VHF Radar Measurements of Waves and Currents in the Nearshore Region

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Introduction

- HF Radars (8 – 30MHz) widely used in the coastal ocean
- Nearshore studies – large bathymetric gradients - require:
  - High temporal & spatial resolution
  - Wave measurements
- Practical applications:
  - Sediment transport studies;
  - Coastal engineering projects;
  - Data assimilation for wave-current interaction models
  - Can VHF Radars satisfy these needs?

Summary - Objectives

- What is the accuracy of VHF systems for nearshore applications?
- Measuring Currents (see Voulgaris et al., CWTM 2011)
- Measuring Waves (wind *vs.* waves)

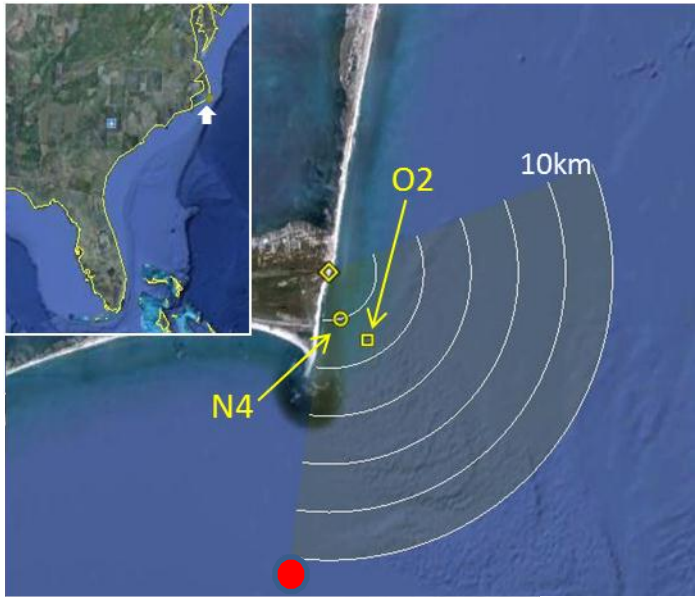
  Forward problem of radar signal under waves.

  Inversion of radar signal using coefficients derived from model.

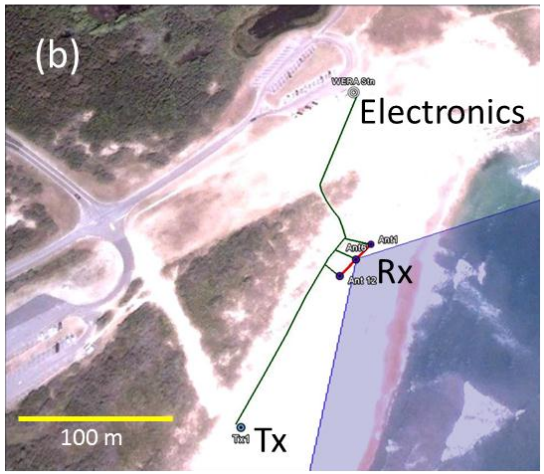
VHF Phased Array Radar Experiments

Radar Characteristics	This Study	Molcart et al. (2009)	Shay et al. (2002) - OSCR	Shrira et al., 2001
Central Frequency (MHz)	**48.00**	45.25	49.9	45
Bragg frequency(Hz)/wavelength (m)	**0.7071 / 3.12**	0.6865 / 3.31	0.721/2.95	0.6846/3.33
Bandwidth (kHz)	**1000**	500	600	250
Raw range resolution (m)	**150**	300	250	600
Processed range resolution (m)	**150**	600	-	600
Number of parallel receive channels	**12**	8	32	16 3x8 @50%
Transmit peak power (W)	**~10**	0.630/15	100	1600
Antenna array length L (m)	**17.16**	24		49.95
Data points collected and rate (Hz)	**4096 @ 0.21Hz**			
Transmit time (UT) (min)	**14.78**	7		
Repeating rate (min)	**30**	30	20	

