Bistatic scattering from sea surfaces at non-near-specular direction via the Polarimetric Two-Scale Model for maritime surveillance with GNSS-R

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Outline

- ✓ Introduction and motivation
- ✓ Theory: PTSM
- ✓ Results
- ✓ Conclusions

Introduction and motivation

Recent increasing interest in the application of GNSS-R to the field of maritime surveillance and ship detection.

Examples:

- GNSS-R signals for maritime surveillance from fixed receivers located on the coast[1].
- detection of large structures over the ocean using U.K. TechDemoSat-1 delay-Doppler maps (DDMs)[2]

But

current spaceborne GNSS-R systems are not suited for ship detection applications.

[1]H. Ma, M. Antoniou, A. G. Stove, J. Winkel and M. Cherniakov, "Maritime Moving Target Localization Using Passive GNSS-Based Multistatic Radar," in IEEE Transactions on Geoscience and Remote Sensing, vol. 56, no. 8, pp. 4808-4819, Aug. 2018.

[2]A. Di Simone, H. Park, D. Riccio, and A. Camps, "Sea target detection using spaceborne GNSS-R delay-Doppler maps: Theory and experimental proof of concept using TDS-1 data," *IEEE J. Sel. Topics Appl. Earth Observ.*, **10**, 9, pp. 4237-4255 (2017).

Introduction and motivation

Current spaceborne GNSS-R systems have been conceived for sea state monitoring:

Sufficient SNR → receiver designed to acquire from the specular or near-specular area on the sea

For ship detection this is the worst situation: low signal-to-clutter , low resolution

non-near-specular acquisition geometry would be desirable!

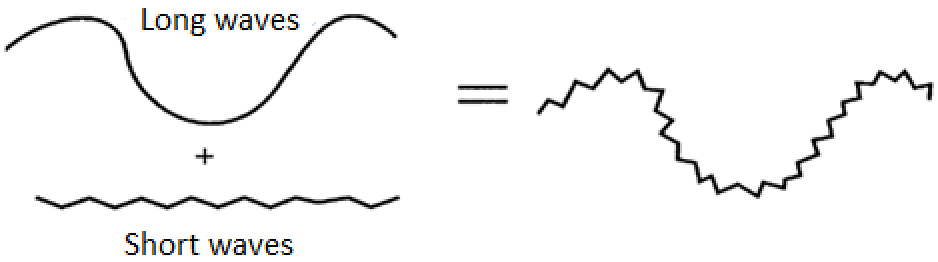
To be assessed via simulation: scattering models for ship and sea surface

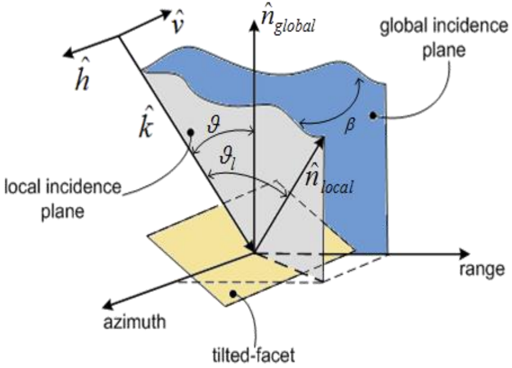
Scattering from the sea at non-near-specular direction: Two-Scale Model

Closed form available in backscattering. Here: extension to bistatic scattering

Theory: PTSM

Two-Scale Model (TSM)





Total NRCS = large scale roughness NRCS (computed via GO) + small scale roughness NRCS (computed via SPM)

The GO term dominates at near-specular directions, the SPM term dominates at non-near-specular directions

Range of validity: union of GO and SPM ones.

no cross-pol and de-pol unless SPM term is averaged over random slopes of tilted mean plane

Average over slopes –> numerical integration!

J. W. Wright, "A New Model for Sea Clutter", *IEEE Trans. Antennas Propagat.*, vol. 16, pp. 217-223, 1968.
G. R. Valenzuela, "Scattering of Electromagnetic Waves from a Tilted Slightly Rough Surface", *Radio Sci.*, vol. 3, pp. 1057-1066, 1968.

Theory: PTSM

- Recently[1] we showed how to analytically compute in closed form the average integral, with a moderate slope approximation, in the backscattering case, so introducing the Polarimetric Two-Scale Model (PTSM)
- PTSM allows accounting for cross- and de-polarisation effects actually present in measured data even when surface scattering is the only present mechanism.
- Based on it, we devised a soil moisture retrieval scheme for bare soils, making use of the SAR measured copol and crosspol ratios[1] (or copol ratio and correlation coefficient[2])
- Generalization to the bistatic case (and to sea surface) is needed.

