Dual Use Multi-Frequency Radar For Current Shear Mapping and Ship Target Classification

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***Abstract* – A new radar is in final stages of development and testing by Imaging Science Research (ISR), Inc., sponsored by the Office of Naval Research. The system is based on digital receiver technology incorporated into a PC operating environment. A digital receiver eliminates the need for man[1]y radio frequency analogue components, providing more robust temperature-insensitive operation and lowers hardware costs. The digital approach allows operation beyond the High Frequency (HF) band, which occupies 3-30 MHz, and our current plan is to cover 2-55 MHz with a single system. The system can be tied to our ISR Rubidium Clock option, allowing bistatic operation using a single receive array and processing station with multiple transmit sites, for vector measurements of velocity. Here we provide a description of our digital transceiver, our radar block diagram, and our transmit and receive antenna arrays. Measurements of the radar cross section (RCS) of small boats are presented, based on work done by the author in the mid-70's, suggesting that ships and small boats can be classified based on their RCS radar frequency spectral properties. Results from a pilot experiment are displayed, demonstrating multi-frequency operation using 32 radar frequencies over the HF band.**

I. INTRODUCTION

New advances in digital technology driven by cellular phone and other communications systems can be integrated into radar systems to reduce the size, weight and cost of commercial systems. An improvement in system quality control is also achieved using digital technology, as temperature sensitivity of analogue components is eliminated. ISR is currently under contract to the Office of Naval Research to develop a digital transceiver card for bistatic radar operation. Under a second contract, we are utilizing this transceiver card in the development of a multi-frequency HF radar for ocean current shear measurements. The capability of using a large number of frequencies in the HF band simultaneously offers an opportunity to perform HF radar target "RCS Spectroscopy", the calibrated measurement of the unique frequency response of a target in the HF band and beyond. Such a capability holds promise for the classification of targets, in particular, ships and small boats. We discuss our new system in the following paragraphs, and provide some examples of multi-frequency RCS measurements made in the mid 1970's while the author was a member of the Radar Division of the Naval Research Laboratory.

II. DIGITAL TRANSCEIVER PCI CARD

A. Digital Timing and Transmitter System

Figure 1 shows a block diagram of our new digital transceiver PC card, which provides both a transmit and 8-channel receiver capability. The timing of the card is tied to a pair of phased-locked Direct Digital Synthesizer (DDS) chips, which provide a programmable pulse code for transmission, and clock signals for the Analogue-to-Digital Converter (ADC) chips for recording. A GPS receiver is a part of the system design, to allow transmission of pulses on a timely basis for integrated operation with other radar systems. One can use the on-board temperature controlled crystal oscillator (TCXO) clock if monostatic operation is desired, or one can input a signal from our rubidium clock option, which is in turn locked to universal time by the GPS receiver. The latter option is necessary for bistatic operation, where a signal is transmitted from one or more unattended transmit-only sites and received by the master station. In this case, the master station also acts as a transmit site to collect monostatic data, and receives the one or more bistatic transmit signals to provide vector velocity measurement capability using a single receive and processing station. All sites are tied together under radio network control.

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The transmission of signals is programmable via the DDS chips, and can be simple pulse, frequency-modulated (FM) pulse, FM continuous wave (CW), phase modulated, and random noise. Radar frequency can be changed pulse-to-pulse, thus allowing simultaneous collection over all frequencies of interest for Doppler processing. The sequence is tied to Universal Time, so that the exact frequency and time slot is defined for all systems. While not shown in Figure 1, the DDS-1 waveform is mixed with a programmable envelope waveform for transmit-spectrum sidelobe control. Output signal levels to the High Power Amplifier (HPA) can be as large as ±1 volt, peak-to-peak. We have also designed our own HPA unit and pre-amplifier box input and output devices indicated in the block diagram.

