Platform measurements of Ka-band sea surface radar Doppler characteristics

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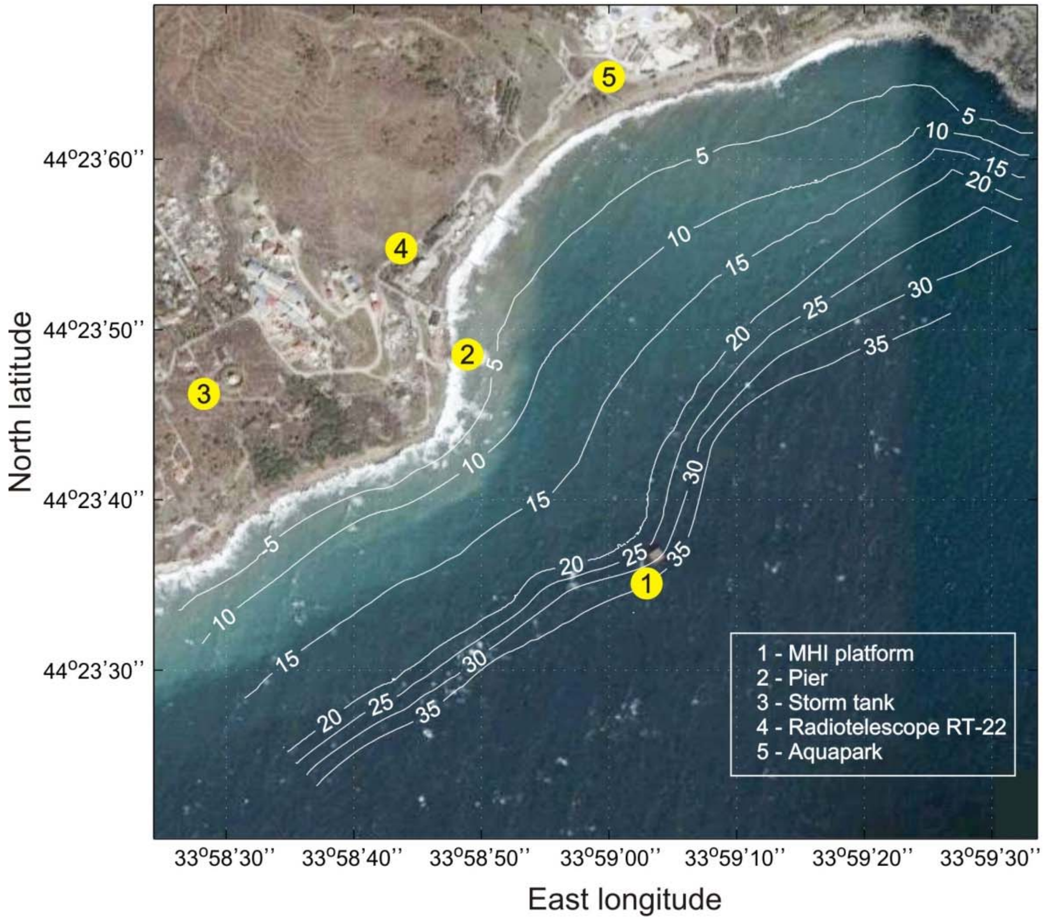
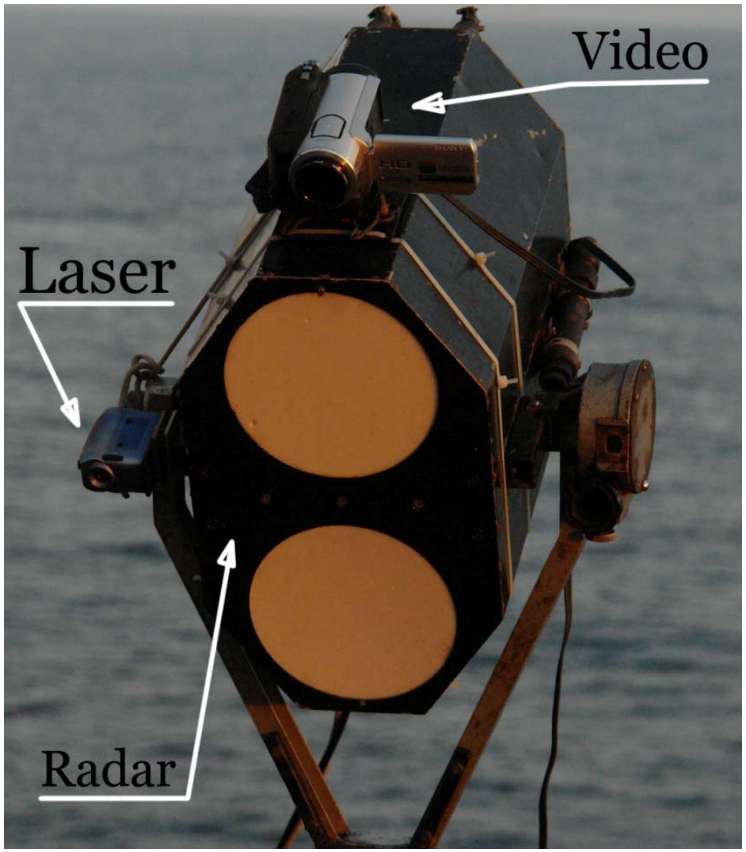
Outline

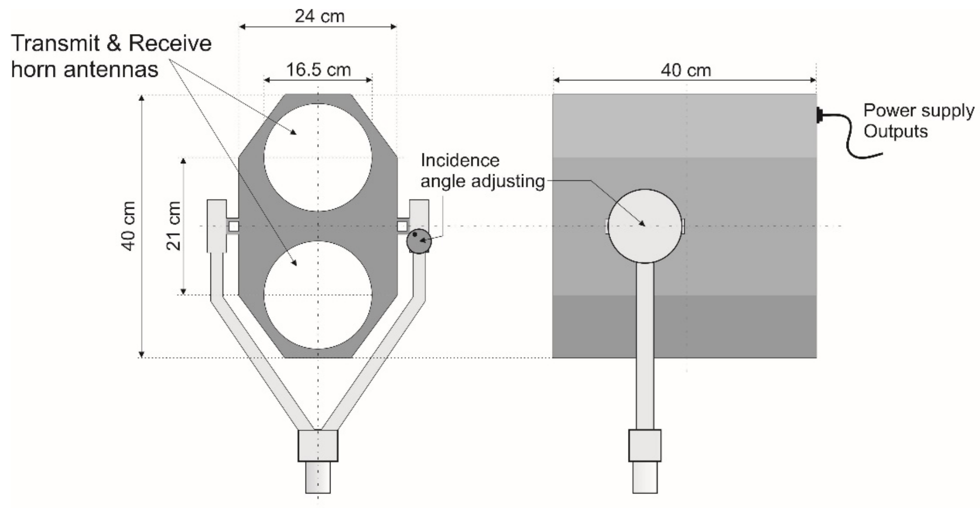
- Instrument and site description
- Processing
- What we can learn from raw Doppler velocity?
- Empirical KaDop parameterization
- Comparison with C-band empirical model (Cdop) and Doppler Radar Imaging Model (DopRIM).

