

Unpolarized infrared emissivity of oil films on sea surfaces



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- **General context of the study:**

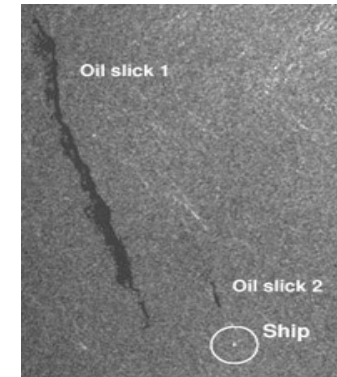
- **Remote sensing of oil slicks on sea surfaces**

Better oil slick detection, characterization,
and estimation of thickness

⇒ More effective direction of oil spill countermeasures



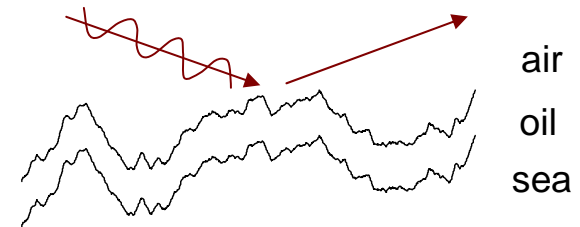
Modeling of the EM waves emitted
by oil slicks on sea surfaces
at infrared (IR) wavelengths



- **EM emission → thermal IR emissivity**

• EM emission → thermal IR emissivity

- one single interface → air/sea interface: relatively **well-known**
- **two rough interfaces** → air/oil and oil/sea interfaces: research in progress



• Different possible approaches:

rigorous

- + 'exact'
- long computing time
- large memory space

asymptotic (approximate)

- + fast
- restricted validity domain

cf. oil slick detection

I. Introduction

II. Hydrodynamic modeling (surfaces)

1. Natural surfaces: Statistical description
2. Case of clean and contaminated seas
3. Spectrum of clean and contaminated surfaces
4. Contaminated sea: Thin film with identical parallel interfaces

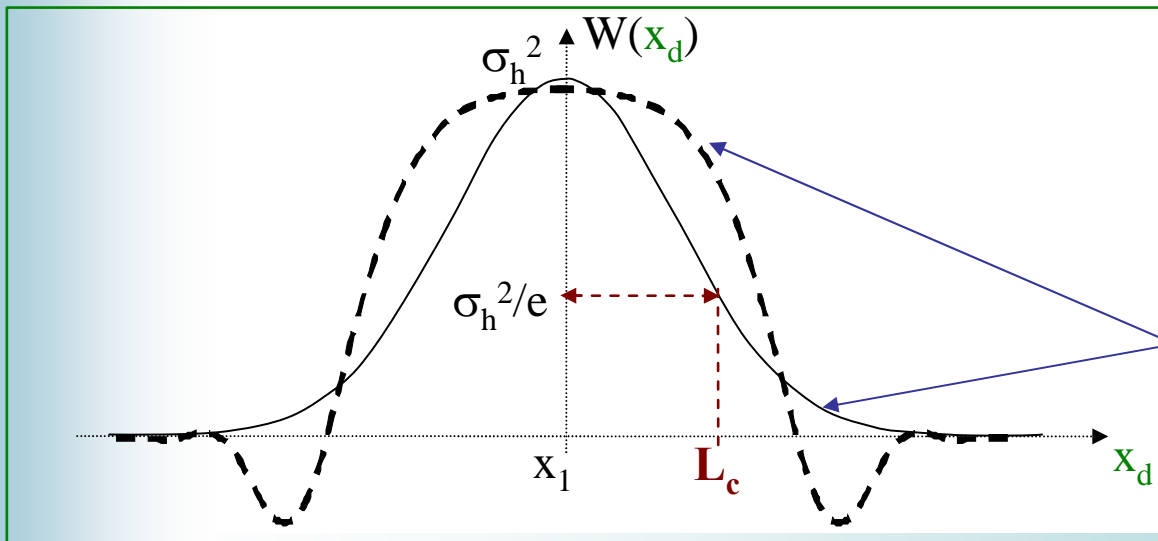
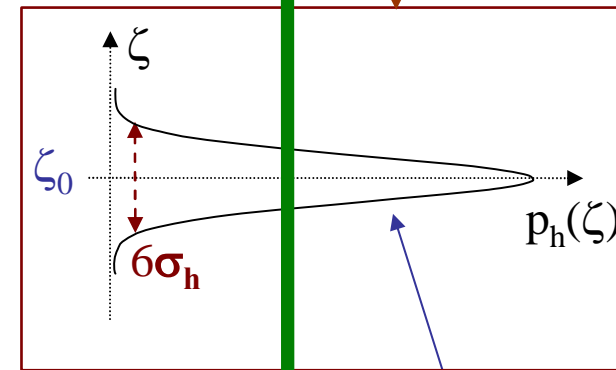
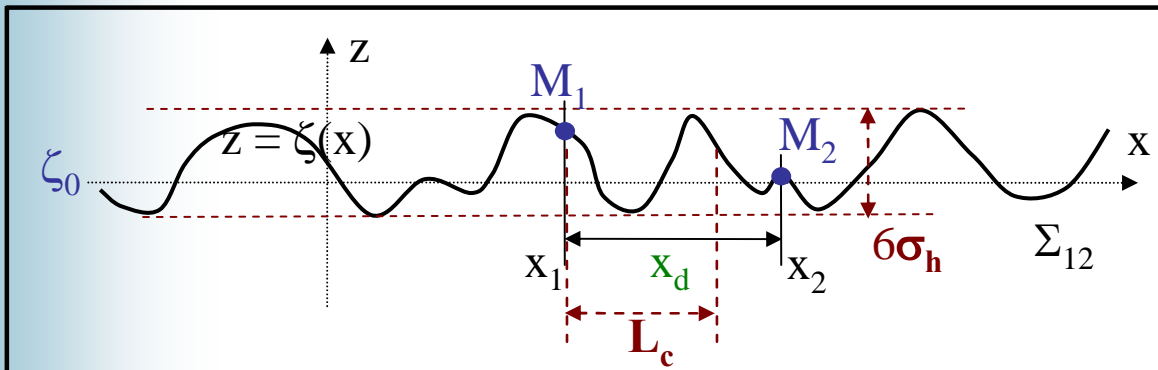
III. EM modeling: Thermal IR emissivity

IV. Conclusion & Future work

2 main description tools:

Height distribution (PDF): $p_h(\zeta)$

Height spectrum: $S(k=2\pi/x_d, \phi)$



generally Gaussian

Gaussian

Sea: much more complex...