[1] A. Iodice, A. Natale, D. Riccio, "Retrieval of Soil Surface Parameters via a Polarimetric Two-Scale Model", *IEEE Trans. Geosci. Remote Sens.* vol. 49, no. 7, pp. 2531-2547, July 2011.

[2] A. Iodice, A. Natale, D. Riccio, "Polarimetric Two-Scale Model for Soil Moisture Retrieval via Dual-Pol HH-VV SAR Data", *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.* vol. 11, no. 3, pp. 1163-1171, June 2013.

Theory: PTSM

Surface description

1) Small-scale roughness PSD: directional Elfouhaily spectrum $W_{2D}(\kappa,\varphi) = W(\kappa)\Phi(\kappa,\varphi)$

$$W(\kappa) = \frac{\pi \alpha_m c_m}{c\,\kappa^4} \exp\left[-\frac{1}{4}\left(\frac{\kappa}{\kappa_m} - 1\right)^2 \right] \cong \frac{S_0}{\kappa^{3.5}}$$

$$\Phi(\kappa,\varphi) = 1 + \Delta(\kappa)\cos\left[2(\varphi_w - \varphi)\right]$$

2) Large-scale roughness slopes, s_x and s_y: correlated zero-mean jointly Gaussian variables

$$s_x\ ,\ s_y \sim N\left(0;\sigma_x^2,\sigma_y^2,\rho\right)$$

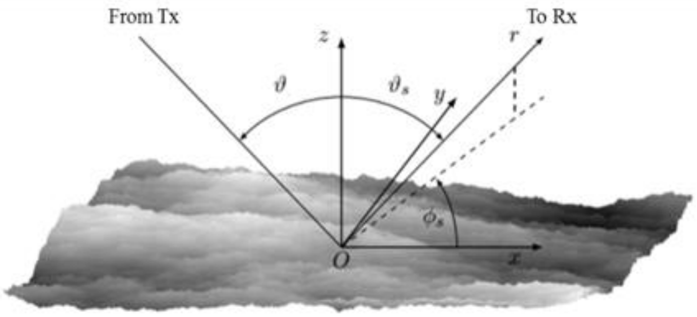
$$\sigma_{up}^2 = 0.45\left[0.00316 \cdot 6\ln(u_{10})\right]$$

$$\sigma_{cross}^2 = 0.45\left[0.003 + 0.00192 \cdot 6\ln(u_{10})\right]$$

$$\sigma_x^2 = \sigma_{up}^2 \cos^2\varphi_w + \sigma_{cross}^2 \sin^2\varphi_w$$

$$\sigma_y^2 = \sigma_{cross}^2 \cos^2\varphi_w + \sigma_{up}^2 \sin^2\varphi_w$$

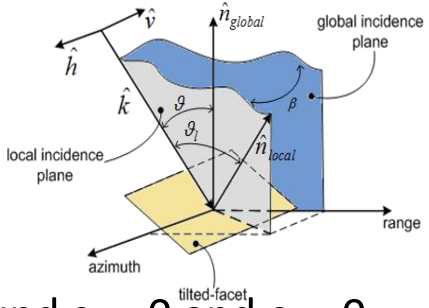
$$\rho = \frac{1}{2}\sin 2\varphi_w \frac{\sigma_{cross}^2 - \sigma_{up}^2}{\sigma_r \sigma_a}$$



Isotropic approximation: $\Phi(\kappa,\varphi) \cong 1 \qquad \sigma_x = \sigma_y = \dfrac{\sigma_{up} + \sigma_{cross}}{2} \ ,\ \rho = 0$

Theory: PTSM

1) Compute tilted surface's polarimetric covariance matrix via SPM in terms of the local incidence ϑ_{li} and scattering ϑ_{ls}, φ_{ls} angles, and of rotation angles β_i and β_s of incidence and scattering planes



2) Express ϑ_{li}, ϑ_{ls}, φ_{ls}, β_i and β_s in terms of global incidence ϑ_i and scattering ϑ_s, φ_s angles and of local surface slopes s_x and s_y

3) Second order expansion of tilted surface's covariance matrix around $s_x = 0$ and $s_y = 0$

