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INTRODUCTION TO HIGH-FREQUENCY RADAR: REALITY AND MYTH

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The concept of using High Frequency (HF) radio pulses to remotely probe the ocean surface has been around for decades. In this note, and the companion paper by Teague et al. (this issue), we strive to introduce this technique to a broad oceanographic audience. Teague et al. provide the historical context plus an outline of different system configurations, while we focus on the measurements of primary interest to coastal oceanographers, i.e., maps of near-surface currents, wave heights, and wind direction. Another goal of this note and, indeed, this entire issue is to present a realistic assessment of the state-of-the-art in HF radar techniques vis-á-vis coastal oceanography. When evaluating any new measurement technique, it is important to separate issues related to system design from fundamental limitations of the technique. The former are engineering short-comings, which are subject to continuous improvement. The latter are real limitations in the use of the particular geophysical signal in the presence of realistic noise. Most of the “myths” about HF radar measurments, in our view, stem from the confusion of these two issues.

One common misconception about HF radar stems from the word “radar” itself. A more descriptive name would be HF “radio,” as the HF portion of the electromagnetic spectrum is within portions of the spectrum. The HF band, with frequencies of ~3-30 Mhz and wavelengths of ~10-100 m, sits between the spectral bands used for television and (AM) radio transmissions. More commonly, the term radar is applied to instruments operating in the microwave portion of the spectrum, for which wavelengths are measured in milimeters or centimeters.

Throughout oceanography, many different instruments exploit many different portions of the electromagnetic spectrum. Figure 2 illustrates several of these remote sensing techniques used to extract information about the ocean surface. The figure is adapted from the review by Shearman (1981) and it contrasts space-borne systems, such as altimeters and scatterometers, which use microwave frequencies with shore-based systems, which use a range of frequencies depending on the application. (Not shown are aircraft-borne systems, which also operate in the microwave band.) The figure also illustrates the different types of transmission paths, including true line-of-sight paths, “sky-wave” paths, which reflect off the ionisphere, and “ground-wave” paths, which exploit coupling of the radiowaves with the conducting ocean water to achieve extended ranges. For HF radars, instruments that operate using sky-wave transmissions are often referred to

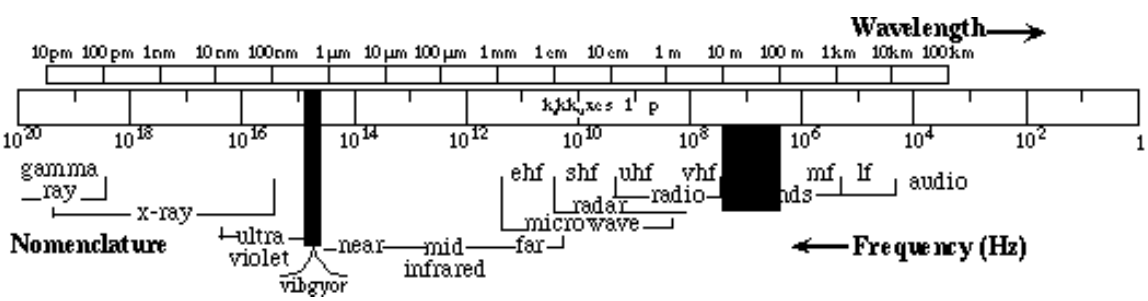

Fig. 1: Electromagnetic spectrum showing the HF band relative to other radio wave bands and the broader spectrum.

the radio bands. Figure 1 shows a broad range of the electromagnetic spectrum, including the nomenclature commonly applied to different as over-the-horizon (or OTH) radars (e.g., Georges, 1980), although HF ground-wave radars, which are the major focus of this issue, also achieve beyond-the-horizon ranges.

Reflection (or backscatter) of electromagnetic energy from the sea surface can be expected to produce an energy *spectrum* at the receiver, even if the energy source was single-frequency, because of

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the complicated shape and motion of the sea surface. Interpreting these spectral returns for various transmit frequencies is the key to extracting information about the ocean. Many instruments rely upon a resonant backscatter phenomenon known as "Bragg scattering," which results from coherent reflection of the transmitted energy by ocean surface waves whose wavelength is exactly one half as long as that of the transmitted radar waves. The inset in Fig. 2 attempts to illustrate this process by showing how energy reflected at one wave crest is precisely in phase with other energy that traveled 1/2 wavelength down and 1/2 wavelength back to reflect from the next wave crest. These coherent reflections result in a strong peak in the backscatter spectrum. Scatterometers exploit Bragg scattering from capillary waves (~1 cm) to obtain information about winds. HF radars, on the other hand, exploit Bragg scattering from surface gravity waves (~10 m) to obtain information about currents (and winds).