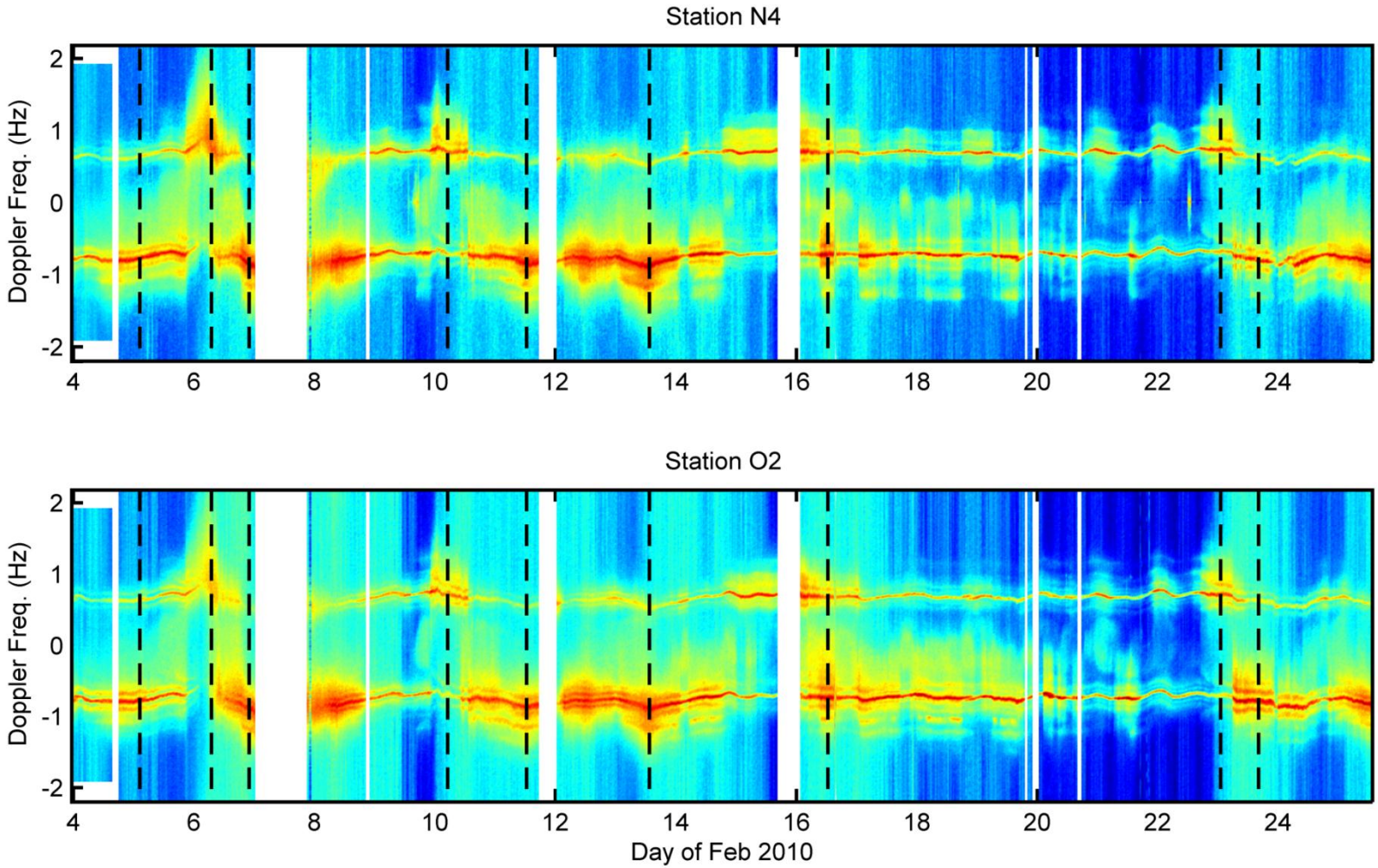
VHF Single Station WERA Site



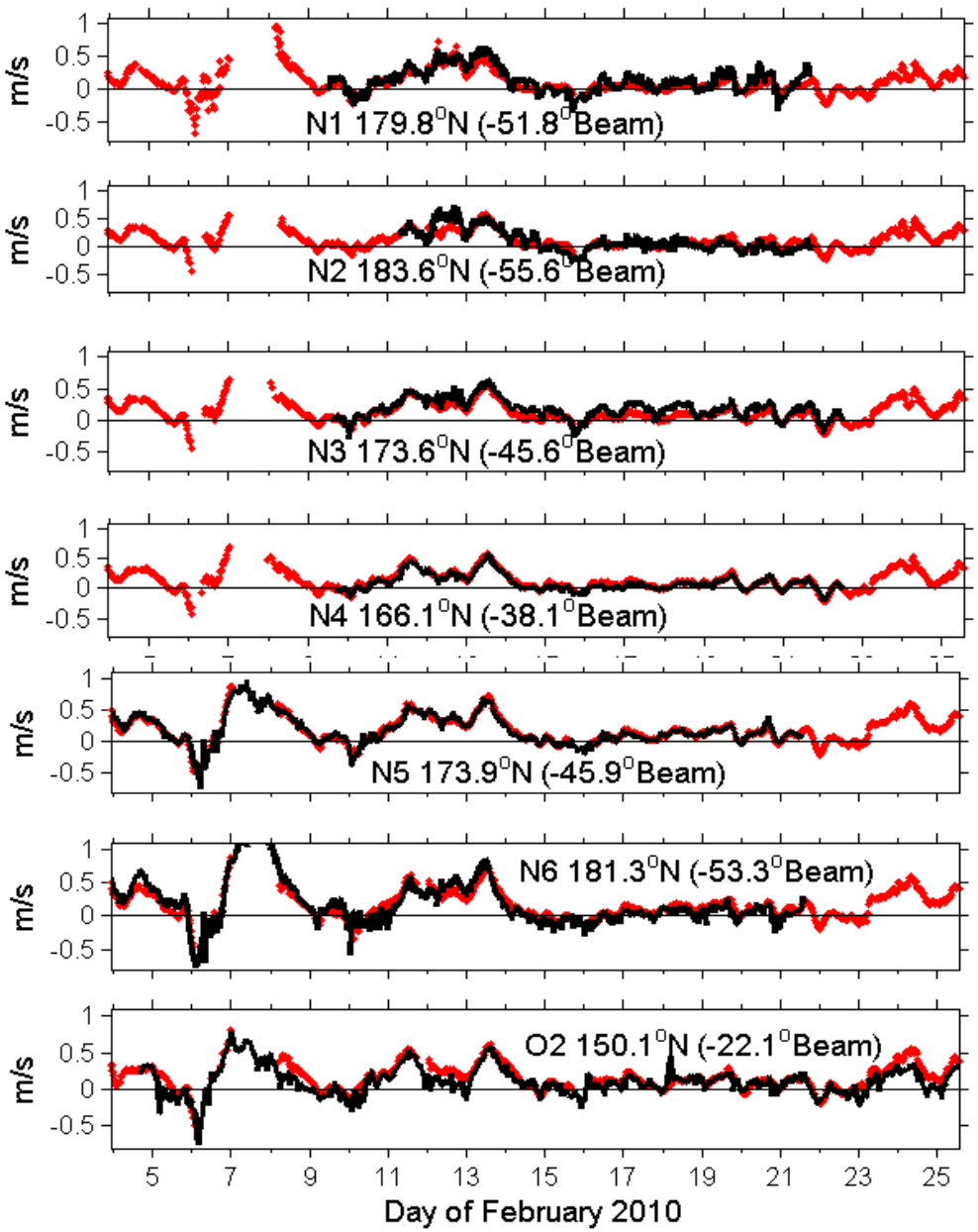
O2, N4: Sites of in-situ acoustic sensors used for wave inver-sion

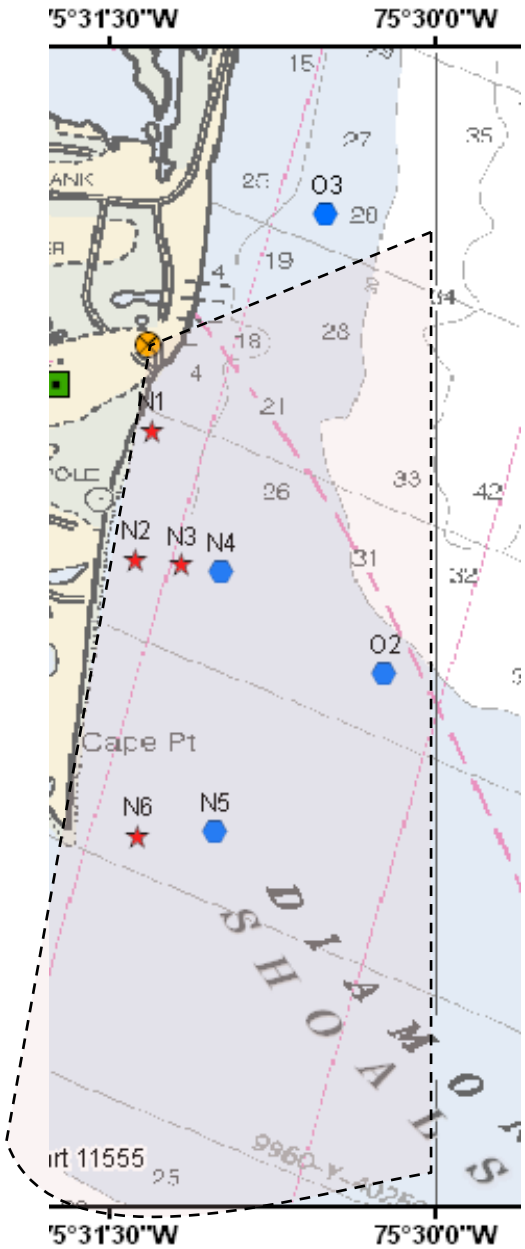


WERA Doppler Spectra Time-stacks at Instrument Locations



Radial Velocity Comparisons (Black: in-situ stations, Red: Radar radials





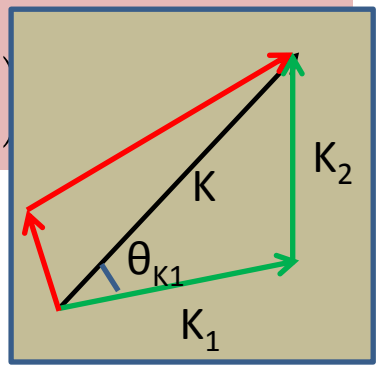
Gill's (1999) Radar Cross-section Model

Limits: H_{rms}<=1/2$k_{o,}$ for 48MHz , H_{rms}=0.5m, H_{sig}=0.7m

$$\sigma_1(\omega) = 2^4 \cdot \pi \cdot k_0^2 \cdot \sum_{m_i=\pm 1} S_1\left(m_i \vec{K}\right) \cdot \frac{K^{2.5}}{\sqrt{g}} \cdot \Delta\rho_s \cdot Sa^2\left[\frac{\Delta\rho_s}{2} \cdot \left(\frac{K}{\cos\phi_0} - 2k_0\right)\right]$$

$$\sigma_2(\omega) = 2^6 \cdot \pi^2 \cdot k_0^4 \cdot \cos^4\phi_0 \cdot \sum_{m_1=\pm 1} \sum_{m_2=\pm 1} \int_{-\pi}^{\pi} \int_{0}^{\infty} S_1\left(m_1 \vec{K}_1\right) \cdot S_2\left(m_2 \vec{K}_2\right)$$

$$\cdot \left|{}_s\Gamma_p\right|^2 \cdot \delta\left(\omega + m_1\sqrt{gK_1 \tanh(K_1 h)} + m_2\sqrt{gK_2 \tanh(K_2 h)}\right)$$

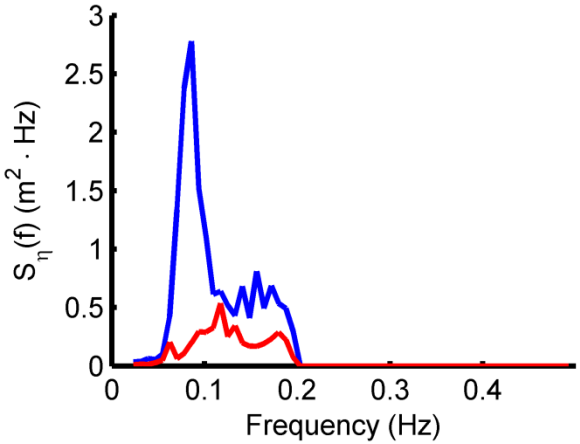


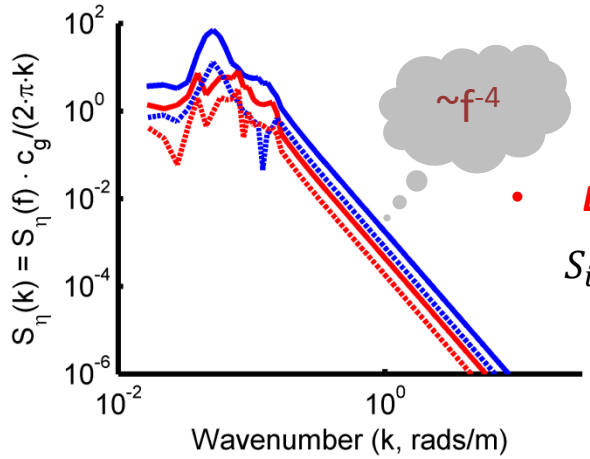
$$\sigma(\omega) = \sigma_1(\omega) + \sigma_2(\omega) + \text{noise}$$

