

IREENA

Institut de Recherche en Electrotechnique et Electronique
de Nantes-Atlantique.



Study of asymptotic models of electromagnetic wave scattering from natural interfaces – Application to a sea covered in oil –

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Polytech'Nantes

Outline

I. Introduction

1. Context
2. Objective

II. Scattering from natural interfaces: Generalities

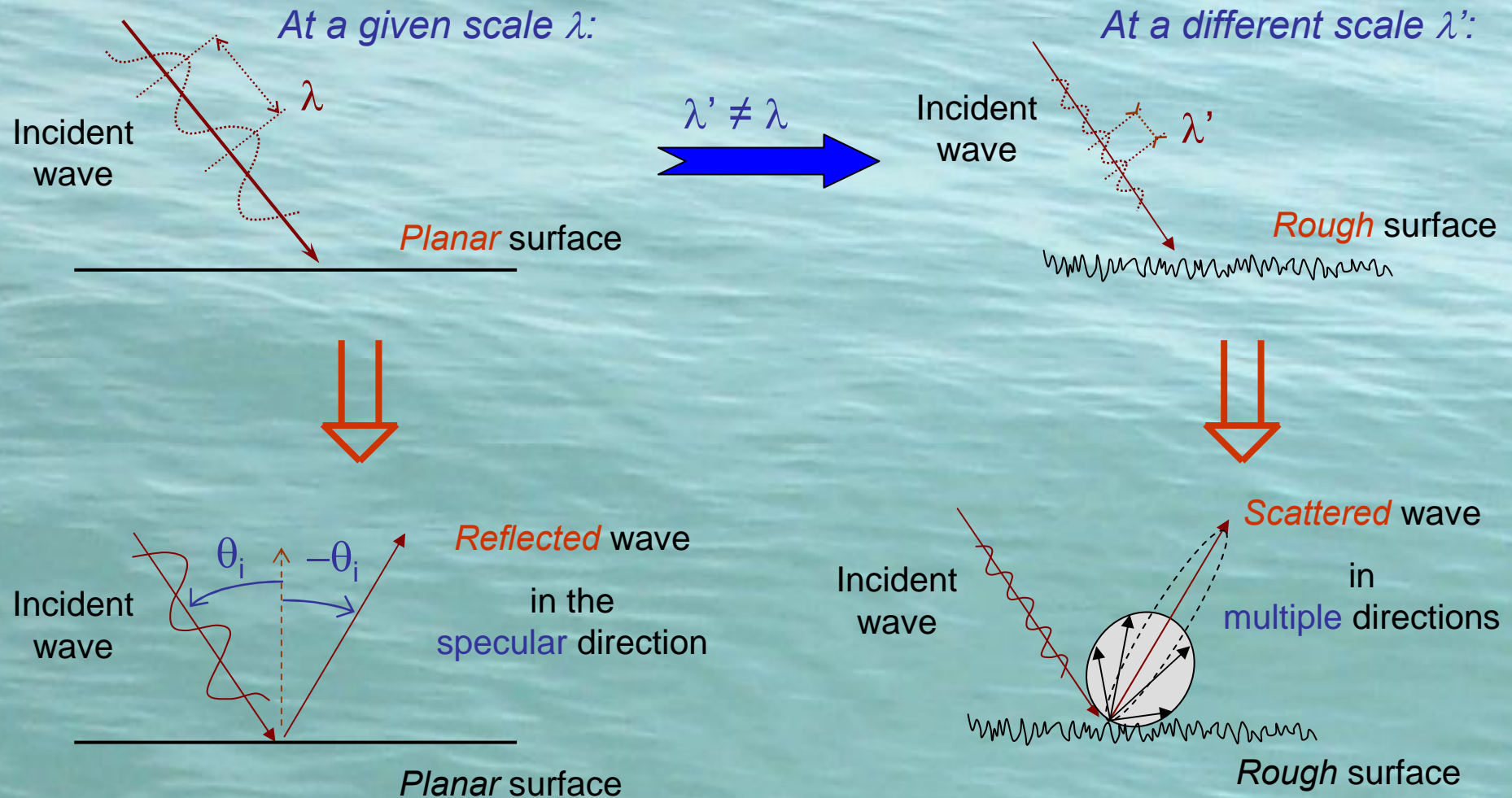
III. Scattering from a very rough interface

IV. Scattering from a very rough layer

V. Conclusion & Prospects

I.1. Context (1/2)

Rough Interfaces (EM): No surface is perfectly planar at *all scales*:

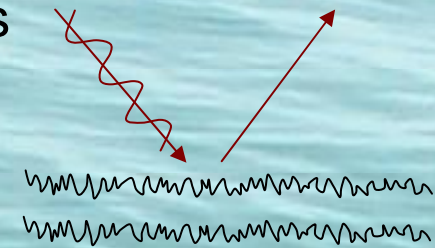
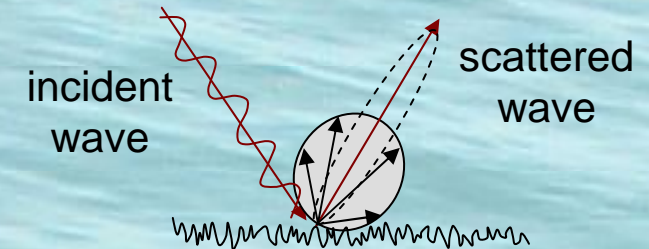


I.1. Context (2/2)

- **EM scattering → Scattering Coefficient (SC)**

$$SC \sim \frac{\text{scattered power}}{\text{incident power}}$$

- one single interface: relatively **well-known**
- **two (or more) rough interfaces**: research in progress

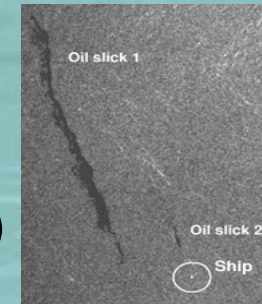


- **Case of 2 rough interfaces: Applications:**



- ✓ **Optics**
(characterization of optical materials, detection of defaults, etc.)

- ✓ **Remote sensing**
(sand on granite, ice on sea, oil on sea, etc.)

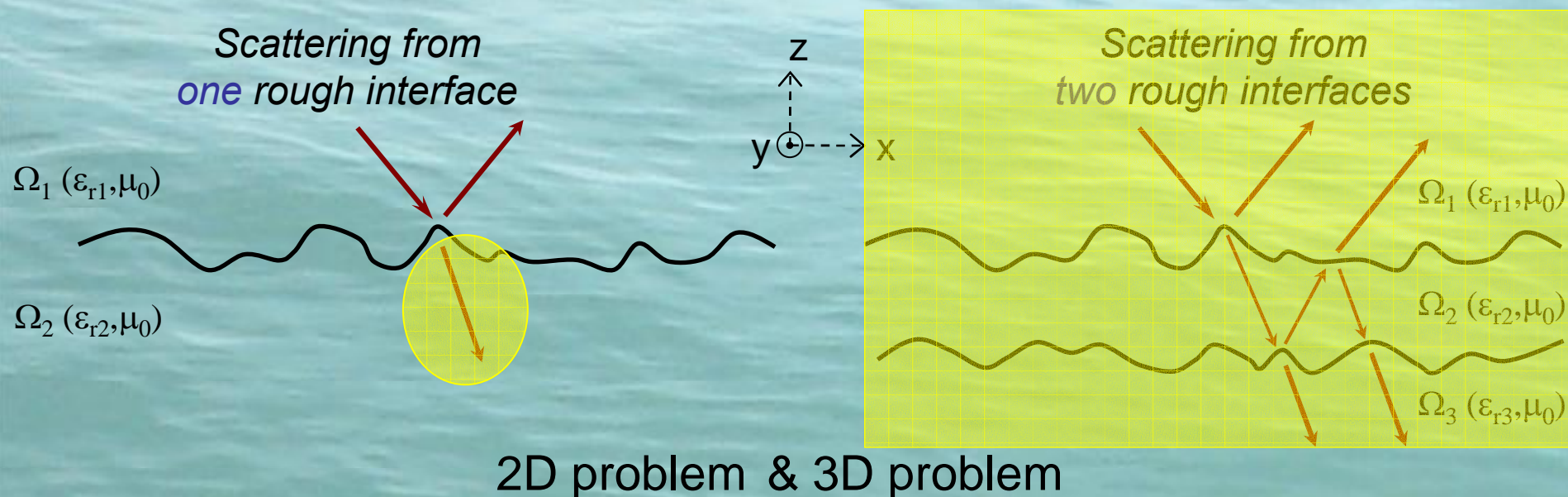


- ✓ Biological tissues sounding, painting and varnish Industry, etc.

