Radar sensing of surface waves: An evaluation of waveheight estimates

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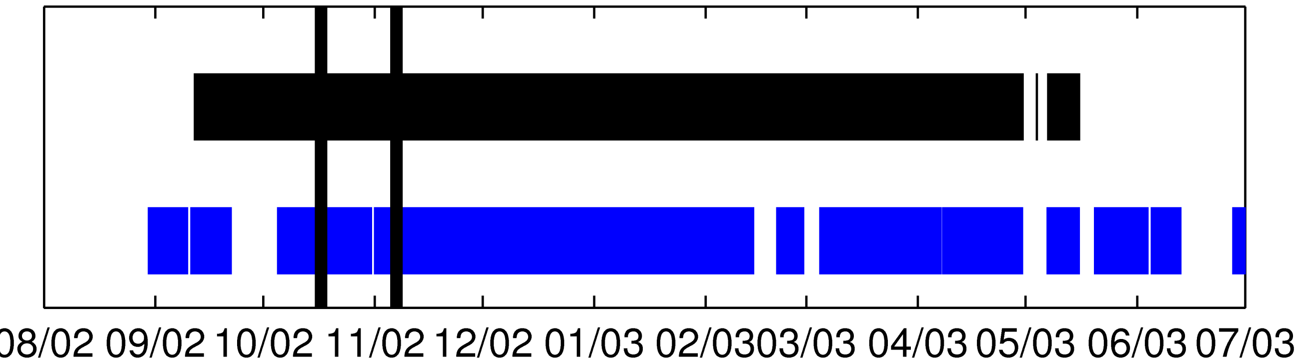
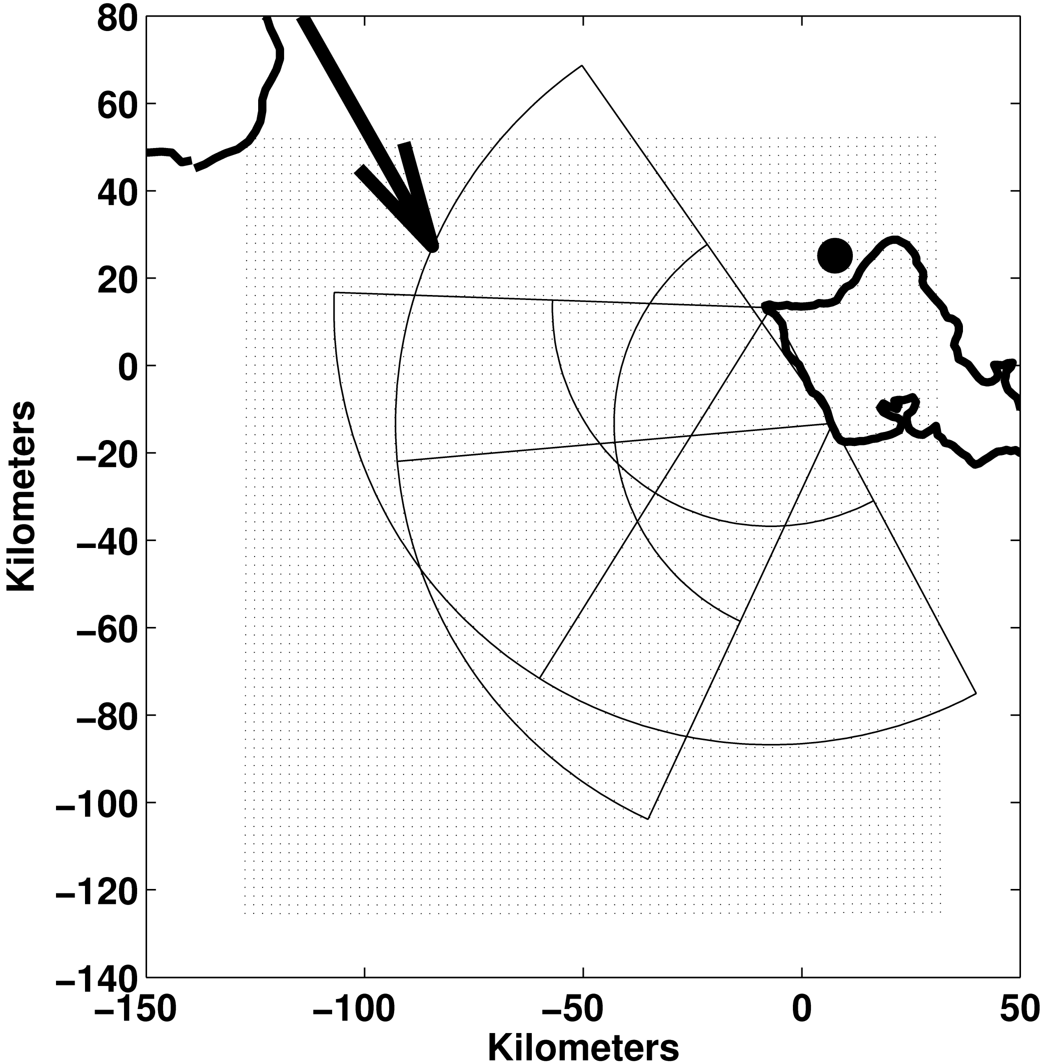
Kaena



17-Oct to 06-Nov 2002, 21 days

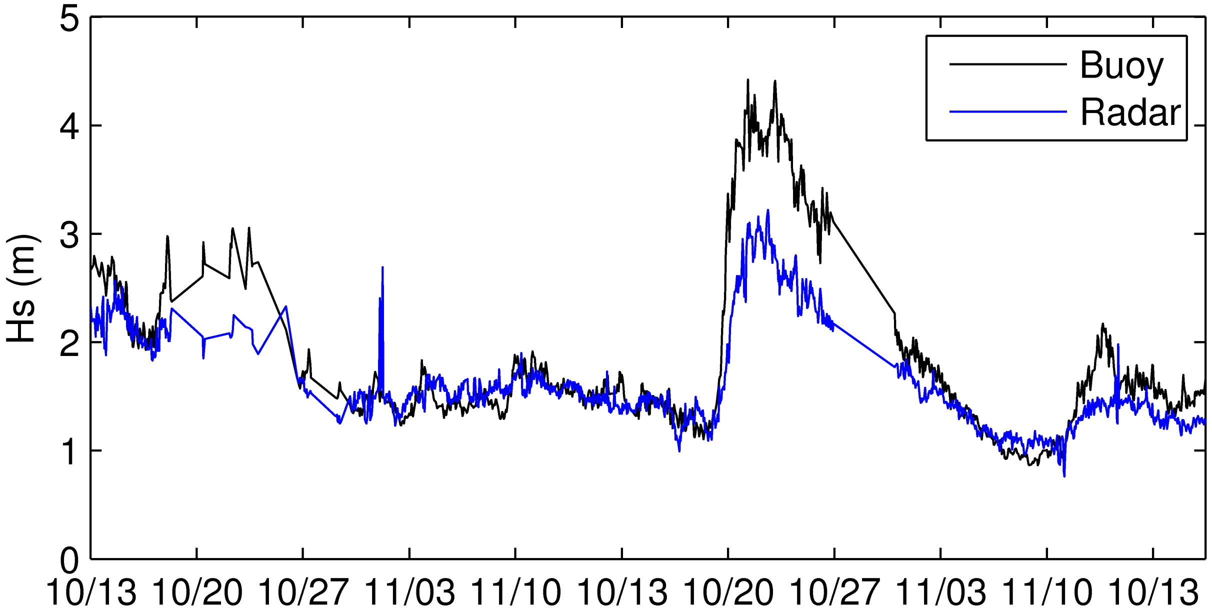


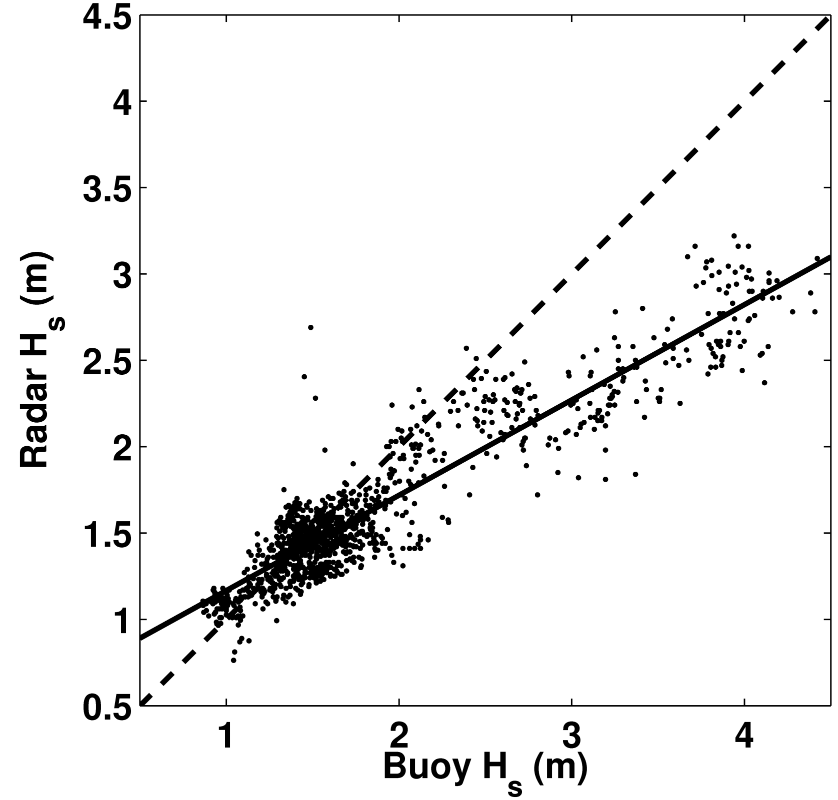
- 16 MHz transmit frequency
- 100 km nominal range
- 7.2 deg angular resolution
- 1.5 km range resolution

Bragg scattering ocean waves:

- 9.38 m wavelength
- 2.45 s period
- 0.41 Hz frequency

Significant waveheight (Hs):
Waimea Buoy & WERA





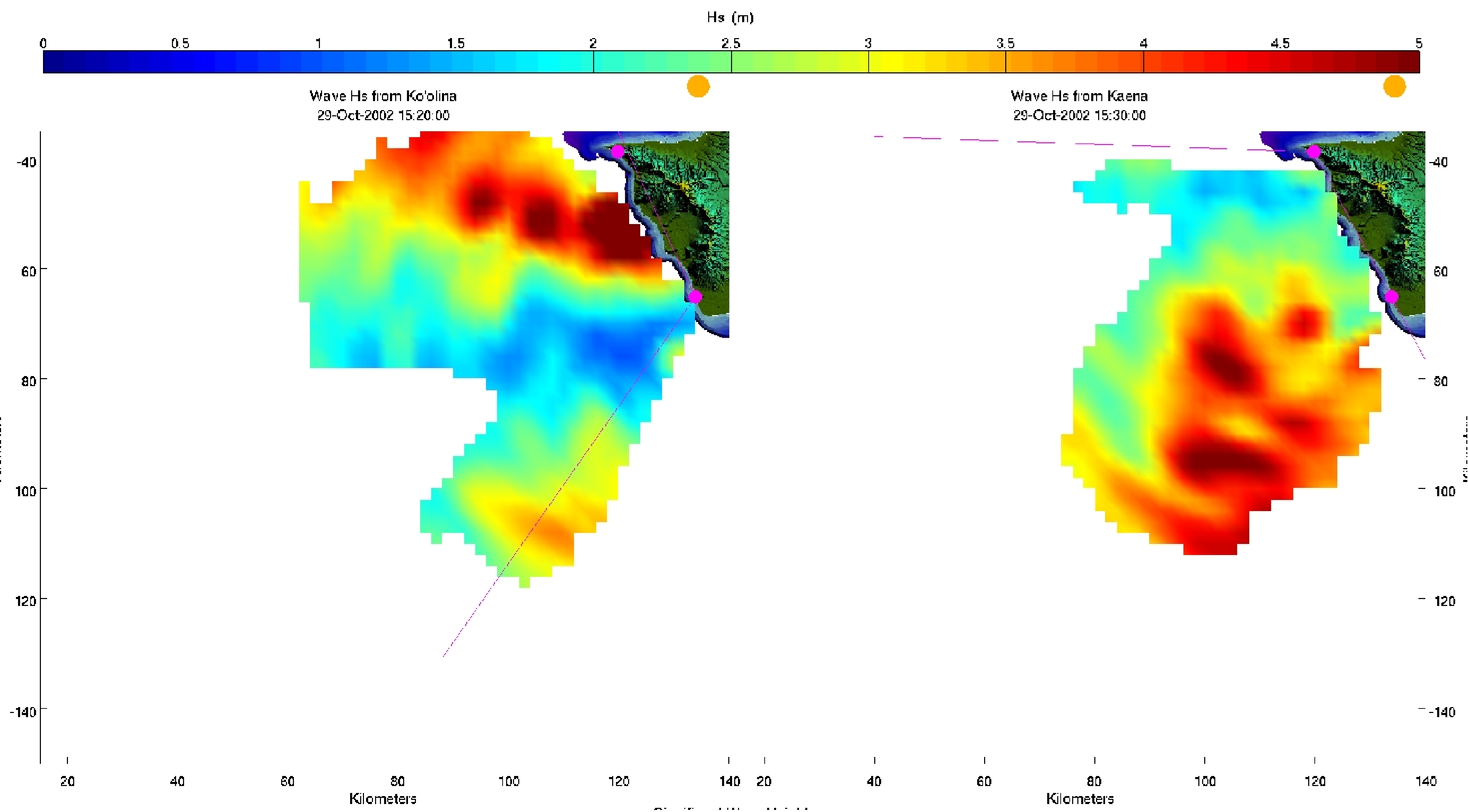
Correlation r = 0.93
RMS error = 0.43 m
RSE error = 0.16 %

Table 1.1: Comparison studies of radar to buoys

	radar	λ_B (m)	Observed H_{rms} (m)	Correlation	σ
Maresca and Georges [1980]	WARF*	9-15	0.3-0.8		7,17%
Heron et al. [1985]	COSRAD	5	0-1		$>15\%$
Heron et al. [1998]	OSCR	6	0-1	0.97	20%
Wyatt and Green [2002]	PISCES,WERA	6-15,10-25	0.5-4	0.94	10.5%
Wyatt et al. [2003]	WERA		1-8	0.94	16.6%
Wyatt et al. [2005]	OSCR		0.5-3	0.88	
Wyatt et al. [2006]	PISCES	15-21	0.5-8	0.90	33.8%
	WERA	**9.4**	**1- 4**	**0.93**	**16 %**

λ_B: Bragg wavelength, σ: normalized standard deviation, i.e. relative standard error

