Target Classification, Recognition and Identification with HF Radar

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SUMMARY

Radars operating in the HF band achieve extremely long range detection by exploiting propagation modes which preclude many of the standard target classification techniques, at least in their conventional form. Yet, in order to take full advantage of an over-the-horizon detection capability, reliable target classification, recognition and identification is essential. This paper explores the options for target classification at HF, reviews some of the results which have been achieved, mainly but not exclusively with reference to skywave radars, and assesses the prospects for operational target classification, recognition and identification.

1.0 INTRODUCTION

Radars operating in the HF band are well known for their 'over-the-horizon' detection capabilities, whether via skywave propagation as with Jindalee [1] and ROTHR [2], for instance, or via surface wave propagation, as with SECAR [3], SWR503 [4], the AMS HFSWR [5] and others. These radars achieve extremely long range detection by exploiting propagation modes which preclude many of the established target classification techniques, at least in their conventional form. Indeed, given the vicissitudes of the ionosphere and the losses encountered with any form of over-the-horizon propagation, it is remarkable that even the detection mission can be achieved with adequate reliability. When one also takes into account the dramatic constraints on spatial resolution imposed by aperture and bandwidth limitations, and the fact that the radar wavelength is of the same order as the target dimensions, the prospect of determining target class, type, or possibly even identity, would appear remote.

From the operational perspective, this prognosis has long been a major concern. In order to take full advantage of an over-the-horizon detection capability, reliable target classification, recognition and identification is regarded as essential. This applies not only to the need to satisfy rules of engagement in the event of hostilities but, more routinely, to situational awareness, to the assignment of other assets on the basis of HF radar cueing, and to potential intelligence collection and analysis. Indeed, from the operational perspective, the value of virtually all wide area surveillance products generated by HF radar is substantially reduced in the absence of a moderately capable target classification functionality.

In spite of this motivation, with few exceptions the technical challenges posed by target classification at HF have not succumbed to the efforts of the radar researchers. Nevertheless, considerable progress has been made in a number of areas. On the basis of many experiments, much of the relevant physics is now understood, a variety of approaches to differentiating between targets of interest have been conceived and explored by experiment or modelling, concepts for integrating these schemes within the radar tasking and control architecture have been proposed, and many mathematical and computational tools have been devised to model and interpret radar observations. Moreover, the realisation that the ability to classify targets depends on the degree of control over radar resources, and radar design, is now taken into consideration when proposing enhancements to existing radar systems.

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Techniques which have been explored in the quest for an NCTR capability in existing HF radar systems include :

- (i) statistics of target echo magnitude
    - a. shape of the distribution
    - b. absolute RCS via calibration using co-located scatterers
    - c. ratios of RCS for different targets
- (ii) multi-frequency interrogation
    - a. discrete spanning set
    - b. target-matched illumination
    - c. wide sweep waveforms
- (iii) bistatic and multi-static scattering geometries (all of the above)
- (iv) modulation signatures
- (v) micro-Doppler information
- (vi) distributed scattering signature analysis
- (vii) nonlinear scattering
- (viii) accurate determination of target kinematics

This paper explores the options for target classification at HF, reviews some of the results which have been achieved, mainly but not exclusively with reference to skywave radars, and assesses the prospects for operational target classification, recognition and identification.

2.0 THE SEMANTICS OF CLASSIFICATION, RECOGNITION AND IDENTIFICATION

At the outset, it is essential to clarify the terminology used to describe the various levels of specificity with which a sensor might distinguish between different targets. According to NATO definitions (Source: AAP-6 NATO Glossary of Terms and Definitions) :

IDENTIFICATION *is the indication by any act or means of one's own friendly character or individuality. The determination by any act or means of the friendly or hostile nature of a detected person, object or phenomenon.*

RECOGNITION *is the determination of the nature of a detected person, object or phenomenon, and possibly its class or type. This may include the determination of an individual within a particular class or type. There are consequently various degrees of recognition :*

- ***General recognition****: recognise an object by class e.g. recognise a vehicle as tank, infantry fighting vehicle, or truck, or recognise an aircraft as either a bomber or a fighter. A lower level of general recognition might be to recognise a vehicle as tracked or wheeled, or recognise an aircraft as swept winged or straight winged*
- ***Detailed recognition****: recognise an object by type e.g. recognise a vehicle as either a T-80 tank or an M-1 Abrams tank, or recognise an aircraft as an Su-27 or a Tornado. It may entail the recognition of an individual person or object e.g. "finger printing."*

These definitions were no doubt adopted to serve important operational purposes, but they are not entirely consistent with their etymology, nor do they span the range of possible scenarios. In particular, the use of *identification* as the signifier of *intent* is unfortunate. One might suggest, only half in jest, a new term – ***intentification*** – to fill this need. Accordingly, the following alternatives and additions, based on usage in the domain of statistical pattern recognition, are adopted in this paper. For clarity they are formulated as *verbs* rather than as *nouns*.

Proceeding from the most general level,

Classify *– associate with, or assign to, one of a number of sets (classes) which are distinguished by one or more criteria, irrespective of whether there is any prior knowledge of the class membership or class boundaries.*

Recognise *- establish membership of one of a number of disjoint* ***known*** *sets (classes)*

Identify *– establish the absolute sameness with one of a number of possible individual members of a class of known elements*

For example, suppose we were to take a number of aircraft and, for each, measure (i) its weight, and (ii) its median RCS (over some range of parameter values). If we were then to plot the results as points on the plane, we might find that they tend to cluster in two groups, with larger weights generally associated with larger RCS values. Without even labelling the axes, or knowing anything about what the points represent, a given point could be associated with one cluster or the other by means of purely statistical measures. To ***classify*** objects in the most general sense is to perform this kind of assignment. Now if we are told that there are only two types of aircraft involved – fighters and bombers – we might label the two classes appropriately, even if we don't have confirmation that any particular point is in the correct class. If some points are labelled – the case of ***supervised training*** – we can use these points first to design our classifier, allowing for subsequent *unsupervised training* if desired. Then, confident in our labelling of the classes, we have the possibility of ***recognition***, that is, assignment to a *known* class. Finally, if that class is feature-rich, and there is adequate prior information, the prospect of ***identifying*** the individual members of the class can be entertained.
With this hierarchy, a typical sensor mission has the structure shown in Figure 1, where the additional term *discrimination* is used to denote the acceptance of some input patterns and the rejection of others, as with situations where strong clutter is present. This, of course, is equivalent to increasing the number of pattern classes.

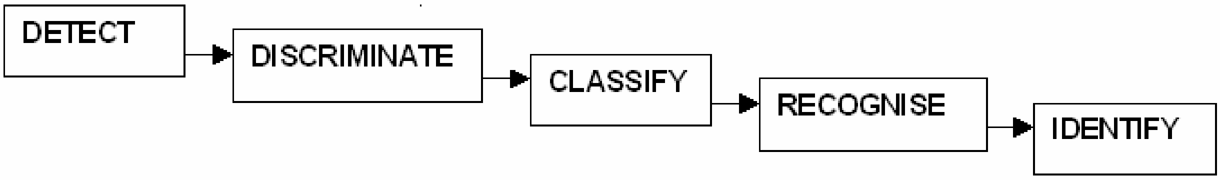

Figure 1: The sequence of progressively more intimate assignment as implemented in many sensor systems

2.0 HF RADAR SYSTEMS

Radars operating in the HF band can be classified according to the propagation mechanisms they exploit, noting that the mode of propagation from transmitter to target may differ from that occurring between target and receiver. A taxonomy based on this classification is presented in Figure 2. The key to understanding this diagram is to note the use of the columns to refer to transmitter-to-target aspects and rows for the receiver-to-target aspects. Common sense suggests that it would be unreasonable to expect any single classification technique to be effective for such a diverse group of radar configurations, and this turns out to be indeed the case. Further, quite striking differences exist between alternative implementations of radars from each of the principal categories shown in Figure 2, so that what may be possible with the Australian Jindalee radar, for example, may not possible with the US Navy's ROTHR, or vice versa., though both these radars are bistatic land-based skywave-out, skywave-back radars. For this reason, the discussion which follows will attempt to avoid system-specific judgments. Further, the emphasis will be placed on skywave radars, with surface wave radars treated in lesser detail, noting that though there are numerous commonalities.

