SHIP DETECTION USING AIRBORNE POLARIMETRIC SAR

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ABSTRACT

The Canadian Department of National Defence (DND) conducted a joint mission involving ship detection in the Grand Banks area of Canada in March, 2000. Among the objectives of the mission were the characterization of ocean clutter and ships using fully polarimetric airborne SAR. In this paper, we summarise the data acquisition both in terms of the airborne SAR acquisitions and in terms of the ship and surface truth information from the trial. Some preliminary observations are made on the properties of the SAR data and general conclusions are drawn about the polarimetric properties of the ship and ocean signatures.

1. INTRODUCTION

Ship/Ocean remote sensing with radar has been the subject of a large volume of studies using single channel radars. Few studies have exploited the full power of polarimetric radar combined with detailed wind-, surface- and vessel-truth information that were available in the DND CRUSADE mission. In this paper, we describe the mission and the contribution of the SAR-580 system to the measurement of ocean and ship polarimetric signatures at C-band during the trial. Overview information is given on the acquisition strategy, processing and calibration and ancillary data. Preliminary results from single channel and polarimetric evaluation are provided with conclusions.

1.1. Crusade-2000 Mission

During the last two weeks of March, 2000, the Environment Canada SAR-580 system [1] participated in a multi-sensor, multi-vessel ocean trial on the Grand Banks of Newfoundland, Canada. Participating in the mission were a large number of agencies both from the public and private sector. These included: The Department of National Defence, Defence Research Establishment, Ottawa (DND/DREO); Natural Resources Canada, The Canada Centre for Remote Sensing (NRCan/CCRS); Environment Canada , The Canadian Ice Service (EC/CIS); The Department of Fisheries and Oceans (DFO); *Satlantic,* Halifax; *SARCorp,* Ottawa; *Provincial Airlines, (PAL);* Naval Research Laboratory, and Environment Canada, Emergency Science Division (EC/ESD). The program was led by DND/DREO.

Of principal interest in this paper was the opportunity to image several well-characterized and instrumented ships in an ocean environment. In Table I, we list the three main ships involved.

Table I. Characteristics of Principal Ships in the Trial.

Ship	***Size (ft)***	***Estimated RCS (dBm^2)***			
		Incidence Angles			
		25º	***35º***	***45º***	***55º***
M/V Anne S Pierce	116	31	32	33	34
M/V Arctic Pride	60	24	25	26	27
HMCS Ville de Québec	436	44	45	46	47

The radar cross sections listed are computed from empirical formulae developed by Vachon *et al.* [2]. Photographs of these three ships taken during the trial are shown in Figure 1. Both Table I and the structural details shown in Figure 1 demonstrate quite different characteristics in terms of size and configuration. The smaller vessels are for domestic fishing. *M/V Anne S Pierce* is a scalloper and the *M/V Arctic Pride* is a trawler. The *HMCS Ville de Québec* is a modern navy Halifax class frigate [3] built in 1994 and was the largest vessel officially participating in the trial.

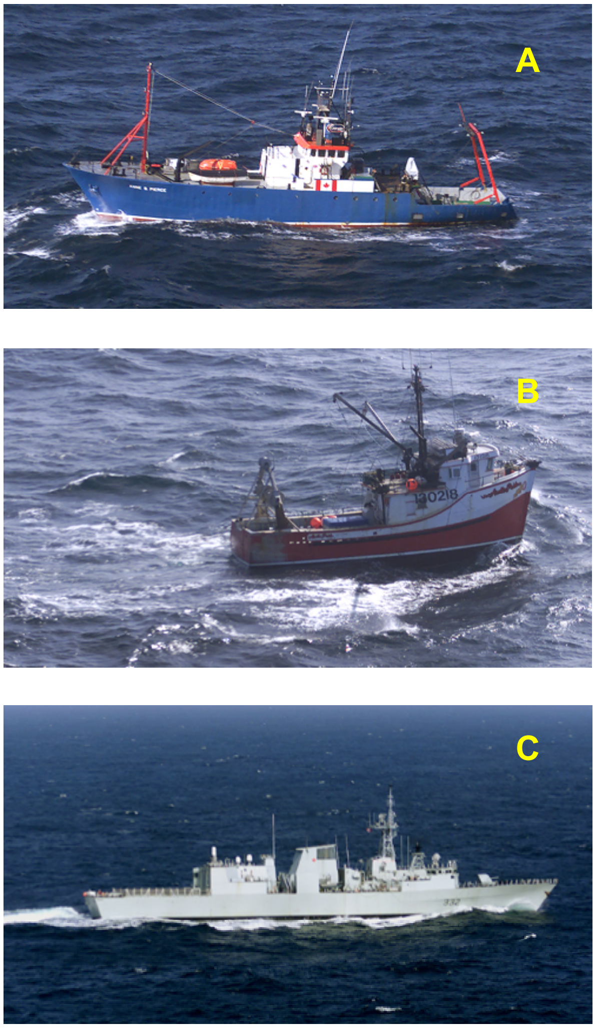

Figure 1, Principal trial ships used in CRUSADE-2000. At the top (A) is the *M/V MS Pierce*, a scalloper. In the middle (B) is the *M/V Arctic Pride*, a trawler. At the bottom, (C) is the *HMCS Ville de Québec*, a Canadian navy frigate.

