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30 Years of CMTC and CODAR

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Abstract-**The year 1978 saw the first of these CMTC meetings, at Newark, DE. At that initial symposium, CODAR was introduced to the current measurement community. The word CODAR had been coined by the author at NOAA two years earlier, to describe a novel HF radar technique that now routinely maps surface currents from hundreds of coastal sites in real time. This presentation describes the CODAR concept and its evolution over the past 30 years.**

HF radar investigations by this author began in 1967 with large phased array antennas spanning hundreds of meters at the coast. The original operations were done to evaluate its surveillance potential against military targets, including ships. Cost-effectiveness limitations mitigated against the HF radars for military targets. It became immediately obvious, however, that the very strong sea echo could be used to measure currents and monitor sea state.

When I joined NOAA in 1972 in order to develop this technology for real-time environmental current mapping, our management and I recognized a major drawback that had to be overcome: the large size and resulting costs of the conventional phased array antennas needed at HF. We solved this by adapting for radar -- for the first time -- direction-finding (DF) rather than beam forming to measure bearing to the target cell. This allowed highly compact, low-cost portable antennas to replace the impractical phased arrays. We reported the very first current maps from HF radar in a 1977 Science paper done with our NOAA compact-antenna CODAR.

Over the next 30 years -- both within NOAA and after the inventors left in 1983 to form CODAR Ocean Sensors, Ltd. and commercialize the product -- hundreds of comparison studies were done by us and others. These led to a robust technology and varied product line suited for different customers' applications, from great range (200 km) to high resolution suitable for harbors (200 m) and even rivers (5 m). More than 250 SeaSondes have been sold; most operate in real time. This number constitutes 90% of all HF radars produced by everyone worldwide.

I. HFSWR BEFORE CODAR

HF surface-wave radar (HFSWR) has five identifying characteristics: (i) It is a very old technology; (ii) Very few HF radars exist in the world (less than 350), compared with perhaps a billion microwave radars; (iii) It has the advantage that it can see beyond the horizon above the sea when vertical polarization is used; (iv) Frequencies used are 1000 times lower than the much more common microwave radars; (v) It has not proven cost effective for hard (e.g., military) targets, but is unsurpassed for mapping ocean surface currents and monitoring sea state from the coasts.

This author led HFSWR studies in the 1960s for the military where the purpose was to detect ships, aircraft, missiles, and/or even submarine wakes. In studies conducted on San Clemente Island off California, these targets were all detected, but the benefits did not outweigh costs compared with other sensor technologies, and hence they never became operational.

One unexpected application was discovered during that era: the systems were actually quite good at monitoring surface currents and waves. The sea echo is quite large and well defined. And unlike microwave radars, the mathematical models that explain the signal's Doppler spectrum are quite simple. The dominant sea echoes have narrow spectral peaks that originate from waves half the radar wavelength moving toward and away from the radar. I named these "Bragg peaks" because of the mechanism is the same as Bragg scatter of X-rays in crystals discovered over 100 years ago [1, 2].

Those early systems used conventional phased array antennas that form and scan beams in azimuth. Because the wavelength is so long (typically 30 m), the lengths of the arrays needed to form narrow beams span hundreds of meters. One system I commissioned for San Clemente Island in 1970 is shown in Fig. 1.

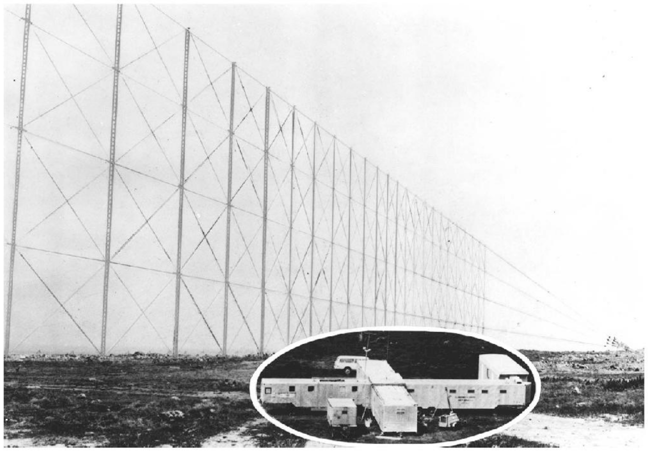

Figure 1. HF Phased array antenna built by this author in 1970 on San Clemente Island, CA for sea surface monitoring.

