

Ocean Wave Height Retrieval Using Airborne Polarimetric Remote Sensing

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September 6, 2022

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) 06-09-2022			2. REPORT TYPE NRL Memorandum Report		3. DATES COVERED (From - To) 03/2020 – 03/2021	
4. TITLE AND SUBTITLE Ocean Wave Height Retrieval Using Airborne Polarimetric Remote Sensing					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER NISE	
6. AUTHOR(S) Erika D. Johnson					5d. PROJECT NUMBER	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER 1Y86	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory 4555 Overlook Avenue, SW Washington, DC 20375-5320					8. PERFORMING ORGANIZATION REPORT NUMBER IR-7233-21-9-U	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Research Laboratory 4555 Overlook Avenue, SW Washington, DC 20375-5320					10. SPONSOR / MONITOR'S ACRONYM(S) NRL-NISE	
					11. SPONSOR / MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES Karles Fellowship						
14. ABSTRACT Accurate quantification of ocean waves is essential to defining the overall hydrodynamics of the upper ocean. However, existing methods of remotely quantifying ocean waves over large spatial areas either present logistical difficulties or lack the ability to resolve the entirety of spatial scales present in the wave field. A new approach using polarimetric cameras is developed and validated here. It is demonstrated that by measuring the angle of polarization from reflected light from the ocean surface, the two-dimensional wave slope field can be determined and then integrated to yield significant wave height. The impact of camera viewing angle and atmospheric path contributions on wave slope measurements are also demonstrated.						
15. SUBJECT TERMS Ocean waves Remote sensing Polarimetric imaging						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT U	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON Erika Johnson	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) (202) 766-5944	

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Karle Fellowship White Paper
Ocean Wave Height Retrieval Using Airborne Polarimetric Remote Sensing

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Abstract

Accurate quantification of ocean waves is essential to defining the overall hydrodynamics of the upper ocean. However, existing methods of remotely quantifying ocean waves over large spatial areas either present logistical difficulties or lack the ability to resolve the entirety of spatial scales present in the wave field. A new approach using polarimetric cameras is developed and validated here. It is demonstrated that by measuring the angle of polarization from reflected light from the ocean surface, the two-dimensional wave slope field can be determined and then integrated to yield significant wave height. The impact of camera viewing angle and atmospheric path contributions on wave slope measurements are also demonstrated.

Introduction

Waves, whether they are generated by wind, tides or storms, are a dominant source of energy for the upper ocean. They drive upper ocean circulation and nearshore currents. Waves also play a major role in the exchange of gases, heat, and momentum between the ocean and atmosphere.

Accurate quantification of ocean waves (e.g. significant wave height and directional spectra) are essential to defining the hydrodynamics of the upper ocean. Timely and accurate sea state measurements are vital for safe navigation. These measurements are also key inputs into the ocean circulation and wave models (e.g. Delft3D, SWAN, and NCOM) used by the Navy for forecasting in regional and coastal areas. Moreover, there is a growing desire within the modelling community to run models at increasingly finer resolution. This desire necessitates high spatial ($\vartheta(10)$ m) and temporal resolution (up to 15 Hz) of ocean waves over large spatial areas ($\vartheta(10)$ km).

Existing *in situ* methods of measuring wave statistics have largely proven to be accurate, however, broadly speaking, these methods have limited spatial coverage. These methods typically involve buoys or bottom-mounted pressure gages both of which make highly localized measurements of the wave field. Further, the installation of these sensors can be fraught with logistical difficulties. The instrument body can also disturb the local flow by virtue of their presence in the water.

Existing remote methods of quantifying ocean waves either present logistical difficulties or lack the ability to resolve the entirety of spatial scales present in the wave field. These methods involve laser-altimeters, LIDAR and stereophotogrammetry. Using laser altimeters, which have a limited spot size within which the measurement is made, it can be challenging to measure ocean waves over the required spatial area. While

stereophotogrammetry is capable of quantifying wave heights over large spatial areas of interest, achieving acceptable accuracy using stereophotogrammetry in changing sky light conditions can be difficult. Further, the baseline separation distance required in stereophotogrammetry to image ocean waves from an aircraft is logistically difficult.

