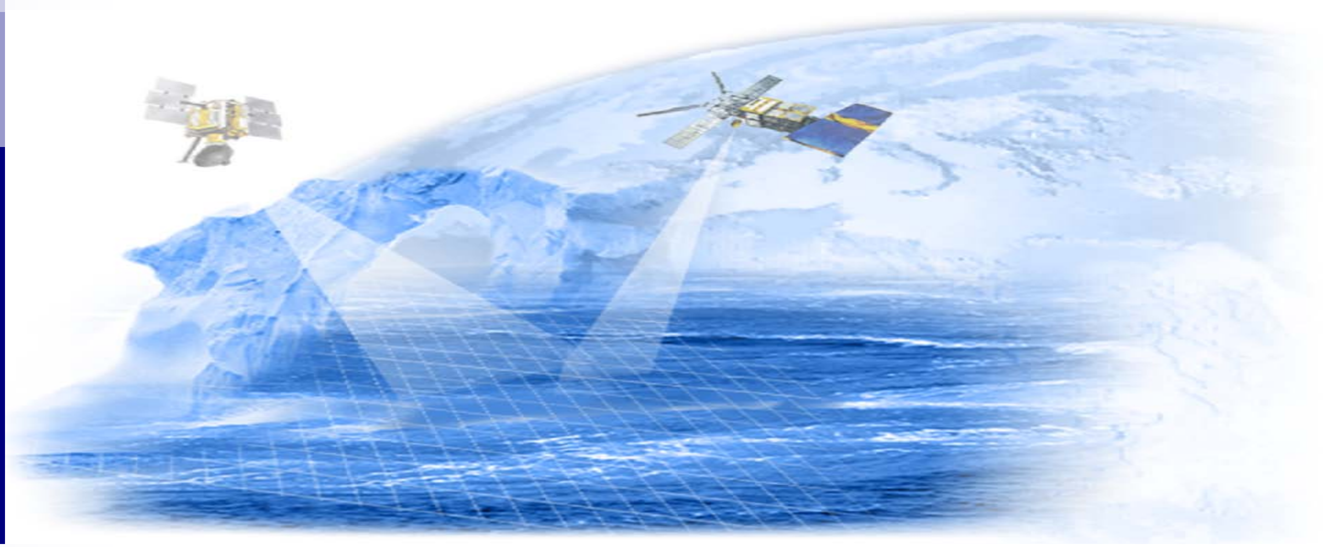
Government of Canada Gouvernement du Canada

Canada



Measurement of Ocean Waves with RADARSAT-2 Fully Polarimetric SAR Image

Biao Zhang, William Perrie, Yijun He

Outline

- Introduction
- Dataset
- Methodology
- Case Studies
- Conclusions

Conclusions

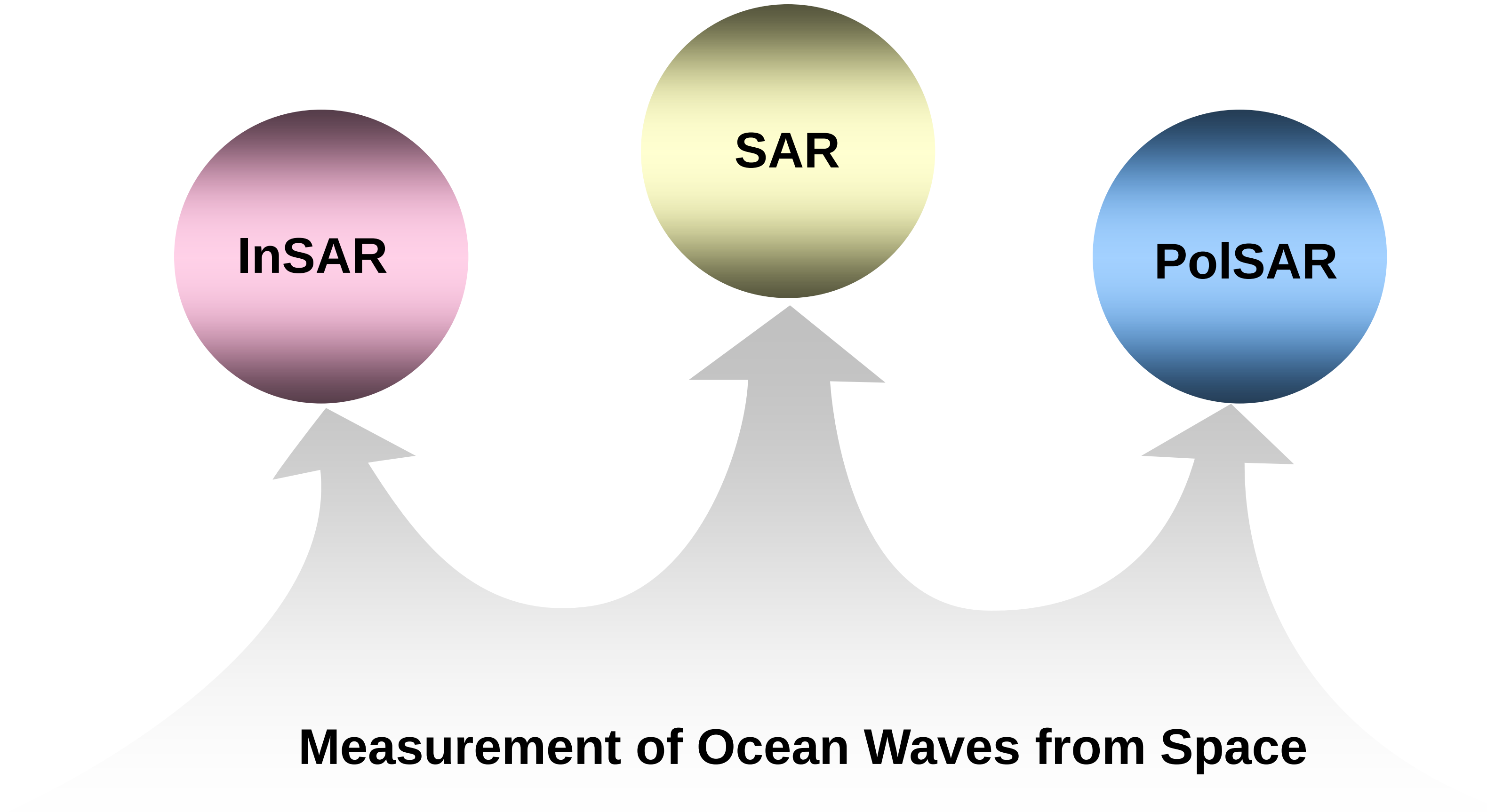
1: Co- and cross-pol SAR measurements directly used to get waves.

2: Wave slope in the azimuth and range directions can be estimated.

3: Hydrodynamic modulation function not needed for even large SAR radar incidence angles.

4. Results ➔ SAR-retrieved parameters in good agreement with NDBC

- Hs, significant wave height
- Tp, wave period
- wavelength
- wave direction


SAR
InSAR
PolSAR
Measurement of Ocean Waves from Space

Introduction

SAR

Need 1st guess wave spectrum from wave model or wind vector by scatterometer

.

Hasselmann et al.(1991)
Plant et al.(1997)
Mastenbroek et al. (2004)
Susanne Lehner et al. (2004)
Schulz-Stellenfleth et al. (2007)
Li et al. (2009)

JGR & IJRS

InSAR

Validated and retrieved for airborne C- and X-band AT-InSAR.

Vachon et al.(1999)
He et al.(2003)
Zhang et al.(2009)

IEEE TGRS & JGR

PolSAR

Fully polarimetric measurements can be used.

Only L& P band

Schuler et al. (2004)
He et al. (2006)

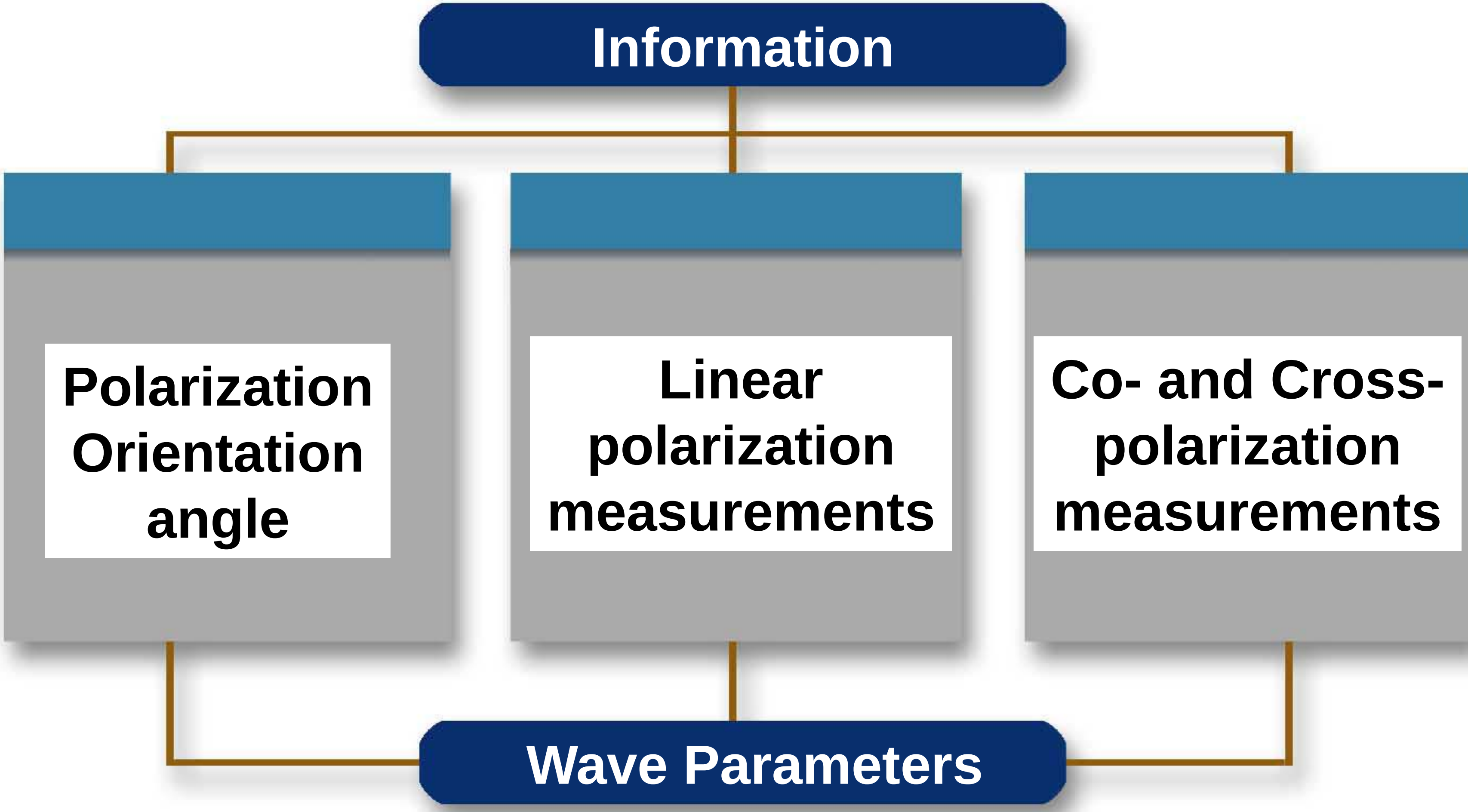
Sigma_hv?