This array of 25 elements spans 500 m in length. It operated between 4 and 30 MHz. Forming and scanning beams in the conventional manner, it demonstrated great promise for current and wave monitoring and spurred efforts during our next phase to make this technology practical.

II. TRANSITION INTO THE NOAA CODAR

In 1972 I joined NOAA (National Oceanic and Atmospheric Administration) with the mandate to develop HFSWR into a useful tool that could be used for routine current mapping and

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wave monitoring. Initial impetus was to understand the environmental impact of floating spilled oil, as part of the government plans to license offshore fields, and for emergency response after a spill happens. It was patently obvious that the biggest impediment to such plans was the huge antenna size, its cost, and coastal obtrusiveness of a structure similar in size to that of Fig. 1. Hence, the phased array and conventional beamforming (requiring a large aperture in terms of wavelength) became a quick casualty.

An alternative to wide-aperture beam forming for extracting bearing information is the use of direction finding (DF). This can be done with much smaller, compact antennas. The risk was in abandoning conventional radar practice for an untested method that had only been used for determining direction of radio signals. In order to sell NOAA management on the concept I had in mind, I used an artist sketch of Fig. 2.

Figure 2. Sketch of DF antenna proposed to NOAA to replace phased array.

In this concept, I envisioned two crossed loops and a monopole, constructed along the same vertical axis. The loops have a cosine pattern while the monopole's is omni-directional. In software, the signals from the three would be used with an algorithm that would find the direction of arrival of the radar echo.

Before the Fig. 2 crossed-loop design was implemented, we tried other DF schemes at NOAA, feeling that perhaps the drastic size reduction to a single mast was too risky. These intermediate versions involved a semi-compact square array of four vertical monopoles. A photo of this is shown in Fig. 3. Also, Fig. 4 is a picture of the transmit antenna we used then, which was a YAGI meant to focus the radiated energy within a 160° field of view. Transmit and receive antennas were separated by several wavelengths.

Figure 3. Photo of NOAA CODAR receive DF square array at 25 MHz.

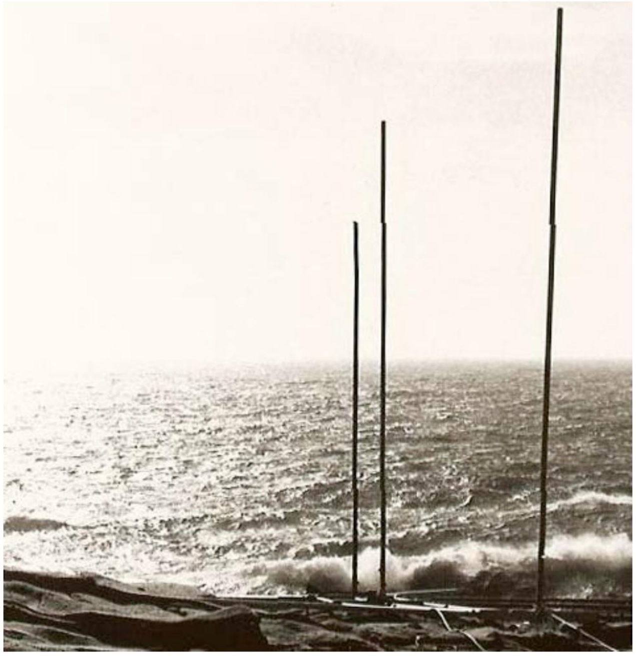

Figure 4. Photo of NOAA CODAR transmit YAGI antenna at 25 MHz.

The original NOAA systems operated at 25 MHz, as this was viewed as the best compromise for good, medium-range current mapping as well as wave monitoring. There were no commercial off-the-shelf vendors of HF radar componentry, and so both the antennas as well as the transmitter/receiver hardware originated at NOAA. For the antennas, I relied on colleagues at Lawrence Livermore Laboratories who were developing the powerful NEC (numerical electromagnetics codes) to finalize the designs I needed [3]. I used some of the competent Stanford HF radar engineers to design the receiver, transmitter, and calibration transponders we required. Our intention was to produce final output data in the field as close to real time as possible. Nine-track tapes and DEC PDP 11/23 mini-computers rounded out the radar system electronics. Fig. 5 is a photo of an early version of this system.