Radar Wavenumber	$k_0 = \frac{2\pi f_{radar}}{c}$	Doppler angular frequency	$\omega = 2\pi f$
Normalizing wavenumber	$K = 2 \cdot k_0 \cdot cos(\phi_0)$	Water depth	h
Bi-static angle	ϕ_0 (=0)	Wavenum. dir. wave spectrum	$S_i(m_i \vec{K}_i)$
Patch width	$\Delta\rho_s$	$Sa(x) = \frac{sin(x)}{x}$	
Coupling coefficient	$\Gamma_p = \Gamma_{em} + \Gamma_{hydro}$		

From Gill, 1999

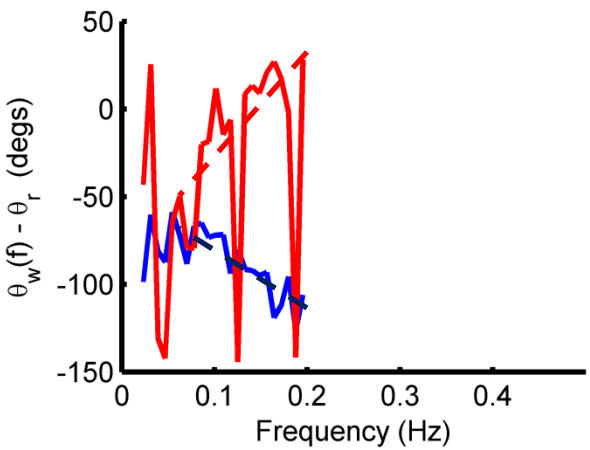
Input of Measured Nearshore Dir. Wave Spectrum

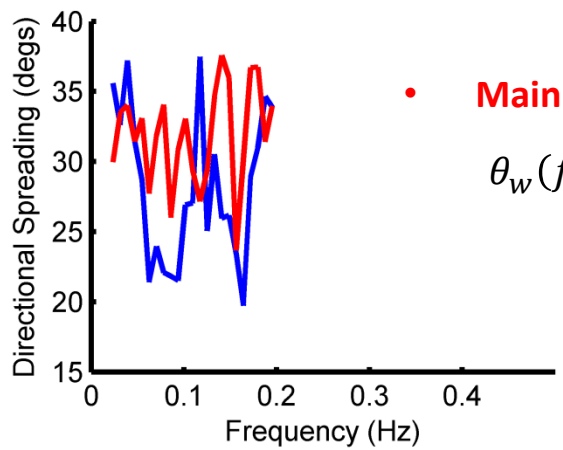




- ***Directional wave spectrum***

$$S_i(m_i, \vec{K}_i) = \frac{c_g}{2 \cdot \pi \cdot k} S(f) \cdot G(m_i, \theta, f)$$





- **Main wave direction**

$$\theta_w(f) = 0.5 \cdot tan^{-1}\left(\frac{2 \cdot C_{uv}(f)}{C_{uu}(f) - C_{vv}(f)}\right)$$

- ***Directional spreading width around main direction***

$$\sigma_\theta(f) = \sqrt{0.5 \cdot \left(1 - \left(a_2(f) \cdot cos(2 \cdot \theta_w(f)) + b_2(f) \cdot sin(2 \cdot \theta_w(f))\right)\right)}$$

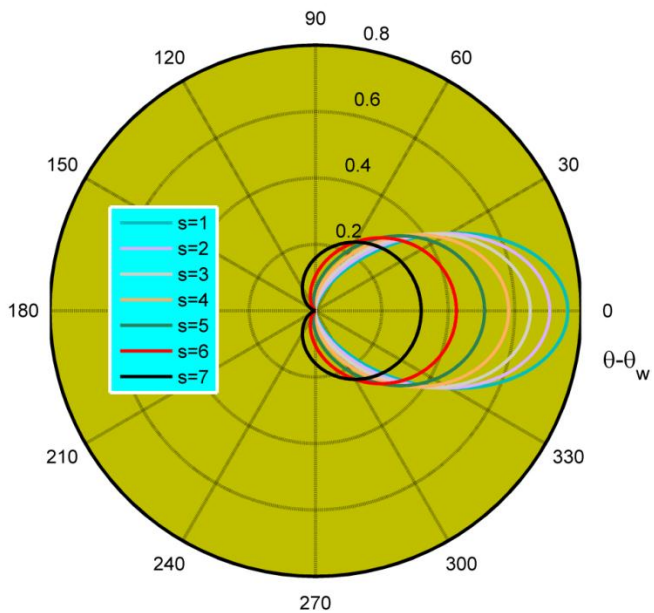
See Herbers et al. (1999), JGR

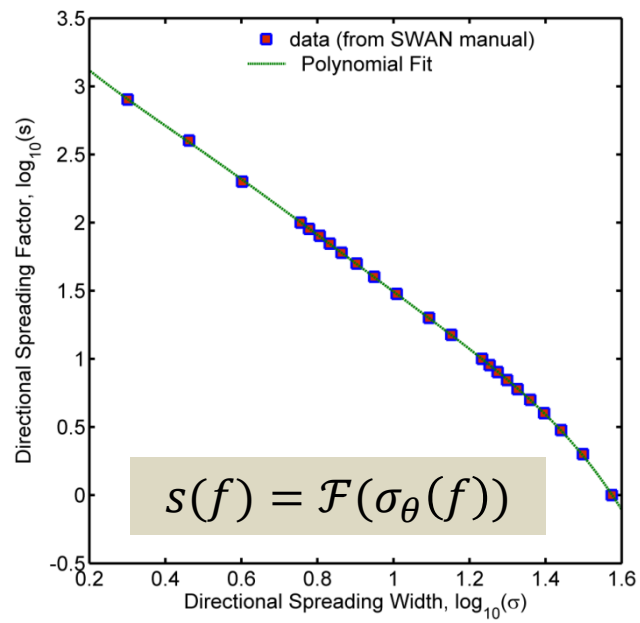
Directional Spreading (s) & Width (σ_θ)

$$G(m,\theta-\theta_w,f)=\frac{2^{2\cdot s(f)-1}\cdot\Gamma(s(f)+1)^2}{\pi\cdot\Gamma(2\cdot s(f)+1)}cos^{2\cdot s(f)}\left(\frac{1}{2}\left(\theta-\theta_w(f)+(1-m)\frac{\pi}{2}\right)\right)$$

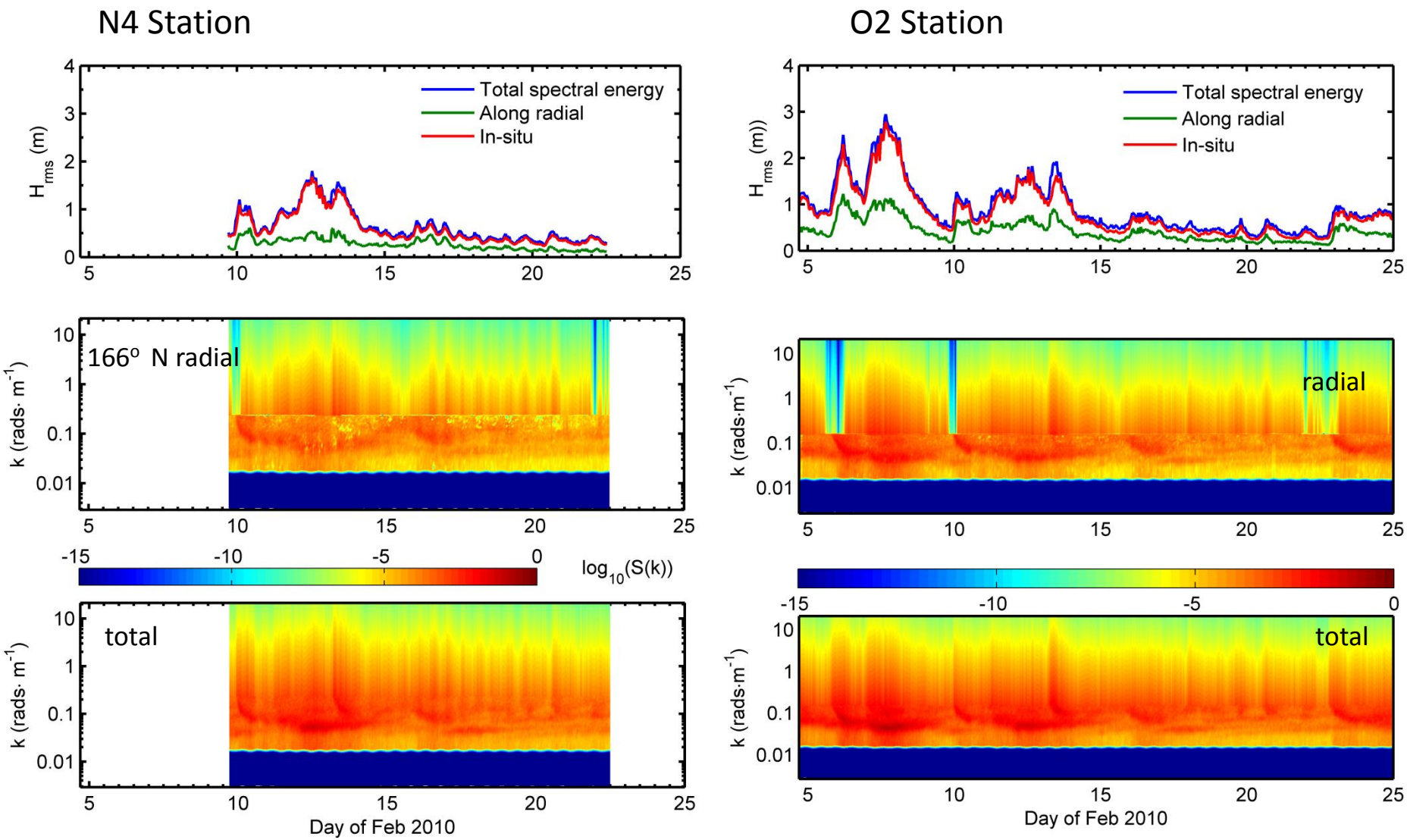
$$\int_{-\pi}^{\pi}G(\theta,f)d\theta=1$$