* skywave radar

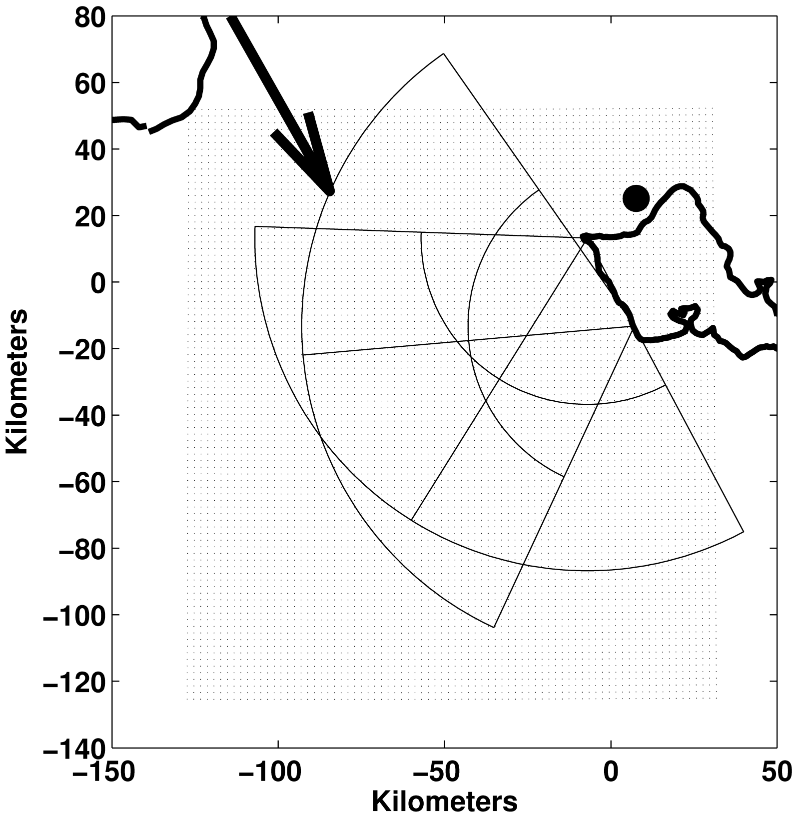


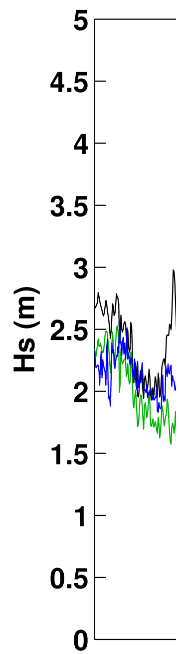
Spatial field of Hs estimates showed large variations in space and time. *O*(5) m differences within 25 km and 1 hour

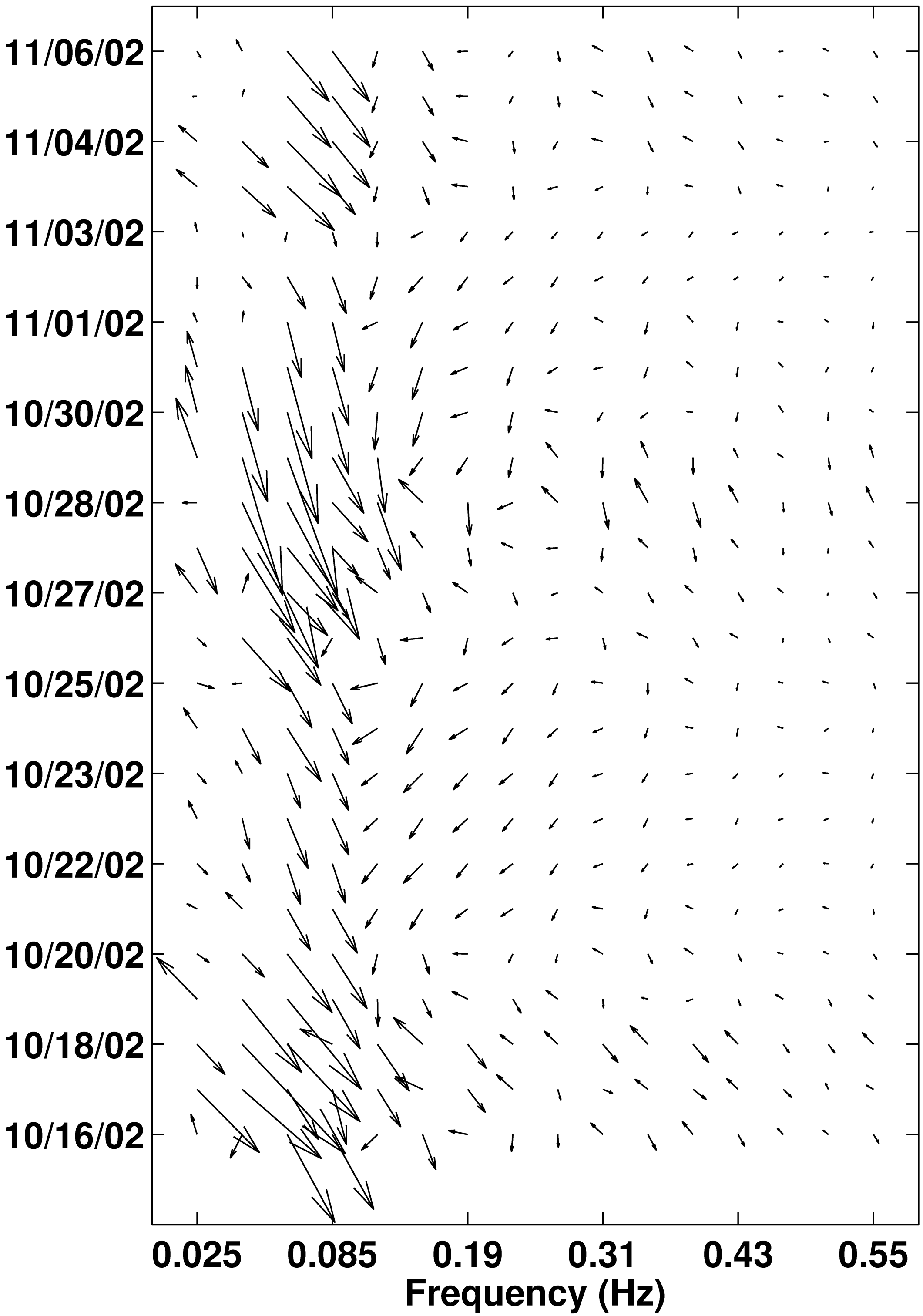
Outline

1. Theory
    1. First order measurement
    2. Second order measurement
2. Noise
3. CEOF
4. Model-based
5. SNR filtering

Land Shadowing



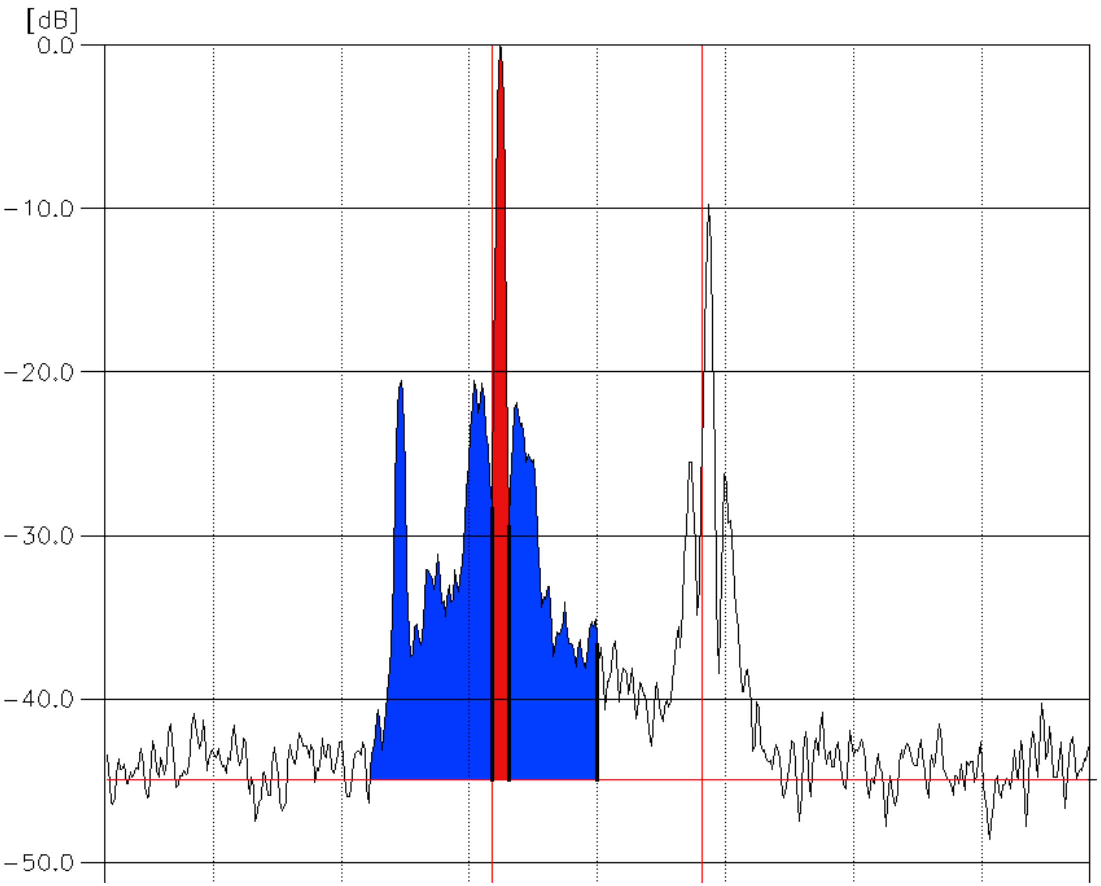




Significant wave height

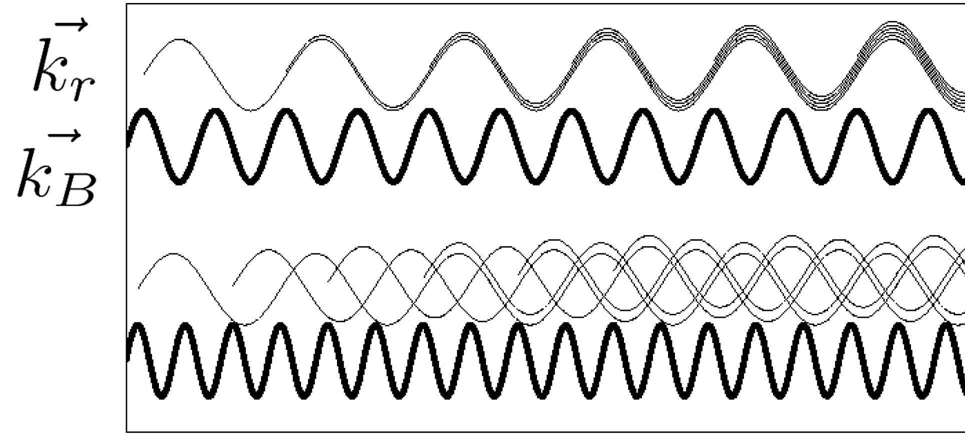
$$h_{rms}^2 = \frac{2\int_{-\infty}^{\infty} \sigma_2(\omega_d)/\Gamma d\omega_d}{k_0^2 \int_{-\infty}^{\infty} \sigma_1(\omega_d) d\omega_d}$$

Using theory derived from electromagnetic and hydrodynamic first principles, the radar is capable of measuring Hs as a ratio of integrated first order (linear) to second order (non-linear) energies.



First Order Bragg Scattering

To any order, coherent signal will only occur from surface features with the Bragg wavelength



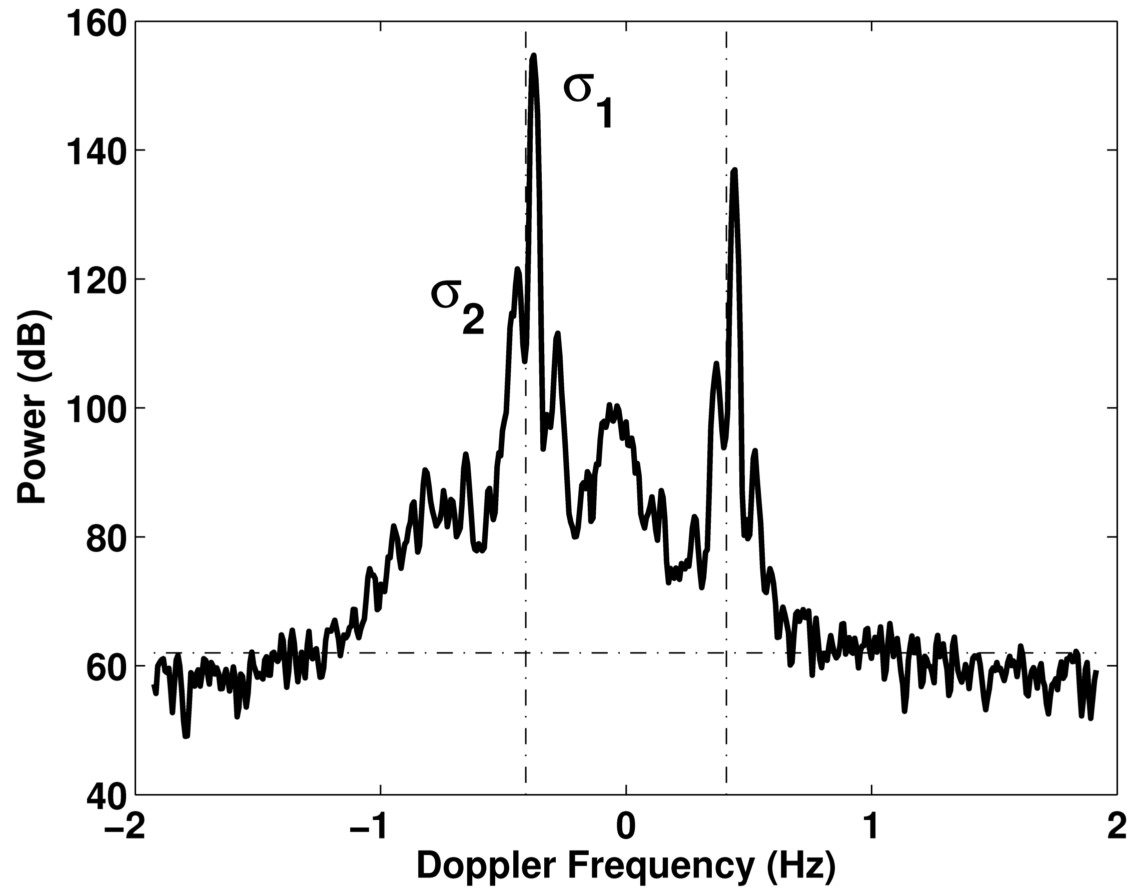
$$\sigma_1(\omega_d) = 2^7 \pi k_0^4 S(\vec{k_r}) \delta(\omega_d - \omega_r)$$

First order scattering is a simple proportional relationship between the EM and ocean waves.