B. Digital Receiver System

Eight incoming pre-amplified receive signals from an antenna array are input in Figure 1 to eight independent ADC channels, where they are digitized at 8-bits at a programmable rate of up to 100 MHz, directly at the radio frequency in our case. Four such cards can be used in a single receive system to support a 32-element receive array if required. These signals are then digitally filtered to the bandwidth transmitted using a pair of four channel DDC chips, which increases the dynamic range by the ratio of ADC input to DDC output frequency, and is typically handled as two-byte complex words at this stage. The pair of Field Programmable Gate Array (FPGA) chips are used both for housekeeping and additional signal averaging, making use of First-In First-Out (FIFO) chips, where additional dynamic range improvement is achieved, with a reduction in the recorded

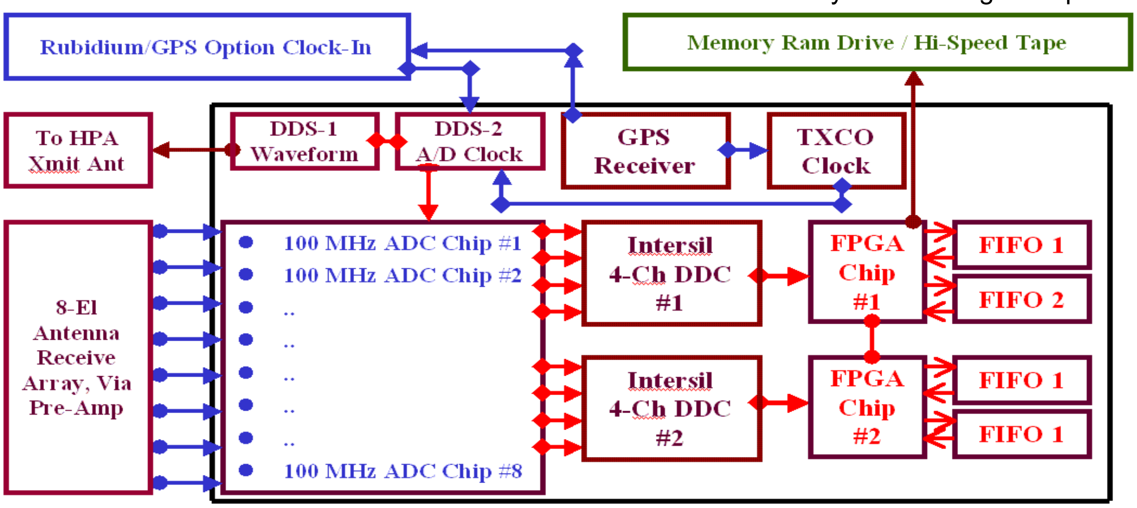


Figure 1. Block Diagram of ISR transceiver card.

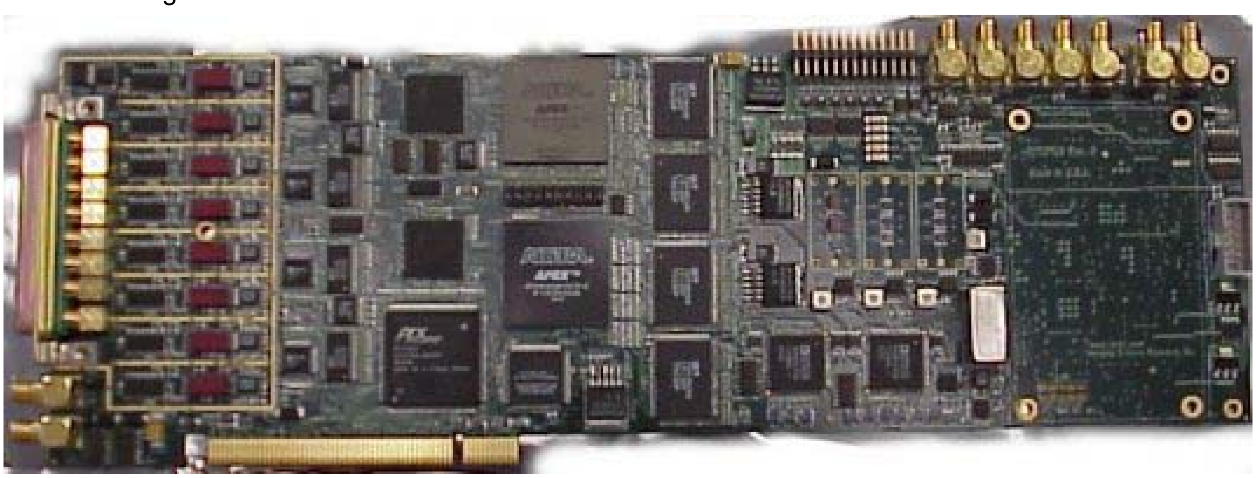


Figure 2. Photo of finished ISR transceiver card.