SWAN Manual & Kuik et al. (JPO 1988)

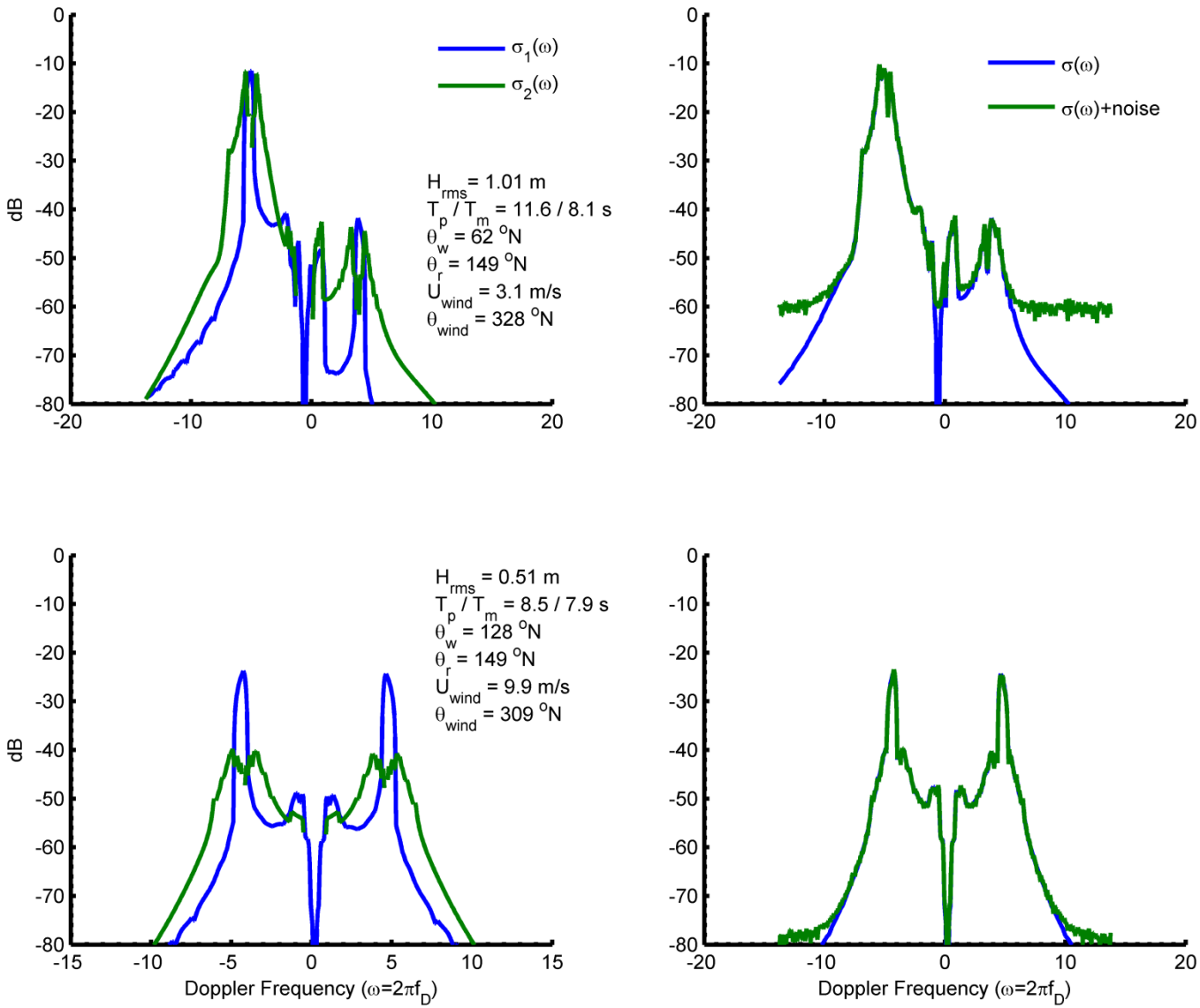




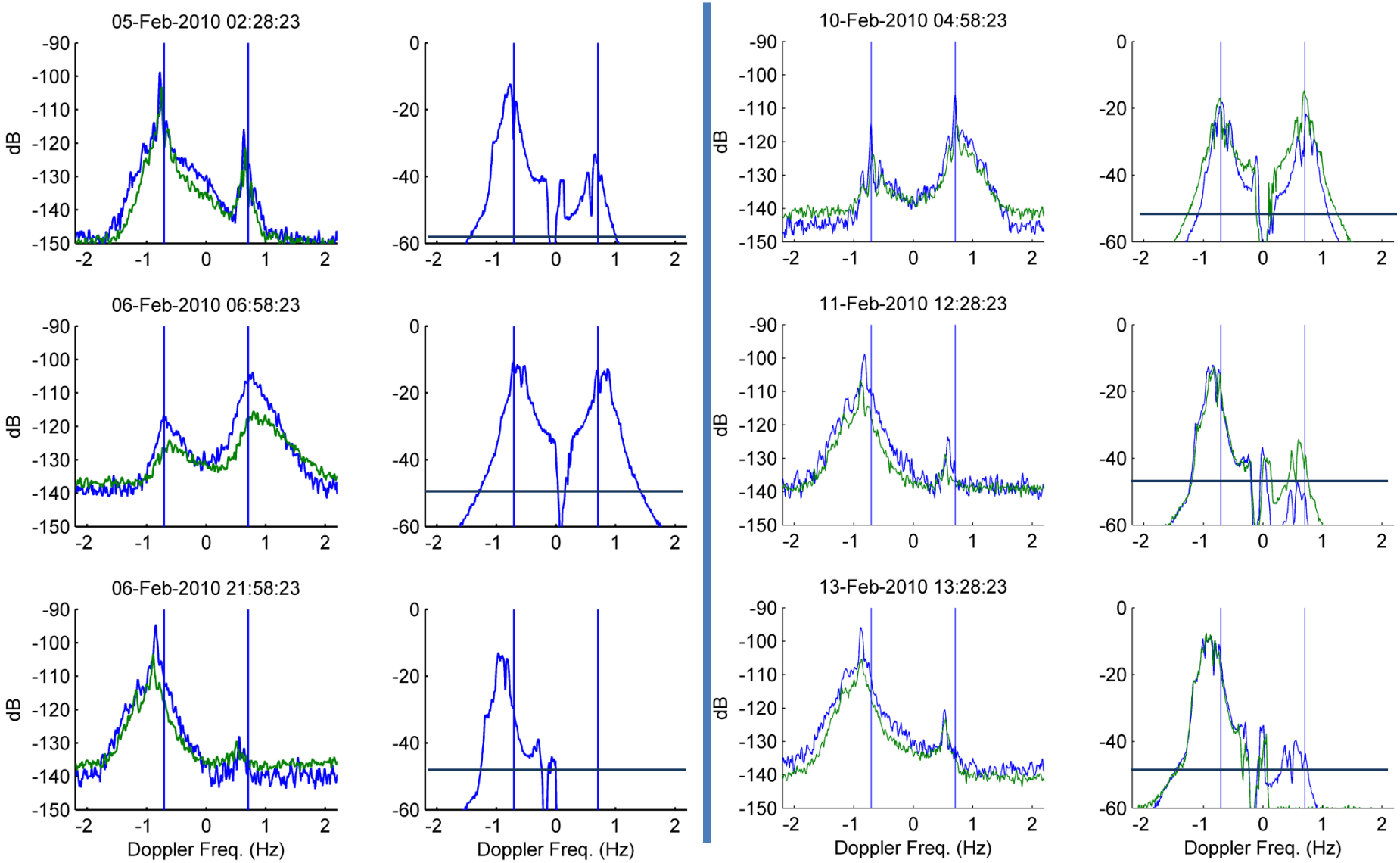
Measured Wave Spectral Signal Input to Radar Gill's Cross-section model