Only *ONE* ocean wavelength causes coherent scattering.
It is a known constant.

$$2\vec{k_r} = \vec{k_B}$$

$$\sigma_1(\omega_d) \quad \omega_d$$



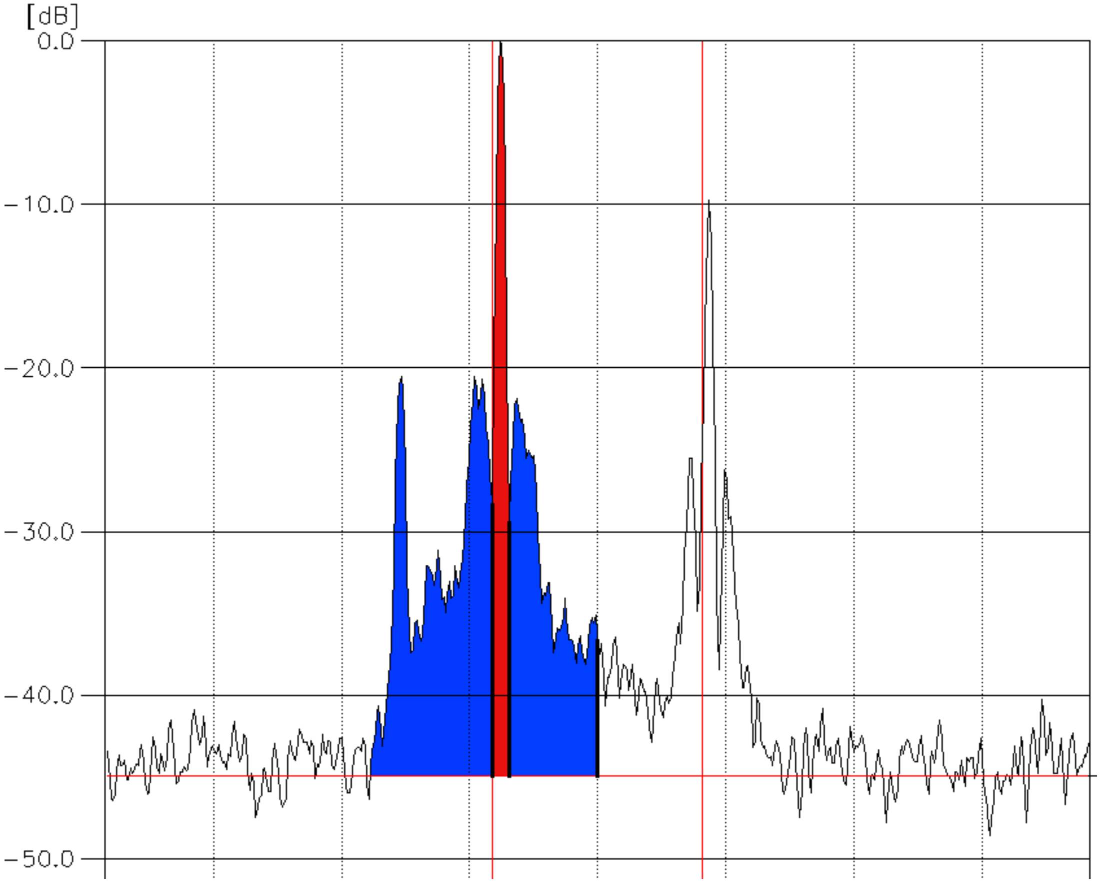
Second Order Scattering

$$\sigma_2(\omega_d) = 2^4 \pi k_0^4 \int \int_{-\infty}^{\infty} |\Gamma(\vec{k_1}, \vec{k_2})|^2 S(\vec{k_1}) S(\vec{k_2}) \delta(\omega_d - \omega_1 - \omega_2) d\vec{k}$$

$$\vec{k_B} = \vec{k_1} + \vec{k_2}$$

$$\omega_d = \omega_1 + \omega_2$$

Information encoded primarily in amplitude



Again, Second-Order signal can only occur for coherent scattering off features with the Bragg wavelength.

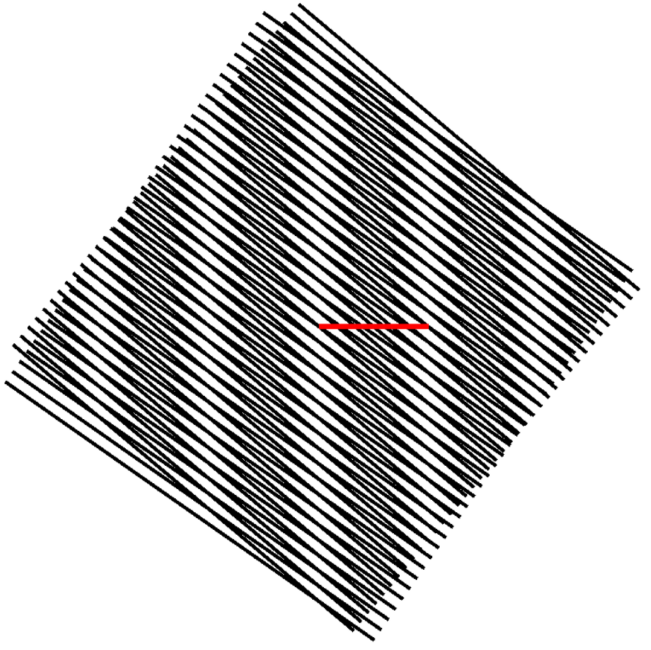
These are *nonlinear ocean waves*, and EM double-scattering

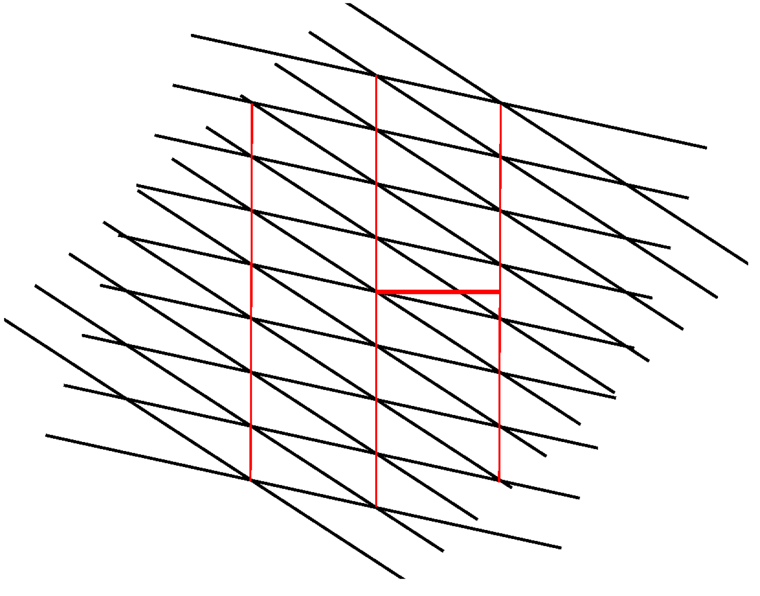
Perturbation expansion of nonlinear equations for free water surface and the EM fields yields second-order terms.

Represented as coupling coefficient Gamma.

Coupling Coefficient, i.e. Second-Order Weighting Function

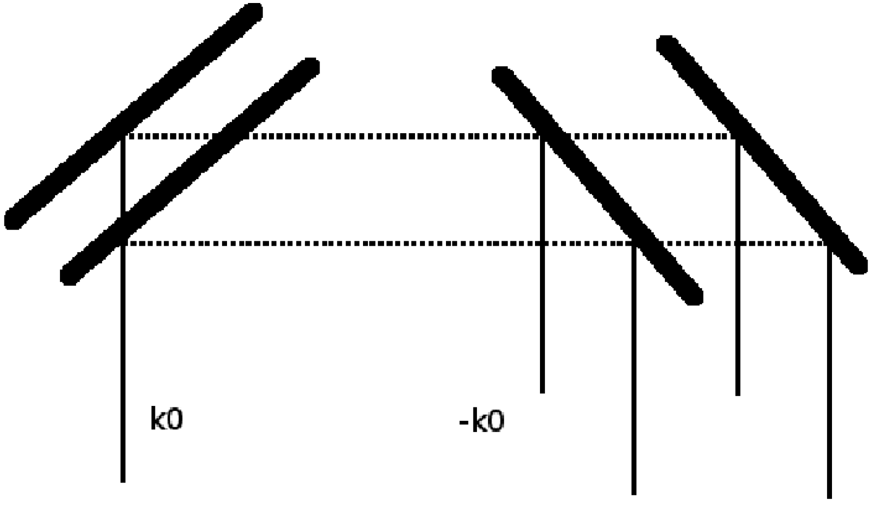
$$\Gamma = \Gamma_H + \Gamma_E M$$





Hydrodynamic

$$\vec{k_B} = \vec{k_1} + \vec{k_2}$$

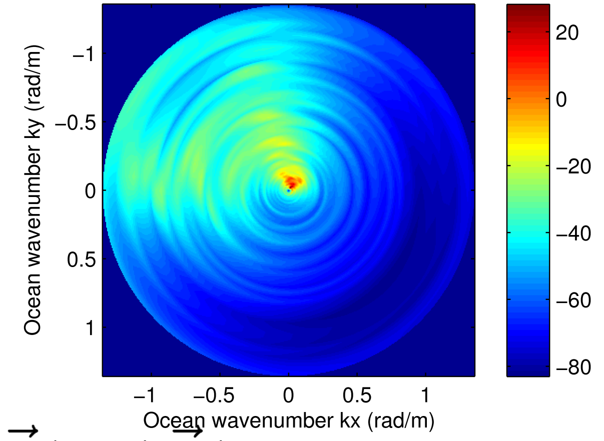


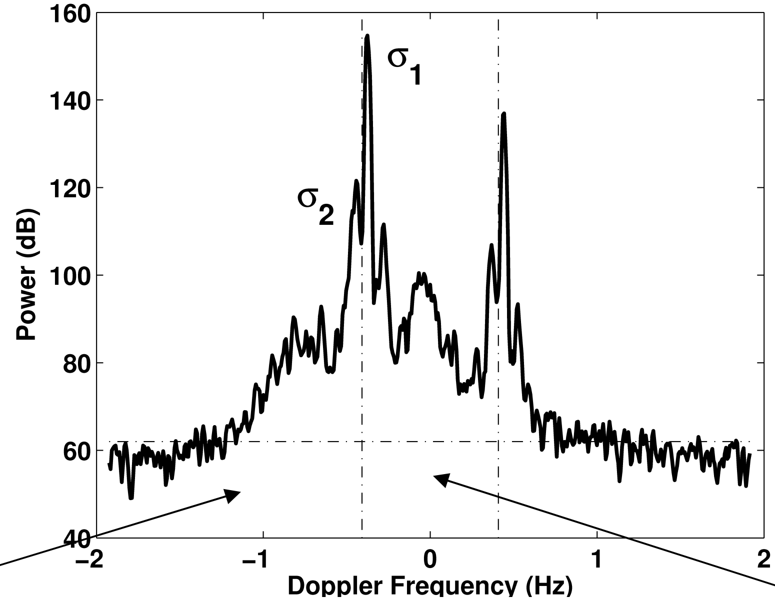
Electromagnetic

$$\sigma_2(\omega_d) = 2^4 \pi k_0^4 \int \int_{-\infty}^{\infty} |\Gamma(\vec{k_1}, \vec{k_2})|^2 S(\vec{k_1}) S(\vec{k_2}) \delta(\omega_d - \omega_1 - \omega_2) d\vec{k}$$

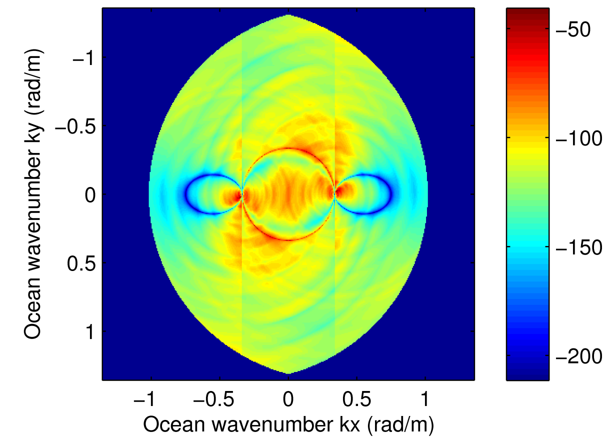
The second order integral relationship is a convoluted mapping of the ocean wave directional spectrum to the radar spectrum.
Each radar frequency is an integration over a closed wavevector contour.

$$S(\vec{k})$$



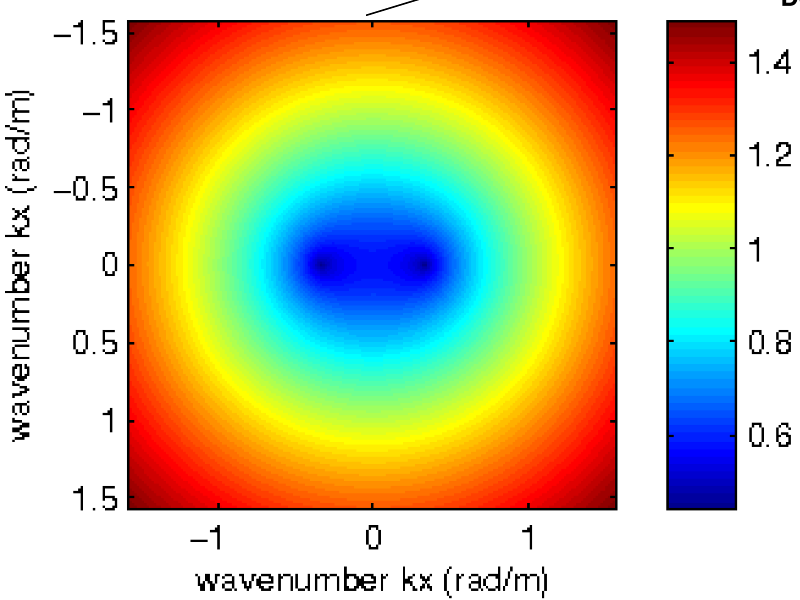


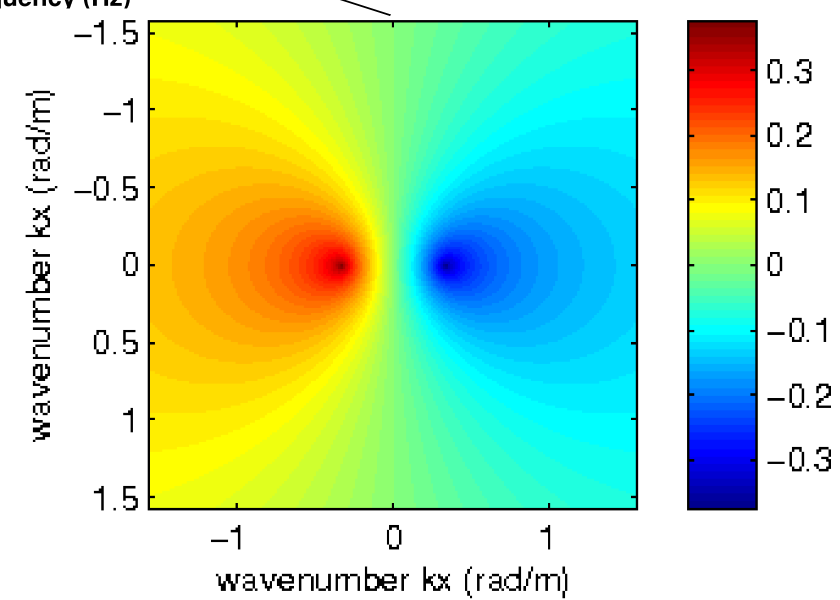
$$|\Gamma|^2 S(\vec{k_1}) S(\vec{k_2})$$



