Semi-Empirical Model for the Ka-band Sea Surface Doppler Centroid

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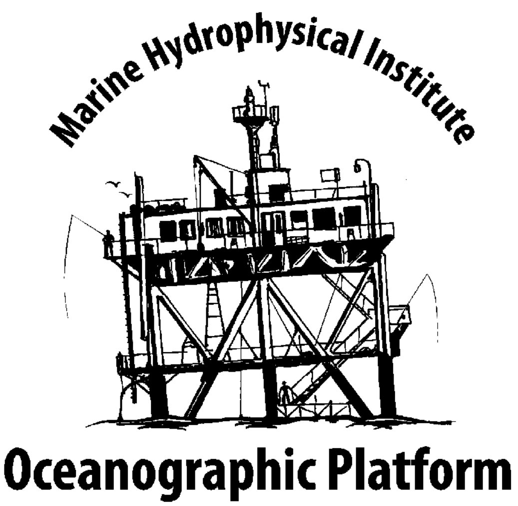
Russian Science Foundation

Supported by RCSF grant 17-77-30019



Motivation

• Doppler shifts are linearly related to the surface velocity →

• Doppler scatterometer is a promising tool for the (satellite) **sea surface current** (SSC) monitoring

• Additional Doppler velocity measurements can be inverted to the SSC using GMF-based approach, similarly to the wind retrieval → A **GMF** for the Doppler velocity, as well as its theory, are required

• Switching to higher microwave bands (**Ka-band**) allows to increase Doppler velocity measurement accuracy → planned missions: DopplerScatt (WaCM), Seastar, SKIM,...

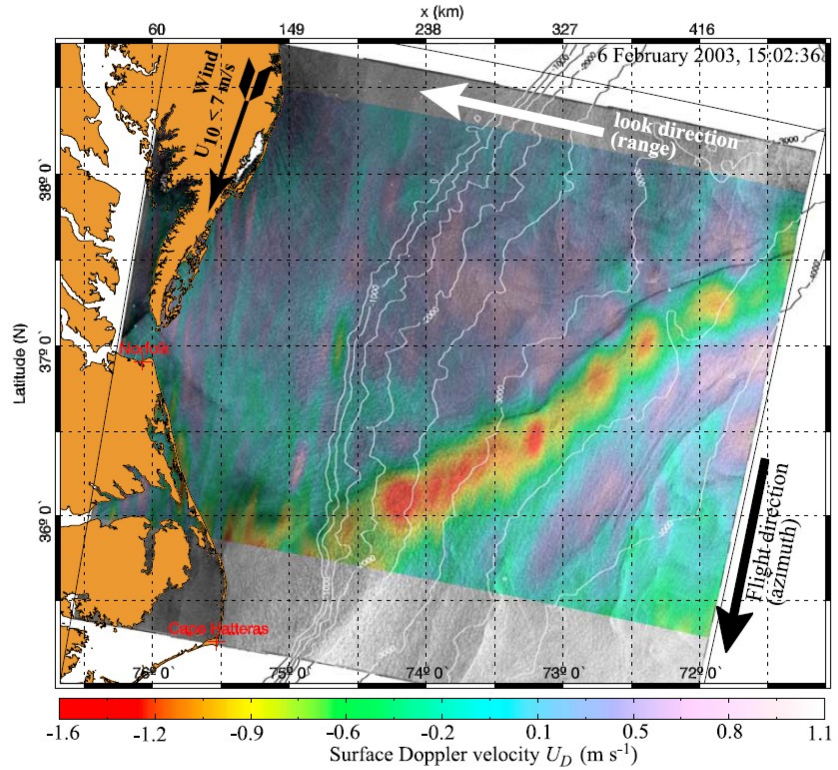


Figure 1. Normalized radar cross-section σ_0 (gray shades) and Doppler velocity U_D (colors), analyzed from a wide-swath image obtained by ENVISAT on 6 February 2003 at 1512 UTC. Oceanic fronts appear as sharp gradients of σ_0, while the surface velocity seen by the radar appears to be related to the Gulf Stream.

[Chapron, Collard, Ardhuin, 2005, JGR]

[Goldstein & Zebker, 1987, Nat.],
[Romeiser & Thompson, 2000, TGRS],
[Chapron et al., 2005, JGR], [Ardhuin et al. 2017, OSD],
[Bao et al. 2017, TGRS], [Rodriguez et al., 2018, RS]

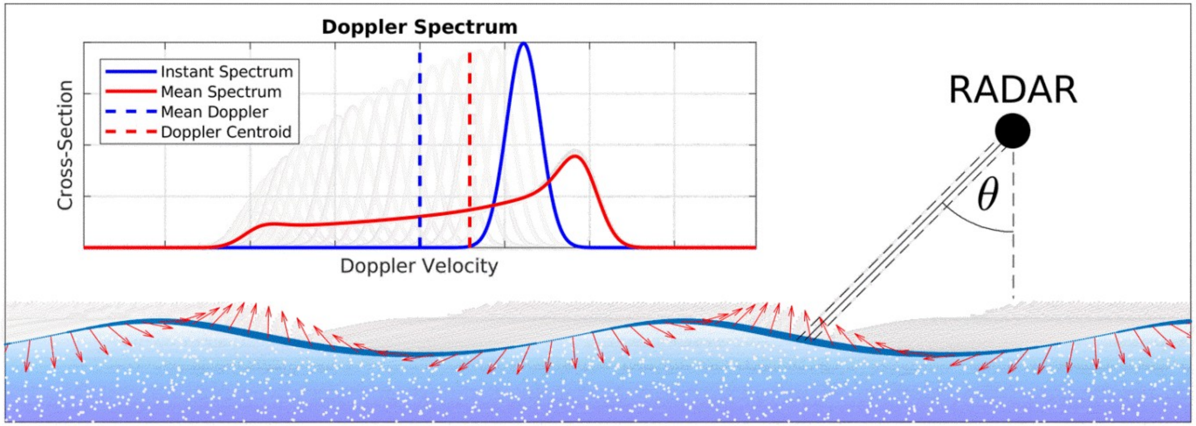
Doppler Velocity of the Sea Surface

Geophysical Doppler anomaly (time/space-resolved Doppler spectrum centroid):

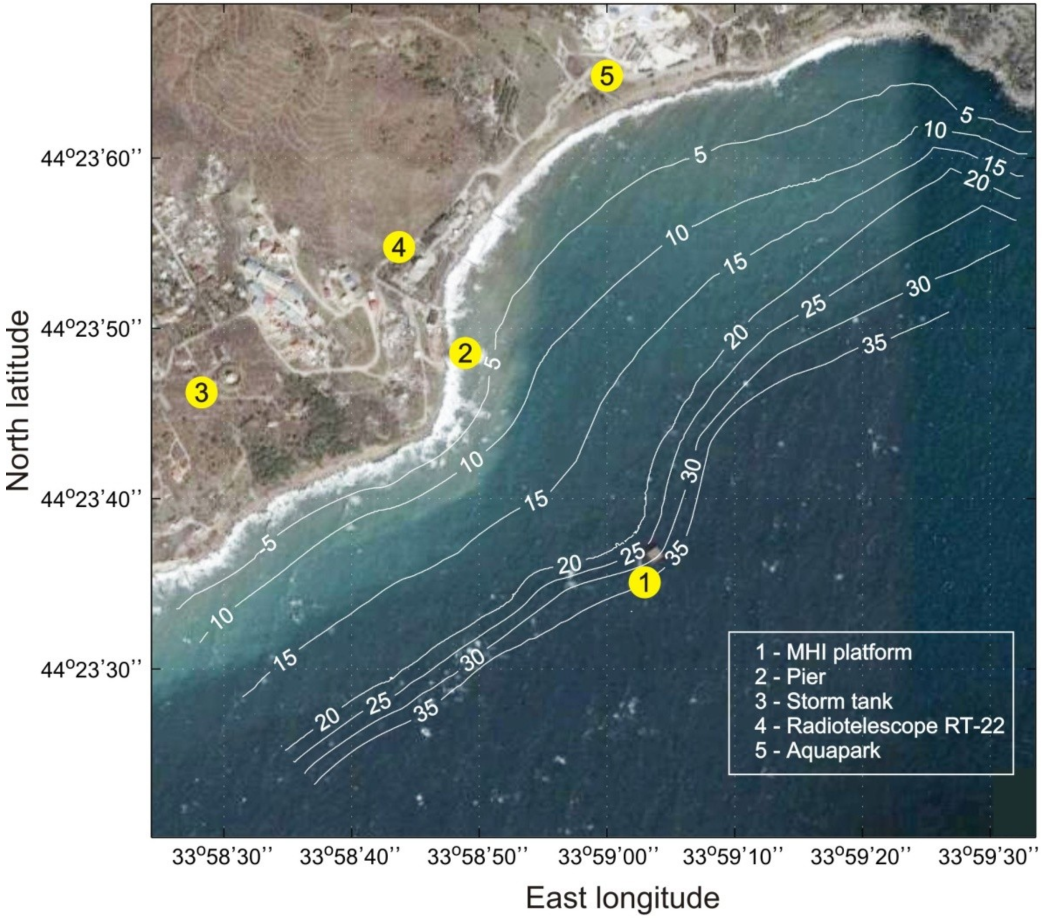
$$v = \left(\left[\mathbf{v_c} + \mathbf{v_s} + \overline{\sigma'\mathbf{u}'}/\overline{\sigma}\right] \cdot \mathbf{k_r}\right)/|\mathbf{k_r}|$$

v_c is the surface current velocity
v_s is the scatterer velocity in terms of two-scale model
σ’ is the NRCS variation
u’ is the orbital velocity component
k_r is the radar wave number