The approach chosen and developed here, is to use polarimetric cameras to remotely measure the two-dimensional wave slope field, which can be integrated to yield significant wave height and other higher order statistics (e.g., directional spectra). An airborne mounted polarimetric imager is capable of remotely quantifying ocean surface waves at a spatial and temporal resolution that is useful to ocean modelers and allows the physics of important ocean phenomena (e.g., fronts) to be explored. Building off of previous efforts in this area [Baxter (2012), Baxter, et al. (2009) and Zappa, et al. (2008)], this research effort leverages an existing remotely collected polarimetric data set to develop and validate (for the first time) this capability in field conditions.

This report is organized as follows. After an introductory discussion of the polarimetric slope sensing technique and a description of the field experiment, preliminary results are presented and discussed. This is followed by a discussion of the future direction of this project, both scientifically and in terms of operating in Naval Battlespace Environments.

Polarimetric slope sensing technique

The polarization state of light contains valuable information about the imaged scenes that cannot be obtained from luminance and spectral measurements alone (Baxter 2012). Information such as surface orientation, surface roughness, and index of refraction can be determined by observing the reflected polarization state of light. Considering the problem of remotely characterizing ocean wave heights, the reflection of light at the water surface generates polarization that is determined by the surface orientation. This polarization can be measured with polarimetric cameras and the surface orientation or water surface slope, $\nabla\eta(x, t)$, can be remotely determined. The water surface slope can then be integrated to produce a measurement of ocean wave height field. From this important ocean wave metrics, such as significant wave height and directional spectra can be determined. Thus, an alternative approach to remotely measuring ocean waves is developed.

The state of the polarization light field is completely described by the Stokes vector $[S_0, S_1, S_2, S_3]$ where S_0 is the total intensity of light, S_1 is the amount of linear horizontal or vertical polarization, S_2 is the amount of linear $+45^\circ$ or -45° polarization, S_3 is the amount of circular polarization. Circularly polarized light, S_3 , can be created in the ocean however, the circumstances under which it occurs is limited and rare. We, therefore, neglect it in this report ($S_3=0$). Light that is partially polarized can be described as a linear combination of natural light and completely polarized light as follows,

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = (1 - DOLP) \begin{bmatrix} S_0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + DOLP \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad \text{eq. [1]}$$

In the above $DOLP$ is the degree of linear polarization given by,

$$DOLP = \frac{(S_1^2 + S_2^2 + S_3^2)^{1/2}}{S_0} \quad \text{eq. [2]}$$

The angle of polarization (AOP) or orientation angle is related to the Stokes parameters by,

$$AOP = \frac{1}{2} \text{atan} \left(\frac{S_2}{S_1} \right) \quad \text{eq. [3]}$$

The Stokes vectors can be determined by measuring the intensity of the polarized light using polarimetric cameras that are equipped with directional wire grid filters oriented in four directions (e.g., 0° , 45° , 90° , and 135°). Given a system that can measure the polarization orientation in these four directions (such as the Versatile Imager for the Coastal Ocean or VICO), the following relationships can be used to compute the Stokes parameters from the measured intensities:

$$\begin{aligned} S_0 &= I_0 + I_{90} = I_{45} + I_{135} = \frac{1}{2}(I_0 + I_{45} + I_{90} + I_{135}) \\ S_1 &= I_0 - I_{90} \\ S_2 &= I_{45} - I_{135} \end{aligned} \quad \text{eq. [4]}$$

In the above, I_x represents the intensity measured with a polarization filter placed at the orientation in degrees specified by the subscripted number x . Since here we neglect the circular polarization, the DOLP reduces to,

$$DOLP = \sqrt{S_1^2 + S_2^2} / S_0 \quad \text{eq. [5]}$$

and the AOP remains as previously stated.