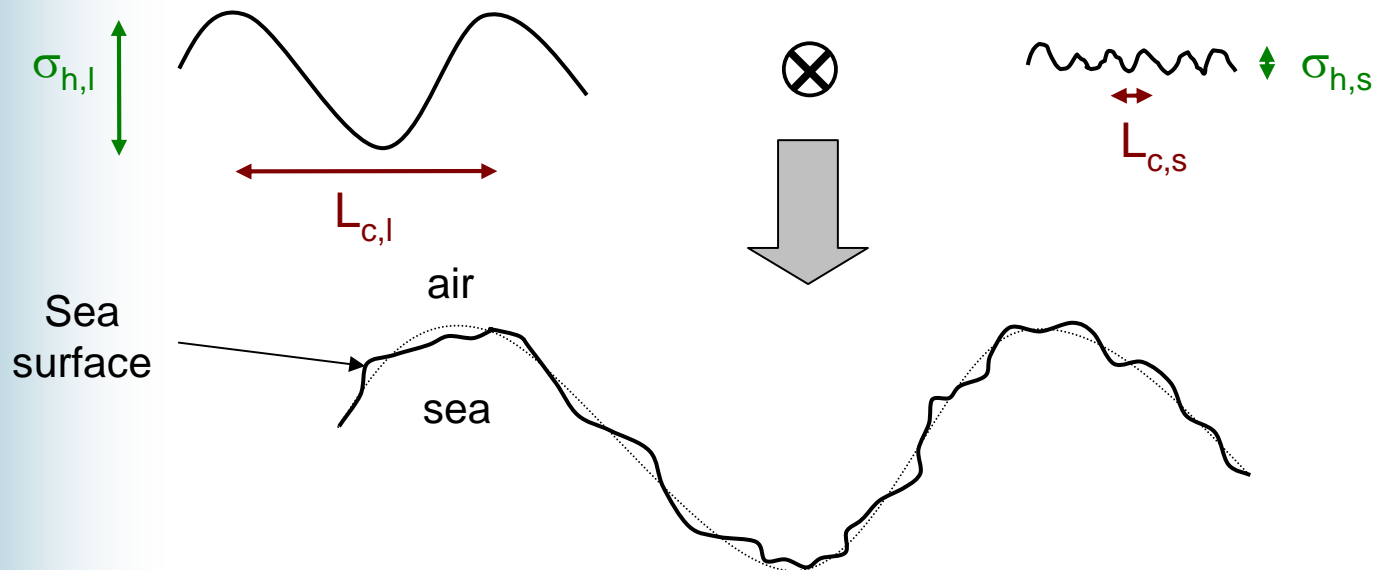
- Clean sea → Qualitative description:
Gravity and capillary waves:

Gravity waves:

- Large roughness $\sigma_{h,l}$
- Long correlation $L_{c,l}$

Capillary waves:

- Small roughness $\sigma_{h,s}$
- Short correlation $L_{c,s}$



Several roughness scales

- Contaminated sea → Qualitative description:

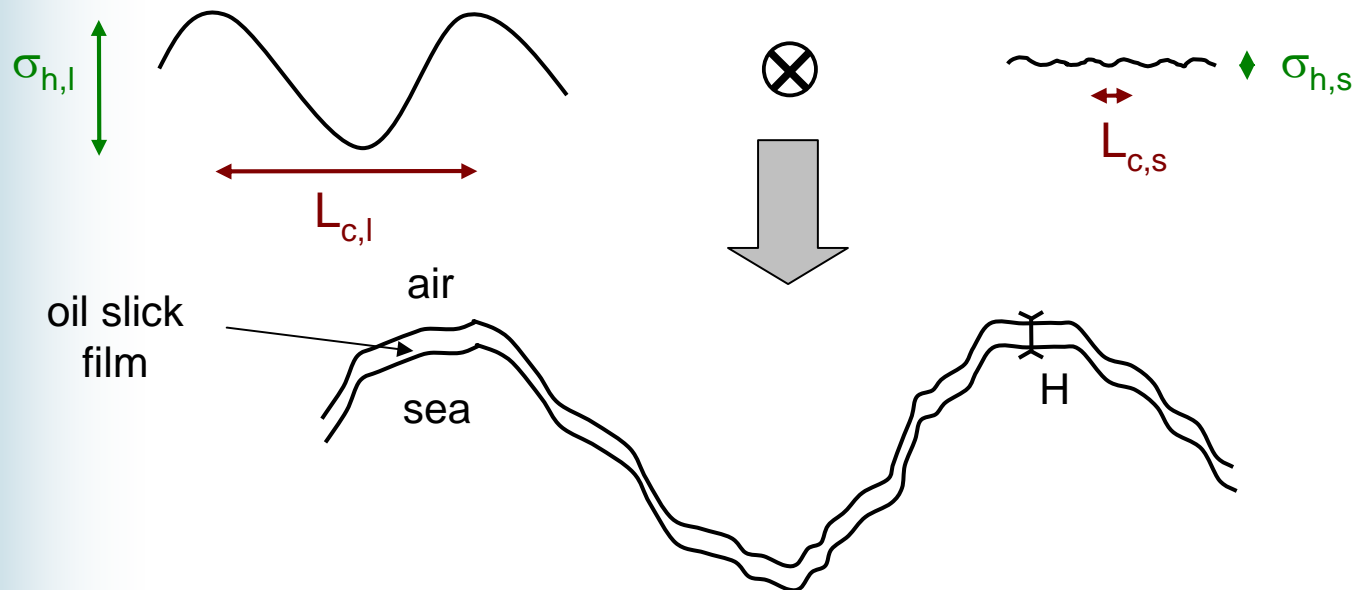
Damping of capillary waves
of both surfaces (air/oil and oil/sea)

Gravity waves:

- Large roughness $\sigma_{h,l}$
- Long correlation $L_{c,l}$

Capillary waves:

- **Smaller** roughness $\sigma_{h,s}$
- Short correlation $L_{c,s}$



Yet damping dependent on various parameters (hydrodynamics)

- Height spectrum $S(k=2\pi/\lambda_d, \phi) \rightarrow$ Modeling:

- Clean sea surface:

Elfouhaily et al. surface spectrum model [Elfouhaily et al., JGR, 1997]:

- Semi-empirical model
- Consistent with Cox & Munk experimental model

[Cox and Munk, JOSA, 1954]

