Infrared Sea Surface Modeling

K. Caillault - S. Fauqueux - C. Bourlier - P. Simoneau
Introduction

Context

- Development of a new version of MATISSE (infrared background scene generator)

- Sea surface optical properties: spatial variability from 1-m to large scale on background, including sub-pixel variability

Waveband 8-12 µm
Sea surface radiance

Radiance of a portion $S$ of sea surface

$$L(S) = \int \int_{\Omega_{\text{sun}}} f(S, \tilde{u}_\omega, \tilde{u}_{\text{obs}}) L_{\text{sun}}(\omega) \cos \theta_\omega \, d\omega$$

$$+ \int \int_{\Omega_{\text{sky}}} f(S, \tilde{u}_\omega, \tilde{u}_{\text{obs}}) L_{\text{atm}}(\omega) \cos \theta_\omega \, d\omega + \epsilon(S, \tilde{u}_{\text{obs}}) L_{\text{BB}}[T(S)]$$

$\Rightarrow$ Evaluate $f(S, \tilde{u}_\omega, \tilde{u}_{\text{obs}})$ and $\epsilon(S, \tilde{u}_{\text{obs}})$ for any surface $S \geq 1 \text{ m.}$

$\Rightarrow$ Optical properties model
Model hypotheses

- $\lambda = [3; 13 \mu m] <<$ surface variability (capillarity $\approx$ mm)
  $\Rightarrow$ **First-order geometrical optics approach**

- **Sea surface:** Gaussian stochastic process
  $\Rightarrow$ Determined by its power spectrum (Elfouhaily & al)
    - Gravity & capillarity waves
    - In agreement with JONSWAP spectrum and Cox & Munk measurements

**Included Parameters**
- wind (constant intensity and direction);
- Fetch;
- Temperature (Database);
- Salinity (constant);

**Not modeled Phenomena**
- bathymetry (deep water);
- currents;
- coasts, crossed sea (fully developed sea);
- breaking waves and foam;
- turbidity, phytoplanktons (clear water);
- multiple reflections.
Emissivity and BRDF depend on:

- Solar and observation angles
- Local reflectivity (Fresnel coefficient)
- Mono/bi-static shadowing function (Uncorrelated Smith)
- Probability density (Gaussian)
  - Variance
  - Average

Values?

\[ L > n \times \text{correlation length} \Rightarrow \text{low resolution} \]
\[ L < n \times \text{correlation length} \Rightarrow \text{high resolution} \]
Optical properties model

- $\gamma$ stochastic gaussian process describing surface slopes
- $\gamma$ decomposed into 2 independent processes $\gamma_c$ and $\gamma_g$

\[ \gamma_c: \quad S_{\gamma_c}(k) = \begin{cases} S_\gamma(k) & \text{si } k \geq k_c \\ 0 & \text{si } k < k_c \end{cases} \]

Hyp: 1 realization $\sim$ all the statistics

- Capillarity
- Gravity

- $m_c=0$, $\sigma_c$ given by $S_{\gamma_c}$
- $m_g$, $\sigma_g$

$\Rightarrow m = m_g + m_c$ and $\sigma^2 = \sigma_g^2 + \sigma_c^2$

Model:

<table>
<thead>
<tr>
<th>$L \geq n.L_c$</th>
<th>$L &lt; n.L_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low resolution</td>
<td>High resolution</td>
</tr>
<tr>
<td>$k_c = 0$;</td>
<td>$k_c = \pi \sim \Delta x = 1m$;</td>
</tr>
<tr>
<td>no geometrical surface generation</td>
<td>FFT + patch or sinusoids sum</td>
</tr>
<tr>
<td>$m_g = 0 \rightarrow m = 0$</td>
<td>$m$, $\sigma^2$</td>
</tr>
</tbody>
</table>
Results: 2D low resolution

\[ L(S) = \int_{\Omega_{\text{sun}}} \int f(S, \bar{u}_\omega, \bar{u}_{\text{obs}}) L_{\text{sun}}(\omega) \cos \theta_\omega \, d\omega \\
+ \varepsilon(S, \bar{u}_{\text{obs}}) L_{BB}[T(S)] \]

\[ u_{10} = 10 \text{ m.s}^{-1} \]
\[ \lambda = 4\mu\text{m} \]
\[ \theta_{\text{sun}} = 55^\circ \]
\[ \theta_{\text{obs}} = 84^\circ \]
Results: 2D high resolution

\[ L(S) = \int_{\Omega_{\text{sun}}} \int f(S, \tilde{u}_\omega, \tilde{u}_{\text{obs}}) L_{\text{sun}}^\uparrow(\omega) \cos \theta_\omega \, d\omega \]
\[ + \epsilon(S, \tilde{u}_{\text{obs}}) L_{BB}[T(S)] \]

\[ u_{10} = 10 \, \text{m.s}^{-1} \]
\[ \lambda = 4 \, \mu\text{m} \]
\[ \theta_{\text{sun}} = 55^\circ \]
\[ \theta_{\text{obs}} = 84^\circ \]
Model validation

Approach:

- Comparisons 1D optical properties with reference model
- Comparisons 2D optical properties with measurements

Reference model:

- Heights generation by sinusoids sum with Δx=0.125 mm
  - Over-metric variability ($k_c < \pi$)
  - Average on n draws for sub-metric variability ($k_c > \pi$)
- Shadows estimations through geometrical ray tracings
Validation: 1D Emissivity: Analytical/Reference

$u_{10}=10\ \text{m.s}^{-1}$

$u_{10}=20\ \text{m.s}^{-1}$
Validation: 1D BRDF: Analytical/Reference

\( u_{10} = 10 \text{ m.s}^{-1} \)

\( L=1\text{m} \)

\( L=8\text{m} \)

\( L=64\text{m} \)

\( \theta_{\text{obs}} = 0^\circ \)

\( \theta_{\text{obs}} = 72^\circ \)

\( \theta_{\text{obs}} = 88^\circ \)
Validation: 2D Emissivity: Analytical/Measurements

*Niclos et al., 2003

Wind direction
\[ \phi = 284 \pm 32^\circ \]

\[ u_{10} = 4.5 \pm 0.9 \text{ m/s} \]

\[ u_{10} = 10.3 \pm 1.1 \text{ m/s} \]
Convergence of high resolution OP to low resolution OP

\[ u_{10} = 10 \, \text{m.s}^{-1} \]

**Emissivity**

**Reflectivity**
Conclusion

- Analytical optical properties model: from 1-m to large scale, including sub-pixel variability
- Solar glint included

- Shadowing functions at grazing angles
- Validation measurements with grazing geometry
- Sea foam and whitecaps to be included