Figure 5. Photo of NOAA CODAR transmitter, receiver, DEC mini-computer, tape drive, and electronic test equipment -- vintage 1975.

III. CODAR EVOLVES AT NOAA, DEBUTS AT CMTC

The radical departure of the NOAA HFSWR from the conventional beam-forming phased arrays of prior years, exemplified in Fig. 1, deserved a special name. CODAR was chosen, the outcome of a contest I sponsored at our boisterous FAC (Friday afternoon club) events. The name CODAR was chosen first, with the hunt for appropriate words behind the acronym producing “Coastal Ocean Dynamics Applications Radar”. During the period between 1974 and 1984, over 17 field deployments -- from Cook Inlet, Alaska, to the German North Sea, and Malaga, Spain -- solidified and confirmed the accuracy and utility of CODAR.

This new sensor technology caught the attention of NOAA management, who wanted to see it evolve from our R&D laboratory into the operational arena. After all, there had been no way of mapping surface currents that was continuous over space and time. Instruments in the corrosive, short-lived undersea environment are at best a point measurement. Tracked drifters involved labor-intensive operations, for a few “spaghetti tracks” that challenged interpretation. The applications to oil spill response and prevention, fisheries management, search and rescue, not to mention oceanographic research, were evident.

The other inventors and I patented the CODAR technology [4]. The team received the Dept. of Commerce Gold Medal award in 1977, the year that saw the announcement of the breakthrough in *Science* [5]. To ensure that commercial versions of this technology would emerge, NOAA set up a Transitional Engineering Program for CODAR, guided by Bill Woodward of NOS. It was also Bill who was an organizer of the very first CMTC meeting at Newark, DE in 1978. He persuaded me to give a presentation there, introducing and describing this new CODAR technology to the current measuring community.

As a finalè to the Transitional Engineering Program, we convened a workshop to which key industries were invited -- those who had backgrounds in the earlier military HF radar programs. Our group at NOAA described the technology, and offered both hardware schematics as well as software source code to an industry partner who would develop and offer a commercial version. Although the industry engineers in attendance were excited, their managements were less than enthralled. It is one thing to work on $10-15 million contracts for DoD, but quite another to offer a complete commercial product for ~$100,000 per radar system. Unless they could see a $100 million per year market in their five-year future, the investment required to bring it to commercial status couldn’t justify their “jumping into the water” on this.

Hence, NOAA management suggested to me and our core group that perhaps a small, start-up company could make a success of this commercialization venture, large companies would not undertake -- i.e., inviting us to leave and launch this quest with their support (meaning they would buy the first several systems back from us). This was spurred also by interest from the oil industry for use on offshore platforms, at a time when oil prices were high and investment in new technologies was common. An oil-company “joint industry program” in fact was the first source of funding for our fledgling firm.

It immediately became obvious that our “compact” square antenna arrays of Fig. 3 & 4 (compared to the earlier behemoth phased arrays) were still too big for deployment on an offshore oil platform. We began inventing/designing the crossed-loop/monopole dream of Fig. 2 envisioned earlier, even before we had left NOAA. Our investigations then showed that this system was not only as accurate as our older approach, but overcame some technical limitations of that antenna array and its signal processing [6, 7].

IV. THE FIRST COMMERCIAL CODAR AND ANTENNAS

Setting up shop in Boulder/Longmont, CO not far from our NOAA “parents”, we set out to re-do the antennas (as well as transmitter/receiver). We stayed with the radar waveform that we used for the NOAA CODARs, a conventional pulse train with a 1.5% duty factor that transmitted a peak power of 10 kW and average power of 150 watts. The radar hardware, still locked into the DEC 11/73 minicomputer and 9-track tape drives of that era, was reduced in size and made more robust, occupying only one of the containers shown in Fig. 5..

The challenge with the new antenna design was to build three co-located, coaxial elements (two crossed loops and the monopole) so that they would realize the physical and electrical orthogonality we desired: that is, so they could reside at the same location but not interact or couple with each other. This design, shown in the photo of Fig. 6, was used at

25 MHz for over a decade, up to 1992. Operated from oil rigs as well as at the coast, it was about 2.5 m high, measured from the horizontal ground radial elements. The unit would transmit from the vertical monopole, while receiving from monopole and both single-turn air loops. The weatherproof box beneath the ground radials contained the transmit/receive switching electronics. All three antennas were designed to be efficient, i.e., perfectly matched with no internal losses.