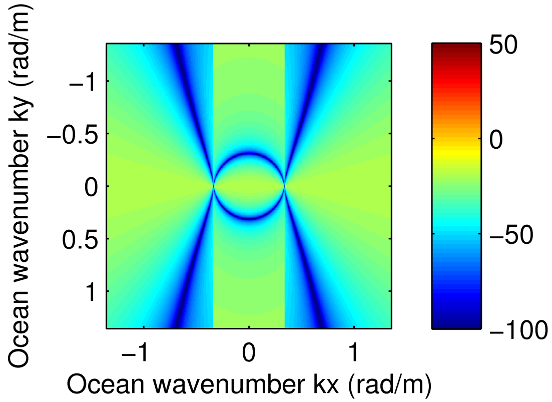
$$\omega_d = \omega_1 + \omega_2$$

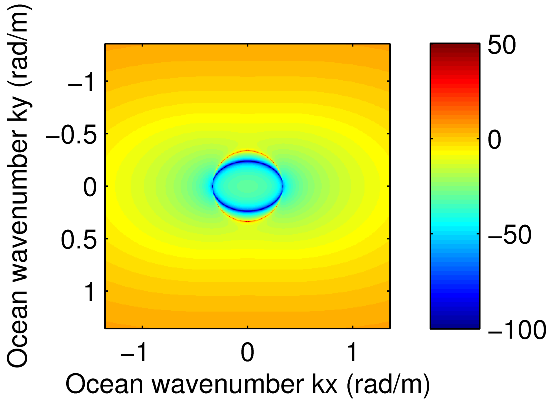
$$\vec{k_B} = \vec{k_1} + \vec{k_2}$$

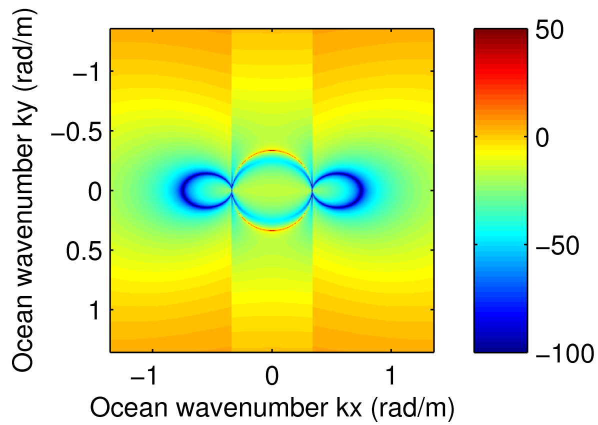


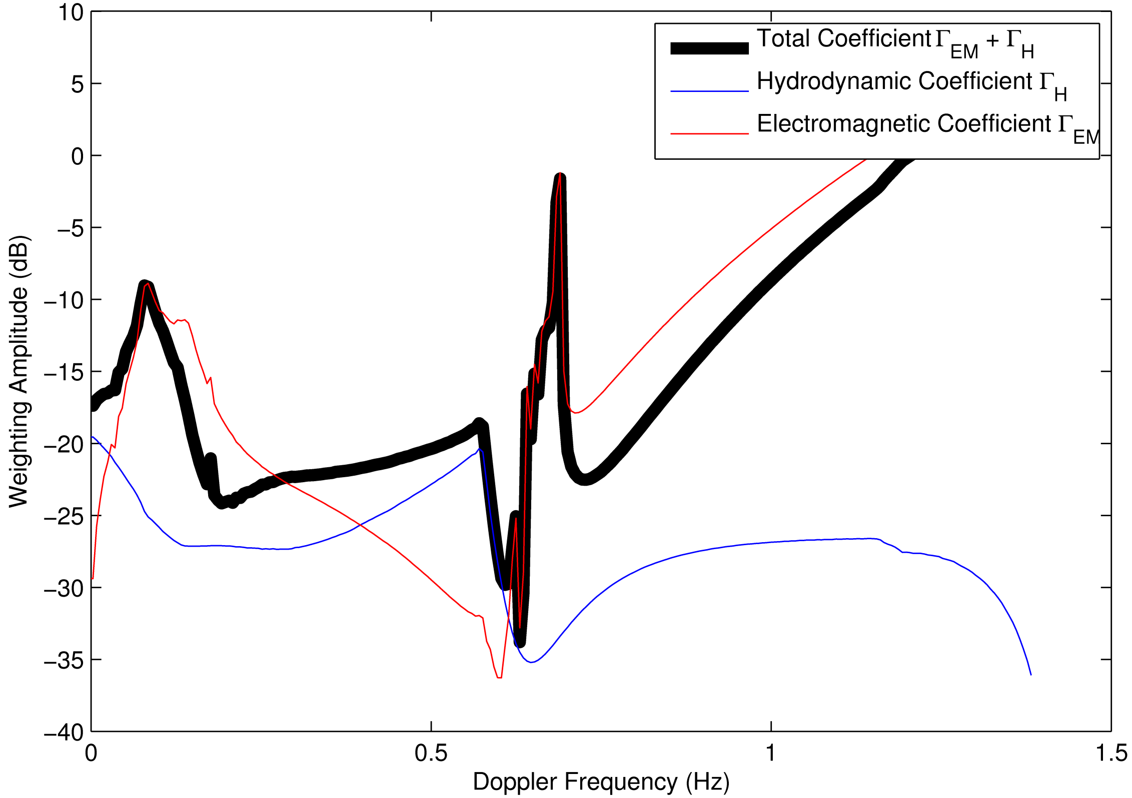


$$\Gamma = \Gamma_H + \Gamma_E M$$





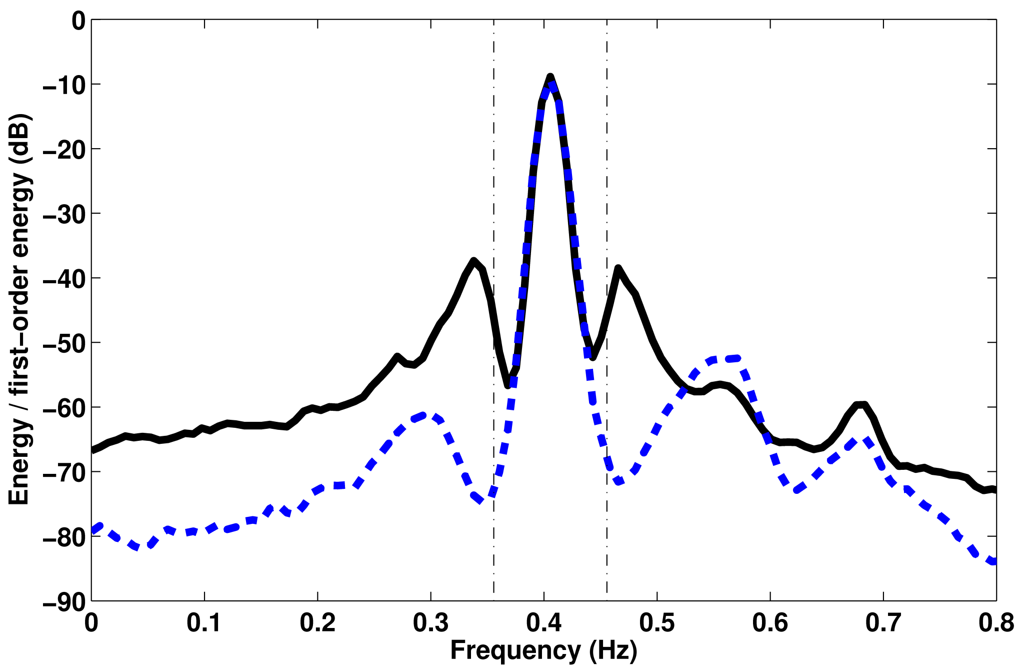


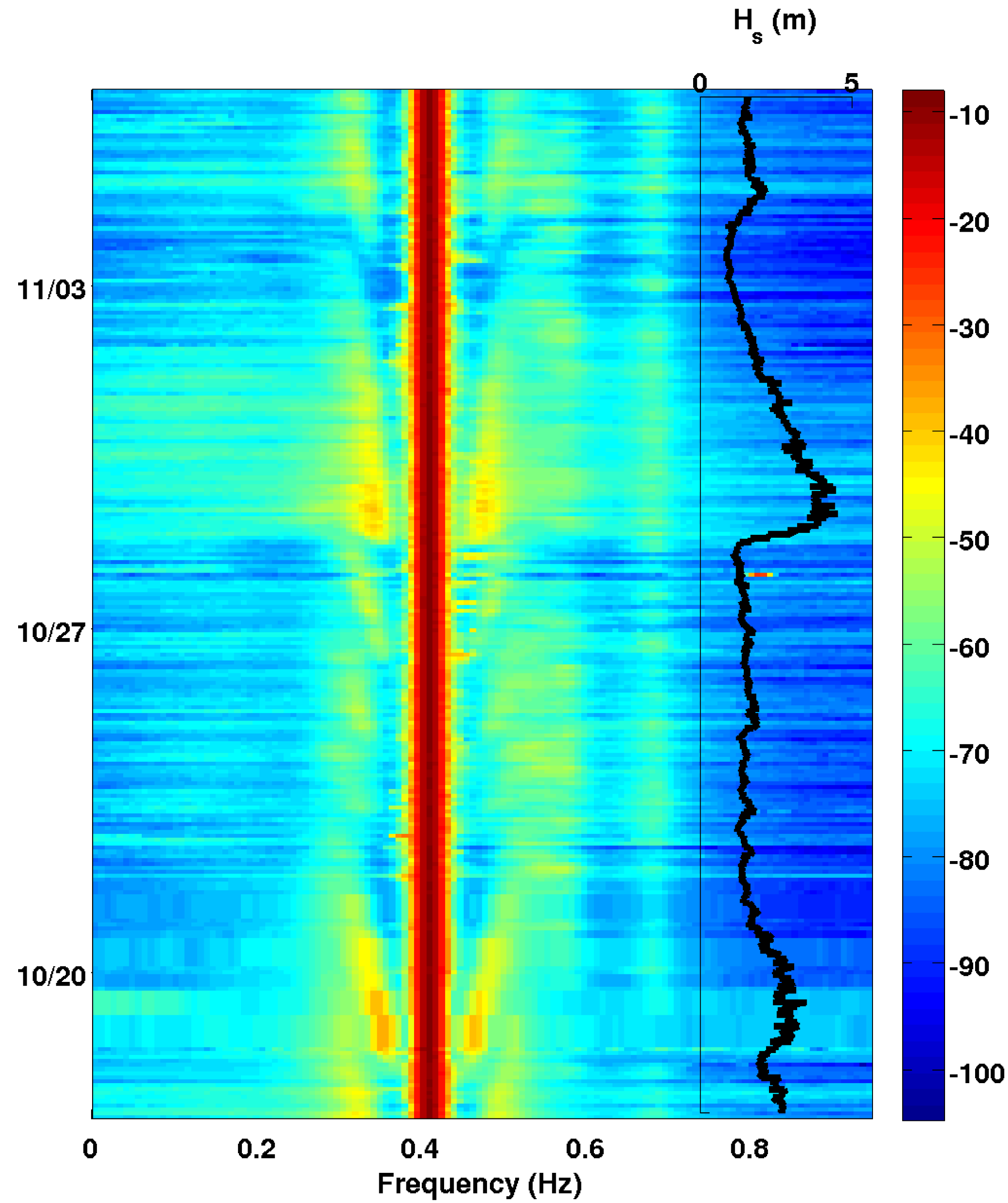


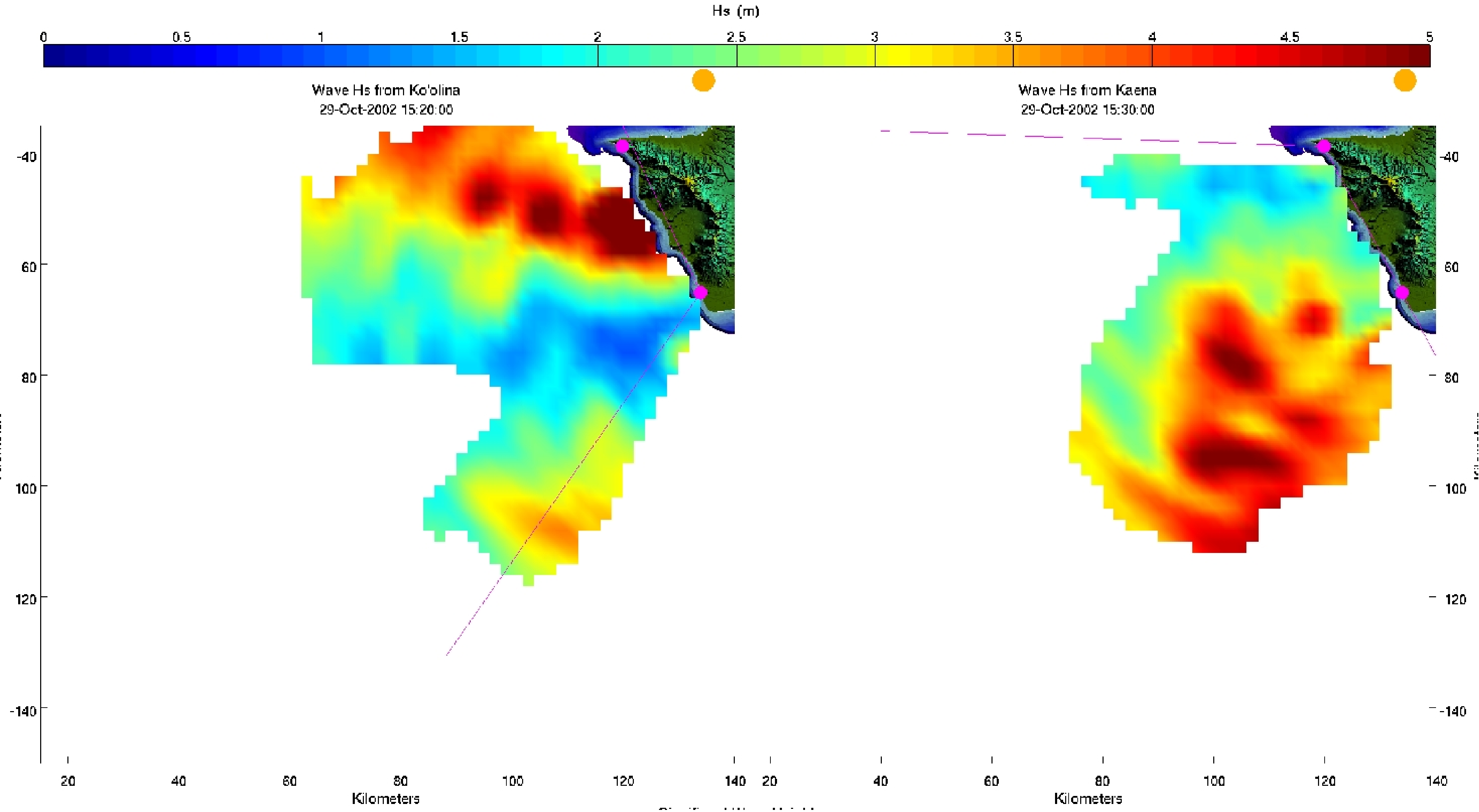
Waveheight bias

Scattering theory predicts the frequency separation between first and second order peaks will decrease as the ocean swell moves to lower frequencies.