\rightarrow RMS slope σ_s

- Contaminated sea (air/oil and oil/sea) surfaces: few results:

Lombardini et al. damping model [1] (Marangoni damping coefficient):

- Independent of the oil film thickness H
- Simple to use: 2 hydrodynamic parameters (oil)

Jenkins et al. damping model [2]:

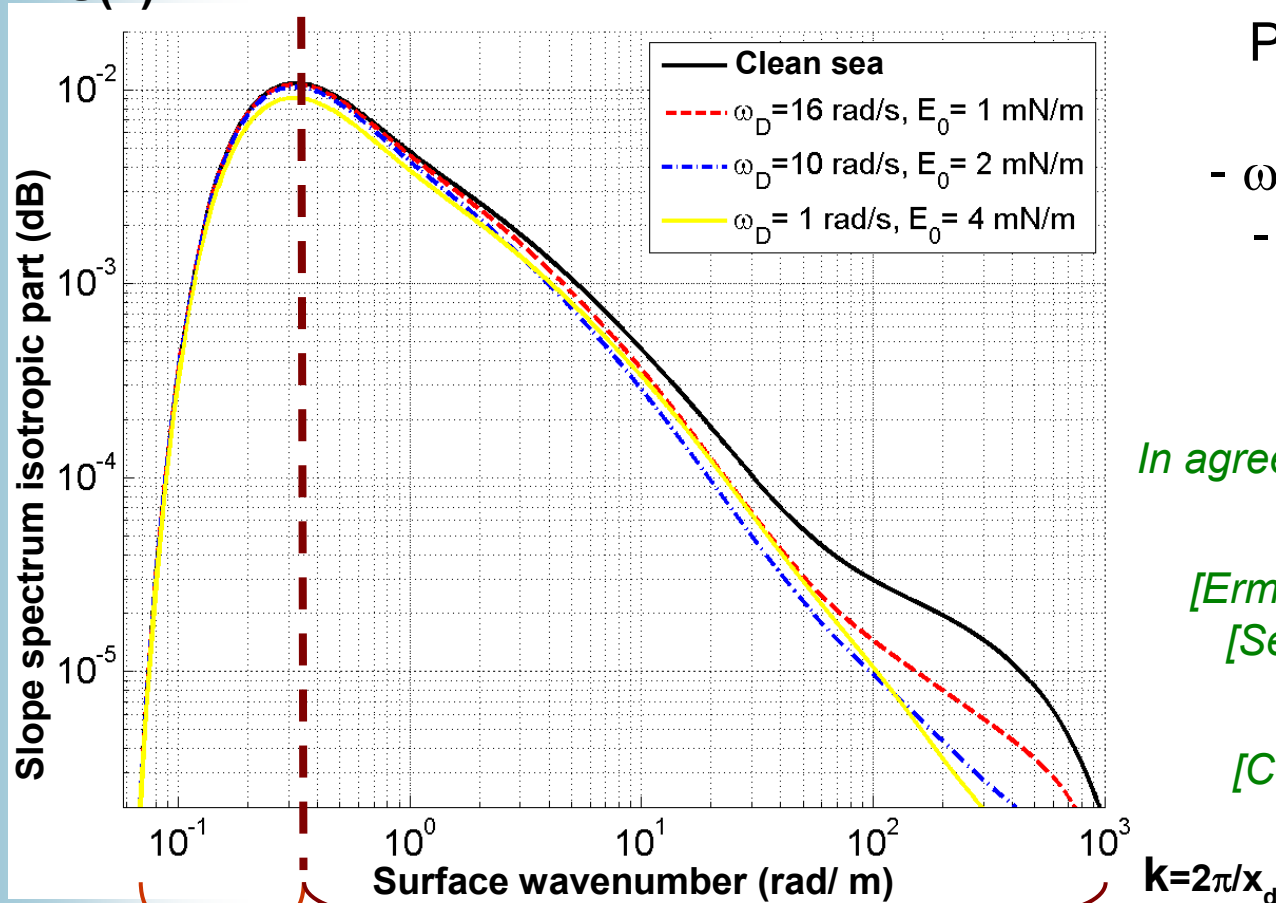
- Dependent on the oil film thickness H
- Harder to use: 8 hydrodynamic parameters (oil)

...

[1] : [Lombardini et al., JAOT, 1989]

[2] : [Jenkins and Jacobs, PF, 1997]

- *Lombardini et al.* spectrum [1,3]: Independent of the oil film thickness H : $k^2 S(k)$



Gravity waves:
Weak damping

Capillary waves:
Significant damping

Parameters relative to
the oil type:

- ω_D (characteristic pulsation)
- E_0 (elasticity modulus)

In agreement with experimental results:

[Ermakov, BIS Symposium, 2008]

*[Sergievsakaya and Ermakov,
BIS Symposium, 2008]*

[Cox and Munk, JOSA, 1954]

[1] : *[Lombardini et al., JAOT, 1989]*

[3] : *[Pinel et al., TGRS, 02/2008]*

- At thermal IR wavelengths:

Values of relative permittivities (ϵ_r^{sea} , ϵ_r^{oil}):

- Sea relative permittivity ϵ_r^{sea} : assez bien connu
- Oil relative permittivity ϵ_r^{oil} : only a few results of the literature, but...
at IR wavelengths λ : ϵ_r^{oil} can significantly vary with f and with the oil type

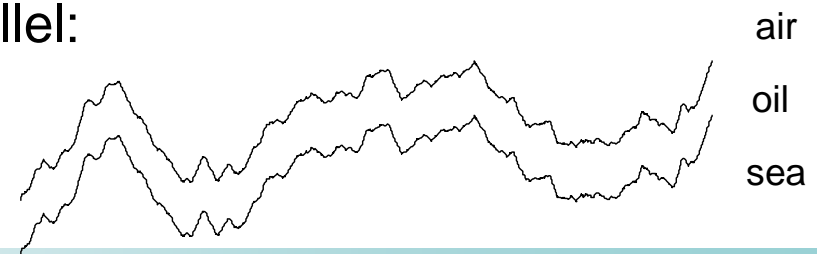
⇒ Interesting for oil type characterization

- Homogeneous oil slicks (not emulsions):

Applicable to wind speeds $u_{10} < \sim 8\text{-}10\text{m/s}$

- Use of the Lombardini *et al.* damping model:

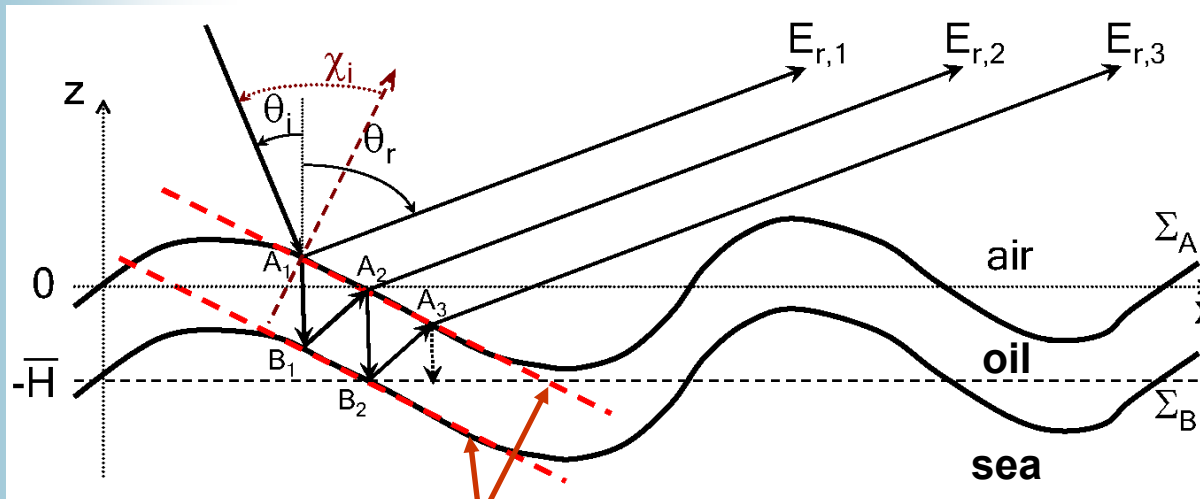
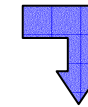
Surfaces assumed to be identical and parallel:



- Use of the height spectrum for an EM model:

Development of an asymptotic model

using an **intuitive approach**



Oil films:

- 2 identical and parallel surfaces
- + Low to moderate thicknesses
- + Damping of capillary waves



Locally flat parallel interfaces (← **capillary wave damping**)

$$\Rightarrow \sigma^{cont} = \left| \frac{r_{eq}(\chi_i)}{r_{12}(\chi_i)} \right|^2 \times \sigma^{oil} \quad \chi_i = -\frac{(\theta_r - \theta_i)}{2}$$



Application to an asymptotic model (thermal IR emissivity):

Geometric Optics Approximation (GOA) with shadowing effect

I. Introduction

II. Hydrodynamic modeling (surfaces)

III. EM modeling: Thermal IR emissivity

1. Thermal IR emissivity: Principle
2. Simple case of flat surfaces
3. Numerical results

IV. Conclusion & Future work

- **Emissivity $\epsilon(\theta, \phi)$ under the GOA:**

$$\epsilon(\theta, \phi) = \frac{1}{1 + \Lambda(\theta, \phi)} \int_{-\infty}^{+\mu} d\gamma_X \int_{-\infty}^{+\infty} [1 - \mathcal{R}(\chi)] p_s(\gamma_x, \gamma_y) \left(1 - \frac{\gamma_X}{\mu}\right) d\gamma_Y$$

with

- p_s : slope probability density function (PDF): \approx Gaussian
- \mathcal{R} : unpolarized power reflection coefficient
- χ : local emission angle

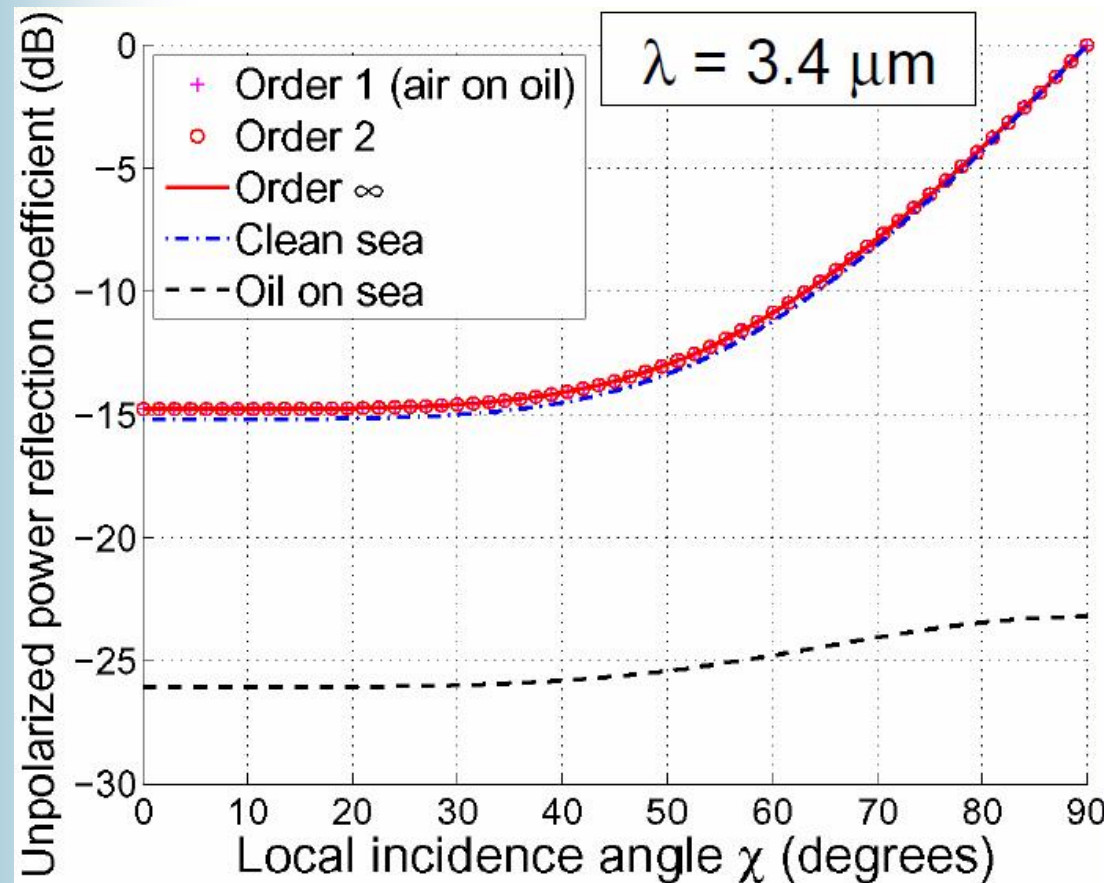
shadowing terms:

- Λ : *angular* shadowing effect
- $\gamma_X < \mu$: *propagation* shadowing effect

- Local emissivity ε of perfectly flat surfaces:

$$\varepsilon(\theta=\chi) = 1 - \mathcal{R}(\chi)$$

⇒ Computation of the unpolarized power reflection coef. $\mathcal{R}(\chi)$:



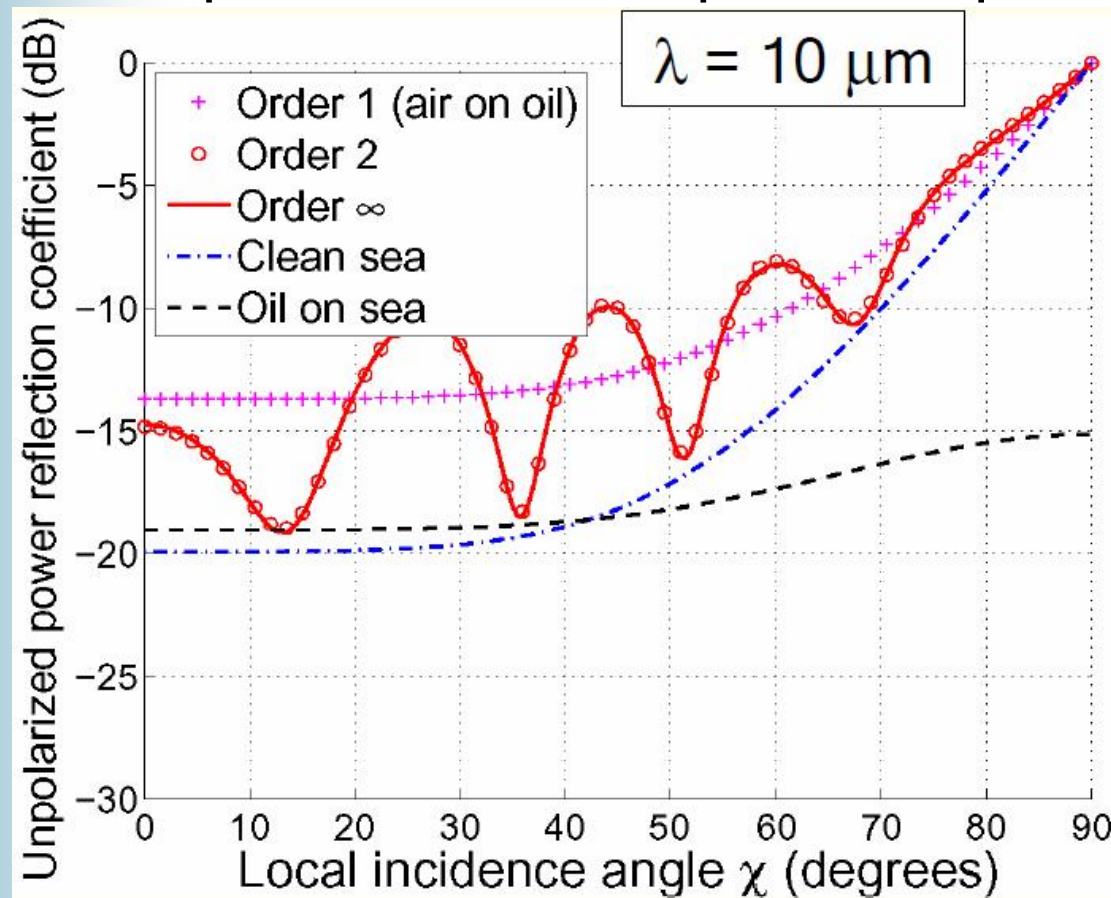
No oscillations
of the oil case

Very small differences
between clean and
contaminated seas

- Local emissivity ε of perfectly flat surfaces:

$$\varepsilon(\theta=\chi) = 1 - \mathcal{R}(\chi)$$

⇒ Computation of the unpolarized power reflection coef. $\mathcal{R}(\chi)$:



Significant oscillations
of the oil case

Significant differences
between clean and
contaminated seas
for moderate χ

- Simulation parameters:

- Thermal IR wavelengths λ :

$$\lambda = 3.4 \mu\text{m} \Rightarrow \begin{cases} \varepsilon_r^{\text{sea}} = 75 + 250j \\ \varepsilon_r^{\text{oil}} = 2.25 + 0.01j \end{cases} \quad \lambda = 10 \mu\text{m} \Rightarrow \begin{cases} \varepsilon_r^{\text{sea}} = 70 + 41j \\ \varepsilon_r^{\text{oil}} = 2.25 + 0.01j \end{cases}$$

- Wind speed (at 10 meters above the sea surface) u_{10} :