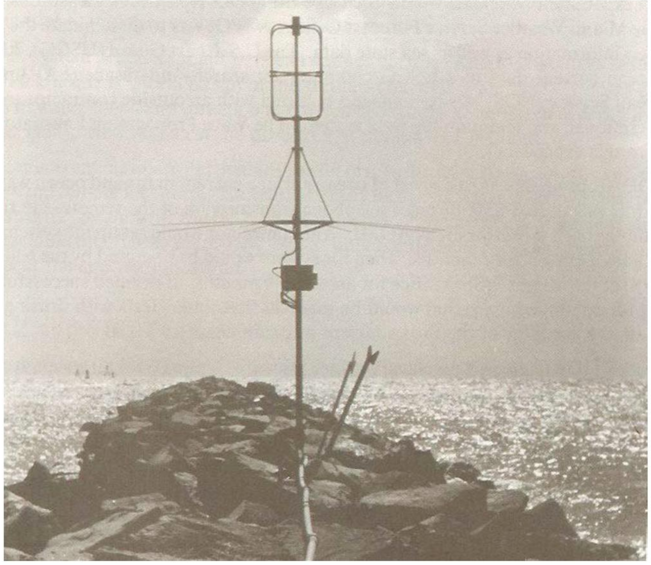

Figure 6. CODAR commercial crossed-loop/monopole transmit/receive antenna for 25 MHz

V. THE MODERN SEASONDE

The first era of the commercial CODAR described above was basically an extension of the older NOAA version. That came to a close with the collapse of oil industry procurements when the price of crude plummeted from $40 to $10 per barrel in 1985. Our company enterprises were re-organized into CODAR Ocean Sensors, Ltd. The first order of business was to re-design the radar to be even more compact, take advantage of modern PC technology for on-site real-time processing, and come in at a lower price. In developing the new version that we called the SeaSonde, we moved from Boulder, CO to Mountain View, CA where we had ready access to coastal test sites. The primary new features we designed into this major update are the following.

1) A Highly Compact Loopstick Receive Antenna Unit: We recognized an important point about the nature of the HF world that still escapes others even today. Because external atmospheric noise dominates internal noise by many orders of magnitude (unlike microwave radars), *receive antennas need not be efficient*. Thus, the large air loops and quarter-wave monopole elements of Fig. 6 are unnecessary, and can be traded for yet smaller size and lower cost. What we recognized is that -- although lower efficiency reduces the target signal echo -- it also reduces the noise, so that signal-to-noise ratio (SNR) remains the same, up to a point. The trick is to recognize when that point is reached in optimizing the design, so that SNR does not suffer [8]. This has now led to a unit where the loops are contained in a small, circular pod mounted on a dipole mast. By getting rid of the monopole concept, the ungainly horizontal ground whips that serve as the ground counterpoise are eliminated (see Fig. 7). Having a sleek, unobtrusive appearance eases the process of obtaining site approvals, where objections arise to any large, eye-offending structure on otherwise pristine beaches.

Figure 7. Latest SeaSonde crossed-loop/dipole antenna from 4 to 50 MHz.

2) New Signal Format and Processing: Another major change was begun in 1987. We abandoned our classic, simple pulsed signal format for a better alternative. In the early 1970s, I had pioneered a linearly frequency modulated continuous wave (FMCW) signal and its processing. This had been used in those days for the massive skywave over-the-horizon military HF radars. Unlike the microwave-radar "chirp" waveform that is processed with a matched filter in the time domain, this signal at HF is processed in the frequency domain. By demodulating received echoes with a replica of the transmitted waveform, the signal can be digitized at a very low, audio rate. Thus, its processing to get range data can be done on simple PC laptop computers, in real time.

Although this had been known since 1973, it was not useful for backscatter radars, i.e., where transmitter and receiver are colocated. When the receive antenna sits very near the transmitting antenna, the signal is so strong that it it masks the weak target echoes. (In skywave OTH radars, transmitter and receiver are separated by 100 km or more, and so the transmit signal is sufficiently reduced that it is not a limitation.) We solved this challenge by pulsing/gating the FMCW signal. A crude version of this waveform had been described earlier -- called FMICW -- where the "I" stands for interrupted; however, a methodology for optimizing the parameters of the pulsing had never been revealed, and so it had never found operational utility until our discoveries in the late 80s. These led to an invention [8] that reveals how to design the frequency sweeping and pulsing parameters to achieve surveillance over the sea to ranges and resolutions useful for current mapping and wave monitoring.