In considering an airborne remote platform that measures the intensity of polarized light, there are three contributing sources to the measured polarized intensity measured by the sensor that must be considered. Not surprisingly, sunlight is natural source of randomly oriented polarization. When this light is scattered by the atmosphere, reflected off the ocean surface or even transmitted through the water surface, the nature of the polarization changes and, in many cases, is enhanced. The three contributions to the polarization measured by the sensor can be quantified as follows,

$$\mathbf{S}_{total} = \mathbf{S}_p + \mathbf{S}_r + \mathbf{S}_u \quad \text{eq. [6]}$$

where \mathbf{S}_{total} is the total amount of polarization measure by the sensor. \mathbf{S}_p represents the *path* contribution to the total polarization. Rayleigh scattering in the path between the sensor and the ocean surface can increase the degree of linear polarization and therefore must be accounted for. \mathbf{S}_r represents skydome radiance that is *reflected* off the ocean surface and transmitted back to the sensor. The process that is here responsible for the

increase in the degree of linear polarization is called Fresnel reflection. Finally, S_u represents the radiance *upwelling* from below the surface of the water that is measured by the sensor.

In eq. [6] the above, S_{total} is what is measured by the sensor. However, it is the reflected contribution from the ocean surface, S_r , that will allow calculation of the ocean wave slope. The contributions to the overall polarization from atmospheric path, S_p , and from the upwelled signal, S_u , must therefore be removed from the total signal in order to isolate the reflected contribution.

To account for the contributions of the path and upwelled radiance, we make the following assumptions:

- 1.) The upwelling component is largely composed of light which has been scattered many times in the water column. The overall effect of the multiple scatterings is to depolarize the light. Further, for randomly polarized light, transmission through the water-air interface generates a small degree of polarization (<4%). There have been two approaches in the literature for dealing with the upwelled component. The work of Baxter (2012) neglects this slight partial polarization and assumes that the upwelling component is completely depolarized ($S_u=0$). Zappa, et al. (2008) also concludes that the upwelling component is likely small and removes its effects by imposing a flatness constraint on the recovered surface. We experiment with both approaches in this report.
- 2.) For the path component, Baxter (2012), who uses airborne polarimetric cameras, optimizes the camera viewing angle relative to the sun to minimize this contribution. Further, in calculating the local wave heights, she assumes that the atmospheric path contribution is slowly varying trend across the images. She fits this trend with a polynomial function (of maximum degree two) and removes it. Similarly, Zappa, et al. (2008) also assume this contribution to be negligible. However, because they observed the ocean surface from pier above the water, this assumption is likely valid in this case. Following Baxter et al. (2009), we restrict our analysis to images collected looking away from the sun to minimize the path polarization component. Future research efforts in this area will model the path contribution to degree of polarization using a vector radiative transfer code.

Making these two assumptions greatly simplifies the problem and the measured AOP can be used directly to determine the wave slopes. Integration of these slopes yields the wave height field. The significant wave height is then readily calculated as,

$$H_{m0} = 4\sigma_\eta, \quad \text{eq. [7]}$$

where σ_η is the standard deviation of wave displacement.

Experimental Setup

The polarimetric images analyzed herein were collected during a field deployment over Chesapeake Bay. The objective of that deployment was to use a polarimetric imager to collect information about water constituents, such as particle size and type. This existing

data set was leveraged as part of this project to investigate the possibility of using polarimetric imaging to quantify surface wave height. Details about that deployment can be found (Bowles, et. al., 2015).

The Versatile Imager for the Coastal Ocean or (VICO) was developed at the Naval Research Laboratory (NRL) to provide an airborne platform to measure the polarized light field at several wavelengths above the ocean surface (Bowles, et. al., 2015). The system consists of four co-aligned panchromatic cameras each equipped with a color and a polarimetric directional filter. The cameras are mounted on a rotation stage that controls the camera pointing (see Figure 1). The stage is equipped with a GPS/IMU system, which provides location and attitude information at 10 Hz. This positioning information is used in the rectification of the images. The stage is mounted in the large observation port in the main cabin of a Twin Otter plane.

