High Resolution Sea Surface Mapping Radar System

June 1, 2004

Sponsored by
Defense Advanced Research Projects Agency (DOD)
(Controlling DARPA Office)

ARPA Order P372/24

Issued by U.S. Army Aviation and Missile Command Under

Contract No. DAAH01-03-C-R253

Submitted by

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Effective date of contract: 7/1/2003
Short Title of Work: Phase I SBIR Final Report

Contract Expiration Date: 2/28/2003
Reporting Period: June 1st, 2003 through March 24th, 2004

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 JUN 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **High Resolution Sea Surface Mapping Radar System**	5a. CONTRACT NUMBER **DAAH01-03-C-R253**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **ProSensing, Inc., 107 Sunderland Road, Amherst, MA 01002**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**16**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Declaration of Technical Data Conformity

The Contractor, **ProSensing Inc.**, hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No. **DAAH01-03-C-R253** is complete, accurate, and complies with all requirements of the contract.

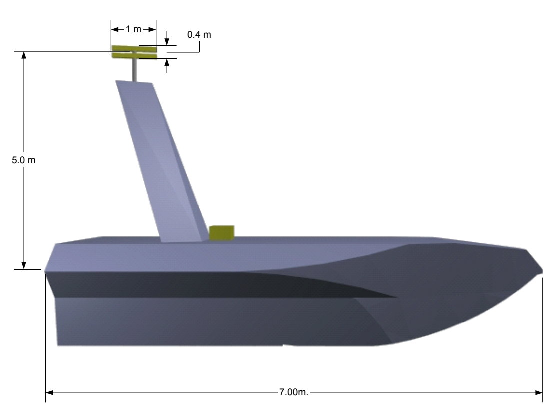
Date: 12/19/2003

Name and Title of Authorized Official: **Dr. Ivan PopStefanija**

Executive summary

This Phase I SBIR Final Report addresses the development of a novel rapid scanning radar interferometer designed to map the surface topography of the ocean surface within several hundred meters of an unmanned surface vehicle (USV). A system capable of mapping local sea conditions can help stabilize a USV in high seas by providing input data to an adaptive vessel control system. The proposed interferometer will operate in much the same way as conventional marine radar, enclosing a rotating pair of fan beam antennas in a radome near the top of the USV to provide 360-degree coverage. The system described in this report is based on proven radar interferometry technology developed for oceanographic research applications. As part of this contract we developed a software simulation of the mapping process, accounting for realistic sea states and expected radar parameters. Based on the results of these simulations we designed a prototype system, including the radar, data system, and auxiliary sensors and interfaces necessary to implement real-time stabilization of a USV.

The interferometer operates in much the same way as a conventional marine radar, enclosing a pair of azimuthally scanning fan beam antennas in a radome near the top of the USV to provide 360 degree coverage. To create an interferometer, the antennas are stacked one above the other, with a vertical gap of several tens of wavelengths separating the antennas. Data from the antenna pairs are cross-correlated and processed to extract a map of the surface contour with 3 m range resolution to ranges in excess of several hundred meters. These maps, updated every 1-2 seconds, can be used to track ocean waves and with further processing may be used to automatically steer the USV.



Introduction

Problem Statement

In the future, naval missions in the littoral zone will depend more heavily on a variety of unmanned platforms, including unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs) and unmanned surface vehicles (USVs) [1]. For example, the U.S. Navy will spend $55 million over the next six years to develop the unmanned Spartan Scout USV, based on existing high-speed Rigid Hull Inflatable Boats (RHIBs). Shown in Figure 1, the Spartan Scout will add defense and weapons systems to the RHIBs and will be configured for autonomous or remotely piloted use. The Spartan will be used in a variety of missions, including littoral antisubmarine warfare, mine warfare, torpedo defense, and intelligence, surveillance and reconnaissance [2,3].

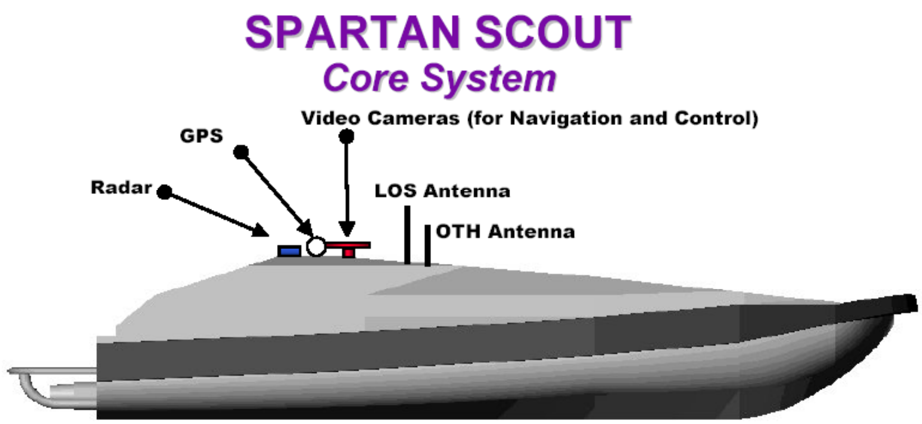


Figure 1. Spartan Scout Unmanned Surface Vehicle, figures courtesy [2,3].

One outstanding issue for the use of USVs is stabilization of the vessel in storms and heavy seas. A system capable of mapping local sea conditions and commanding an adaptive vessel control system would have the ability to implement throttle control to avoid large waves, and to steer the boat to minimize rolling and pitching. A key element of any adaptive stabilization system would be a remote sensing system that could rapidly map the ocean surface height profile at short ranges (less than 0.5 km).