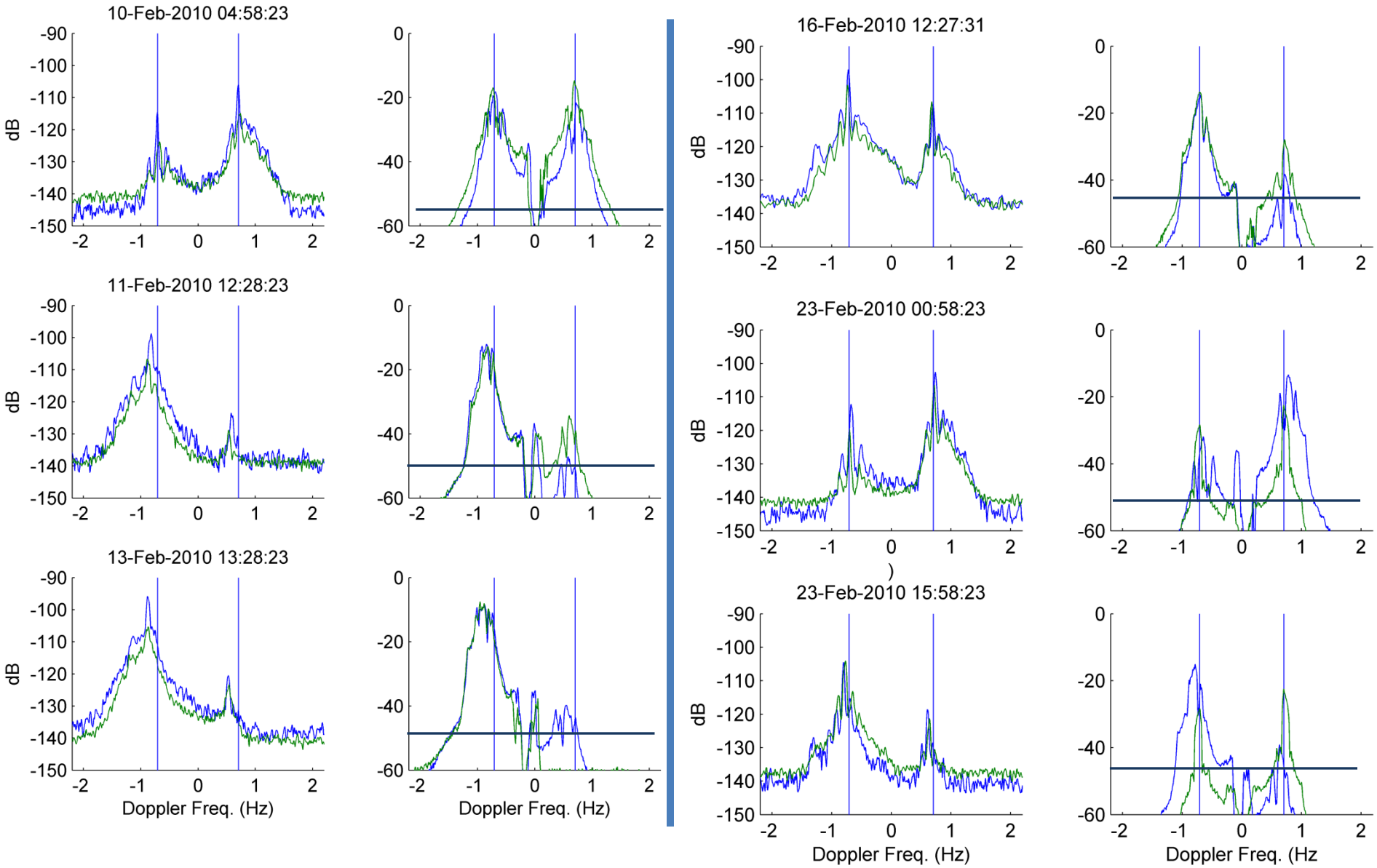
Examples of cross-section model results (O2 site)



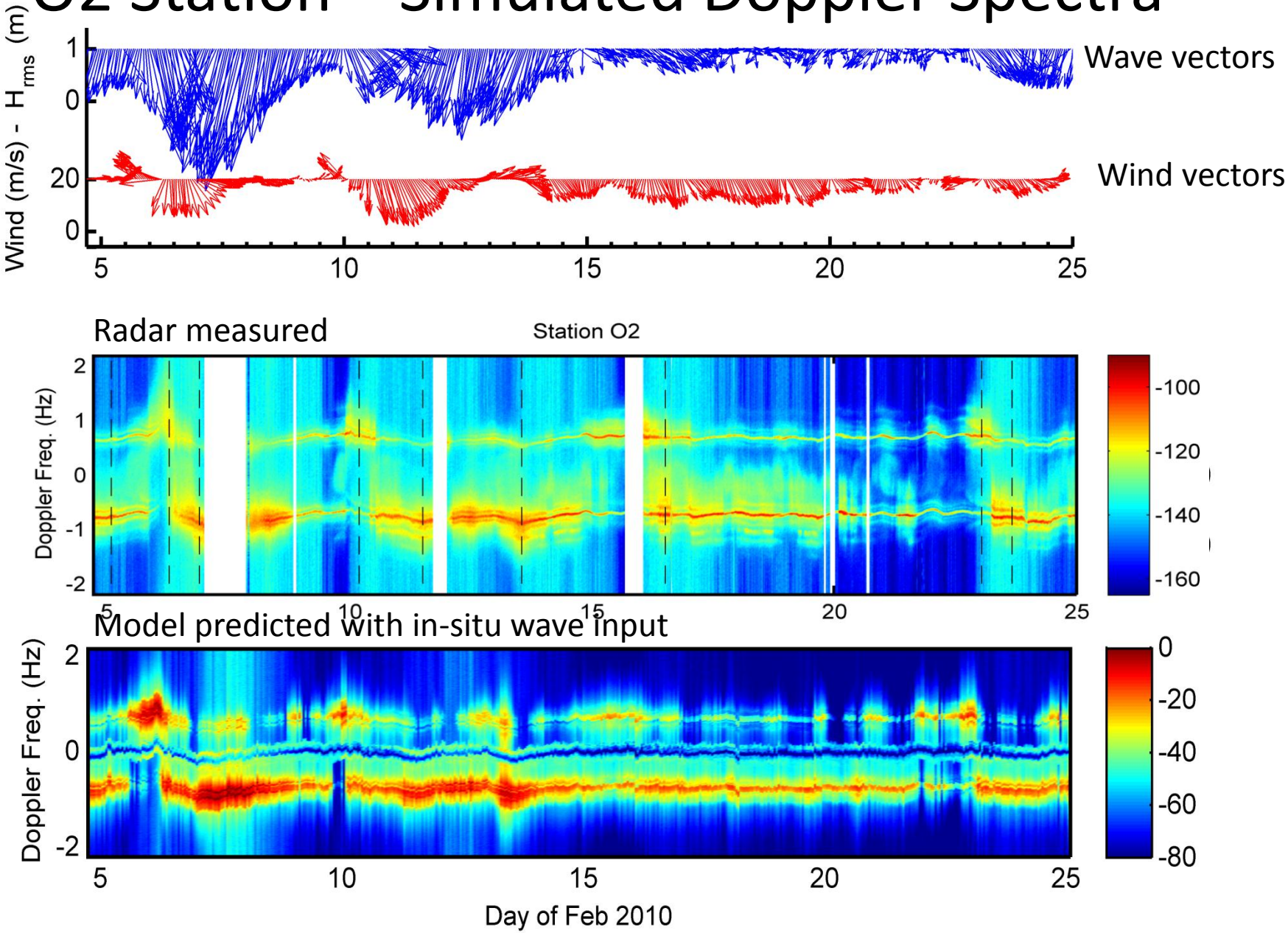
Measured (left column) *vs.* Simulated (right column) Spectra 1 of 2