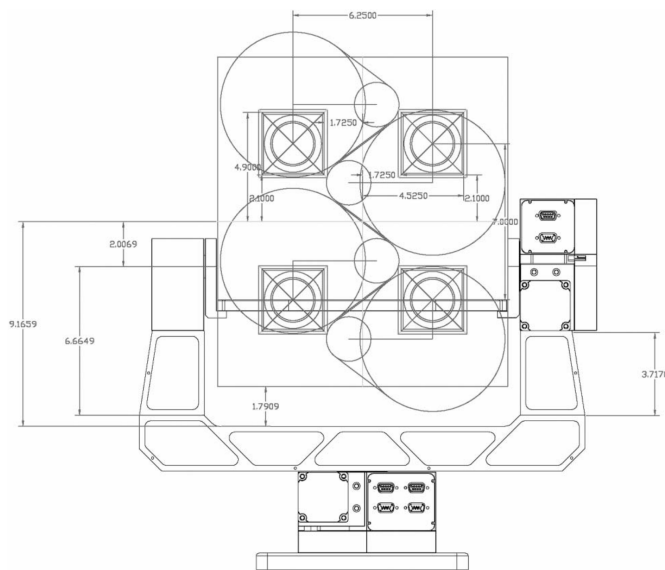


Figure 1. Schematic of the VICO mounted on the stage. The four cameras are indicated by the X's and the tear drop-shaped structure is the color filter wheel. The cameras are mounted onto a square plate which is held by a U-shaped structure which is the stage. (Bowles, et. al., 2015).

The cameras are each large format (4872×3248 pixels) panchromatic cameras (Imperx model IPX16M3L). Each are equipped with a single wire grid polarizing filter oriented at 0° , 45° , 90° , or 135° . In addition to the polarimetric filters, a color filter wheel (tear drop structure in Figure 1) was used such that each camera simultaneously imaged the ocean surface through a red (centered at 625 nm), green (550 nm), blue (435 nm), near IR (750 nm) or a dark bandpass filter. The results presented herein focus on images collected with the red filter. Each camera is also fitted with a 50 mm lens yielding a field of view of $\sim 39^\circ$ by 26° .

Field Deployment

VICO was flown in the back of a Twin Otter aircraft on 29 August 2014 over Chesapeake Bay just south of the Chesapeake Bay Bridge. The data collection took place between 14:32-14:47 UTC (local time is 4 h earlier). During that time, the solar zenith angle changed slightly from 44.9° to 42.6° .

The plane flew at an altitude of ~ 1685 m yielding a typical GSD of that varied from ~ 0.30 - 0.40 m over the imaged scene. The aircraft was flown along a number of short straight paths or transects at different “compass” directions relative to the azimuthal direction of the sun (0° , 20° , 45° , and 75°) as shown in Figure 2. At ~ 90 knots flying speed and each transect took 120 s. For each pass the cameras were fixed on the same, central point (see Figs. 2). This was achieved by incrementally changing the pointing position of the rotation stage. Figure 3 depicts how the pitch, roll and heading for the stage was changed to maintain the central point in the field of view. It took ~ 15 min to collect the data in the star pattern configuration shown in below and even over such a short duration, portions of the images are affected by sun glint.

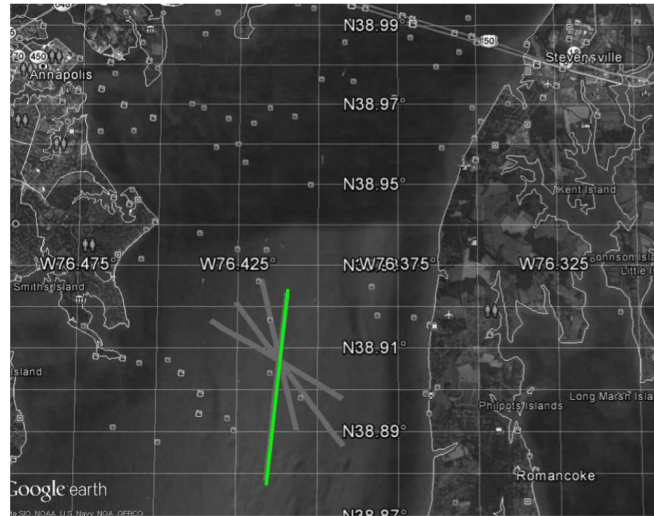


Figure 2. The gray and green lines show the position of the plane while data was being collected. The camera/stage system tracks the center location at (38.9031°N , 76.4119°W), which is approximately 10 km south of the Chesapeake Bay Bridge in Maryland. (Bowles, et. al., 2015). The green line is the track considered in this report.