To meet this need, ProSensing carried out a Phase I SBIR study of a **rapid scanning radar interferometer**, based on proven technology developed for oceanographic research applications. The interferometer operates in much the same way as a conventional marine radar, enclosing a pair of azimuthally scanning fan beam antennas in a radome near the top of the USV to provide 360 degree coverage. To create an interferometer, the antennas are stacked one above the other, with a vertical gap of several tens of wavelengths separating the antennas. Data from the antenna pairs are cross-correlated and processed to extract a map of the surface contour with 3 m range resolution to ranges in excess of several hundred meters. These maps, updated every 1-2 seconds, can be used to track ocean waves and with further processing may be used to automatically steer the USV.

Benefits from the interferometer system

1. Improved survivability of USV in heavy seas through automatic throttle and steering to avoid or minimize the ship's response to large waves.

2. Navigational aide for small to mid-sized vessels to optimize course in heavy seas.

3. Combining interferometer data with forward prediction models, brief periods of quiescent seas can be predicted allowing launch of weapon systems, or safer shipboard landing of aircraft.

4. Fatigue mitigation by reducing vertical and horizontal motion of ship through automatic steering (human factors).

Baseline technology

Currently there is no navigational aid that reports sea state or waves surrounding small to mid-size boats. Instead, ships pilots must interpret the visible sea surface and ships handling to judge the sea state.

Radar Interferometer Principals of Operation

In general, interferometers consist of two or more independent receivers, separated by a known distance, typically much greater than the operating wavelength. By comparing the phase of the received signal from a common source, e.g., the scattering cell on the ocean surface, the height of the source can be measured, relative to a reference plane. Referring to Figure 2, the instantaneous surface height, *h*, can be found knowing the radar wavelength, λ, antenna separation, B_a, antenna tilt angle, α, the incidence angle, θ, the radar range, R_1, and the short term average phase difference, $\phi = \arg\langle V_1 V_2^* \rangle$, between the measured voltages at the antennas, V_1 and V_2:

$$h = H - R_1 \cos\theta$$

where

$$\theta = \cos^{-1}\left[\frac{(R_1 + \Delta R)^2 - B_a - R_1^2}{2B_a R_1}\right] - \alpha$$

and

$$\Delta R = R_1 - R_2 = \frac{\arg\langle V_1 V_2^* \rangle \lambda}{2\pi}.$$

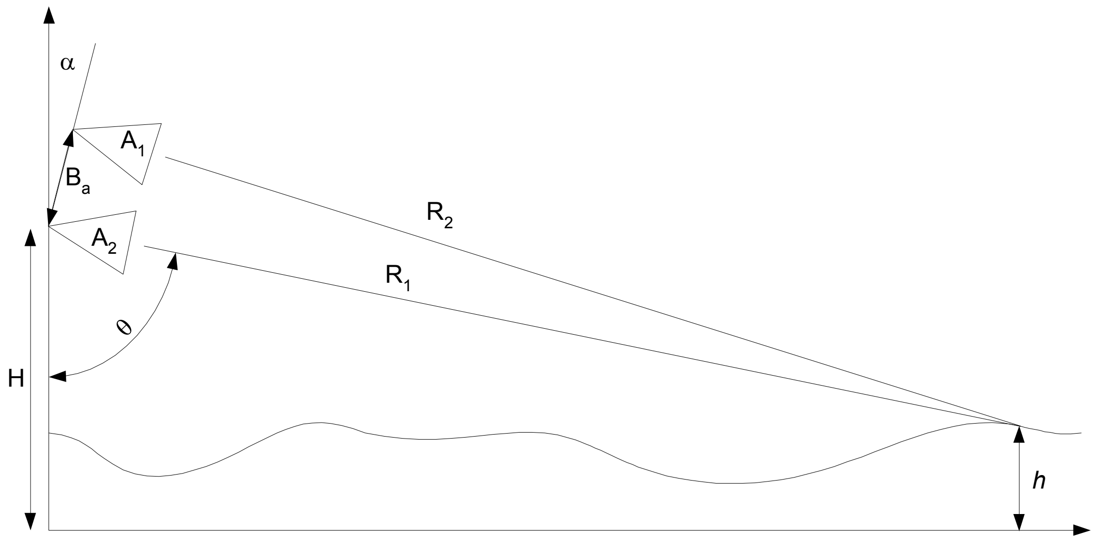


Figure 2. Geometry for interferometer measurement of surface height, h.

Thus, estimates of the phase differences between antenna voltages V_1 and V_2 as a function of range and scan angle can be used to map the surface topography. The surface topography imaging problem is constrained by the necessity of gathering a sufficient number of independent samples necessary to estimate $\arg\langle V_1 V_2^* \rangle$, somewhat limiting the scan rate of the radar. Furthermore, aliasing of $\arg\langle V_1 V_2^* \rangle$ as a function of height, *h*, requires the use of a phase unwrapping algorithm to properly map the surface topography.

Radar simulator software development

During the first half of Phase I, we focused on the development of software designed to simulate the wave measurement process. Figure 3 shows the flow chart of this software, which captures its main features.