RME & JAOT

Spaceborne PolSAR measure ocean waves?

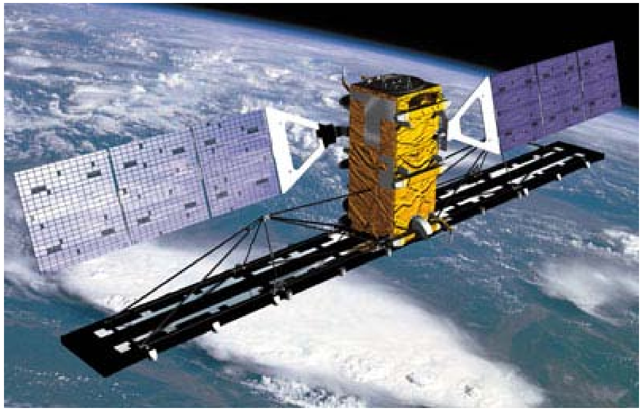
Zhang Biao, Will Perrie and Yijun He (2009), Remote sensing of ocean waves by along-track interferometric synethtic aperture radar, *J. Geophys. Res.*, 114, C10015, doi:10.1029/2009JC005310.

Introduction



Datasets

1 RADARSAT-2 Quad-Pol Images → **HH+VV+HV+VH**



Beam Mode: Fine Quad-Pol

Azimuth Resolution: 8.0 m

Range Resolution: 5.4 m

Azimuth Pixel Spacing: 5.1 m

Range Pixel Spacing: 4.7 m

Scene Size: 25*25 km*km

Incidence angle: 20-41 deg

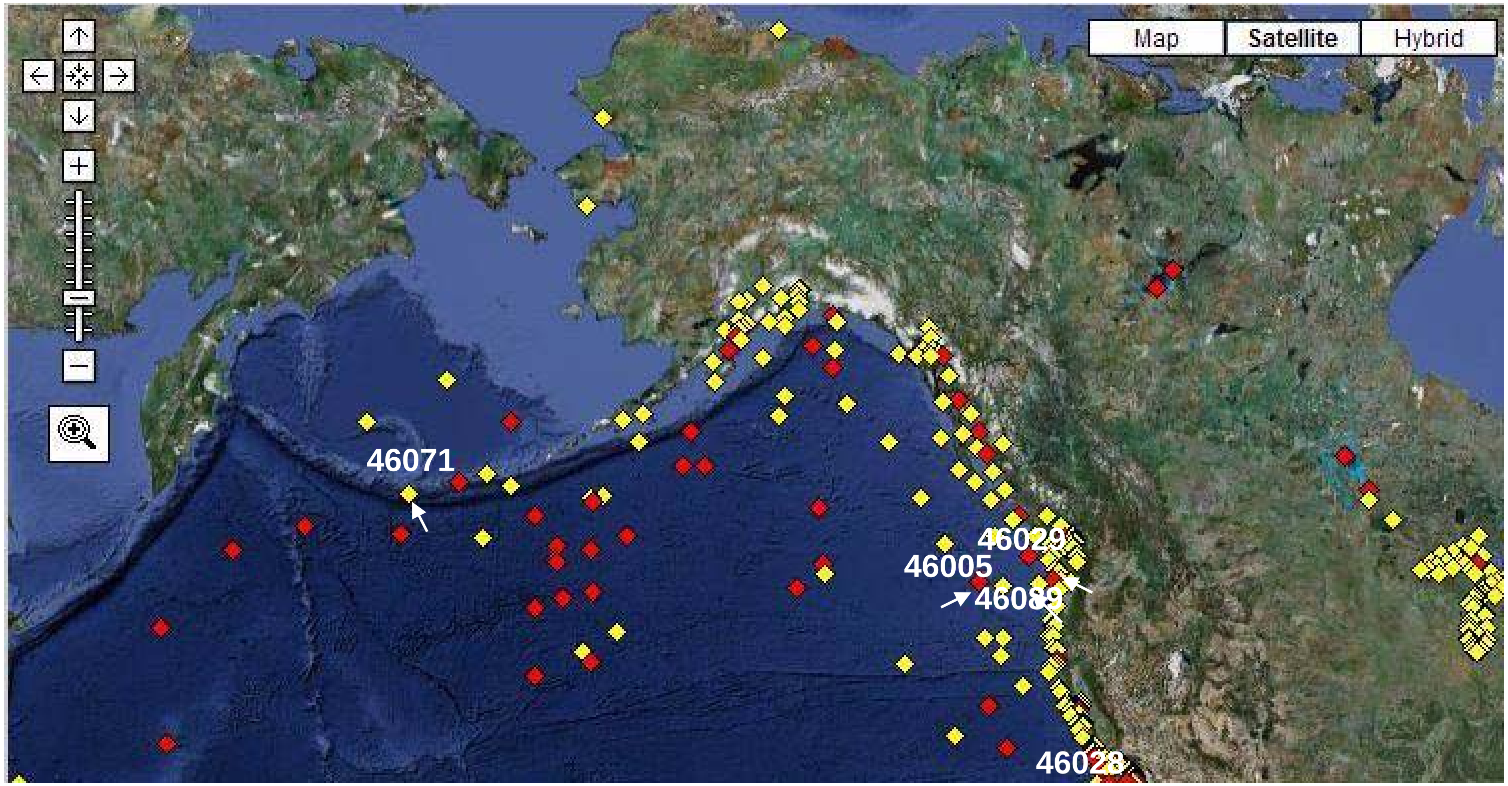
Datasets

Radar Band	C-band
Radar Center Frequency (GHz)	5.40
Pulse Repetition Frequency (Hz)	2769.3
Satellite Height (km)	795.8
Platform Velocity (km/s)	7.46
Track Angle (deg)	10.91
Slant range to velocity ratio (s)	137.6
Acquisition Type	Fine Quad Polarization
Polarizations	HH VV HV VH
Sampled Pixel Spacing (m)	4.73
Sampled Line Spacing (m)	4.79

Table1. RADARSAT-2 fully polarimetric image parameters

Datasets

2 NDBC Buoy Observations



Datasets

Image id	Acquired time (UTC)	Buoy time	Image central site	Buoy site	Wind Speed (m/s)	Wind direction (deg)
1	02:25:04 11 Jan 2009	02:50:00 11 Jan 2009	46°04'06"N 131°02'22"W	46°03'00"N 131°01'12"W	9.0	240
2	14:30:58 18 Jan 2009	14:50:00 18 Jan 2009	45°57'43"N 125°39'18"W	45°54'28"N 125°45'37"W	3.7	97
3	02:09:26 25 Feb 2009	01:50:00 25 Feb 2009	35°44'43"N 121°55'42"W	35°44'29"N 121°53'03"W	5.3	321
4	05:47:58 28 Feb 2009	05:50:00 28 Feb 2009	51°07'18"N 178°53'10"W	51°09'17"N 179°00'02"W	4.0	270
5	14:39:15 17 Mar 2009	14:50:00 17 Mar 2009	46°07'05"N 124°33'25"W	46°08'37"N 124°30'37" W	7.7	246
6	14:31:05 22 Aug 2009	14:50:00 22 Aug 2009	46°05'06"N 124°30'01"W	46°08'37"N 124°30'37" W	3.0	20

Table2. RADARSAT-2 fully polarimetric SAR and NDBC buoys.