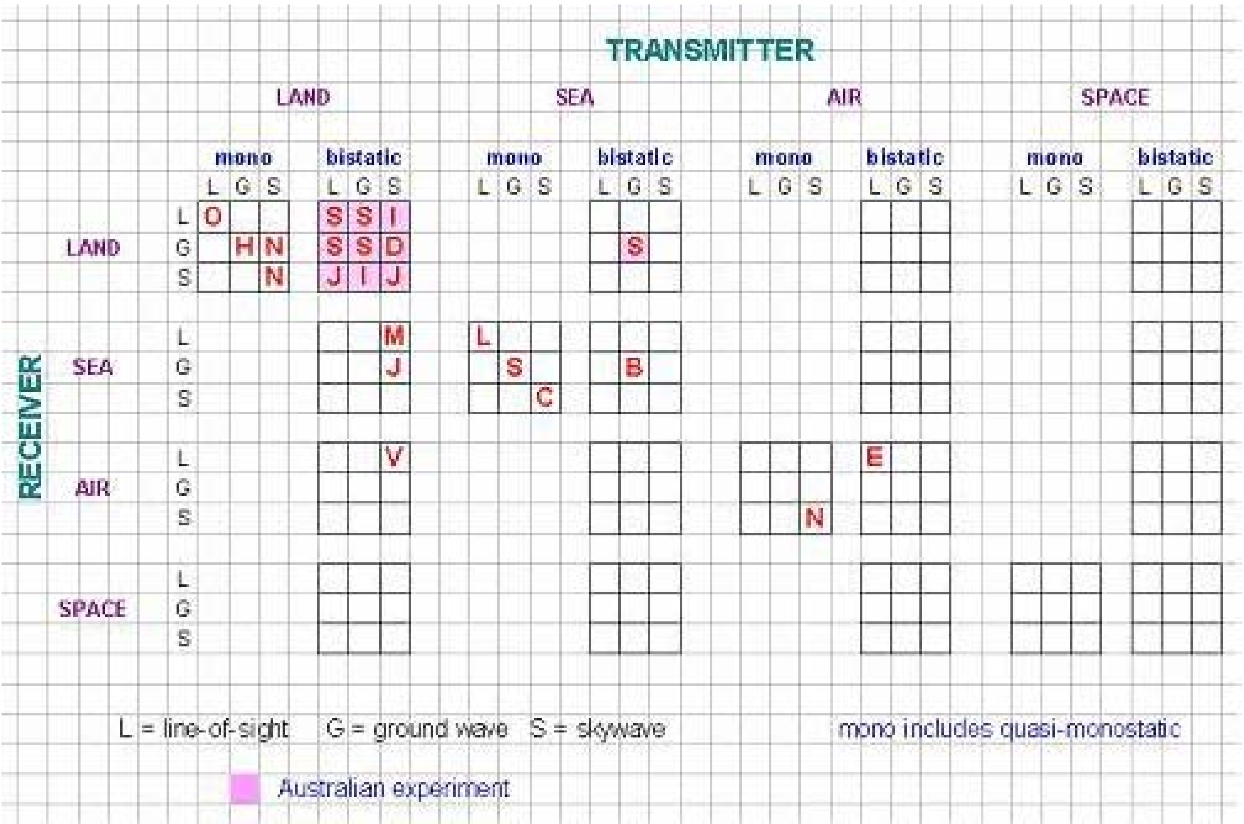

Figure 2: Taxonomy of HF radar configurations, with selected radars indicated

2.1 Radar Process Models

The starting point for an analysis of target classification at HF is a model of the radar process, that is, a formal representation of the relationship between the *measurements* and *the system being measured*. Such a model has been developed and used extensively for HF skywave radar applications [6-8]. Following [7], the radar process model allowing for multihop propagation can be written

$$s = \tilde{P} \sum_{n_B=1}^{N} \tilde{R}\,[\prod_{j=1}^{n_B} \tilde{M}_{S(j)}^{S(j+1)} \tilde{S}(j)]\,\tilde{M}_{T}^{S(1)} \tilde{T} w$$

$$+ \tilde{P} \sum_{l=1}^{N_J} \sum_{m_B=1}^{M} \tilde{R}\,[\prod_{k=1}^{m_B} \tilde{M}_{S(k)}^{S(k+1)} \tilde{S}(k)]\,\tilde{M}_{N}^{S(1)} n_l + m$$

where

w represents the selected waveform

$\tilde{T}$ represents the transmitting complex, including transmitters and antennas

$\widetilde{M}_T^{S(1)}$ represents propagation from transmitter to the first ground scattering region

$\widetilde{S}$ represents all scattering processes in the current region

$\widetilde{M}_{S(j)}^{S(j+1)}$ represents propagation from j-th scattering region to the (j+1)-th region

$S(n_B)$ and $S(m_B)$ represent the receiver location

n_l represent external noise sources, interferers or jammers

$\widetilde{M}_N^{S(1)}$ represents propagation from a noise source to its first ground scattering region

m represents internal noise

$\widetilde{R}$ represents the receiving complex, including antennas and receivers

P represents the signal processing

s represents the signal decomposition after processing

When appropriate substitutions are made, and the squared modulus of this 'voltage' formulation taken, equation (1) reduces to the familiar scalar radar equation,

$$\sigma = \frac{(4\pi)^3 R^4 kTB.SNR}{P_T G_T G_R \lambda^2}$$

This conventional form is of little use for HF radar applications, even when various system and propagation losses are incorporated in the form of multiplicative loss factors With HF skywave radar, the range dependence of signal intensity is governed by the electron density profile of the ionosphere and the modal structure of the earth-ionosphere waveguide, not by a simple power law. For HF surface wave radar, the range dependence of signal intensity is dominated by diffraction processes, modified by the prevailing surface roughness.

2.2 Observables, signatures and the classification domain

The raw materials on which the target classification process operates are the sensor responses to the universe around it – the ***observables***. In the main, these are related to the intrinsic physical attributes of the target which govern its interaction with the electromagnetic field of the radar signal, but the electromagnetic field in the vicinity of the target is not *observed* by the radar, nor even is the field arriving at the receiving antenna. In most cases, though, the observables can be represented mathematically by an integral operator which maps the set of target 'states' into the space of radar output signal parameters. One other category of observable needs to be mentioned – perturbations to the target's environment which might be independently observable, such as ship wakes. Of course, the interaction with the environment also reacts on the target's intrinsic observables, such as the airframe oscillations causing micro-Doppler modulation.

Clearly, the first issue to be decided in any target classification task is to establish which observables will be available for consideration. The second step is to explore their information content, as embodied in their statistical properties, so that the classification scheme can make most effective use of the 'evidence'. Subsequent development deals with the design of the classifier and the prediction of its performance; these later stages will not be addressed in this paper.

Target classification may thus be viewed as a statistical decision theoretic problem based on observations of the radar output *s,* subject to specified constraints on the degrees of freedom of the radar measurements. For example, the observations may take the form of :

- a single look, by which is meant (for HF radar) almost invariably the spectral decomposition of time series corresponding to a single coherent integration period, from a number of simultaneous spatial cells
- a sequence of looks, with the advantage of multiple sampling of any stochastic behaviour, as well as the prospect of establishing a track on each target
- a sequence of measurements carried out with different radar parameters (eg carrier frequency, scattering geometry), possibly as an adaptive decision-making process

The process of classifying (recognising, identifying) a target echo may exploit any information thus obtained, and make use of any ancillary information, such as anticipated target behaviour, in conjunction with the direct information which has been imprinted on the received radar signal by the physics of scattering from the target and retrieved by the radar reception and signal processing.