I.2. Objective (1/2)

- **Objective**

- ✓ A **fast** method in order to determine the SC scattered by **one** or **two** rough interfaces separating **homogeneous** media



Scattering in **reflection** as well as
in **transmission**

I.2. Objective (2/2)

- **Different possible approaches:**

rigorous

- + 'exact'
- extensive computing time
- extensive memory space

asymptotic

- + fast
- restricted domain of validity

cf. oil slick detection

- **Asymptotic models** (validated by rigorous models):

Analytic determination of the EM response from rough surfaces (SC)
=> Integration in imagery simulators

Outline

I. Introduction

**II. Scattering from natural interfaces:
Generalities**

1. Natural interfaces: Statistical description
2. Case of sea and oil slick surfaces
3. Electromagnetic roughness: Rayleigh parameters

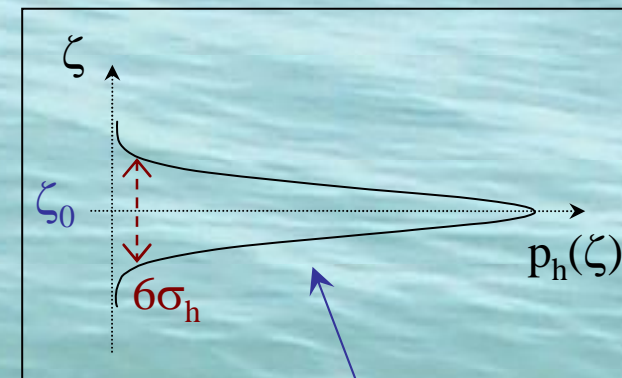
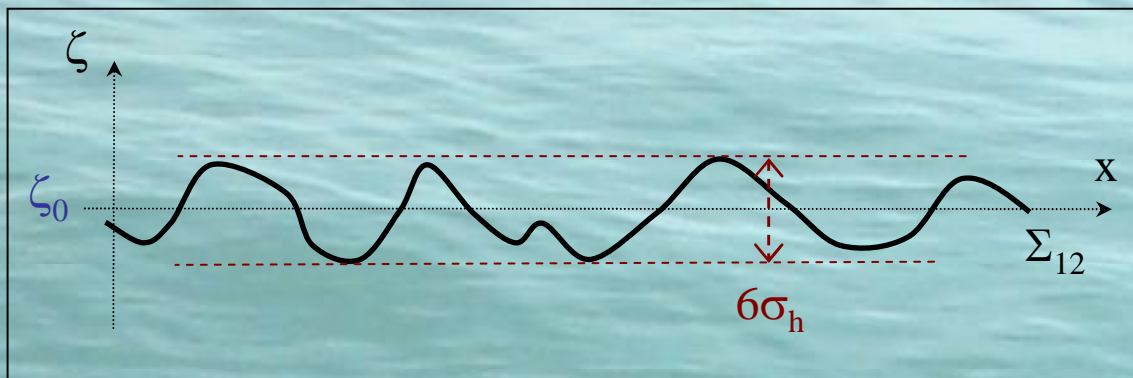
III. Scattering from a very rough interface

IV. Scattering from a very rough layer

V. Conclusion & Prospects

II.1. Natural interfaces: Statistical description (1/3)

- Height distribution: $p_h(\zeta)$
 - Mean value $\zeta_0 = \langle \zeta(x) \rangle$
 - Characteristic dispersion around ζ_0 : Standard deviation σ_h



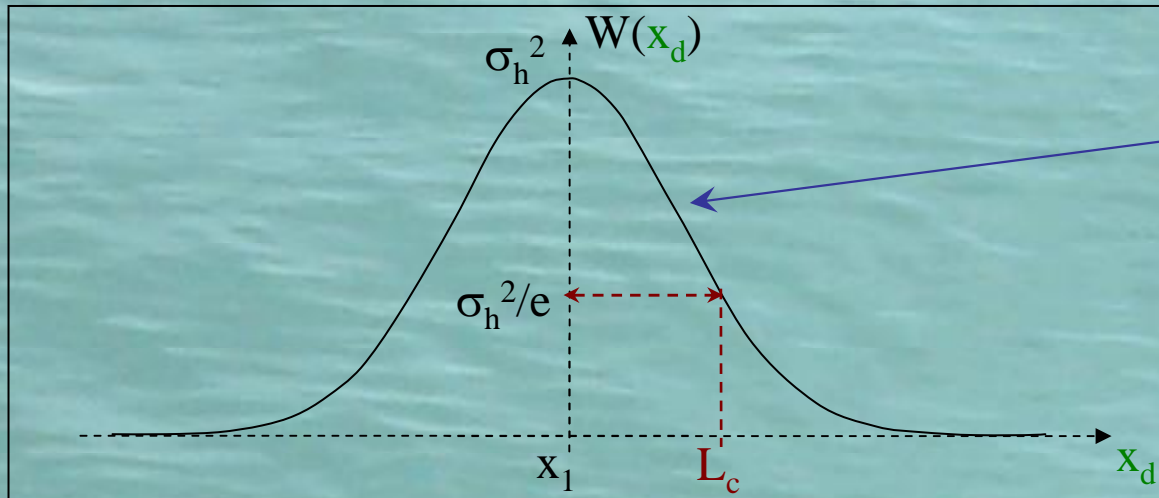
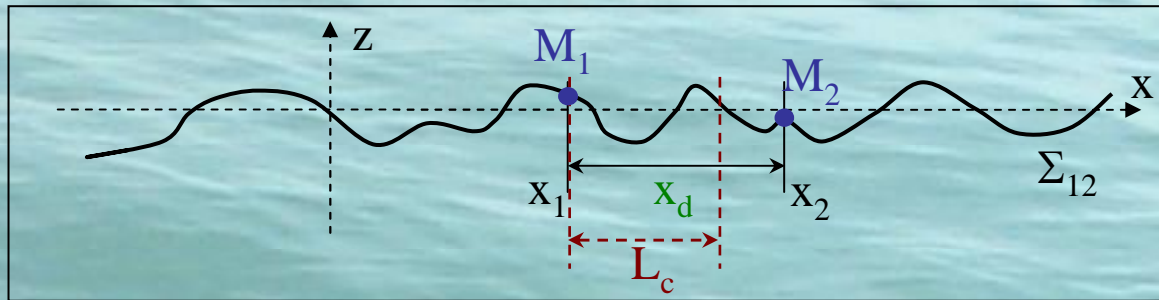
- Height autocorrelation function: $W(x_d)$
- Other statistical description tools

II.1. Natural interfaces: Statistical description (2/3)

- Height autocorrelation function: $W(x_d) = \langle \zeta(x_1) \zeta(x_2) \rangle$

– Correlation length L_c :

$$x_d \gg L_c \Rightarrow M_1, M_2 \text{ uncorrelated}$$



II.1. Natural interfaces: Statistical description (3/3)

- Other statistical description tools:
 - Slope distribution $p_s(\gamma)$
 - Height spectrum $S(k, \phi)$ (*FT of height autocorrelation function*)
 - Slope spectrum $k^2 S(k, \phi)$
 - etc. (*other derivatives of height spectrum*)

Different types of distributions:

- Simple distributions: Gaussian, etc.
- Natural interfaces => more complex descriptions...