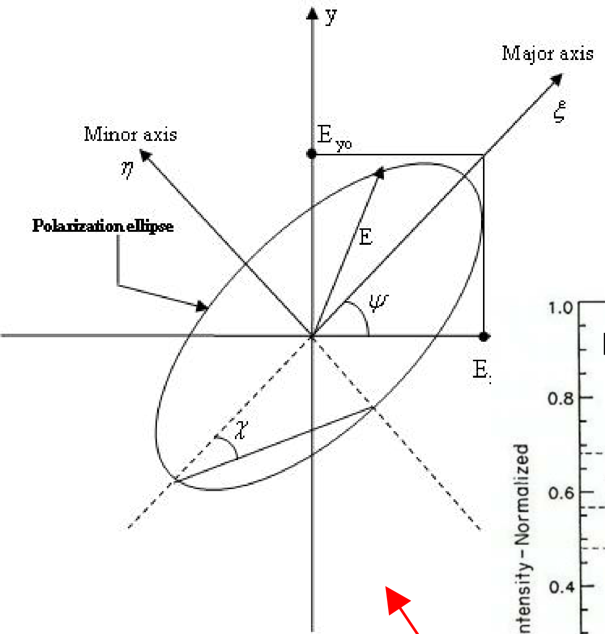
Datasets

2 NDBC Buoy Observations

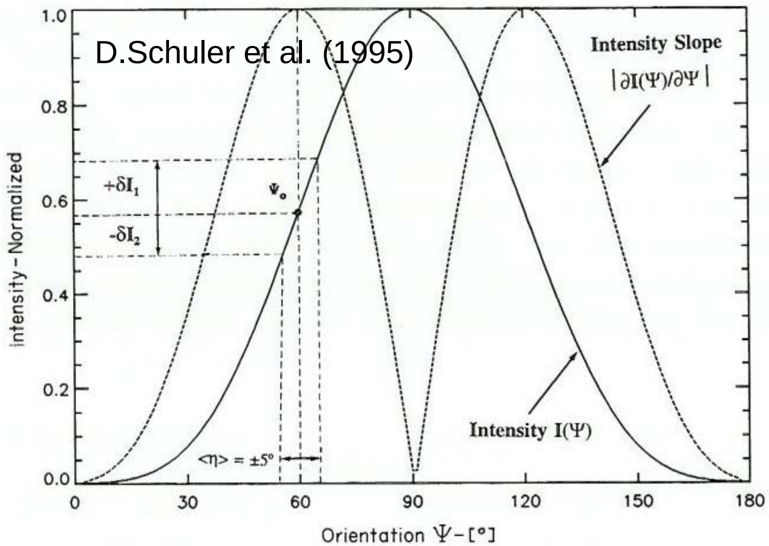
3-meter discus buoy

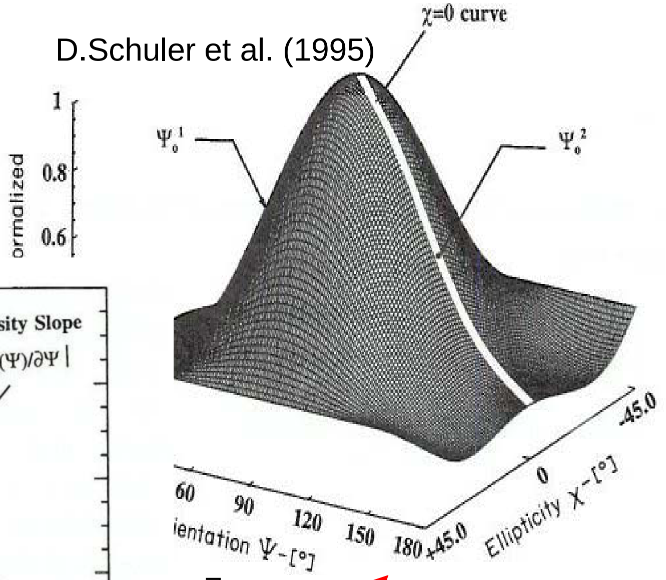
6-meter NOMAD buoy

Methodology



$\sigma(\chi,\psi$





(1)

Because max. sensitivities to wave slopes are obtained using linear polarizations

➔the ellpticity χ is set to zero [*Schuler and Lee*, 1995], and the backscatter cross section is

$$\sigma(0,\psi)=\frac{1}{4}(\sigma_{hh}+\sigma_{vv})\cdot\left[1+\cos^2(2\psi)\right]+\frac{1}{2}(\sigma_{hh}-\sigma_{vv})\cos(2\psi)$$

$$+\sigma_{hv}+\frac{1}{2}\mathrm{Re}(\sigma_{hhvv})\sin^2(2\psi) \qquad (2)$$

Methodology

2 Wave slopes in the azimuth and range directions

Via linear modulation theory, ocean surface elevation ξ and variations of local backscatter cross section $\sigma(\mathbf{r},t)$ may be represented as

$$\xi(\mathbf{r},t)=\sum_k \xi_k \exp i(\mathbf{k}\cdot\mathbf{r}-\omega t)+c.c \tag{5}$$

$$\sigma_{pp}(\mathbf{r},t)=\overline{\sigma}_{pp}\left\{1+\left[\sum_k T^R_{kpp}\xi_k \exp i(\mathbf{k}\cdot\mathbf{r}-\omega t)+c.c\right]\right\} \tag{6}$$

$$T^t_{kpp}+T^h_k+T^p_{kpp}+T^{rb}_k$$

For single-Pol SAR, T^v_k (+) T^p_{kpp} (-)

$$\frac{\Delta\sigma_{hh}(\mathbf{r},t)}{\overline{\sigma}_{hh}}=\sum_k T^t_{khh}\xi_k \exp[i(\mathbf{k}\cdot\mathbf{r}-\omega t)]+c_1+R \tag{7}$$

$$\frac{\Delta\sigma_{vv}(\mathbf{r},t)}{\overline{\sigma}_{vv}}=\sum_k T^t_{kvv}\xi_k \exp[i(\mathbf{k}\cdot\mathbf{r}-\omega t)]+c_2+R \tag{8}$$

Methodc

2

Wave slopes in the azimu

$$T^p_{\mathbf{k}} = -\frac{ik_x}{A_0}\left[\left(1+\left(\frac{1+\sin^2\theta}{\cos^2\theta}\right)^2\right)\cos(2\varphi) + \left(1-\left(\frac{1+\sin^2\theta}{\cos^2\theta}\right)^2\right) - 2\left(\frac{1+\sin^2\theta}{\cos^2\theta}\right)\cos(2\varphi)\right]\frac{\sin(2\varphi)}{\sin\theta}$$

He et al. 2004

For linear polarization SAR with orientation angle ψ

$$\frac{\Delta\sigma_{\psi\psi}(\mathbf{r},t)}{\bar{\sigma}_{\psi\psi}} = \sum_k (T^t_{k\psi\psi} + T^p_{k\psi\psi})\exp[i(\mathbf{k}\cdot\mathbf{r}-\omega t)] + c_3 + R \qquad (9)$$

only modulation transfer for tilt + polarization orientation angle depend on polarization ➔

$$\frac{\Delta\sigma_{vv}(\mathbf{r},t)}{\bar{\sigma}_{vv}} - \frac{\Delta\sigma_{hh}(\mathbf{r},t)}{\bar{\sigma}_{hh}} = \sum_k (T^t_{kvv} - T^t_{khh})\xi_k \exp i(\mathbf{k}\cdot\mathbf{r}-\omega t) + c_1 \qquad (10)$$

$$\frac{\Delta\sigma_{\psi\psi}(\mathbf{r},t)}{\bar{\sigma}_{\psi\psi}} - \frac{\Delta\sigma_{vv}(\mathbf{r},t)}{\bar{\sigma}_{vv}} = \sum_k (T^t_{k\psi\psi} + T^p_{k\psi\psi} - T^t_{kvv})\xi_k \exp i(\mathbf{k}\cdot\mathbf{r}-\omega t) + c_2 \qquad (11)$$

When $\psi = 0$ then $T^t_{kvv} = ik_x \dfrac{4-0.5(1-\sin^2\theta)}{\tan\theta(1-\sin^2\theta)}$ $T^t_{khh} = ik_x \dfrac{4-0.5(1+\sin^2\theta)}{\tan\theta(1+\sin^2\theta)}$ (12)

Methodology

2 Wave slopes in the azimuth and range directions

With some algebra we get

$$\frac{\Delta\sigma_{vv}}{\bar{\sigma}_{vv}} - \frac{\Delta\sigma_{hh}}{\bar{\sigma}_{hh}} = -\frac{8\tan\theta}{1+\tan^2\theta}\frac{\partial\xi}{\partial x} \tag{13}$$

$$\frac{\Delta\sigma_{\psi\psi}}{\bar{\sigma}_{\psi\psi}} - \frac{\Delta\sigma_{vv}}{\bar{\sigma}_{vv}} = a\frac{\partial\xi}{\partial x} + b\frac{\partial\xi}{\partial y} \tag{14}$$

where $\partial\xi/\partial x$ and $\partial\xi/\partial y$ are wave slopes in the range and azimuth directions.

$$a = \frac{a_2}{a_0} - a_3,\ b = \frac{a_1}{a_0}$$

$$a_0 = \frac{1}{4}\left\{1+\left[\frac{(1+\sin^2\theta)}{(1-\sin^2\theta)}\right]^2\right\}[1+\cos^2(2\psi)]$$

$$-\frac{2\sin^2\theta}{1-8\sin^2\theta+8\sin^4\theta}\cos(2\psi) + \frac{1+2\tan^2\theta}{2}\sin^2(2\psi)$$

$$a_1 = -\left[\left\{1+\left[\frac{(1+\sin^2\theta)}{(1-\sin^2\theta)}\right]^2\right\}\cos(2\psi) + \left\{1-\left[\frac{(1+\sin^2\theta)}{(1-\sin^2\theta)}\right]^2\right\}\right.$$

$$\left. -2\left[\frac{(1+\sin^2\theta)}{(1-\sin^2\theta)}\right]\cos(2\psi)\right]\frac{\sin(2\psi)}{\sin\theta}$$

$$a_2 = \left[\frac{2\tan\theta}{\sin^2\theta\cos^2\theta}[1+\cos^2(2\psi)]\right] - \frac{4\tan^3\theta}{\sin^2\theta}\cos(2\psi) + \frac{2\tan^3\theta}{\sin^2\theta}\sin^2(2\psi)$$

Methodology

2 Wave slopes in the azimuth and range directions

Average wave height of dominant wave can be estimated with rms slope:

$$S_{rms} = [(< S_{az} \sin\Phi >)^2 + (< S_r \cos\Phi >)^2]^{1/2} \quad (15)$$

$$S_{az} = \partial\xi / \partial y \qquad S_r = \partial\xi / \partial x \quad (16)$$

$$\tan(S_{rms}) = H_d / (\lambda_d / 2) \quad (17)$$

Methodology

2 Wave slopes in the azimuth and range directions

To extract wave parameters from RADARSAT-2 Fine Quad-Pol mode images:

1

Select 512*512 pixel size HH, VV, HV-polarized image, and Transfer slant-range image into ground range image using linear interpolation in the range direction.