4) Averaging tilted surface's NRCS and other entries of the covariance matrix over s_x and s_y by using: $\langle s_x \rangle = \langle s_y \rangle = 0$, $\langle s_x^2 \rangle = \sigma_x^2$, $\langle s_y^2 \rangle = \sigma_y^2$, and $\langle s_x s_y \rangle = \rho \sigma_x \sigma_y$

Expressions for ϑ_{li} and β_i are already available, while those for ϑ_{ls}, φ_{ls} and β_s are an original contribution of this work

Theory: PTSM

$$\cos\vartheta_{li} = \frac{\cos\vartheta_i + s_x \sin\vartheta_i}{\sqrt{1 + {s_x}^2 + {s_y}^2}} \qquad \tan\beta_i = \frac{s_y}{-s_x \cos\vartheta_i + \sin\vartheta_i}$$

$$\cos\vartheta_{ls} = \frac{-s_y \sin\vartheta_s \sin\varphi_s - s_x \sin\vartheta_s \cos\varphi_s + \cos\vartheta_s}{\sqrt{1 + s_x^2 + s_x^2}}$$

$$\cos\varphi_{ls} =$$

$$\frac{(\sin\vartheta_i - s_x\cos\vartheta_i)(\sin\vartheta_s\cos\varphi_s + s_x\cos\vartheta_s) + s_y\cos\vartheta_i(-s_y\cos\vartheta_s - \sin\vartheta_s\sin\varphi_s) + s_y\sin\vartheta_i(-s_x\sin\vartheta_s\sin\varphi_s + s_y\sin\vartheta_s\cos\varphi_s)}{\sqrt{(\sin\vartheta_i - s_x\cos\vartheta_i)^2 + {s_y}^2}\cdot\sqrt{(\sin\vartheta_s\cos\varphi_s + s_x\cos\vartheta_s)^2 + (-s_y\cos\vartheta_s - \sin\vartheta_s\sin\varphi_s)^2 + (-s_x\sin\vartheta_s\sin\varphi_s + s_y\sin\vartheta_s\cos\varphi_s)^2}}$$

$$\tan\beta_s = \frac{s_y\cos\varphi_s - s_x\sin\varphi_s}{s_y\cos\vartheta_s\sin\varphi_s + s_x\cos\vartheta_s\cos\varphi_s + \sin\vartheta_s}$$