Marine Hydrophysical Institute (MHI) Research platform



Instruments

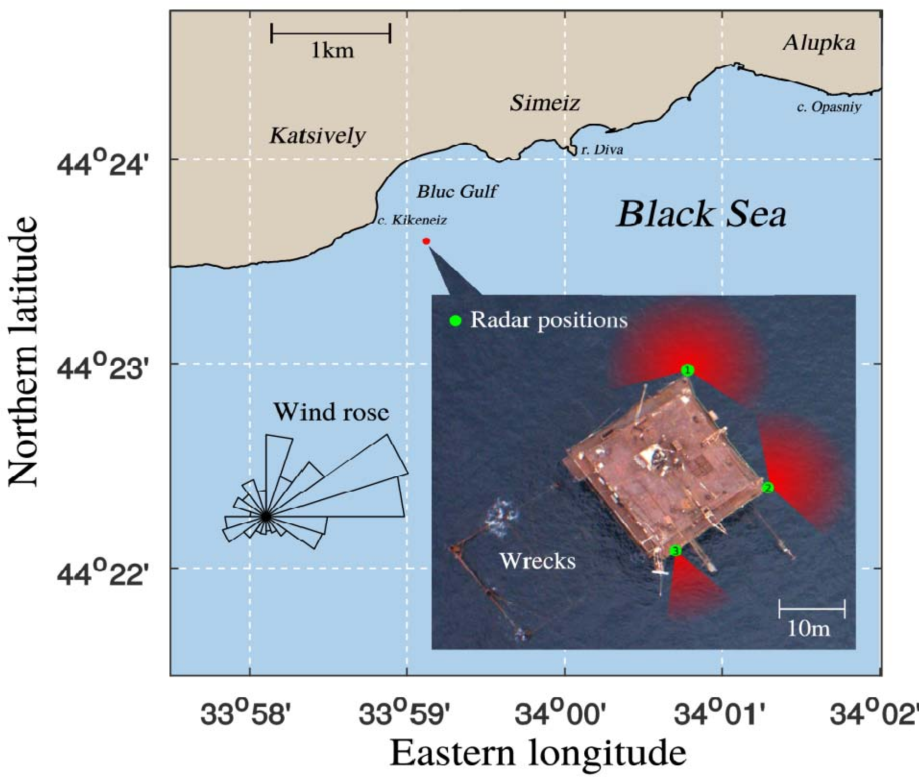


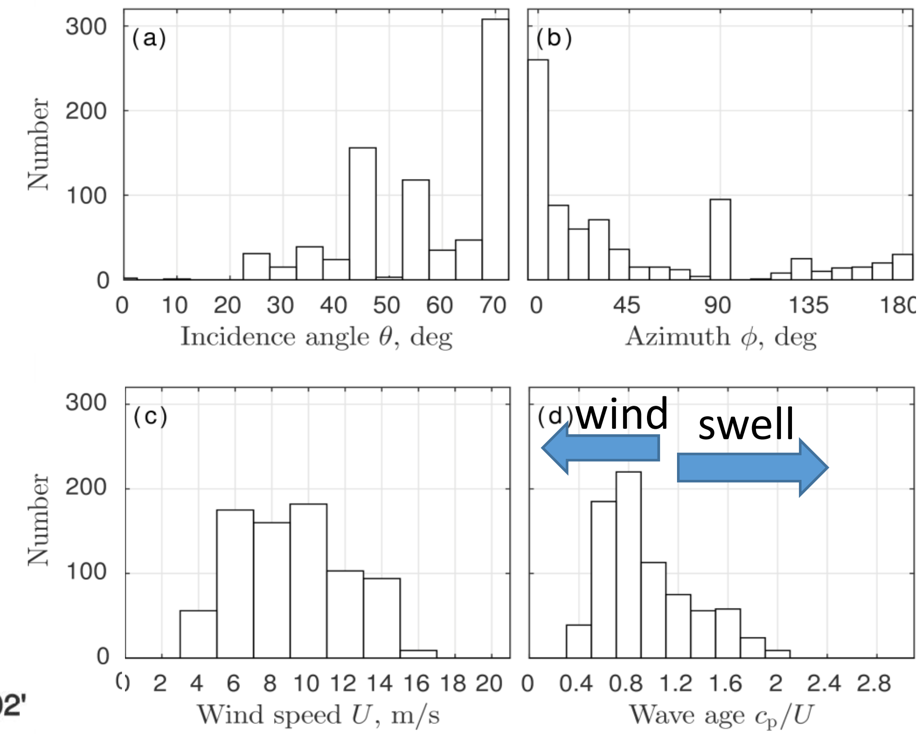


Radar	CW dual-polarized Doppler hybrid polarization, slant (45°) transmit polarization plane
Polarization	VV, HH
Wavelength	8 mm, 37.5 GHz (**Ka-band)**
Power	100 mW
Antenna design	Conical horns for Tx and Rx

