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A Novel Technique for Measuring the Surface Wave Green's Function in the Open Sea, with Applications to HFSWR

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Abstract

We describe a technique for the accurate measurement of HF surface wave propagation over the sea, avoiding many of the factors that limit existing methods.

1 Introduction

While there are numerous theoretical studies devoted to modelling surface wave propagation, it is not easy to validate these experimentally with high absolute accuracy. The reason is that to launch and receive an HF radio wave requires a transmitting antenna and a receiving antenna, along with the associated electrical systems. Measurements with these structures, shore-based or shipborne, introduce many system parameters such as antenna directivity and gain, receiving channel losses and distortion, water-edge diffraction, and so on. Even in sophisticated HF radar systems, it is exceptionally difficult to obtain and maintain an accurate energy budget from end to end. What we would really like is a means of extracting the propagation characteristics between two canonical elements located in the open sea, separated by a meaningful distance, and somehow contrived to be independent of the system factors mentioned above.
In the following sections we describe a technique to achieve this.

2 Method

We employ two identical monopole antennas, mounted on floating buoys and deployed in the illuminated zone of an HFSWR, as pictured in Figure 1. At its base, each antenna has a switch that alternately opens and closes the electrical connection to the sea – the electrical 'ground'. As the impedance of the antenna changes according to the switching state, any single frequency signal scattered by the antenna has the rectangular wave modulation impressed upon it. Being a thin monopole, the gain is isotropic in azimuth. Now, suppose each monopole has a unique switching frequency, and further suppose that the system is sufficiently sensitive and the antennas sufficiently close that the reradiated signal from one propagates to the other where it receives a second modulation before reradiating and propagating to the shore-based receiver. A sensible choice of modulation frequencies avoids harmonically-related values, so different orders of multiple interactions can be separated and identified.

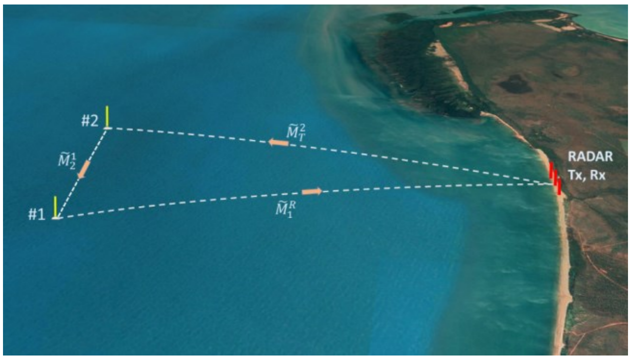

Figure 1. The dual antenna measurement geometry.

The procedure is conveniently expressed using the radar process model formalism of [1-3]. The general form of this representation is as follows:

$$s = \sum_{n_B=1}^{N} \tilde{R}\left[\prod_{j=1}^{n_B} \tilde{M}_{S(j)}^{S\lfloor j+1\rfloor}\tilde{S}(j)\right]\tilde{M}_T^{S(1)}\tilde{T}w + \sum_{l=1}^{N_J}\sum_{m_B=1}^{M} \tilde{R}\left[\prod_{k=1}^{n_B} \tilde{M}_{S(k)}^{S\lfloor k+1\rfloor}\tilde{S}(k)\right]\tilde{M}_N^{S(1)} n_l + m \quad (1)$$

where

w represents the selected waveform,
$\tilde{T}$ represents the transmitting complex, including amplifiers and antennas,
$\tilde{M}_T^{S(1)}$represents propagation from transmitter to the first scattering zone,
$\tilde{S}(j)$ represents all scattering processes in the j-th scattering zone,
$\tilde{M}_{S(j)}^{S\lfloor j+1\rfloor}$represents propagation from the jth scattering zone to the (j+1)-th zone,
n_B denotes the number of scattering zones that the signal visits on a specific route from the transmitter to the receiver,
N_J denotes the number of external noise sources or jammers,
$\tilde{M}_N^{S(1)}$represents propagation from the i-th noise source to its first scattering zone,
m_B denotes the number of scattering zones that the ith noise emission visits on a specific route from its source to the receiver,

N, M denote the maximum number of zones visited by signal and external noise, respectively,
$\tilde{R}$ represents the receiving complex, including antennas and receivers,
m represents internal noise,
s represents the signal delivered to the processing stage.

