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Polarimetric Two-Scale Model for Rough Surface Bistatic Scattering Evaluation

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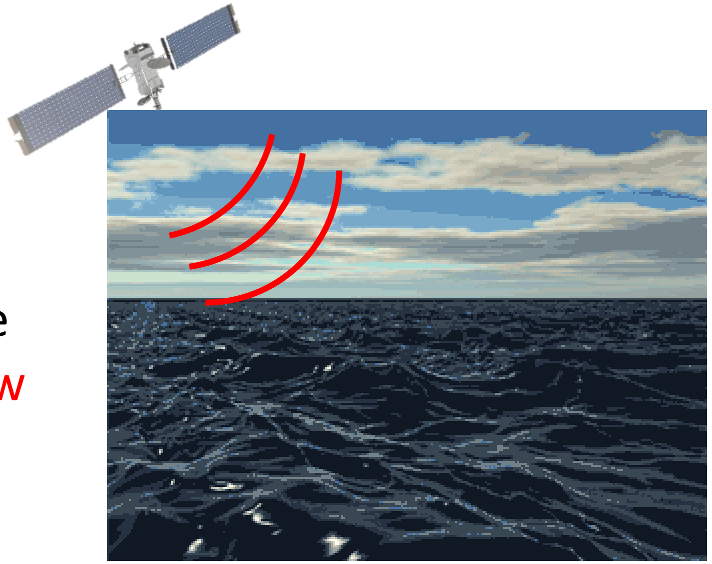
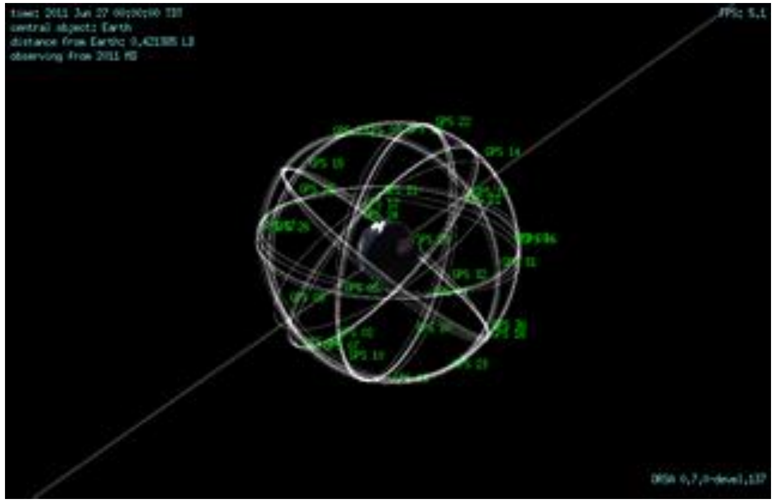
Introduction and motivation

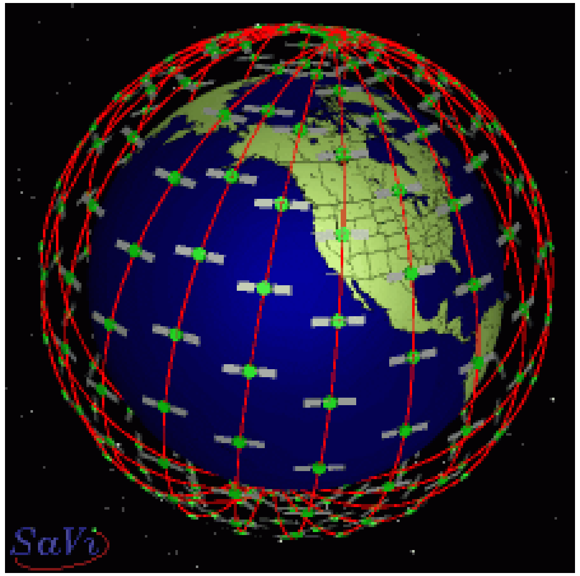
- Microwave sea observations are of fundamental importance, since they allow retrieving parameters of the sea and of objects on the sea surface.





- In recent years the interest in GNSS reflectometry (GNSS-R) is increasing, due to the promise of low revisit times and low costs.

- For similar reasons, low-orbit small-satellite constellations have become a hot research topic, too



- Appropriate electromagnetic models are required to design the system, assess its performance through simulation tools, and to support the development of adequate inversion techniques.

Introduction and motivation

What surface model?