1.2. SAR-580 System

In this paper, we concentrate on the acquisition and data collected by the SAR-580 system. Although this system is capable of several configurations including both along-track and across track interferometry, the focus of this work was with the polarimetry at C-band. A brief summary of the system characteristics is given in Table II. Important to this discussion is the 6-bit ADC and the hardware range-compression employed in the system architecture which will be discussed further in §1.3. In polarimetry mode, a ferrite switching system channels the transmit signals alternately between pulses to the H and V polarizations, and both polarizations are received. Although the system records 4096 complex samples from each of the two channels from each pulse, not all of this swath falls within incidence angles of interest (20 to 60°). In Figure 2, a typical acquisition geometry is illustrated. It shows that only the near swath is required to meet these needs and this is important in choosing radar configurations which meet restrictions on the dynamic range of the ADC.

Table II. SAR-580 System Parameters.

Parameter	***Units***	***Value***
Antenna		
Polarization		H and V
Peak Gain	dB	27
Elevation Width	°	16
Azimuth Width	°	3
Transmitter		1
		TWT
Chirp Generation		SAW
Power	kW	16
Frequency	GHz	5.3
PRF/V	1/m	3.32 or 2.57
PRF_max	Hz	383x2
Receivers		2
Compression		SAW^{-1}
Digitization		I +Q
		6-bit
Resolution		
Az	m	0.8
Rg	m	6

In addition, the signal timing control (STC) is disabled during polarimetric acquisitions to simplify range-dependent phase and amplitude corrections necessary to calibrate the data.

1.3. Radiometric Challenges

For a 6-bit ADC, the dynamic range of the signal is about 30 dB. Normally the system gain level is set for distributed targets using modelled Gaussian statistical properties of the range-compressed clutter signal. This is not adequate for point targets. In the CRUSADE experiment, there was both the ocean clutter and the ship targets simultaneously present in the scene. Because the range-compression is done through SAW devices and digitization follows this step, the point target energies can be significantly higher than in the 'raw' data stream used in most SAR systems which do not compress the data before digitization.

In Figure 3, we show how the signal power level (in dB) is influenced by a number of factors including range fall off, antenna gain, backscatter level, and target position and size for the HH channel of the radar**.** At the top are the σ^o for an ocean model with 15 knot winds and σ^o_{NE} for the SAR-580 system. There is clearly a

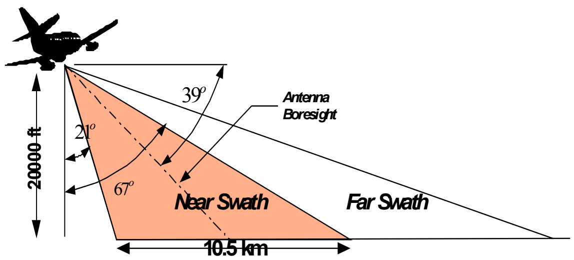

Figure 2. SAR-580 geometry for CRUSADE-2000. The geometry shown is typical of many of the acquisitions. Receive window and antenna pointing were adjusted for specific objectives with consideration of ocean clutter and target size, orientation, and incidence angle.

good SCR over the whole range of incidence angles, θ_{inc}. The red vertical lines show where the ¼ (1024 pixel) range-swath boundaries occur. Below this is the two-way antenna gain for an antenna depression of 30°. The profile of the actual signal level from the clutter after range compression [4] follows. In this case the mean clutter signal varies over 10 dB in the first half swath. At the bottom, is the profile of the SCR (signal to clutter ratio)

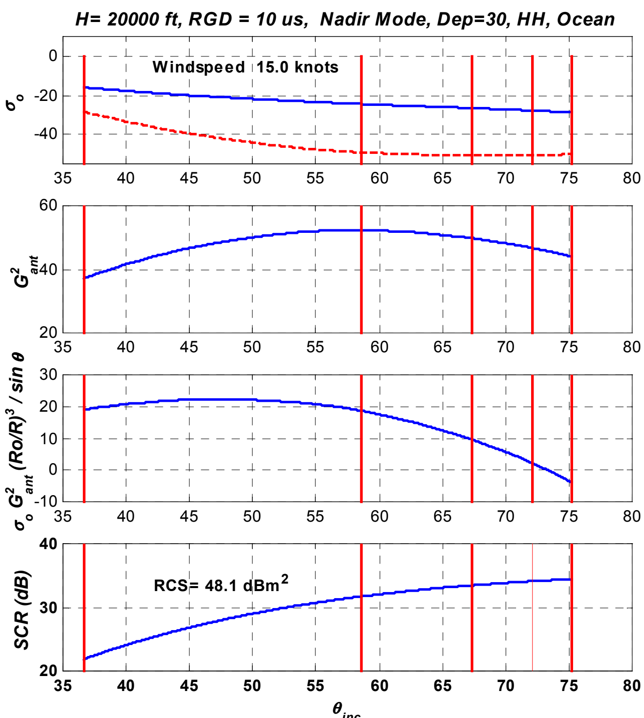

Figure 3. Signal level considerations for CRUSADE-2000.

for the *Ville de Québec* which varies between 20 and 30 dB above clutter. It is clear from considerations like these that successful acquisition of the CRUSADE data set would require a careful acquisition strategy. This is addressed in §1.4.