Theory: PTSM

Linear polarization basis

$$
\begin{cases}
\langle R_{hhhh}\rangle|_{sx,sy} = C_{0,0}^{hhhh} + \sigma^2\left[C_{0,2}^{hhhh} + C_{2,0}^{hhhh} + \dfrac{C_{0,0}^{vhvh} - C_{0,0}^{hhhh}}{\sin^2\vartheta_s} + \dfrac{C_{0,0}^{hvhv} - C_{0,0}^{hhhh}}{\sin^2\vartheta_i} + \dfrac{2\cos\varphi_s\left(Re\{C_{0,0}^{hhvv}\} + Re\{C_{0,0}^{hvvh}\}\right)}{\sin\vartheta_s\sin\vartheta_i}\right] \\
\langle R_{vvvv}\rangle|_{sx,sy} = C_{0,0}^{vvvv} + \sigma^2\left[C_{0,2}^{vvvv} + C_{2,0}^{vvvv} + \dfrac{C_{0,0}^{hvhv} - C_{0,0}^{vvvv}}{\sin^2\vartheta_s} + \dfrac{C_{0,0}^{vhvh} - C_{0,0}^{vvvv}}{\sin^2\vartheta_i} + \dfrac{2\cos\varphi_s\left(Re\{C_{0,0}^{hhvv}\} + Re\{C_{0,0}^{hvvh}\}\right)}{\sin\vartheta_i\sin\vartheta_s}\right] \\
\langle R_{hvhv}\rangle|_{sx,sy} = C_{0,0}^{hvhv} + \sigma^2\left[C_{0,2}^{hvhv} + C_{2,0}^{hvhv} + \dfrac{C_{0,0}^{hhhh} - C_{0,0}^{hvhv}}{\sin^2\vartheta_i} + \dfrac{C_{0,0}^{vvvv} - C_{0,0}^{hvhv}}{\sin^2\vartheta_s} - \dfrac{2\cos\varphi_s\left(Re\{C_{0,0}^{hhvv}\} + Re\{C_{0,0}^{hvvh}\}\right)}{\sin\vartheta_i\sin\vartheta_s}\right] \\
\langle R_{vhvh}\rangle|_{sx,sy} = C_{0,0}^{vhvh} + \sigma^2\left[C_{0,2}^{vhvh} + C_{2,0}^{vhvh} + \dfrac{C_{0,0}^{vvvv} - C_{0,0}^{vhvh}}{\sin^2\vartheta_i} + \dfrac{C_{0,0}^{hhhh} - C_{0,0}^{vhvh}}{\sin^2\vartheta_s} - \dfrac{2\cos\varphi_s\left(Re\{C_{0,0}^{hhvv}\} + Re\{C_{0,0}^{hvvh}\}\right)}{\sin\vartheta_i\sin\vartheta_s}\right] \\
\langle R_{hhvv}\rangle|_{sx,sy} = C_{0,0}^{hhvv} + \sigma^2\left[C_{0,2}^{hhvv} + C_{2,0}^{hhvv} - \dfrac{C_{0,0}^{hvvh} + C_{0,0}^{hhvv}}{\sin^2\vartheta_i} - \dfrac{C_{0,0}^{vhhv} + C_{0,0}^{hhvv}}{\sin^2\vartheta_s} + \dfrac{\cos\varphi_s\left(C_{0,0}^{hhhh} - C_{0,0}^{hvhv} - C_{0,0}^{vhvh} + C_{0,0}^{vvvv}\right)}{\sin\vartheta_i\sin\vartheta_s}\right] \\
\langle R_{hvvh}\rangle|_{sx,sy} = C_{0,0}^{hvvh} + \sigma^2\left[C_{0,2}^{hvvh} + C_{2,0}^{hvvh} + \dfrac{C_{0,0}^{hhvv} - C_{0,0}^{hvvh}}{\sin^2\vartheta_i} + \dfrac{C_{0,0}^{vvhh} - C_{0,0}^{hvvh}}{\sin^2\vartheta_s} + \dfrac{\cos\varphi_s\left(C_{0,0}^{hhhh} - C_{0,0}^{vhvh} - C_{0,0}^{hvhv} + C_{0,0}^{vvvv}\right)}{\sin\vartheta_i\sin\vartheta_s}\right] \\
\langle R_{hhhv}\rangle|_{sx,sy} = C_{0,0}^{hhhv} + \sigma^2\left[C_{0,2}^{hhhv} + C_{2,0}^{hhhv} + \dfrac{-C_{0,0}^{hvhh} - C_{0,0}^{hhhv}}{\sin^2\vartheta_i} + \dfrac{C_{0,0}^{vhvv} - C_{0,0}^{hhhv}}{\sin^2\vartheta_s} + \dfrac{\cos\varphi_s\left(C_{0,0}^{hvvv} - C_{0,0}^{hhvh} - C_{0,0}^{vhhh} + C_{0,0}^{vvhv}\right)}{\sin\vartheta_i\sin\vartheta_s}\right] \\
\langle R_{vvhv}\rangle|_{sx,sy} = C_{0,0}^{vvhv} + \sigma^2\left[C_{0,2}^{vvhv} + C_{2,0}^{vvhv} + \dfrac{C_{0,0}^{vhhh} - C_{0,0}^{vvhv}}{\sin^2\vartheta_i} + \dfrac{-C_{0,0}^{hvvv} - C_{0,0}^{vvhv}}{\sin^2\vartheta_s} + \dfrac{\cos\varphi_s\left(C_{0,0}^{hhhv} - C_{0,0}^{vhvv} - C_{0,0}^{vvvh} + C_{0,0}^{hvhh}\right)}{\sin\vartheta_i\sin\vartheta_s}\right]
\end{cases}
$$

$$
\begin{cases}
F_{hh} = \dfrac{(\varepsilon_r - 1)\cos\varphi_s}{\left(\cos\varphi_s + \sqrt{\varepsilon_r - \sin^2\vartheta_s}\right)\left(\cos\vartheta_i + \sqrt{\varepsilon_r - \sin^2\vartheta_i}\right)} \\
F_{hv} = \dfrac{\sin\varphi_s\left[(\varepsilon_r - 1)\left(\sqrt{\varepsilon_r - \sin^2\vartheta_s}\right)\right]}{\left(\sqrt{\varepsilon_r - \sin^2\vartheta_s} + \varepsilon_r\cos\vartheta_s\right)\left(\cos\vartheta_i + \sqrt{\varepsilon_r - \sin^2\vartheta_i}\right)} \\
F_{vh} = \dfrac{\sin\varphi_s\left[(\varepsilon_r - 1)\left(\sqrt{\varepsilon_r - \sin^2\vartheta_i}\right)\right]}{\left(\sqrt{\varepsilon_r - \sin^2\vartheta_i} + \varepsilon_r\cos\vartheta_i\right)\left(\cos\vartheta_s + \sqrt{\varepsilon_r - \sin^2\vartheta_s}\right)} \\
F_{vv} = \dfrac{(\varepsilon_r - 1)\left[\sqrt{\varepsilon_r - \sin^2\vartheta_i}\sqrt{\varepsilon_r - \sin^2\vartheta_s}\cos\varphi_s - \varepsilon_r\sin\vartheta_i\sin\vartheta_s\right]}{\left(\varepsilon_r\cos\vartheta_s + \sqrt{\varepsilon_r - \sin^2\vartheta_s}\right)\left(\varepsilon_r\cos\vartheta_i + \sqrt{\varepsilon_r - \sin^2\vartheta_i}\right)}
\end{cases}
$$