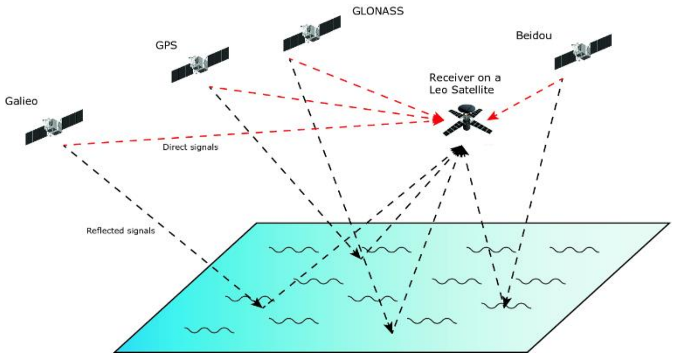
Sea surface

Anisotropic roughness

What scattering model?

GNSS or constellation

Bistatic scattering



What applications?

Sea state

Specular or near specular acquisition geometry

Object detection

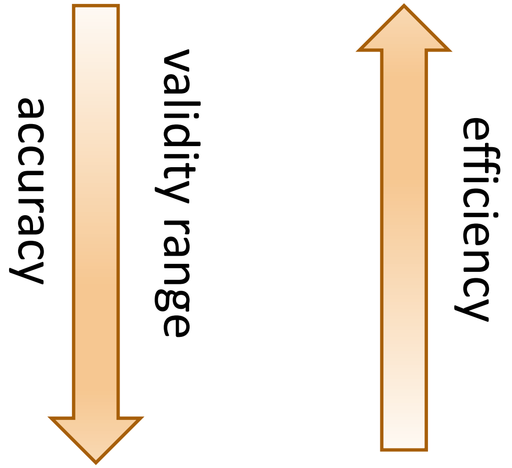
Far from specular acquisition geometry

Wide range of scattering angles

Introduction and motivation

Models for scattering from natural (randomly rough) surfaces

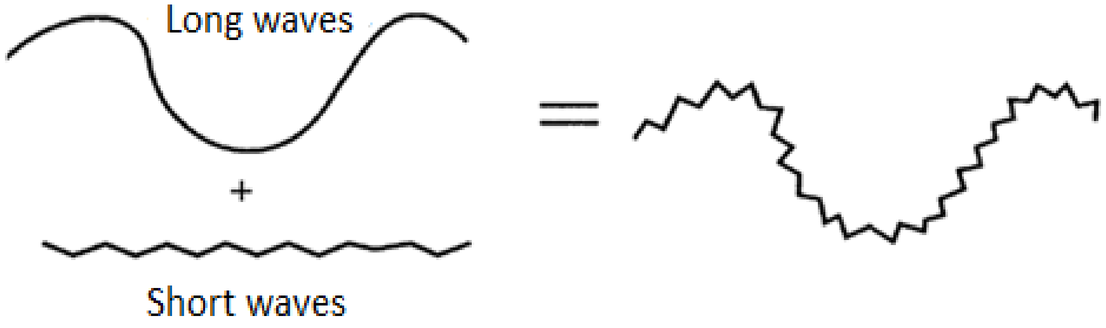
- Approximate analytical, closed-form (SPM, GO, empyrical)
- Approximate analytical/numerical (TSM, SPM2, SSA, SSA2)
- “Exact” fully numerical (MoM + Monte Carlo simulation)



TSM is widely used to model the scattering from the sea surface

Introduction and motivation

Two-Scale Model (TSM)



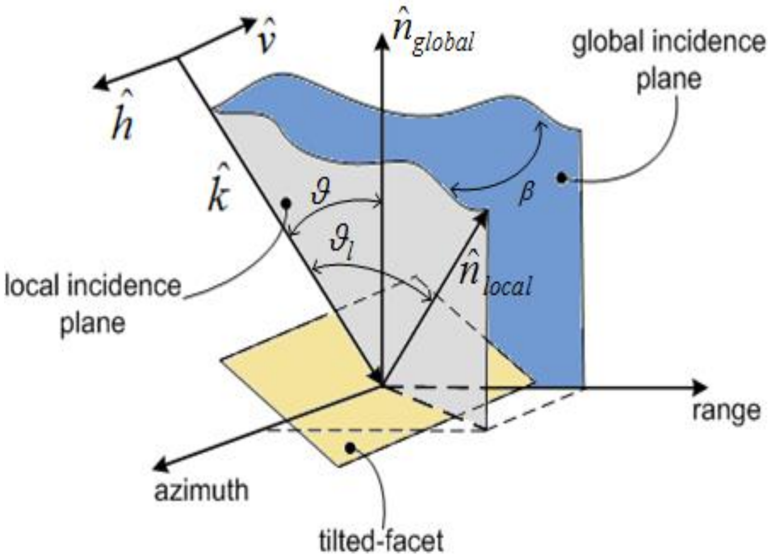
Total NRCS = large scale roughness NRCS (computed via GO) + small scale roughness NRCS (computed via SPM)