2

Estimate linearly polarized images with ground range images using with equation (2) and polarization orientation angle $\psi = 45^{\circ}$

3

Compute wave slopes and wave slope spectra, as well as wave parameters.

Case Studies

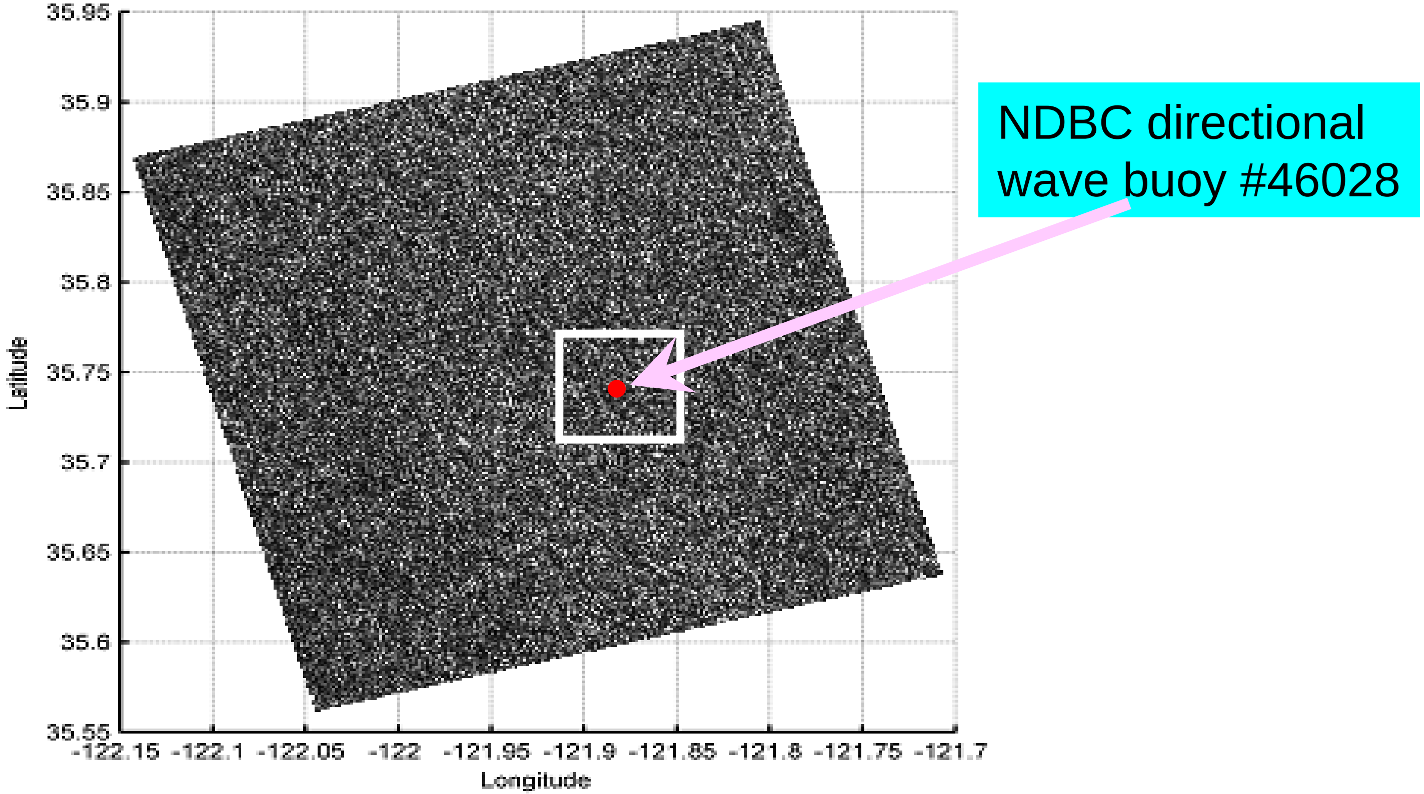
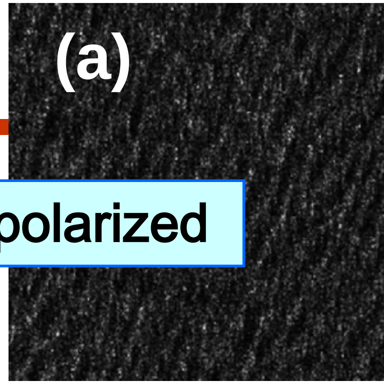
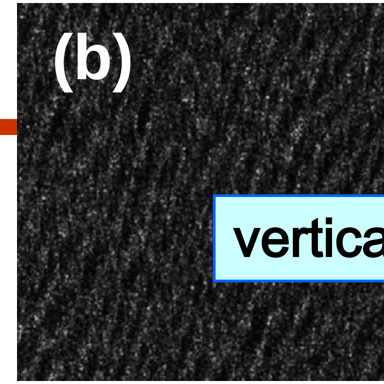


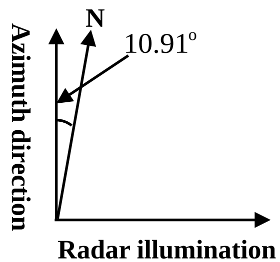
Figure 1. A C-band, VV polarization image of northwest of Morro Bay, California acquired by RADARSAT-2 at 02:09 on February 25, 2009 UTC.