Pulse Repetition Frequency (PRF). Output word size can be as high as 4-byte in-phase and quadrature (I/Q) words. Data are written to system memory in real time, and can be rewritten to hard disk on the fly.

C. Exciter Card

For a bistatic site, only the transmit portion of the card is required. Thus, a separate exciter card has also been built, based on the same PCI footprint of the transceiver card, but with the acquisition portion eliminated. It includes both DDS chips, the GPS receiver, a single FPGA chip for housekeeping control, as well as the same set of output ports available on the transceiver card that can be used for viewing signals at several stages in the transmission process.

III. SOFTWARE CONTROL

The software setup control system is based on a personal computer (PC) Windows format. Control and setup of the exciter and transceiver card are similar, as the former constitutes a subset of the latter. One sets up the following components for the transmission characteristics in this order: the trigger source & characteristic, clocks sources, I/O ports on the board, DDS sample rate and radar frequency selection, envelope shape and amplitude. An image of the control software the user is given is shown in Figure 3.

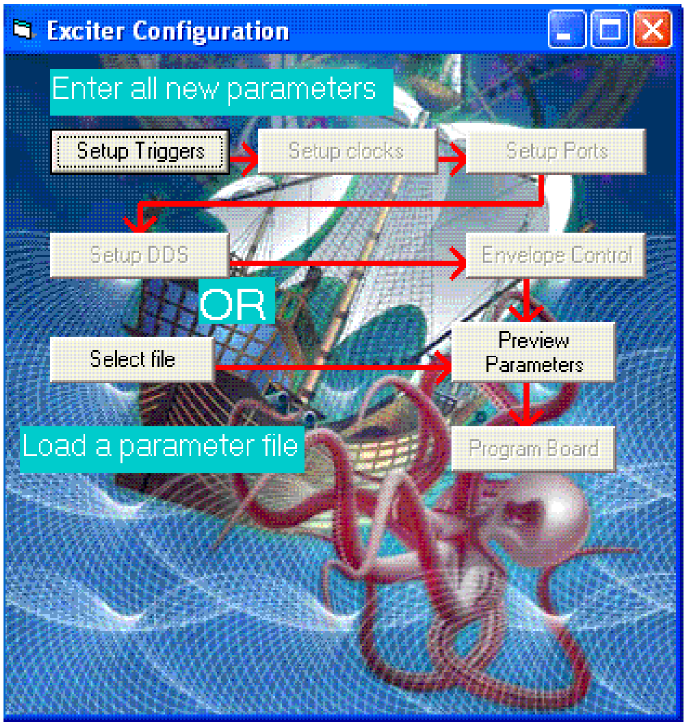


Figure 3. Windows configuration format for transceiver parameter setup.

The trigger 1-PPS clock source can be the GPS 1-s tick edge or an external source, The trigger source clock can be the system reference clock (chosen later), the 1-PPS source, internally generated software trigger, or one of two input trigger sources. The number of triggers is selectable as a constant, as when used in a transceiver mode, or can be continuous, as when used in the exciter mode. The pulse length of the DDS signal, which has a rectangular envelope output, is chosen here. A receiver blanking output pulse is also available, for protection of an external preamplifier system from the transmit pulse, if necessary. This allows operation of the transmit and receive systems relatively close by, with no true limit is spacing if the blanking is utilized, as we do. The blanking interval should be as long as necessary to eliminate the transmit pulse, and will be longer than the pulse length in the case of a bistatic geometry, if the direct path signal is to be protected against.

The clock sources can be chosen as one of several internally derived clocks, or an external clock, such as a rubidium 20 MHz reference, which we provide as an option. The auxiliary signal connector shown on the top of the board in Figure 2 attaches via individual SMA cables to a flying bracket mounted on a PC card slot for access to a rather large number of signals. Signals include the waveform envelope and the mixer (of envelope and DDS waveform product) output, as well as other diagnostic outputs.

