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ELECTROMAGNETIC SCATTERING FROM A CANONICAL TARGET OVER AN ANISOTROPIC ROUGH SURFACE USING GEOMETRICAL OPTICS

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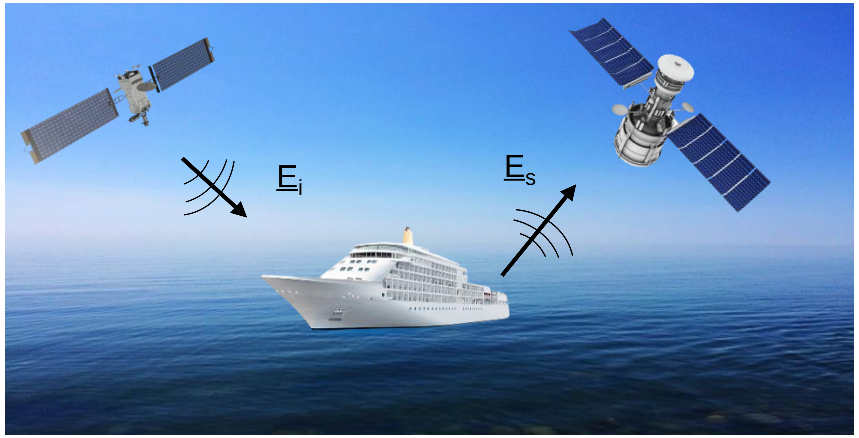
Introduction

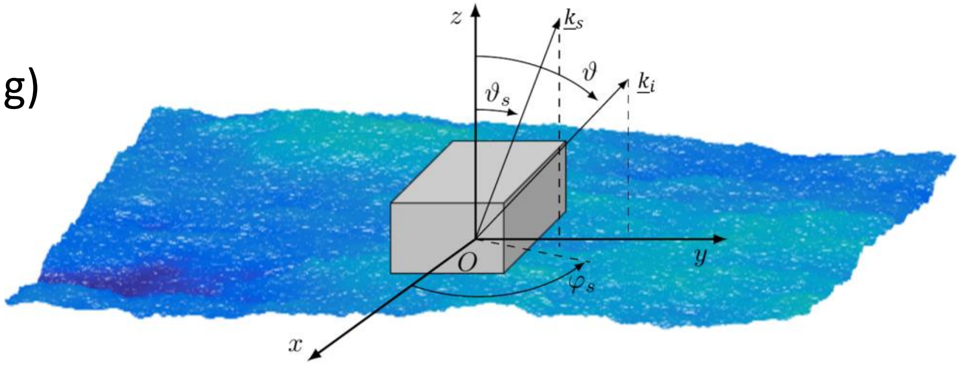
- Specific microwave remote sensing applications, e.g., ship target detection/classification, building parameters retrieval (height, material composition), might benefit from a (even) rough idea of the scattering properties of the sensed surface.
- As opposed to numerical techniques, asymptotic approaches allow for closed-form expressions of the EM scattered field.
- Ref. [1] studies the bistatic EM scattering from a composite target including a parallelepiped target over a rough background surface.
- An isotropic background surface was considered there.
- However, natural surfaces, e.g., bare soils, sea, typically exhibit anisotropic spectrum, which may lead to significant modification of the scattering properties that require to be properly analyzed.



[1] A. Di Simone *et al*., "Analytical Models for the Electromagnetic Scattering From Isolated Targets in Bistatic Configuration: Geometrical Optics Solution," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 58, no. 2, pp. 861-880, Feb. 2020, doi: 10.1109/TGRS.2019.2941140.

Geometrical Model

- Target
  - rectangular parallelepiped with smooth dielectric faces (ship, building)
- Rough background surface
  - normally-distributed stochastic process with variance σ^2 and power spectral density (PSD) S($\underline{\kappa}$)
- Surface local slopes z_x and z_y:
  - Bivariate normal distribution with zero mean and covariance matrix $\underline{\underline{C}}$



$$\underline{\underline{C}} = \begin{bmatrix} \sigma_x^2 & \rho\sigma_x\sigma_y \\ \rho\sigma_x\sigma_y & \sigma_y^2 \end{bmatrix}$$

- The parameters σ^2, σ_x^2 and σ_y^2 can be all retrieved from the surface PSD S($\underline{\kappa}$):

$$\sigma^2 = \int_0^{2\pi}\int_0^{\kappa_{cut}} \kappa S(\kappa,\psi)\, d\kappa\, d\psi,$$

$$\langle z_u z_v\rangle = \int_0^{2\pi}\int_0^{\kappa_{cut}} \kappa\kappa_u\kappa_v S(\kappa,\psi)\, d\kappa\, d\psi,$$

➡

$$\rho = \frac{\langle z_x z_y\rangle}{\sigma_x\sigma_y}$$

$\rho \in [0,1]$: correlation coefficient
σ_x: standard deviation of the *x*-slope
σ_y: standard deviation of the *y*-slope
$\underline{\kappa}$: surface wavenumber vector
ψ: phase of $\underline{\kappa}$
κ: amplitude of $\underline{\kappa}$
u, v: *x* or *y*

- For sea surfaces, the PSD depends upon the wind speed and direction.