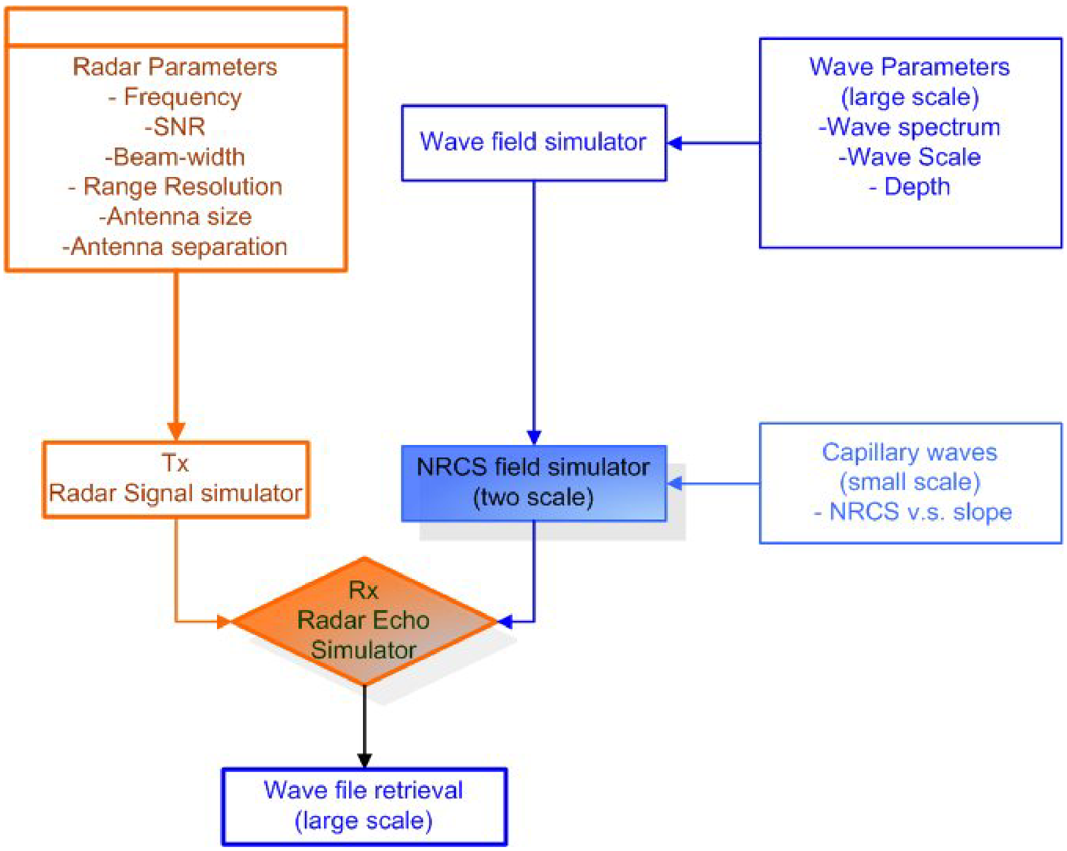


Figure 3 Wave sensor simulator flow chart

The software consists of two distinct modules:

- **Wave Simulation.** Input parameters to this module include: ocean wave spectra, spatial resolution, ocean depth, energy fraction, capillary waves spectrum and Normalized Radar Cross Section (NRCS). It generates following products (in this order):
  1. Directional Wave Spectrum
  2. Time-evolving wave-field (ocean surface) and
  3. NRCS field of the ocean surface

- **Radar signal simulator** is used to generate description of the transmitted radar signal. Inputs to this module include a wide range of parameters grouped into three categories:
  1. Basic radar parameters such as pulse width, pulse repetition frequency (PRF), center frequency, etc.
  2. Radar geometry, including the number of antennas, antenna beamwidth and bandwidth and placement of the transmitting and receiving antennas.
  3. Inteferometric modes, including single pulse interferogram, alternating pulse interferogram, single transmitting antenna or switching transmitting antennas.

The simulation software was developed using the IDL language. The user configures and executes the simulation through the GUI shown in Figure 4. Selectable wave spectrum parameters are shown in Figure 5.