$$
C_{k,n-k}^{pqrs} = \frac{1}{n!}\binom{n}{k}\left.\frac{\partial^2\left(Wk^4\cos^2\vartheta_{li}\cos^2\vartheta_{ls}F_{pq}F_{rs}^*\right)}{\partial a^k\partial b^{n-k}}\right|_{sx=sy=0}
$$

Theory: PTSM

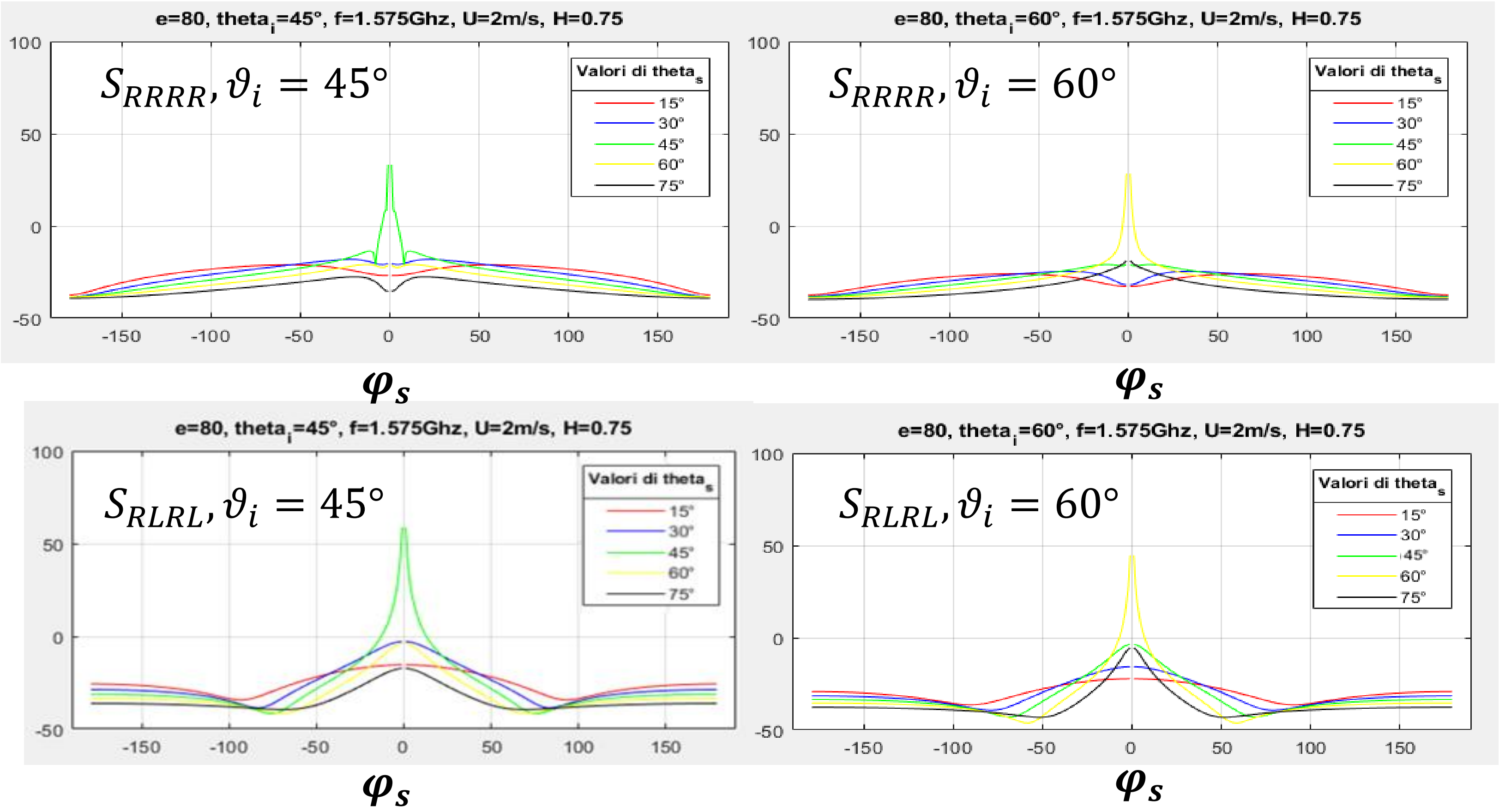
Circular polarization basis

$$
\begin{cases}
F_{RR} = (F_{hh} - F_{vv} + iF_{hv} + iF_{vh})/2 \\
F_{LL} = (F_{vv} - F_{hh} + iF_{hv} + iF_{vh})/2 \\
F_{RL} = (iF_{hh} + iF_{vv} + F_{hv} - F_{vh})/2 \\
F_{LR} = (iF_{hh} + iF_{vv} - F_{hv} + F_{vh})/2
\end{cases}
$$

$$
\begin{cases}
|\chi_{RR}|^2 = \frac{1}{4}(|F_{hh}|^2 + |F_{vv}|^2 + |F_{hv}|^2 + |F_{vh}|^2 - 2Re\{F_{hh}F_{vv}^*\} + 2Re\{F_{hv}F_{vh}^*\} + 2Im\{F_{hh}F_{hv}^*\} + 2Im\{F_{hh}F_{vh}^*\} - 2Im\{F_{vv}F_{hv}^*\} - 2Im\{F_{vv}F_{vh}^*\}) \\
|\chi_{RL}|^2 = \frac{1}{4}(|F_{hh}|^2 + |F_{vv}|^2 + |F_{hv}|^2 + |F_{vh}|^2 + 2Re\{F_{hh}F_{vv}^*\} - 2Re\{F_{hv}F_{vh}^*\} - 2Im\{F_{hh}F_{hv}^*\} + 2Im\{F_{hh}F_{vh}^*\} - 2Im\{F_{vv}F_{hv}^*\} + 2Im\{F_{vv}F_{vh}^*\}) \\
\chi_{RR}\chi_{LL}^* = \frac{1}{4}(-|F_{hh}|^2 - |F_{vv}|^2 + |F_{hv}|^2 + |F_{vh}|^2 + 2Re\{F_{hh}F_{vv}^*\} + 2Re\{F_{hv}F_{vh}^*\} - 2iRe\{F_{hh}F_{hv}^*\} - 2iRe\{F_{hh}F_{vh}^*\} + 2iRe\{F_{vv}F_{hv}^*\} + 2iRe\{F_{vv}F_{vh}^*\})e^{-i2(\beta_i+\beta_s)} \\