+ Approaching
- Receding



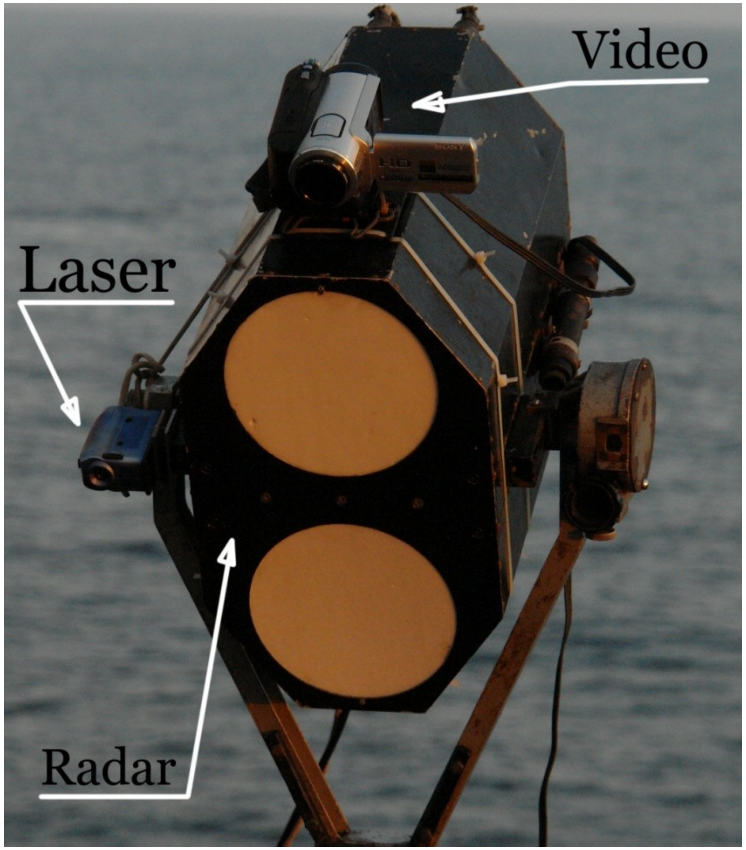
Marine Hydrophysical Institute (MHI RAS) Research Platform

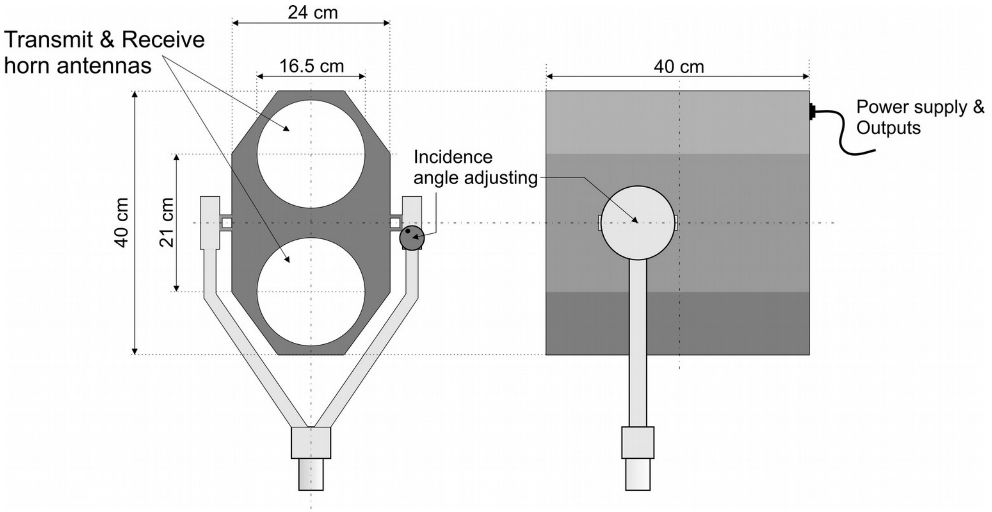


MHI RAS Research platform

Wavelength upto 60 m at U=20 m/s

Instruments



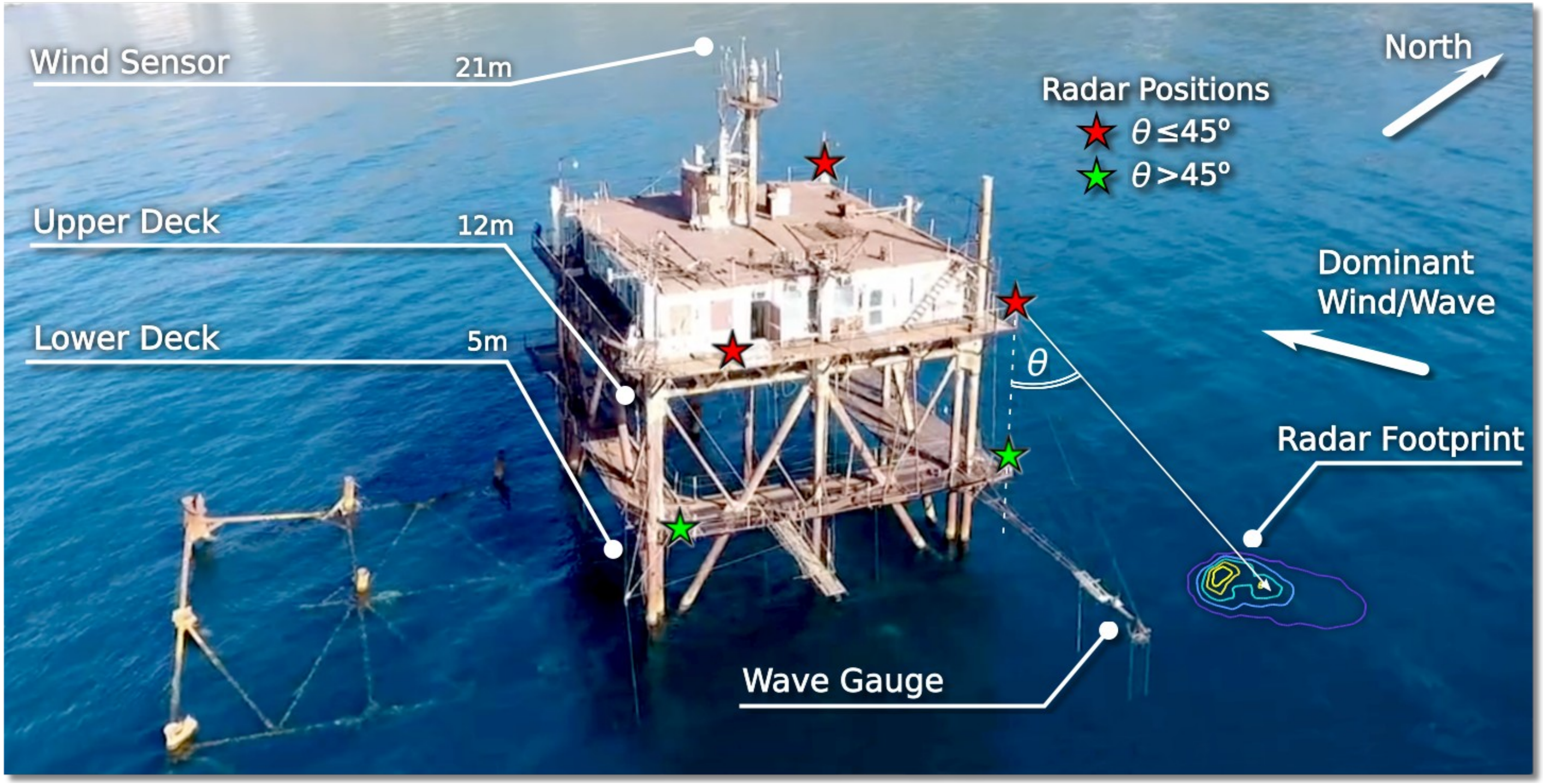


Type	CW Doppler Scatterometer
Polarization	VV,HH
Wavelength, Freq.	8 mm, 37.5GHz
CW Power	100 mW
Antenna	Conical horns for Tx and Rx