1.4. Acquisition Strategy

To accommodate the wide dynamic range for the ships and clutter, it was necessary to estimate the system gain settings required for the ship targets before each flight line. Predetermined adjustments were then made down the line in a series of steps: first setting up the radar for normal clutter measurements and adjusting for azimuth

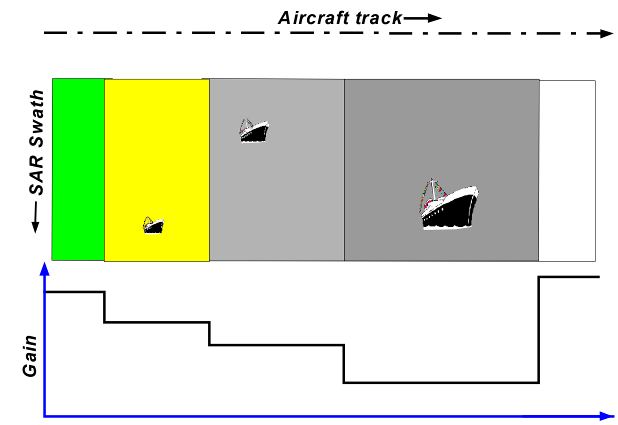

Figure 4. Data collection strategy to manage dynamic range. At the top, a schematic of the image strip is shown with three ships with varying size and orientation in the ocean clutter. The gain, shown as a line graph below, is stepped successively to settings appropriate to the clutter, the three ships, and finally for a noise BITE at the end of the line. This avoids receiver saturation for all target classes provided that the nominal RCS of the ships can be estimated *a priori*.

steering using the clutter lock, locking the steering and lowering the gain in steps for each of the ship targets. This is illustrated in Figure 4.

An objective of the CRUSADE mission was to obtain data over incidence angle ranges between 25° and 55° and aspect angle ranges from broadside to head on. In general, the ships were instructed to maintain headings along the wind direction and flight lines were planned to illuminate several incidence angles and aspect angles by flying a series of passes in a wagon wheel pattern, as illustrated in Figure 5.

Over the two-week acquisition period of the CRUSADE-2000 campaign, the SAR-580 system made 7 sorties and flew 64 flight lines. The conditions and dates of the flights are summarized in Table 3. It shows wind conditions varying from 10 to 35 knots and waves varying from 1 to 5 m. These provided significant challenges especially for the participating small vessels.

1.5. Processing and Calibration

In polarimetric systems, careful attention needs to be afforded to both the relative phase and amplitude of processed data for each of the four channels.

Table III. Summary of SAR-580 Sorties.

Date	*Lines Flown*	*Wind Speed*	*Waves*	*Ships Detected*
		(knots)	(m)	
22-Mar	13	25		16
23-Mar	4	Sea Ice		
24-Mar	11	15	1	10
28-Mar	13	20	4	26
30-Mar	11	35	3-4	19
31-Mar	12	10	1.5	19
Total	**64**			**90**

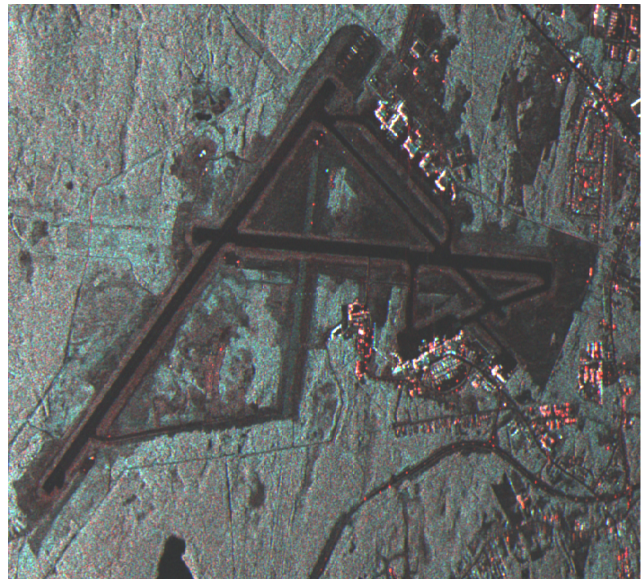

Figure 6. Calibration site at St John's International Airport. Along the middle runway are the image replicas of several tridhedral corner reflectors and active radar calibrators.

For the SAR-580 system, a systematic approach has been developed that relies on both internal and external calibration [5], [6]. Internal calibration involves injection of a common broadband ovenized noise source into the two receivers and using the recorded signal as a measure of the relative gain of the two channels. Absolute calibration and relative channel phase calibration is achieved by use of corner reflectors and active radar calibrators. Because the channel isolation is large, there is no need to an use unmixing formula to separate the channels. During CRUSADE, each aircraft sortie was supported by separate data takes over the point targets deployed on an unused runway which provided a low clutter background. Figure 6 shows real-time imagery over this site.

Processing involves a large number of steps. Briefly these include:

- Stripping the range compressed data from high density media to computer compatible files.
- Examination of the raw data for saturation.