Electromagnetic Model - I

E_0	complex amplitude
$\hat{e}_i$	polarization state
$\hat{k}_i$	propagation direction
k	EM wavenumber
$\underline{r}$	observation point

- The incident field is modeled as a plane wave

$$\underline{E}_i(\underline{r}) = E_0 \hat{e}_i \exp(jk\hat{k}_i \cdot \underline{r})$$

$$\hat{k}_i = -\sin\theta\hat{y} - \cos\theta\hat{z}. \qquad \hat{k}_s = \sin\theta_s\cos\phi_s\hat{x} + \sin\theta_s\sin\phi_s\hat{y} + \cos\theta_s\hat{z}$$

- Under KA-GO, the scattered field $\underline{E}_s(\underline{r})$ is completely characterized by the scattering matrix and the scattering integral [1]

$$\begin{bmatrix} E_{\text{Sh}} \\ E_{\text{Sv}} \end{bmatrix} = jk\frac{e^{jkr}}{4\pi r} \boxed{\begin{pmatrix} S_{\text{hh}} & S_{\text{vh}} \\ S_{\text{hv}} & S_{\text{vv}} \end{pmatrix}} \begin{bmatrix} E_{0\text{h}} \\ E_{0\text{v}} \end{bmatrix} \boxed{I_{\text{A}_0}}$$

- The scattering matrix does not depend on the surface PSD and, therefore, its expression can be found in [1] for all scattering contributions.
- Similarly, single-scattering from target can still be expressed as in [1].
- Here we focus on the evaluation of the scattering integral which depends on the surface roughness

$$I_{\text{A}_0} = \iint_{\text{A}_0} e^{jk(\eta_x x + \eta_y y + \eta_z \boxed{z(x,y)})}\, dxdy \qquad \underline{\eta} = \hat{k}_i - \hat{k}_s,$$

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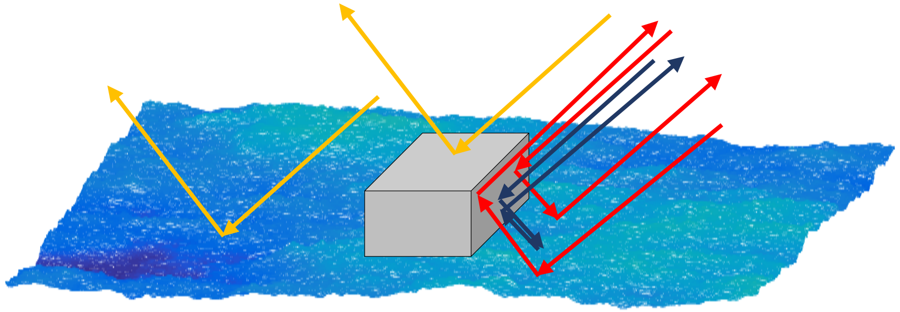
Electromagnetic Model - II

- In our scenario different scattering contributions arise:
    - single-scattering from target and ground;
    - double-scattering ground-wall and wall-ground;
    - triple-scattering wall-ground-wall.



- For both single- and multiple-scattering contributions, the mean value of the scattering integral $\langle I_{A_0} \rangle$ does not depend on the PSD of the surface and, therefore, can still be expressed as in Ref. [1].
- For any scattering term, its mean square value $\left\langle \left| I_{A_0} \right|^2 \right\rangle$ can be expressed in compact form as

$$\langle |I_{A_0}|^2 \rangle = A_0 \frac{2\pi}{\eta_z^2 k^2 \sigma_x \sigma_y \sqrt{1-\rho^2}} \exp\left[-\frac{\sigma_y^2 \eta_x^2 + \sigma_x^2 \eta_y^2 - 2\rho \sigma_x \sigma_y \eta_x \eta_y}{2\eta_z^2 \sigma_x^2 \sigma_y^2 (1-\rho^2)} \right]$$

- The surface local slopes parameters σ_x^2, σ_y^2, and ρ account for the surface anisotropy.
- The area term A_0 is the portion of rough surface contributing to the scattered field. Its expression depends on the scattering contribution as well as the incident and scattering directions, target size and orientation, but not on the surface PSD and, therefore, can still be expressed as in Ref. [1].