II.2. Case of sea and oil slick surfaces (1/6)

- Sea surface: Qualitative description:

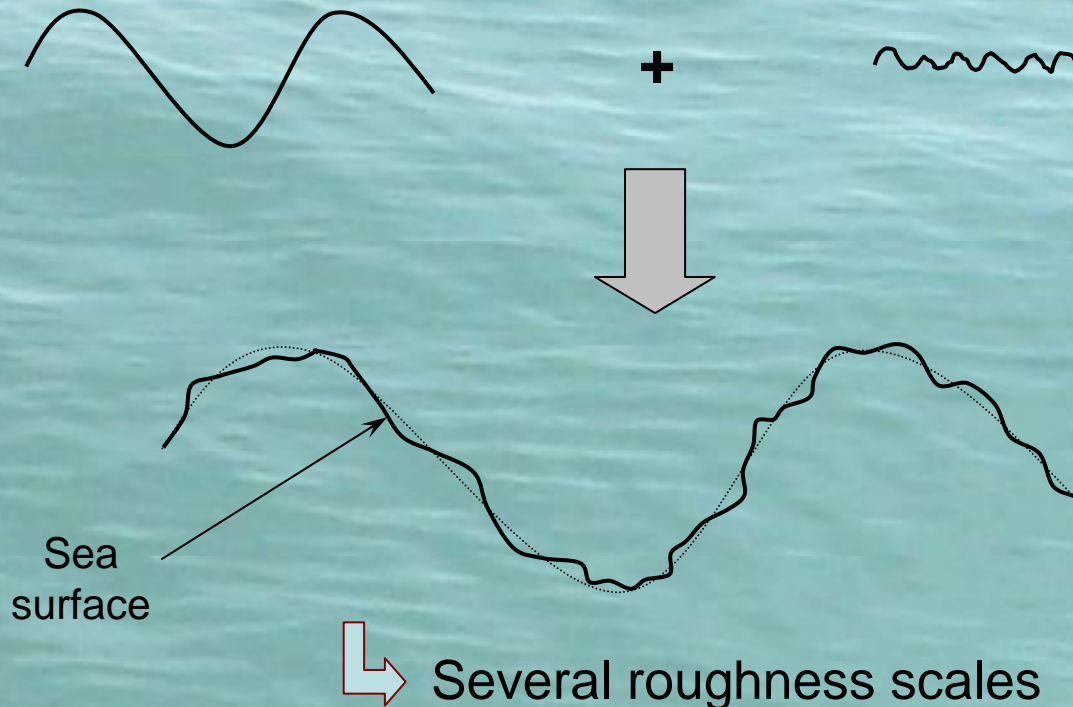
Gravity and capillarity waves:

Gravity waves:

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

Capillarity waves:

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



II.2. Case of sea and oil slick surfaces (2/6)

- Sea surface: Statistical description:
 - Height distribution function $p_h(\zeta)$: ~ Gaussian
 - Height spectrum $S_{\text{sea}}(k, \phi)$:
Elfouhaily et al. spectrum model [1]:
 - Semi-empirical model
 - Consistent with Cox & Munk experimental model [2]
→ slope variance σ_s^2
 - Slope distribution function $p_s(\gamma)$: ~ Gaussian

[1]: [*Elfouhaily et al., Journal of Geophysical Research, 1997*]

[2]: [*Cox and Munk, J. Opt. Soc. Am., 1954*]

II.2. Case of sea and oil slick surfaces (3/6)

- Sea covered in oil: Qualitative description:

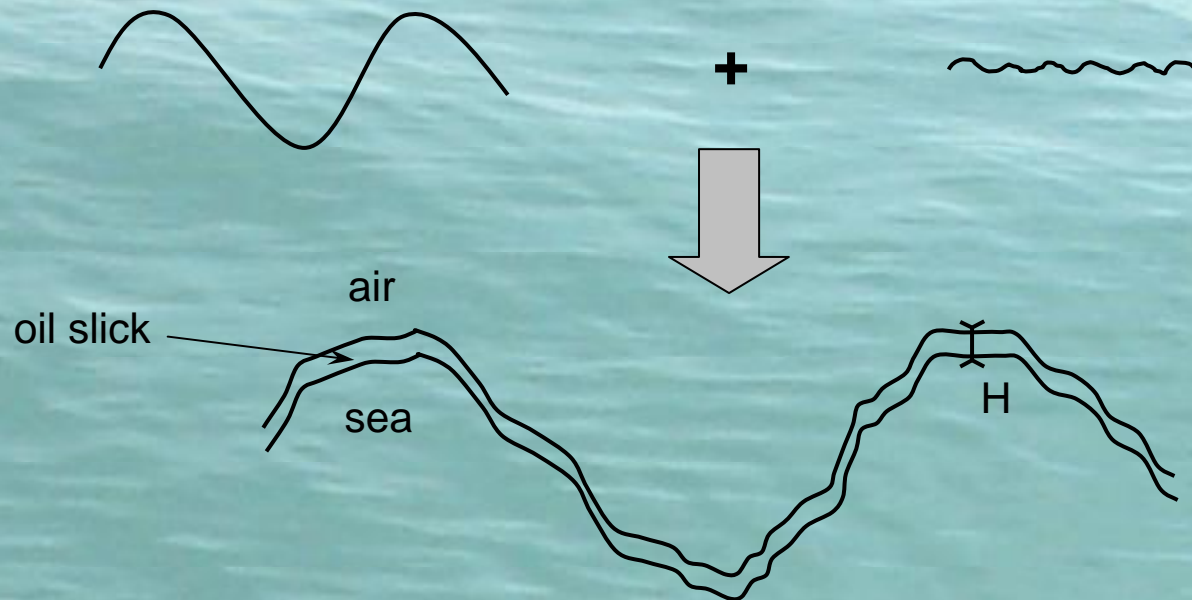
Damping of capillarity waves of both surfaces:

Gravity waves:

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

Capillarity waves:

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



Yet damping dependent on various parameters (layer thickness, ...)

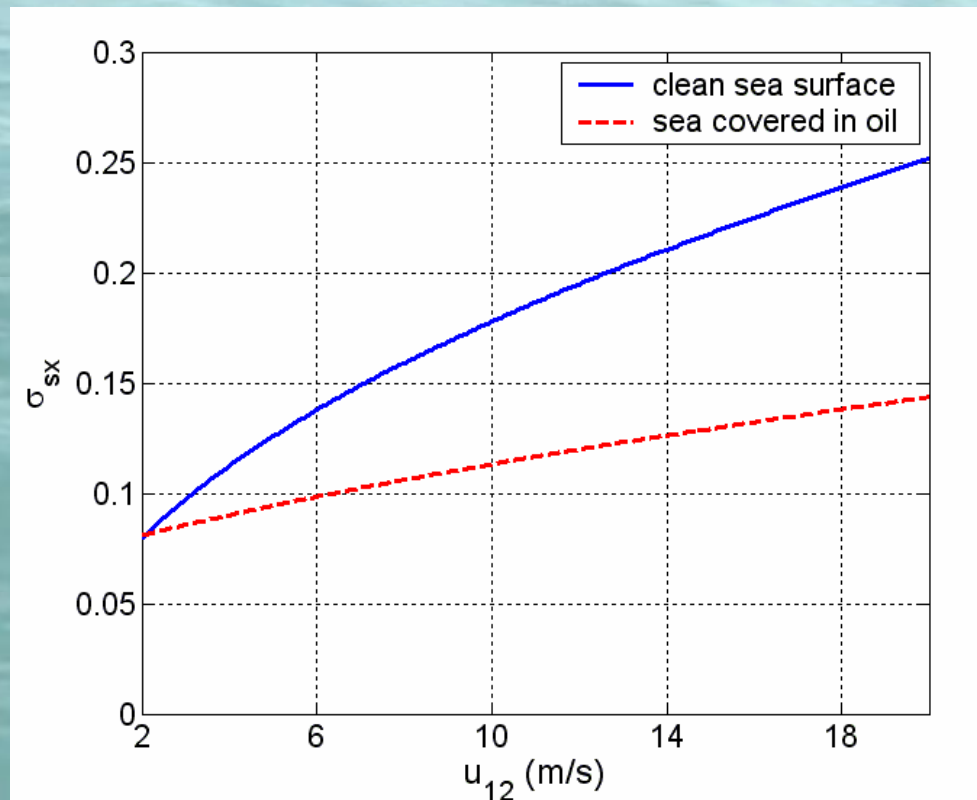
II.2. Case of sea and oil slick surfaces (4/6)

- Slope variance comparison:

- Clean sea surface: $\sigma_{sx}^2 \approx 3.16 \times 10^{-3} u_{12}^2$ [2]

- Sea covered in oil: $\sigma_{sx}^2 \approx 0.78 \times 10^{-3} u_{12}^2 + 5 \times 10^{-3}$ [2]