#	ACCESSIBLE FUNCTIONALITY	OBSERVATION METHODOLOGY	CLASSIFICATION DOMAIN
5	network control	stereoscopic operation multistatic operation cooperative waveforms	multi-aspect RCS bistatic RCS nonlinear scattering
4	individual radar control	multi-frequency operation spatial mapping optimised clutter calibration spatio-polarisation agility	multi-frequency RCS ratios distributed echo analysis absolute RCS polarisation scattering matrix
3	signal processing (beyond basic range-azimuth-Doppler decomposition)	high-resolution Doppler time-frequency analysis higher-order spectrum analysis harmonic extraction	micro-Doppler time-varying parameters nonlinear scattering periodic internal motions
2	processed data - multiple dwells	target dynamics statistical echo analysis targets in company multimode analysis track history inter-track correlation track future	performance data monostatic RCS RCS ratios differential RCS point-of-origin mission analysis response to stimuli
1	processed data - single dwell	peak amplitude peak coordinates peak phase modulation	monostatic RCS performance data environmental coupling

Table 1: Levels of system control and corresponding domains for target classification

This latter quantity – the information imprinted on the radar signal by the target – is usually termed the target's ***radar signature***. Unfortunately such a definition is lacking in two respects. First, it appears to confine attention to the electromagnetic phenomena occurring at the target, and fails to mention the role of the observing radar – 'the paper on which the signature is written and the pen which writes it'. Second, it ignores certain target-related perturbations to the received signal, such as shadow effects and some multiple scattering processes. While this is true for all radars, it acquires special significance in the case of HF radars, where propagation is often hard to separate from scattering. For this reason there is merit in adopting a more pragmatic definition.

Following [9], the ***generalised radar signature (GRS)*** of an object ***x*** is defined as :

GRS (x) = response of radar when x is present - response of radar when x is absent

This immediately raises the question as to how radar resources should be allocated and scheduled in order to provide the best outcome because the radar timeline is generally heavily committed, so opening up possibilities for extracting more detailed information is generally possible only at the expense of coverage or revisit rate. The situation is complicated by the variability of the HF propagation environment, which impacts on tasking through the need to balance mission priority against the ability of the prevailing conditions to support that mission. Thus it is highly probable that a radar attempting to classify targets will be obliged to operate in modes which are sub-optimum insofar as they do not allocate the maximum of potentially useful resources to this task. Table 1 presents a plausible hierarchy of accessible functionality, together with the corresponding options for radar signature measurements relevant to target classification.

2.3 Complications arising with HF systems, propagation and scattering

With most conventional radars, operating at microwave frequencies, the various terms in the radar equation can be assumed known or calculable to reasonable precision. Propagation losses are dominated by the inverse square law dependence, noise by internal thermal noise, antenna gains are accurately known, the transmitted polarisation is the same as the polarisation incident on the target, range resolution cell size can be orders of magnitude smaller than overall target dimensions, and so on. Correction terms for additional losses due to polarisation mismatch, antenna insertion loss, etc, are often introduced, but these effects are relatively modest and, in any event, generally known with considerable accuracy. Thus, it is normally possible to interpret the received echo power directly in terms of the effective RCS of the scattering object. Under these circumstances, target classification has a very favourable prognosis.

In the case of HF radars, virtually all these convenient idealisations must be discarded, as departures from the idealised models mentioned above are typically measured in tens of dB. The reasons for this are evident from a consideration of the properties of the individual operators in the radar process model and the environmental phenomena which impact on them; some of these are summarised in Table 2.

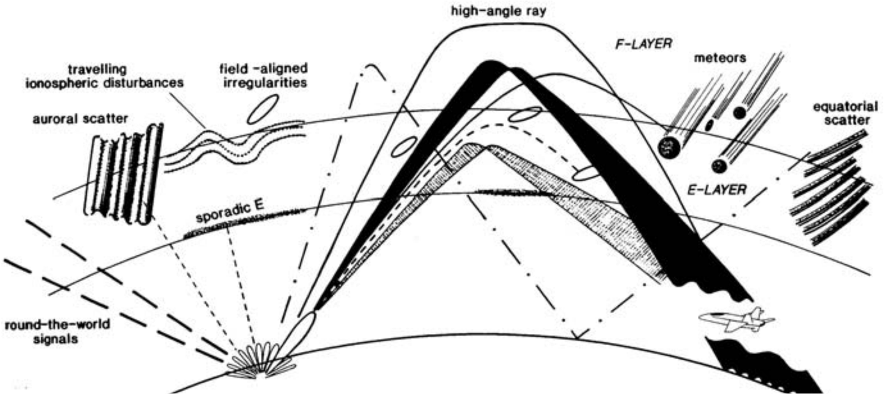

Figure 3: Some features of ionospheric radiowave propagation

OPERATOR	ATTRIBUTE or ENVIRONMENTAL PHENOMENON
T	- limited to fixed linear (V or H) polarisation - antenna array gain is imprecisely known
M_{SKY}	- path losses are frequency dependent, with deviative and non-deviative absorption - wave-like disturbances in the ionosphere tilt, focus and defocus the radiowaves - various large-scale processes in the ionosphere modulate the phase of traversing radiowaves, causing Doppler shifts and Doppler broadening - generalised Faraday rotation causes unknown random, time-varying, frequency-dependent transformation of the polarisation state of the radiowave on each transit - only a limited band of frequencies will propagate to a given region at one time - the available frequency band can change on time-scales of 10 minutes - phase and group paths are strongly frequency-dependent, limiting signal bandwidth and hence range resolution - wavefronts after ionospheric reflection are no longer planar/cylindrical but corrugated, so scattering geometry is not strictly determinstic - the ionospheric plasma supports nonlinear coupling mechanisms by which different transitting signals can cross-modulate
$M_{SURFACE}$	- multiple scattering of surface waves modulates them in phase/Doppler, direction of travel, time delay, and azimuthal angle of arrival
S	- the radar wavelength is comparable with target size, denying access to target detail - ship targets are immersed in a field of scattering water waves with comparable speeds and RCS, with no prospect of spatial domain separation - uncertainty in the propagation path means that the scattering geometry is not accurately known, especially in elevation
R	- only a single polarisation component of the received field is measured (V or H) - array calibration is difficult and may depend on direction of arrival, etc - imperfections in receivers cause severe significant distortion
n	- under almost all conditions, HF radars are externally noise-limited - the external noise is strongly non-Gaussian

Table 2 : Phenomena impacting on the process model operators at HF

3.0 MODELLING AND MEASUREMENT OF TARGET SIGNATURES

As mentioned in Section 2.2, the first stage in NCTR development is to identify the observables which will be used for the analysis. A list of possible candidates is provided in the Introduction and, in a slightly different form, in column 3 of Figure 1. The stochastic nature of almost signature component measurements means that classifier design and the achievable performance will be governed by the underlying probability distributions of these observables. These distributions are not always accessible to direct measurement, but a deep understanding of the physical origins of stochastic behaviour can be used instead to infer statistical behaviour, construct models, and generally facilitate a Bayesian estimation approach. In this section, some of the more obvious observables used for target classification, recognition and identification are considered and illustrated with data from various Australian HF radar programs.

3.1 Classification based on target RCS estimates

The scattering of radar signals from a deterministic target is usually described by the target polarisation scattering matrix which relates the scattered field to the incident field,

$$\vec{E}_{scat} = \tilde{S}\,\vec{E}_{inc}$$

from which the conventional RCS for the scattering process where the incident field is α-polarised and the scattered field β-polarised is defined by

$$\sigma_{\beta\alpha} = S_{\beta\alpha}^{*}.\ S_{\beta\alpha}$$

At HF the linear V-H polarisation basis is normally appropriate because of antenna designs. This representation applies for bistatic and monostatic scattering. A key advantage of the scattering matrix formulation at HF is that the most important subspaces – those spanning the azimuthal bistatic geometry combinations – are conveniently represented graphically, as illustrated in Figure 4. In almost all practical situations, the variations with elevation are less sensitive and occur operationally on much slower timescales. Classification based on RCS attempts to establish a mapping between scalar RCS estimates and the set of candidate targets. Unfortunately, as discussed in Section 2.3, ionospheric polarisation transformations and propagation losses intervene to complicate this process, forcing a statistical treatment.