+ meteo station, wire wave gauge, video camera, submerged current sensors

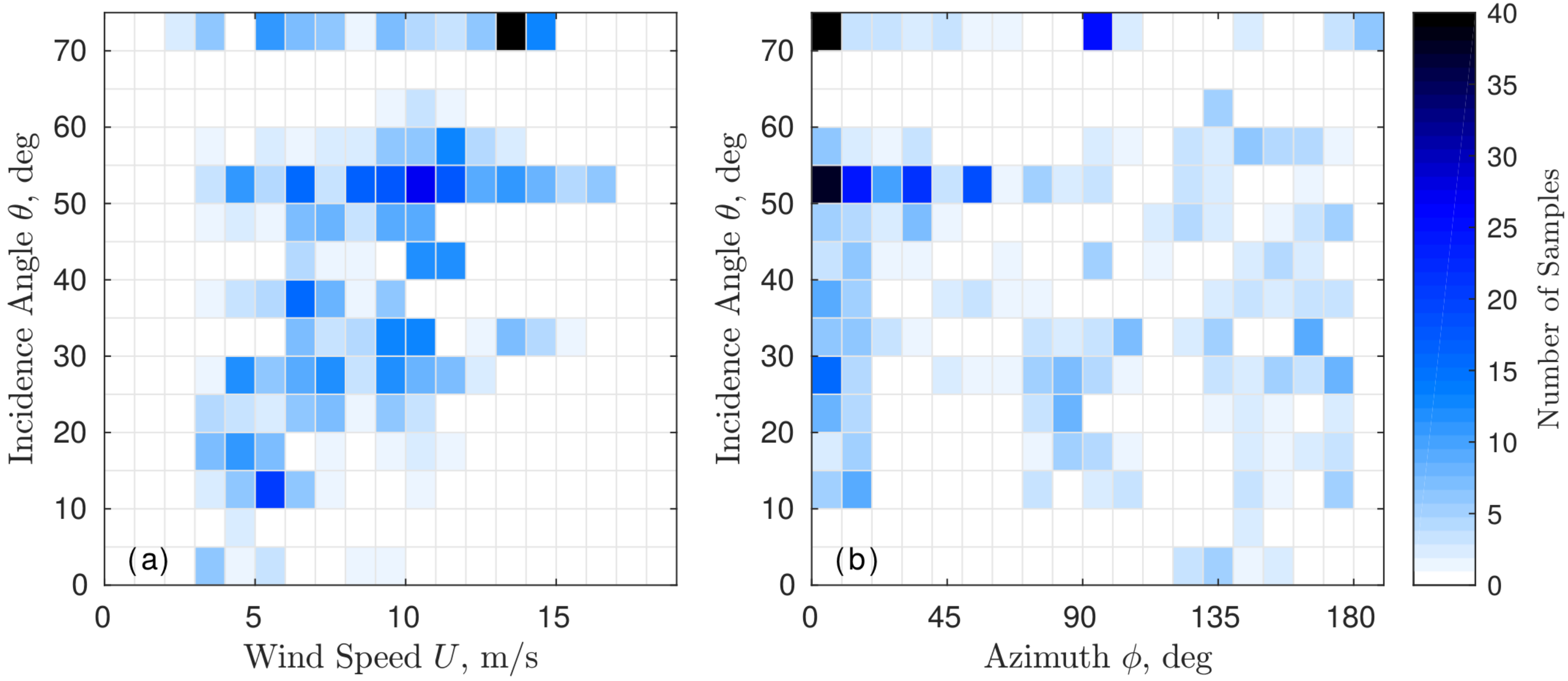
Measurements

The measurements are carried out in 2009 - now.



Measurements

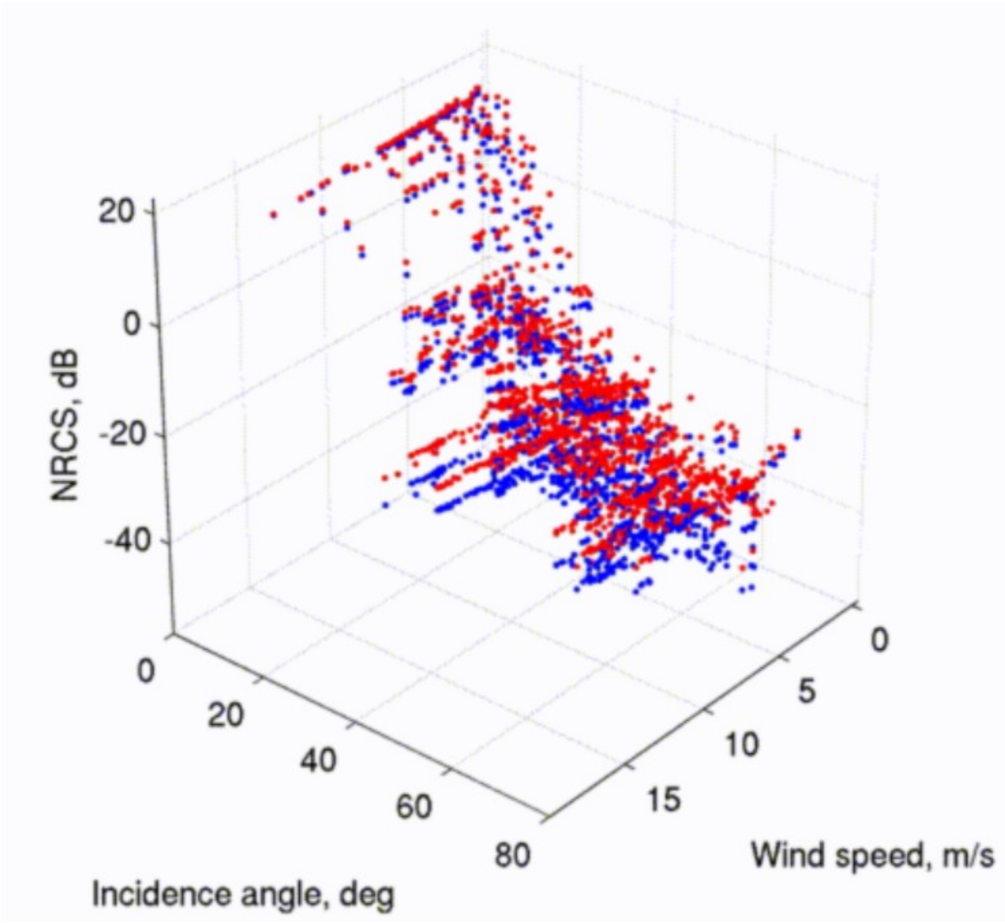
Data sample distributions over incidence angle, azimuth, and wind speed.

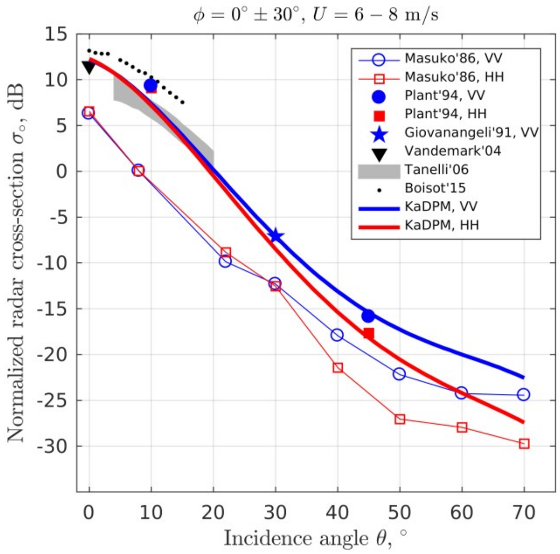


Contents

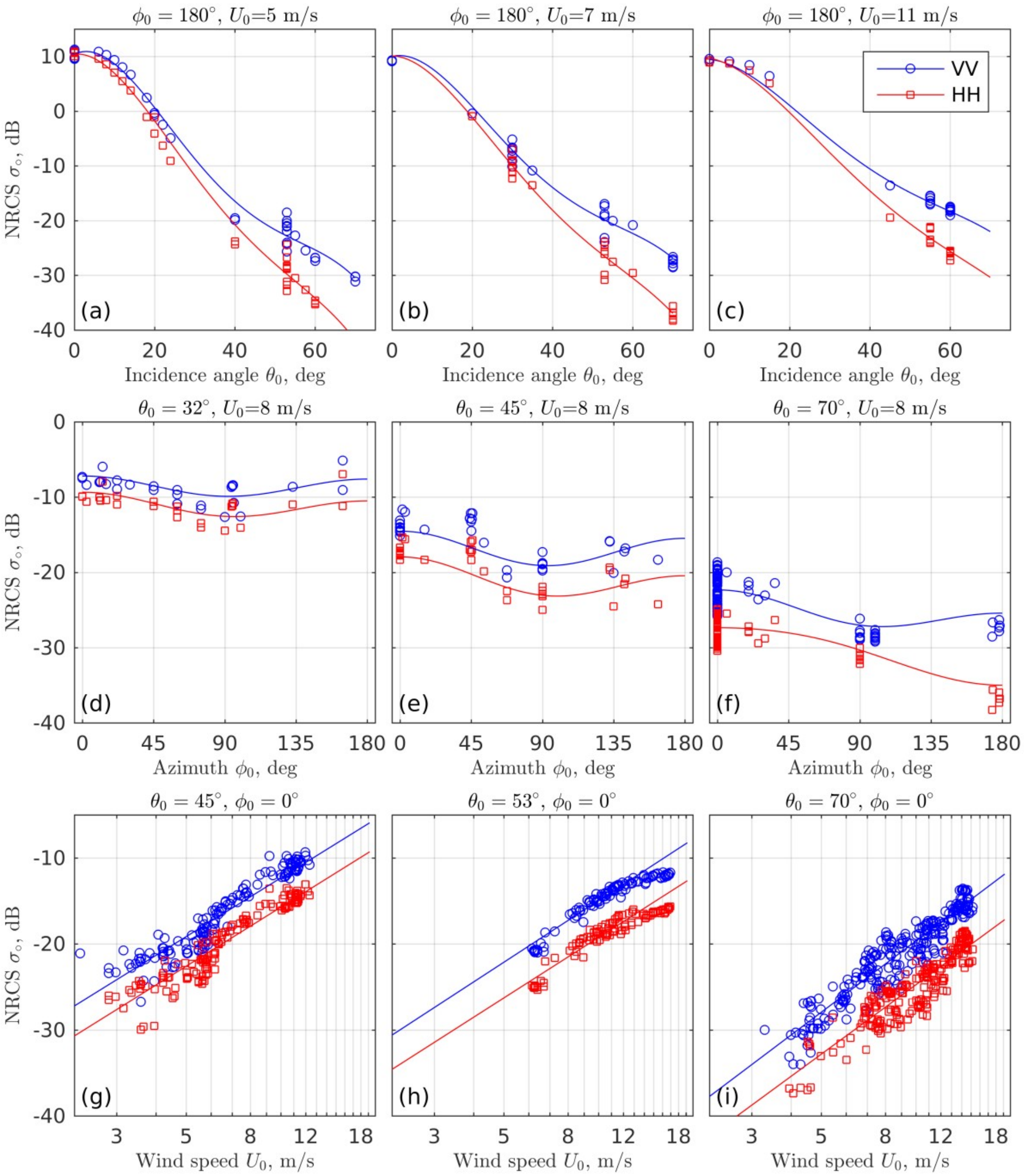
[Y. Y. Yurovsky, V. N. Kudryavtsev, S. A. Grodsky, and B. Chapron, “Ka-Band Dual Copolarized Empirical Model for the Sea Surface Radar Cross Section,” IEEE Transactions on Geoscience and Remote Sensing, vol. 55, no. 3, pp. 1629–1647, 2017]