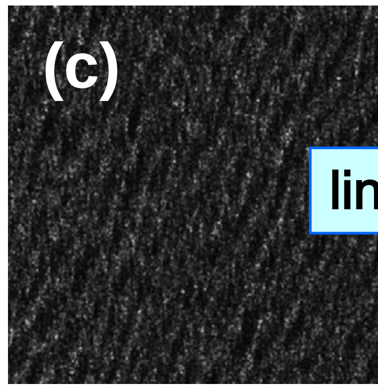


horizontally polarized

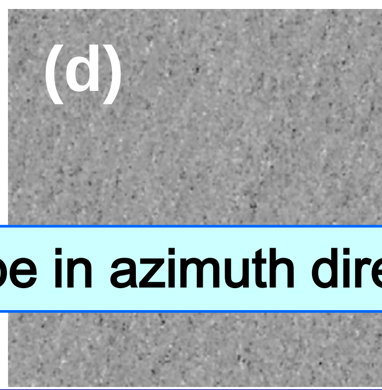


vertically polarized

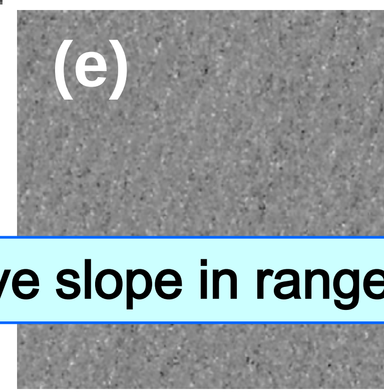




linearly polarized



wave slope in azimuth direction

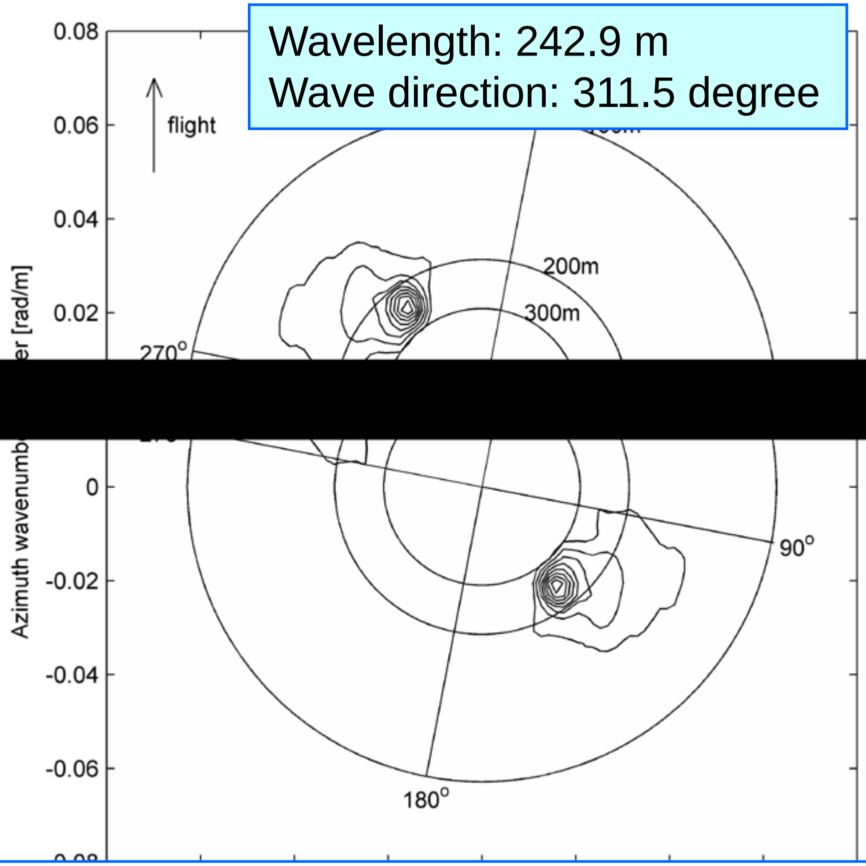


wave slope in range direction

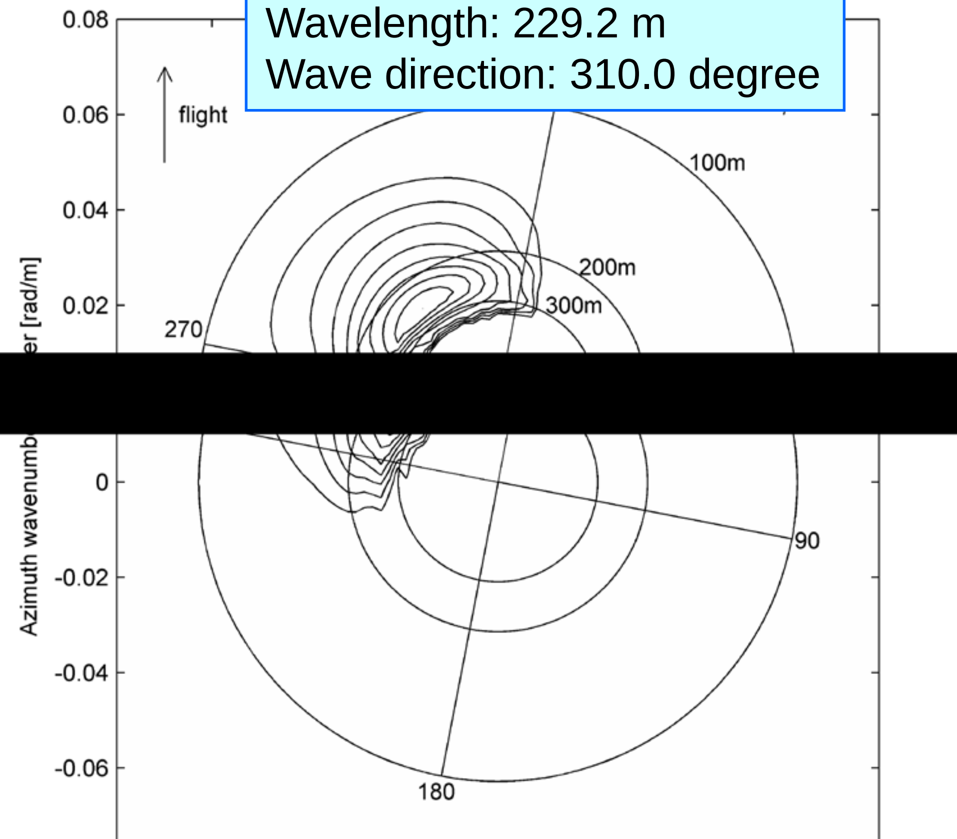
RADARSAT-2 fully polarized images

Case Studies