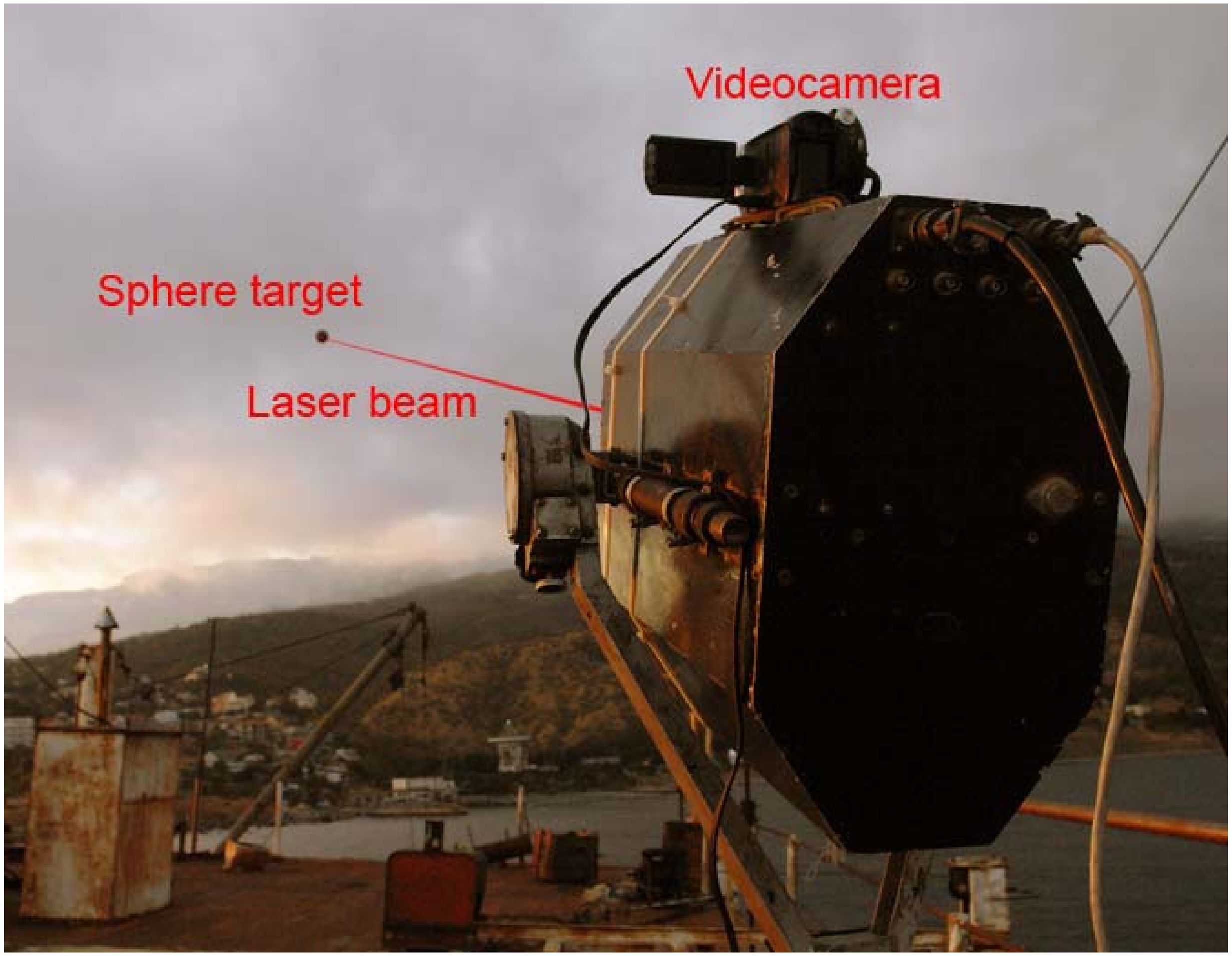
+ weather station and wire wave guage

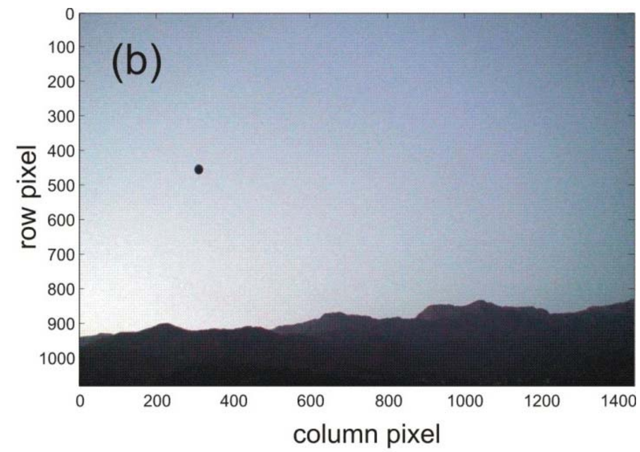
Measurements, 2009-2015

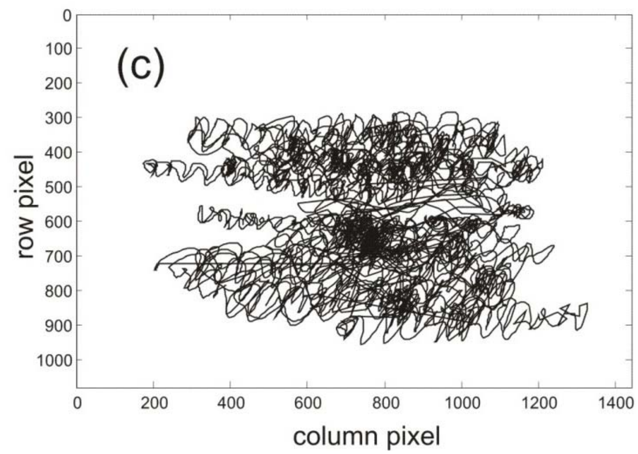




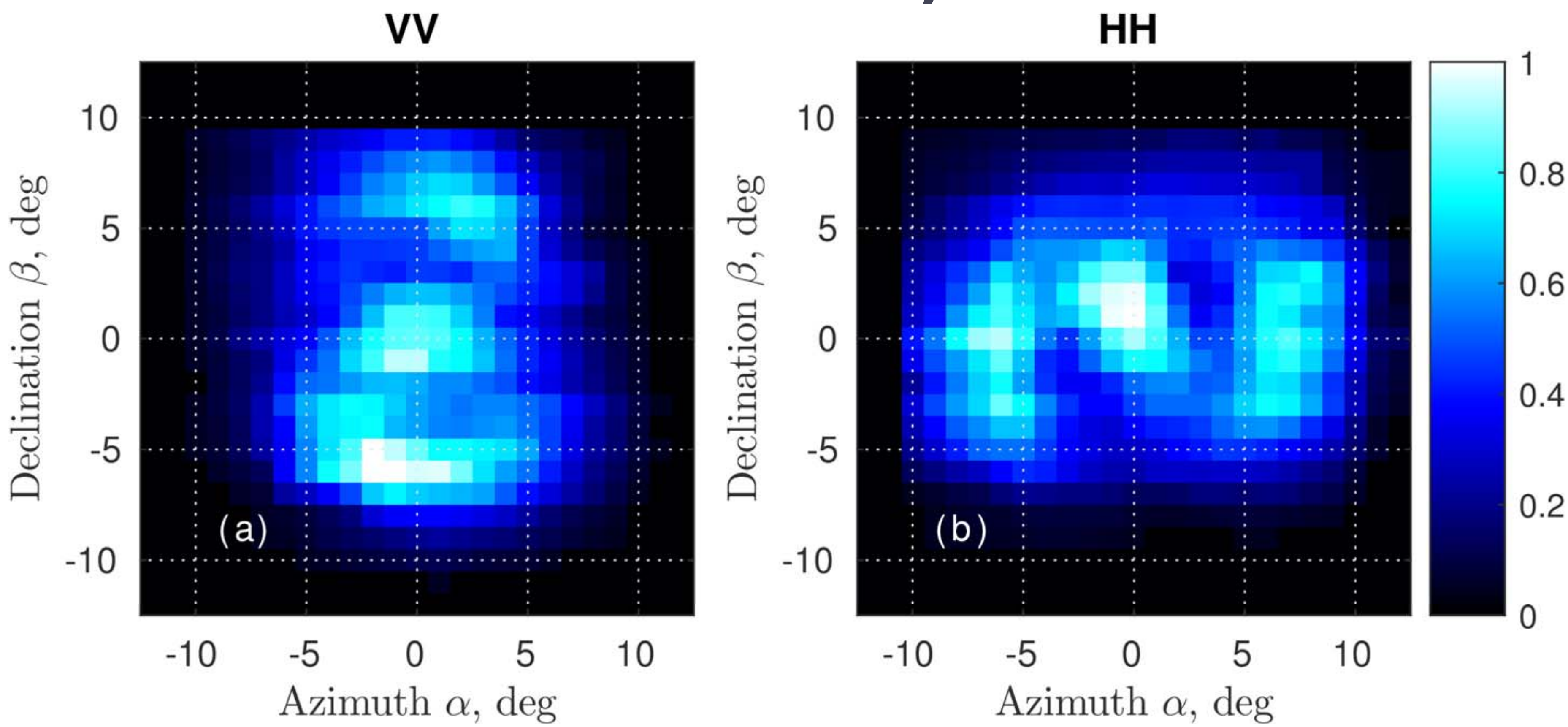
Calibration and pattern correction



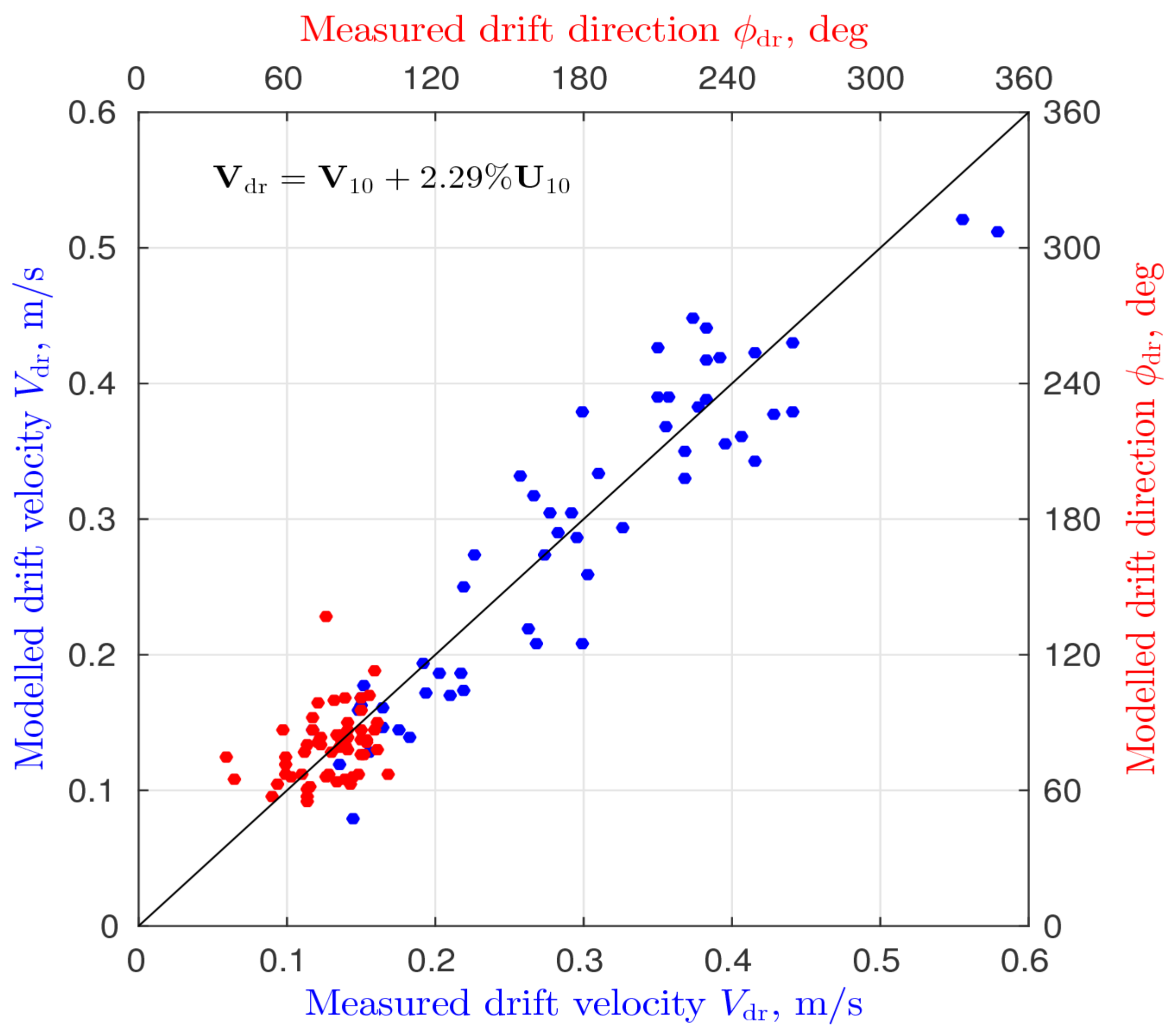




Radar antenna pattern (transmit + receive)



Surface Currents



(i) Direct - marker velocity on video records

(ii) Indirect - current meter at z=10m (V10) + empirical wind-driven velocity shear, **0.023*U10**

Scatter diagram of surface current speed (blue points) and direction (red points) from (x-axis) video data and (y-axis) current at z=10 m corrected for wind-driven shear in the upper 10m.