As the energy of the peaks is convolved, their ratio is biased towards one, i.e. the Hs is biased low.

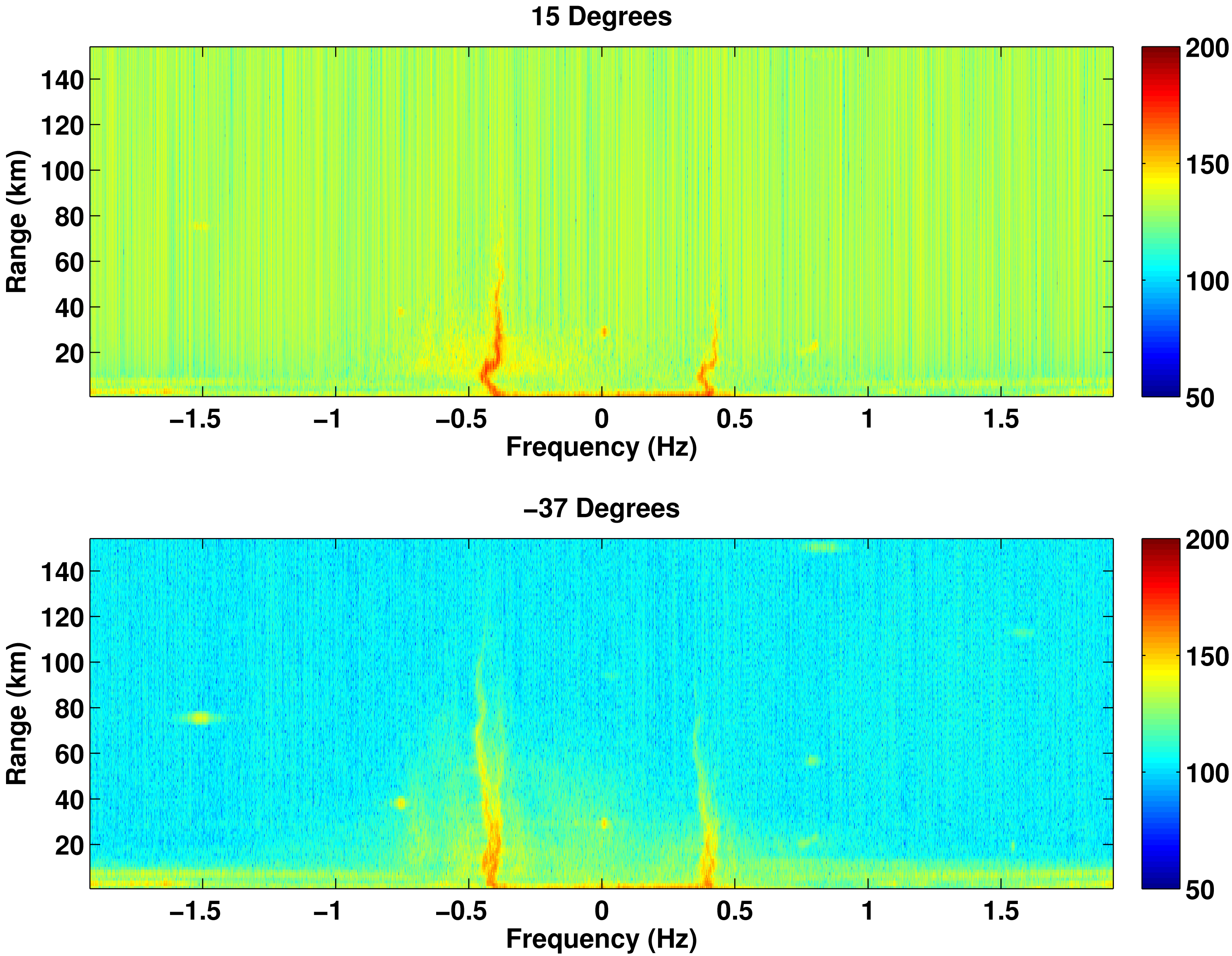






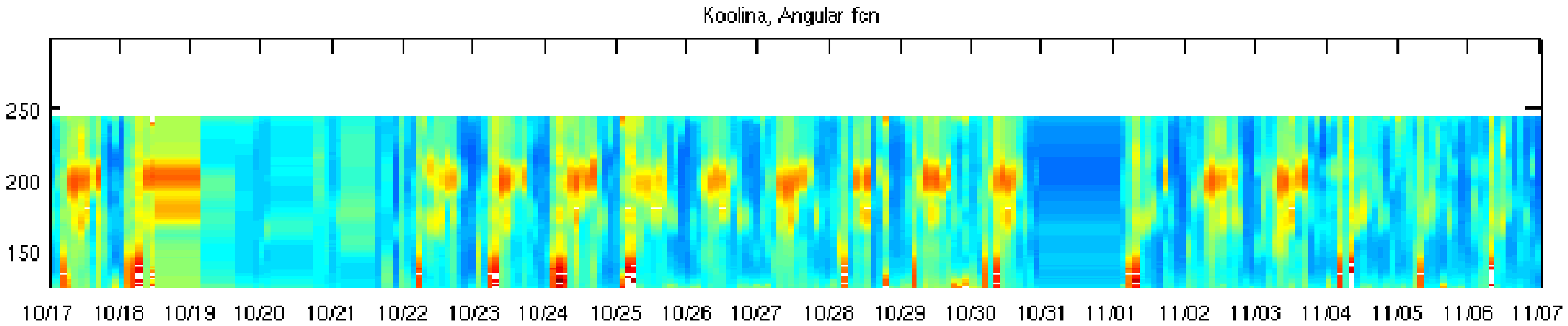
Spatial field of Hs estimates showed large variations in space and time. *O*(5) m differences within 25 km and 1 hour

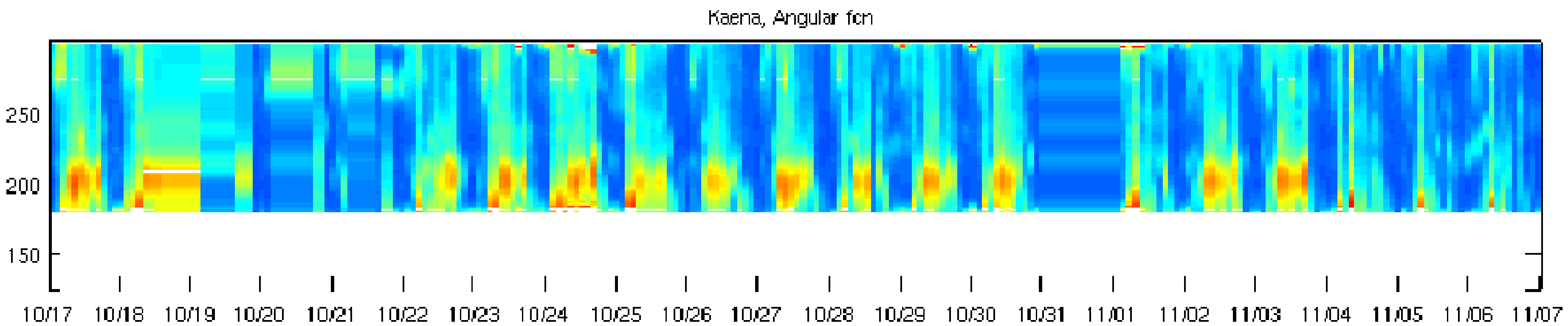
- Noise is contaminating spectra
- Range-independence is characteristic of external interference, not systematic



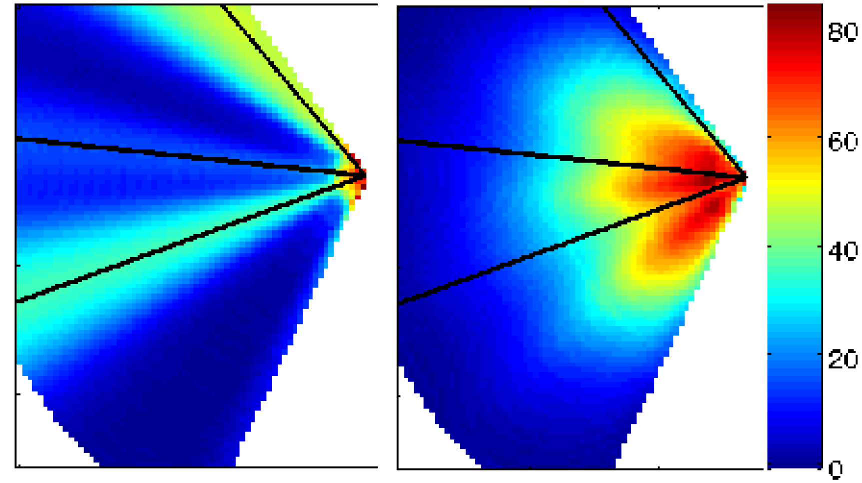
Noise level timeseries as a function of angle

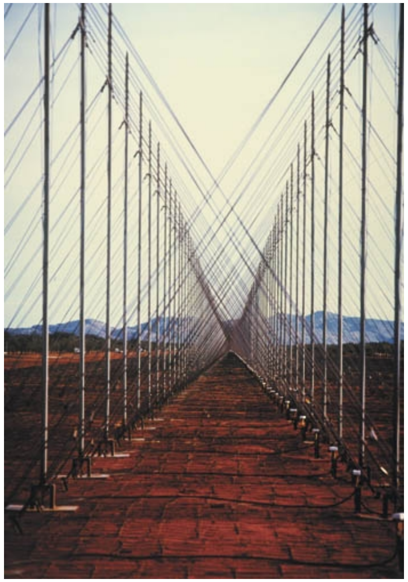
- Both sites have strong interference at 200 deg incident