Wavelength: 242.9 m
Wave direction: 311.5 degree



Wavelength: 229.2 m
Wave direction: 310.0 degree



Wave slope spectrum by <u>SAR</u> for NW Morro Bay, CA at 02:09 Feb. 25, 2009

NDBC <u>buoy</u> (#46028) directional wave spectrum at 01:50 on Feb. 25, 2009

Case Studies

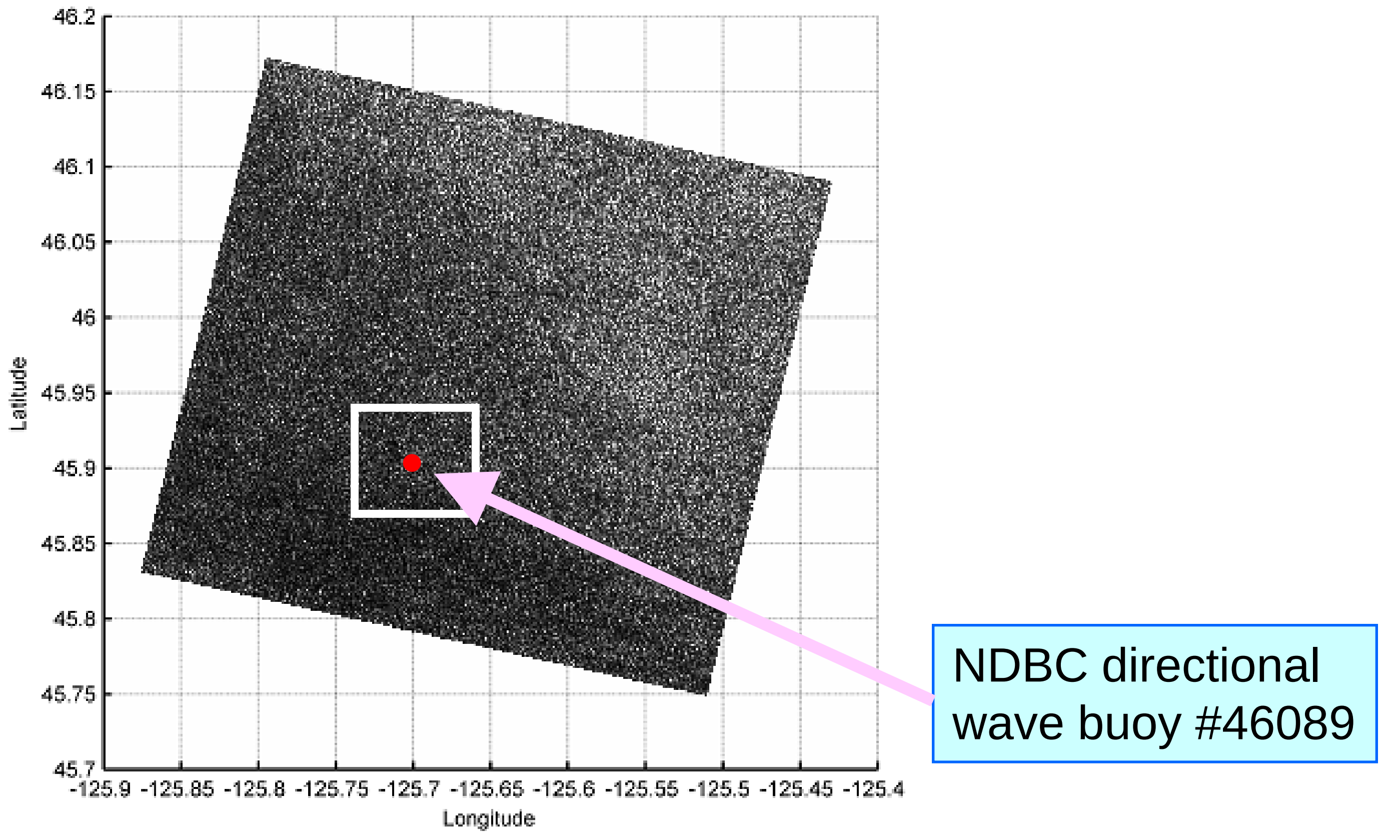
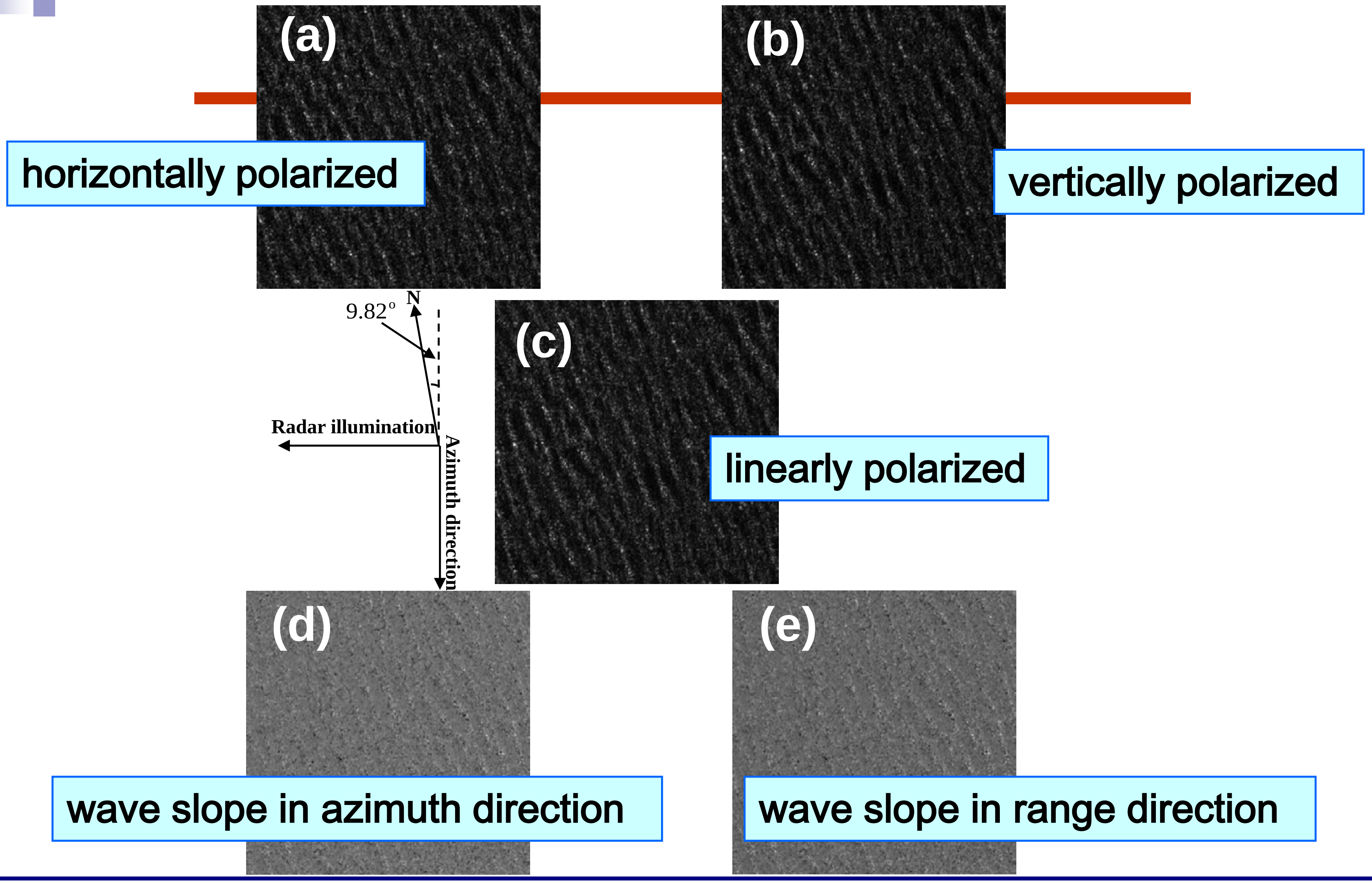
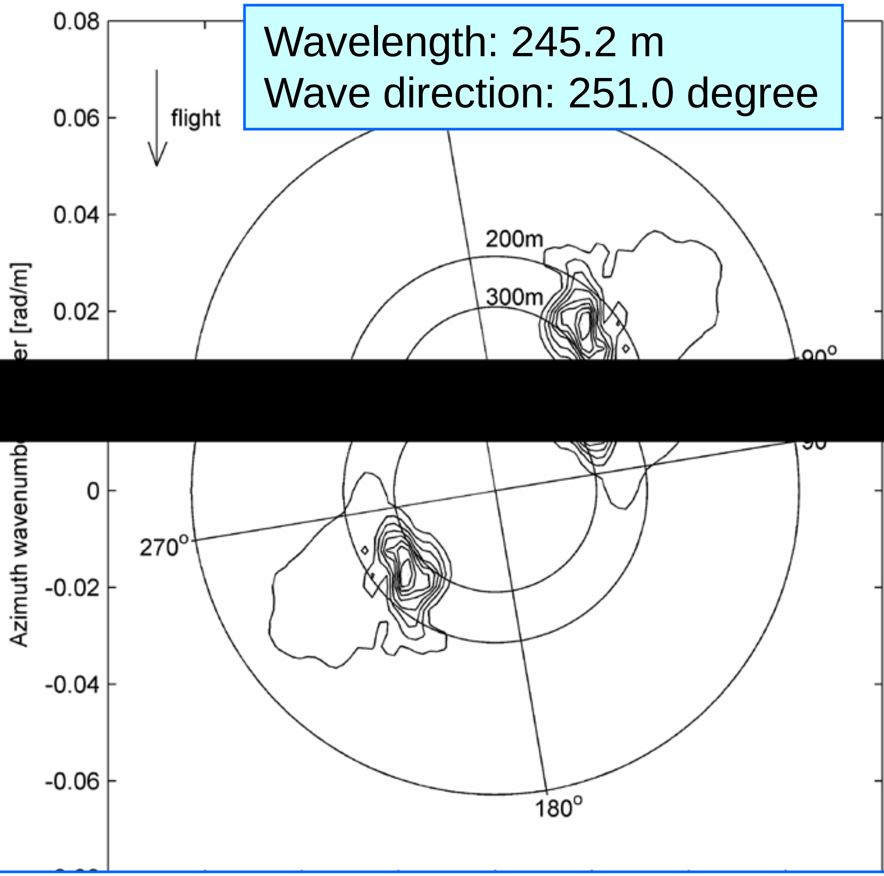