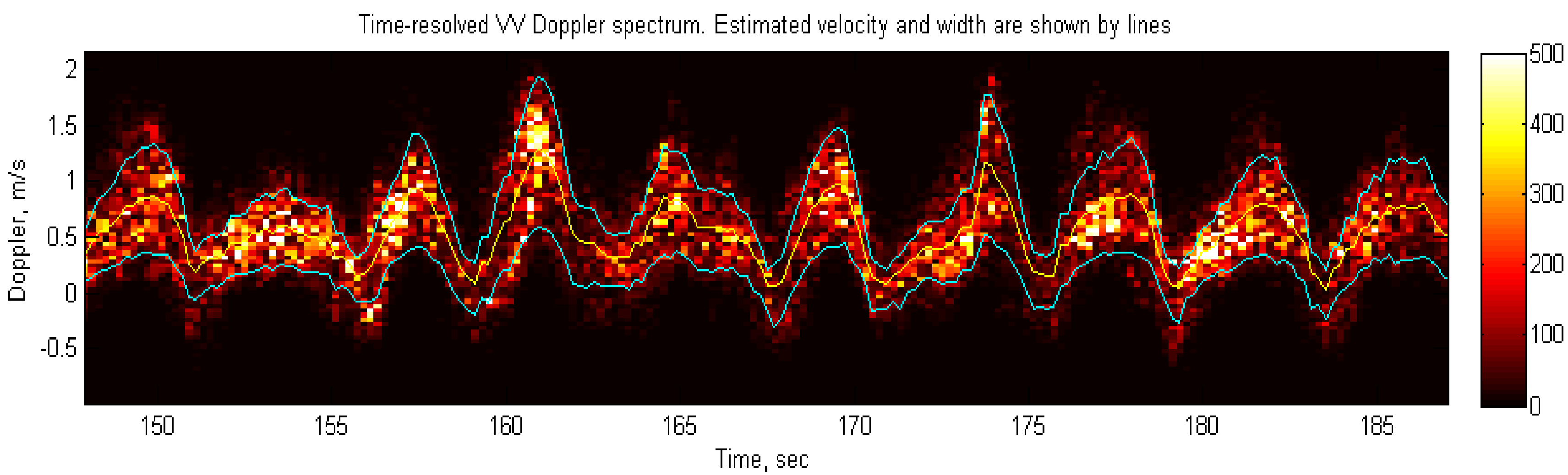
Processing

* Digitization rate 40 kHz

* Instantaneous Doppler spectrum, $S(f,t) = |FFT(I + iQ)|^2$, is computed from 0.2s segments using in-phase, $I(t)$, quadrature, $Q(t)$, components.

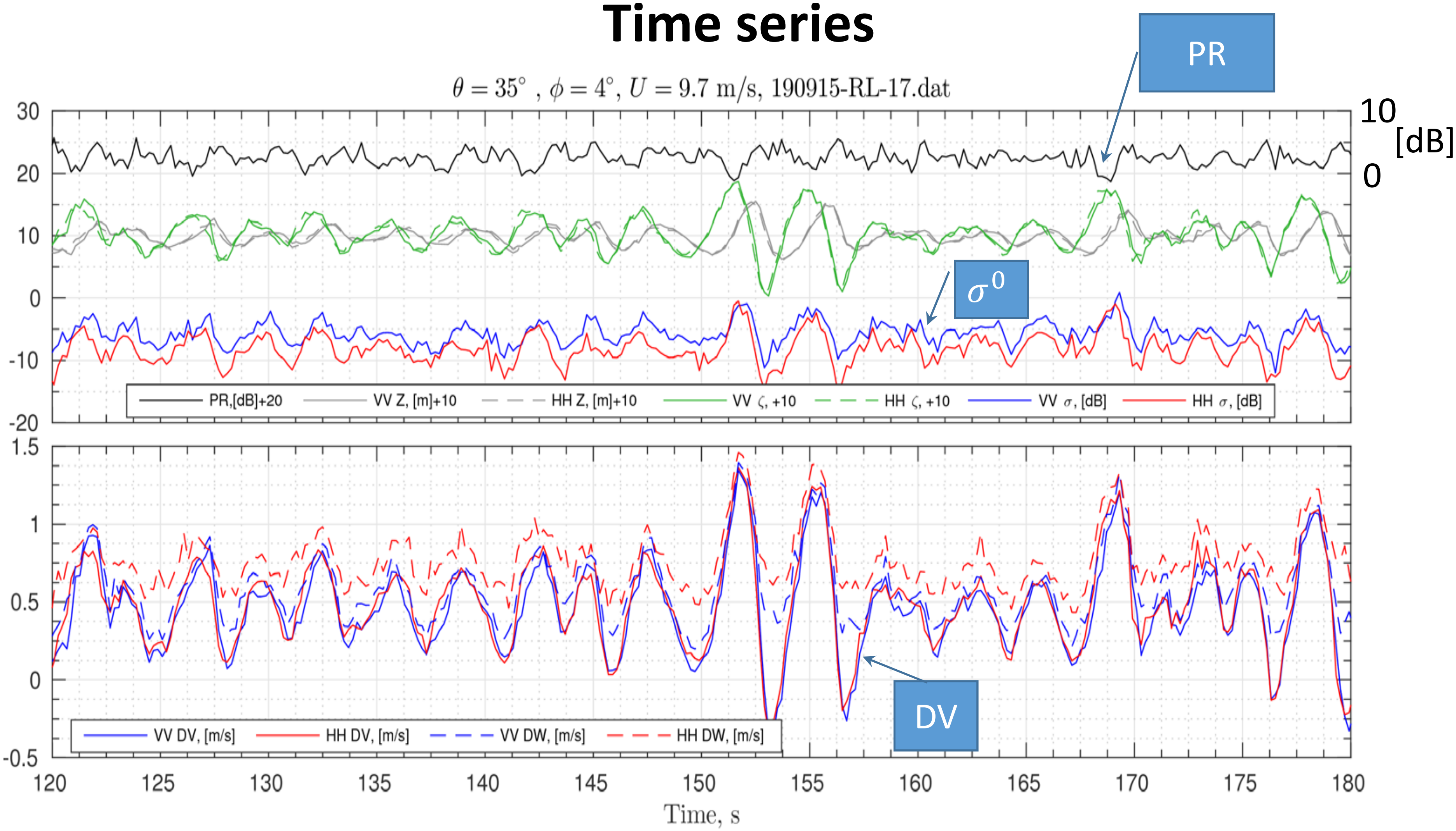
* Instantaneous NRCS, $\sigma(t) = \int S(f,t)df$, Doppler frequency, $\bar{f}(t) = \int fS(f,t)df / \sigma(t)$, and Doppler bandwidth, $DW^2 = \int \left(f - \bar{f}(t)\right)^2 S(f,t)df / \sigma(t)$

* Instantaneous line-of-sight (LOS) Doppler Velocity, $IDV = \pi\bar{f}(t)/k_R$, where k_R is the radar wavenumber.



Sample VV Doppler spectrum (θ=53°, upwind, U_{10}=10 m/s) as a function of time. Doppler velocity (yellow, middle line), Doppler spectrum width (cyan, top and bottom lines). Shades correspond to spectrum density.

Time series

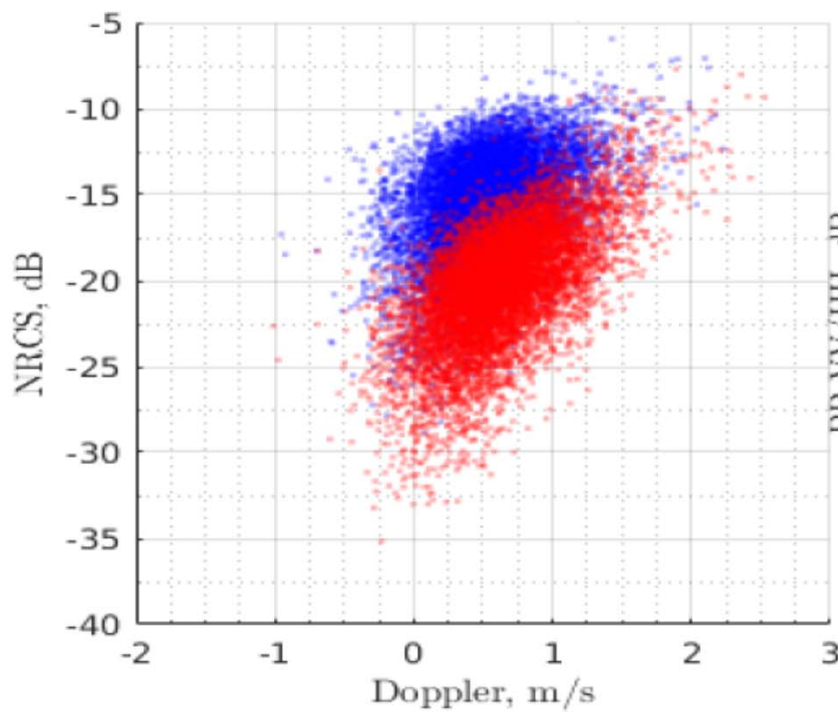


Sample timeseries of polarization ratio (PR=$\sigma^0_{VV}/\sigma^0_{HH}$) and Doppler velocity (DV, [**m/s**]). Positive DV corresponds to wave crests where PR decreases occasionally to 0 [**dB**], (PR=1).