The output ports available are the 1-PPS (typically GPS), the trigger output, and the reference clock output in TTL format. The

The DDS setup currently allows choice of pulse types (simple pulse, FM pulsed, or phase-shift keyed), currently up to 64 radar frequencies, the output sampling clock rate, the DDS output amplitude (0-1 v range).

Finally, the envelope control allows one of a series of shapes, including cosine to the 2N power or triangular, length of the envelope, and an additional amplitude control (1-100% factor) beyond that provided for the DDS output earlier. This allows for employing a lookup table to account for DDS output non-linearities from board to board, with a table provided for each board.

As seen in Figure 3, one can load in parameters from a previous file if one so chooses, and edit these to avoid repeating the setup sequence each time the exciter or transceiver is employed.

Further characteristics of the A/D and DDC setup parameters will be given elsewhere.

IV. ANTENNA SYSTEM

A. Receive Array

The receive array elements are currently loop elements, with broad band amplifier chips to bring the signal level up to a moderate level before cable losses are encountered. A photograph of a Navy sponsored loop element is shown in Figure 3, which was used in some Navy sponsored experiments. Our design has moved to a circular loop, with a redesign of the amplifier onboard for broader band operation than those developed for the earlier Navy projects.

One advantage of such a loop element is that a null in the pattern occurs normal to its plane, providing protection against a nearby transmit antenna. Additional protection is provided with a blanking circuit in each loop element, that makes use of the blanking signal from the transceiver card discussed earlier.

B. Transmit Array

The transmit antenna is a special ISR design for broad band operation. It is a log-periodic array (LPA), with monopoles at the higher frequencies, and a patent-pending ISR element design for the lower bands. The system shown in Figure 4 has transmitted between 2.2 and 50 MHz successfully, and occupies just 20 meters in length. The system is shown set up at the U.S. Army Core of Engineers (USACE) Field Research Facility (FRF) at Duck, NC, where system tests and experiments are ongoing. The system features a drive-away air-conditioned radar equipment trailer that allows radar set up within a day after arrival on site and power is provided.

The log-periodic array offers several advantages for HF operation. It has an excellent front-to-back ratio, of the order of 12 to 20 dB, so that little energy is transmitted back onto land. This is a feature that the FCC finds favorable regarding interference with other users. The peak gain is 6.4 dBi in the forward direction, and has an azimuthal pattern with a beamwdith of the order of 120^{o}. The antenna is fed at a single point with one cable, and the elements that are near resonance with the transmit frequency, typically three to four, extract energy from the transmission line and provide the transmitting portion.

The length and number of elements in the LPA are chosen by design. We have chosen 10 active elements, with the very first element shown a director that is not fed. A balun is used to match the impedance of the array to that expected by the high power amplifier (HPA), typically 50 ohms. The balun prevents reflected energy back to the HPA, which could cause burnout if the standing wave ratio (SWR) is above three. Our design maintains a SWR of less than three over the 2-50 MHz design range. We have designed this array for selection of any frequency within the band. However, if a fixed number of four to six frequencies are selected for operation, the number of elements and their resonant frequencies can be chosen so as to reduce the number of elements and the antenna length with little affect on the total gain and front-to-back ratio. Our low frequency element design reduces markedly the length required, which would be so high as to fit the line tangent to the first five shorter elements of the array shown, clearly an advantage in deployment. Not shown are two additional 10’ elements to the right.

Figure 4. Transmit and receive antennas deployed.

V. RCS MEASUREMENTS VS RADAR FREQUENCY

A set of experiments were performed at the Naval Research Laboratory in the 1970's, in support of the Navy interest in range safety and tracking and identification of small fishing boats in the area of cruise missile development flights off the San Diego area. NRL utilized the NOAA/Navy San Clemente Island radar to conduct these experiments. The radar was operable between 2 and 30 MHz, designed primarily for Over-the-Horizon (OTH) propagation via ionospheric reflections, for illumination of the Gulf of Alaska. However, as its antenna elements were vertically polarized and coupled to the ocean surface with a wire ground screen for low elevation angle propagation enhancement, the surface wave mode could also be used for local experiments. The author participated in the collection, analysis, and reporting on these experiments and results were published in an NRL Memorandum Report [1], but never in a journal paper.