Figure 2. A C-band, VV polarization image of northwest of Tillamook Bay, OR acquired by RADARSAT-2 at 14:30 on January 18, 2009 UTC.

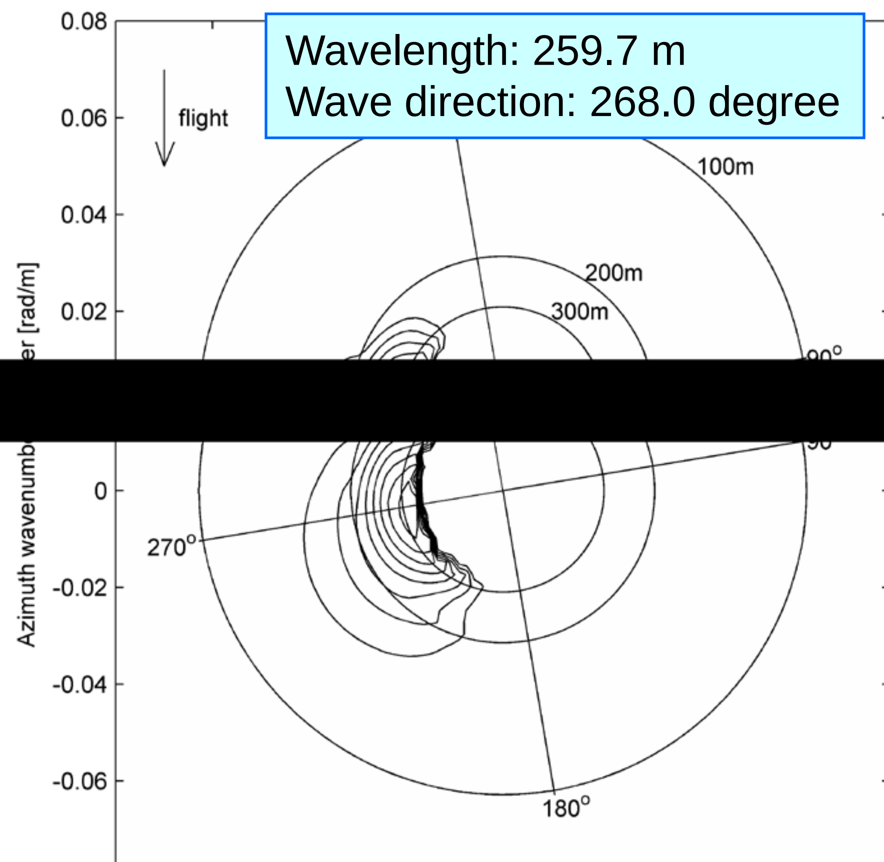


RADARSAT-2 fully polarized images

Case Studies



Wave slope spectrum by SAR for NW of Tillamook Bay OR at 14:30 Jan. 18, 2009



NDBC buoy (#46089) directional wave spectrum at 14:50 on Jan. 18, 2009

Case Studies

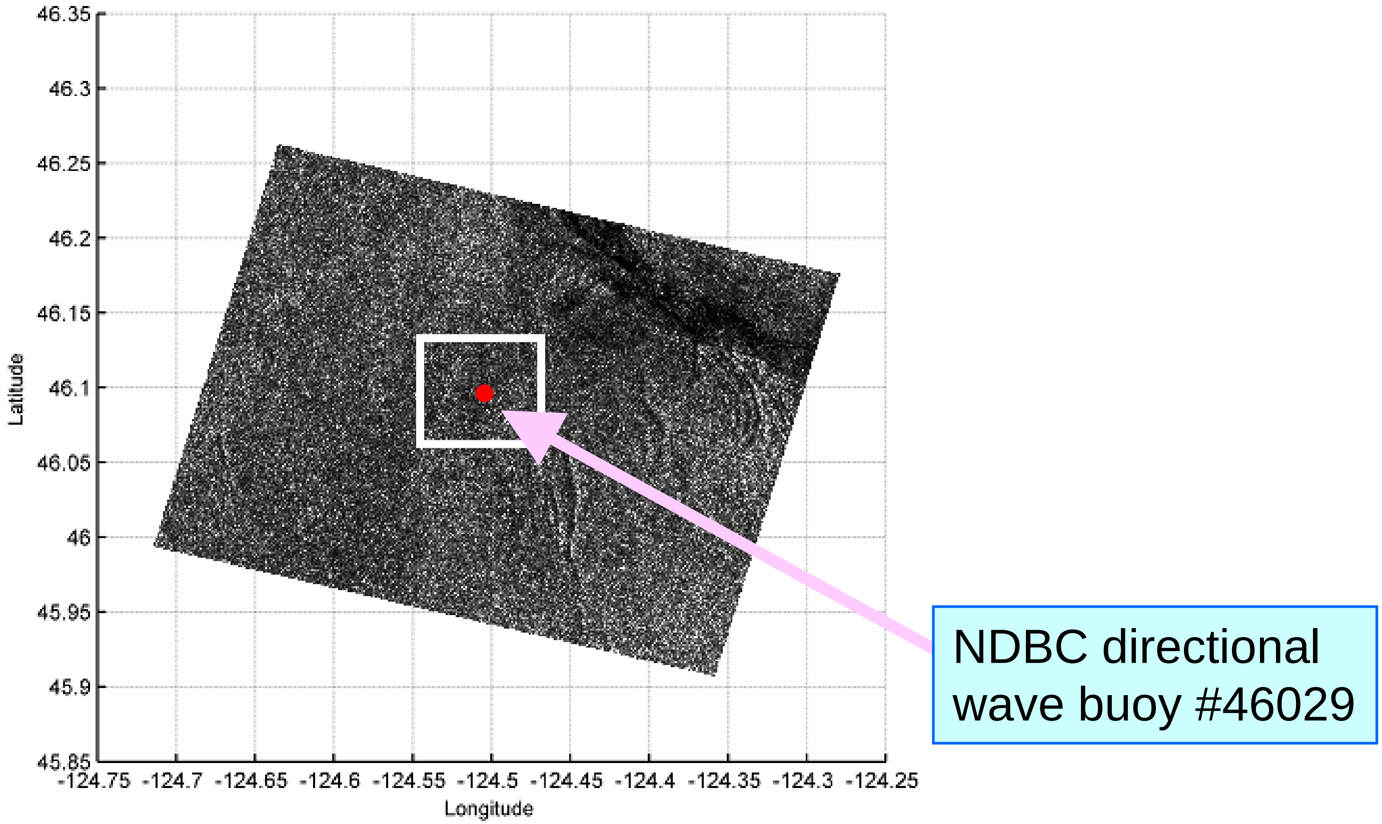
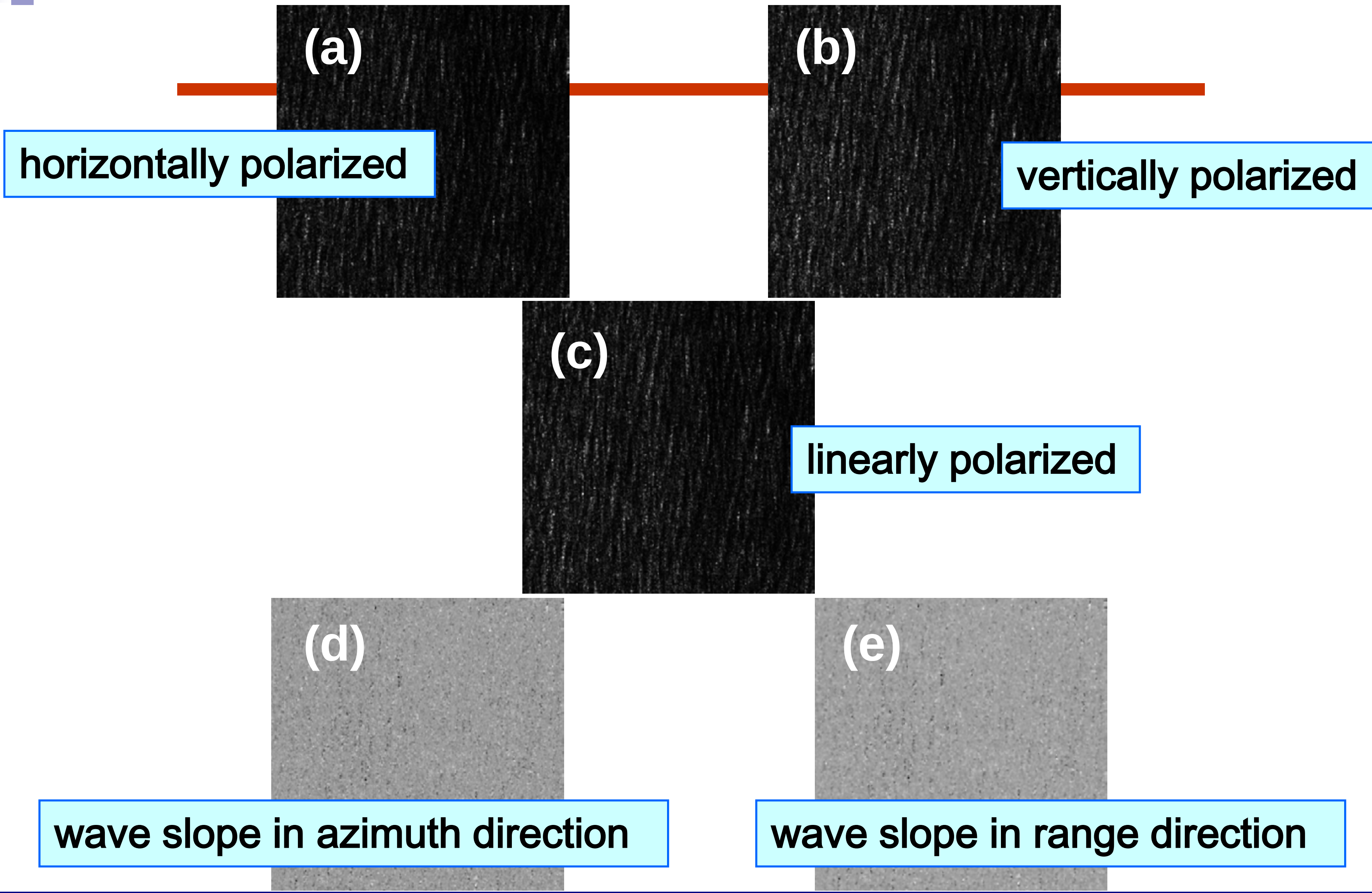
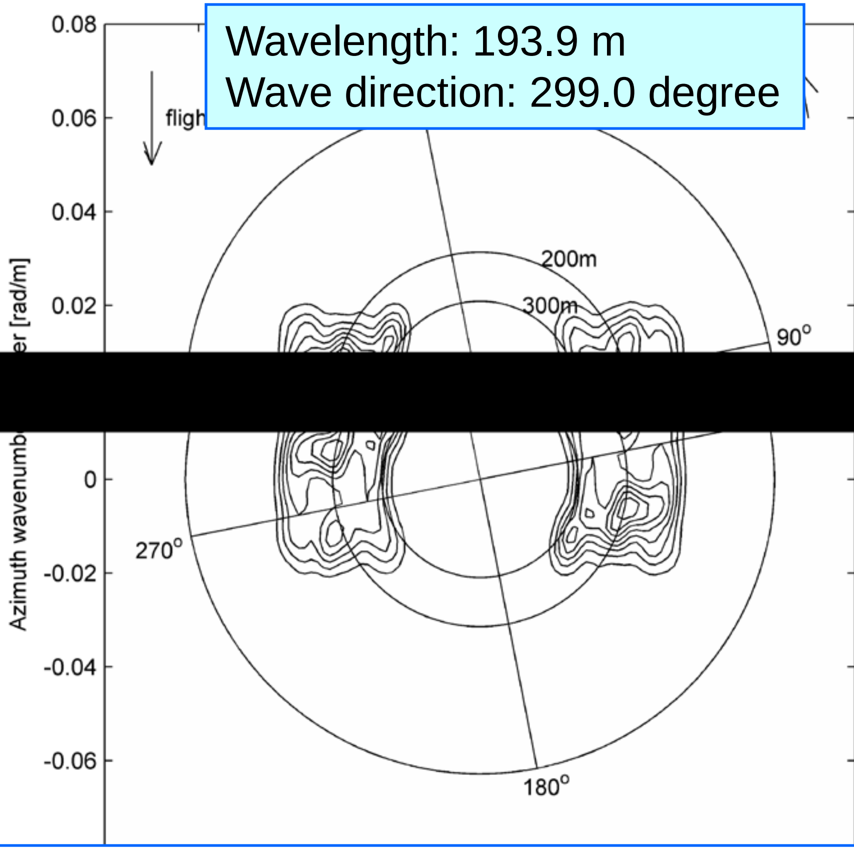


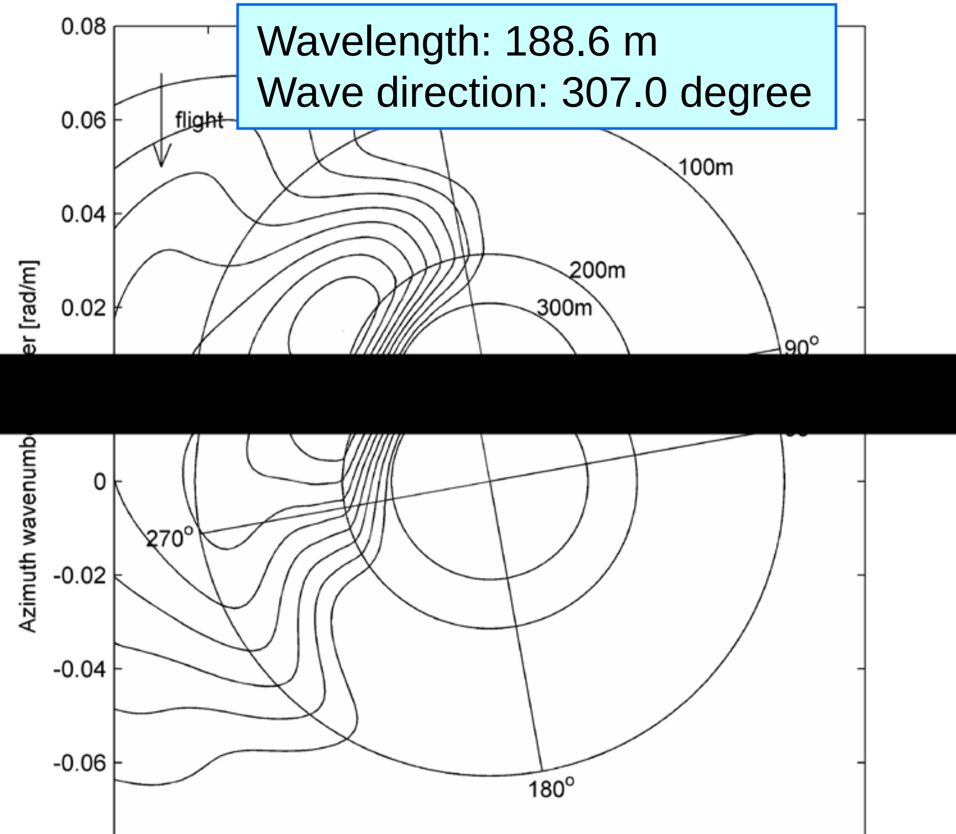
Figure 3. A C-band, VV polarization image of west of Columbia River Mouth acquired by RADARSAT-2 at 14:31 on August 22, 2009 UTC.



RADARSAT-2 fully polarized images

Case Studies





Wave slope spectrum by <u>SAR</u> for west of Columbia R. Mouth at 14:31 Aug. 22, 2009