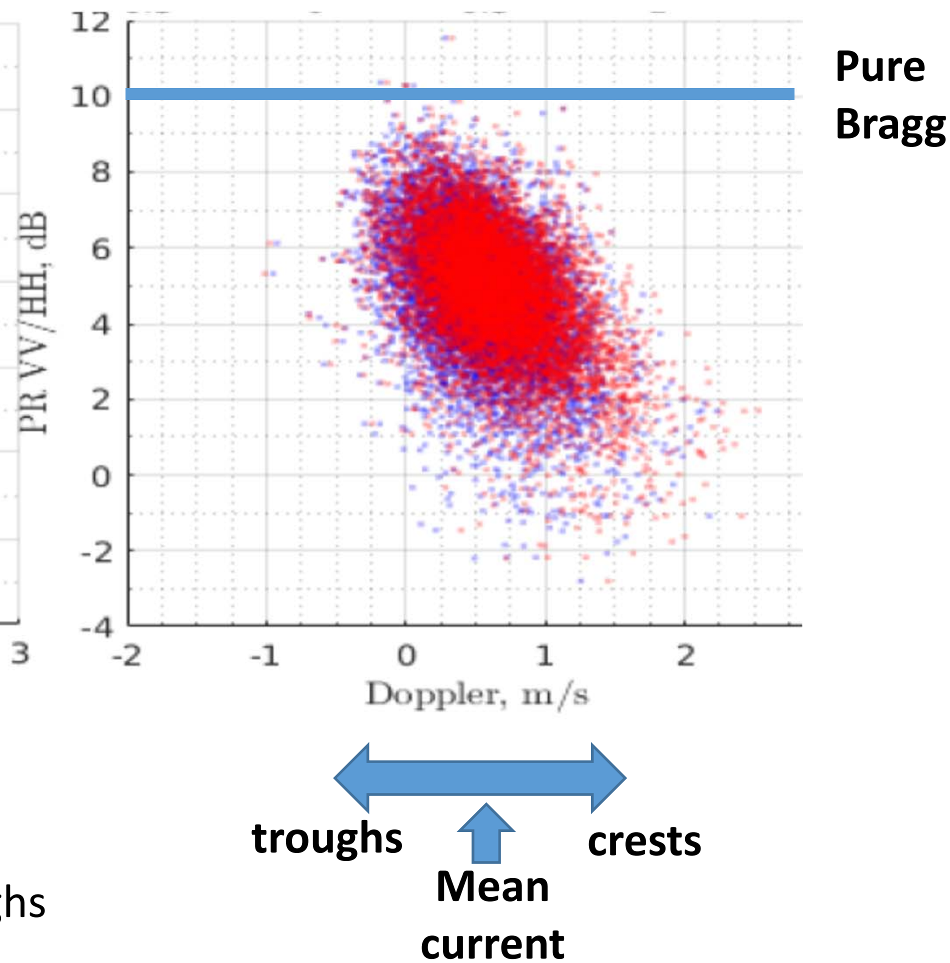
- Strong peaks of the NRCS occur in-phase with minima in the polarization ratio (PR), which occasionally drops down to $PR = 1$ (0 dB).
- Such weakly polarized events are associated with wave breaking, but surprisingly do not cause Doppler velocity spikes.
- An expected magnitude of such spikes is of the order of phase velocity of breaking wave. Because PR →1, such occasional strong breakers cover almost entire radar footprint of ~2m. The wavelength of carrying breaking wave should be at least 10 times of the footprint size, $\lambda \approx 20$m, that corresponds to the phase speed of 5 m/s.
- Apparently, the highest IDV values are well beyond that level. This suggests that *intrinsic breaker velocity is lower than the phase velocity of the carrying breaking wave*.
- Wave breaking contributes to the NRCS and is strongly modulated by the LW. Breaking instability develops on LW crests and propagates with its phase speed. *But once a breaking crest is broken, it generates disturbances that are embedded in water, and thus move with LW orbital velocity*.
- This observation is in contrast with the previous assumption employed in Doppler echo models that associate the intrinsic speed of breaker-related scattering facet with the phase speed of the breaking wave.

Scatter diagrams, U10=10m/s, upwind, incidence angle =53°

NRCS vs Doppler velocity



Polarization ratio vs Doppler velocity (DV)



- Mostly Bragg scattering from wave troughs
- Composite scattering from wave crests
- No wave breaking induced spikes in DV.
- Intrinsic speed of wave breaking facets is lower than LW phase speed

Doppler velocity parameterization (KaDop)

Satellite Doppler radar detects NRCS-weighted DV, $WDV = \bar{v} + \overline{v'\sigma'}/\bar{\sigma}$,
where $\bar{v}$ and $\bar{\sigma}$ are the time mean LOS Doppler velocity and NRCS, and v' and σ' are wave-induced fluctuations.

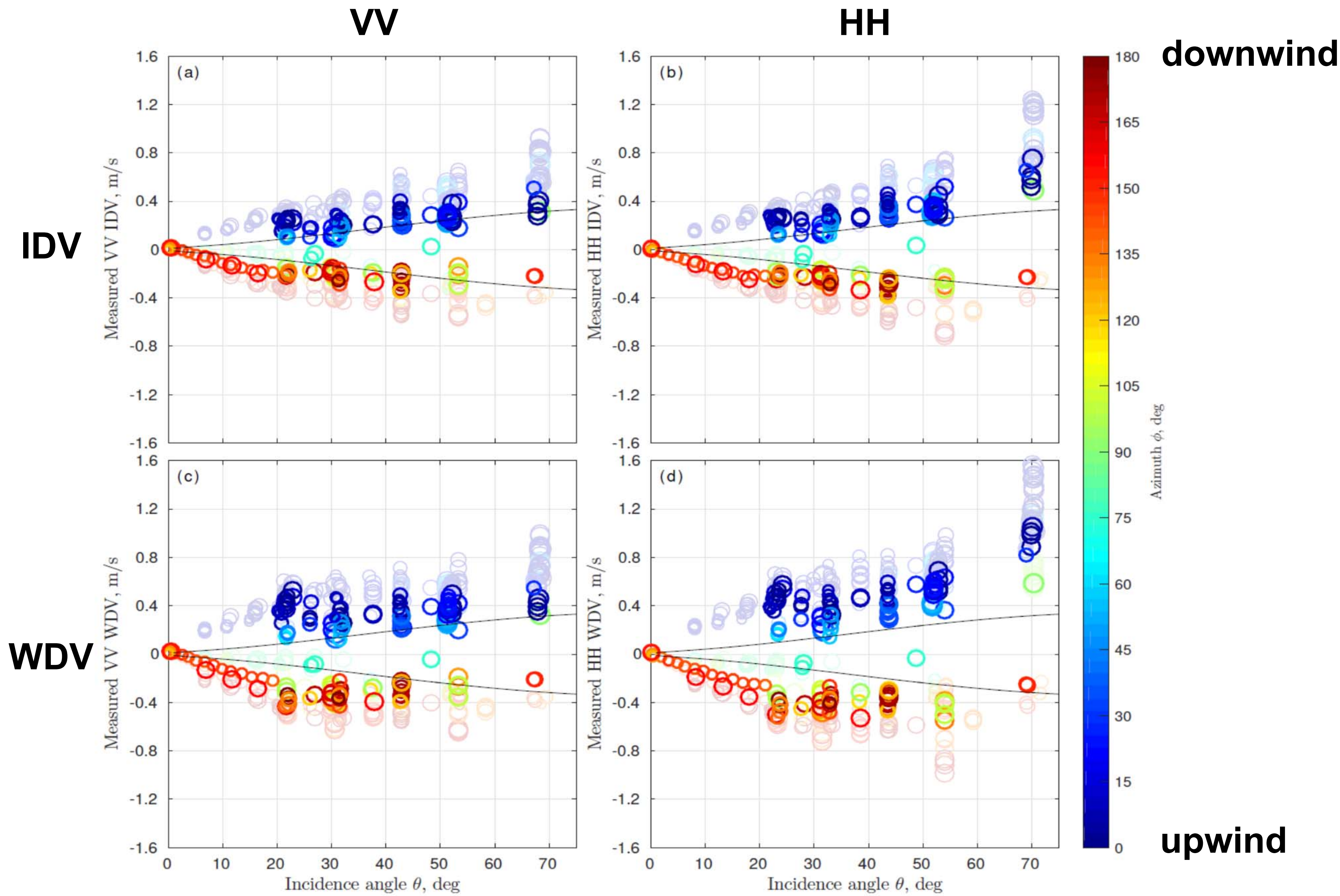
Instantaneous Doppler Velocity (IDV) measured by an ideal radar with infinitively narrow antenna pattern (a research platform-based radar), IDV=v+v'. Simple time mean, $\overline{IDV} = \bar{v}$, while NRCS-weighted time average, $\overline{v\sigma}/\bar{\sigma}$, is similar to satellite measurements.