\chi_{RL}\chi_{LR}^* = \frac{1}{4}(|F_{hh}|^2 + |F_{vv}|^2 - |F_{hv}|^2 - |F_{vh}|^2 + 2Re\{F_{hh}F_{vv}^*\} + 2Re\{F_{hv}F_{vh}^*\} - 2iRe\{F_{hh}F_{hv}^*\} + 2iRe\{F_{hh}F_{vh}^*\} - 2iRe\{F_{vv}F_{hv}^*\} + 2iRe\{F_{vv}F_{vh}^*\})e^{i2(\beta_i-\beta_s)} \\
\chi_{RR}\chi_{RL}^* = \frac{1}{4}(-i|F_{hh}|^2 + i|F_{vv}|^2 + i|F_{hv}|^2 - i|F_{vh}|^2 + 2Im\{F_{hh}F_{vv}^*\} + 2Im\{F_{hv}F_{vh}^*\} + 2Re\{F_{hh}F_{hv}^*\} - 2iIm\{F_{hh}F_{vh}^*\} - 2iIm\{F_{vv}F_{hv}^*\} + 2Re\{F_{vv}F_{vh}^*\})e^{-i2\beta_i} \\
\chi_{RR}\chi_{LR}^* = \frac{1}{4}(-i|F_{hh}|^2 + i|F_{vv}|^2 - i|F_{hv}|^2 + i|F_{vh}|^2 + 2Im\{F_{hh}F_{vv}\} - 2Im\{F_{hv}F_{vh}\} - 2iIm\{F_{hh}F_{hv}^*\} + 2Re\{F_{hh}F_{vh}^*\} + 2Re\{F_{vv}F_{hv}^*\} - 2iIm\{F_{vv}F_{vh}^*\})e^{-i2\beta_s} \\
\chi_{RL}\chi_{RR}^* = \frac{1}{4}(i|F_{hh}|^2 - i|F_{vv}|^2 - i|F_{hv}|^2 + i|F_{vh}|^2 + 2Im\{F_{hh}F_{vv}^*\} + 2Im\{F_{hv}F_{vh}^*\} + 2Re\{F_{hh}F_{hv}^*\} + 2iIm\{F_{hh}F_{vh}^*\} + 2iIm\{F_{vv}F_{hv}^*\} + 2Re\{F_{vv}F_{vh}^*\})e^{i2\beta_i} \\
\chi_{RL}\chi_{LL}^* = \frac{1}{4}(-i|F_{hh}|^2 + i|F_{vv}|^2 - i|F_{hv}|^2 + i|F_{vh}|^2 - 2Im\{F_{hh}F_{vv}^*\} + 2Im\{F_{hv}F_{vh}^*\} + 2iIm\{F_{hh}F_{hv}^*\} - 2Re\{F_{hh}F_{vh}^*\} - 2Re\{F_{vv}F_{hv}^*\} + 2iIm\{F_{vv}F_{vh}^*\})e^{-i2\beta_s}
\end{cases}
$$