GO dominates at low incidence angles
SPM dominates at intermediate/high incidence angles

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

- Almost ten years ago the Polarimetric Two-Scale Model (PTSM) was introduced[1], allowing for closed-form evaluation of the average integral, via a moderate slope approximation.
- PTSM allows accounting for cross- and de-polarisation effects actually present in measured data even when surface scattering is the only present mechanism.
- PTSM has been used to devise soil moisture retrieval schemes for bare soils[1].
- Recently PTSM has been extended to the case of the anisotropic sea surface (A-PTSM)[2], but in backscattering configuration only.

Extension to the case of bistatic scattering configuration is considere in this work.

[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] G. Di Martino, A. Iodice, D. Riccio, "Closed-Form Anisotropic Polarimetric Two-Scale Model for Fast Evaluation of Sea Surface Backscattering", *IEEE Trans. Geosci. Remote Sens.*, vol. 57, no. 8, pp. 6182-6194, Aug. 2019.

Theory

Surface description

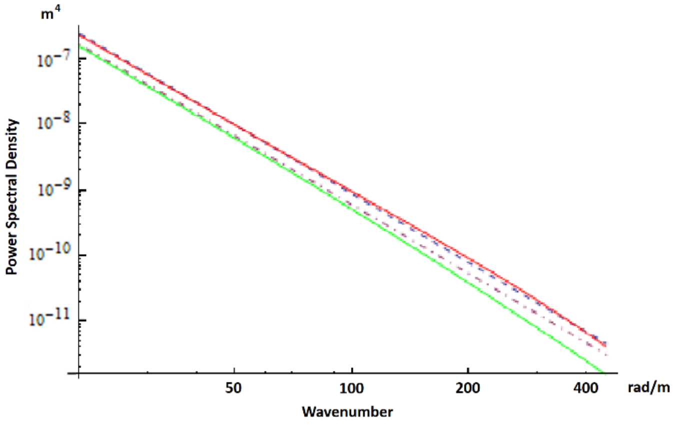
Small-scale roughness:

High-frequency part of the directional Elfouhaily spectrum

$$W_{2D}\left(\kappa,\varphi\right)=W\left(\kappa\right)\Phi\left(\kappa,\varphi\right)$$

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

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



$$c=\sqrt{\frac{g}{\kappa}\left[1+\left(\frac{\kappa}{\kappa_m}\right)^2\right]}$$

$$u^*=\sqrt{C_d}\;u_{10}$$

$$\alpha_m=\begin{cases}0.01\left[1+\ln\left(u^*/c_m\right)\right] & \text{for}\quad u^*\leq c_m\\ 0.01\left[1+3\ln\left(u^*/c_m\right)\right] & \text{for}\quad u^*>c_m\end{cases}$$

$$\kappa_m=363\text{ m}^{-1}$$

$$c_m=0.23\text{ m/s}$$

$$\Delta\left(\kappa\right)=\tanh\left[0.173+4\left(c/c_p\right)^{2.5}+a_m\left(c_m/c\right)^{2.5}\right]$$

$c_p \cong u_{10}/0.84$ and $a_m = 0.13u^*/c_m$

u_{10} : wind velocity

φ_w : wind direction

if $20\text{ m}^{-1} < \kappa < 200\text{ m}^{-1}$

$$c\cong\sqrt{g/\kappa}\qquad W\left(\kappa\right)\cong\frac{S_0}{\kappa^{3.5}}\qquad \Phi\left(\kappa,\varphi\right)\cong\Phi\left(\varphi\right)=1+\Delta\left(\kappa_0\right)\cos\left[2\left(\varphi_w-\varphi\right)\right]\qquad \Delta(\kappa)<\sim 0.2$$

Theory

Surface description

Large-scale roughness:

Up-wind and cross-wind slopes s_{up} and s_{cross}: independent zero-mean Gaussian variables with σ_{up} and σ_{cross} standard deviations.