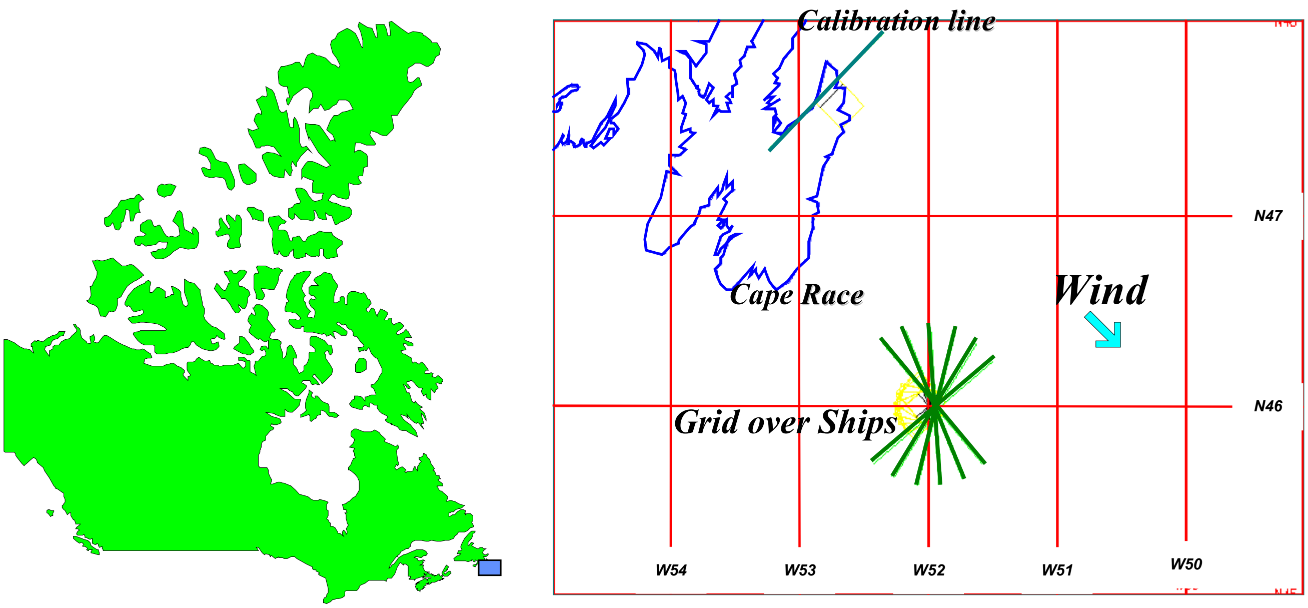

Figure 5. March 28th acquisition plan. At the left is the map of Canada with a blue box indicating the region of the acquisition off the coast of the Province of Newfoundland. Ships were located in the vicinity of 46ºN and 53ºW. A wagonwheel grid pattern was flown around the ships to access the aspect and incidence angles of interest. A calibration line shown near St John's is also indicated.

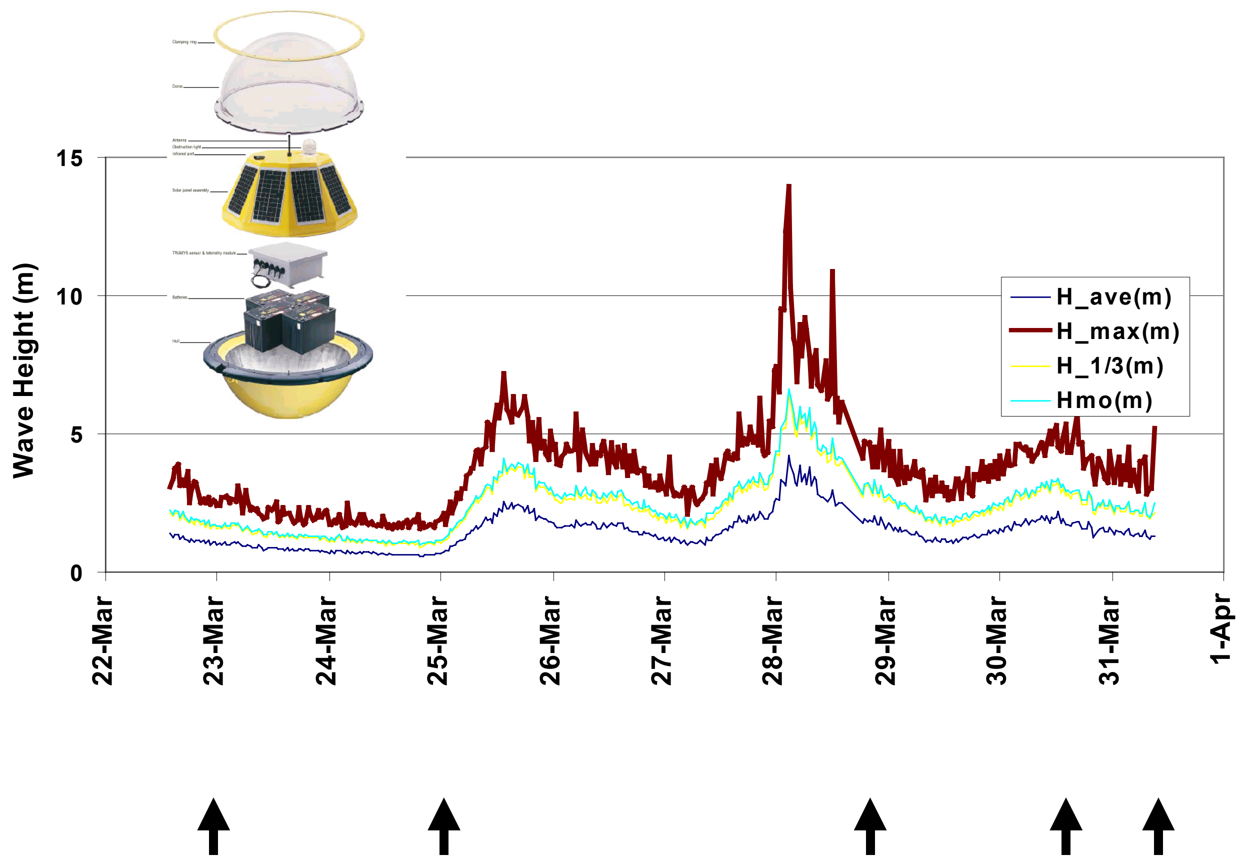

Figure 7. Wave Height Measurements from Buoy Data. The average wave height data are shown as average , maximum, $H_{1/3}$ and mode. Across the bottom , indicated by the arrows, are the actual acquisition times of the airborne sorties. Inset is an exploded view of the buoy from *Axys Environmental Technologies*.