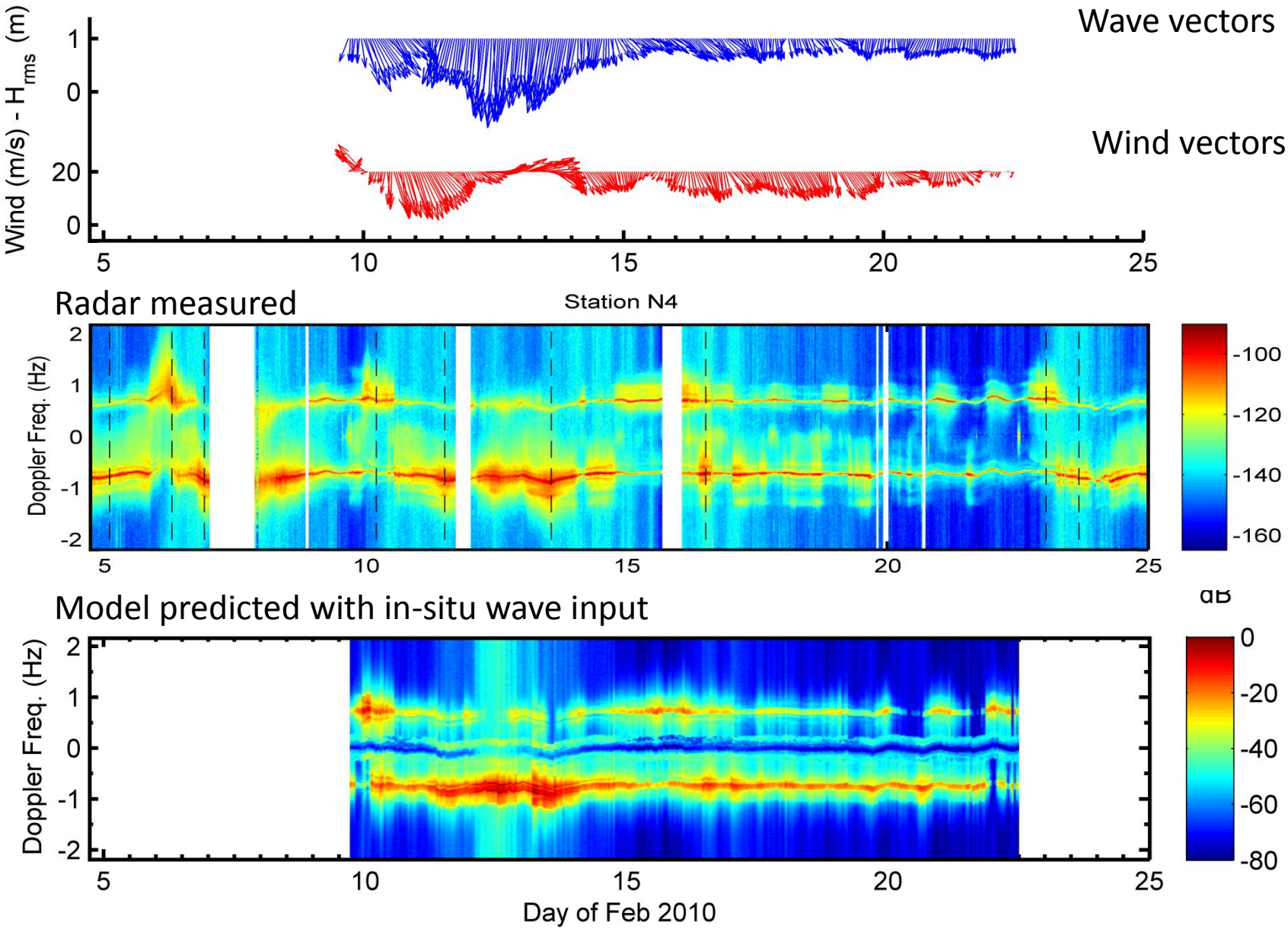
Measured (left column) *vs.* Simulated (right column) Spectra 2 of 2

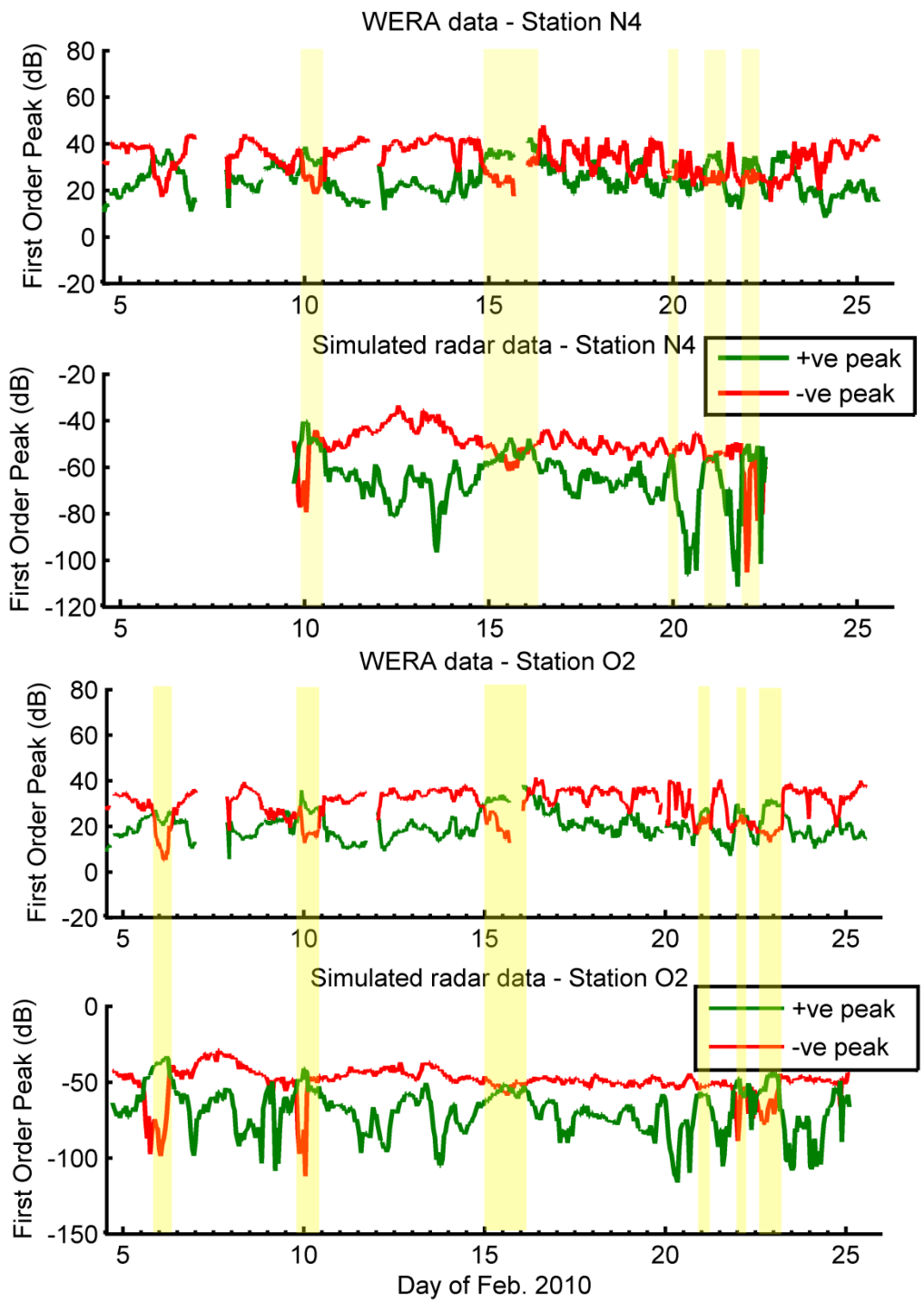


O2 Station – Simulated Doppler Spectra



N4 Station – Simulated Doppler Spectra





1st Order Peak Temporal Variability

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Waves from 2nd order

- Empirical method (?) Barrick (1977):

$$H_{rms} = \frac{2\int_{-\infty}^{+\infty} \sigma_2(f_D) \Big/ W(f_D/f_B) \cdot df_D}{{k_o}^2 \cdot \int_{-\infty}^{+\infty} \sigma_1(f_D)\, df_D}$$

$$S_\eta(f) = \frac{\sigma_2(f) \cdot a(f)}{{k_o}^2 \cdot \int_{f_B-\Delta f}^{f_B+\Delta f} \sigma_1(f)\, df} = a(f) \cdot \frac{R_w(f)}{{k_o}^2} \qquad f = \mathcal{F}(f_D - f_B)$$