NRCS Model function



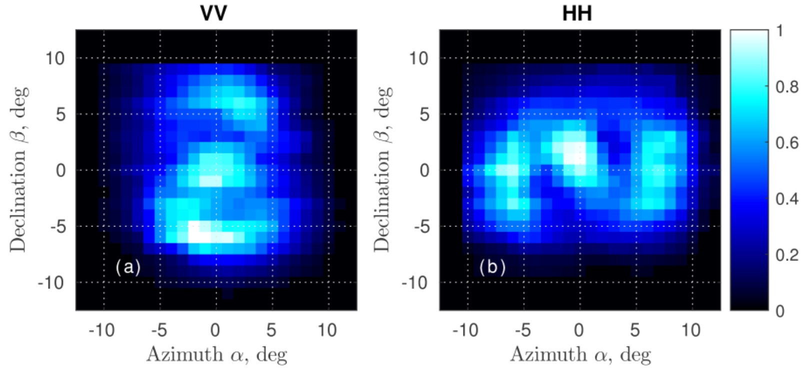


NRCS Model (KaDPM)



- Points – measurements
- Lines – polynomial fit
- Standard 2-harmonic azimuth spreads
- Some saturation at winds > 15 m/s
- Pure measurements suffer from antenna impacts (different at VV and HH) → “weird” polarization ratio at small incidence angles

Data fitting. Antenna pattern correction

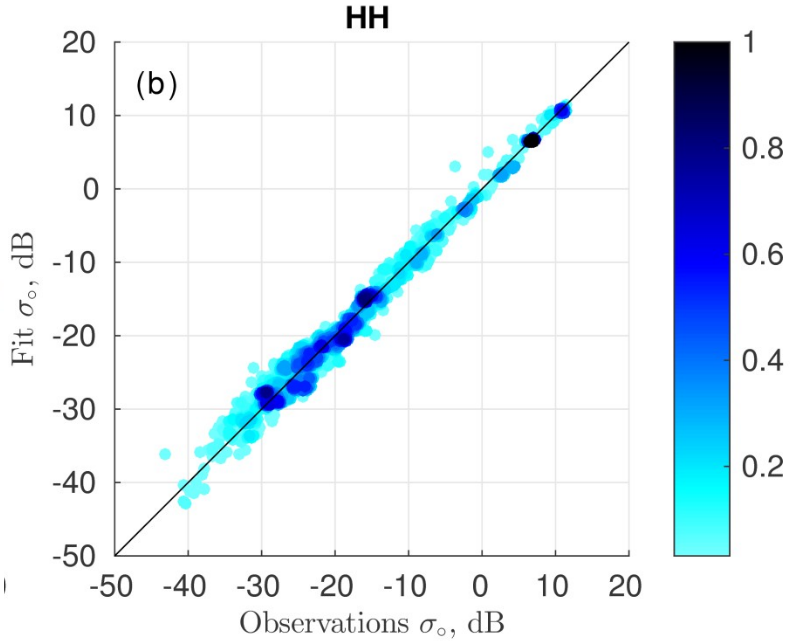


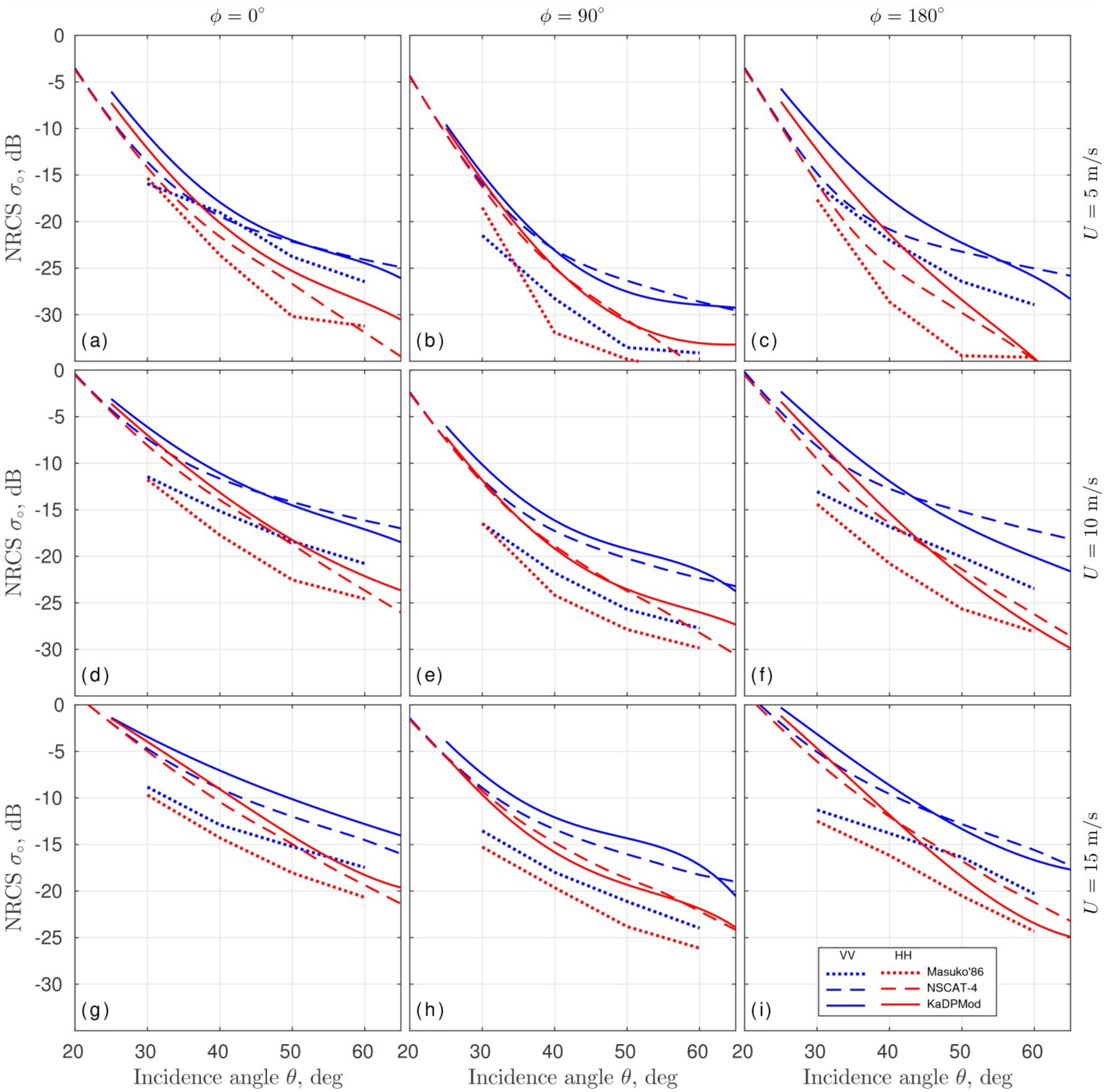
$$\sigma_{\text{oeff}}(\theta_0,\phi_0,U) = \frac{\int \Gamma_{\text{eff}}(x,y)\sigma_o(x,y,U)\mathrm{d}x\mathrm{d}y}{\int \Gamma_{\text{eff}}(x,y)\mathrm{d}x\mathrm{d}y} = \qquad (4)$$

$$= \frac{\int \Gamma_{\text{eff}}(\theta,\phi)\sigma_o(\theta,\phi,U)J(\theta,\phi)\mathrm{d}\theta\mathrm{d}\phi}{\int \Gamma_{\text{eff}}(\theta,\phi)J(\theta,\phi)\mathrm{d}\theta\mathrm{d}\phi},$$