For our present purpose we can ignore jamming and the external and internal noise terms. The signal s arriving at the radar receiver consists of direct returns from the sea, along with those from individual antennas, together with those from signal paths that include paths from one antenna to the other. Explicitly we can write

$$s = s_c + s_1 + s_2 + s_{21} + s_{12} \qquad (2)$$

$$= \tilde{R}\begin{bmatrix} \tilde{S}_{\vec{r}}\widetilde{M}_T^{\vec{r}} + \widetilde{M}_1^R\tilde{S}_1\widetilde{M}_T^1 + \widetilde{M}_2^R\tilde{S}_2\widetilde{M}_T^2 \\ + \widetilde{M}_2^R\tilde{S}_2\widetilde{M}_1^2\tilde{S}_1\widetilde{M}_T^1 + \widetilde{M}_1^R\tilde{S}_1\widetilde{M}_2^1\tilde{S}_2\widetilde{M}_T^2 + \cdots \end{bmatrix}\tilde{T}w \qquad (3)$$

where the terms in the bracket on the right hand side correspond to echoes received at the HFSWR via (i) scattering from the sea surface, ie sea clutter, (ii) scattering from buoy antenna #1, (iii) scattering from buoy antenna #2, (iv) scattering from buoy antenna #2 after first scattering from buoy antenna #1, and (v) scattering from buoy antenna #1 after first scattering from buoy antenna #2.

In order to isolate the different contributions to s, we rely on the modulations impressed on the antennas by switching of their loads between open and closed states, noting that as the impedance of an antenna steps between the two states, its RCS is modulated in amplitude at the same frequency. From the Fourier Convolution Theorem, it follows that the spectrum impressed on a sinusoidal signal incident on the antenna will take the form of a family of harmonics spaced by the switching cycle frequency, ie, the Fourier transform of the periodic rectangular amplitude modulation and with an amplitude that decreases with the order of the harmonic. In particular, the first modulation sideband presents an effective RCS given by

$$\sigma_{mod} = \sigma_{closed} - 20\,log_{10}\left(\frac{1 - 10^{-R/20}}{\pi}\right)$$

where

$$R = \sigma_{short} - \sigma_{open}$$

For large values of R,

$$\sigma_{mod} \approx \sigma_{closed} - 20\,log_{10}\left(\frac{1}{\pi}\right) = \sigma_{closed} - 9.94$$

The RCS of a shorted monopole at resonance is ~ 23 dBsm, so it is a strong source of radar echoes.

The buoy structure can be very simple; Figure 2 shows two designs that were tested in the course of this investigation.

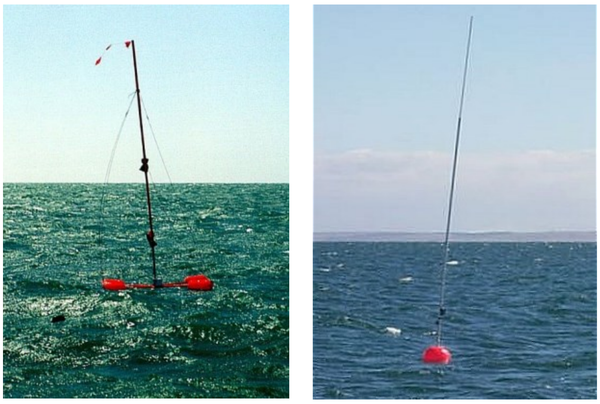

Figure 2. The buoys RCD1 and RCD2 deployed at sea.

The Doppler spectrum from a single range cell containing an antenna is shown in Figure 3; the zeroth and first order modulation sidebands are indicated.