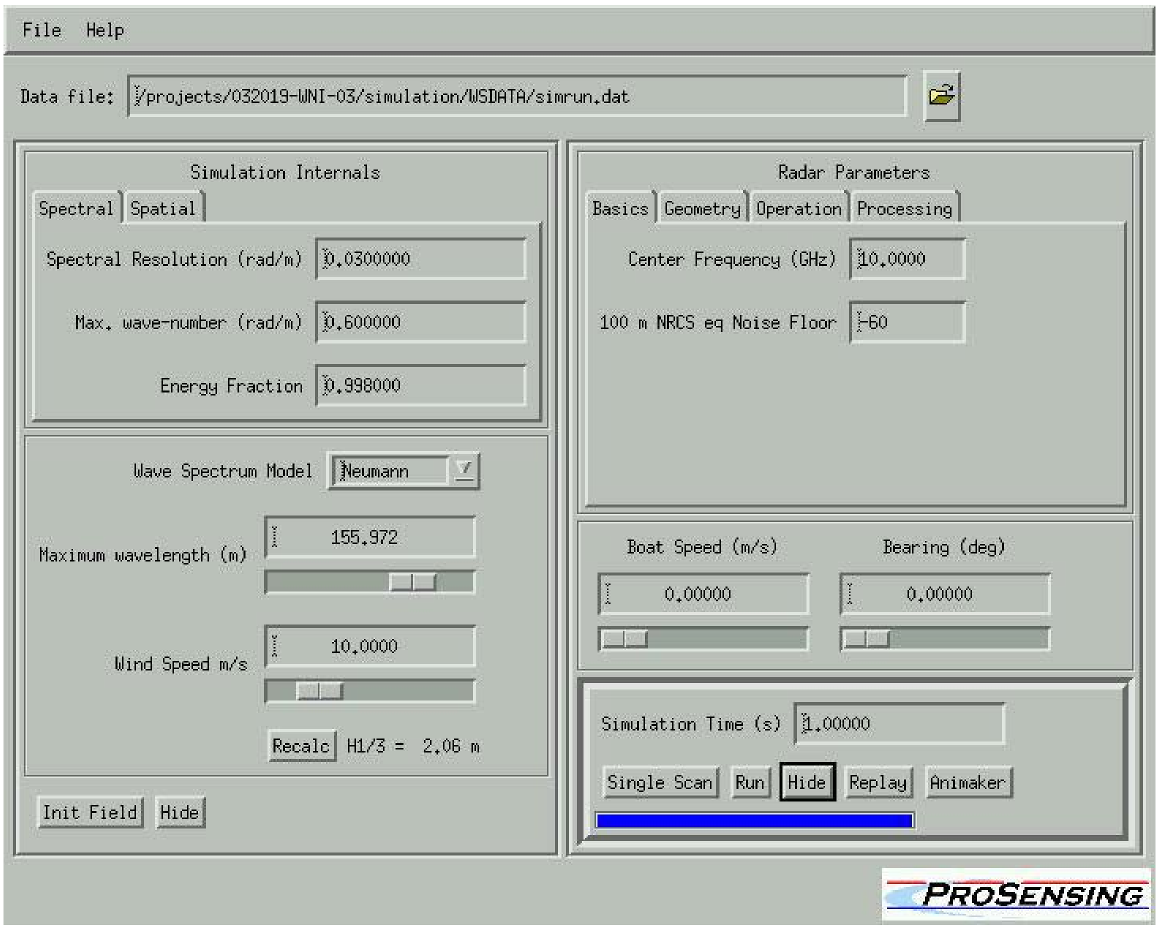


Figure 4 GUI for the Wave Sensor Simulation Software

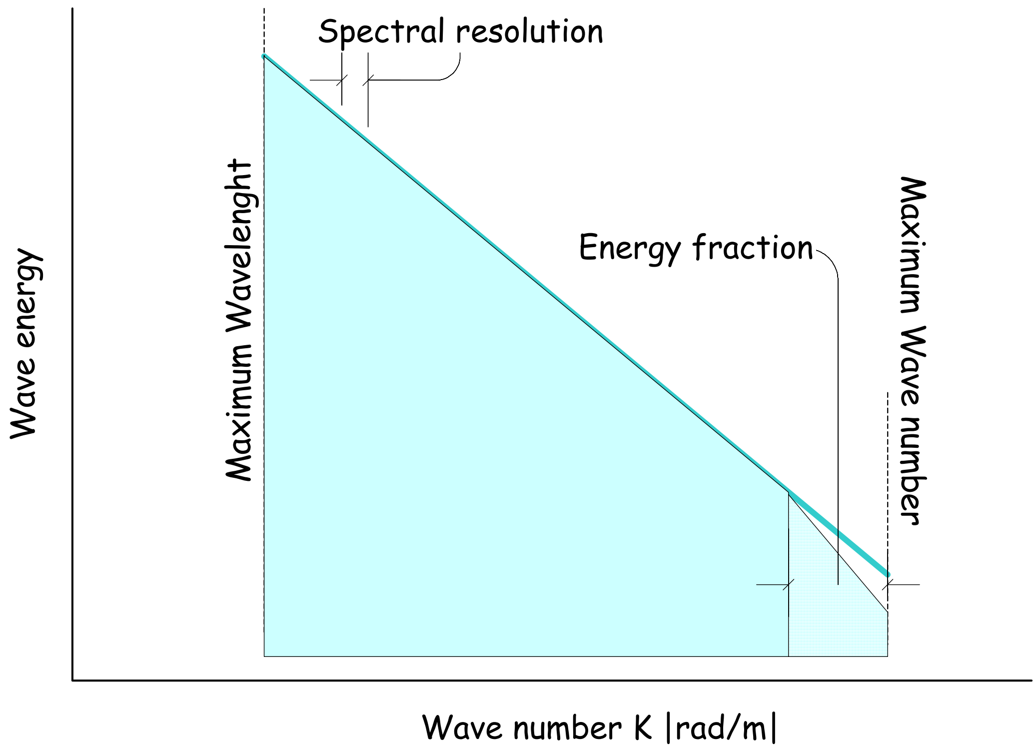
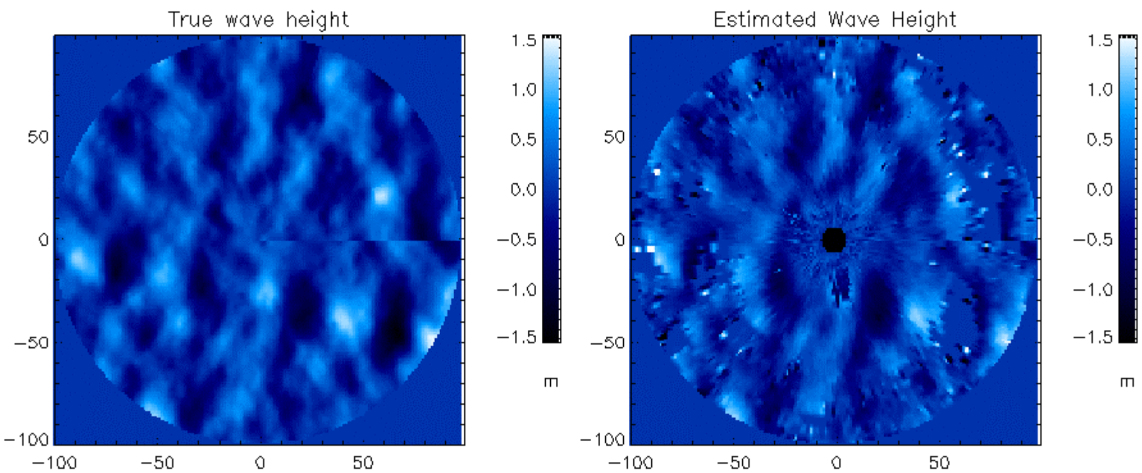