$$\log\sigma_o = A_0(\theta,U) + A_1(\theta,U)\cos\phi + A_2(\theta,U)\cos 2\phi, \quad (6)$$

$$A_j = \sum_{m=0}^{4}\sum_{k=0}^{1} C_{mjk}\theta^m(\log U)^k, \qquad (7)$$





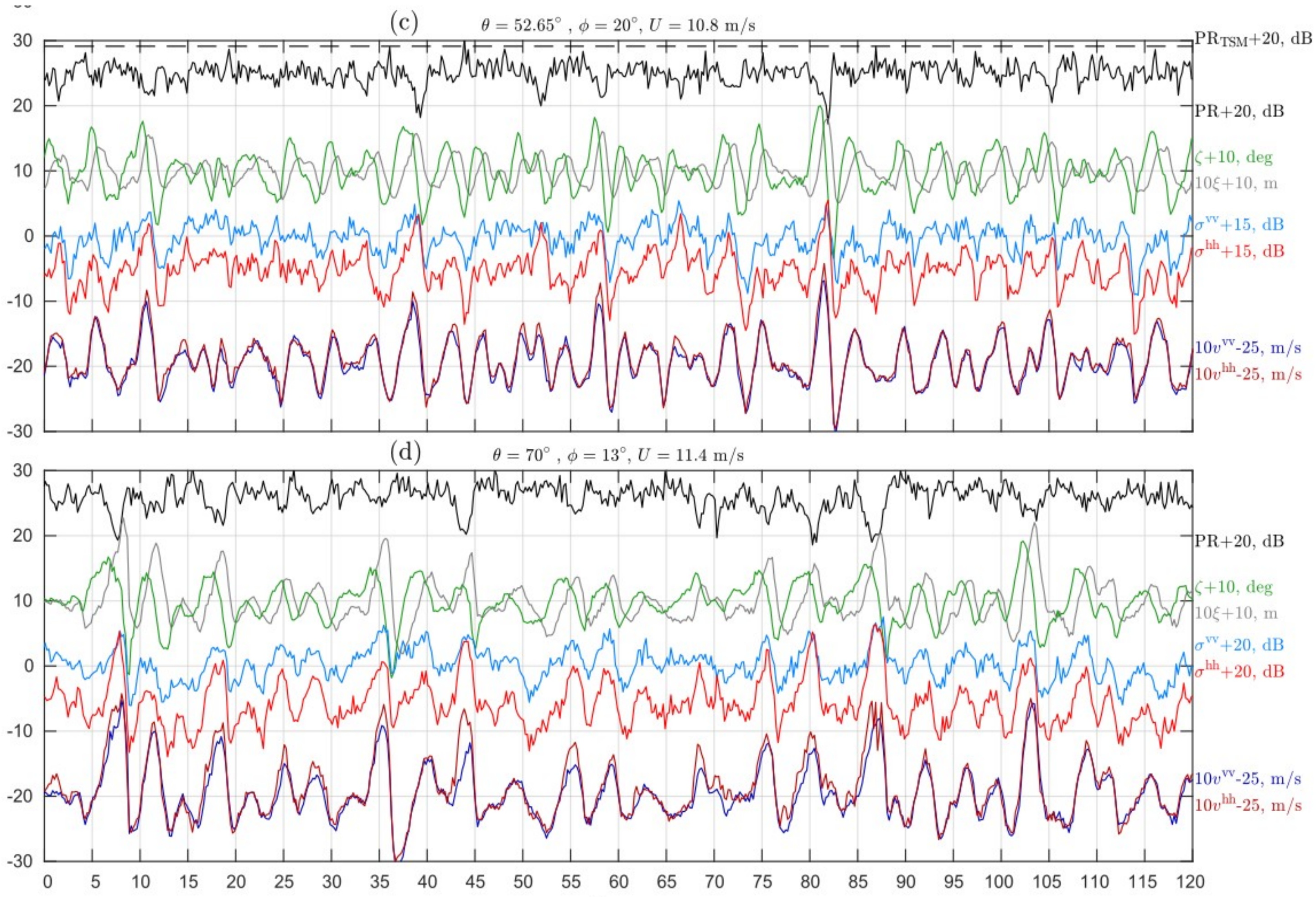
- Fits are more reliable after the correction
- Our Ka-band data (KaDPM) is quite close to the Ku-band (NSCAT-4)
- Data by [Masuko et al. 1986] are much lower

Contents

1. Radar cross-section (NRCS)
2. NRCS Modulation
3. Doppler centroid model

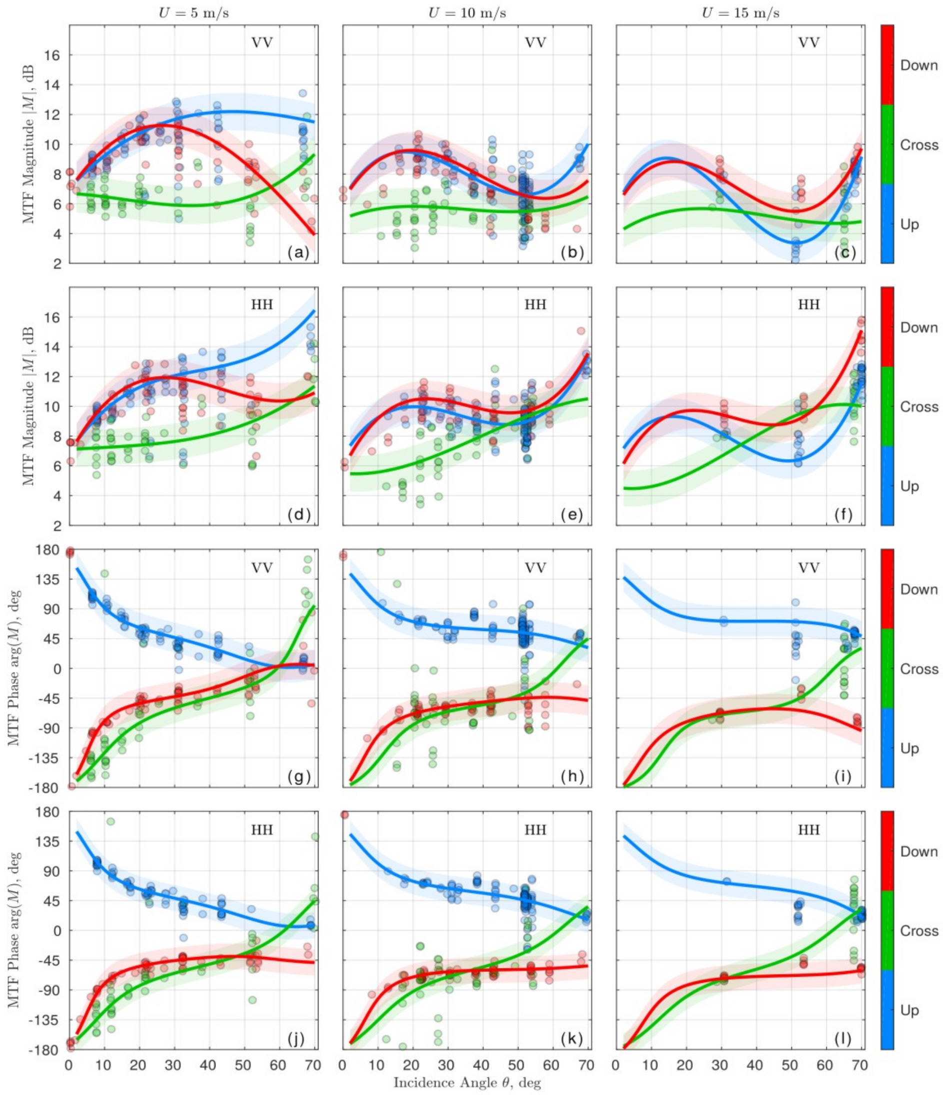
[Y. Y. Yurovsky, V. N. Kudryavtsev, B. Chapron, and S. A. Grodsky "Modulation of Ka-Band Doppler Radar Signals Backscattered From the Sea Surface", IEEE Transactions on Geoscience and Remote Sensing, vol. 56, no. 5, pp. 2931-2948, 2018]

Doppler Signal Time Series



- DV spikes are much weaker than NRCS spikes
- DV spikes are presumably the PHASE velocities of breakers ??? [Jessup et al. 1991, Hansen et al. 2012]
- DV spikes correspond to the phase velocities of waves much shorter than peak waves ???
- Conclusion: breaker roughness is embedded in the surface

Modulation Transfer Function



- MTF reflects the distribution of NRCS variation over the long wave profile

$$M = \frac{\sigma'}{\bar{\sigma} a k} = \frac{gG}{\bar{\sigma}\omega}\frac{S_{\sigma v}}{S_{vv}}$$