- Recovery of aircraft motion information from inertial and GPS sensors and processing this information to complete the motion compensation step.
- Channel registration and azimuth compression.
- Application of calibration information recovered from external and internal techniques and correction for other systematic issues such as antenna pattern and range falloff.

1.6. Ancillary Data

One of the strengths of the CRUSADE experiment was the instrumentation of several of the participating vessels with weather, position, and motion sensors which allows good characterisation of the total environment of the measurements. Table IV lists the ancillary instruments deployed in the CRUSADE mission.

Figure 7 shows the significant wave height recorded by the wave buoy deployed during the experiment and Figure 8 shows the windspeed and direction information over the same period. Acquisition times by the SAR-580 are indicated by the black arrows. To get a precise correlation of the SAR-580 data with the in-situ data, statistics were gathered over the aperture time of the acquisition for each ship at the ranges appropriate to them

Although only preliminary analysis and integration has been done on the ancillary data set, it is expected that these measurements will be important in the overall interpretation of the results.

2. RESULTS

Most of the results from the CRUSADE-2000 mission are of a preliminary nature [7], [8], [9] because the processing and calibration has been long and arduous so that little time has been available to conduct much analysis. We divide the results below into two sections in which the single channel amplitude data are reviewed and finally the full polarimetric properties of the data set are explored.

2.1. Single Channel Results

In this section, we review single channel results. Previous studies [10] have indicated that at C-band, HH polarization is optimal for ship detection for some conditions while under other circumstances where adequate SNR is available, HV is a better choice. Yeremy *et al.* [7] have suggested that this may be related to incidence angle.

Table IV. Ancillary In-Situ Measurements taken During CRUSADE-2000 Campaign.

Instrument	Measurement	Data Rate	Location	Reference
SeaPath 200	Heading Attitude Position Velocity Heave Roll rate	50 Hz	*Anne S Pierce*	www.seatex.no
POS-MV	Position Roll Pitch Heading Heave	20 Hz	*Anne S Pierce*	ashtead-technology.com
Satlantic MET1000	Wind speed Wind direction Barometric pressure Total radiation Air Temperature Relative Humidity Sea Surface Temperature	1/60 Hz	*Anne S Pierce*	www.satlantic.com
RMC Marine Radar	Directional surface Wave Spectra			
USDOD GPS	GPS recording	1/min	*Anne S Pierce* *Arctic Pride*	
TriAxys Wave Buoy	Aceleration Attitude Wave spectral data	2 /hr		axystechnologies.com

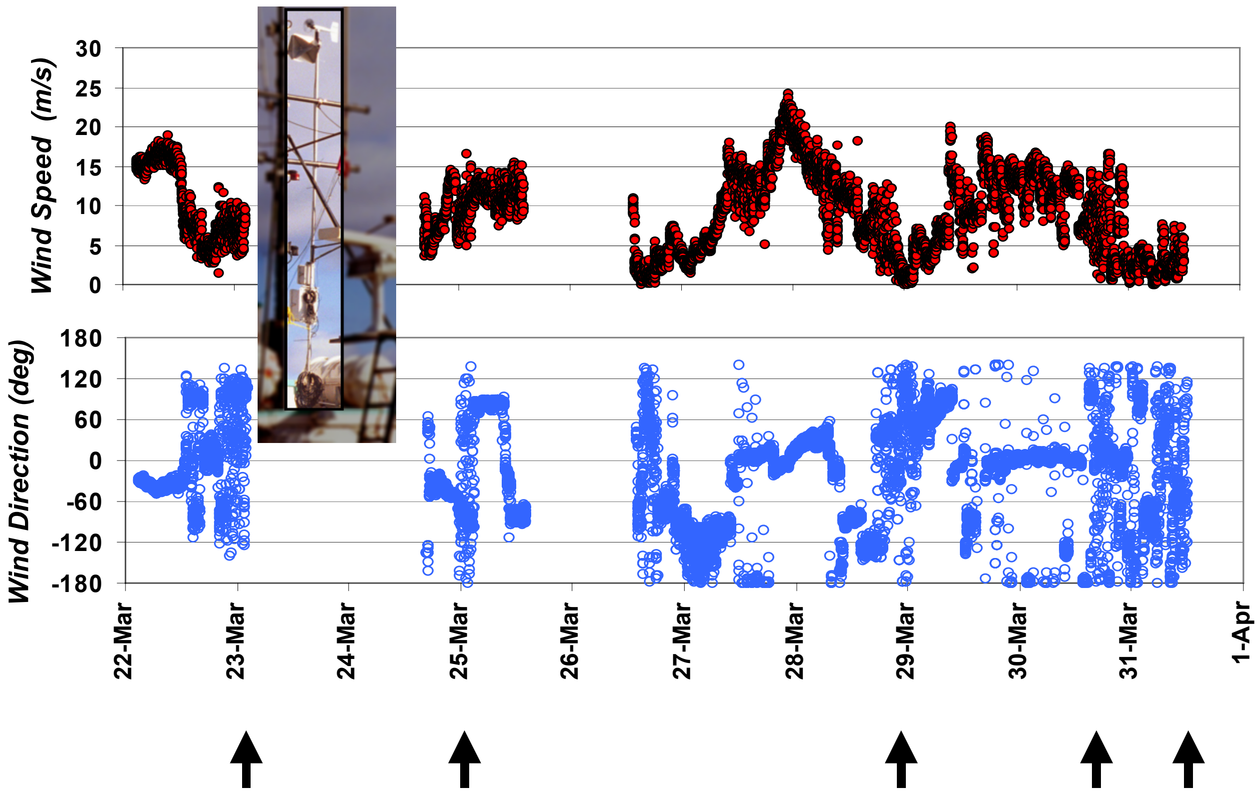

Figure 8. Wind speed and direction measurements over the CRUSADE acquisition period. At the top is the set of individual wind speed and below is the wind direction information. Inset is the weather mast installed on *MV Anne S Pierce* and used to take the measurements.