Measuring Currents

The history of HF backscatter measurements is better outlined by Teague et al. (this issue). We point to the work of Crombie (1955) as the first to identify strong sea echoes in the HF band with resonant Bragg scattering. Bragg waves in the HF band happen to be "short" surface gravity waves, which can be assumed to be traveling as deep-water waves, except in very shallow depths of a few meters or less. This is important because it allows information contained in the Doppler shift of Bragg peaks to be used to estimate ocean currents.

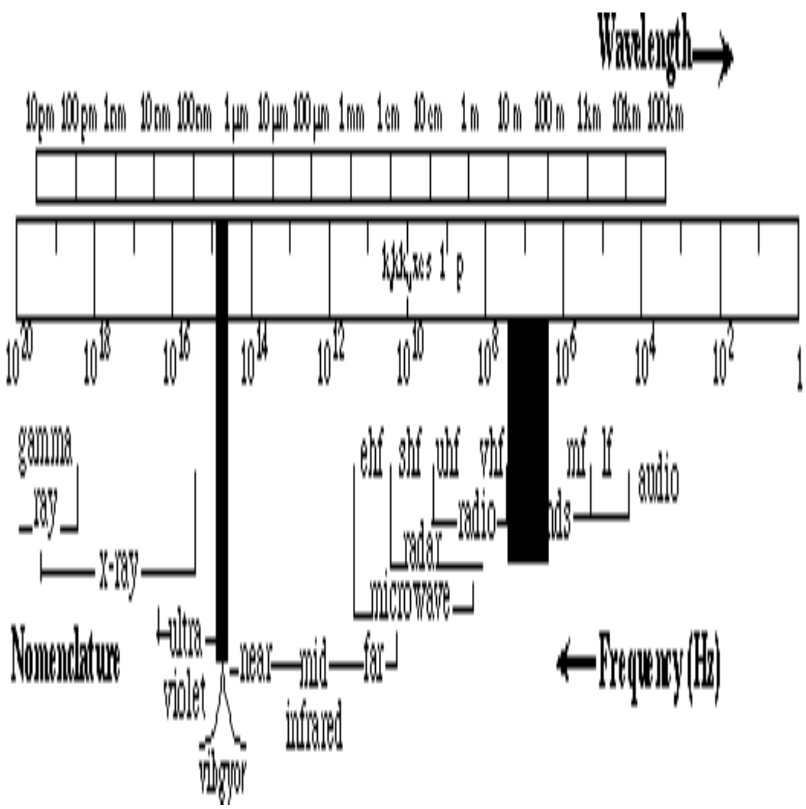

Fig. 2: Scematic representation of various remote sensing methods exploiting signals backsattered from the sea surface (after Shearman, 1981). The inset illustrates the resonant Bragg scattering process that occurs due to reflection from waves whose wavelength is 1/2 as long as that of the incident energy.

Figure 3 illustrates the Doppler technique for ocean current determination from HF radar back-scatter. It shows an actual spectrum from the Ocean Surface Current Radar (OSCR) system. The spectrum contains obvious Bragg peaks due to the presence of Bragg waves traveling toward and away from the receiver. The frequencies of these peaks are offset from that of the transmitted energy for two reasons: 1) the Bragg waves are moving with the deep-water phase speed given by $c = \mathrm{sqrt}(g\lambda/4\pi)$, where λ is the wavelength of the transmitted energy and g is the gravitational acceleration, and 2) the Bragg waves are moved by the underlying ocean current. Because the expected Doppler shift due to the Bragg waves is known, any additional Doppler shift is attributed to the current as shown in Fig. 3.

It is important to keep in mind the following points about HF radar-derived currents: 1) a single radar site is capable of detecting only the component of flow traveling toward or away from the site for a given look angle, 2) the effective depth of the measurement depends on the depth of influence of the Bragg waves and is quite shallow (~1 m), 3) stable estimates require scattering from hundreds of wave crests plus ensemble averaging of the spectral returns, which sets the space-time resolution of the instruments, 4) the precision is limited by the frequency resolution of the Doppler spectrum and is typically 2-5 cm s^{-1}, and 5) the accuracy is controlled by numerous factors, such as signal-to-noise ratios, pointing errors, and geometry.

