELINT system on top forms a critical part of the system. The radome was designed and analyzed using modern software tools; however physical insight and experience played a key role in the successful implementation of the radome. The radome was successfully tested at a pressure testing facility both for ultimate strength and fatigue with repeated pressure cycling. The radome electrical design had to cater for the high elevation coverage requirement particularly at UHF and also the requirement that the radome may not degrade the elevation performance of the ELINT. All these objectives were achieved and the COMINT system could be interfaced to a high performance DF and monitoring system.

A very compact DF antenna with five parallel receivers, precision calibration on a suitable outdoor test range and a sophisticated DF algorithm yields exceptional performance. Internal calibration of all RF channels ensures system calibration over time and temperature. Extensive use was made of simulation to identify critical factors influencing accuracy and to continually upgrade algorithms and signal processing. This led to several advanced DF capabilities as described in Section 4. As an interesting result it turned out that the array manifolds of the vertical and horizontal polarizations are sufficiently uncorrelated even over wide frequency bands in order to detect the polarization of an incoming wave.

Here this is more a side effect of the compact antenna design, since no dedicated antenna elements for horizontal polarization are used.

The direction finding system scans continuously over all frequency bands according to a pre-defined mission. It automatically detects all occupied frequency channels by evaluating jointly both power spectrum and directional information, thus providing good signal discrimination even in dense radio environments. This is much more reliable than detection based on averaged power spectra only.

The COMINT system described in this paper has been designed, developed and installed on a recently completed submarine and as such represents the successful application of many techniques and technologies in a real environment and not only ideas for laboratory evaluation.

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