Katzberg model for *f*=1.5 GHz (GNSS)

$$\sigma_{up0}^2 = 0.45\left[0.00316 \cdot 6 \ln\left(u_{10}\right)\right]$$

$$\sigma_{cross0}^2 = 0.45\left[0.003 + 0.00192 \cdot 6 \ln\left(u_{10}\right)\right]$$

Evaluation for generic *f*:

$$\sigma_{up,cross}^2 \cong \sigma_{up0,cross0}^2 + \frac{1}{4\pi^2} \int_0^{2\pi} \int_{\kappa_{cut0}}^{\kappa_{cut}} \kappa^2 \cos^2\left(\varphi - \varphi_w - \psi_{up,cross}\right) W\left(\kappa\right) \Phi\left(\varphi\right) \kappa \, d\kappa \, d\varphi =$$

$$= \sigma_{up0,cross0}^2 + \frac{S_0}{2\pi}\left(1 \pm \frac{\Delta\left(\kappa_0\right)}{2}\right)\left(\sqrt{\kappa_{cut}} - \sqrt{\kappa_{cut0}}\right) \qquad \psi_{up} = 0, \ \psi_{cross} = \pi/2$$

Azimuth and range slopes s_a and s_r: correlated zero-mean Gaussian variables with σ_a and σ_r standard deviations and ρ correlation coefficient. $s_a \ , \ s_r \sim N\left(0; \sigma_a^2, \sigma_r^2, \rho\right)$

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

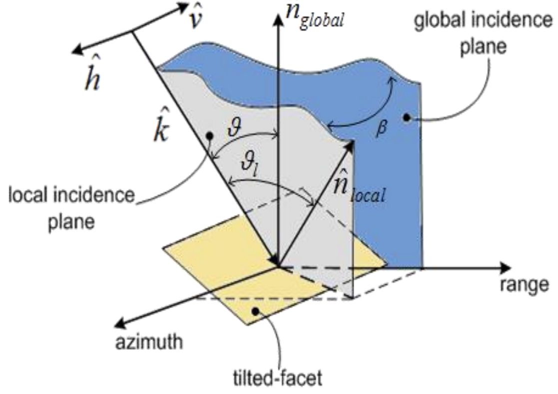
$$\sigma_a^2 = \sigma_{cross}^2 \cos^2 \varphi_w + \sigma_{up}^2 \sin^2 \varphi_w$$

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

Theory

Bistatic A-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: $< s_x > = < s_y > = 0$, $< s_x^2 > = \sigma_x^2$, $< s_y^2 > = \sigma_y^2$, and $< s_x s_y > = \rho \sigma_x \sigma_y$

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

Covariance matrix elements

$$\boldsymbol{\langle R_{pq,rs}^{SPM}(\vartheta_i,\vartheta_s,\varphi_s;s_x,s_y)\rangle_{s_x,s_y} \cong R_{pq,rs}^{SPM}(\vartheta_i,\vartheta_s,\varphi_s;0,0) + + D_{2,0}^{pq,rs}\sigma_x^2 + D_{0,2}^{pq,rs}\sigma_y^2 + D_{1,1}^{pq,rs}\rho\sigma_x\sigma_y}$$

$$\kappa_y = -k\sin\vartheta_s\sin\varphi_s \qquad \bar{\kappa} = \sqrt{\kappa_x^2+\kappa_y^2}$$

$$\kappa_x = -k\sin\vartheta_s\cos\varphi_s + k\sin\vartheta_i \qquad \bar{\varphi} = \arctan\left(\kappa_y/\kappa_x\right)$$

Bragg coefficients

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

Expansion coefficients

$$D_{k,n-k}^{pq,rs} = \frac{1}{n!}\binom{n}{k}\frac{\partial^n R_{pq,rs}^{SPM}}{\partial s_x^k\,\partial s_y^{n-k}}\Bigg|_{s_x=s_y=0}$$

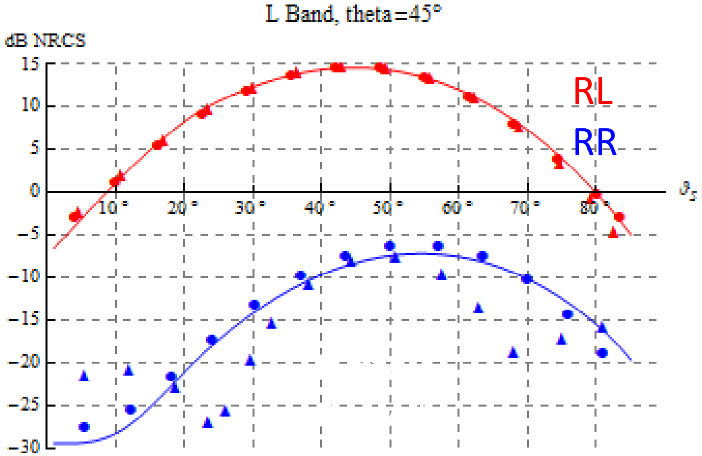
Standard SPM elements covariance matrix

$$R_{pq,rs}^{SPM}(\vartheta_i,\vartheta_s,\varphi_s,0{,}0) = \frac{4}{\pi}k^4\cos^2\vartheta_i\cos^2\vartheta_s\,F_{pq}(\vartheta_i,\vartheta_s,\varphi_s)F_{rs}^*(\vartheta_i,\vartheta_s,\varphi_s)W_{2D}(\bar{\kappa},\bar{\varphi})$$