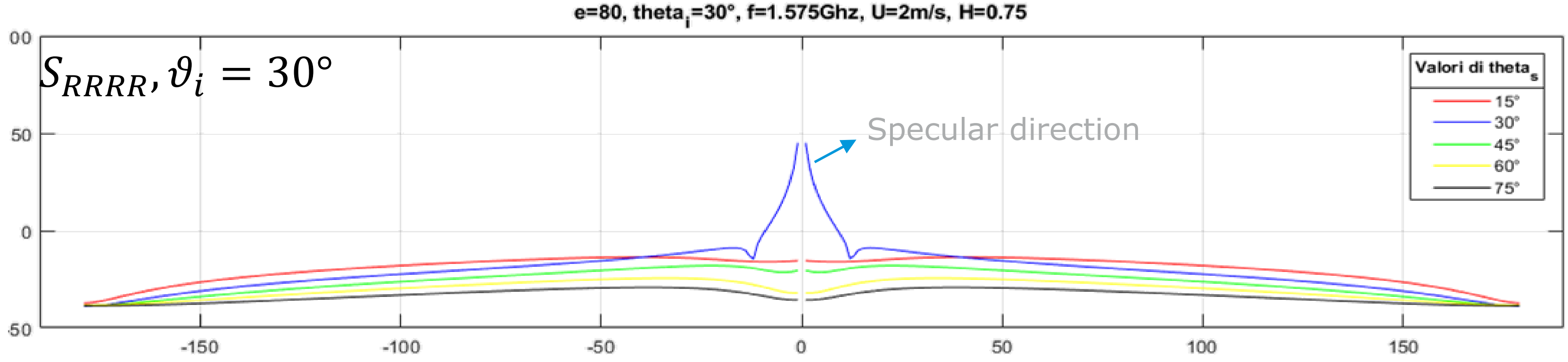
Results

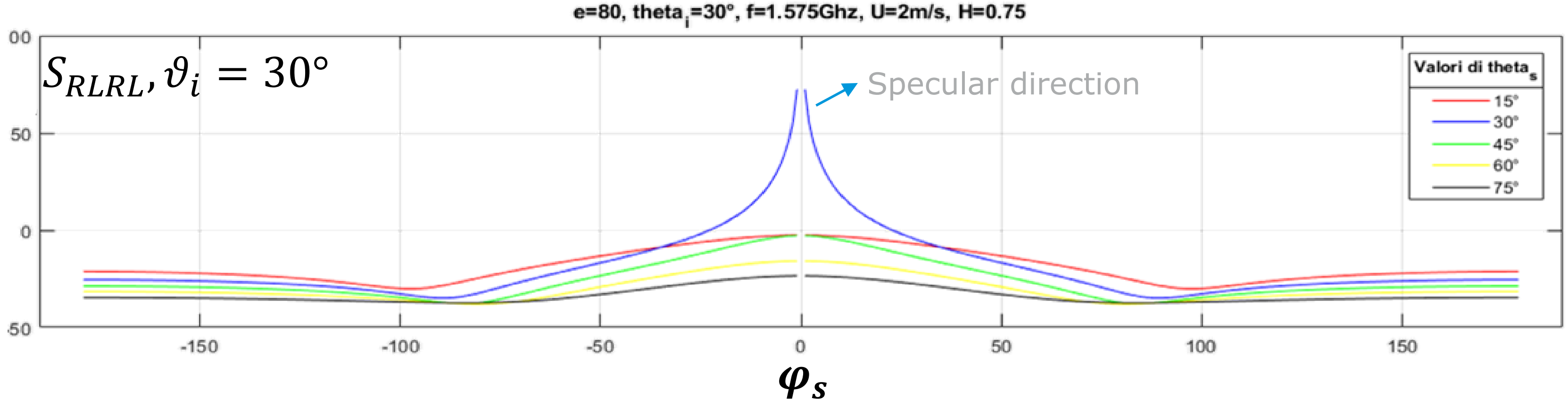
Bistatic NRCS vs φ_s (isotropic sea)