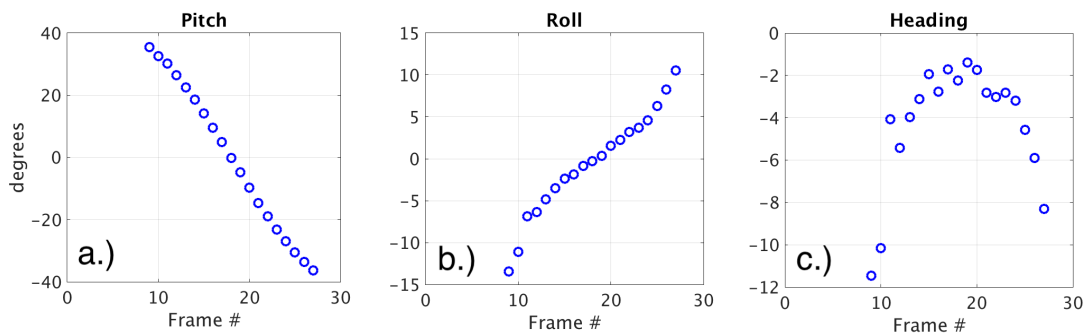


Figure 3. The a.) pitch, b.) roll and c.) heading orientation of the rotation stage for each frame collected during the transect.

During each transect, images were collected at 1.1 Hz, which is the upper limit of the color filter rotation speed. This results in ~25 polarimetric images for each color band for each track. The cameras were oriented with the long (4872 pixels) side in the cross-track direction; during each transect each of these 25 images covers about 26° in the along-track direction.

Camera Calibration

In order to radiometrically calibrate the cameras, a dark filter was included on the color filter wheel and with each rotation of the filter wheel a dark image was collected. The mean of all the dark images was calculated and was subtracted from each image used in the analysis contained herein.

To correct the cameras for lens distortion, the cameras were installed on the rotation stage and were placed in front of an illuminated pinhole at the focus of a parabola in the lab. The stage was systematically rotated while images were captured. A composite image of each pinhole image was constructed yielding a pattern from which the camera calibration coefficients were calculated.

Image registration

Each camera was triggered simultaneously to capture an image, however because the cameras are located at a position relative to others (see Figure 1), the field-of-view or what each camera sees varies slightly. Registering the images accounts for this difference by performing transformations to bring all the images into alignment. An intensity-based registration routine in MATLAB (*imregister*) was used in this study to bring the images into alignment with one another.

Image rectification

The location and attitude information of the stage was recorded by a GPS/IMU system at 10 Hz. The position information, along with the camera calibration information was used to rectify each image for the given transect. The rectification algorithm developed by Pawlowicz (2003) was used to rectify the polarized images.

Results

For the purpose of this report, only one leg of the star-shaped pattern shown in figure 3 is considered herein. This line is shown in green in figure 3 and has a bearing of ~6° and was flown at a mean altitude of ~1685 m. The solar azimuth for this data collection was 120.6° and the flight direction is ~66° relative to the solar azimuth. Because this transect is oriented away from the sun, we can use the assumption that the path contribution to the DOLP is small.