Time mean IDV equals to the sum of surface current and time mean scatter velocity, $\bar{v} = u_s + c$. After removing the surface current from observed DV, the intrinsic scatter velocity is represented as, $c = c_{Bragg} + \Delta c$.

WDV=$(u_s \cos\varphi_u + c_{Br} \cos\varphi / |\cos\varphi|) \sin\theta + \Delta c$ +WIDV

The residual term, Δc, accounts for contributions of non-Bragg scattering and the averaging effect of antenna footprint. It primarily depends on observation geometry and is parametrized as polynomials of θ and φ. Dependence on the sea state (wind speed, etc) is omitted.

Instantaneous (IDV) and sigma-weighted (WDV) Doppler velocity for drift-corrected (solid symbols) and non-corrected (transparent symbols) estimates. Solid lines are $c_{br}\ sin\ \theta$. Colors correspond to radar-to-wind azimuth, symbol size ~ U10.



<u>W</u>ave-<u>I</u>nduced <u>D</u>oppler <u>V</u>elocity (WIDV=$\frac{\overline{\sigma' v'}}{\bar{\sigma}}$) parameterization

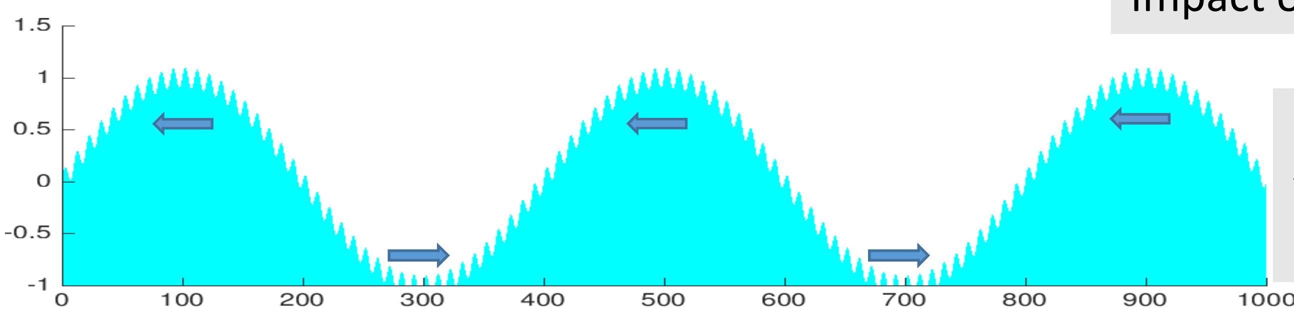
* NRCS variation, σ', is related to Long Wave (LW) elevation, ζ, via the traditional radar modulation transfer function (MTF): $M = \sigma'/(\bar{\sigma}K\zeta)$

* DV fluctuations produced by LW orbital velocity: $v' = G(\theta,\varphi)\Omega\zeta$, where $G = \cos\varphi \sin\theta + i\cos\theta$ is the geometric transformation coefficient projecting the wave orbital velocity onto the radar LOS direction.

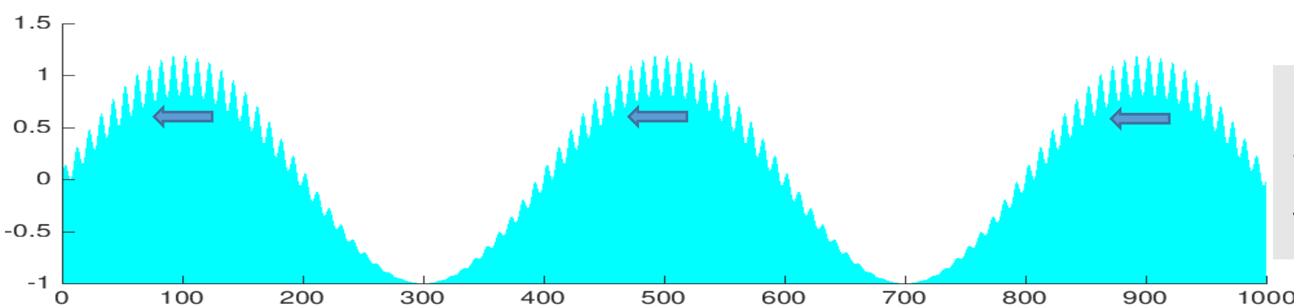
* WIDV is represented in terms of the MTF: $WIDV = \frac{\Omega}{\mathrm{gG}} Re\int MS_{vv}df$

* MTF is inferred from Doppler radar data: $M = \frac{S_{\sigma v}}{\bar{\sigma}S_{vv}}\frac{g}{\Omega}m^{0.5}G$

Impact of hydrodynamics MTF on WIDV

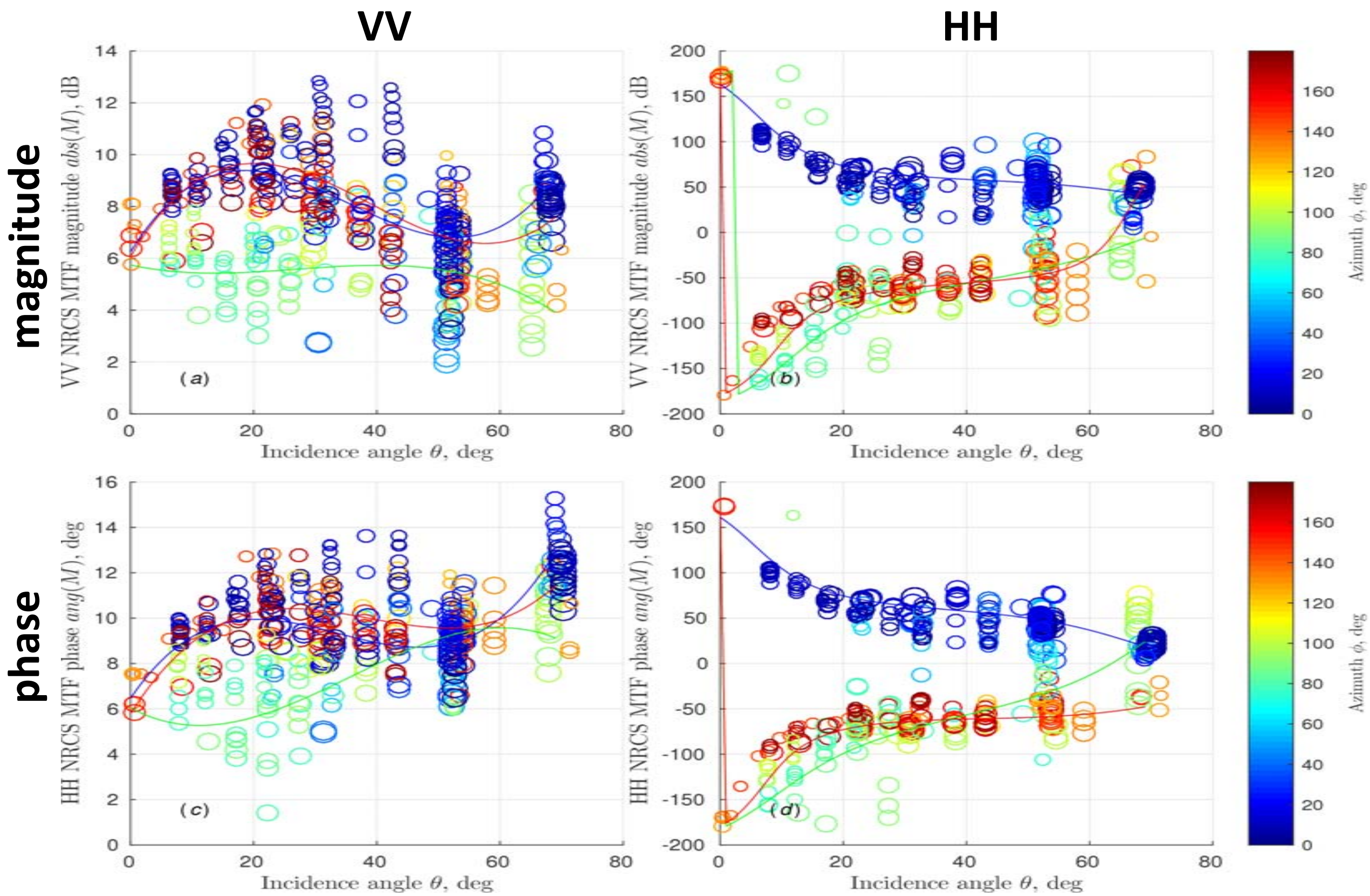


If ripple doesn't vary along long wave, the LW orbital velocities average out.



