MEASURING POLARISATION DYNAMICS OF THE GENERALISED HF SKYWAVE CHANNEL TRANSFER FUNCTION

Stuart ANDERSON and Yuri ABRAMOVICH
Surveillance Systems Division
Defence Science and Technology Organisation
PO Box 1500 Salisbury SA 5108, AUSTRALIA
E-mail stuart.anderson@dsto.defence.gov.au

Introduction

The use of adaptive processing schemes to counter skywave channel fluctuations which impact on amplitude and phase characteristics of communications and radar signals is widespread. In the case of communications signals, sophisticated equalisation schemes are available to reduce error rates by estimating and compensating for variations in the channel transfer function, whilst deconvolving the effects which lead to inter-symbol interference. Radar signals which propagate via the ionosphere, as in HF skywave 'over-the-horizon' radars (OTHR), are similarly affected by the time-varying properties of the signal path, compounded by the fact that two-way propagation is involved. Further, the outbound and inbound paths are generally not identical, as the radar configuration is seldom truly monostatic; in addition, radiowave propagation in the ionosphere is not strictly reciprocal. Despite these complications, some highly effective signal processing schemes have been developed to remove the effects of the dominant physical modulations imposed by the time-varying medium [1].

Notwithstanding the successful implementation of such ameliorative techniques and their integration with spatio-temporal processing techniques for rejecting external noise [2], the consideration of signal physics is incomplete without full regard to the fact that radiowave signals possess the physical attribute of polarisation, which, like phase and amplitude, undergoes transformation in the course of ionospheric propagation. Before we can claim to be exploiting the skywave channel effectively, we must be able to demonstrate that we are minimising the loss of information which arises as a consequence of polarisation effects.

In this paper we describe an experiment which is being conducted to measure the generalised ionospheric channel transfer function, focussing on the polarisation dynamics; knowledge of this function is necessary for the design of appropriate signal processing schemes, as well as being an essential factor in the design of radar antennas, configurations and waveforms.

Low-dimensional models for the skywave channel

The need for practical assessment of the quality of skywave links has arisen in numerous radar and communications applications, which has motivated a number of researchers to develop representations of the channel characteristics. Shepherd and Lomax [3] pioneered a simple model - the *channel scattering function* - which takes no account of angles of arrival or polarisation, projecting the signal onto the time delay – Doppler frequency plane as a power spectral density. This description cannot be used for effective signal enhancement but has been widely employed as a guide to propagation conditions, especially with regard to the presence of multimode and the extent of Doppler spread. For example, Figure 1 shows sample outputs from the CSF mode of the frequency management system developed for the Jindalee OTH radar by Earl and Ward [4]. Similar measurement systems have been reported by numerous authors and exploited for geophysical as well as operational purposes.

Another widely investigated class of channel characterisations is associated with monitoring signal direction-of-arrival (DOA), most commonly associated with radio-location.. Many large-scale processes in the ionosphere influence the DOA of skywave signals, and their dynamics can be studied in some detail via analysis of the temporal and spectral properties of measured signal DOA. This component of the skywave channel transfer function is of special interest to OTH radar because the data emerge naturally from automatic target tracking algorithms.

Corresponding experimental studies of the way in which skywave channels transform the polarisation state of the incident signal are relatively rare, though of course the theoretical aspects of propagation in model ionospheres have been thoroughly investigated. Anderson [5] described experiments which measured a range of polarisation phenomena :

(i) the frequency dependence of the polarisation at a distant location. This is related to the concept of polarisation bandwidth, which is defined as the variation in frequency required to rotate the axis of polarisation by 90 degrees over a one-way path
(ii) the frequency dependence of the received polarisation state of an echo originating from a point in the radar footprint. This is the two-way analogue of (i) above
(iii) the spatial distribution of polarisation state over the illuminated radar footprint
(iv) the spatial distribution of polarisation across the radar receiving array from a given point scatterer in the radar footprint
(v) the temporal characteristics of all the above

though the receiving array used was only one-dimensional. Bertel and his co-workers at Universite de Rennes I have described various measurements carried out using a linear array of dual-polarisation elements to decompose the skywave signal into power spectra defined over time delay – Doppler – single angle-of arrival – polarisation space (see eg. [6]).

Definition of a comprehensive channel transfer function

In the ionosphere, the characteristic time scales Tj of the dynamical processes of interest, $\{P_j\}$, satisfy the inequality

$$Tj \,.\, \nu \gg 1$$

for frequencies ν in the HF band. Accordingly, it is appropriate to describe the signal transformation properties of the skywave link between two stations in terms of its impulse response $\mathbf{h}(\tau;t)$ or, equivalently the Laplace transform of $\mathbf{h}(\tau;t)$, $\mathbf{H}(\omega;t)$, usually referred to as the system transfer function. The functional dependence on t denotes the slow variations associated with $\{P_j\}$.