Figure 5. Wave spectrum input parameters.

Having selected a set of ocean wave and radar operating parameters, the software generates a simulated two-dimensional ocean surface radar echo. This echo evolves with time, as the simulated ocean surface wave field moves through the radar's field of view. The interferometric phase difference between the upper and lower antenna is then used to compute the absolute wave height, from which other parameters, such as wave slope, may be derived. These data products (wave height and slope) are the products that would be used for boat steering and navigational purposes.

The software displays the "true" wave height and slope, which was generated by the wave simulator, simultaneously with the radar-estimated wave height and slope. Figure 6 shows the input and retrieved wave height, while the input and retrieved wave slope are shown in Figure 7. Estimated RMS height and slope errors based on input and retrieved wave fields are plotted in Figure 8.



• Figure 6 Simulated input wave height (left) and retrieved wave height (right) as measured by the wave sensor.

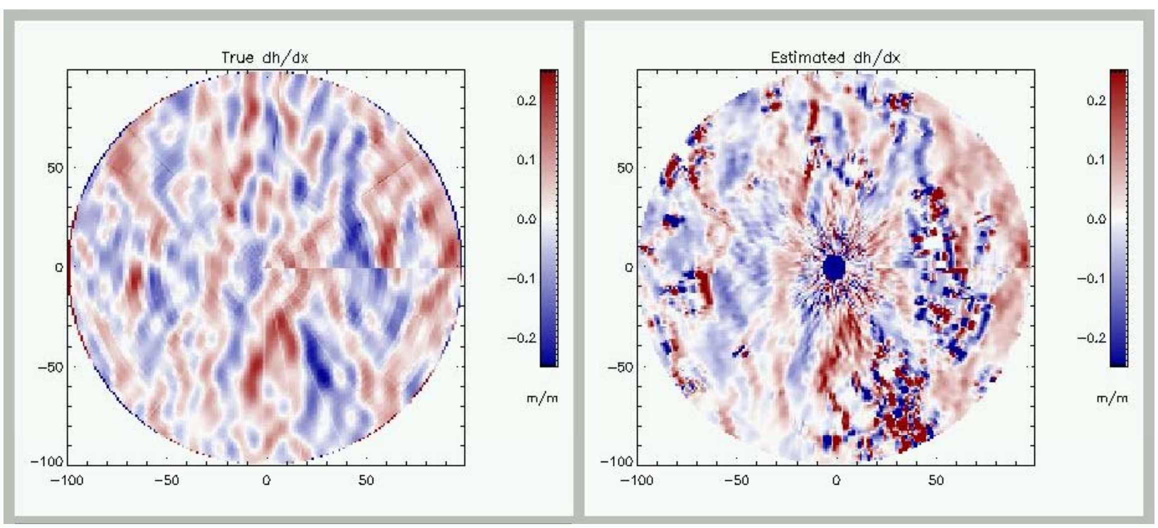


Figure 7 Simulated input wave slope (left) and retrieved wave slope (right) as measured by the wave sensor.

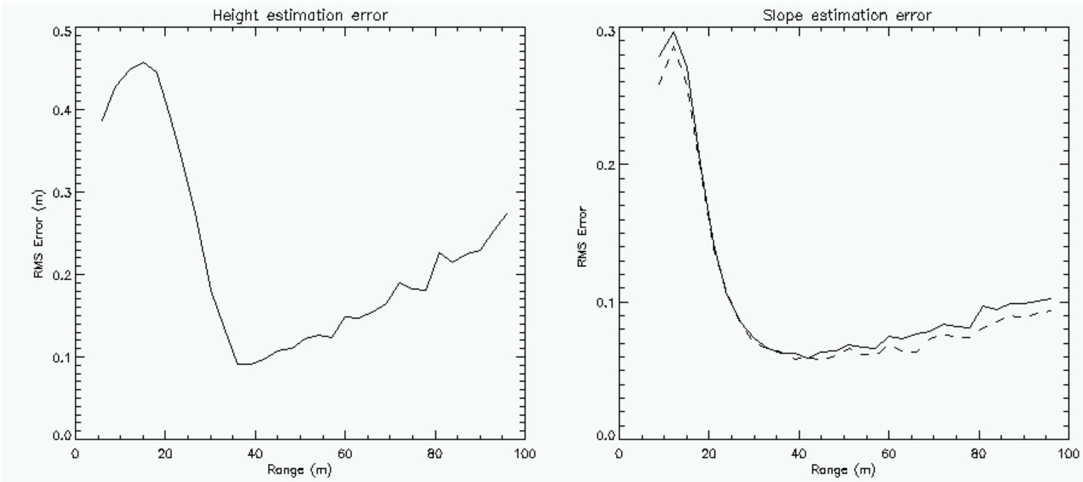


Figure 8. Height estimate error for choppy sea (H1/3=1.4 m).