found that for incidence angles greater than ~45°, HH polarization is advantageous while below incidence angles of ~45°, HV may be more advantageous in terms of SCR. This conclusion is supported by the data shown in Figures 9 , 10, 11, and 12 in which the single channel amplitude data are shown for a sequence of increasing incidence angles. HH polarization is shown across the top and HV polarization across the bottom. The clear advantage of cross polarization at smaller incidence angles is evident at these typical wind speeds Not enough data have been analysed to shown how universal this conclusiion may be.

Measured RCS (Radar Cross Section) with mean and peak SCR are shown for the same ship in Figure 10. We note for broadside

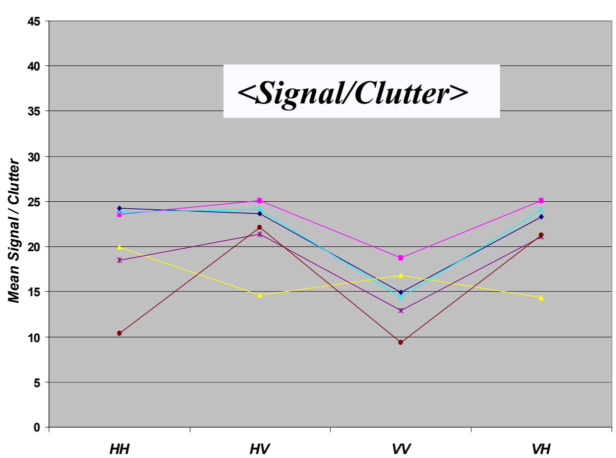

Figure 9. Mean Signal to Clutter for *Anne S Pierce.* The traces represent incidence angles between 35 and 56° and aspects angles between 85 and 288°.

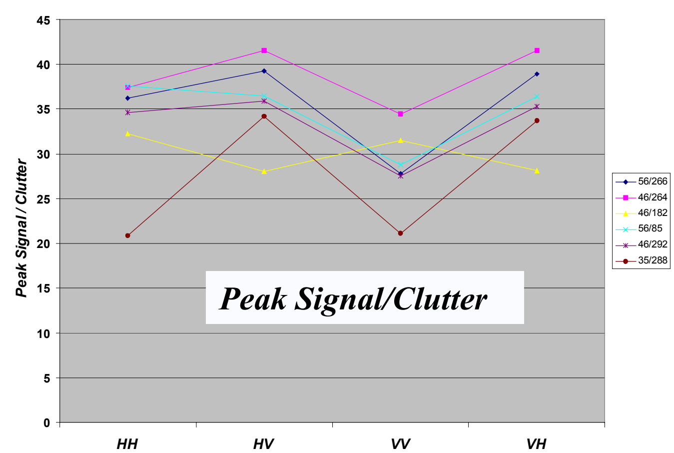

Figure 10. Peak Signal to Clutter for *Anne S Pierce.*

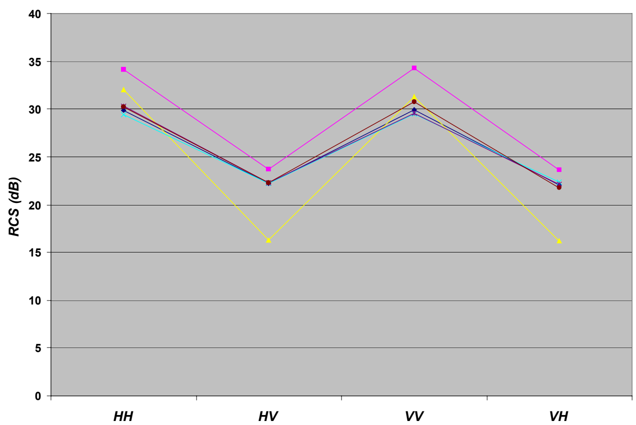

Figure 11. Measured RCS for *Anne S Pierce.*

configurations that $SCR_{HH,HV,VH} > SCR_{VV}$ and that modelled RCS is approximately the same as the measured result with cross polarized RCS typically 7-8 dB lower than like polarized RCS. Peak SCR may be as much as 20 dB higher than average SCR at the highest resolutions available in this experiment. Radar contrast of more than 10 dB were available, however, in all polarizations.

2.2. Polarimetric Results

Relative phase information is added to the amplitude component in polarimetric signatures. To this point, the data set has not been fully assessed but some survey comparisons have been made and some of these are included here.

In Figure 13 are shown the phase properties of the processed data in the vicinity of the *HMCS Ville de Québec* on March 28, 2000 line 3 pass 3. The incidence angle was 59° and the radar viewed the ship toward the stern at an orientation of 149° (as indicated by the inset pictogram). Winds were 4 m/s from 66°.

On the left is the raw unwrapped phase image varying over a range of $-\pi \le \varphi \le \pi$. For the clutter and most of the region of the ship, the phase is random. There is, however, a deterministic pattern in the phase over the central part of the ship that can be discerned with careful observation.