If ripple is present only on long wave crests, the WIDV~ orbital velocity~0.1*U10~1m/s.

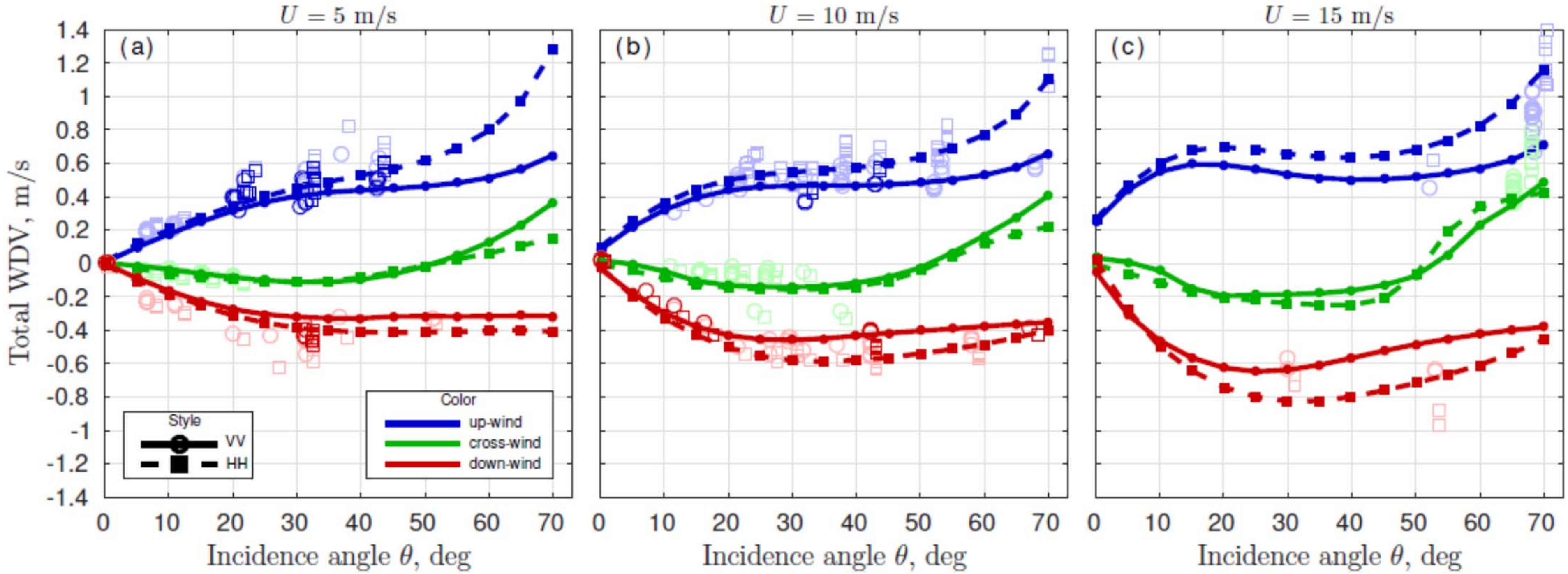
Measured magnitude and phase of Ka-band MTF



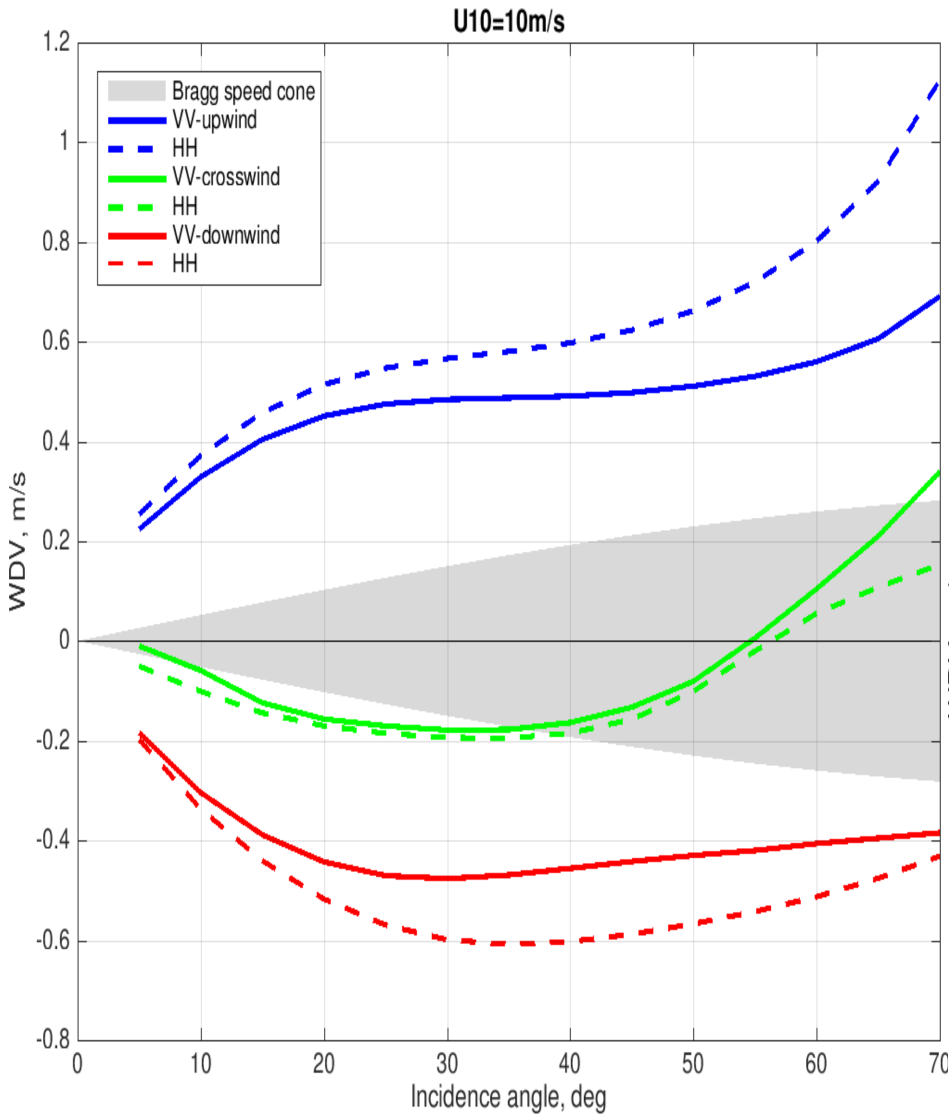
Symbol size ~U10, colors - radar-to-wind direction (blue –upwind). MTF is averaged over LW frequency range, $f_p < f < f_{cut}$. Cutoff corresponds to antenna ground footprint.