One boat that was used for the tests is shown in Figure 5, a fishing boat named the Bill Kettner.

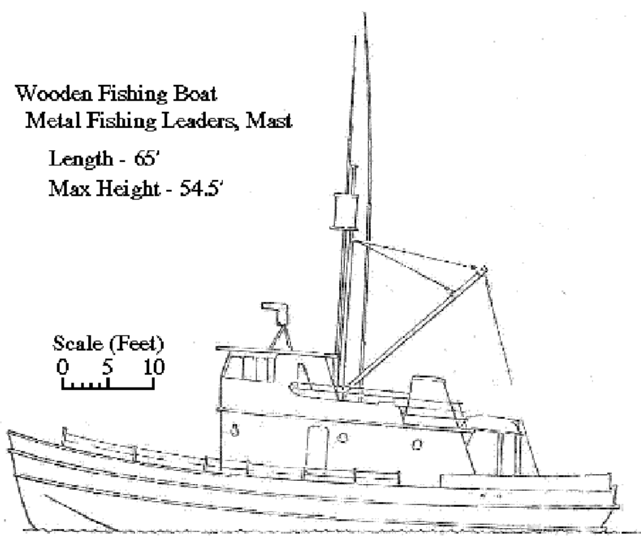


Figure 5. Small wooden fishing boat with metal mast.

The RCS at HF of such a radar scatterer might be expected to be dominated by the long metal structures, which respond as a quarter-wavelength monopole over a perfectly conducting ground plane, with a dipole radar cross section. The mast height indicated in the figure was 54.5 ft, or 16.6 meters, thus $\lambda/4$ resonant at a radar frequency of 4.5 MHz.

Runs were made both toward and away from the radar, to provide a Doppler offset to permit identification of the target by Doppler shift, and to allow aspect differences in the RCS to be made. Figures 6 and 7 below show RCS responses versus radar frequency.

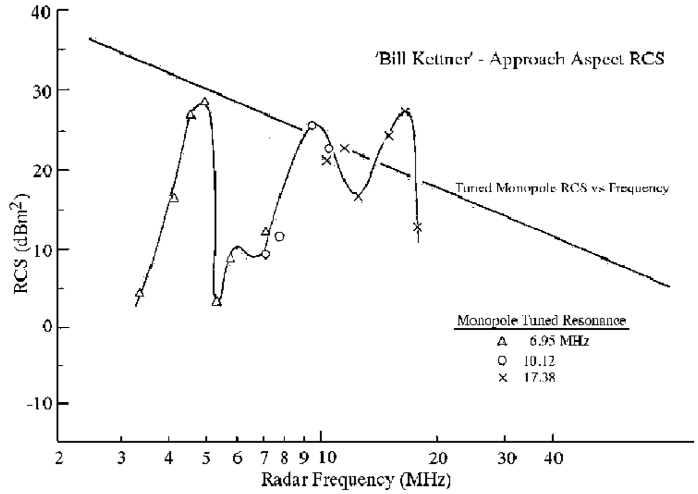


Figure 5. Kettner RCS for approach aspect.