} From experiments

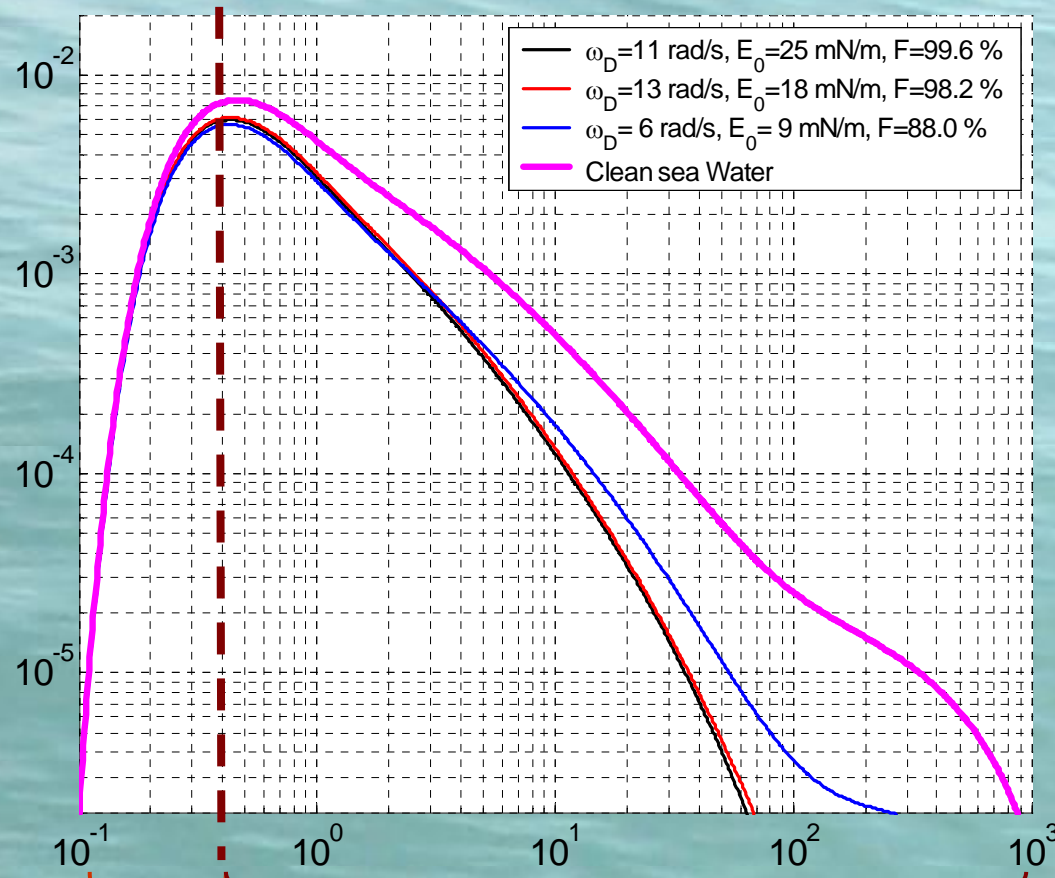


Oil → damping of slopes

[2]: [Cox and Munk, *J. Opt. Soc. Am.*, 1954]

II.2. Case of sea and oil slick surfaces (5/6)

- *Lombardini et al. [3]*: independent of layer mean thickness H :



Parameters relative to oil type:

$$\omega_D, E_0$$

*Retrieval from experiments
in the Sicilian Channel
and the Gulf of Maine*

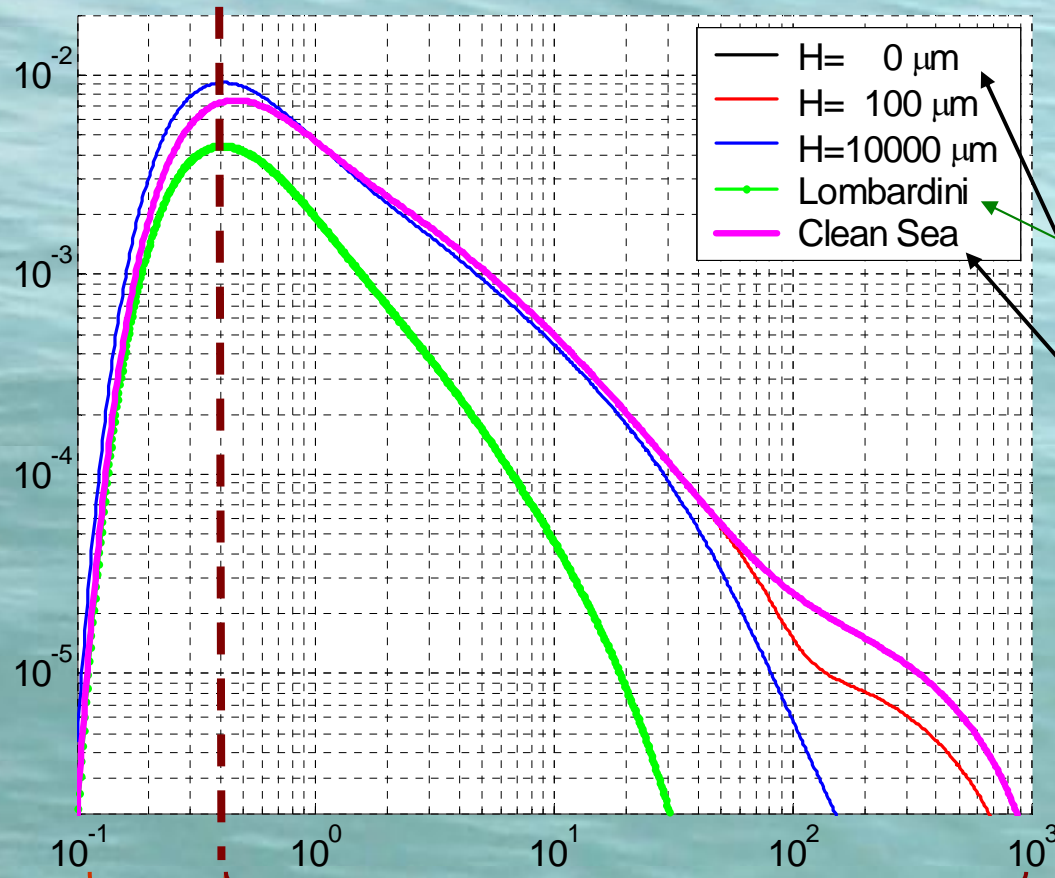
Gravity waves:
Weak damping

Capillarity waves:
Strong damping

[3]: [*Lombardini et al., J. Atm. Oc. Tech., 1989*]
[*Bourlier, APS/URSI Conf., 2006*]

II.2. Case of sea and oil slick surfaces (6/6)

- *Jenkins and Jacobs* [4]: dependent on layer mean thickness H :



Parameters relative to oil type:
8 parameters (fluid mechanics)

$$\omega_D = 11 \text{ rad/s}, E_0 = 25 \text{ mN/m}$$

Identical

Stronger damping for
Lombardini et al. model

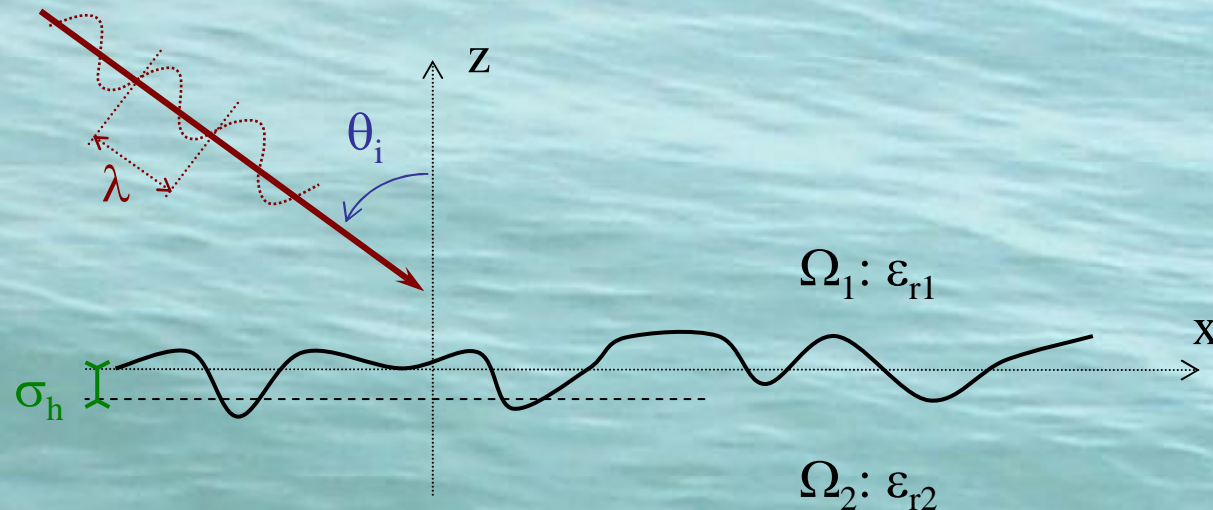
Gravity waves:
Weak damping

Capillarity waves:
Strong damping

[4]: [*Jenkins and Jacobs, Physics Fluids, 1997*]
[*Bourlier, APS/URSI Conf., 2006*]