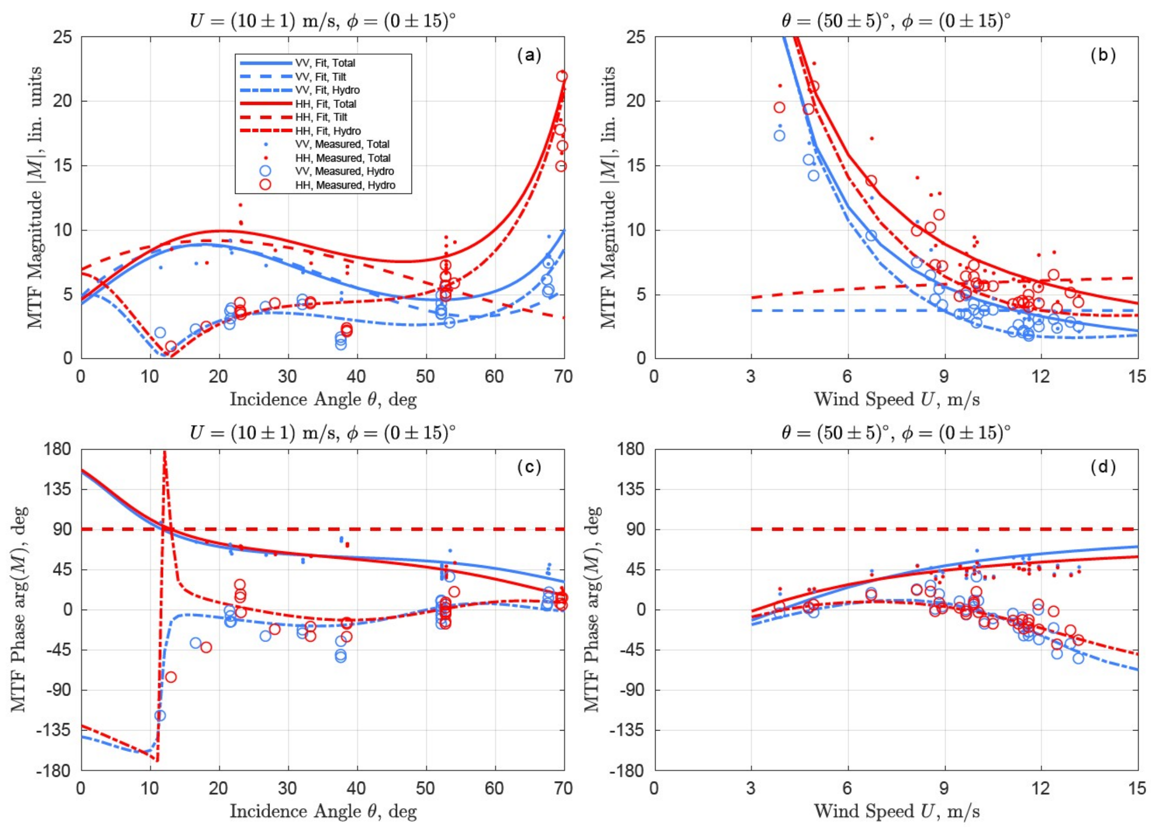
$$G = \cos\phi \sin\theta + i\cos\theta$$

- NRCS peaks at the front slope in upwind direction, and at the rear slope in downwind direction

- MTF magnitude has a peak at 20-30°, and increases after 65°.

$$\frac{\overline{v'\sigma'}}{\bar{\sigma}} = \mathrm{Re}\int g^{-1} G^{*} \omega^{3} M S_{zz} \mathrm{d}\omega$$

Modulation Transfer Function



- Contrast inversion at 12-13 deg → Hydro-MTF flip
- This is close to SKIM incidence angle → weakest wind variability → better discrimination between wind-sea/slicks/ships etc.

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1. Radar cross-section (NRCS)
2. NRCS Modulation
3. <u>Doppler centroid model</u>

[Yurovsky, Y.Y.; Kudryavtsev, V.N.; Grodsky, S.A.; Chapron, B. Sea Surface Ka-Band Doppler Measurements: Analysis and Model Development. Remote Sens. 2019, 11, 839.]

Model

---------- Moderate incidence angles (SPM+TSM) ----------

- MTF definition: $M = \frac{\sigma'}{\overline{\sigma} a k} = \frac{g G}{\sigma \omega} \frac{S_{\sigma v}}{S_{vv}}$

- Wave-induced Doppler:

$$\begin{aligned} \overline{\sigma' u}/\overline{\sigma} &= \mathrm{Re}\{MG\}\Omega^3 g^{-1} A^2/2 = \mathrm{Re}\{MG\} C K^2 A^2/2, \\ G &= \cos\phi_{\mathrm{wa}} \sin\theta - i\cos\theta, \end{aligned}$$

------------------ Small incidence angles (GO) ------------------

- GO specular point velocity [Longuet-Higgins, 1957]:

$$c_{\mathrm{sp}} = \cos\phi_{\mathrm{wi}} \int_L c k^{-2} \cos(\phi) B(\mathbf{k}) \mathrm{d}\mathbf{k} / \overline{\zeta^2_{Lup}} + \sin\phi_{\mathrm{wi}} \int_L c k^{-2} \sin(\phi) B(\mathbf{k}) \mathrm{d}\mathbf{k} / \overline{\zeta^2_{Lcr}},$$

- GO radar cross-section: $\sigma(\theta) \sim \sec^4\theta \exp\left(-\frac{\tan^2\theta}{2\overline{\zeta^2_{Lup}\zeta^2_{Lcr}}} [\overline{\zeta^2_{Lcr}} \cos^2\phi_{\mathrm{wi}} + \overline{\zeta^2_{Lup}} \sin^2\phi_{\mathrm{wi}}] \right)$

- Tilt-MTF definition: $M_{\mathrm{T}} = \frac{\partial \ln\sigma}{\partial \tan\theta} = \tan\theta \left(\frac{\cos^2\phi_{\mathrm{wi}}}{\overline{\zeta^2_{Lup}}} + \frac{\sin^2\phi_{\mathrm{wi}}}{\overline{\zeta^2_{Lcr}}} \right)$

- Mean Doppler shift: $c_{\mathrm{sp}} \sin\theta = \mathrm{Re}\{MG\} C K^2 A^2/2,$

- Final Doppler centroid model:

$$V = v_{\mathrm{dr}} \sin\theta \cos\phi_{\mathrm{dr}} + v_{\mathrm{sc}} \sin\theta + \int_L \mathrm{Re}\{MG\} c k^{-2} B(\mathbf{k}) \mathrm{d}\mathbf{k},$$

$$V = v_{\mathrm{dr}} \sin\theta \cos\phi_{\mathrm{dr}} + v_{\mathrm{sc}} \sin\theta + g^{-1} \int_0^{2\pi} \mathrm{Re}\{M(\theta,\phi,U)G(\theta,\phi)\} \int_L \omega^3 S(\omega,\phi) \mathrm{d}\omega \mathrm{d}\phi,$$

$$\int_L \omega^3 S(\omega) \mathrm{d}\omega \approx \beta \cdot H_{\mathrm{s}}^2 \omega_{\mathrm{p}}^3,$$ ...for Pierson-Moskowitz spectrum

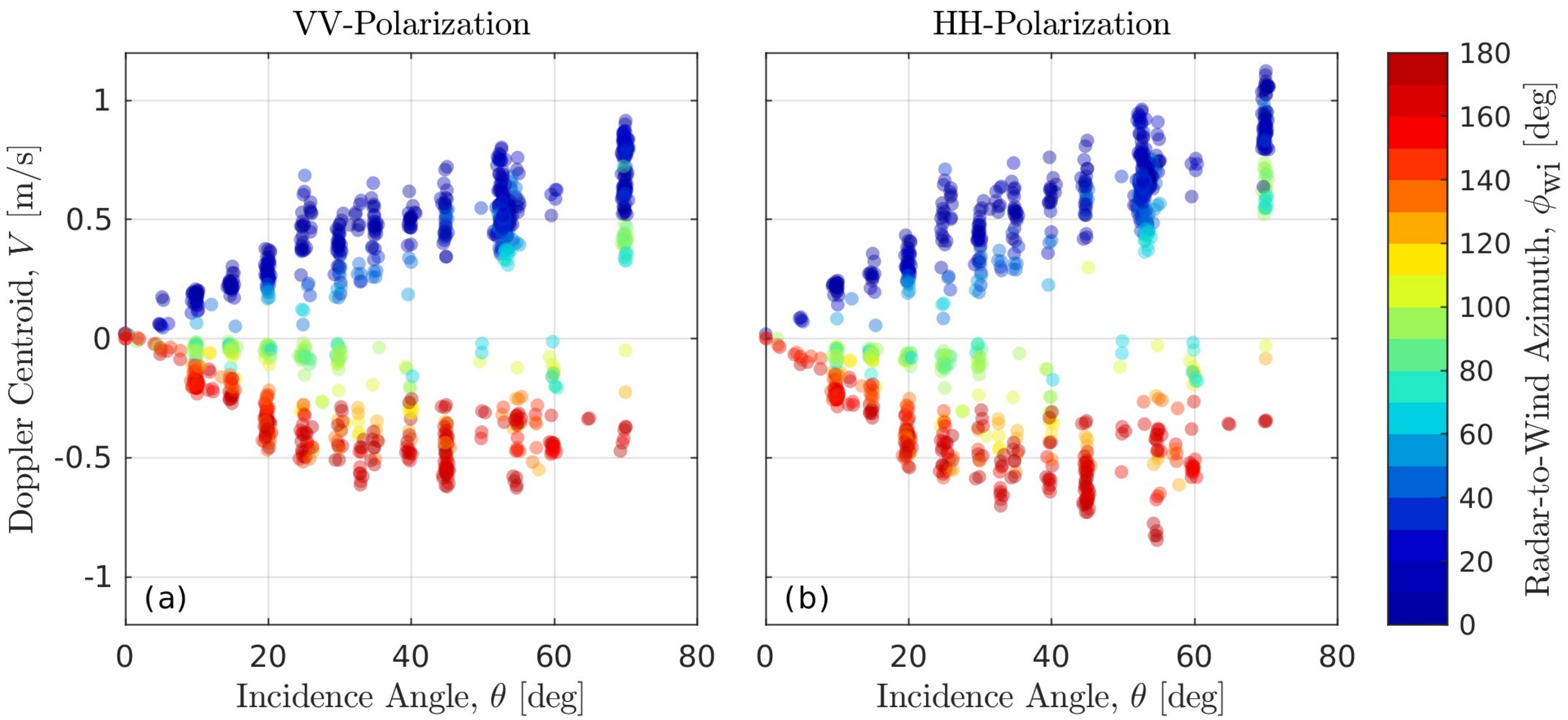
$$V = v_{\mathrm{dr}} \sin\theta \cos\phi_{\mathrm{dr}} + v_{\mathrm{sc}} \sin\theta + g^{-1} \sum_N \beta_N \cdot \mathrm{Re}\{M(\theta, \phi_{\mathrm{wa}N}, U)G\} H_{\mathrm{s}N}^2 \omega_{\mathrm{p}N}^3,$$