Results

Bistatic NRCS vs φ_s (isotropic sea)

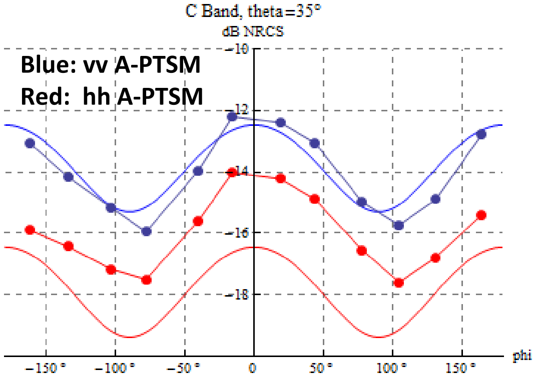


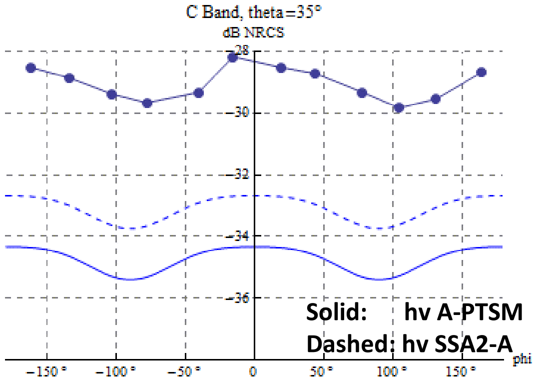


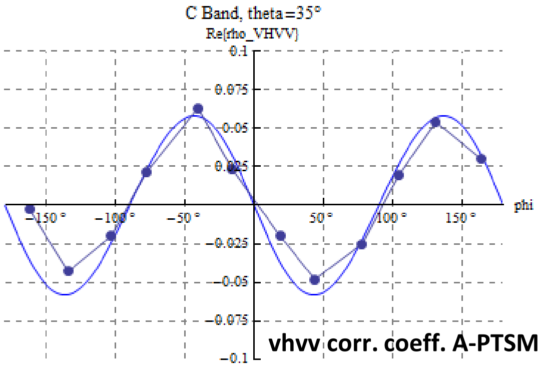
Results

Monostatic NRCS vs φ_w (anisotropic sea) C band u_{10} = 10 m/s theta=35°

Connected dots: experimental data







To be compared to Fig. 5 of Ref. SSA2, see below

SSA2: A. G. Voronovich and V. U. Zavorotny, "Full-polarization modeling of monostatic and bistatic radar scattering from a rough sea surface", *IEEE Trans. Antennas Propagat.*, vol. 62, no. 3, pp. 1362–1371, March 2014.

SSA2-A: C. A. Guérin and J. T. Johnson, "A simplified formulation for rough surface cross-polarized backscattering under the second-order small-slope approximation", *IEEE Trans. Geosc. Remote Sens.*, vol. 53, no. 11, pp. 6308–6314, Nov 2015.

Conclusions

- Closed-form PTSM extended to the bistatic case (B-PTSM) and applied to scattering from the sea surface
- All elements of the polarimetric covariance matrix analytically expressed in closed form, both in the linear and in the circular polarization bases

- In backscattering: Very good agreement with numerically evaluated TSM, Reasonable agreement with SSA2 and experimental data, except for HV NRCS (as expected)

- To be done: validation vs real scattering data for the fully bistatic case, implementation in a simulation tool

Thank you for your attention