At the right, in contrast to this, is the relative phase image (HH used as reference) which shows a clear difference in the phase of the ocean clutter and a distinct phase signature in each of the contrasted polarizations.

Other examples which demonstrate the additional information available from the full polarimetric signatures are the application of polarimetric filters [11] or classifiers [12], [13]. Although the Cameron decomposition method detects simple geometric shapes, the aggregate of these elemental scattering types may not be suitable for a moderate resolution radar like the SAR-580. This method can be combined with thresholding [7] to illustrate the potential of one more advanced technique of utilizing the full potential of polarimetric SAR.

In Figure 14, we show the application of this technique to ship targets from the trial. It is likely with adequate resolution and sufficient study that unique decompositions might be possible for particular classes of ships. Clearly the example shows the potential of such methods. It is not however held up as being optimal.

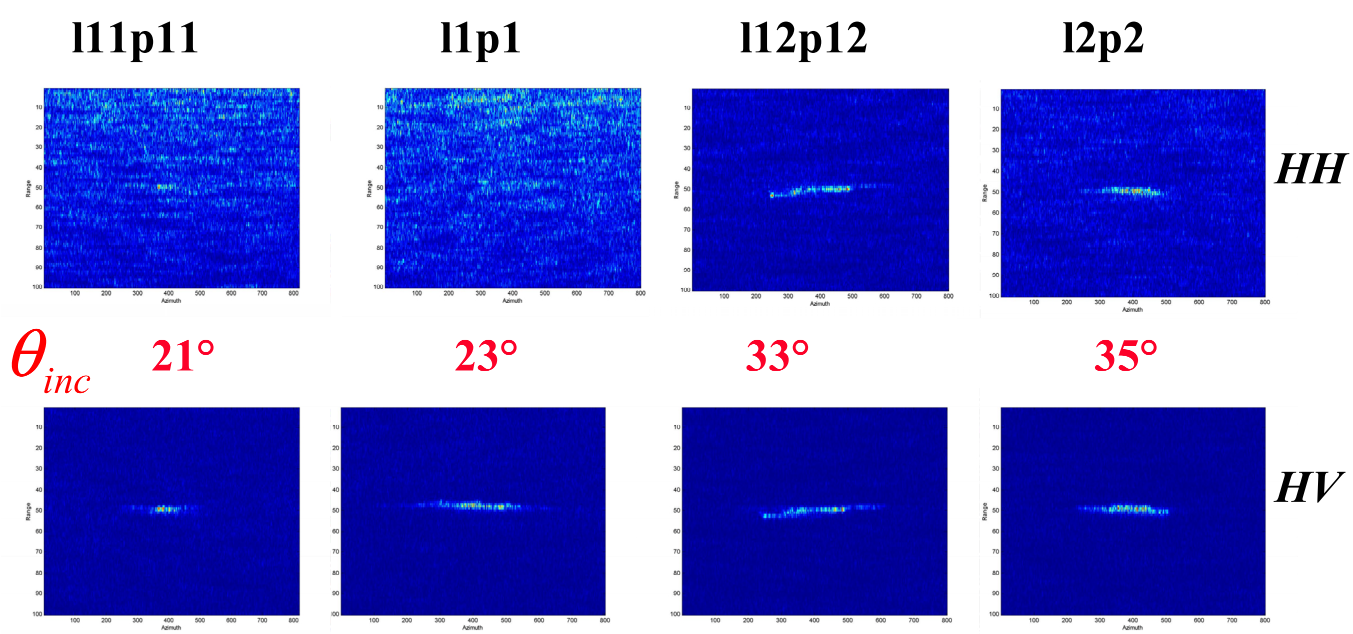

Figure 12. Comparison of HH and HV channel from *MV Anne S Pierce* on March 22, 2001.

3. CONCLUSIONS

In this paper, we have tried to give an overview of the CRUSADE-2000 experiment emphasizing the work done with the SAR-580 system. The experiment was carefully planned to include adequate information concerning the position and orientation of the participating vessels, and the wind and wave conditions during the mission. Although the SAR-580 system is somewhat dated in its capabilities and was designed for work with distributed targets [4] limitations in the system were overcome in the acquisition and many passes including ships at different orientations and incidence angles were obtained.

Although the analysis of the data sets are still at a preliminary stage, some conclusions have been reached from observations of specific ships. The generality of these results need to be tested with more examples and further analysis on the rest of the data set. We expect that this work will continue with contributions from several of the partners in this experiment.

