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Multiple scattering of HF radar signals in stochastic media: Applications to surveillance and remote sensing

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Abstract

Radar observations in realistic environments are inevitably complicated by stochastic phenomena involving the target, the propagation medium and the radar system itself. Often multiple scattering is inextricably linked to the stochastic behaviour. We show, in the context of HF radar, how multiple scattering phenomena impact on the radar observables and illustrate the exploitation of multiple scattering signatures for propagation diagnosis and for optimisation of siting and frequency selection.

Keywords: Radiowave propagation; Ionosphere; Ocean waves; Remote sensing

1. Introduction

Radar measurement of discrete targets in free space is generally a deterministic boundary value problem, which can be solved by a variety of established techniques. When the target manifests some random structure, or executes motion with a random component, the formulation of the radar measurement model must accommodate this behaviour. And when the propagation medium is spatially or temporally varying in a stochastic sense, this additional source of non-deterministic effects imposes its own signature on the radar observations.

Many of these random effects are themselves of interest, either because they embody additional target-related information, or because they are directly related to prevailing geophysical conditions. It is often the case that much of this information is associated with low-order multiple scattering processes, corresponding to the interaction of the radiowave with the propagation medium, the interaction of the target with its environment and the selectivity of scattering mechanisms. Thus, the extraction of target and environmental parameters generally involves the inversion of equations, which are stochastic and non-linear. In order to solve such equations, it is helpful to establish or confirm by experiment the structure of the theoretical scattering kernels, so that efficient approximations can be employed and their domains of validity confirmed. Here, we illustrate this procedure in the context of radars operating in the HF band, commonly known as ‘over-the-horizon’ radars.

2. Process models

Under fairly general conditions, a radar observation can be represented as a concatenation of operators that model the progression of the radar signal from its generation and radiation to the analysis of its echoes. We refer to this as a process model, which can be written formally as [1]

$$\tilde{s} = \tilde{P}\sum_{n_B=1}^{N}\tilde{R}\left[\prod_{j=1}^{n_B}\tilde{M}_{S(j)}^{S(j+1)}\tilde{S}_j\right]\tilde{M}_T^{S(1)}\tilde{T}w + \tilde{P}\sum_{l=1}^{N_J}\sum_{m_B=1}^{M}\tilde{R}\left[\prod_{k=1}^{m_B}\tilde{M}_{S(j)}^{S(j+1)}\tilde{S}_j\right]\tilde{M}_T^{S(1)}\tilde{n}_l + \tilde{m},$$

where the signal w is transmitted, propagates ($\tilde{M}$) and scatters ($\tilde{S}$) up to n_B times before being received and analysed. In addition, there may be N_J external noise sources present, each also subject to multiple scattering, together with internal noise $\tilde{m}$.

In order to associate multiple scattering signatures unambiguously with specific terms in the process model, such as outbound propagation, $\tilde{M}_T^S$, or scattering involving

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the target, $\tilde{S}$, some prior knowledge is required. This kind of information is provided by theoretical models supported and validated by suitably designed experiments, which establish the general characteristics of the individual physical phenomena to which the radar signal is subjected. There is a latent expectation that well-chosen radar parameters will enable the different effects to be separated. Here, we ignore the additive noise terms and focus on multiple scattering arising from (i) the propagation medium and (ii) the targets of the observation. The first objective in each case is to quantify the significance of the higher-order effects relative to the first-order terms. Once this is established, signature extraction and inversion techniques can be designed and optimised.

3. Multiple scattering processes at HF

Experiments with the Jindalee HF skywave radar [2] and the SECAR HF surface wave radar (HFSWR) [3] have demonstrated that the following multiple scattering phenomena are observable:

- weak scattering of forward propagating waves by small-scale plasma irregularities in the ionosphere,
- reflection processes involving multiple ocean wave trains on the rough sea surface; includes evanescent modes,
- diffuse surface scatter occurring in the course of multi-hop skywave propagation,
- phase modulation of HF surface waves propagating across the rough sea surface,
- electromagnetic interaction between low-flying targets and the sea surface,
- backscatter from field-aligned plasma structures generated by Kelvin–Helmholtz instabilities in the lower E-region.

In the following section, we examine two of these multiple scattering processes and establish their radar signatures.

4. Examples of multiple scattering phenomena in HF radar

4.1. Reflection of radiowaves from the turbulent ionosphere

The ionospheric plasma is host to many wave processes and instabilities, which result in spatial and temporal fluctuations in the electron density over a wide range of scales. These variations and irregularities modulate any transiting radiowaves, spatially in the sense of perturbing the wavefront from a quasi-planar form, and temporally in the sense of varying the phase path and hence imposing a time-dependent Doppler shift. The local fluctuations in electron density are generally weak, but their effects accumulate along the nominal propagation path. Accordingly, the interaction of the radiowave with the plasma may be represented as a sum over all orders of multiple scattering events.

In order to measure these effects and to devise inversion procedures, suitable metrics must be defined. First, we adopt as a measure of wavefront non-planarity a function of the Euclidean distance ζ between the vector of measured phases across the array and the nearest point on the *array manifold*, that is the space of responses to plane waves from any direction.

We define

$$p_k(\vec{\theta},t) = \frac{\left|s^H(\vec{\theta})x_k(t)\right|^2}{s^H(\vec{\theta})s(\vec{\theta})x_k^H(t)x_k(t)}$$

and set

$$\varsigma = \min_{\vec{\theta}\in S}\left\{1 - p_k(\vec{\theta},t)\right\}.$$

This metric is illustrated in Fig. 1.

In addition to measuring the departure from wavefront planarity by means of this metric, we can define the degree of irregularity of the departure in terms of the entropy of the set of eigenvalues of the covariance matrix of the residuals.

One prospective application of these signal attributes is the estimation of the signal propagation mode, that is the

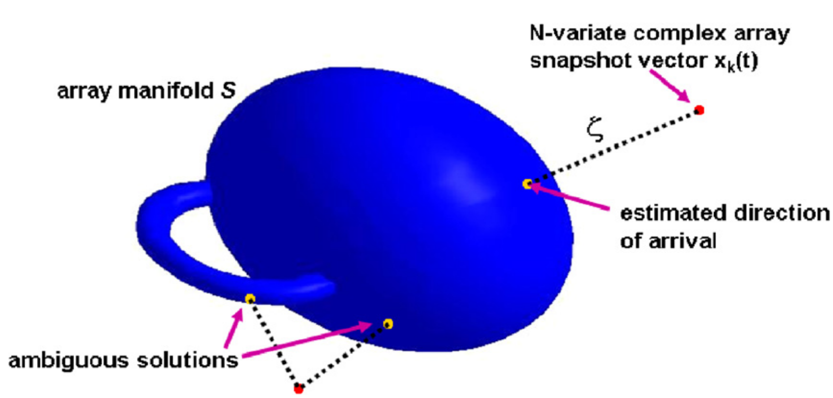

Fig. 1. The wavefront planarity metric, defined as the distance ς between the measured phase profile across the array and the nearest point on the array manifold.