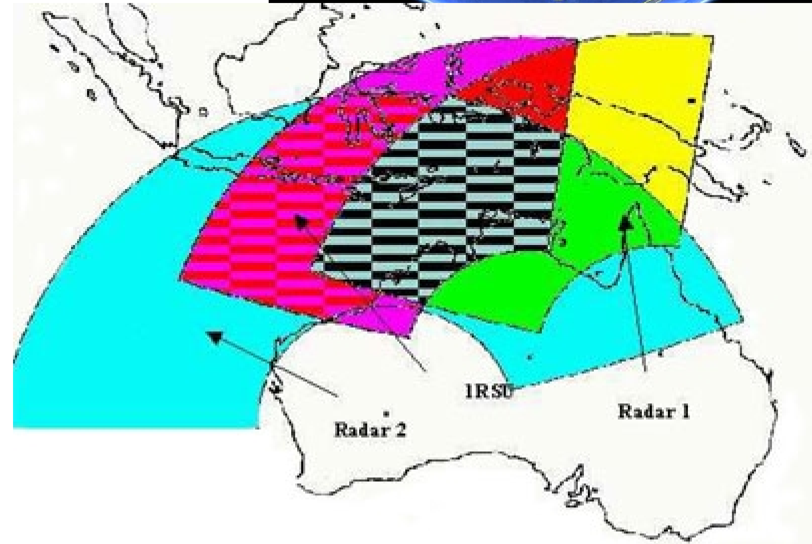




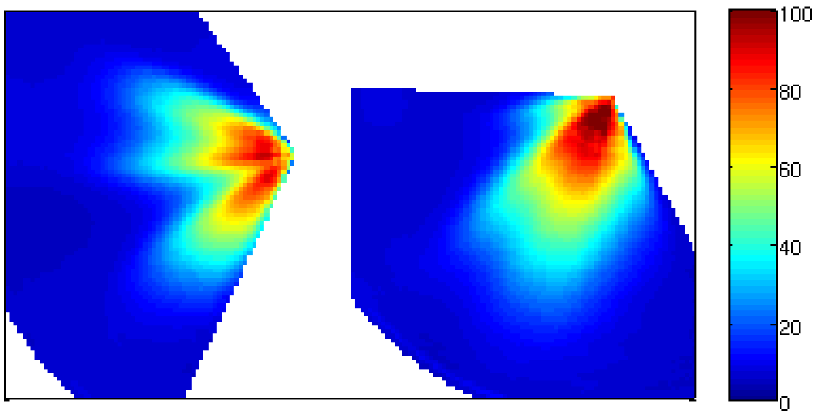
External Interference

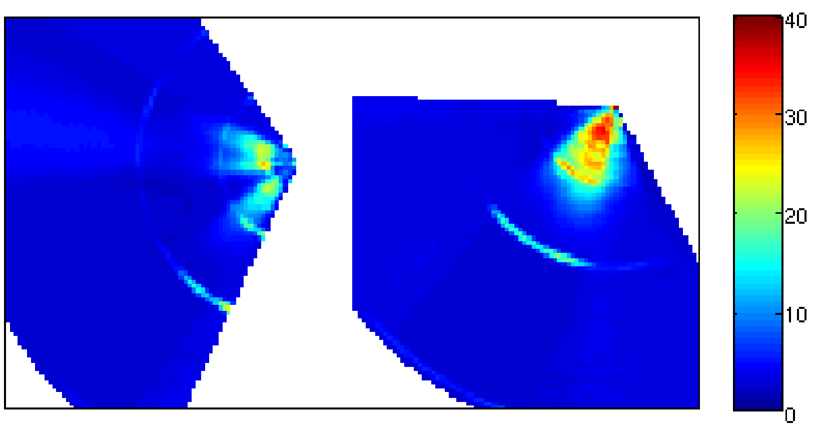


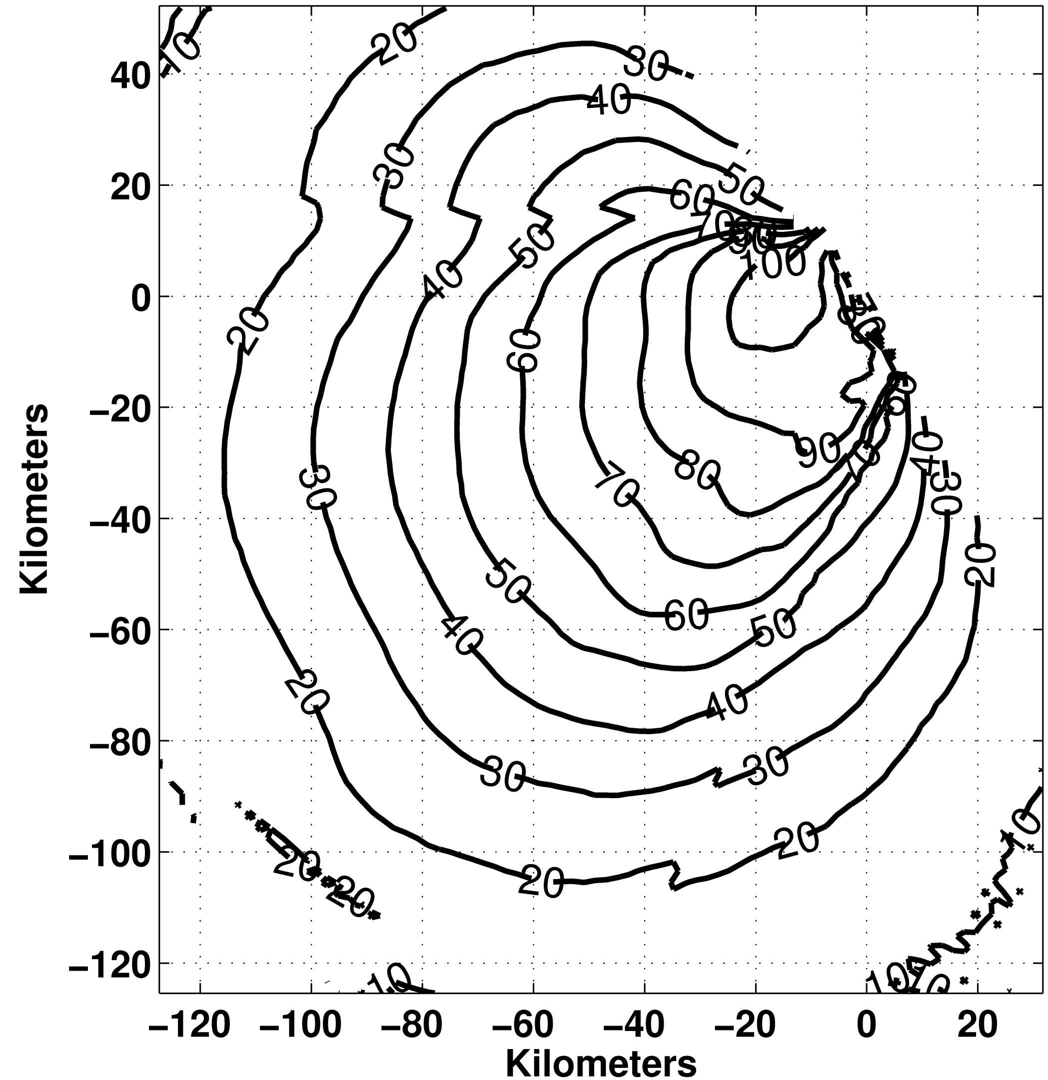




Signal-To-Noise Ratio (SNR)



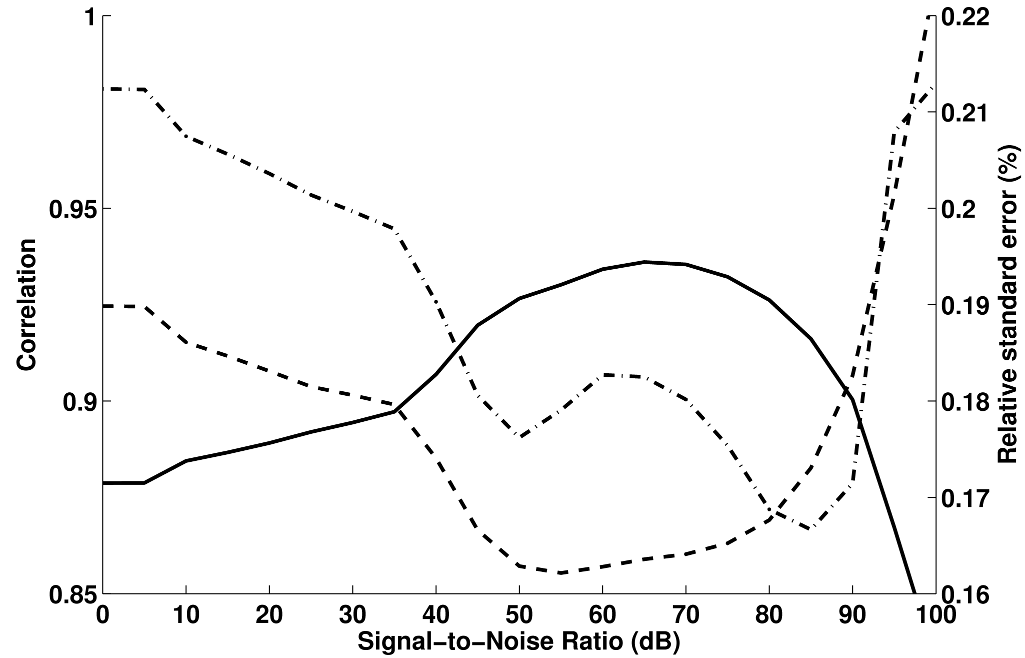


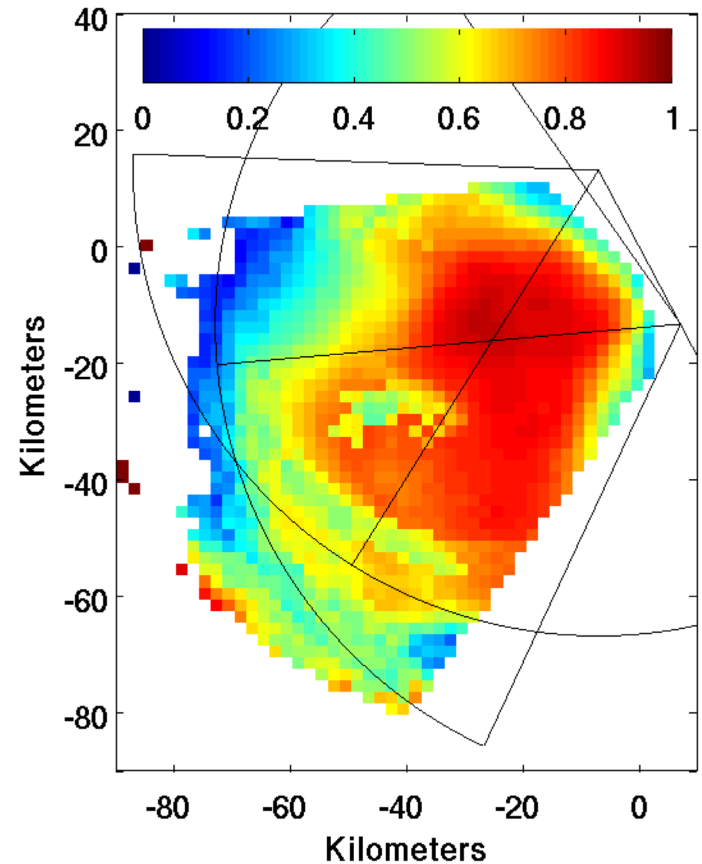


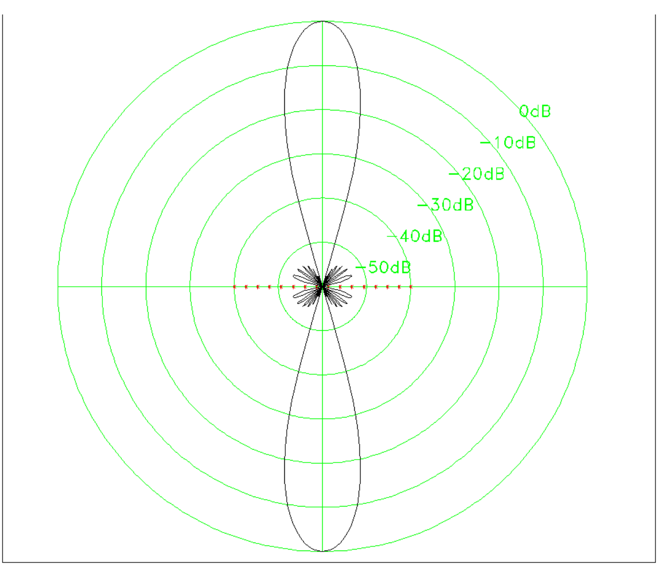
- Mean SNR of 50 dB to ~ 70 km
- Second order energy mostly degraded

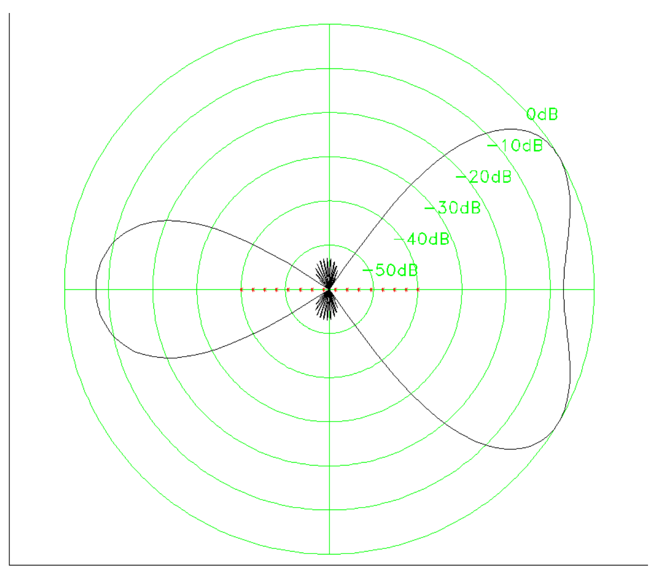
SNR Filtering

- Small improvement to accuracy:
- + 0.05 r, - 3% normalized error
- Maximum accuracy occurred at intersection of center-beams; attributed to optimal beamforming
- 80% reduction is usable data
- *Spatial accuracy is not significantly improved*