II.3. Electromagnetic roughness: Rayleigh parameters (1/6)

- EM roughness → term **non intrinsic** to the surface:
dependent not only on λ , but also on (σ_h, θ_i)



- Determines the choice for the asymptotic method to be used to solve the problem

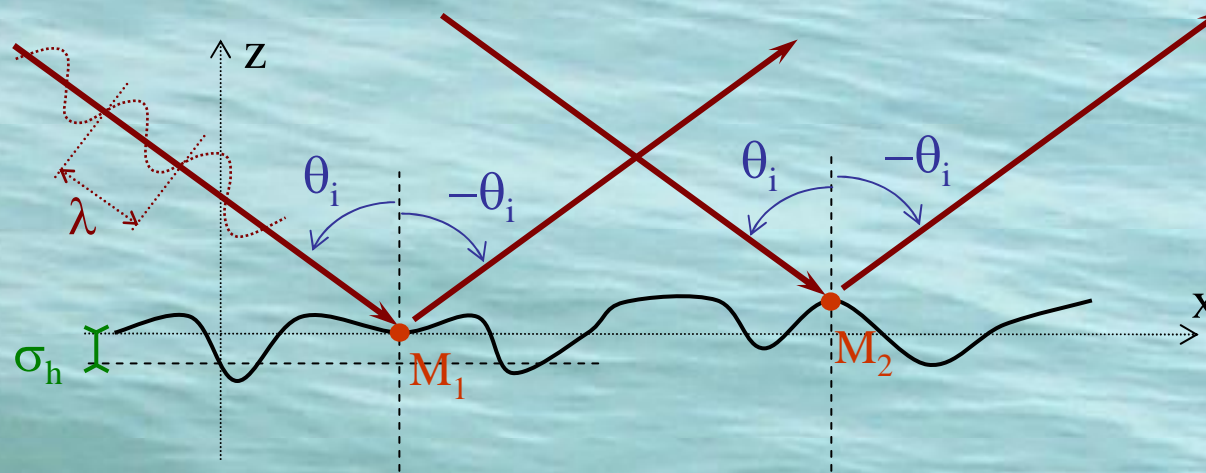
- Characterized by a parameter:

Rayleigh roughness parameter (R_a): $R_a \leftarrow \Delta\phi_{M_1M_2}$

$\Delta\phi_{M_1M_2}$ = phase difference between two arbitrary points (M_1, M_2) of the surface

II.3. Electromagnetic roughness: Rayleigh parameters (2/6)

- R_a : expressed for the case of **reflection** on the surface



- For a surface of infinite extent:

$$R_a = 2\pi \left(\frac{\sigma_h}{\lambda} \right) \cos\theta_i$$

Qualitatively, it is said for the choice of asymptotic models:

- $\sigma_h \ll \lambda$: Small Perturbation Method (SPM) can be used
- $\sigma_h \gg \lambda$: **Geometric Optics Approximation (GOA)** can be used

II.3. Electromagnetic roughness: Rayleigh parameters (3/6)

$$E_s = \underbrace{\langle E_s \rangle}_{\text{Mean component}} + \underbrace{\delta E_s}_{\text{Random component}}$$

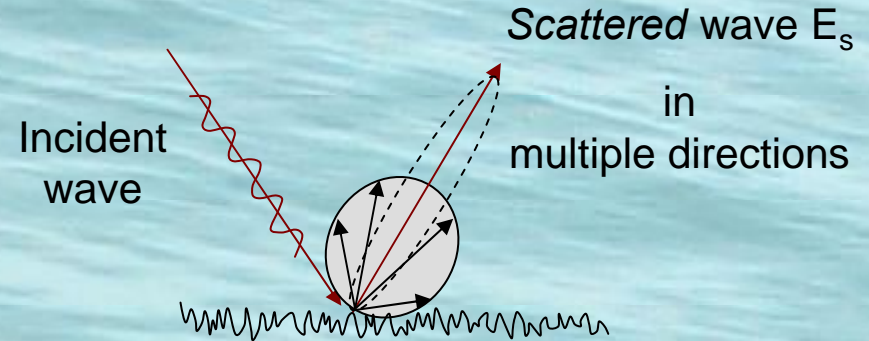
Mean component

In specular direction:

$$\langle E_s \rangle \sim E_{r0} \exp(-2R_a^2)$$

(Gaussian)

Random component
In multiple directions



$$\text{Scattered power } P_s \sim \langle |E_s|^2 \rangle \begin{cases} \text{Coherent power } P_{s,\text{coh}} \sim |\langle E_s \rangle|^2 \sim |E_{r0}|^2 \exp(-4R_a^2) \\ \text{Incoherent power } P_{s,\text{inc}} \sim \langle |\delta E_s|^2 \rangle \end{cases}$$

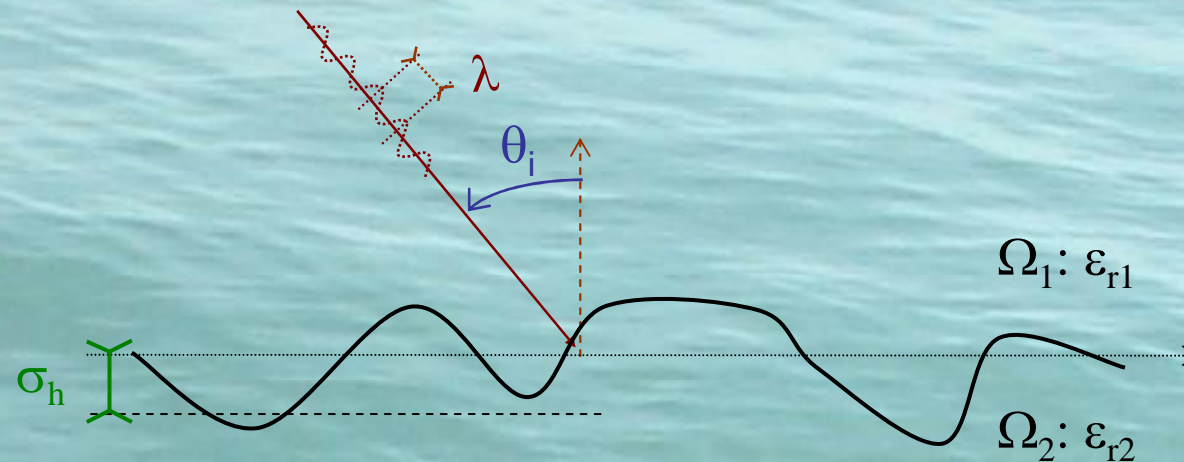
$$\begin{cases} P_{s,\text{coh}} \gg P_{s,\text{inc}} \Rightarrow R_a \ll 1 \Rightarrow \sigma_h \ll \lambda/2\pi \\ P_{s,\text{coh}} \ll P_{s,\text{inc}} \Rightarrow R_a \gg 1 \Rightarrow \sigma_h \gg \lambda/2\pi \end{cases}$$

II.3. Electromagnetic roughness: Rayleigh parameters (4/6)

- GOA Model (single scattering):

- $P_{s,coh} \ll P_{s,inc} \Rightarrow R_a \gg 1 \Rightarrow \sigma_h \gg \lambda/2\pi$ (moderate θ_i):