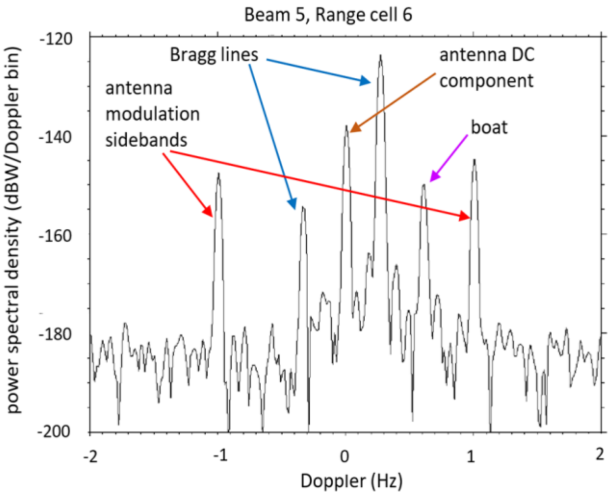

Figure 3. The Doppler spectrum from a range cell containing a single modulated antenna, showing the DC component and first sidebands of the antenna signature, a boat echo and the Bragg lines of the sea clutter

Now consider the following expression :

$$\Gamma = \frac{s_{21}s_{12}}{s_1 s_2}$$

Cancelling all the common factors, and noting that the propagation is reciprocal and that the modulations are commutative,

$$\Gamma = \frac{\tilde{R}\,(\varphi_1)\widetilde{M}_1^R\tilde{S}_1\widetilde{M}_2^1\tilde{S}_2\widetilde{M}_T^2\tilde{T}(\varphi_2)w.\tilde{R}\,(\varphi_1)\widetilde{M}_2^R\tilde{S}_2\widetilde{M}_1^2\tilde{S}_1\widetilde{M}_T^1\tilde{T}(\varphi_2)w}{\tilde{R}\,(\varphi_1)\widetilde{M}_1^R\tilde{S}_1\widetilde{M}_T^1\tilde{T}(\varphi_1)w.\tilde{R}\,(\varphi_2)\widetilde{M}_2^R\tilde{S}_2\widetilde{M}_T^2\tilde{T}(\varphi_2)w}$$

For monostatic radars, $\tilde{T}(\varphi_2) \cong \tilde{T}(\varphi_1)$ and $\tilde{R}\,(\varphi_2) \cong \tilde{R}\,(\varphi_1)$; moreover, as we shall be concerned with narrow-band , constant modulus waveforms, typically linear FMCW, we can cancel most of the other terms common to numerator and denominator. In addition, the thin monopoles are isotropic radiators in the azimuth plane.

Therefore, up to a constant phase factor,

$$\Gamma = \frac{\widetilde{M}_1^R \tilde{S}_1 \widetilde{M}_2^1 \tilde{S}_2 \widetilde{M}_T^2 . \widetilde{M}_2^R \tilde{S}_2 \widetilde{M}_1^2 \tilde{S}_1 \widetilde{M}_T^1}{\widetilde{M}_1^R \tilde{S}_1 \widetilde{M}_T^1 . \widetilde{M}_2^R \tilde{S}_2 \widetilde{M}_T^2}$$

$$= \tilde{S}_1 \widetilde{M}_2^1 \widetilde{M}_1^2 \tilde{S}_2$$

$$= \left[\tilde{S}_1 \widetilde{M}_2^1\right]^2$$

whence

$$\widetilde{M}_2^1 = \frac{1}{\tilde{S}_1} \sqrt{\frac{s_{12} s_{12}}{s_1 s_2}}$$

Thus all the system-related frequency-dependent factors cancel, and by forming the ratio of the received powers of the respective echoes and scaling by the known radar cross section of the monopole antenna, we obtain the propagation factor – the Green's function – for the field propagating between the two buoy antennas.

The experiment can be conducted at different antenna separations for the same antenna length, and repeated at different radar frequencies by adding the appropriate antenna extensions, so we can measure $\widetilde{M}_2^1(|\vec{r}_2 - \vec{r}_1|, f)$.

3 Conclusion

We have described a scheme whereby simple buoy-mounted antennas could be used in combination to measure the propagator of Green's function of HF surface waves propagating over the sea surface. The use of single modulated antennas has been common practice for many years but the concept proposed in this paper has been demonstrated only once, in preliminary trials. We can report that the double modulation signature was observed at a separation of ~ 2 km; a detailed exploration of the potential of the technique is yet to be carried out.

Acknowledgments

Mr Mark Tyler of DSTG designed the RCD2 buoy, once some short-comings of the electrical switch mountings on the RCD1 buoy were identified. The initial experiment was performed as part of the Iluka and SECAR trials carried out by the Australian Defence Science and Technology Group [4].

References

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