Surface current

Wave-induced term

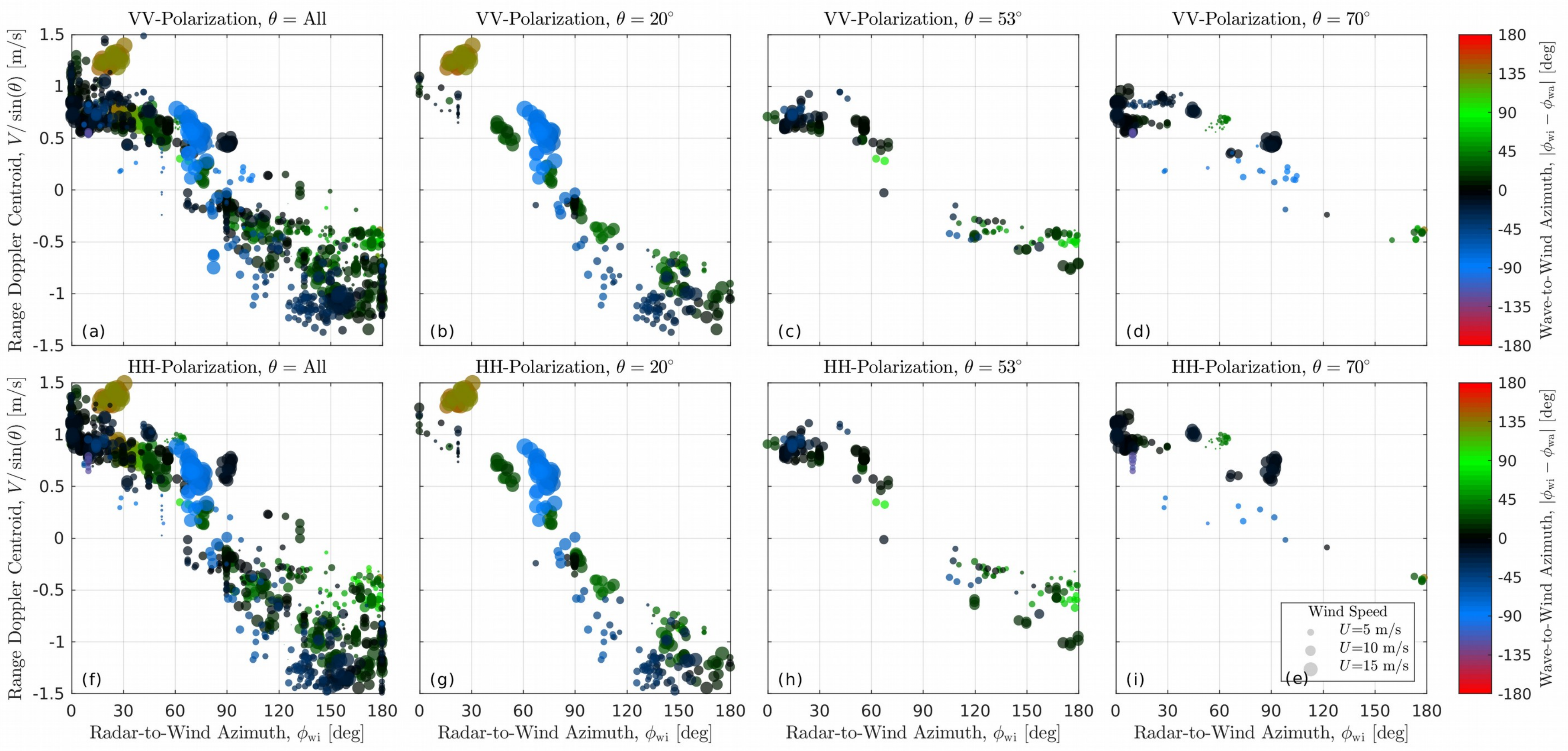
Bragg wave velocity

Measurements. Incidence angle dependence



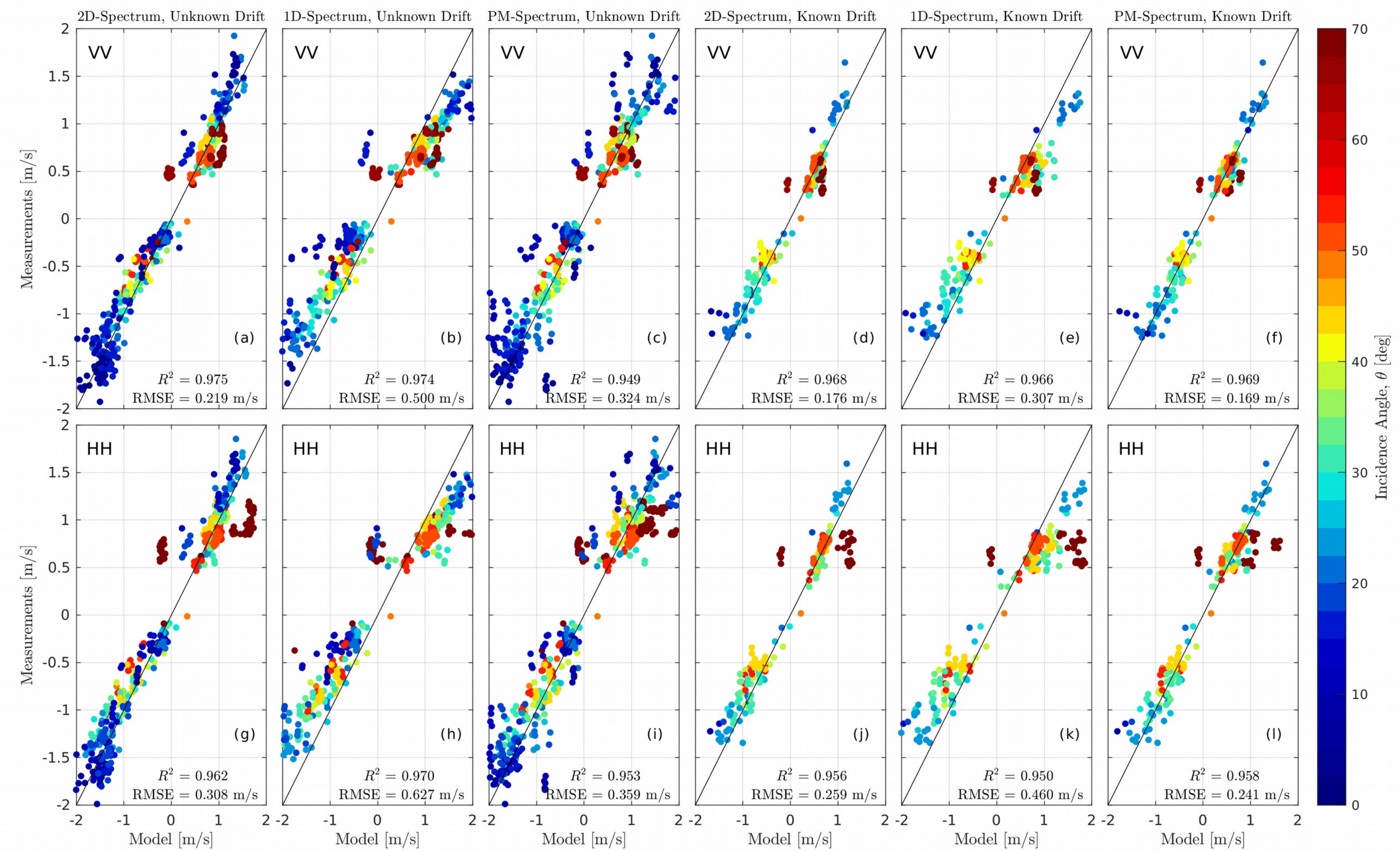
Doppler centroids versus incidence angle, θ, for dual co-polarized (**a**) vertical transmit–receive polarization (VV) polarization and (**b**) horizontal transmit–receive polarization (HH) polarization. Color indicates radar-to-wind azimuth. Only co-aligned winds and waves, $|\phi_{\rm wi} - \phi_{\rm wa}| < 25°$, are shown. Gaussian noise is added to the nominal θ for better visibility, $\mathrm{STD}(\theta_{\rm noise}) = 0.25°$.