NDBC <u>buoy</u> (#46029) directional wave spectrum at 14:50 on Aug. 22, 2009

Case Studies

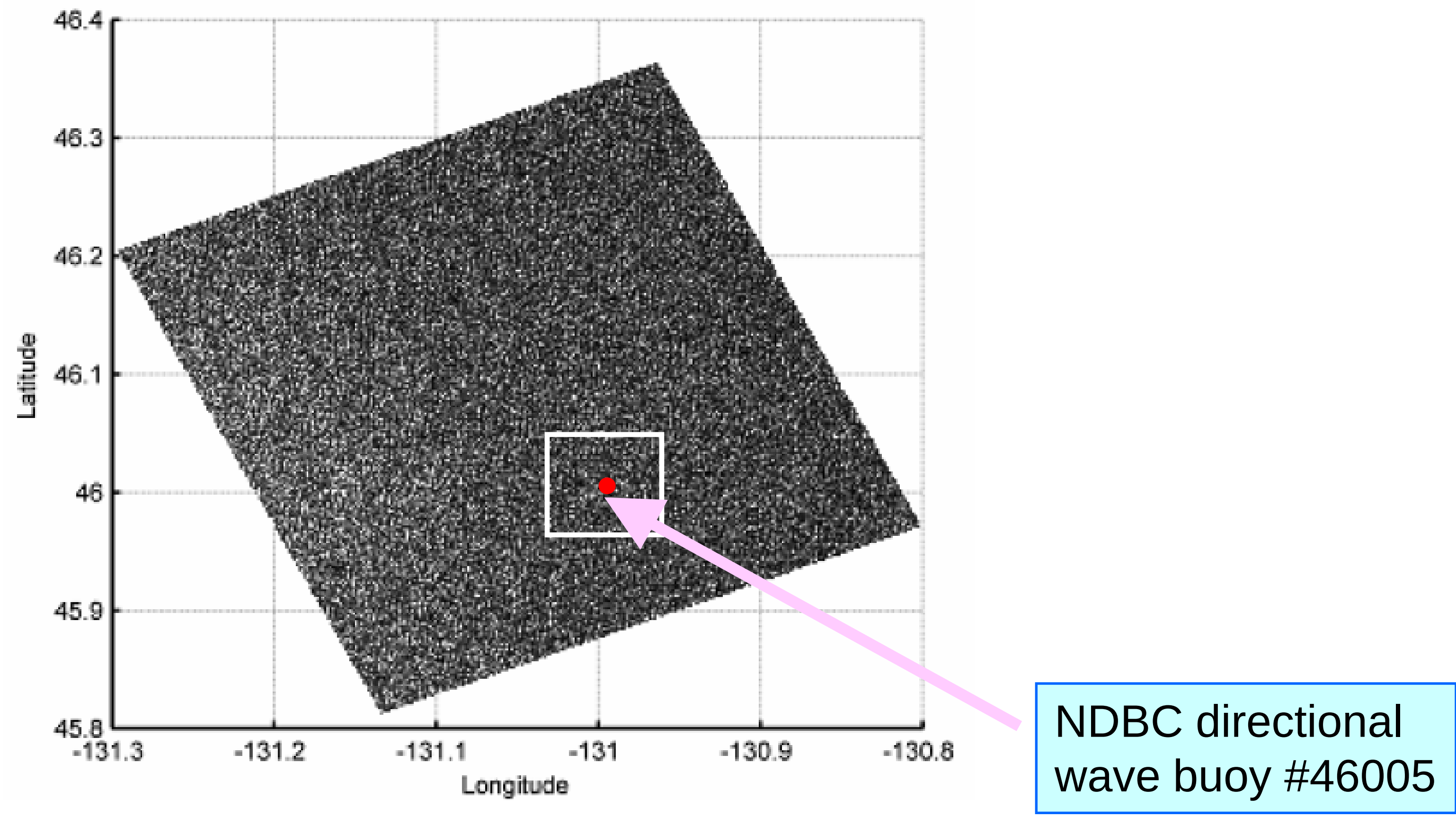
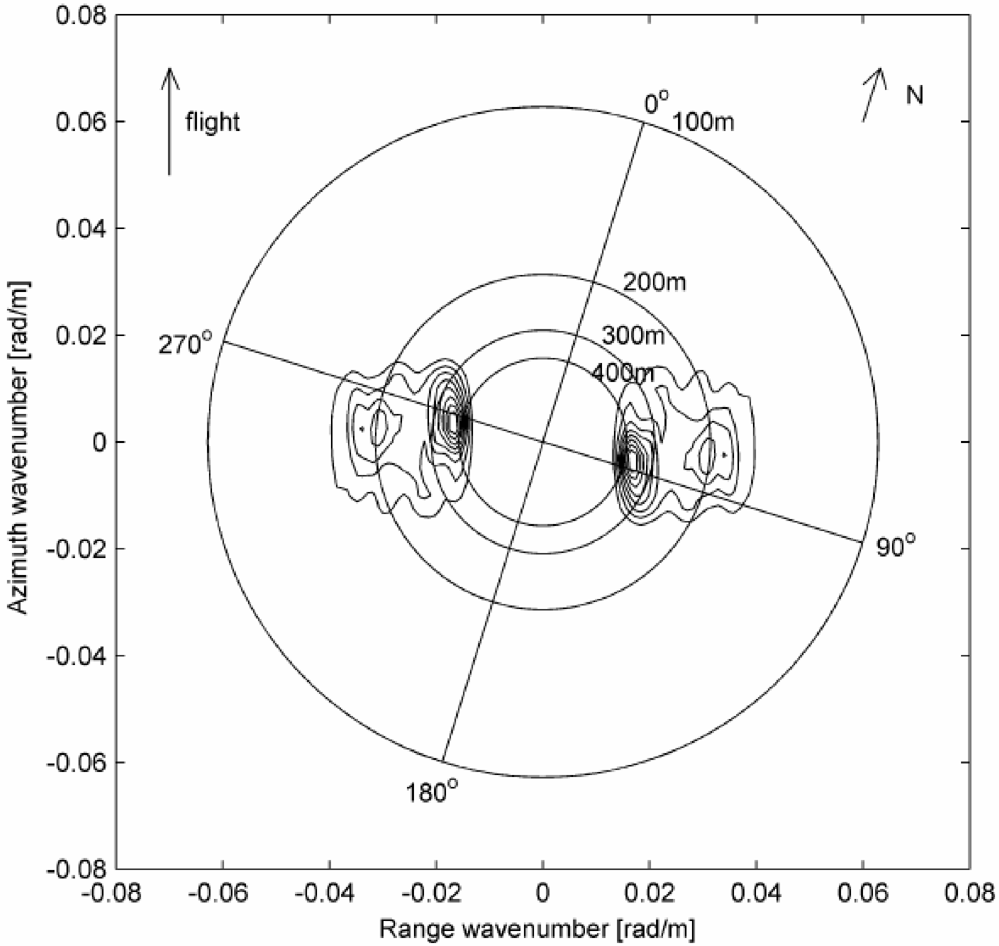
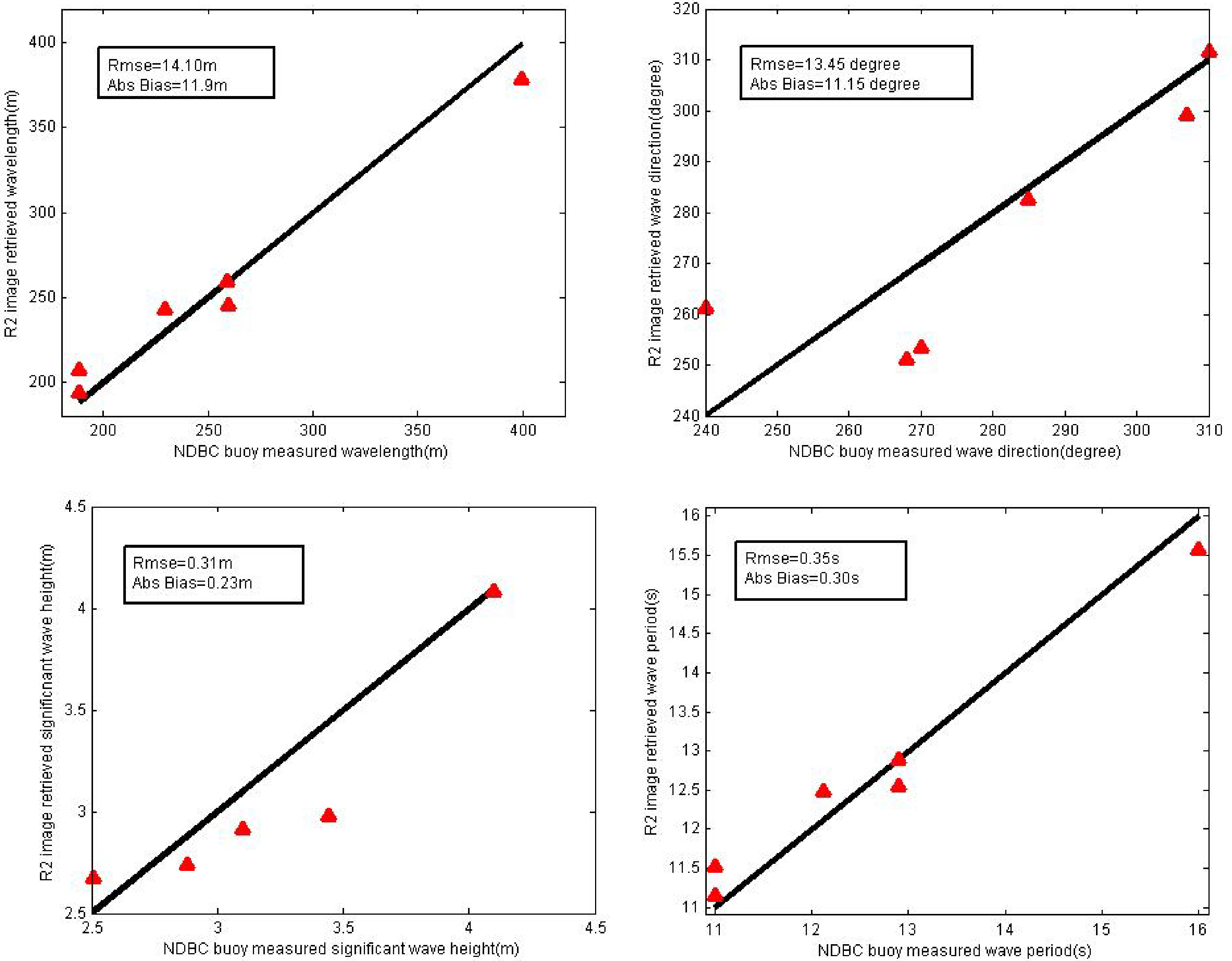


Figure 4. A C-band, VV polarization image of an area west of Aberdeen, WA acquired by RADARSAT-2 at 02:25 on January 11, 2009 UTC.

Case Studies



Wave slope spectrum by SAR for west of Aberdeen at 02:05 Jan. 11, 2009


Rmse=14.10m
Abs Bias=11.9m
R2 image retrieved wavelength(m)
NDBC buoy measured wavelength(m)
Rmse=13.45 degree
Abs Bias=11.15 degree
R2 image retrieved wave direction(degree)
NDBC buoy measured wave direction(degree)
Rmse=0.31m
Abs Bias=0.23m
R2 image retrieved significnant wave height(m)
NDBC buoy measured significant wave height(m)
Rmse=0.35s
Abs Bias=0.30s
R2 image retrieved wave period(s)
NDBC buoy measured wave period(s)

Thanks for your attention