Wave sensors range of operation

Based on our simulations, the wave sensor should provide ocean surface height estimates to ranges of several hundred meters, depending on the sea state. Combined with a wave prediction algorithm [4] this data would allow for about 10 seconds of ocean wave field predictability. The range resolution of the system will be 3 m, allowing Nyquist sampling of the ocean surface for wavelength in excess of 6 m. This sampling resolution will allow wave mapping for all waves equal or larger than the length of a smallest USV (7 m to 10 m).

System design

A functional block diagram of the interferometer system is shown in Figure 9. Details of the design are presented below.

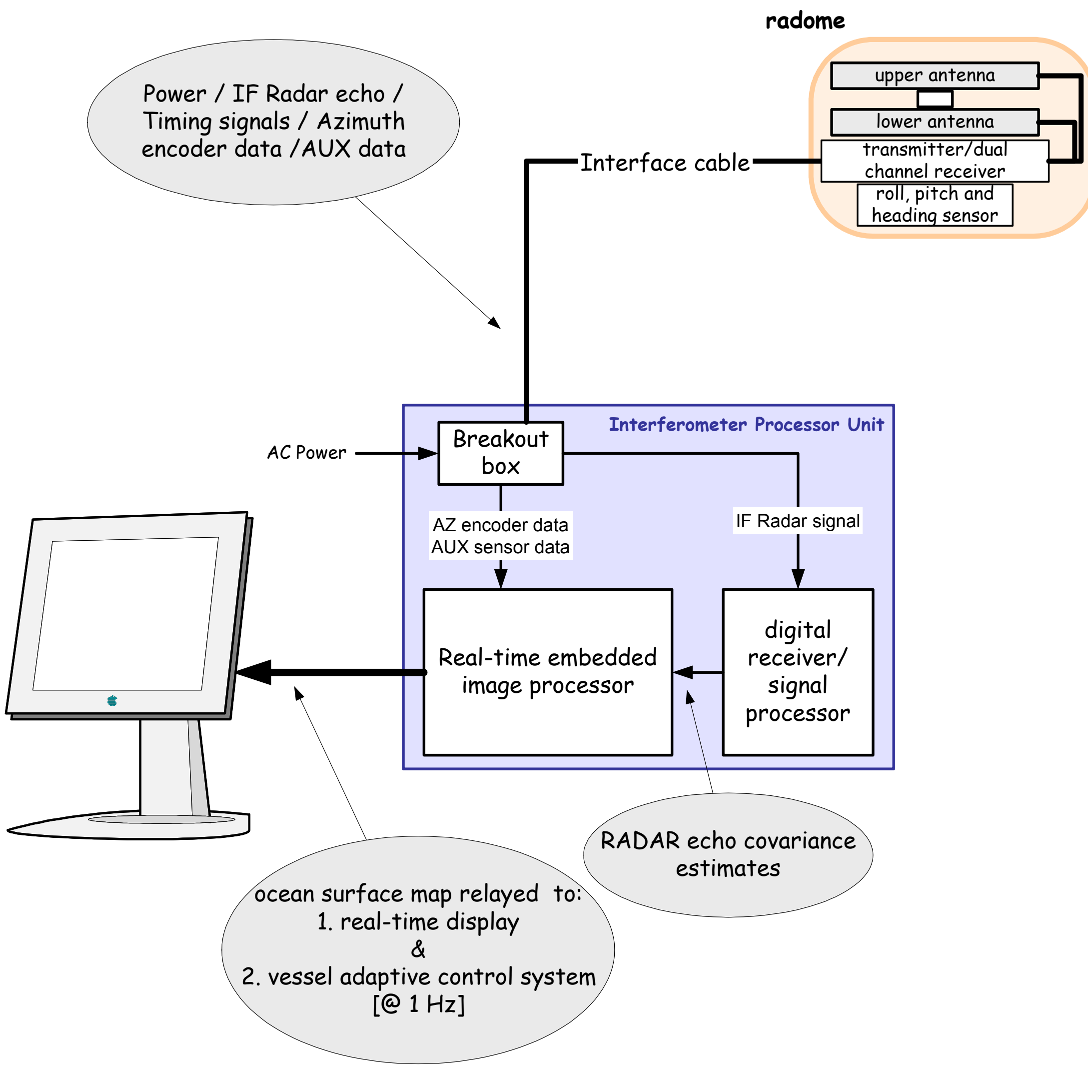


Figure 9. X-band Interferometer system block diagram.

Operating frequency

The optimal operating frequency for a ocean surface interferometric radar is approximately 10 GHz. The rationale for this choice included the following factors:

1. The radar sea echo at off-nadir incidence angles depends on the presence of capillary waves, sometimes also called wind waves. Higher frequency radar signals interact with short capillary waves of shorter wavelengths. These short wavelength capillary waves exist on the ocean surface for a short time, on the order of few seconds, and their presence is highly correlated with wind gusts. On the other hand, X-Band signals interacting with centimeter ocean waves have much longer lifetime.

This provide for a more stable backscatter more evenly distributed over the scanned ocean surface area.

2. Choosing a lower frequency, such a C-Band (4 to 8 GHz), will lead to impractical antenna sizes to achieve the desired azimuthal image resolution. The choice of X-Band allows for design of small compact system which will be practical to use even on a small vessels such as the 7 meter SPARTAN USV.