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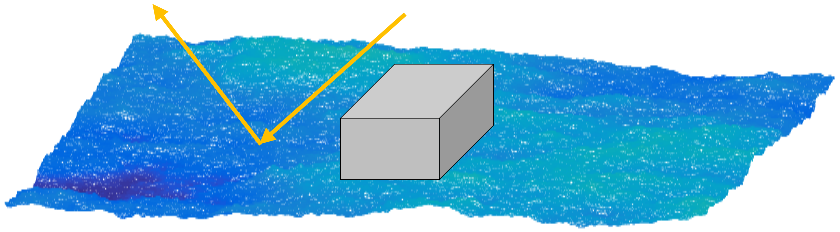
Electromagnetic Model - III

$$\langle |I_{A_0}|^2 \rangle = A_0 \frac{2\pi}{\eta_z^2 k^2 \sigma_x \sigma_y \sqrt{1-\rho^2}} \exp\left[-\frac{\sigma_y^2 \eta_x^2 + \sigma_x^2 \eta_y^2 - 2\rho\, \sigma_x \sigma_y \eta_x \eta_y}{2\eta_z^2 \sigma_x^2 \sigma_y^2 (1-\rho^2)} \right]$$

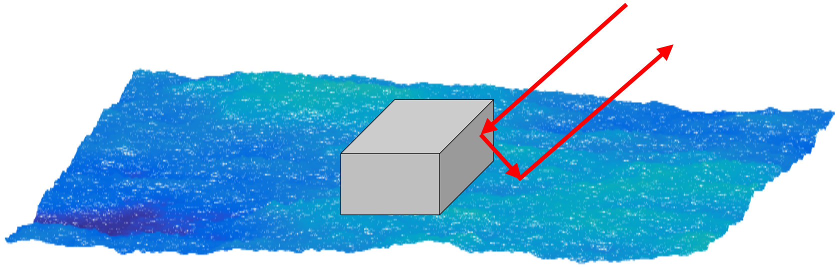
- The difference vector $\underline{\eta}$ has different expressions for the different scattering contributions:

Single-scattering from ground



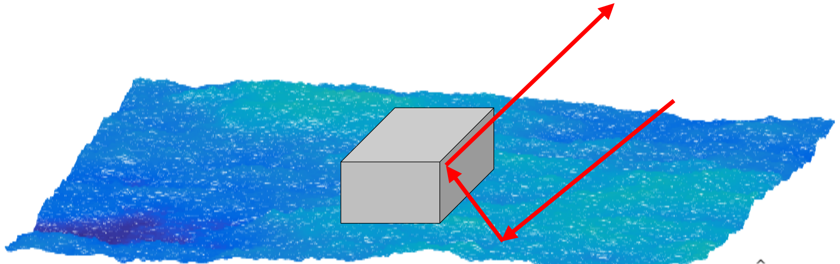
$$\underline{\eta}_G = \hat{k}_{\mathrm{i}} - \hat{k}_{\mathrm{s}}$$

Double-scattering wall-ground



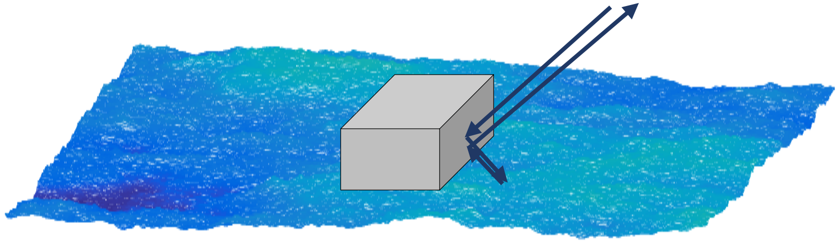
$$\underline{\eta}_{WG} = \hat{k}_{\mathrm{sp}} - \hat{k}_{\mathrm{s}}$$

Double-scattering ground-wall



$$\underline{\eta}_{GW} = \hat{k}_{\mathrm{i}} - \hat{k}_{\mathrm{sg}}$$

Triple-scattering wall-ground-wall



$$\underline{\eta}_{WGW} = \hat{k}_{\mathrm{sp}} - \hat{k}_{\mathrm{sg}}$$

$$\hat{k}_{\mathrm{sp}} = \sin\theta \sin 2\phi_k \hat{x} + \sin\theta \cos 2\phi_k \hat{y} - \cos\theta \hat{z}$$

$$\hat{k}_{\mathrm{sg}} = \sin\theta_{\mathrm{s}} \cos(\phi_{\mathrm{s}} + 2\phi_k) \hat{x} - \sin\theta_{\mathrm{s}} \sin(\phi_{\mathrm{s}} + 2\phi_k) \hat{y} + \cos\theta_{\mathrm{s}} \hat{z}$$

Numerical Results

- Overall RCS in dB of an isolated ship over sea surface.