3.1.1 RCS Modelling

In order to develop a target recognition capability, some library of signature data must be accumulated. Opportunities to collect real-world measurements are obviously limited, and scale model measurements are expensive and time-consuming, so the training sets for RCS-based classification are most conveniently derived by numerical modelling.

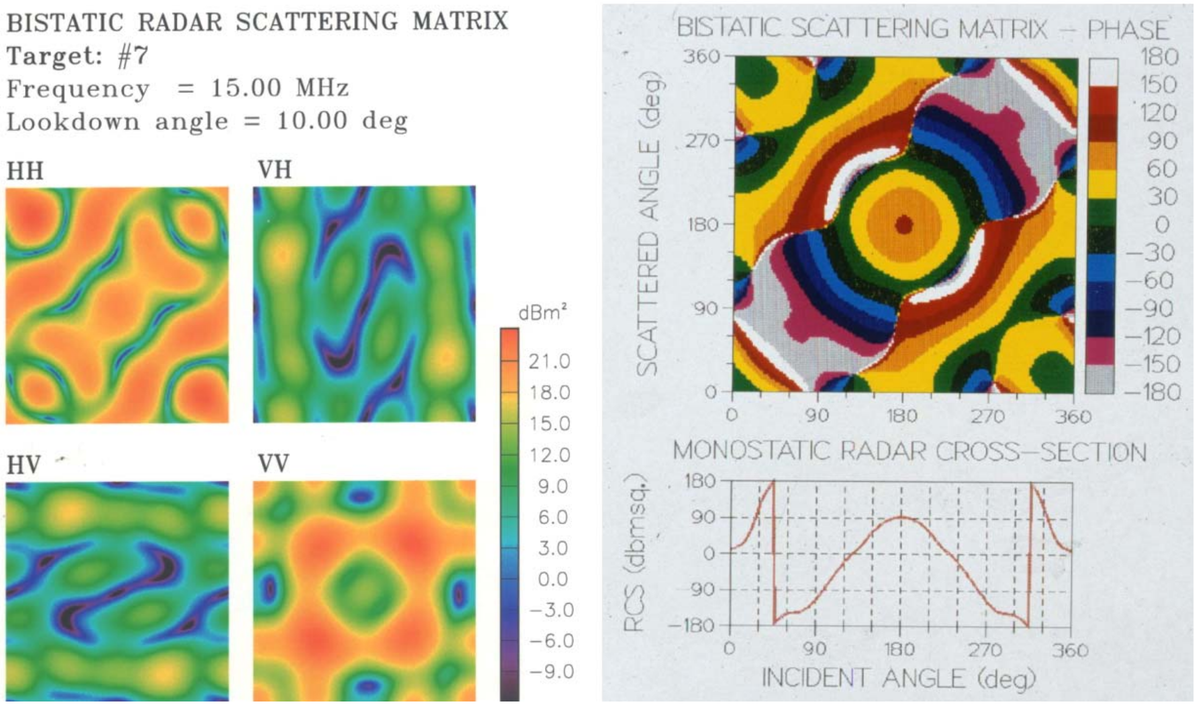

Figure 4: (a) Magnitudes of the elements of the bistatic polarisation scattering matrix of an aircraft, and (b) phase plot of the HH component

Figure 4 shows typical outputs of the Jindalee radar signature modelling facility. In these examples, the magnitude of the elements of the polarisation scattering matrix are plotted for all bistatic Tx – Rx azimuth combinations, at a common fixed elevation angle (left picture). In each coloured square, the abscissa corresponds to incident azimuth, ranging from 0° to 360°, with the ordinate representing scattered azimuth from 0° to 360°. The trailing diagonal is the monostatic solution. On the right, in this example, the phase of the HH element of the polarisation scattering matrix is plotted against the same coordinates.

3.1.2 Model validation

Experimental validation of computer model predictions can be performed in two ways – by scale model measurements in an anechoic chamber, and in field trials with real targets collocated with suitable reference scatterers to provide absolute RCS calibration. Figure 5 shows examples of each of these approaches. In Figure 5(a), anechoic measurements of a 1:144 scale model aircraft are compared with the predictions of NEC2 – the well-known numerical code based on the method of moments technique. In this example, there is agreement to within 2 – 3 dB over most of the (scaled) frequency range 8 – 20 MHz, degrading at lower frequencies. More significantly, a consistent trend is apparent, with the model under-estimating at low frequencies and over-estimating at high frequencies. This is a consequence of the inadequate fidelity of the numerical grid model used for the calculations which was matched to 10 MHz. Adapting the model as a function of frequency yields results to better than 2 dB across the band. Figure 5(b) shows the results of field trials with an HF surface wave radar and a cooperating vessel, which carried out manoeuvres around a calibration buoy at a range of about 50 km from the radar. Despite the complexity of the target and the complications introduced by the rough sea in the vicinity of the target, the discrepancy between theory and measurement (lower panel) is within 3 dB, generally 1 – 2 dB, except near the null which occurred at one aspect. The conclusion to be drawn from these examples is that modelling to within 2 – 3 dB is achievable, even for reasonably complex targets.

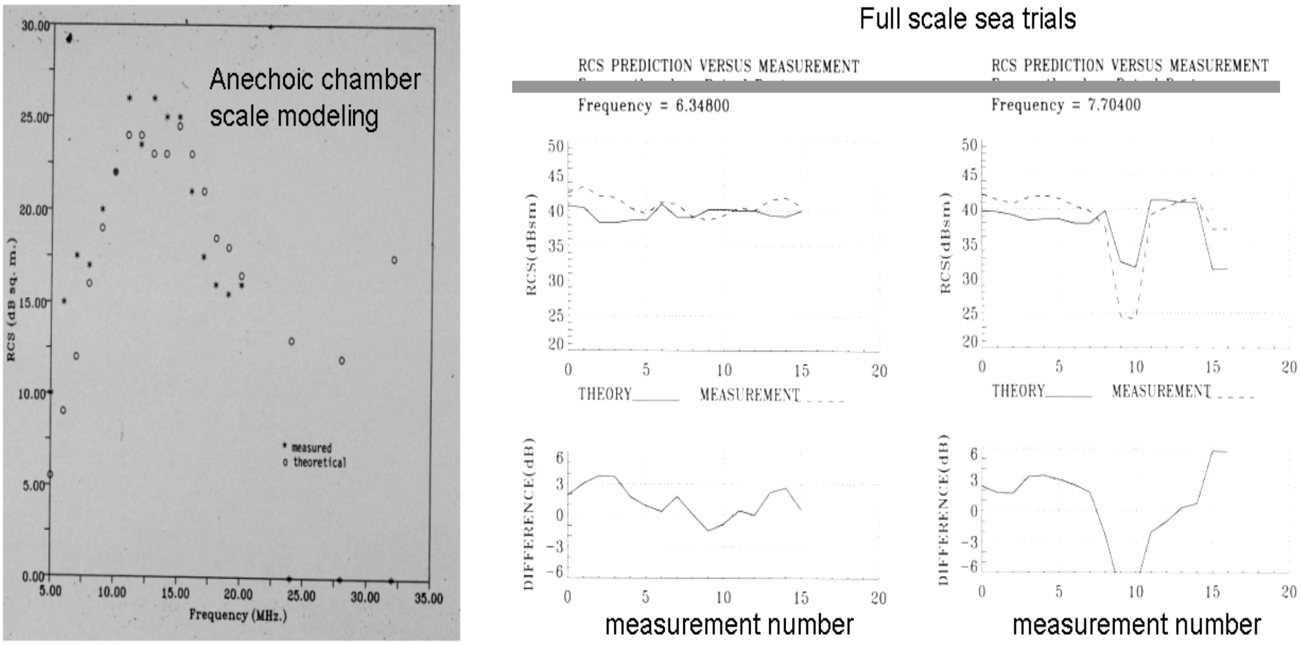

Figure 5: (a) Comparison of theoretical predictions with scale model measurements of the H-H RCS of an aircraft, carried out in the DSTO anechoic chamber, and (b) comparison of theoretical predictions with calibrated at-sea measurements of a ship (V-V component).