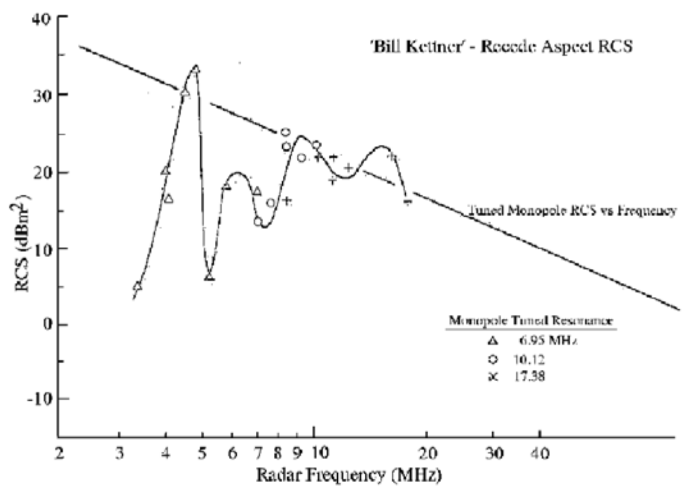


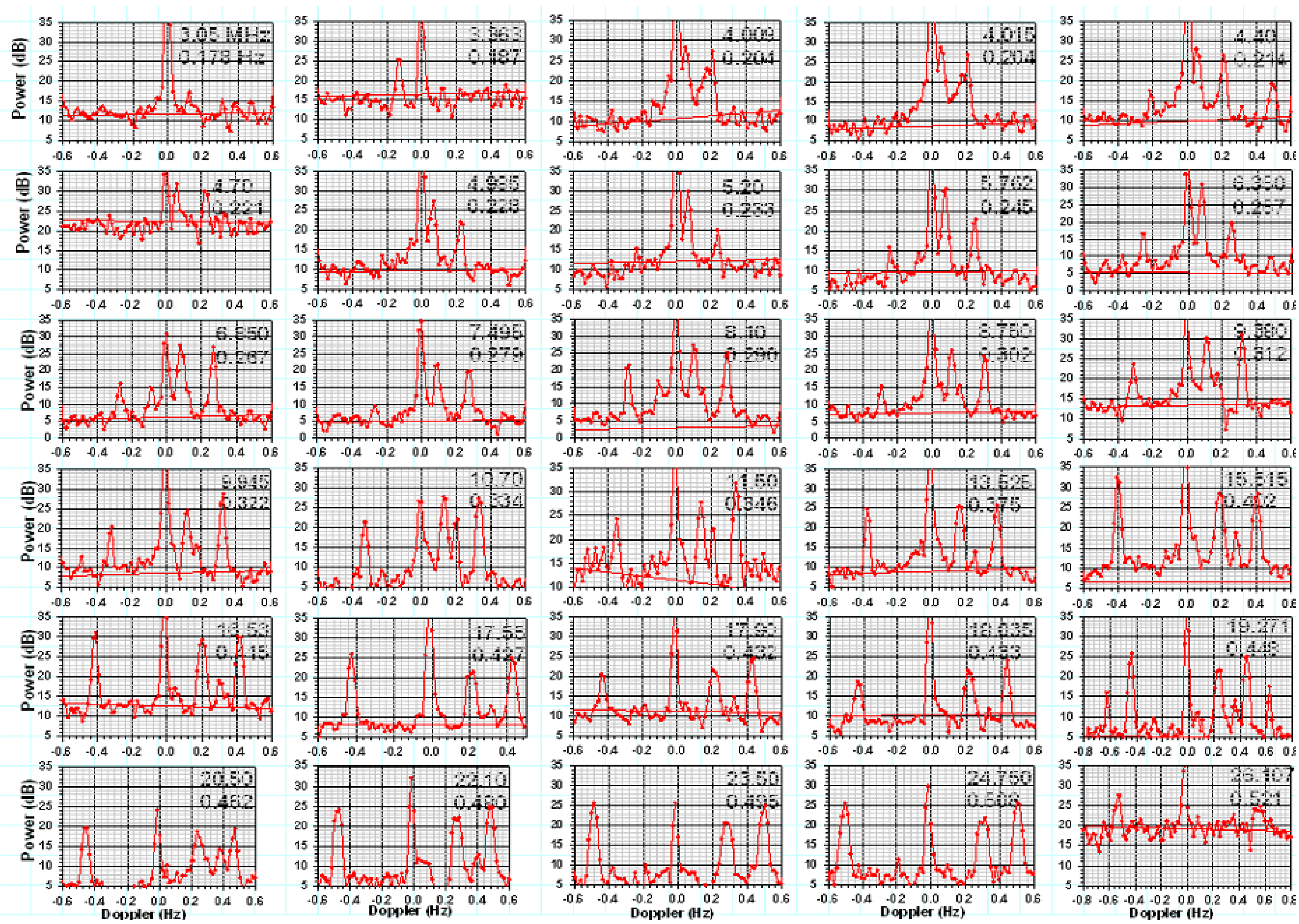
Figure 6. Kettner RCS for recede aspect.