3. RF component technology is well developed at X-Band, with a broad selection of components at low cost.

Antenna system

The proposed antenna system consists of two identical slotted waveguide antennas with a rectangle aperture [horizontal extent = 1 m and vertical extent = 10 cm]. The antennas would be vertically stacked with a separation of approximately 10 cm. The antennas are synchronously rotated in azimuth for a full 360 degrees at a rate of 30-60 rpm.

Both antennas will be used for transmission and reception of the radar signal. In transmit mode, the transmit pulse alternates between the two antennas. The received signal on both antennas is processed simultaneously on each pulse of the radar. This switching mode configuration is implemented to minimize the phase error in the measured radar ocean surface images.

For proper operation of the interferometer, the antenna system needs to be installed at a significant height above the sea surface. The higher the antenna system is, the smaller the obstruction of the transmitted radar signal by large ocean waves (i.e., shadowing effect). This effect becomes prominent at near grazing angles. For example, using the simulation software, we have estimated that for an antenna height of 5 m mild seas (with $H/\lambda = 1/30$, where H is the significant wave height and λ is the dominant wavelength), the shadowing effect becomes predominant for ranges exceeding 160 m (i.e., more than 50% of the ocean surface is shadowed beyond 160 m). Our assessment is that for small vessels like SPARTAN (L = 7 m) the interferometer could be on installed on a mast at least 5 m above the sea surface.

Azimuthal resolution of the interferometer will be limited to the azimuthally antenna beamwidth. For proposed antennas, the beamwidth in azimuth is 1.8 degrees and in elevation about 18 to 20 degrees. This translates into azimuthal spatial resolution of 3 m @ 100 m range and 6 m @ 200 m.

Transmitter

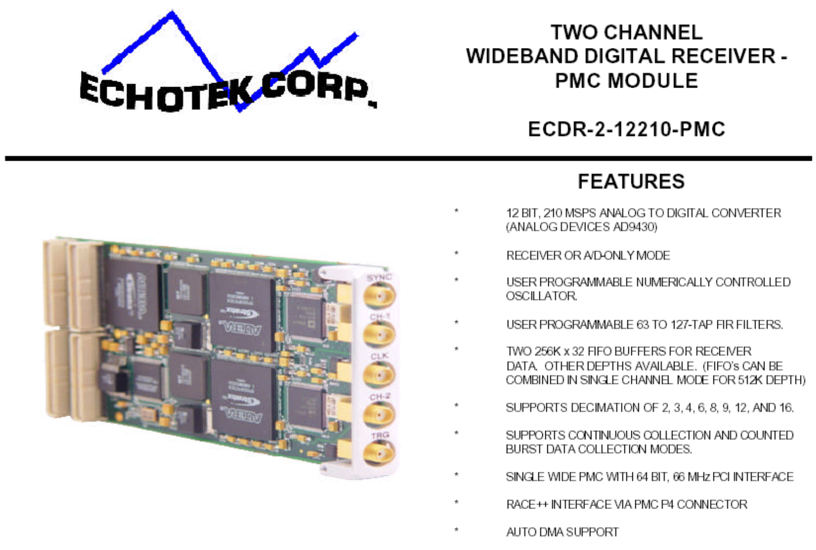
Because of its short range of the operation, the interferometer can use a solid-state transmitter to achieve a high level of sensitivity Solid-state transmitters are small in size and more reliable in comparison with high-voltage tubes and their associated modulators. Based on a signal-to-noise analysis for pulse length limited scattering [5], the minimum detectable NRCS will be –55 dB m2/m2 at 100 m range with a 1W transmitter for 20 ns pulse length (3m range resolution).

Receiver

The level of sensitivity stated above requires a receiver noise figure of 3 dB and receiver front end losses of 2 dB (for the T/R network and short cable run to the antenna). These specifications are easily met with currently available COTS microwave low noise amplifiers, cables and T/R switches. The receiver will employ a single down-converting stage with an output frequency of 160 MHz with 50 MHz of signal bandwidth to preserve the 3 m range resolution.

Digital Receiver and Signal Processing

Commercially available 2-channel digital receivers sampling at 200 MS/s (e.g., Echotek ECDR-2-12210-PMC,) can be used to sample and digitally filter the IF offset signals from the two receiver channels. We have implemented a PC-based data system using a similar single channel digital receiver from Echotek for a weather radar application. This system operates with very high sustained data throughput (50 Mbytes per second) with the host PC providing real-time processing of similar covariance-based algorithms. When operated at 10 kHz PRF, the data rate after digital filtering to 50 MHz will be 32 Mbytes per second for 400 m range coverage.



• Figure 10. Dual channel 200 MHz digital receiver from Echotek Corporation.

Once the covariance estimates are made, additional processing is necessary to adjust for roll, pitch and yaw of the ship. Auxiliary roll/pitch and heading sensor data will be used to realign the radar data into the local horizontal plane. In a previous deployment of a shipboard radar wind profiler, ProSensing used a dual axis tilt sensor and electronic heading sensor to convert radar data from the antenna coordinate system into a world coordinate system through simple matrix manipulations.

Mechanical Layout

A conceptual diagram showing the layout of the X-band radar interferometer is shown in Figure 11. The RF electronics will fit in a small weather tight enclosure that can be mounted directly below the scanning antennas. The size of entire enclosure to be installed on the mast is approximately (in meters) 1.0Wx0.3Hx0.40D; the estimated weight is 30 kg. The IF output of the RF enclosure at 150

MHz is directed through a long cable to the digital receiver card mounted in a PCI slot of a rack-mounted PC. Figure 12 shows the conceptual drawing of the install interferometer on a mast of a small USV. Data display and user interface in the prototype system will be handled from the PC. Commercialized versions of the system will have a custom display and control interface.