Measurements. Azimuth dependence



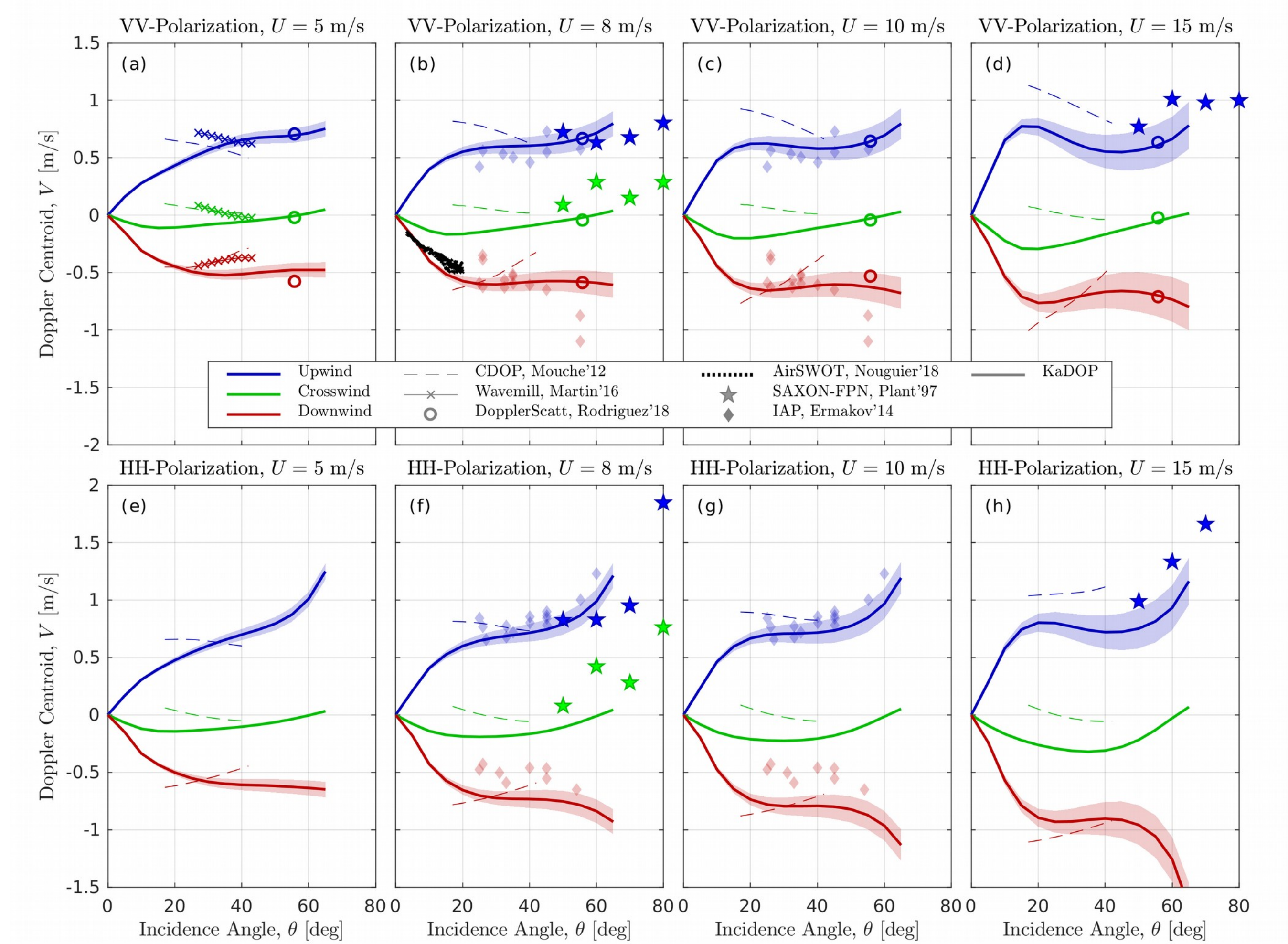
Doppler centroids versus radar-to-wind azimuth for (**top row**) VV polarization and (**bottom row**) HH polarization at (**a**,**f**) all incidence angles, (**b**,**g**) $\theta = 20^\circ$, (**c**,**h**) $\theta = 53^\circ$, and (**d**,**i**) $\theta = 70^\circ$. Color scheme corresponds to wave-to-wind azimuth. Symbol size corresponds to wind speed. All conditions, including non-aligned winds and waves, are shown.

Model validation



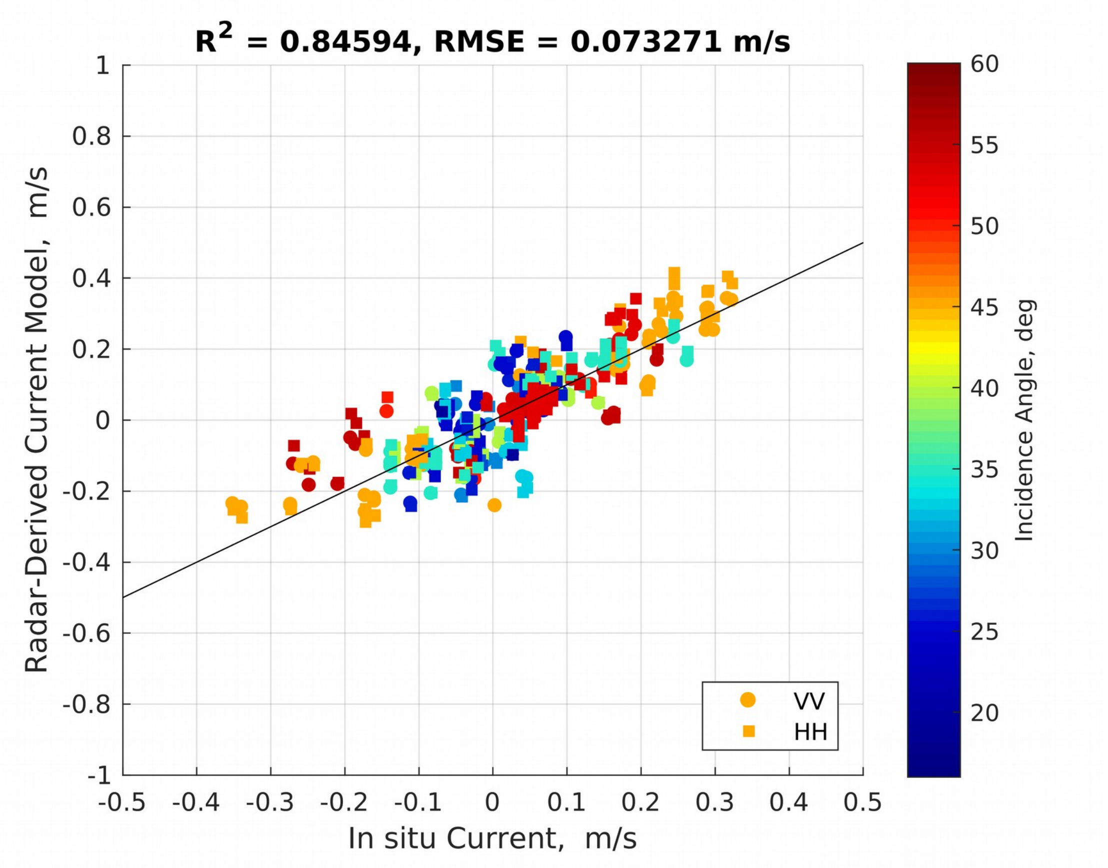
Model versus measurement DC range projection, $V / \sin\theta$. (**top row**) VV-polarization, (**bottom row**) HH-polarization. (**left three columns**) correspond to cases with unknown wind drift (estimated as 1.5%**U**). Left to right: 2D-sea, Equation (14); 1D-sea, Equation (14); equivalent Pierson–Moskowitz (PM) spectral shape, Equation (16). (**right three columns**) are the same, but for cases with known wind drift. Correlation coefficient, R^2, and root-mean-square error (RMSE) are shown in each panel.

Comparison with other data



Doppler centroid versus incidence angle for various wind speeds, left to right: $U = 5, 8, 10, 15$ m/s. (**top row**) VV-polarization, (**bottom row**) HH-polarization. Confidence interval corresponds to wind drift variation from 0 to 3%**U**.

Model inversion test: retrieving line-of-sight surface current from Doppler measurements



Summary

- The MHI platform provides good conditions for Doppler measurements in a well-controlled field experiment.
- The proposed empirical models for the Ka-band NRCS and MTF predict the wave-induced Doppler shift estimate as function of look geometry and sea state.
- Ka-band Doppler centroid model (KaDOP) is proposed based on the MTF model [https://www.mdpi.com/2072-4292/11/7/839].
- KaDOP is a function of incidence angle, azimuth, wind speed, and, generally, wave spectrum. Coupled with long-wave model parameterization, Pierson-Moskowitz spectrum, KaDOP fits well the measurements as well the data found in literature.