The dominant RCS contribution of largest amplitude for both cases is at 4.5 MHz, in agreement with the expected dominant contribution due to the $\lambda/4$ resonant monopole described earlier. Other shorter scattering elements included fishing line leaders and additional communications antennas that corresponds to the other resonances in the figure. The differences in relative RCS, but at similar frequencies, suggest that interference effects and aspect sensitivity of these combined scattering elements plays a major role in determining the "RCS spectrum" of a target. Other measurements of combatants have been reported by Headrick and Rachuba in NRL reports as well [2].

VI. MULTI-FREQUENCY DOPPLER SPECTRA

The radar system discussed above was used to generate data over a 32-frequency sequence on a pulse-to-pulse basis, allowing simultaneous Doppler spectra to be generated. Figure 7 below shows and example of Doppler sea scatter spectra, including targets due to local shipping. Each spectrum is labeled in the upper right hand corner by the radar frequency in MHz, and the Doppler shift of the Bragg line due to first order ocean scatter. The ratio of the approach and recede lines can be used to estimate wind direction, as we demonstrated using the OTH mode of operation over the North Atlantic in the 1970's [3], and which was further demonstrated by Harlan and Georges [4], among others. Additionally, the Doppler shift of these Bragg lines to either side of their predicted positions indicates the measure of a radial current shift of the Doppler spectrum. Two sites measuring two different radial components can be used to measure a current vector at each of a series of cells defined by azimuth and range. A commercially available system has been available for a number of years using a single frequency to make current maps at a single depth using this technique has been available for a number of years [5].

The availability of multiple frequency operation allows such current measurements to be made as a function of depth, which has been demonstrated by Teague, et al, [6] in a series of experiments. Additionally, they demonstrated that this measure of current shear can be inverted to provide a measure of wind shear driving the current shear, and thus allow retrieval of wind speed maps at kilometer scales [7]. Such a capability is of strong interest to oceanographers and atmospheric scientists, and our new technology could be developed into such a measurement system.



VII. SUMMARY

We have provided a description of a new digital transceiver PC card, suitable for use in radars in the HF band, and at higher frequencies with additional design. This digital transceiver has been used as the basis for an HF radar design that features wide-band operation between 2 and 50 MHz. Use of such a wide band of frequencies allows measurement of ship radar cross sections that can be used as a classification tool, based on measurements we made in the mid 1970's. Such a multi-frequency radar can be also used to measure ocean currents as a function of water depth, to provide the oceanographers with a measure of vertical current shear, as has been demonstrated in a series of experiments by both on the east and west coasts. Recently, Vesecky and his group have shown that such current shear measurements can be used to create wind speed vector maps by using the continuity of stress across the ocean-air interface, assuming that all the current shear is forced by the winds. The utilization of multi-frequency HF radars offers another dimension beyond that currently available in the remote mapping of winds and currents, and the dual-use potential for ship classification and tracking adds to its utility and attractiveness.

VIII. REFERENCES

[1]. Bogle, R.W. and D.B. Trizna, "Small boat radar cross section measurements", NRL Memorandum Report # 3322, July 1976.

[2] Headrick, J. and M.E. Rachuba, "High frequency band radar cross sections of ships", NLR Memorandum Report 5309-98-8173, (AD B236-703) 15 July 1998.

[3] Long, A. E. and D. B. Trizna, "Mapping of North Atlantic winds by HF radar backscatter interpretation", IEEE Trans. Antennas & Propagation, **AP-21**, pp. 680-685, 1973.

[4] Harlan, J. A. & T. M. Georges, "An empirical relation between ocean-surface wind direction and the Bragg line ration of HF sea echo spectra", JGR, **99**, No. C4, pp. 7971-7978, 1994.

[5] Barrick, D.E. and B.J. Lipa (1986), "An evaluation of least-squares and closed-form dual-angle methods for CODAR surface-current applications", IEEE J. of Oceanic Engr., vol. **OE-11**, pp. 322 - 326.

[6] Fernandez, D. M., J. F. Vesecky and C. C. Teague, "Measurements of upper ocean surface current shear with high frequency radar", JGR, **101**, pp. 28,615-28,625, 1996.

[7] J.F. Vesecky, J. Drake, C.C. Teague, F.L. Ludwig, K. Davidson, J. Paduan, "Measurement of wind speed and direction using multi-frequency HF radar", Proceedings of the 2002 International Geoscience and Remote Sensing Symposium, Toronto, 24 - 28 June 2002.