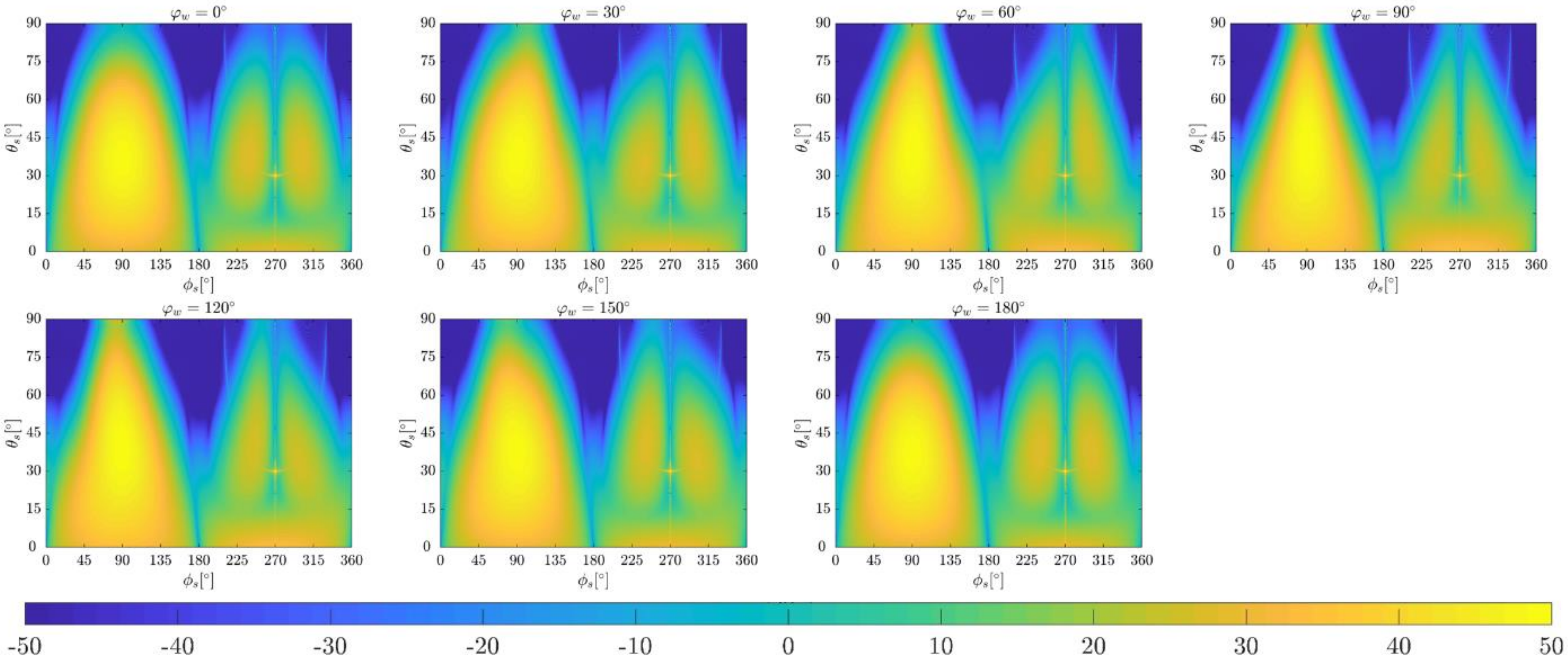


Table 1. Simulation parameters

Parameter	Value
Frequency	1.5GHz
Wind speed	10 m/s
Wind direction	varying
Incidence angle	30°
Sea spectrum	Elfouhaily
Ship orientation	0°
Ship size	$100 \times 30 \times 20$ m^3
Seawater relative permittivity	$70.26 - j39.94$
Ship relative permittivity	$4.45 - j2.72 \times 10^7$

$$\mathrm{RCS} = 4\pi r^2 \frac{\langle |\underline{E}_s(\underline{r})|^2 \rangle}{|E_0|^2}$$

- The wind direction φ_w modifies the angular distribution of the EM energy scattered from the target.
- The single-scattering contribution from the ship deck remains unchanged, see the bright return around $\varphi_s = 270°$.
- A strong return is still localized around the backscattering direction $\vartheta_s = \vartheta$ and $\varphi_s = 90°$ as in the isotropic case.

Conclusions

- The analytical model presented allows for a fast evaluation of the overall RCS of an isolated parallelepiped target over a rough surface.
- KA-GO is adopted for scattering from both target's faces and background surface.
- Main novelty consists in the anisotropy of the rough surface, which is modeled as a normally-distributed process with directional spectrum.
- Numerical simulations of maritime environments show the impact of the anistropy of the background sea surface on the RCS of the ship target.
- Future research lines may regard the derivation of analytical models under different roughness regimes, i.e., KA-PO.