3) Efficient DF Algorithm for Bearing Determination: Up to 1992, the algorithm used for DF bearing extraction was nonlinear least squares [6], where a model was fitted to the signals from the two loop and one monopole receive antennas. This had many limitations, including issues in resolving statistical hypotheses as to how many signals were present from different directions with the same radial velocity (or Doppler shift). A nonlinear 2D grid search was required to find the global minimum solution the the over-derermined least-squares problem, and this sometimes led to spurious results.

I discovered a method called MUSIC (MUltiple SIgnal Classification) that was developed to locate bearings of enemy radio transmitters from aircraft in Southeast Asia for the CIA after the Vietnam War [9]. This had never been applied to radar signals. So we pioneered something new here. In this method, an eigen-analysis is performed on the covariance matrix among the three receive antenna signals. The dominant eigenvalues are associated with signals from different directions, while the weaker ones with noise. A simple linear search is done to find the bearings which cause the model signals to be orthogonal to the weakest noise eigenvectors; orthogonality is by definition an outcome of the eigen-analysis. In this, the model signals are based on the calibrated antenna patterns. These include the effects of the local environment near the antennas, and hence remove the distortions in these patterns from ideal; this latter ability was not available with the older DF algorithms, and hence added to current mapping accuracy and robustness. We received a patent for this invention [10].

4) Compact receiver/transmitter and processor: The breakthroughs described under *2)* and *3)* above allowed a redesign of the non-antenna SeaSonde hardware, so that it is much smaller, lower cost, more robust, and requires lower input power. A photo of our 2008 radar electronics is shown in Fig. 8. Total power to operate all electronics is about 300 watts (providing a radiated average power of 40 watts). In addition to standard AC, the owner can select 24 volt DC input, which is amenable to solar/wind power sources -- an ideal solution that many employ for isolated coastal locations. These systems operate 24 hours a day, backed up with battery storage to carry over during periods of no sun or wind.

Figure 8. SeaSonde transmitter & receiver (right), and Mac Mini processor (left) as used in 2008.

4) GPS Synchronization Allows Frequency Sharing: In earlier days before 10 years ago, each of the few HF radar users could ask for and receive a license for a separate frequency. Now, however, with over 250 SeaSonde radars operating in the world today (at least 85% of all HF radars sold), the spectrum is becoming too crowded to allow separate frequencies. Radars by their nature require more spectral bandwidth than radio voice channels -- the primary user of the HF band until we came along.

Signals in the upper part of the band do not travel so far, and hence SeaSondes tens of kilometers apart can operate on the same frequency without mutual interference. At mid and low HF, the signals we use that provide current maps past 100 km reflect well from the ionosphere, causing interference to users half way around the world. In addition, Long-Range SeaSondes can interfere with each other at distances up to hundreds of kilometers. Since HF radars produce the most accurate data when they operate continuously, simultaneous use of the same limited frequency channels in mid and low HF would seriously degrade the performance of all, without some mitigation method.

Our team and I invented a method [11] of synchronizing the simultaneous signals from several radars by using precisely timed GPS signals available worldwide. This method is tied to the FMCW signal format we pioneered (and presently used by all HF radars worldwide). The beginning of each station's frequency sweeps are staggered, offsetting them by a calculated number of milliseconds. This puts the received signal information from adjacent stations into regions of the processed spectrum that do not overlap, eliminating mutual interference that would reduce the area coverage and produce spurious current estimates. In addition, it allows the echo signals from the other station's transmissions to be used in a bistatic mode, as discussed in the next section. Presently, up to 100 SeaSondes worldwide operate successfully in this manner with GPS-synchronized modulations.

5) Multi-static Capability Extends Coverage and Accuracy: The normal mode of radar operation is backscatter -- or monostatic. In this, transmitter and receiver are colocated, sometimes sharing the same antenna, while in others the transmit and receive antennas may be separated a small distance. More than 99% of all radars are backscatter. It had long been recognized that separating transmitter and receiver by tens or hundreds of kilometers -- called bistatic -- offers interesting possibilities. It has never achieved popularity because of the difficulty of synchronizing widely separated signal sources. Without synchronization, the coherent processing required of transmit signal with a reference in the receiver is not possible.