With the four cameras of the VICO system, each measuring the polarization of the light field at different orientations simultaneously, all the information that is needed to determine the complete polarization state of the light is measured at the same instant. With these images, equations [3-5] were used to calculate the Stokes vector, then the DOLP and the AOP. Typical results for the DOLP and AOP (calculated for Frame 11) along with plots of the mean values for each collected frame are shown below in Figure 4. The DOLP is roughly constant across each frame (Figure 4a) but varies as the look angle changes from

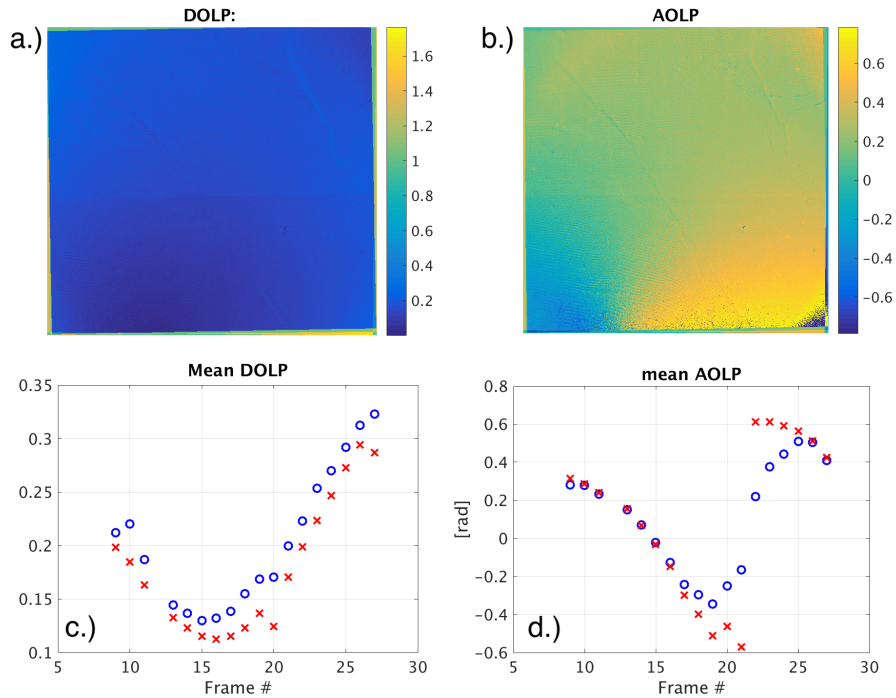


Figure 4. a.) Typical DOLP, and b.) typical AOP from frame 11. Mean (o) and median (x) c.) DOLP and d.) AOP for each collected frame.

frame to frame (Figure 4c). Conversely there is a slow variation in the AOP for each frame (Figure 4b) and the mean of each frame varies strongly, in particular, with the heading (Figure 3c). A flatness constraint was applied to the AOP prior to calculating the wave slope.

To calculate wave slopes from AOP measurements, the image coordinate system must be transformed into the real-world coordinate system. This is achieved by rotating the image about the grazing angle,

$$\nabla\eta = \text{atan}(\tan\psi\cos\theta_{GA}) \quad \text{eq. [8]}$$

where θ_{GA} is the grazing angle or the pitch angle (Figure 3a). The wave height field is then determined via line integration.

The remotely determined wave height field for three frames with different grazing angles is shown in Figure 5, along with the corresponding rectified image. The rms wave height and significant wave height for each frame is given in the table below.

Table 1. Wave heights and grazing angles for select frames. NOAA buoy measure wave height 0.28m.

	θ_{GA}	h_{rms} wave height [m]	H_{mo} [m]
Frame 9	35.42	0.27	0.29
Frame 15	14.2	0.15	0.09
Frame 23	-23.23	0.59	1.39