$$u_{10} = 7 \text{ m/s} \quad (\text{Beaufort scale } 4)$$

- Wind direction ϕ : $\phi = 0^\circ$

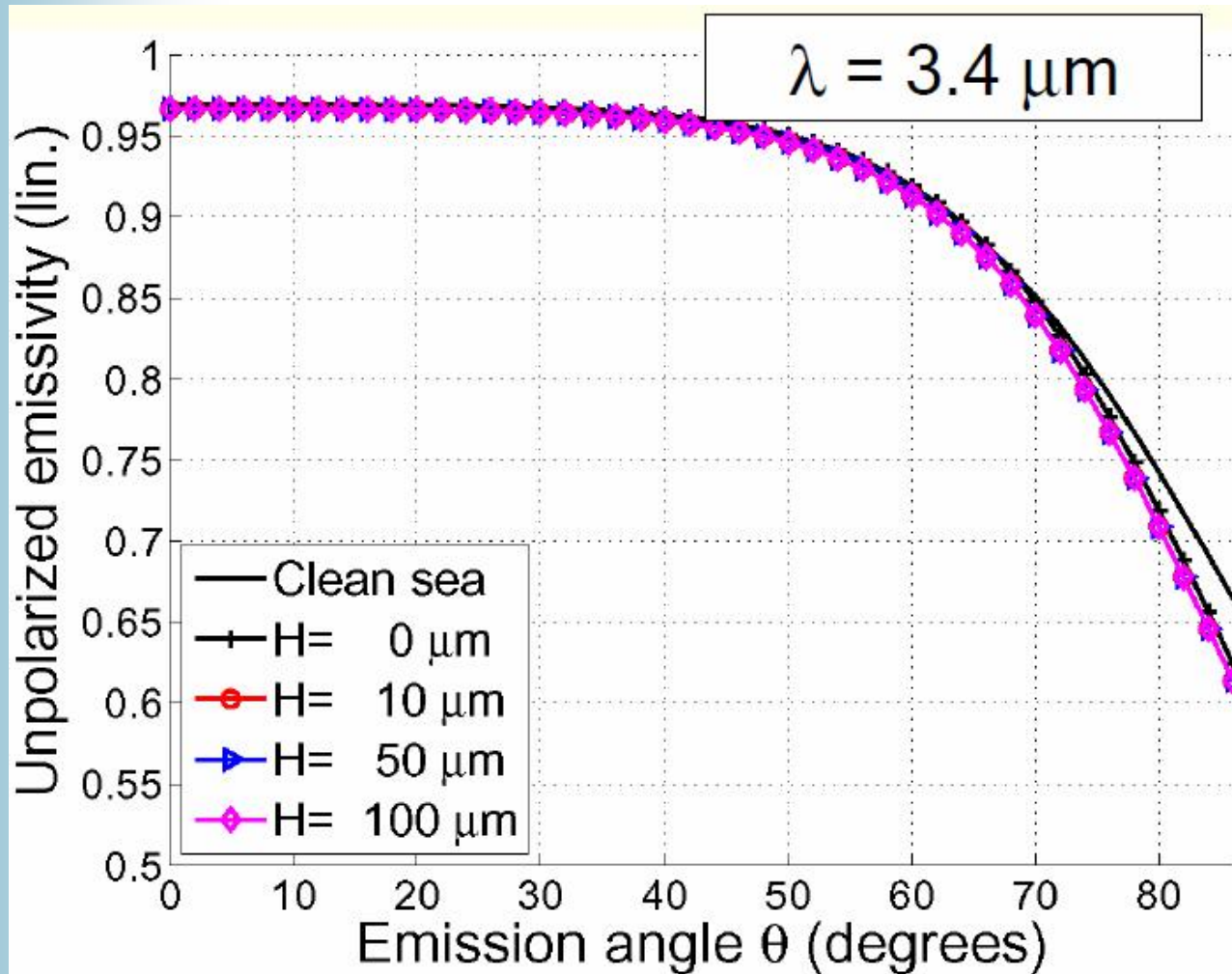
- Oil film thickness H : $H = 50 \mu\text{m}$ OR $H = \{0, 10, 50, 100\} \mu\text{m}$

- Hydrodynamic parameters of the oil slick:

$$\omega_D = 11 \text{ rad/s}, E_0 = 1 \text{ mN/m}$$

\Rightarrow Unpolarized emissivity $\varepsilon(\theta, \phi)$ vs. emission angle θ (degrees)

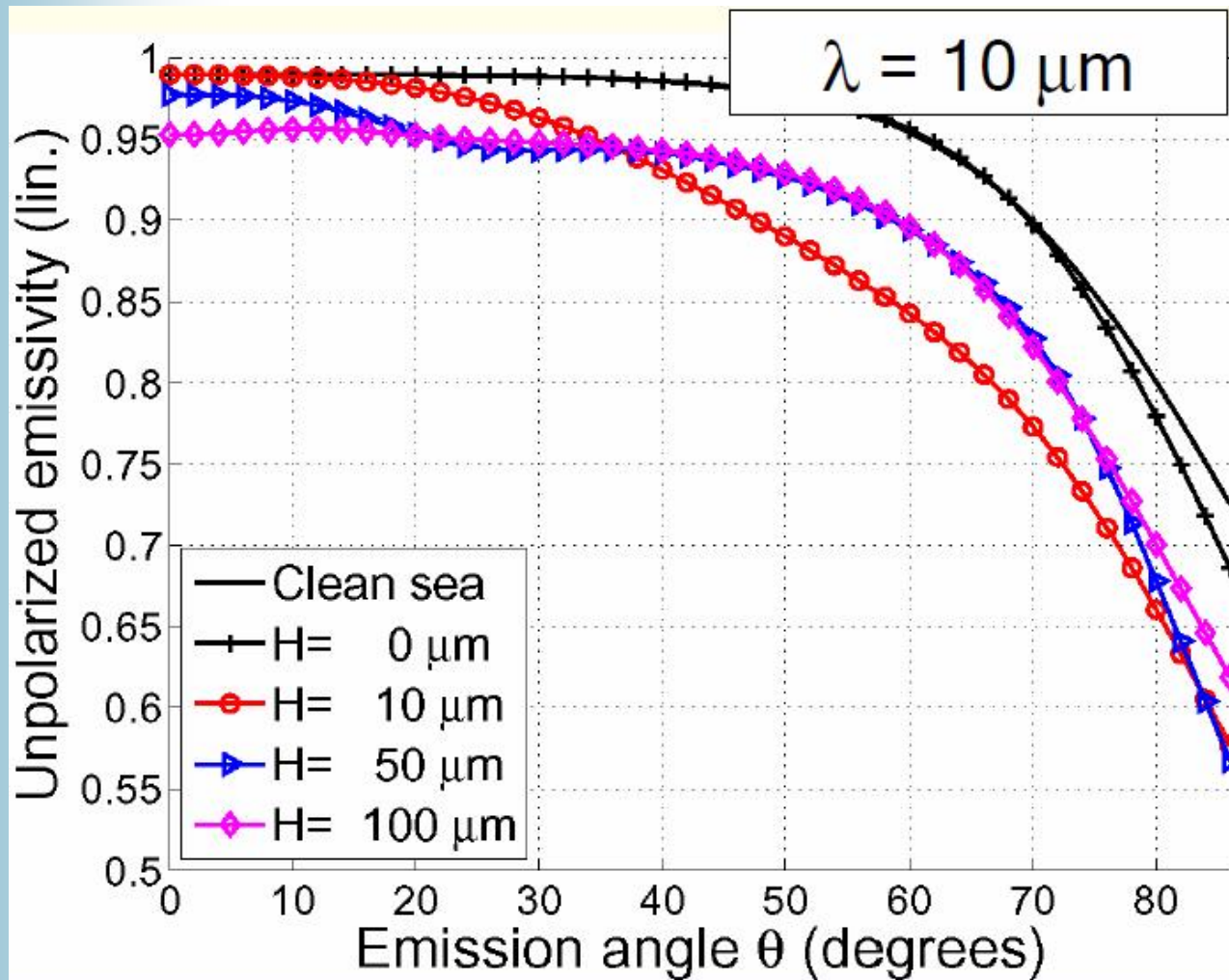
Influence of different oil film thicknesses $H = \{0, 10, 50, 100\} \mu\text{m}$