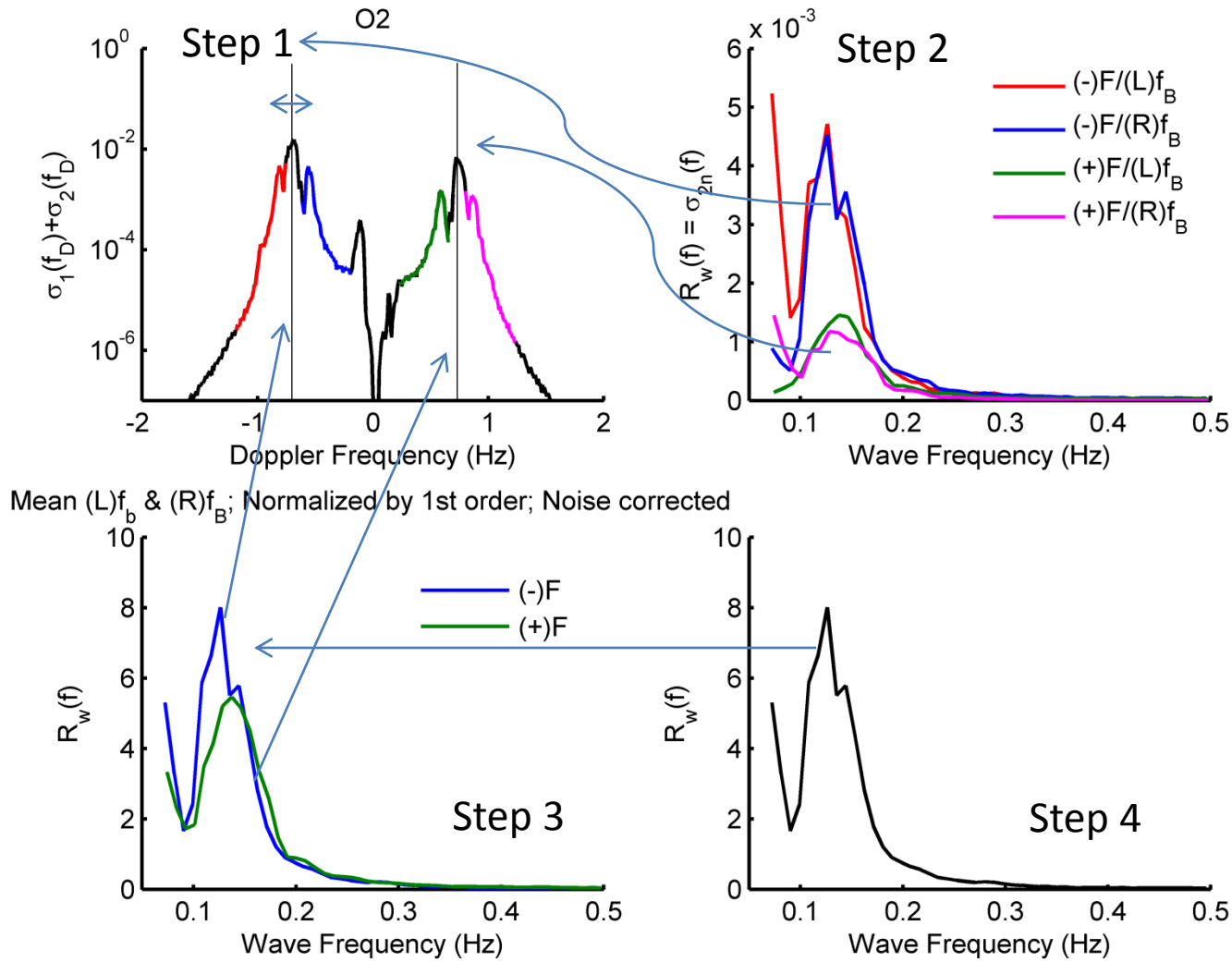
See Heron and Heron, (JOAT, 1998)

Gurgel et al., 2006. IEEE J. Ocean. Eng. 31(4)

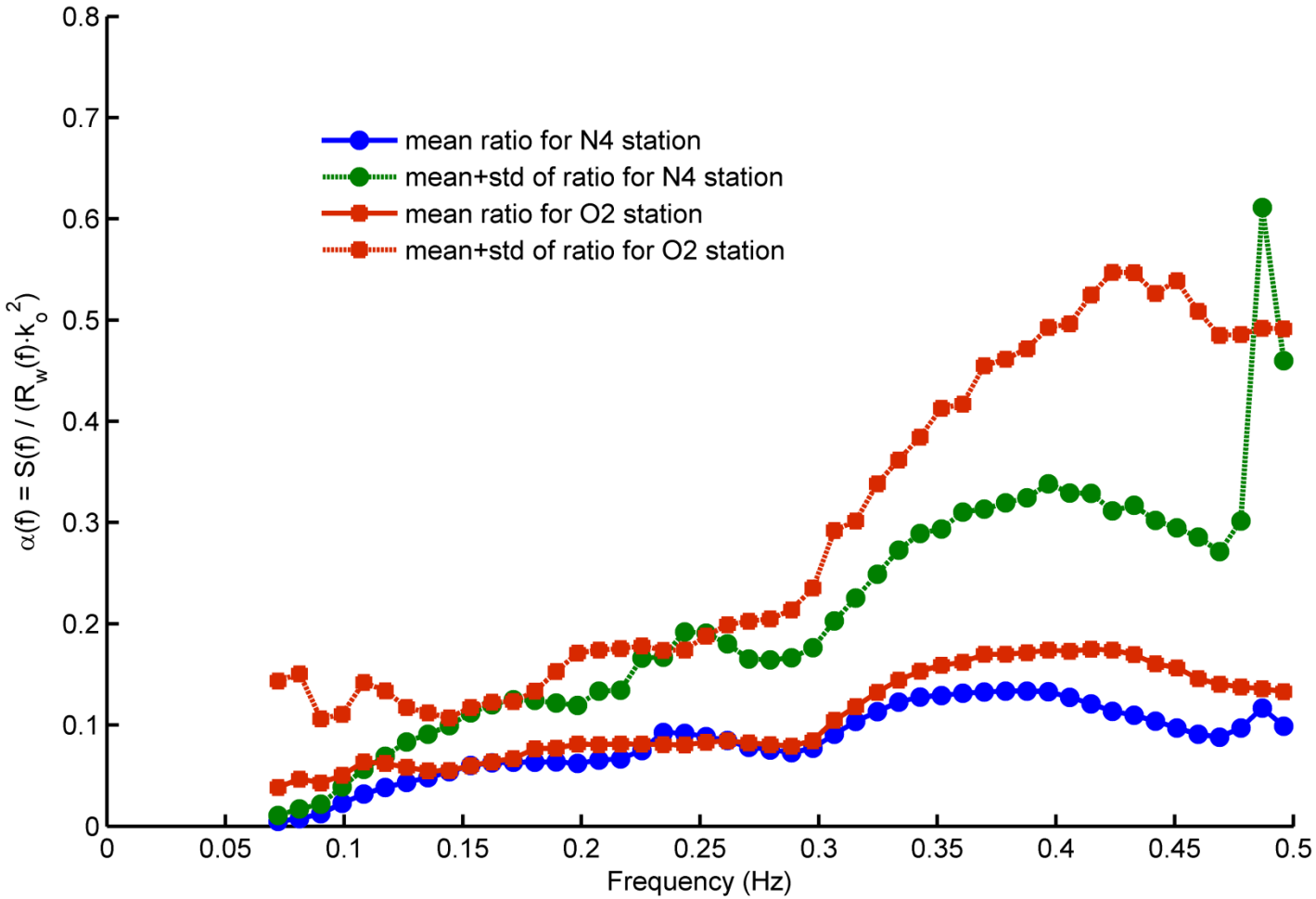
Extracting wave spectrum from Doppler spectrum (as in Heron & Heron,1998 and refs therein)