3.1.3 Precision requirements

In many practical situations the inter-class distances are small, imposing stringent requirements on modelling fidelity. This is illustrated in Figure 6 which shows the close similarity of the bistatic RCS of two aircraft of similar overall dimensions as a function of bistatic angle for illumination at an incidence angle of 30°. The aircraft concerned have very similar dimensions, as shown in Table 3 (this example is taken from a study undertaken in 1986). This type of study establishes minimum requirements for model precision.

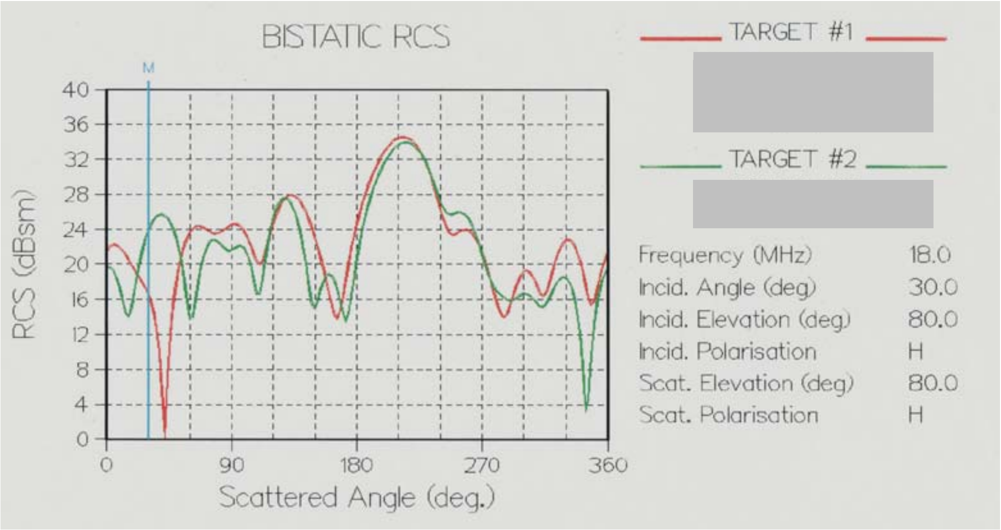

Figure 6: Bistatic RCS comparison for one illumination geometry

AIRCRAFT	LENGTH (m)	WINGSPAN (m)	HEIGHT (m)	CRUISING SPEED (km/hr)
Aircraft #1	42.4	34.3	10.8	900
Aircraft #2	40.6	32.9	10.4	917

Table 3: Major dimensions of Tu-22M-3 and Boeing 727-100

3.1.4 RCS calibration using sea clutter

Sea clutter at HF has a characteristic Doppler spectrum which embodies detailed information about the distribution of waves on the sea surface, that is to say, the directional wave spectrum. Knowledge of this spectrum at one radar frequency suffices to calculate the absolute RCS per unit area of the sea (scattering coefficient) at ***any*** HF frequency. Combined with the resolution cell area, this immediately yields a reference RCS enabling absolute calibration. Techniques for estimating the ocean directional wave spectrum from the radar Doppler spectrum, have been developed by several researchers (eg.[10-12]); an example of this process is shown in Figure 7. On the left is a measured Doppler spectrum, superimposed on which is the 'best fit' Doppler spectrum obtained by optimising a 7-parameter model of the directional wave spectrum. On the right is an example of a measured Doppler spectrum together with the discretised directional wave spectrum computed by an iterative non-parametric technique ([13]).

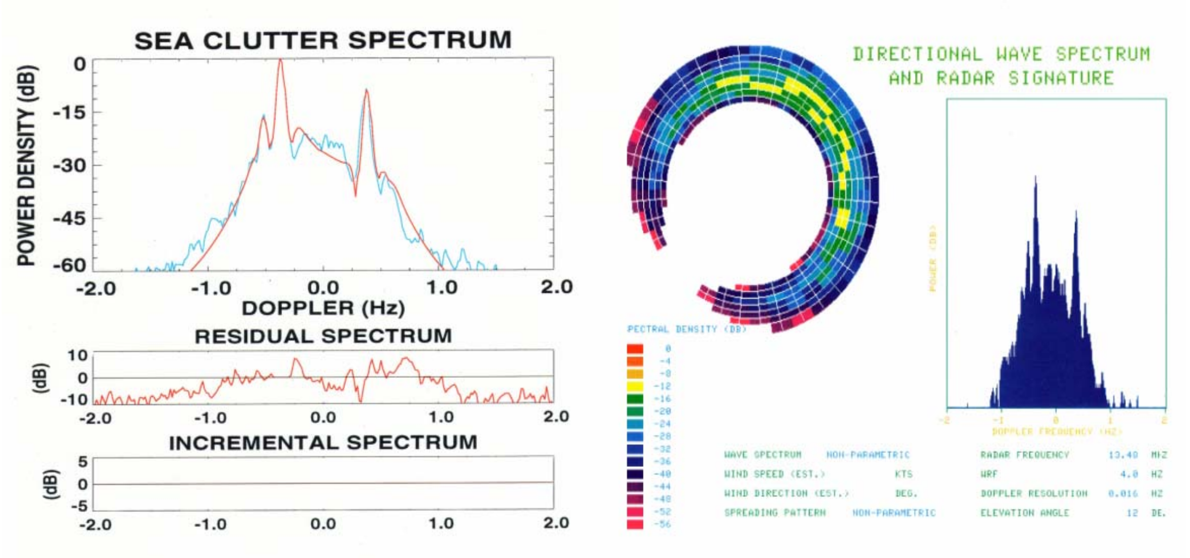

Figure 7: (a) Best-fit 7-parameter sea clutter Doppler spectrum model matched to measured data (b) measured Doppler spectrum (right) with the inferred directional wave spectrum (centre).

3.1.5 Bistatic RCS and stereoscopic observations

Inspection of figures 4 and 8 confirms that target classification information is distributed across the full bistatic domain [14]. The opportunity to collect bistatic RCS only arises when spatially-separated transmit and receive facilities view the same region, which might seem to be a rare (and extravagant) arrangement. One consideration which makes it worthy of serious study is the prospect of exploiting transmitters of opportunity to collect data which supplements that provided by dedicated radar facilities [15].

3.2 Classification based on target RCS ratios

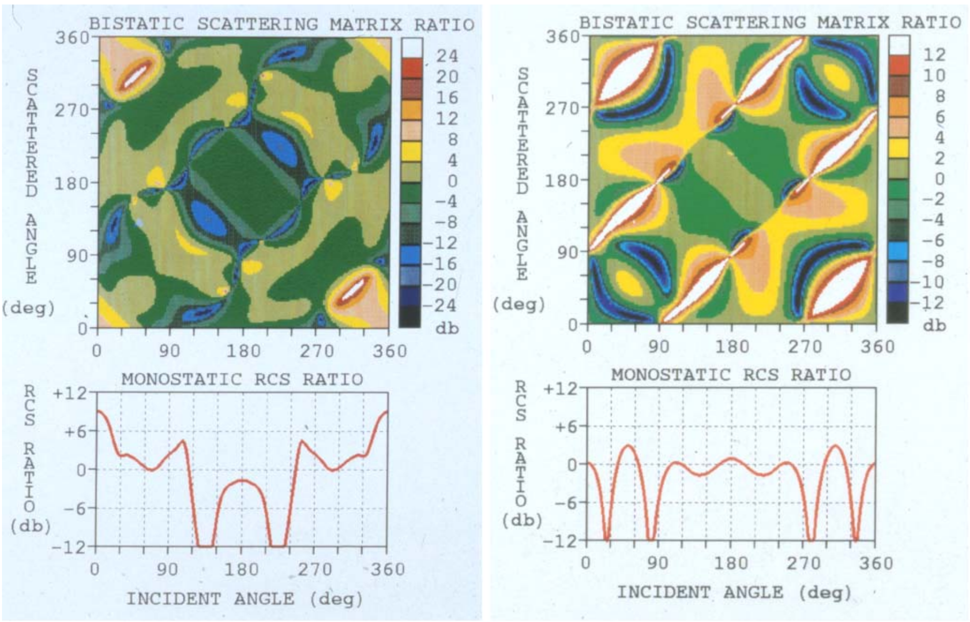

Figure 8: (a) Magnitude of the ratio of the HH bistatic RCS of fighter aircraft #1 at two frequencies, and (b) for fighter aircraft #2 at the same two frequencies.