Since a single radar station measures only the component of flow along a radial beam emanating from the site, "radial" currents from two or more sites should be combined to form vector surface current estimates. Figure 4 illustrates this principle using radial data from two radar sites. It also illustrates the "baseline problem" that occurs where both radar sites measure the same (or nearly the same) component of velocity, such as along the baseline between the sites or at great distances from both sites. Generally two radials must have an angle greater than 30 degrees and less than 150 degrees to resolve the current vector. This geometric sensitivity has been compared to the familiar geometric dilution of precision, or GDOP, in the Global Positioning System (Chapman and Graber, this issue). If currents are assumed to be constant over several radial bins, it is also possible to estimate velocities using a single radar site as was done by Bjorkstedt and Roughgarden (this issue), although the GDOP-related errors will be relatively large in this case.

The current measurement by HF radars is close to a “true” surface current measurement. Because radar pulses scatter off ocean waves, the derived currents represent an integral over a depth that is proportional to the radar wavelength. Stewart and Joy (1974) show this depth to be, approximately, d = $\lambda/8\pi$. Since wavelength depends on the radar frequency, it is feasible to use multi-frequency HF radars to estimate vertical shear in the top two meters of the ocean.

Present system and coverage capabilities of HF radars are quite impressive. Measurements can be made in range as short as 1 km and as long as 150 km from the shore at a resolution of about 1 to 3 km along a radial beam. Radio interference or high sea states can limit the actual range at times as well as the ground conditions in the vicinity of the receive antennas. Wet and moist sandy soils enhance the ground wave propagation, while dry and rocky grounds reduce signal strengths. Typical azimuthal resolutions are ~5°. Near the coast, this gives a measurement width of ~0.5 km; the width is ~10.0 km at range cells 100 km offshore (Fig. 4).

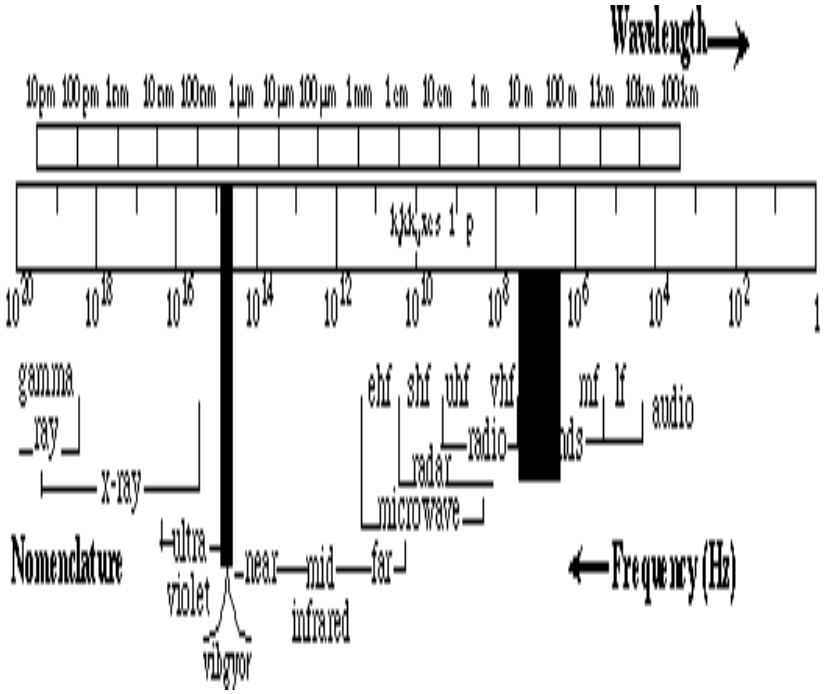

Fig. 3: Sample backscatter spectrum showing prominent Bragg peaks due to waves advancing toward and receding from the receiver. The smaller Dopper shift, Δf, is due to ocean currents that, in this example, are moving away from the receiver.