Oil slick detection possible only at high emission angles θ

Oil thickness estimation impossible for any θ

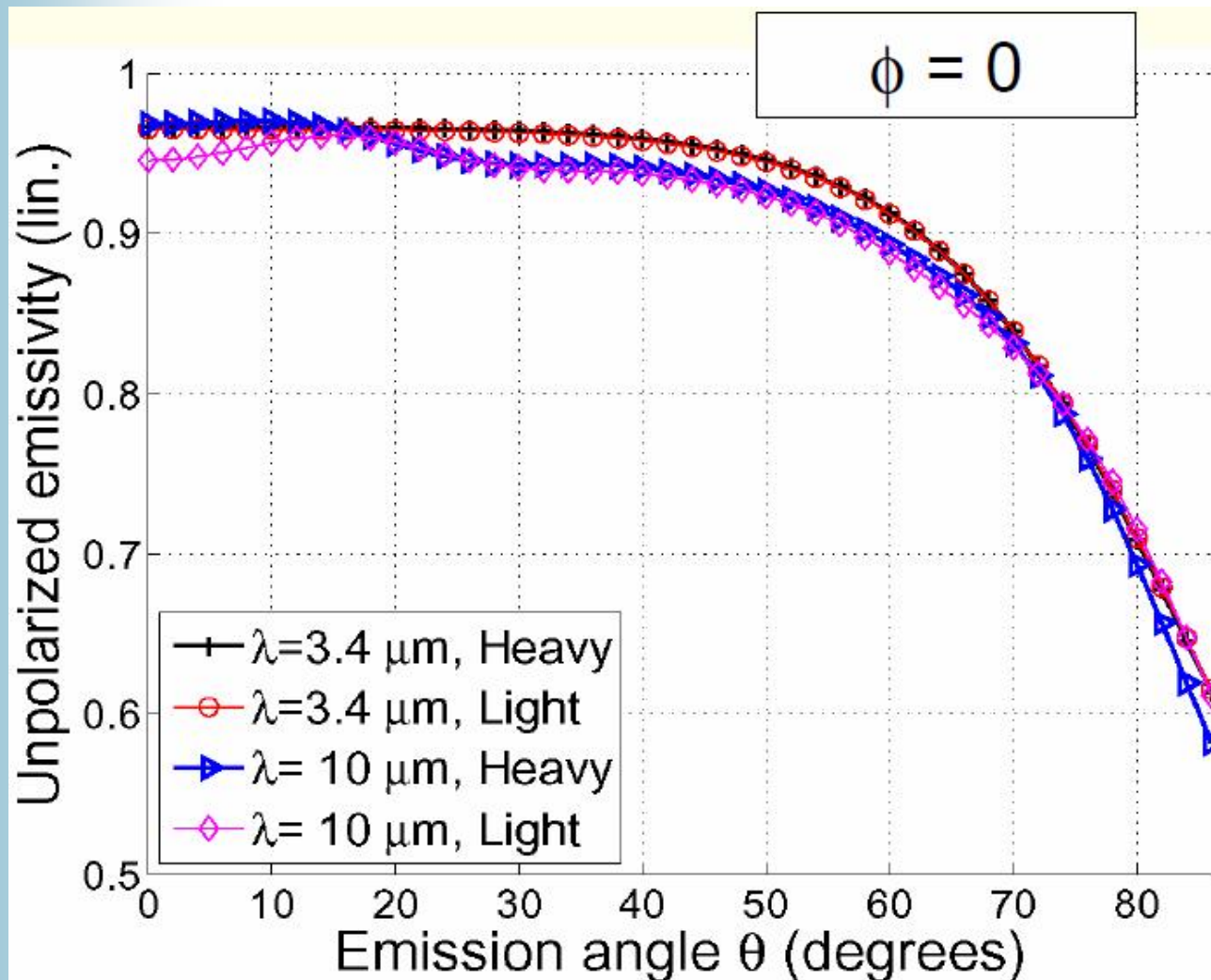
Influence of different oil film thicknesses $H = \{0, 10, 50, 100\} \mu\text{m}$