Given the difficulty and often impossibility of calibrating the target echo by means of sea clutter or other reference scatters in the vicinity of the target, classification based on absolute RCS must often be abandoned in favour of techniques based on target RCS ratios. Figure 8 shows how the ratios of the bistatic RCS (HH component) at two frequencies differ between two fighter aircraft. This kind of information can be used for target discrimination / classification when the propagation losses cannot be inferred. By selecting two frequencies which yield very different RCS values for target #1, say, and such that the differential propagation loss is not likely to exceed some threshold $T < \left| RCS(f_1) - RCS(f_2) \right|$ a simple binary classification rule can be formulated. Repeated application of the rule, with a suitable set of frequencies, provides, in principle, a multi-class recognition capability [16].

3.3 Classification based on target RCS distributions

As noted in Section 2.3, ionospheric propagation subjects the signal to a host of phenomena which modulate the signal's amplitude, phase, frequency, polarisation state, harmonic content, and so on. It is therefore desirable, if not essential, when utilising echo amplitude information, to employ statistics which are commensurate with the required discrimination. The design of suitable statistics is nontrivial, keeping in mind the operational constraints, but modelling and experiment have established some guidelines [17].

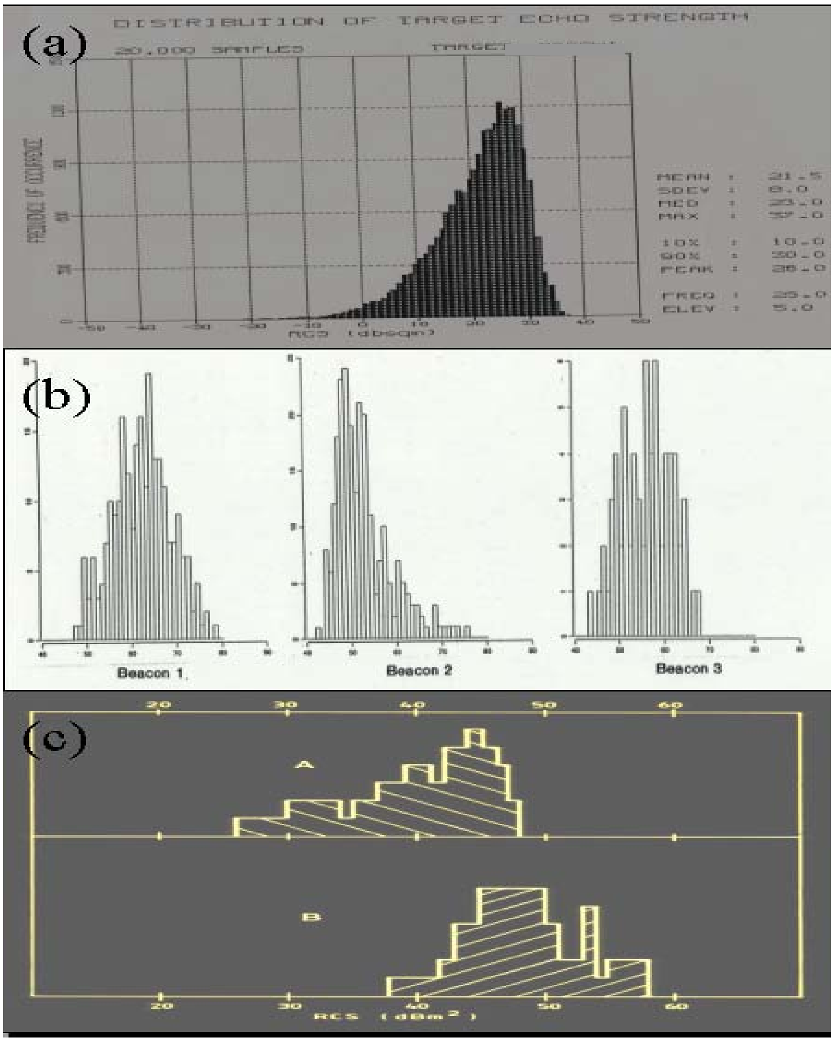

Figure 9: (a) Predicted and measured histograms of inferred scalar RCS.

Figure 9a shows the predicted distribution of inferred RCS for an aircraft target at a prescribed altitude, taking into account the ground reflections and the major ionospheric processes, and employing correct bistatic RCS values, averaging with respect to a designated probability distribution for the generalised Faraday rotation. Figure 9b presents histograms of skywave radar measurements of three specially constructed targets, with different scattering matrices, designed to test the adopted models for the ionospheric propagation phenomena. Finally, Figure 9c compares the measured distributions of inferred RCS from two different ships – one merchant, one naval.

3.4 Classification based on target modulation signatures

At HF the radar wavelength is comparable with the target dimension, so it is not meaningful to attempt to isolate the contributions to the scattered field from individual parts of the target, some of which may be moving relative to others. Instead, for non-relativistic targets, the scattering may be approximated quite accurately by the temporal evolution of the field scattered from a target whose spatial configuration may be taken as instantaneously at rest in the coordinate frame of its centre of mass (the quasi-stationary approximation [18]). The frequency spectrum ('Doppler') of the field scattered from such a time dependent target can then be written

$$\vec{E}_{scat}(\omega) = \int \vec{E}_{scat}(t)\, e^{-i\omega t} dt = \int \tilde{S}(t) \vec{E}_{inc}(t)\, e^{-i\omega t} dt$$

so, for a time-harmonic incident field, $\vec{E}_{inc}(t) = \vec{E}_0\, e^{i\omega_0 t}$,

$$\vec{E}_{scat}(\omega) = \int \tilde{S}(t)\, \vec{E}_0\, e^{-i(\omega-\omega_0)t} dt$$

In the case of periodic modulation of the target geometry (or electrical properties), with some period T and corresponding fundamental frequency $\Omega \equiv T^{-1}$,

$$\tilde{S}(t) = \sum_{k=-\infty}^{\infty} \tilde{S}_k\, e^{ik\Omega t}$$

Substituting,

$$\vec{E}_{scat}(\omega) = \int \sum_{k=-\infty}^{\infty} S_k \vec{E}_0\, e^{-i(\omega-\omega_0-\Omega)} dt$$

$$= \sum_{k=-\infty}^{\infty} \tilde{S}_k \vec{E}_0 \int e^{-i(\omega-\omega_0-k\Omega)} dt$$

$$= \sum_{k=-\infty}^{\infty} \tilde{S}_k \vec{E}_0\, \delta(\omega-\omega_0-k\Omega)$$

so, after demodulation, the signature takes the form of a line spectrum at harmonics of the fundamental frequency of modulation Ω [19] (shifted by the Doppler associated with the forward movement of the helicopter). In the case of a helicopter rotor or aircraft propeller,

$$\Omega = (\mathit{shaft\ rate}) \times (\mathit{number\ of\ blades})$$

so the line spacing alone provides a characteristic signature, unique in almost all cases, and independent of the line intensities or the transmitting and receiving antenna polarisations. Figure 10 shows the modulation signatures of two helicopters measured in 1983 with the Jindalee radar. The discrimination power of these signatures is obvious, so helicopter classification / recognition is a viable mission for HF skywave radar. In contrast, Figure 11(a), which shows a Lockheed P-3C Orion, one of the most common propeller-driven military aircraft, with its 4.11 m diameter 4-bladed propeller. Figure 11(b) is the theoretical spectrum computed for a comparable propeller-driven aircraft. The strongest modulation sideband is almost 50 dB below the 'DC' term (often erroneously referred to as the 'skin' echo), so only if the target SNR were to exceed ~ 60 dB would there be any prospect of recognition.