The subject of our attention is thus the operator which relates the observables of the transmitted signal to those of the field incident on the receiving system after skywave propagation. This radiowave field has a number of attributes, of which the following are of concern here :

(i) time delay – the signal will take a finite time to transit the link, and may arrive distributed over a significant time interval due to multimode propagation, frequency dispersion, high-angle rays and scattering from inhomogeneities
(ii) frequency – this may be spread and shifted slightly from the transmitted frequency because of ionospheric dynamics over a wide range of spatial and temporal scales
(iii) amplitude – this may vary as a consequence of fluctuating absorption loss, focussing and nonlinear effects
(iv) angles of arrival – a variety of deviations caused by ionospheric structure and magnetoionic splitting will shift and spread the signal in azimuth and elevation
(v) wavefront distortion –irregularities in the wavefront arise due to small scale plasma structures; some of these are not sensibly described in terms of a plane wave expansion
(vi) polarisation – in general the received signal will have a different polarisation after propagation through the magnetoionic plasma medium

In addition, we have noted earlier that these properties vary with time, and it is evident that they vary with receiver location for a given transmitter, sometimes over surprisingly short distances. Hence, for some practical applications, we need to add to the above list some additional characteristics :

(vii) spatial variability of all the above, parameterised, for example by their along-path and cross-path derivatives
(viii) temporal variability of all the above, parameterised, for example, by their temporal correlation times or features from their frequency spectra

Thus a reasonably comprehensive channel transfer function should be defined on the domain given by the direct sum of the domains of all these variables, as discussed in [7].

Requirements for measuring the skywave channel transfer function

The multi-dimensional nature of the channel transfer function places heavy demands on the measuring apparatus :

(i) for directionality and angular domain decomposability, an array is needed, and this should be two- or three-dimensional in order to estimate azimuth and elevation independently

(ii) resolution of modes whose angular separation is of the order of 10^{-2} radians is of practical concern, which in practice necessitates an antenna tens of wavelengths in length, given the mode separability in other dimensions

(iii) antenna structures at HF are generally large, consistent with the wavelengths which fall in the range 10 – 50 m, so cost-effective design and construction is a priority

(iv) polarisation structure is observed to vary within this scale, so dual- or triple-polarisation elements are essential

(v) the polarisation response of the antenna must be accurately known, noting that it depends on signal angle-of-arrival

(vi) complex mutual coupling can arise so sophisticated array calibration must be maintained if high resolution, high dynamic range measurements are to be obtained

(vii) the receiving system must be highly linear and of wide dynamic range to function in the hostile HF environment whilst achieving a signal-to-noise ratio commensurate with the measurement accuracy required

(viii) phase stability must be sufficient to ensure that the measured channel transfer function spectral bandwidth is not compromised

The St Kilda CTF measurement facility

Over the past 18 months, we have constructed a dedicated facility at St Kilda, near Adelaide, Australia, to measure the multi-dimensional channel transfer function whilst meeting the design criteria listed above. The main array consists of two linear arms, each with 16 equi-spaced dual-polarised antenna elements, designed to achieve at least 35 dB isolation between polarisations. The materials which form the array simultaneously perform structural and radiative functions to minimise cost. In its initial design, the orthogonal arms are 225 and 440 metres in length and aligned roughly along and transverse to the geomagnetic field. Each antenna element is fitted with two pre-amplifiers (one for each polarisation) and connected to a multi-channel digital HF receiving system with an output filter bandwidth of 40 kHz. The receiver was designed for the purpose, and built by the Research Institute for Long-range Radio Communication (NIIDAR) in Moscow, to exacting specifications. While standard operation with this receiver limits time delay resolution to 25μs, linear sweep deramping at the first local oscillator supports signal bandwidths exceeding 1 MHz.

Gain and phase calibration of the receiving chain is achieved by a novel technique involving special test signals, while the antenna polarisation response has been mapped by means of computer models which have been validated for a range of geometries by test transmissions from portable dual-polarisation sources. The data undergoes real-time processing for display, as well as being recorded continuously on a high capacity disk for off-line analysis.

At present we have 32 receiver channels in operation, with another 64 available. While a fully populated array is planned, the present arrangement can be optimised by allocating the receivers to minimally-redundant subsets, which we have demonstrated can achieve superior noise rejection via space-time adaptive processing [2]. Two smaller secondary antenna arrays are located behind and to one side of the primary array, and we plan to extend and exploit these to determine the spatial variability of the transfer function.