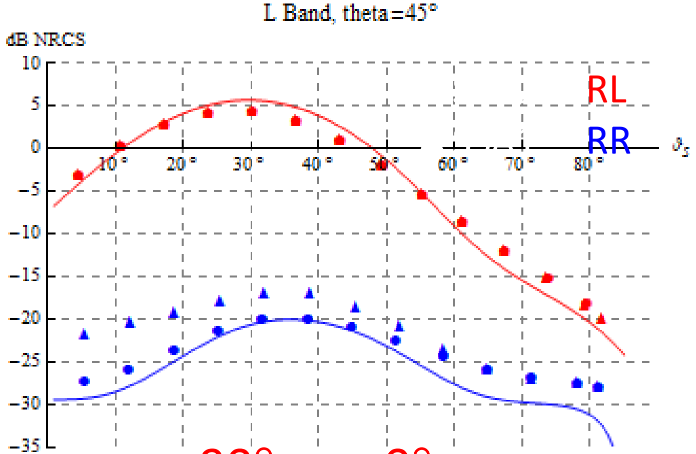
Results

All experiments at L band, ϑ_i = 45°, and u_{10} = 10 m/s.

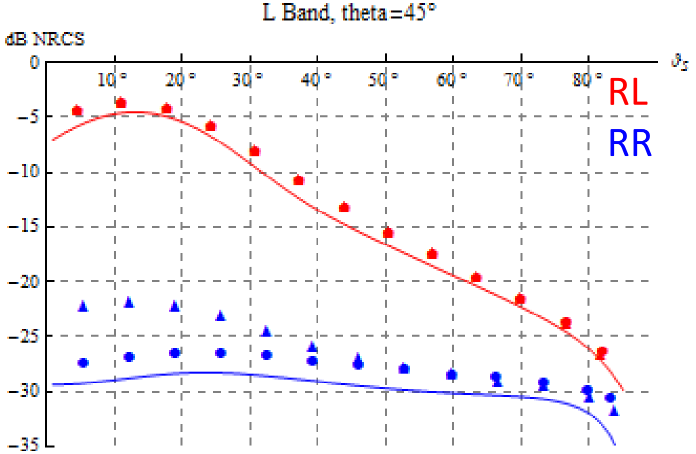
φ_s=0°, φ_w=0°



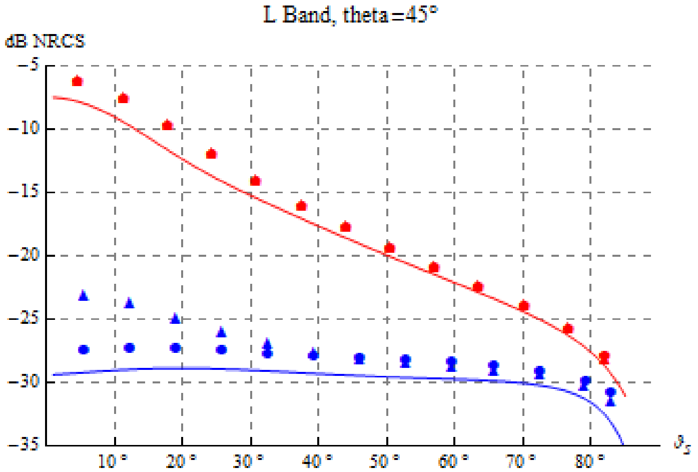
φ_s=30°, φ_w=0°



φ_s=60°, φ_w=0°



φ_s=90°, φ_w=0°



● SSA2
▲ SSA1

Bistatic A-PTSM results are closer to the SSA2 than to the SSA1 ones

SSA2[1] considers multiple scattering (up to second order), but it requires computationally intensive numerical evaluation of fourfold integrals

[1] 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.

Conclusions

- Closed-form PTSM extended to the anisotropic sea surface case (A-PTSM) and to the bistatic scattering configuration

- All elements of the linear polarization polarimetric covariance matrix analytically expressed in closed form

- Reasonable agreement with SSA2, which is more accurate but computationally intensive

- For applications in which computational efficiency is important, use A-PTSM! (for instance, wind speed and direction retrieval, or, more in general, surface parameter retrieval).

- Extendable to the case of agricultural anisotropic soil surfaces, upon appropriate modeling of the roughness

THANK YOU

FOR YOUR ATTENTION!

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