Measuring Winds and Waves

Although the focus of this special issue, and many of the experiments using ground-wave HF radar systems, is on surface currents, it is also possible to extract information about surface waves and winds from HF backscatter spectra. Wave techniques are discussed by Wyatt (this issue) and by Heron and Graber (this issue), while the method for extracting wind direction is discussed by Fernandez et al. (this issue). Very crudely, wave information is obtained by fitting a model of surface wave backscatter to the observed second-order portion of the spectrum (Fig. 3), which is due to reflections from waves at all frequencies and not just the resonant Bragg waves. Wind direction, on the other hand, is related to the *ratio* of the strength of the advancing and receeding Bragg peaks.

System Configurations

While the basic scattering principle is the same for all existing HF radars, distinct differences are found in the antenna configurations that transmit and receive the electromagnetic signals. The compact antenna system utilized by the **C**oastal **O**cean **D**ynamics **A**pplications **R**adar (CODAR) consists of crossed loops and a whip for receiving and a whip for transmitting radio pulses (Barrick et al., 1977). This antenna system is small and lends itself for deployment in highly populated and rocky coastal areas (e.g., cover photos). Radars of this type have been in use in Germany (Essen et al., 1981) and the Monterey Bay area (Paduan and Rosenfeld, 1996; Paduan and Cook, this issue). The omnidirectional characteristic of the cross-loop whip combination makes it possible to scan wider ocean sectors (e.g., Fig. 4), but this requires software-intensive, direction-finding techniques to determine angle for a given range cell (Lipa and Barrick, 1983; Barrick and Lipa, this issue).

In contrast, linear phased-array antennas consist of numerous (typically 8 to 16) elements separated by one ocean wave length and aligned normal to the principal receive direction (e.g., cover photos). These radars, such as the University of Miami’s OSCR system, are positioned at the seaward edge of a beach or cliff and require open space up to 100 m in length. The radio pulses are transmitted from a separate antenna array, which is a four-element Yagi array in the case of OSCR. Azimuthal resolution (direction) is obtained from well-established beam forming techniques. Other radars utilizing phased arrays are found in Germany (Gurgel 1997), Japan (Hisaki, 1996), Australia (Heron et al., 1985), France (Forget et al., 1981), Canada (Howell and Walsh, 1993) and United Kingdom (Wyatt, 1986; Prandle, 1991).

It is misleading to attempt to describe one HF radar configuration that will be optimum for all situations. Direction-finding (DF) and phased-array systems each have their advantages and disadvantages. For example, DF systems like CODAR were developed to be able to deploy the

Fig. 4: Sample radial current coverages for a phased-array radar (site 1) covering a 60° swath, and a direction-finding radar (site 2), which in pricinple can cover up to 360°. At overlapping ocean bins (e.g., dashed circle) a vector current estimate can be made, providing the angular

antennas on a small coastal outcrop, or even on a building, where a long secure stretch of beach or cliff may not be available. In addition, the angular coverage from DF techniques is much greater than the, at most, 60° sector that is available using phased-array pointing techniques.

At the same time, phased-array systems have important advantages over DF systems. Because the "beam" can be steered to a particular look direction, it is possible to collect backscatter spectra from a single patch of ocean (e.g., Fig. 3) and, thereby, infer surface wave characteristics from the second-order portions of the spectra. (DF systems, by contrast, collect spectra based on ocean backscatter over an entire range cell, which obscures the wave information.) The determination of wind direction is also more straight forward when using individual spectra from phased-array systems.

Conclusions

The purpose of this special issue on HF radars is to describe in simple terms how the radars work and demonstrate the usefulness and capabilities of such instrument technology for todays problems in ocean research. The following short feature articles present a wide variety of applications that are important in physical and biological oceanography in the coastal zone. Beyond their utility to the scientist, these measurements are also of great interest to both military and civilian coastal engineers, public safety officers, and planners who must maintain navigational seaways, mitigate ocean pollution, conduct search and rescue operations, and attempt to balance the health of coastal habitats, public access, and private property rights.

The advantages of HF radar as a non-invasive measurement tool that can acquire vector surface current, wave, and wind information should be obvious. However, while the concept of this technology is old, its acceptance in science, government, and industry has been slow. Today there is no reason not to proceed to develop better hardware and software components while, simultaneously, exploiting what existing systems can tell us about the ocean. By analogy, the Acoustic Doppler Current Meter (ADCP) was, a few years ago, considered experimental and mysterious by many in the oceanographic community, while now its use is common. We are confident that the use of HF radars will also become commonplace, and that, as a result, a new level of understanding of the coastal ocean will be possible.

Acknowledgments

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