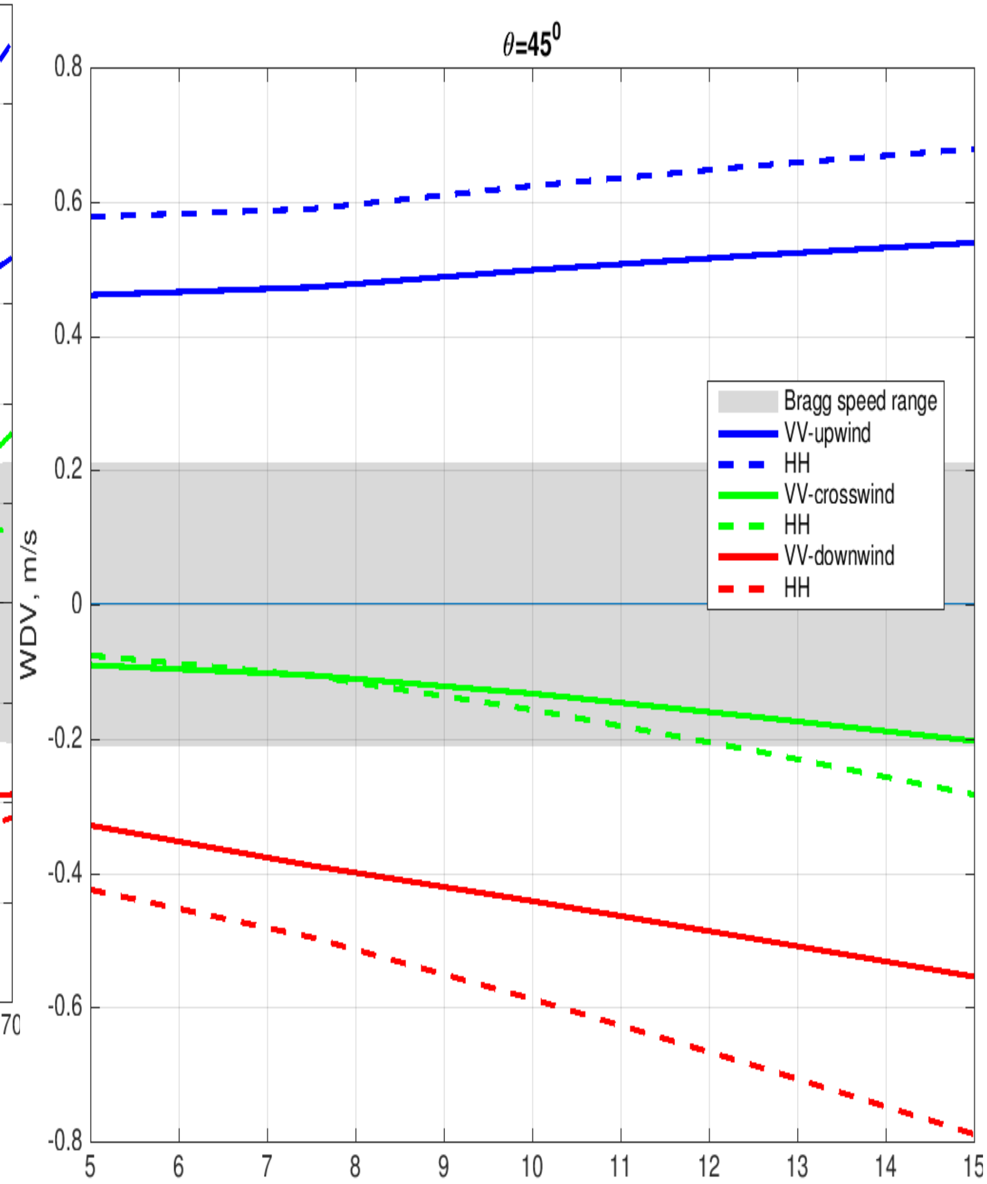
Observed MTF magnitude and phase are almost constant within LW frequency range from the wave peak to the cutoff scale (defined by antenna footprint size), $f_p < f < f_{cut}$. Magnitude and phase of MTF averaged over this frequency range are fitted by polynomials of θ, φ, and $\log U_{10}$. For given MTF, WIDV is calculated using the Toba (1973) spectrum.

KaDop and observed sigma-weighted Doppler velocity, WDV

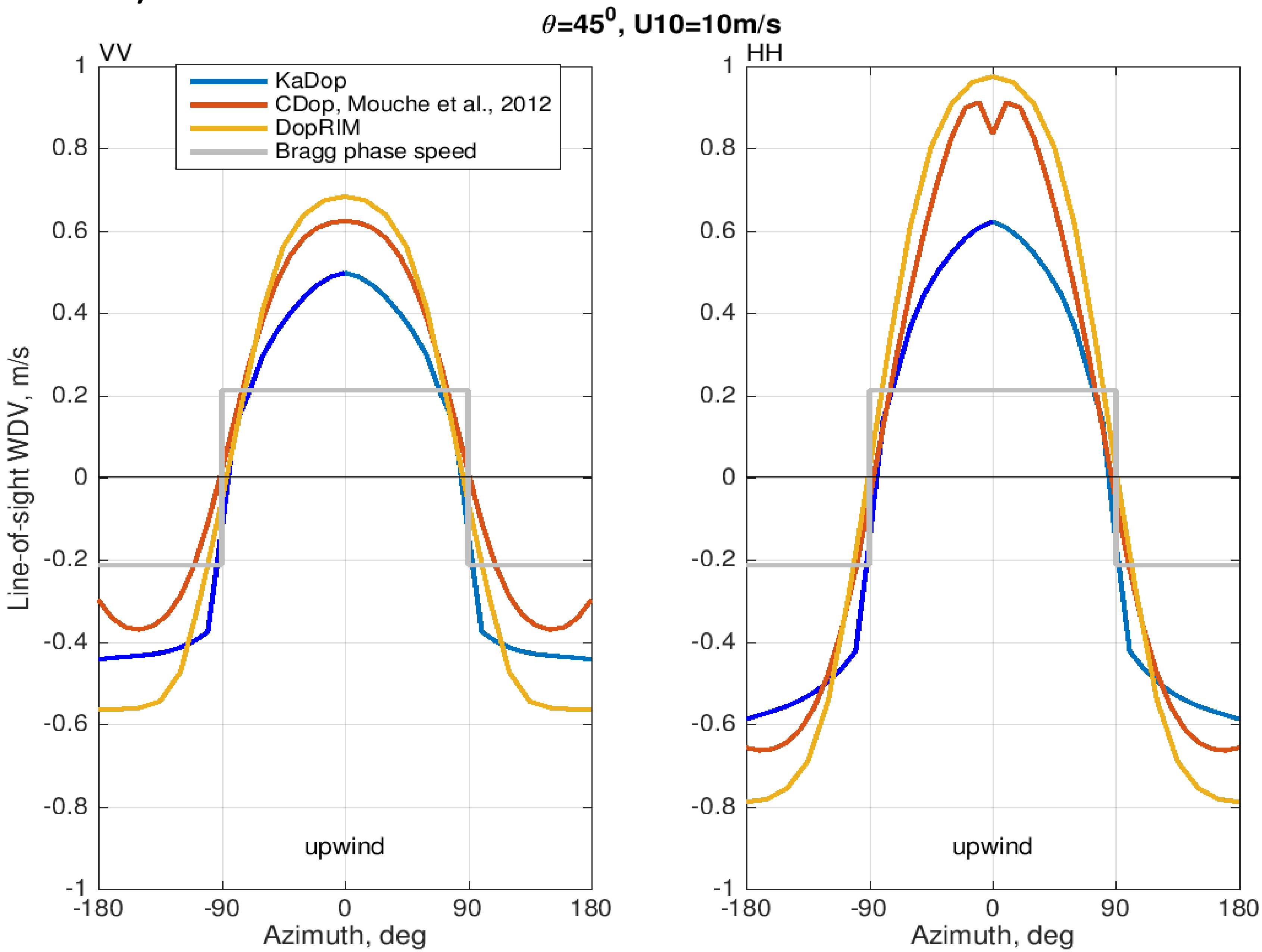


General characteristics of empirical KaDop.





Comparisons with empirical Cdop of Mouche et al. (2012) and DopRIM model (for Ka-band)



Summary and Questions

- Platform data provide both the Instantaneous (**IDV**) and the NRCS-Weighted (**WDV**) Doppler Velocity to distinguish between the mean scattering facet velocity and the Wave-Induced Doppler Velocity (**WIDV**). The WDV is a proxy for satellite measurements that are averaged over spatially large ground footprint.
- After subtracting the surface current, the time mean Ka-band IDV is close to c_{Br}. The difference from c_{Br} is parametrized as a function of observation geometry only.
- WIDV is parameterized in terms of the Modulation Transfer Function (MTF) that is derived from radar measurements using DV as a proxy for wave gauge. Ka-band WDV weakly depends on incidence angle and wind speed. Characteristic deviation of WDV from the line-of-sight Bragg speed is about 20-40 cm/s, which is parametrized as a function of observation geometry and wind speed (an empirical KaDop).
- Non-polarized scattering (PR~1) from sharp and fast breaking facets don’t pair with Doppler velocity spikes (order of the phase speed of breaking wave). Breaking instability develops on LW crests and propagates with its phase speed. *But once a breaking crest is broken, it generates disturbances that are embedded in water and propagate with LW orbital velocity*.

Summary and Questions (continued)

- KaDop needs verification against independent measurements.
- KaDop is based on wind sea (excluding swell). What is possible impact of swell?
- At given conditions and observation geometry, Ka-band KaDop predicts smaller Doppler velocity than C-band CDop. Why wave contribution to Ka-band Doppler velocity is weaker than that in the C-band?