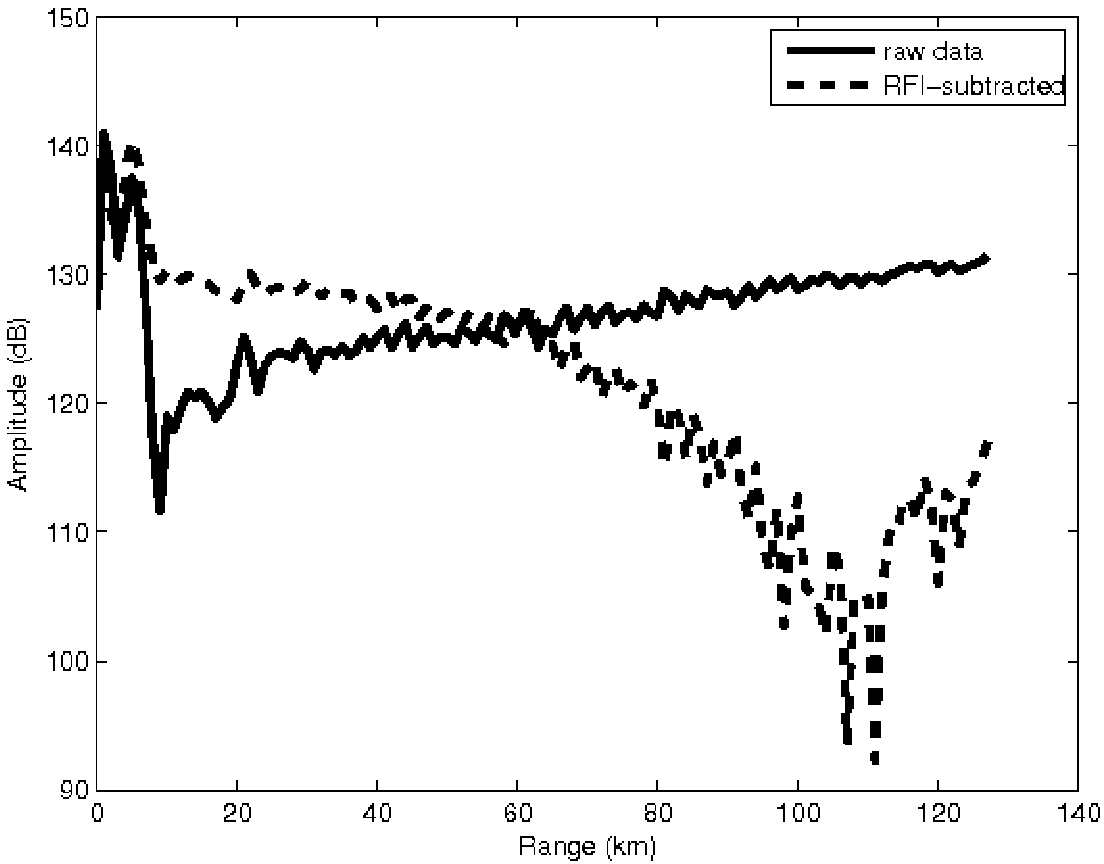


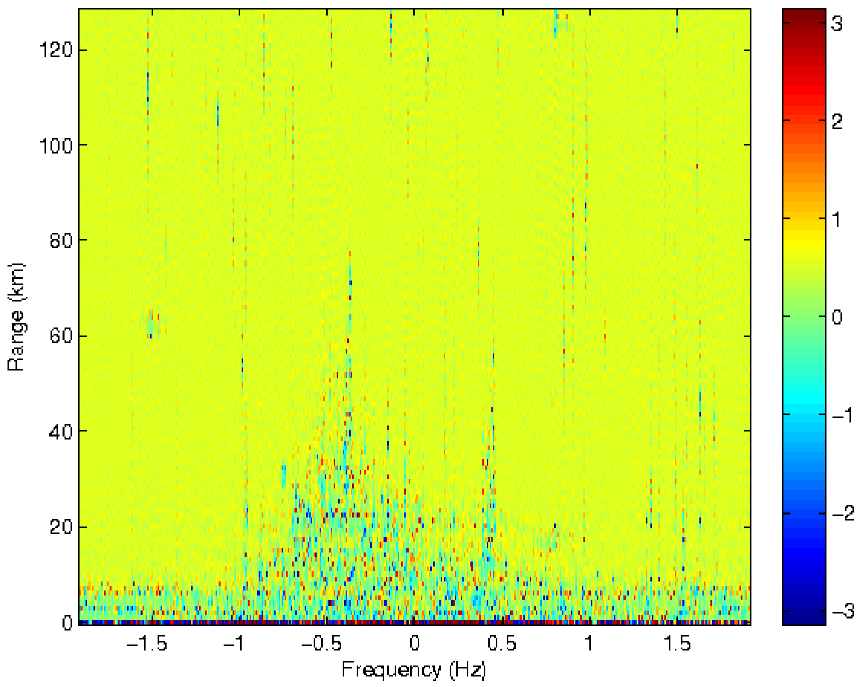


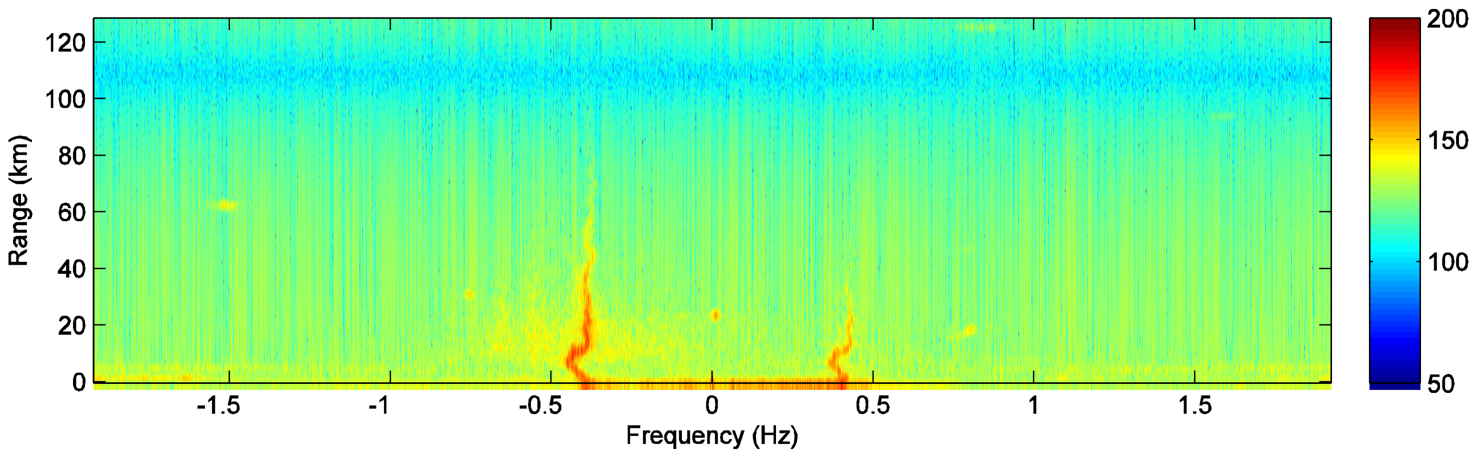




Model-based RFI reduction



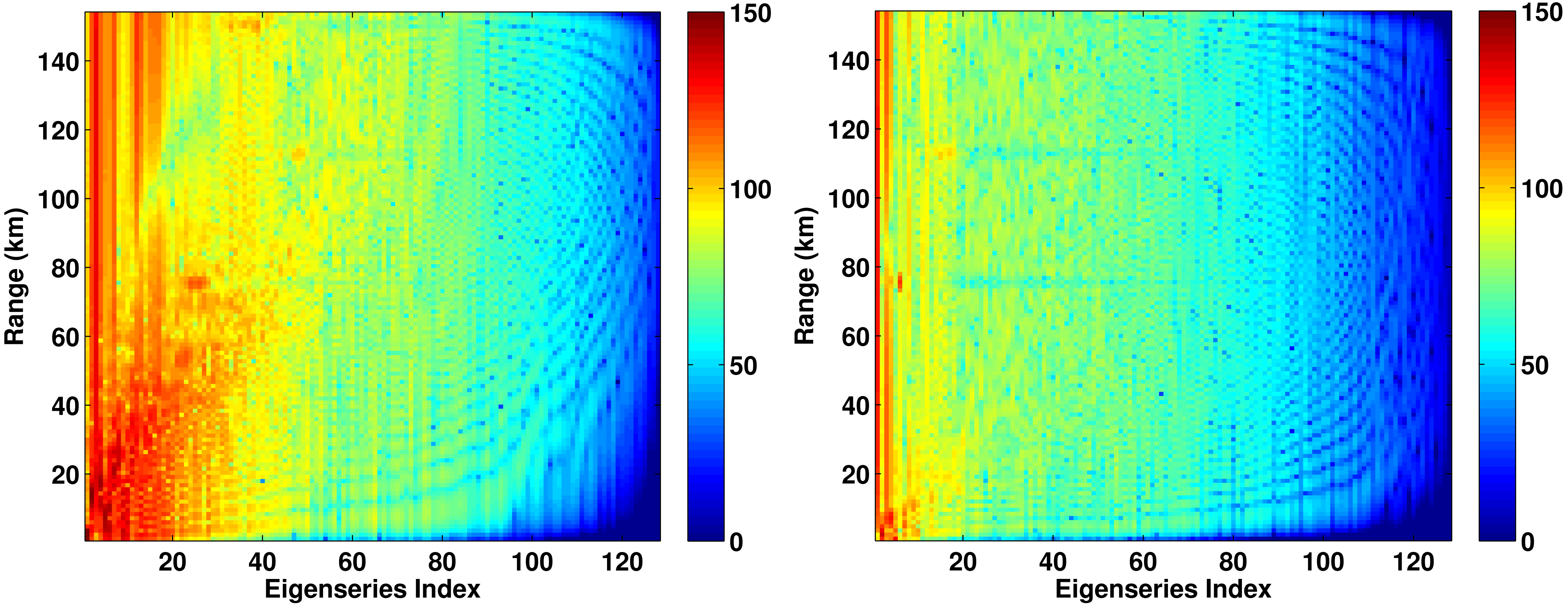




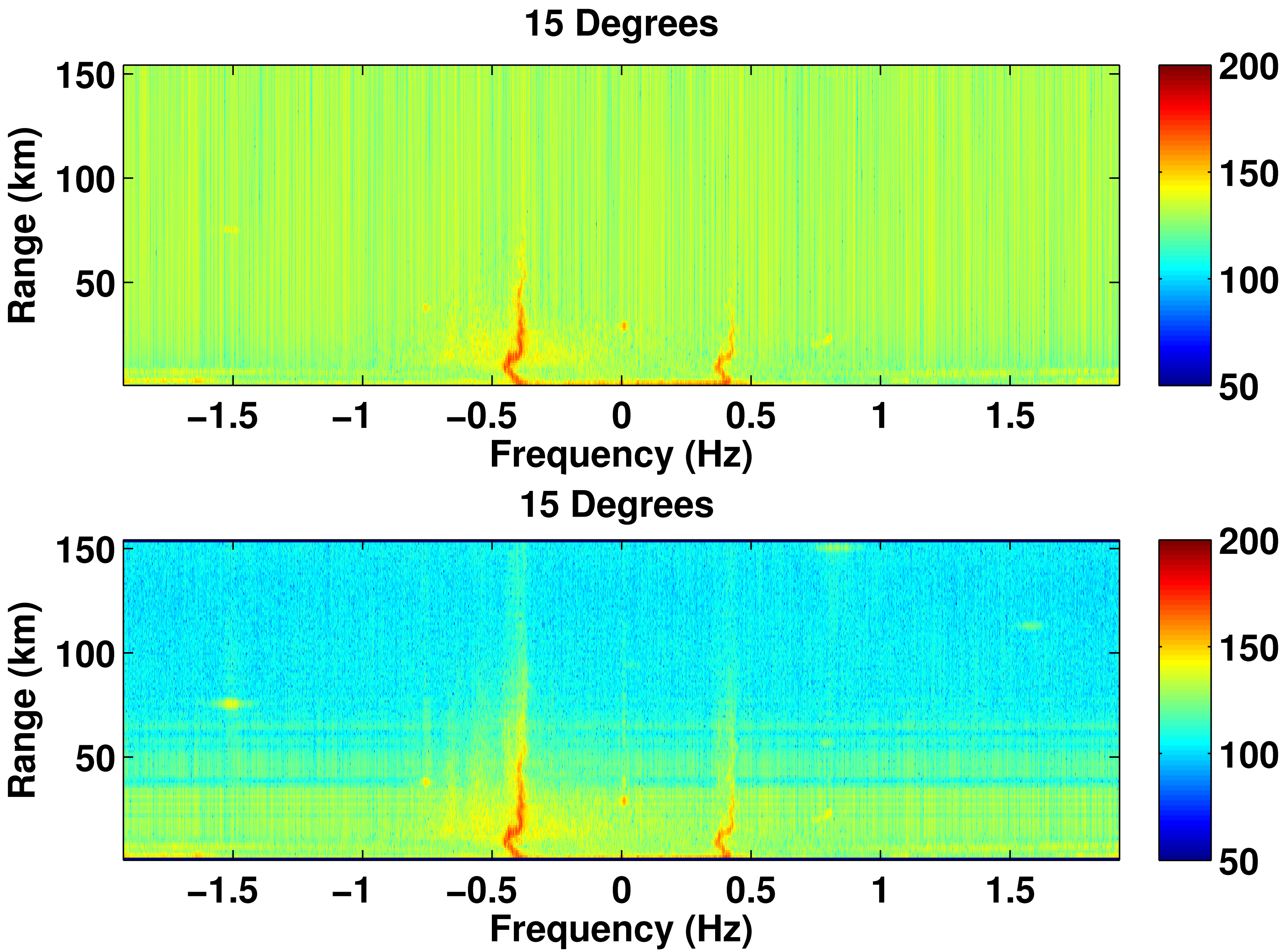
Complex Eigenfunction Filtering

Eigen-decomposition methods are often based on the assumption that signal (or noise) can be represented by only a few independent modes

Energetic noise and signal modes are not independent.



Eigenfunction filtering is only accurate when the signal and noise modes are independent



Acknowledgments

- Mark Merrifield
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- Doug Luther
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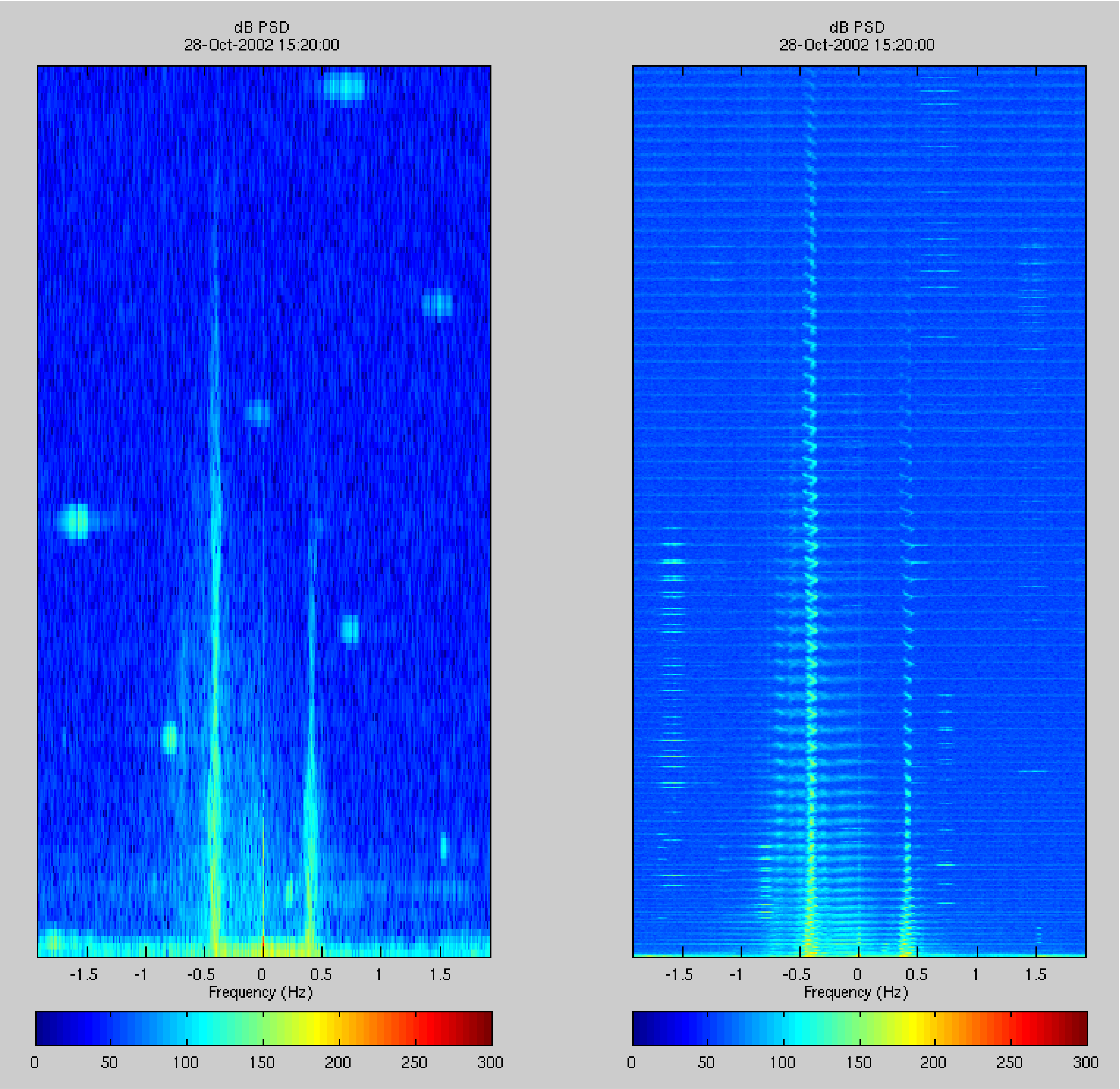
- Francois Ascani
- Jerome Aucan
- Derek Young


dB PSD
28-Oct-2002 15:20:00
-1.5
-1
-0.5
0
0.5
1
1.5
Frequency (Hz)
0
50
100
150
200
250
300
dB PSD
28-Oct-2002 15:20:00
-1.5
-1
-0.5
0
0.5
1
1.5
Frequency (Hz)
0
50
100
150
200
250
300