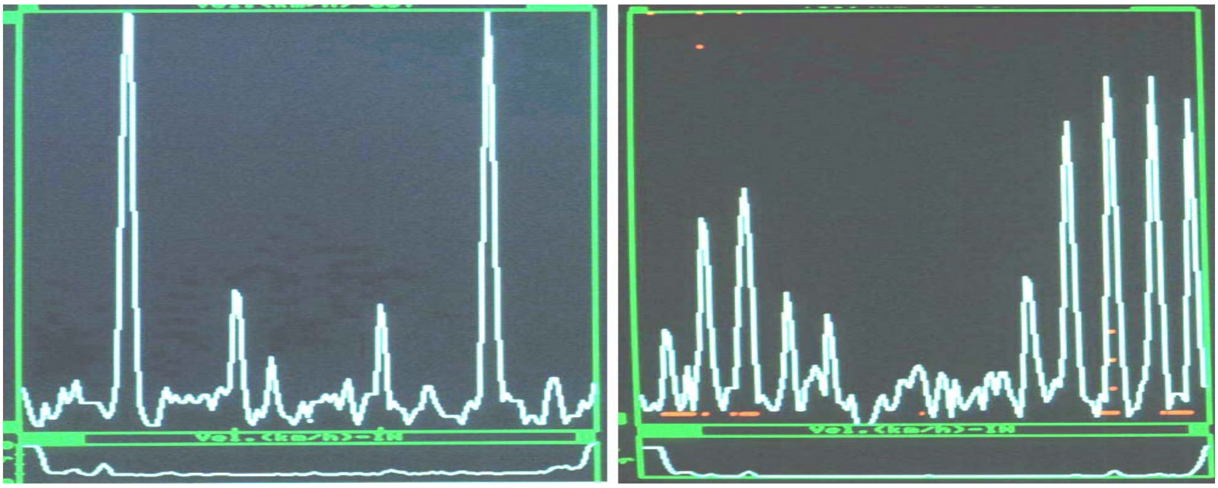

Figure 10: Measured Doppler signatures of two helicopters (Jindalee, 1983)

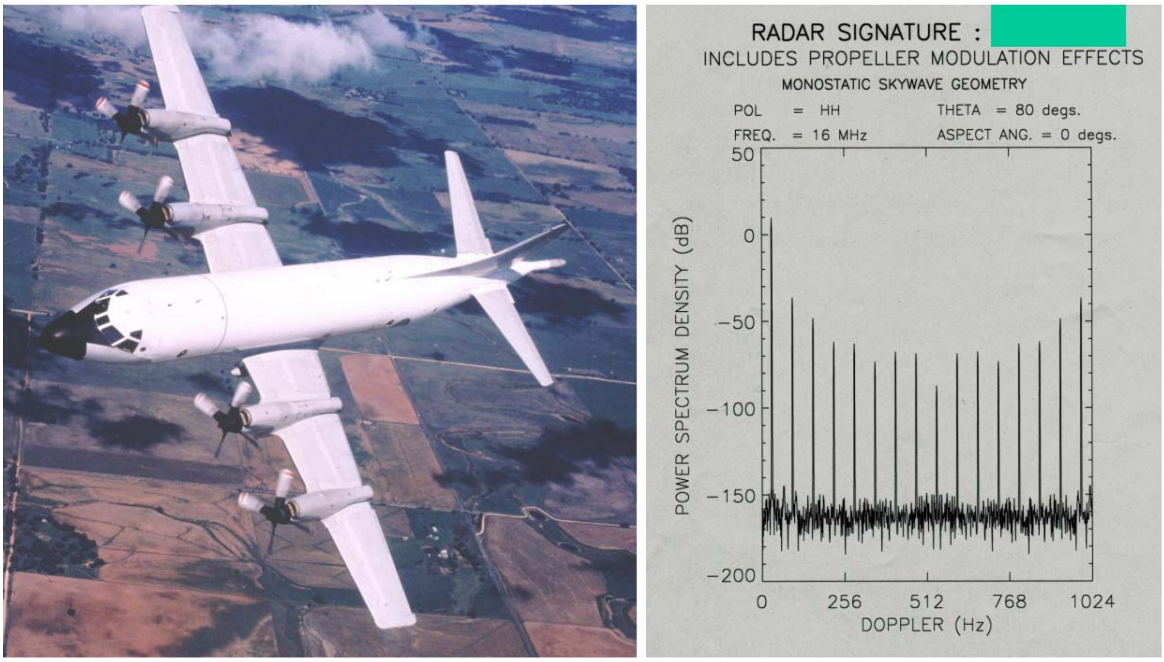

Figure 11: (a) Lockheed P-3C LRMP aircraft showing its 4.11 m diameter propellers, and (b) the computed line spectrum signature for a different propeller-driven aircraft

3.5 Classification based on the target polarisation scattering matrix

The methods discussed so far rely on estimates of target RCS derived from scaled projections of unitary transformations of the scattering matrix, or on statistical distributions or ratios of such projections. Clearly it would be much more informative of the target if the entire complex scattering matrix could be determined [20], rather than samples of the squared modulus of some unknown linear combinations of its elements.

This would seem to be an impossibility – the signal leaving the transmitter undergoes a 'random' polarisation transformation en route to the target, samples the scattering matrix, the undergoes another random transformation en route back to the receiver, so how could the consequences of these unknown transformations be removed ? Figure 12 shows this hypothetical polarisation transformation sequence and the resultant mismatch at the receiving antenna. Surprisingly, as reported in [21], under certain constraints the scattering matrix might be determinable, though development of a practical classification scheme based on this is in its infancy.

Assuming for the moment that the scattering matrix were observable, the question of how to perform classification / recognition arises. One approach, which has been explored in some depth [22], is to compute the characteristic eigenvectors associated with the optimal polarisation states, that is, the states which correspond to solutions of a family of extremal problems, as formulated by Kennaugh (see Huynen [23]) and others in the context of microwave polarimetry. These solutions have varying sensitivities to illumination geometry, radar frequency and so on, but numerical experiments using computed scattering matrices for two fighter aircraft found well-behaved differences which could be used in a target classification scheme based on the geodesic metric on the Poincare sphere. An example from this study is presented in Figure 13, which shows elevation and plan views of the Poincare sphere with the loci of the characteristic eigenvectors traced out as the target azimuth is varied.