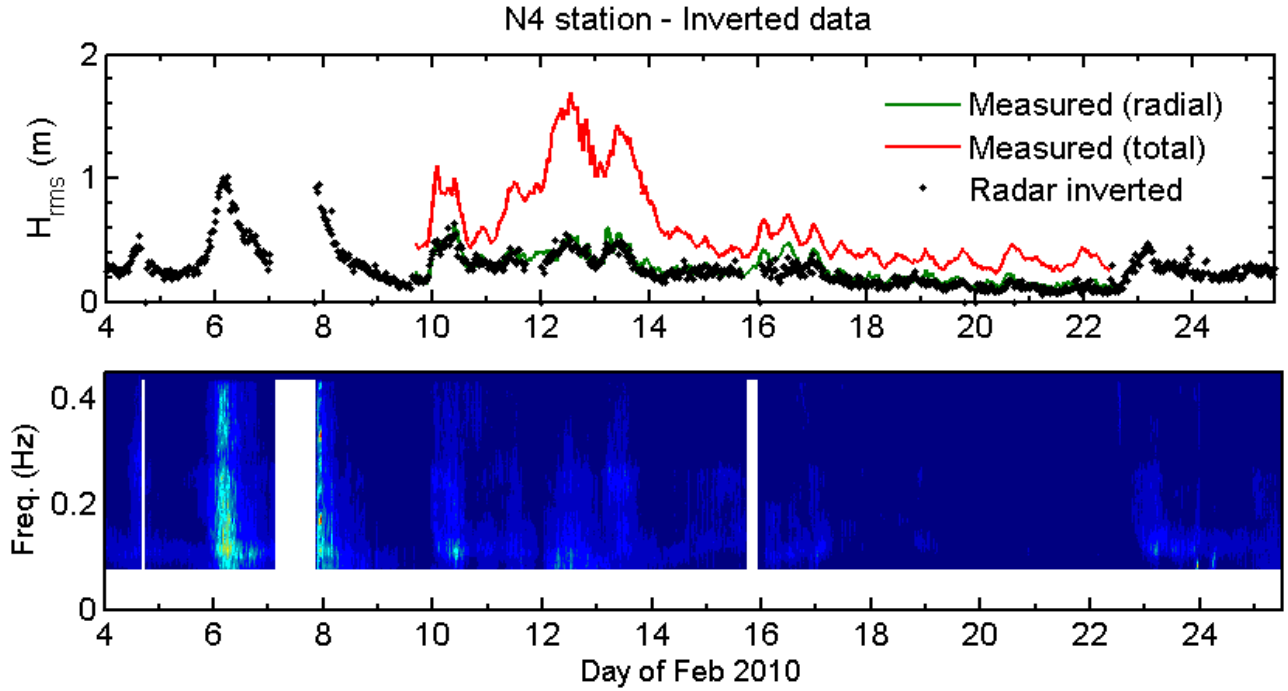
$f_{w,\ low}=f_D-f_B\pm0.07Hz$

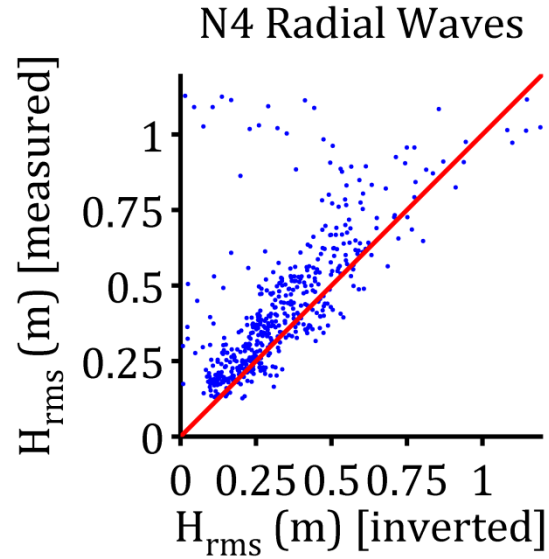
$f_{w,\ high}=f_D-f_B\pm0.50Hz$

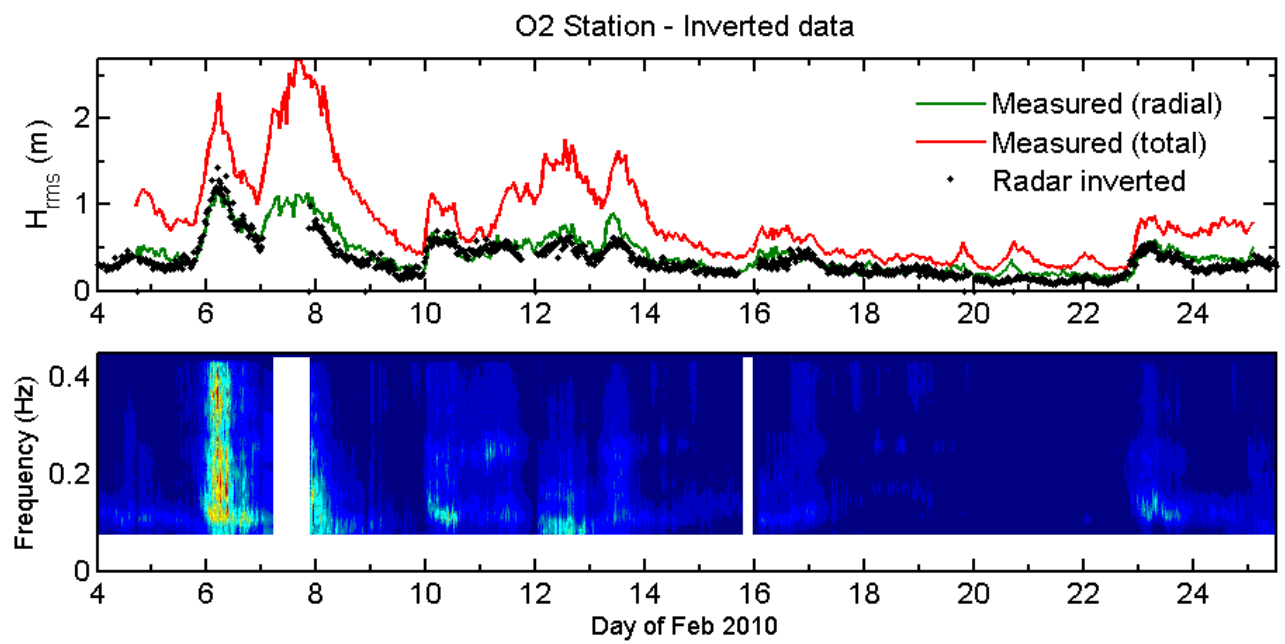


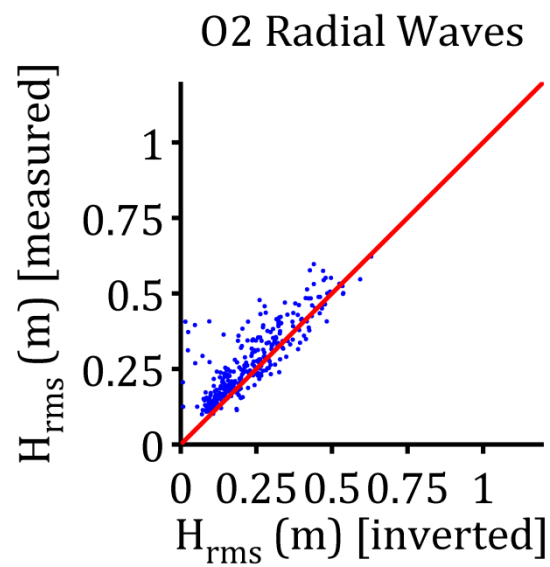
$$S_\eta(f) = \frac{\sigma_2(f) \cdot a(f)}{{k_o}^2 \cdot \int_{f_B-\Delta f}^{f_B+\Delta f} \sigma_1(f)\, df} = a(f) \cdot \frac{R_w(f)}{{k_o}^2}$$




N4 station - Inverted data
Measured (radial)
Measured (total)
Radar inverted
H_{rms} (m)
Freq. (Hz)
Day of Feb 2010


N4 Radial Waves
H_{rms} (m) [measured]
H_{rms} (m) [inverted]


O2 Station - Inverted data
Measured (radial)
Measured (total)
Radar inverted
H_{rms} (m)
Frequency (Hz)
Day of Feb 2010


O2 Radial Waves
H_{rms} (m) [measured]
H_{rms} (m) [inverted]

Conclusions

- The VHF radar system provides surface current measurements in the nearshore with the same variability as traditional acoustic meters.
- The WERA VHF internal current extraction algorithm statistics seem to provide a reliable indicator of data variability (natural or artificial).
- Forward modeling of radar signal Doppler with realistic directional wave spectra has been invaluable of understanding the performance of the system for wave measurements and helped us establish the empirical/theoretical coefficients for VHF system.
- Forward modeling is to be used for evaluating the order of importance of the various quantities used in wave simulations (i.e., directional spreading, frequency range etc).