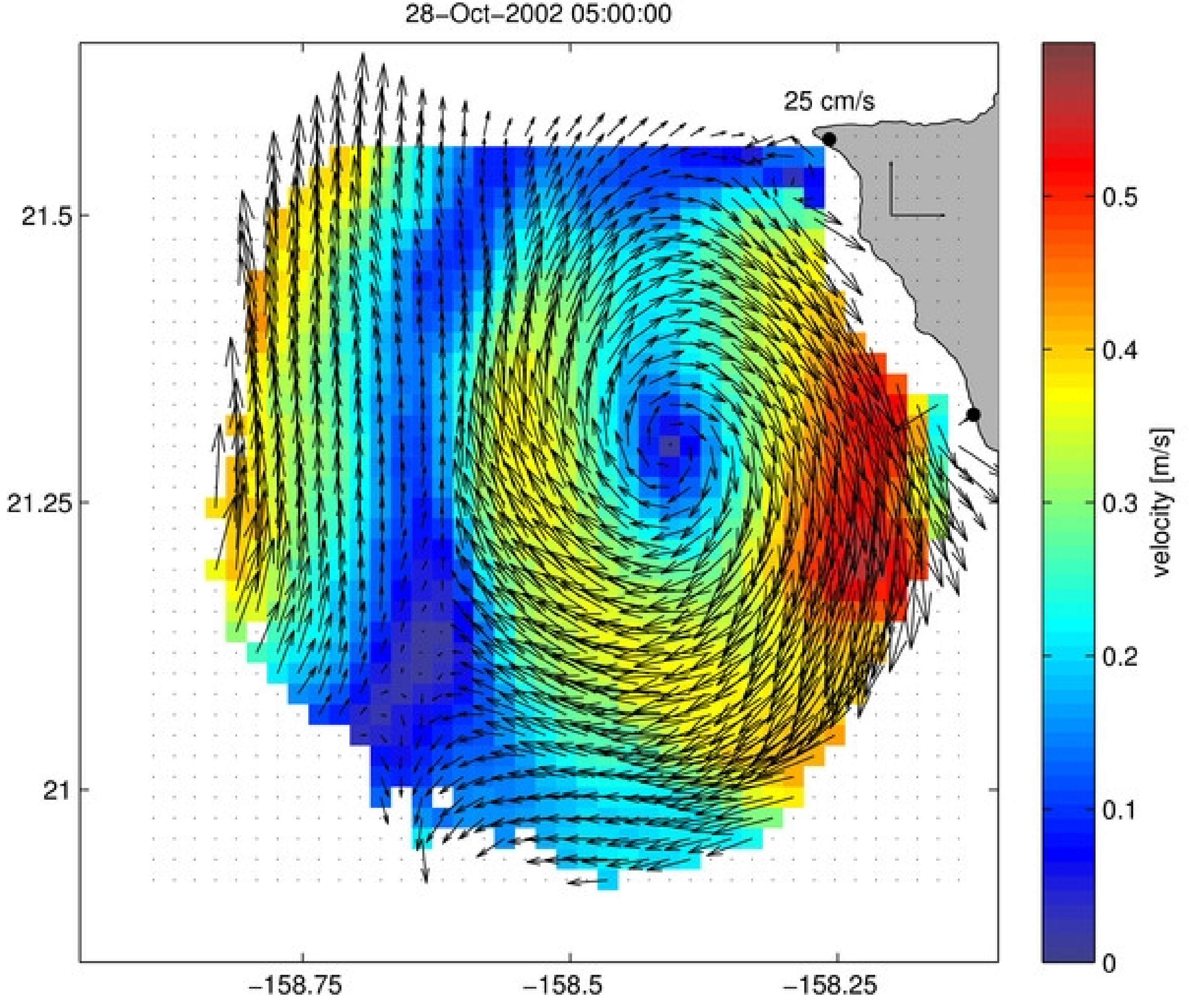
Surface currents derived from First Order scatter

Chavanne, 2007

Current information is carried in the frequency content of the signal, not amplitude

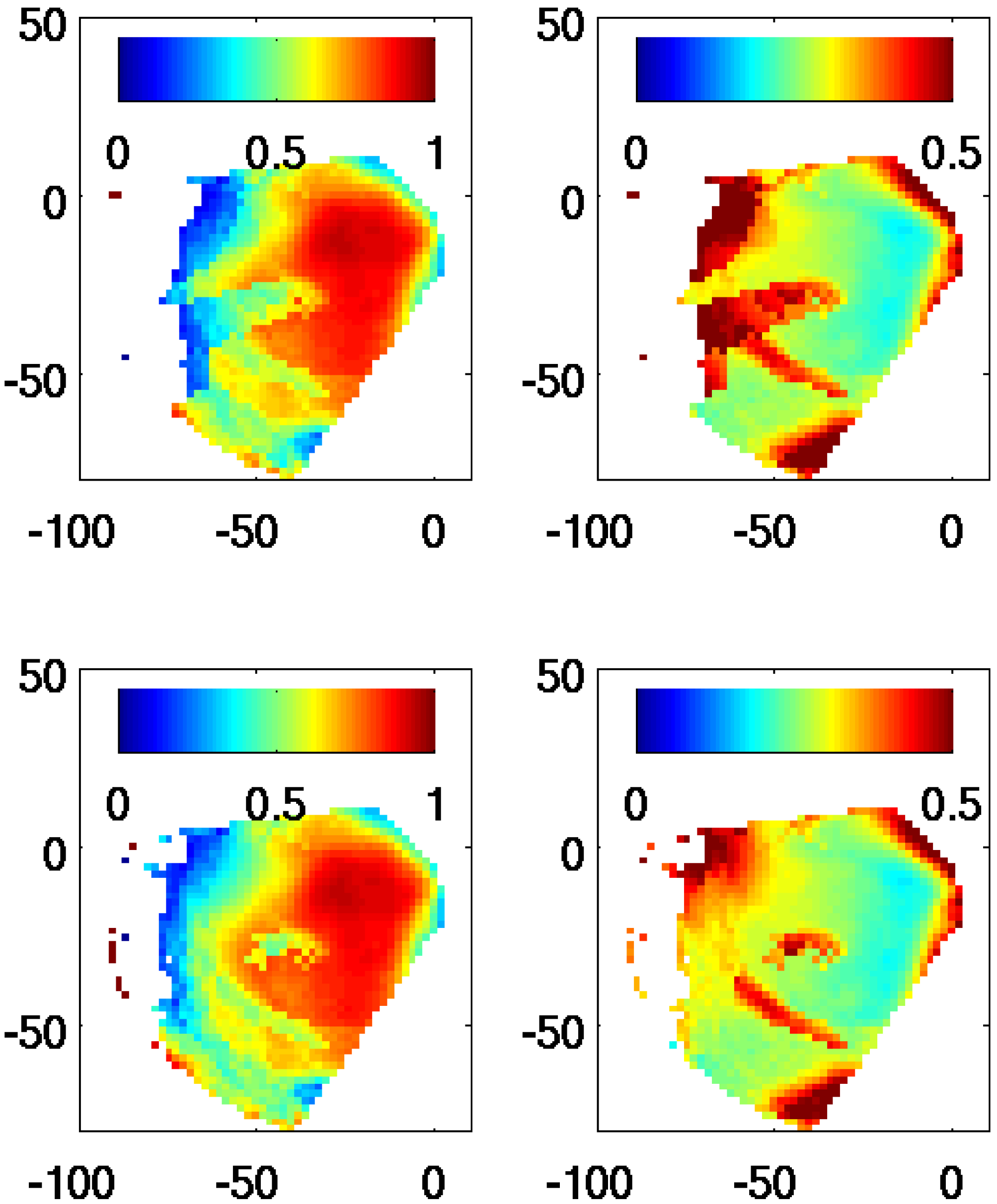
Difference from known frequency is due to surface currents (and Stokes Drift)

$$\Delta c = \sqrt{\frac{g\lambda}{2\pi}} - \lambda f_m$$

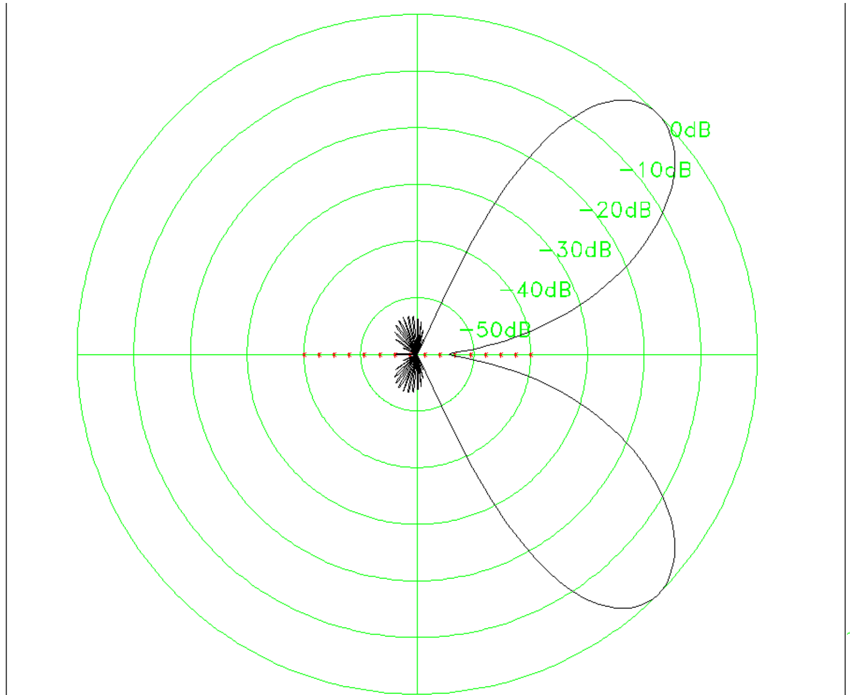


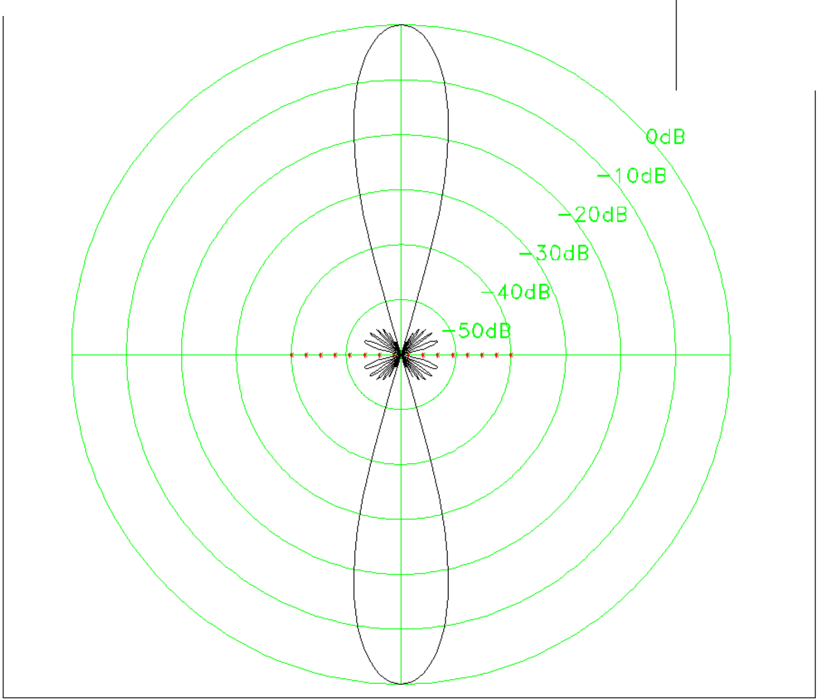
SNR Filtering: before and after

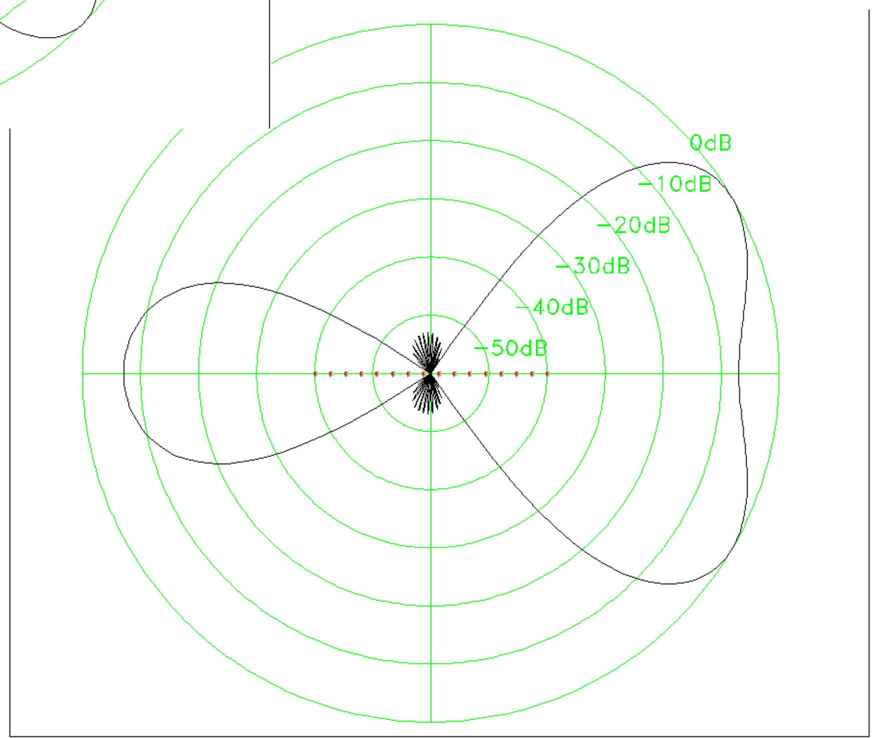
- Spatial accuracy is not significantly improved



Beamforming







Data Products

- Currents
- Significant wave height
- Wind direction
- Wave direction

Physical Processes

- **Current** measurements cover broad band of motions:

  subinertial (<48 h), tidal, inertial (29 h), high frequency (5 h) and residual currents

  Tides, eddies, internal wave surface expression
- **Current-Wave interactions:**

  current-induced shoaling, refraction
- **Wind-Wave** energy exchange

Applications

- Nearshore modeling
- Engineering projects, ship navigation, vessel traffic control
- Mitigation of oil spills, ocean pollutants
- Shoreline protection, beach erosion
- Real-time sea state conditions for the tourism industry