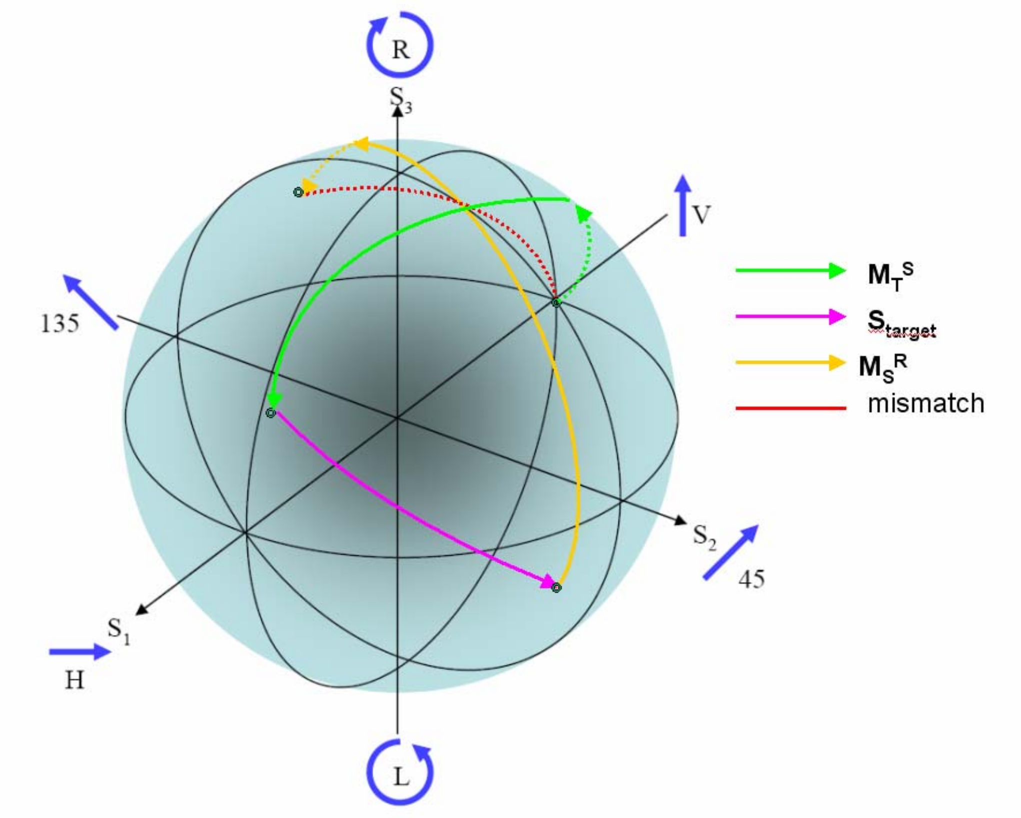

Figure 12: The sequence of polarisation transformations in HF skywave radar

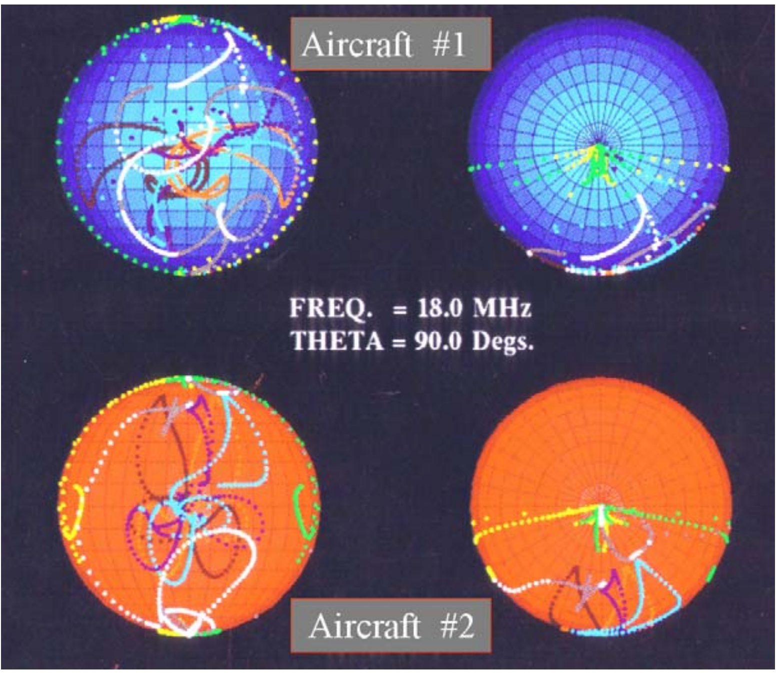

Figure 13: Trajectories of optimum polarisation states under target aspect changes

Of course, in the case of HF surface wave radar, this technique is of no use as the propagation of surface waves over seawater is overwhelmingly confined to vertically polarised fields.

3.6 Classification based on other scattering mechanisms

3.6.1 Nonlinear scattering

Most targets of interest can be modelled as linear media, so the scattering matrix representation is valid. On occasion, though, targets can manifest nonlinear electromagnetic properties – the so called 'rusty bolt' phenomenon associated with ships is an example. Under these conditions, the conventional notion of RCS must be generalised, as described in [24].

3.6.2 Distributed scattering

Multiple and diffuse scattering processes are potentially active in the resolution cell, so energy arriving at the receiver via these mechanisms will be distributed across time delay, azimuth and elevation angle, and Doppler. Detailed modelling (see eg. [15]) has shown that, under some circumstances, these contributions can contribute to target classification for both skywave and surface wave radars.

3.7 Classification based on target kinematics

It is a consequence of aerodynamics and fluid dynamics that aircraft and ships achieve their optimum performance in terms of economy, or speed, or manoeuverability, over a relatively narrow range of kinematic parameters – speed, altitude, climb rate, velocity relative to prevailing seas, and so on. While one cannot presume that classification / recognition based on this kind of target information will be robust under all circumstances, it is surprisingly effective and adds to the dimensionality of the classification space, thereby enhancing classifier performance.

3.8 Classification based on target IFF transponders

So far the discussion has focussed on non-cooperative target classification and recognition. Yet there are situations where IFF is a useful facility, even at over-the-horizon distances. Various beacons able to serve in this capacity have been developed and tested on ships, aircraft and, of course, on land. The example shown in Figure 14 was measured in 1977; the IFF was mounted on a small (30 m) patrol boat.

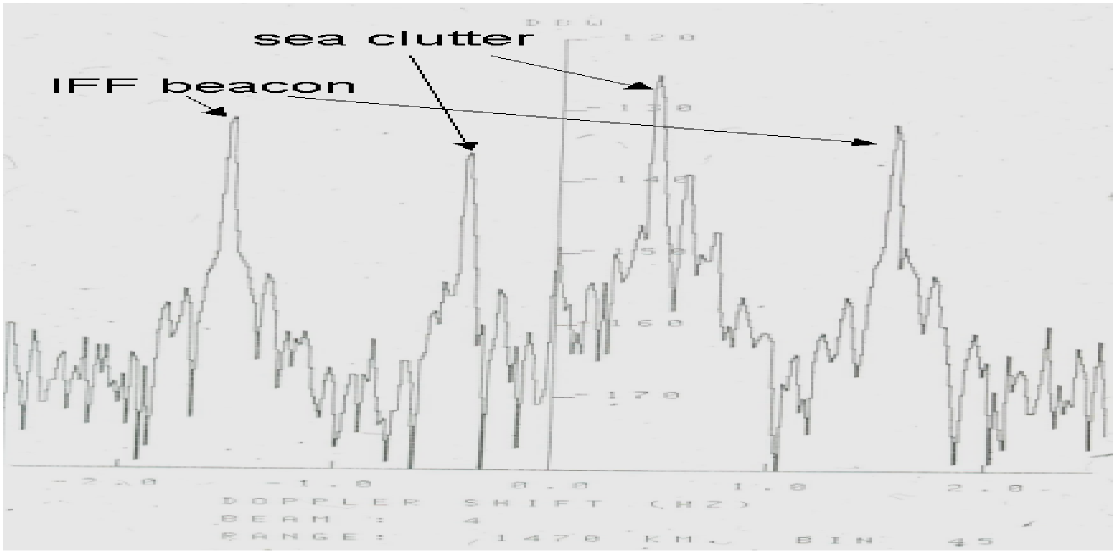

Figure 14: Cooperative target recognition – IFF modulation signature at a range of 1470 km

4.0 CONCLUSIONS

In spite of some daunting challenges posed by the propagation mechanisms involved and the vagaries of the environment, a modest target classification capability is slowly emerging as a potentially viable option for both skywave and surface wave radars. Given a deep understanding of the physics involved, and access to sophisticated computer modelling codes, it would seem possible, in principle, to exploit the technical features of advanced HF radar systems to achieve a limited but still operationally significant target classification capability.

The prospects for the future emergence of a universal target classification and recognition system are not nearly so bright. The fundamental information limits imposed by under-sampling, and the ill-posedness of the corresponding inverse problems, make it unlikely that HF radar will deliver all the classification and recognition capabilities desired by the operational community, while identification in the intimate sense defined in this paper is not likely to emerge except as an outcome of data fusion with other sources.

While it is gratifying that some success has been achieved with these approaches, it is an unfortunate reality that almost all existing HF radar designs have largely ignored the issues related to target classification, and hence fail to incorporate some features which could enhance their ability to extract target information leading to reliable classification, recognition and identification.

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