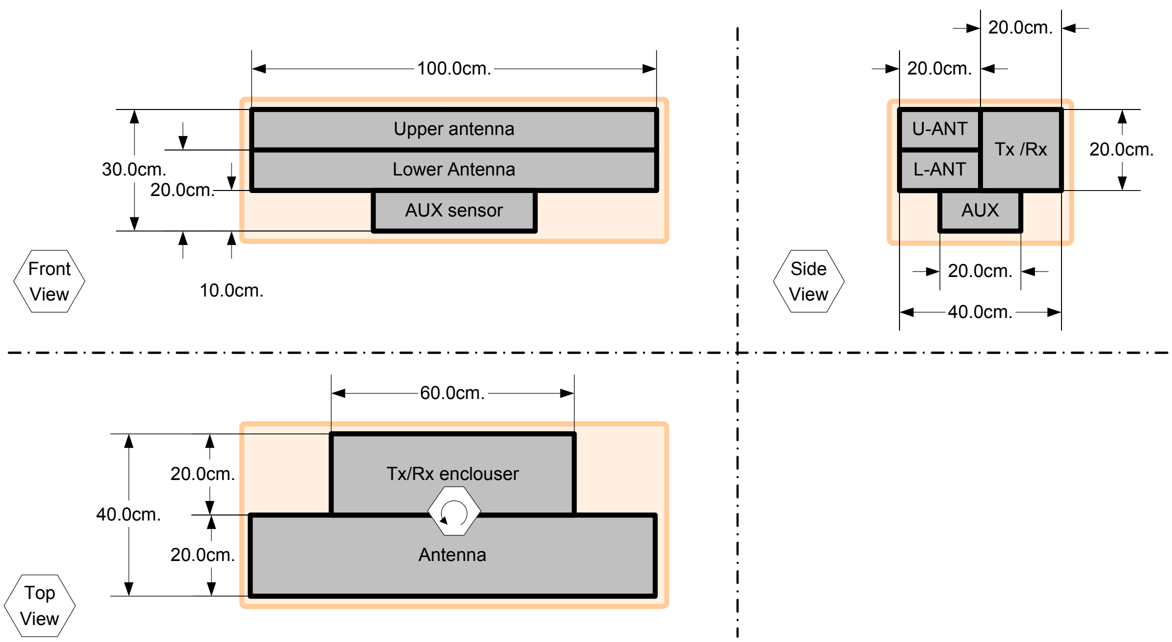
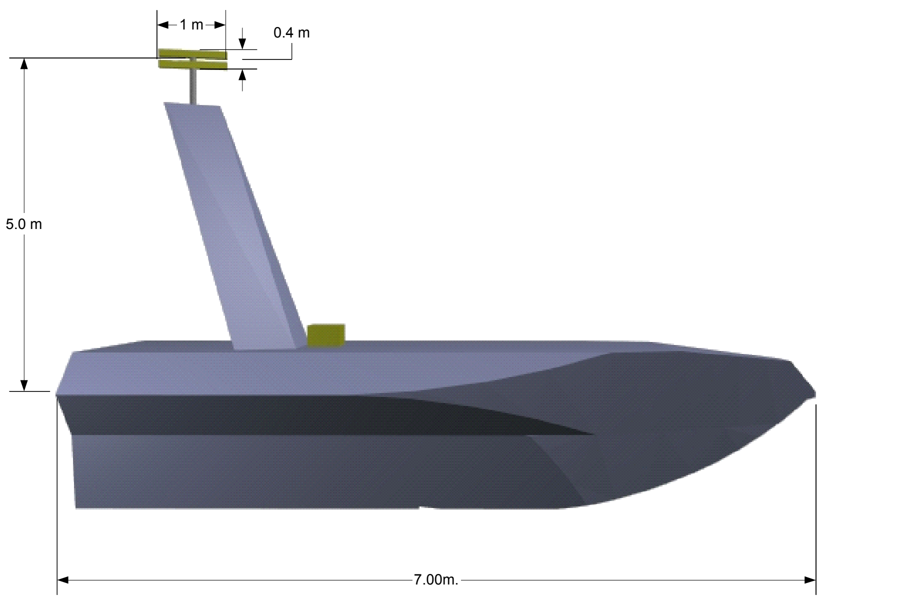


Figure 11 Mechanical drawing of the interferometer antennas and RF electronics.



• Figure 12. Conceptual diagram of radar interferometer system.

Technology Availability

All of the technologies investigated in this report are readily available, either as COTS subsystems (transmitter, receiver, digital receiver and processor), or as routine custom designs (antenna and spinner). Phase II development of the complete instrument can take place in 18 months.

Conclusion

This Phase I SBIR study demonstrates the ability of a low power, solid state X-band radar interferometer to measure ocean surface topography at fine spatial scales (3m x 3m resolution) with fast update rates (1 second per scan). If successful, Phase II will result in the construction and deployment of a demonstration system that will compute and display real-time estimates of ocean surface wave height. Once a prototype is developed, at the end of Phase II, preliminary comparisons to wave meters can be carried out from a research pier, like the one in Duck, NC operated by the Army Corps of Engineer. Further tests from a small vessel can be carried out to demonstrate operation from a moving platform.

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