We saw immediately that the GPS signal synchronization discussed above that allows multiple stations to share the same frequency was also the inexpensive solution that would allow bistatic operation. Thus we not only eliminate mutual interference, but can make use of the other station's signals. In fact, a single coastal station can simultaneously operate in a backscatter mode (using its own transmitted signal's sea echoes), but also using the echoes from several adjacent coastal SeaSondes transmissions. This gives rise to the term multi-static in place of bistatic. A single radar intended for conventional backscatter operation becomes multiple radars, simultaneously processing many sets of echoes. However, in addition to using other SeaSonde radars' signals, stand-alone transmitters on buoys or offshore rigs can operate with several coastal stations in a multi-static mode.

There are two advantages of extending an existing backscatter network to multi-static: (i) it extends the area coverage; (ii) it adds redundancy in the backscatter region, thereby increasing current measurement accuracy and robustness. A normal backscatter radar makes its measurements in polar coordinates, i.e., range and bearing (azimuth). When transmitter and receiver are separated in a bistatic mode, measurements are made in an elliptical coordinate system. Transmitter and receiver locations become the foci of a family of ellipses defined by the time delay between the direct signal and the echo signal.

CODAR has been perfecting the multi-static mode of operation for SeaSonde networks for over six years [12]. In four cases, transmitters were located on buoys and offshore rigs. In the other cases, adjacent coastal SeaSonde radars served as the multi-static signal sources. Soon, when the operating and processing software is deemed robust, it will be introduced as a way of extending the existing backscatter networks in the U.S. and worldwide. With the GPS synchronization already in place, this augmentation simply consists of installing an additional software package.

REFERENCES

[1] D. E. Barrick, "A review of scattering from surfaces with different roughness scales," *Radio Sci.,* vol. 3, pp. 865-868, 1968.

[2] D. E. Barrick, "First-order theory and analysis of MF/HF/VHF scatter from the sea," *IEEE Trans. Antennas Propagat.,* vol. AP-20, pp. 2-10, 1972.

[3] G. J. Burke, A. J. Poggio, "Numerical electromagnetics code (NEC) -- Method of moments, Parts I, II, & III," *NOSC TD 116*, Naval Ocean Systems Center, San Diego, CA, Jan. 1980.

[4] D. E. Barrick and M. W. Evans, "CODAR: A coastal HF radar for real-time current mapping," U. S. Patent 4 172 255, 1979.

[5] D. E. Barrick, M. W. Evans, and B. L. Weber, "Ocean surface currents mapped by radar," *Science,* vol. 198, pp. 138-144, 1977.

[6] B. J. Lipa and D. E. Barrick, "Least-squares methods for the extraction of surface currents from CODAR crossed-loop data: Application at ARSLOE, Appendix E," *IEEE J. Oceanic Engr.,* vol. OE-8, pp. 108-110, 1987.

[7] D. E. Barrick, and B. J. Lipa, "Comments on "A compact direction-finding antenna for HF remote sensing," *IEEE Trans. Geoscience Remote Sensing,* vol. GE-25, pp. 138-144, 1977.

[8] D. E. Barrick, B. J. Lipa, P. M. Lilleboe, and M. Isaacson, "Gated FMCW DF radar and signal processing for range/Doppler/angle determination," U. S. Patent 5 361 072, 1994.

[9] R, O. Schmdt, "Multiple emitter location and signal parameter estimation," *IEEE Trans. Antennas Propagat.,* vol. AP-34, pp. 276-280, 1986.

[10] D. E. Barrick and B. J. Lipa, "Radar angle determination with MUSIC direction finding," U. S. Patent 5 990 834, 1999.

[11] D. E. Barrick, P. M. Lilleboe, and C. C. Teague, "Multi-station HF FMCW radar frequency sharing with GPS time modulation multiplexing," U. S. Patent 6 586 276, 2005.

[12] D. E. Barrick, P. M. Lilleboe, B. J. Lipa, and J. Isaacson, "Ocean surface current mapping with bistatic HF radar," U. S. Patent 6 774 837, 2004.