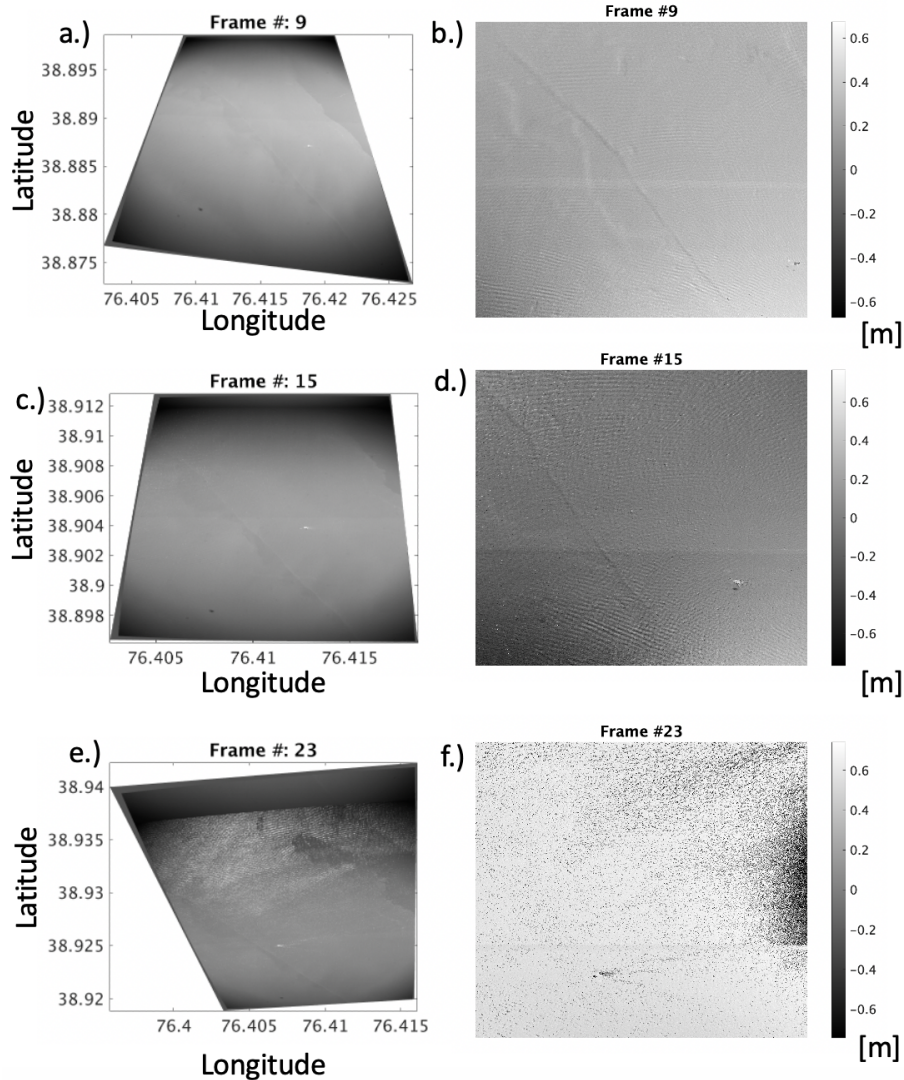


Figure 5. Rectified image from three select frames: a.) Frame 9, c.) Frame 15, e.) Frame 23. Wave height field from three select frames: b.) Frame 9, d.) Frame 15, f.) Frame 23.

At the time these measurements were made, a nearby NOAA buoy recorded the wave height to be 0.28 m. Frame 9 is in very good agreement with this *in situ* measurement. The image corresponding to Frame 23 (Figure 5e) contains sun glint which has an adverse impact on the AOP and subsequently on the wave height field.

Conclusion & Future Work

Quantifying ocean wave heights is critical to the overall characterization of the hydrodynamics of the upper ocean. The ability of polarimetric images of the ocean surface to provide the ocean wave height field at the desired high spatial ($\vartheta(10)$ m) and temporal resolution (up to 15 Hz) over large spatial areas ($\vartheta(10)$ km) has been explored in this report. This preliminary assessment has proved encouraging. Future work in this research direction will include the following:

- 1.) The blue, green and near IR bands will be analyzed to determine the ocean wave field and those results will be compared with the red results presented above.
- 2.) The atmospheric path contribution to the DOLP will be modeled using a vector radiative transfer code.
- 3.) The polarimetric images used in this study will further be analyzed by a two-dimensional, power spectral density code (Johnson et al. 2020) to determine currents and bathymetry.

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