- Strongly** rough surface σ_h comparatively to the EM wavelength λ



- Single scattering: $\sigma_s < 0.5$

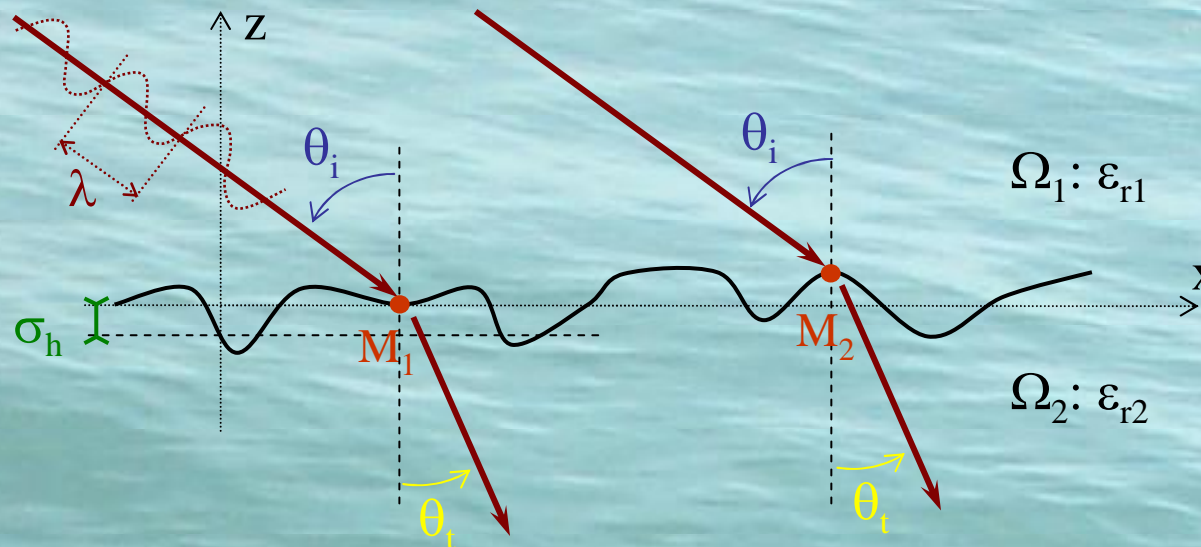
[Ishimaru et al., PIER 14, 1996]

[Bourlier et al., WRM, 2004]

- SC $\sim p_s(\gamma)$, with $p_s(\gamma)$ surface slope PDF

II.3. Electromagnetic roughness: Rayleigh parameters (5/6)

- $R_{a,t}$: extension to **transmission** through the surface



- For a surface of infinite extent:

$$R_{a,t} = k_0 \sigma_h (n_1 \cos \theta_i + n_2 \cos \theta_t) / 2, \quad \text{with } n_1 \sin \theta_i = n_2 \sin \theta_t$$

$$R_{a,r} = k_0 \sigma_h n_1 \cos \theta_i$$

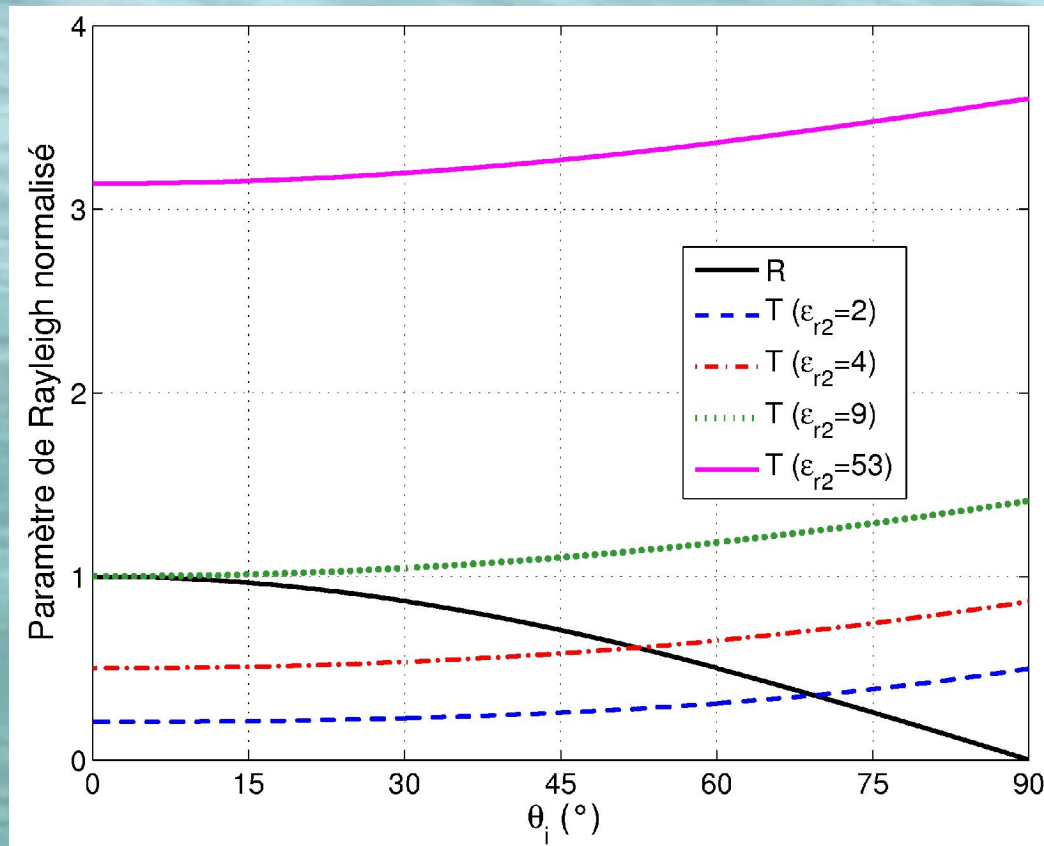


Comparison between $R_{a,r}$ and $R_{a,t}$:

Slightly / Strongly rough surface in case of Ref. or Trans.

II.3. Electromagnetic roughness: Rayleigh parameters (6/6)

Comparison between $R_{a,r}$ and $R_{a,t}$ (for $k_0\sigma_h=1$, $\epsilon_{r1}=1$):



$\epsilon_{r2} > 9$: $R_{a,t} > R_{a,r}$ for all θ_i

$\epsilon_{r2} \leq 9$: $R_{a,t} > R_{a,r}$

for $\theta_i^{rug} > \arccos\left(\sqrt{\frac{\epsilon_{r2} - \epsilon_{r1}}{8\epsilon_{r1}}}\right)$

↳ A surface can be rougher / smoother in reflection / transmission

Outline

I. Introduction

II. Scattering from natural interfaces: Generalities

III. Scattering from a very rough interface

1. Analytic methods: State of the art
2. Kirchhoff Approximation and Geometric Optics Approximation
3. Energy conservation of the model

IV. Scattering from a very rough layer

V. Conclusion & Prospects

a single rough interface



III.1. Analytic (asymptotic) methods: State of the art

Topical Review: [Elfouhaily & Guérin, WRM, 2004]

Small Perturbation Method ($\sigma_h \ll \lambda$)

Reduced Rayleigh Equations ($\sigma_h \ll \lambda$)

Low Frequency approximations

Kirchhoff Approximation ($R_c > \lambda$)

↳ Geometric Optics approximation ($R_c > \lambda + \sigma_h > \lambda/2$)

↳ Scalar Kirchhoff Approximation ($R_c > \lambda + \sigma_h \ll \lambda$)

High Frequency approximations

Small Slope Approximation ($\sigma_s \ll |\gamma_{i,r}|$)

Full Wave Model

Unified approximations

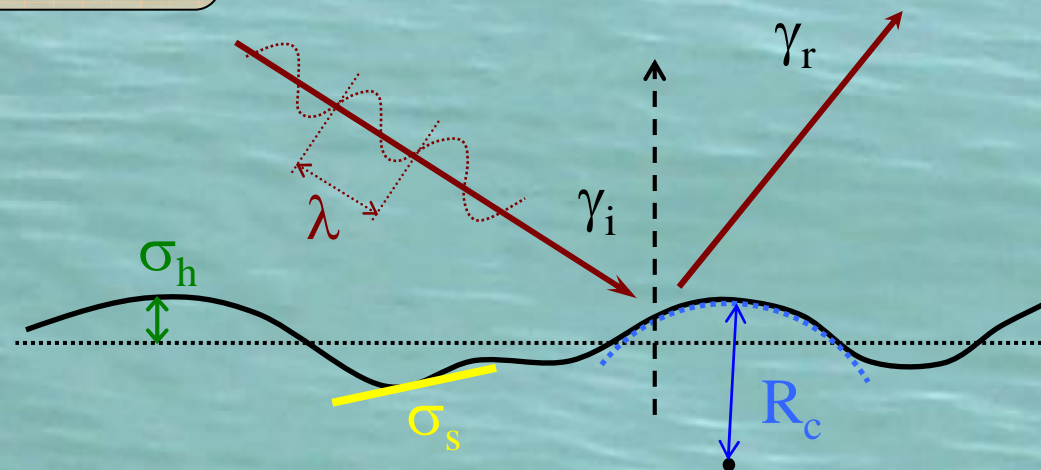
etc.