The primary transmitter for this experiment is part of the Jindalee OTH radar facility at Harts Range in central Australia, located some 1363 km from the receiving array (Figure 2). This provides a typical one-hop path, while a second, collinear, low power transmitter at Darwin, 2584 km from the receiver, can be used to generate one-hop or two-hop signals by appropriate choice of frequency. These transmitters can radiate a wide selection of waveforms, so that the desired space-time and Doppler resolutions can be achieved.

Conclusion

The signal transformation properties of the HF skywave channel are extremely complex, and have hitherto defied comprehensive measurement. We have developed a facility specifically to address this issue and initial testing of its performance has been highly encouraging. At the time of writing, the facility has not recorded the full channel transfer function, though it has been used in conjunction with a nearby transmitter to detect air and surface targets and to study the polarisation distributions associated with sea and land clutter, and of HF signals from broadcast stations, both local and distant. By May 2000 the full range of measurements will have been demonstrated and results from these trials will be presented at ISAP 2000.

References

[1] Anderson, S.J., and Abramovich, Y.I., ‘A unified approach to detection, classification and correction of ionospheric distortion in HF skywave radar systems’, Radio Science, Vol.33, No.4, pp.1055–1067, July-August 1998

[2] Abramovich, Y.I., Anderson, S.J., Gorokhov, A.Y., and Spencer, N.K., ‘Stochastic constraints method in nonstationary hot clutter cancellation, Part I : Fundamentals and supervised training applications’, IEEE Transactions on Aerospace and Electronic Systems, Vol. 34, No. 4, pp. 1271-1292, October 1998

[3] Shepherd, R.A., and Lomax, J.B., ‘Frequency spread in ionospheric radio propagation’, IEEE Trans., Communications Technology, Vol. COM-15, No.2, pp. 268-275, April 1967

[4] Earl, G.F., and Ward, B.D., ‘Frequency management support for remote sea-state sensing using the Jindalee skywave radar’, IEEE Journal Ocean Eng., Vol.OE-11, pp.164-173, 1986

[5] Anderson, S.J., `Ionospheric Faraday Rotation Signatures in the Space-Time-Frequency Domain', Proc. IEE International HF Radio Conference, Edinburgh, Scotland, pp. 167 - 172, July 1991

[6] Edjhou, A., Bertel, L., and Massot, V., ‘Identification des modes et trajets de propagation sur les liaisons HF a l’aide d’un goniopolarimetre’, Proc. 53rd AGARD Symposium on Multiple mechanism propagation paths, Rotterdam, 1993

[7]Anderson, S.J.,`The Challenge of Signal Processing for HF Over-the-Horizon Radar’, Proc. Workshop on Signal Processing and Applications, WOSPA'93, QUT, Australia, December 1993

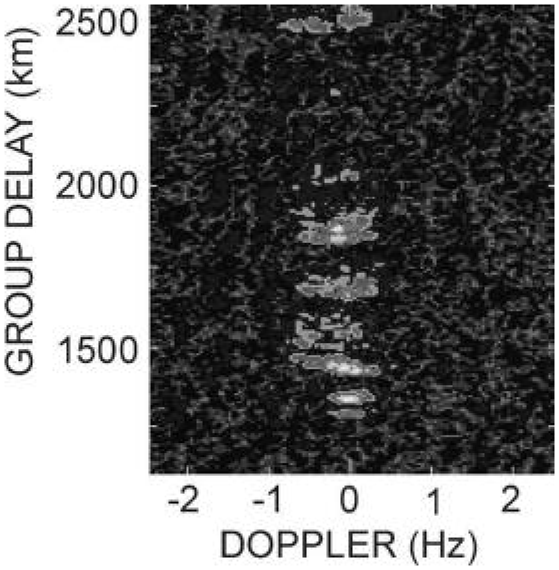

Figure 1 Jindalee channel scattering function

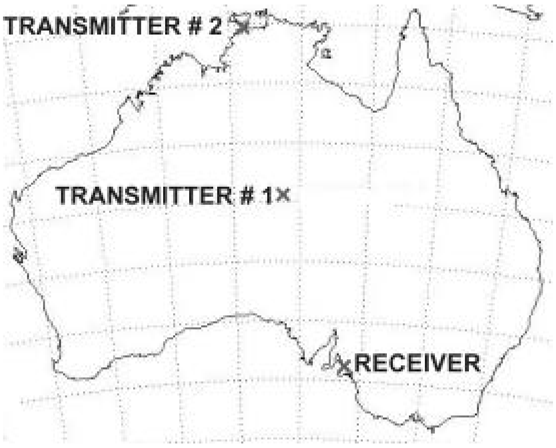

Figure 2 Map showing transmit and receive locations.