Oil slick detection possible for any emission angle θ

Oil thickness estimation possible

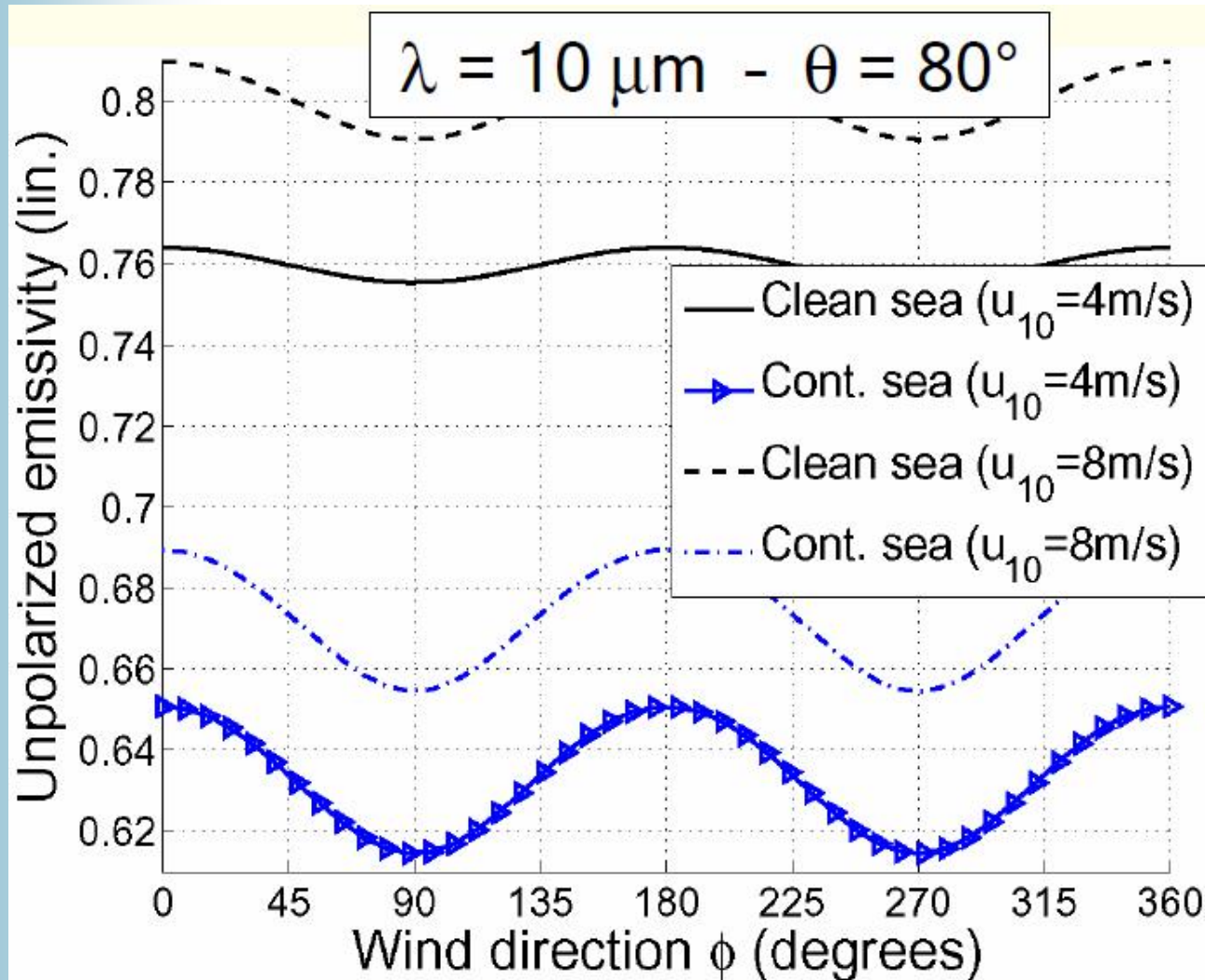
Oil type characterization (heavy or light oil) for $\lambda = \{3.4, 10\} \mu\text{m}$



Oil type
characterization
possible only at
 $\lambda = 10 \mu\text{m}$

for either small or high
emission angles θ

Variations along the wind direction ϕ



Cosine variations along
the wind direction ϕ

I. Introduction

II. Hydrodynamic modeling (surfaces)

III. EM modeling: Thermal IR
emissivity

IV. Conclusion & Future work

- **Hydrodynamic modeling** → Statistical description:
 - ✓ Use of a simple damping model (Lombardini *et al.*)
 - ✓ Surfaces of the contaminated sea assumed to be identical and parallel
- **Electromagnetic modeling:**
 - ✓ Simple intuitive approach (→ Fabry-Pérot interferometer)
 - ✓ Thermal IR emissivity: Application of this approach → GOA
 - ✓ Oil slick detection, characterization, and thickness estimation much easier at $\lambda = 10 \mu\text{m}$
- **Future work:**
 - ✓ Numerical validation of the asymptotic method
 - ✓ More sophisticated damping model
 - ✓ Non Gaussian sea surface with higher orders of emissivity

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UNPOLARIZED INFRARED EMISSIVITY OF OIL FILMS ON SEA SURFACES

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Context and Objective

Context
Maritime domain:
Oil slick detection,
characterization
and quantization

Objective
EM modeling of an oil slick over the sea surface
⇒ To calculate the emissivity of a thin dielectric
homogeneous film separating two rough interfaces

1 rough interface
→ clean sea

2 rough interfaces
→ contaminated sea

Hydrodynamic modeling

Modeling: clean sea / contaminated sea
Surface statistical characterization → 2 key parameters:
1. height distribution (PDF): = Gaussian
2. height spectrum:

- ✓ clean sea: Efochally *et al.* model (Efochally *et al.*, JGR, 1997)
- ✓ contaminated sea: Efochally *et al.* model
- x Marangoni damping coefficient (Lombardi *et al.*, JAGT, 1989)

Characteristics: Independent of layer thickness H

Parameters relative to the type of oil: μ_o, E_o
with values taken to match experimental results:
Zhou and Mann, JOSA, 1994 - (Sengupta and Ermiakoff, 949, 2006)

Isophasic: Homogeneous oil film
Constant oil slick thickness H
Identical parallel interfaces (air/oil and oil/sea)

Gravity waves: Weak damping
Capillary waves: Significant damping

Application to an EM model → Geometric Optics Approximation (GOA)

Oil films: Empirical approach

Empirical approach
Oil slicks on sea surface: low film thicknesses H
⇒ 2 identical surfaces, with capillary-wave damping
⇒ In first approximation, capillary waves neglected

Locally flat parallel surfaces
⇒ Fresnel reflection coefficient r_{ij} of the upper air/oil interface replaced by the equivalent reflection coefficient r_{eq} of the whole air/oil/sea system

$$\Rightarrow r_{eq} = \frac{r_{ao}(\lambda)}{r_{os}(\lambda)} \times r_{os,air}$$

Electromagnetic modeling → GOA

Application to an EM model: GOA:
⇒ Calculation of the emissivity $\epsilon(\theta, \phi)$:

$$\epsilon(\theta, \phi) = \frac{1}{1 + \langle \cos^2 \gamma \rangle} \int \int_{\Omega} (1 - R(\lambda)) \rho_s(\gamma) \cos^2 \gamma \, d\Omega$$

with:

- ρ_s : slope probability density function (PDF) = Gaussian
- ϵ_s : unpolarized power reflection coefficient
- γ : local emission angle

shadowing terms:

- Λ : angular shadowing effect
- $\gamma_s \geq \Lambda$: propagation shadowing effect

Local emissivity of perfectly flat surfaces: $\epsilon^0(\gamma) = 1 - R(\lambda)$
⇒ Computation of $\epsilon(\gamma)$:

Numerical results

Wind speed: $u_w = 7 \text{ m/s}$ - Contaminated sea: Marangoni damp. coef. with $\mu_o = 11 \text{ mN/m}$, $E_o = 1 \text{ mN/m}$

Unpolarized emissivity $\epsilon(\theta, \phi)$ for different oil film thicknesses H

Oil slick detection much easier at $\lambda = 10 \mu\text{m}$ - Thickness estimation possible only at $\lambda = 10 \mu\text{m}$

Oil type characterization for $\lambda = 3.4, 10 \mu\text{m}$

Oil type characterization possible only at $\lambda = 10 \mu\text{m}$

Cosine variations of the emissivity versus the wind direction ϕ