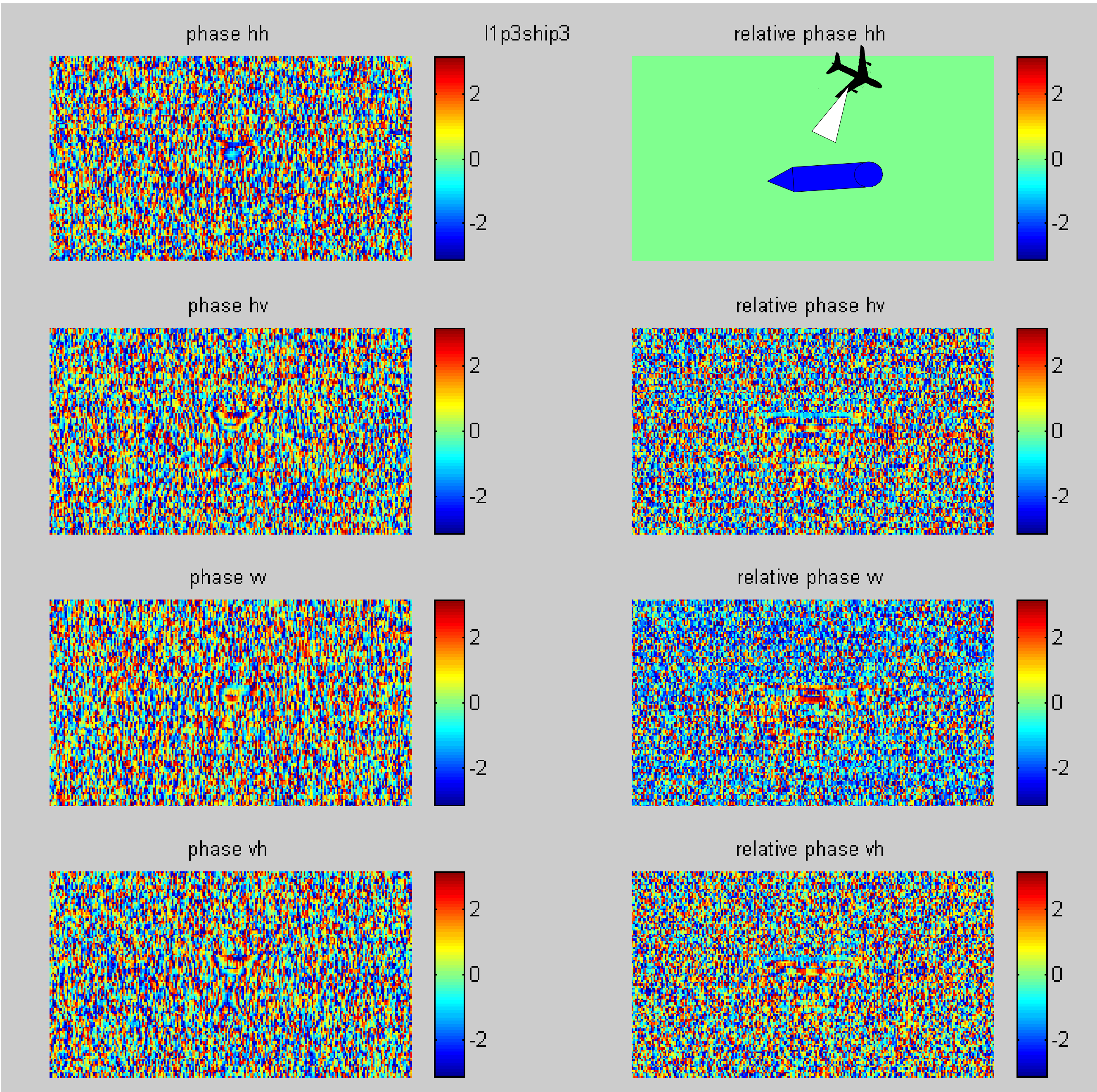

Figure 13. Phase Properties of *HMCS Ville de Québec* from line 3 pass 3 March 28, 2000. At the left is the phase image over the region of the ship and at the right is the corresponding relative phase image. The colour wheel shows the unwrapped phase range of -±π.

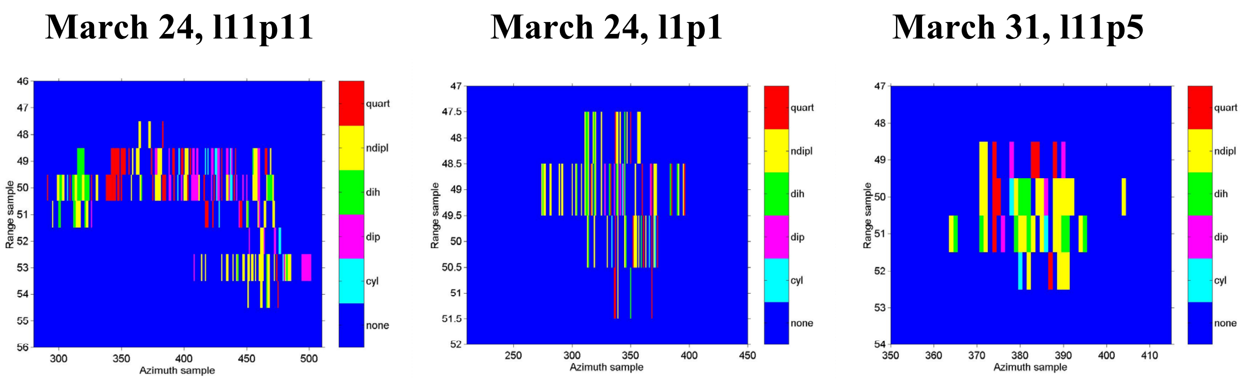

Figure 14. Cameron Decomposition for a series of ship targets.

The opportunity to test new polarimetric tools against a well characterized and calibrated data set has begun and these clearly show that polarimetry can offer improved target discrimination. Work on optimizing these tools is also progressing [11].

4. *ACKNOWLEDGEMENTS*

It is a pleasure to thank the members of the CRUSADE team for their contributions to the success of this multi-discipline activity. Overall coordination of the mission was done by WC Bayer of *SARCORP.* The pilots and crew of the SAR-580 system including Bryan Healey, Bill Chevrier, Reid Whetter, Doug Percy, and Theo Blume were instrumental to its success. The provision and outfitting of the participating vessels with their sensor complement as well as raw data was done by *Satlantic,* in Halifax. The cooperation and support of Environment Canada and especially Carl Brown is also gratefully acknowledged. The advice and guidance of Ridha Touzi, Laurence Gray, John Wolfe and especially of Paris Vachon during and before the trial were also very much appreciated and were instrumental to its success.

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