λ : incident EM wavelength

σ_h : rms surface height

σ_s : rms surface slope

R_c : mean surface curvature radius



III.2. Kirchhoff Approximation (KA)

(Infinite) Tangent plane approximation:

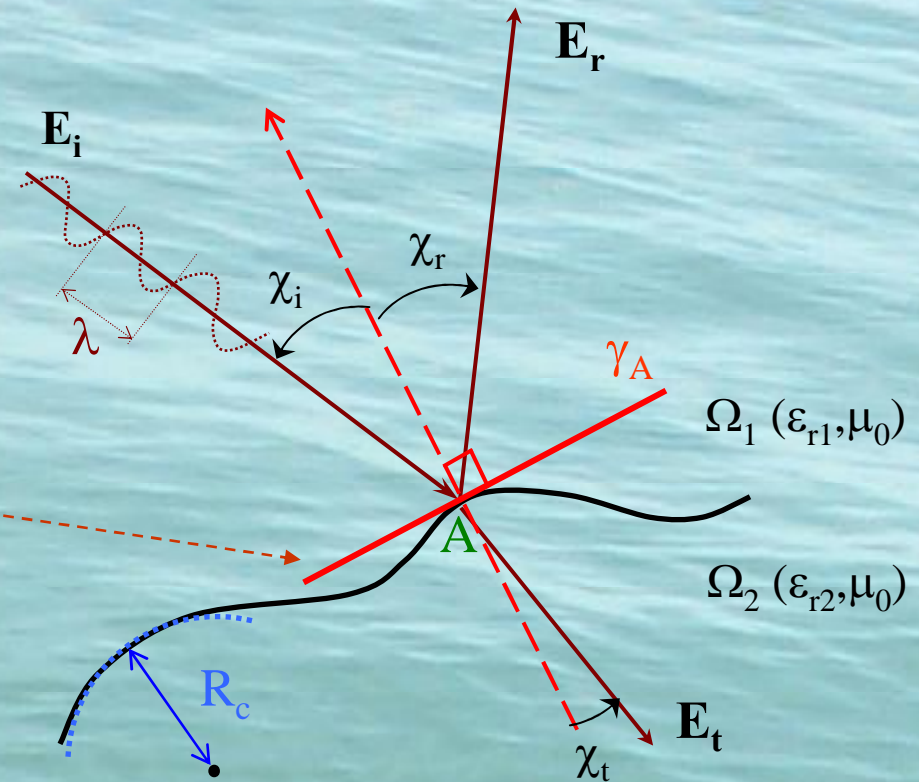
$$R_c > \lambda$$

(infinite) locally smooth surface

At each surface point A :

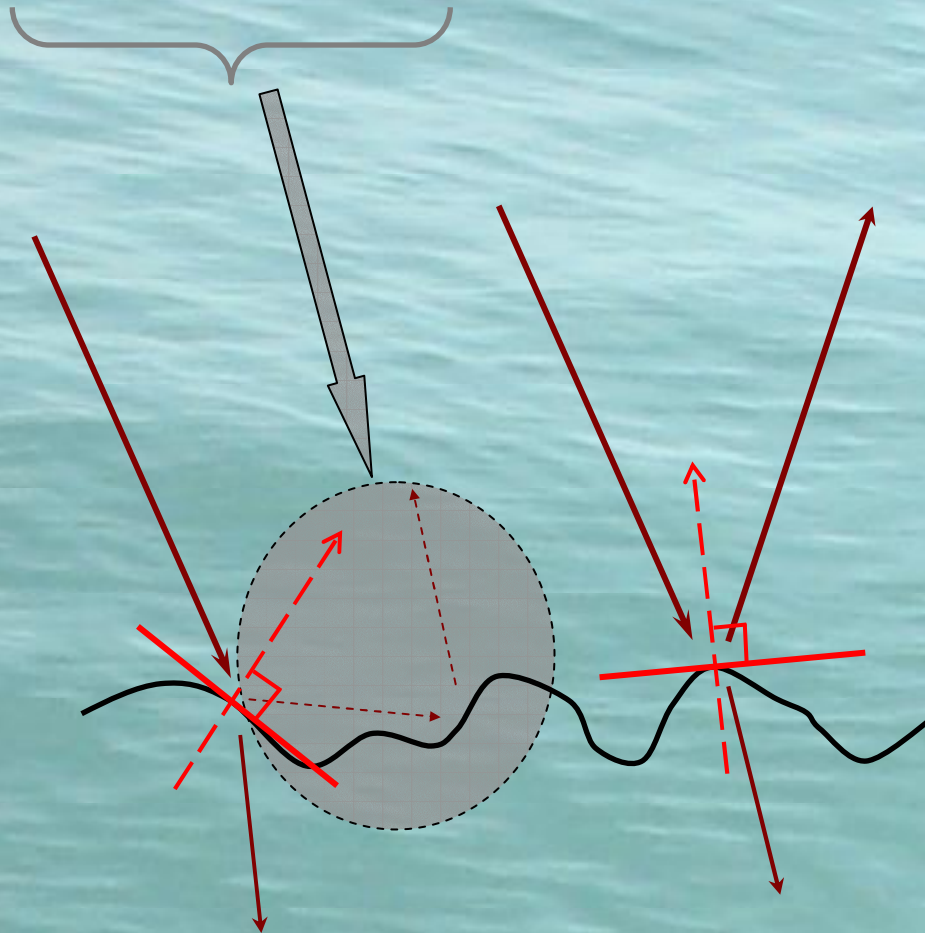
- the Snell-Descartes laws
 - the Fresnel coefficients
- } can be used

\Rightarrow directions and amplitudes of \mathbf{E}_r , \mathbf{E}_t corresponding to each scattering point A (γ_A) at any point of the considered medium



III.2. First-order Kirchhoff Approximation (KA-1)

Multiple scattering phenomenon



Only the
first scattering
is taken into account:

KA-1

valid for $\sigma_s < \sim 0.5$ ($\sim 30^\circ$) [5,6]
 $R_c > \lambda$

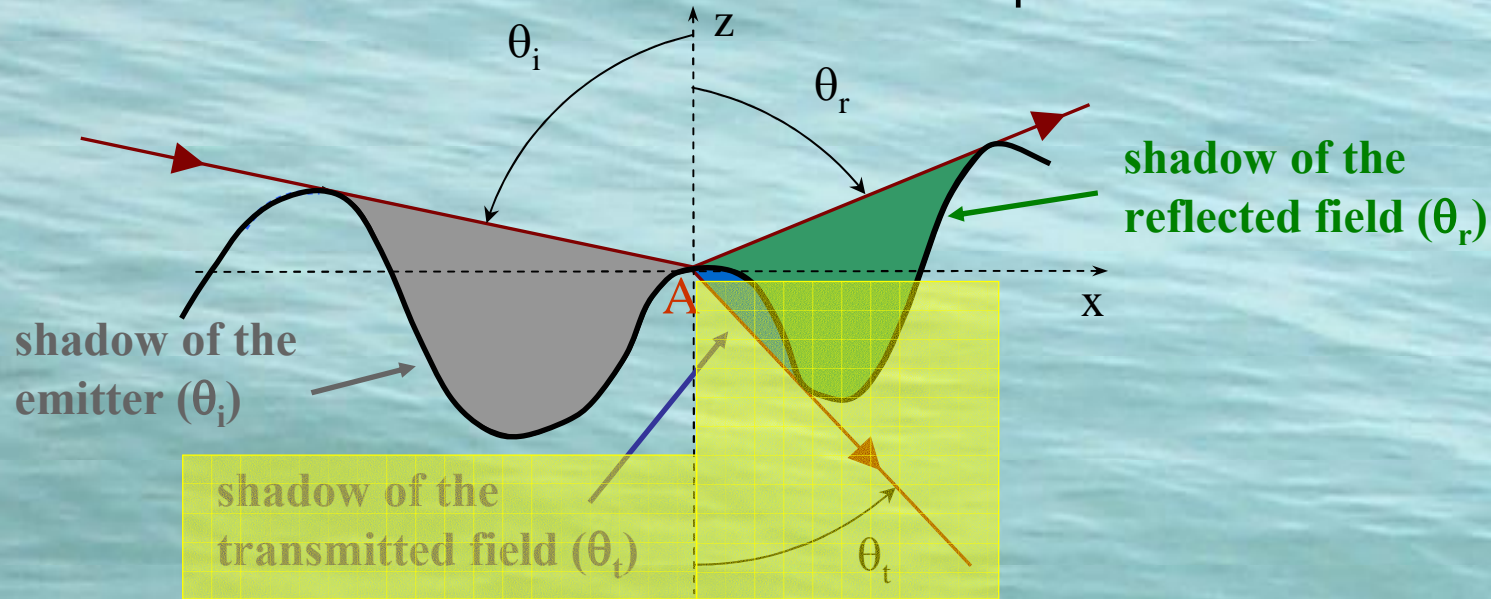
[5]: [Ishimaru et al., PIER 14, 1996]

[6]: [Bourlier et al., WRM, 2004]

III.2. KA-1 improvement: the shadowing function

Grazing angles ($\theta_i, \theta_r, \theta_t$): a part of the surface is in the *shadow*

↳ over-prediction of the SC (KA-1)



⇒ Illumination function $\Sigma(A)$

$$\begin{cases} = 1 & \text{if } A \text{ is not in the shadow} \\ = 0 & \text{if } A \text{ is in the shadow} \end{cases}$$

↳ Average shadowing function

$$\begin{cases} S_{11}(\theta_i, \theta_r) & \text{[Wagner, JASA, 1967],} \\ & \text{[Bourlier et al., WRM, 2002]} \\ S_{12}(\theta_i, \theta_t) & \text{[Pinel et al., OL, 2005]} \end{cases}$$

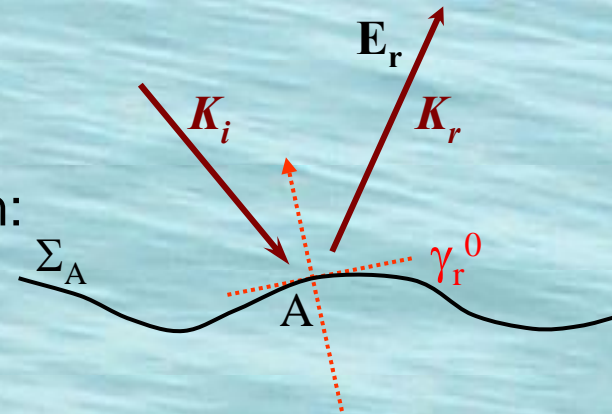
+ does not increase the computing time – more precise model

III.2. Simplifications to the model

- **Method of stationary phase (MSP):**

The main contribution of the scattered field $E_{r,t}$ comes from regions around the specular direction:

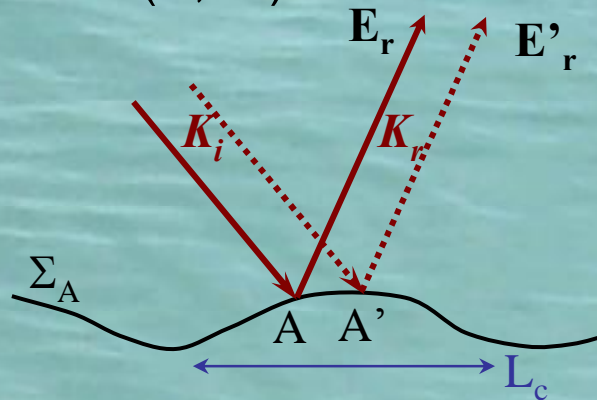
$$\gamma_A \rightarrow \gamma_{r,t}^0 \text{ determined by } \mathbf{K}_i \text{ and } \mathbf{K}_{r,t}$$



- **Geometric Optics Approximation (GOA) or ray optics:**

$$\text{valid if } P_{r,t,\text{coh}} \ll P_{r,t,\text{inc}} \Rightarrow k_0 \sigma_h \gg 1 \text{ (moderate } \theta_i)$$

The scattered power $P_{r,t}$ contributes only for closely-located correlated points (A, A') of the surface: $|x_{A'} - x_A| \ll L_c$



=> Simple expressions of the SC $\sigma_{r,t}$: no numerical integration

III.2. Analytic expression of $\sigma_{r,t}$ under AK+MSP+GOA

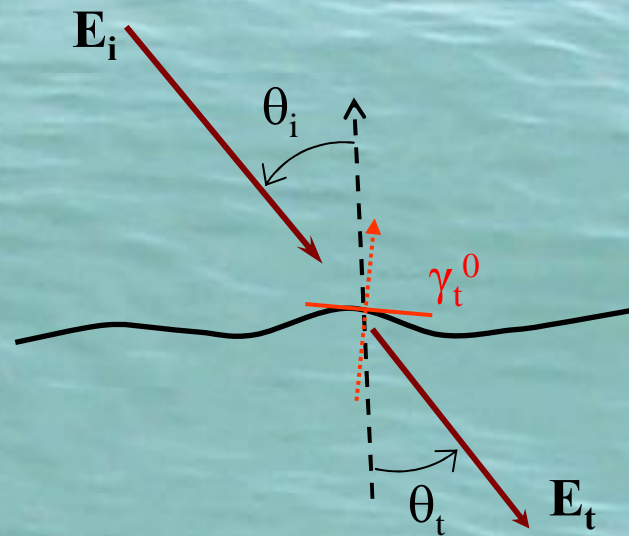
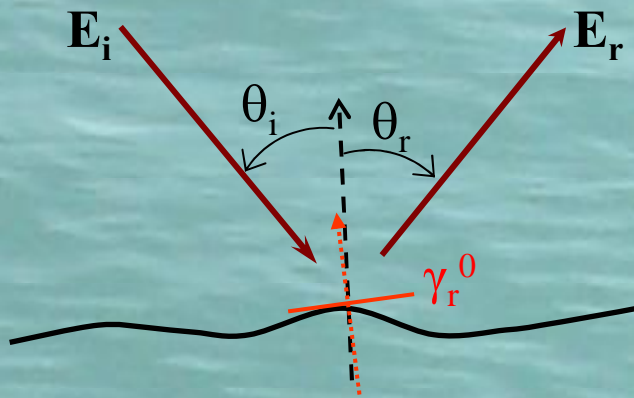
Reflection / Transmission Scattering Coefficient $\sigma_{r,t}$:

$$\sigma_{r,t} = f(\theta_i, \theta_{r,t}) \times p_s(\gamma_{A,r,t}^0) \times S(\theta_i, \theta_{r,t})$$

dependent on the Fresnel reflection / transmission coefficient

probability density function (gives the specular direction)

shadowing function $\in [0,1]$



III.3. Energy conservation of the model

- Calculation of reflectivity and transmissivity: in 2D:

$$\mathcal{R}(\theta_i) = \frac{P_r(\mathbf{K}_i)}{P_i(\mathbf{K}_i)} = \int_{-\pi/2}^{+\pi/2} \sigma_r(\mathbf{K}_r, \mathbf{K}_i) d\theta_r,$$
$$\mathcal{T}(\theta_i) = \frac{P_t(\mathbf{K}_i)}{P_i(\mathbf{K}_i)} = \int_{-\pi/2}^{+\pi/2} \sigma_t(\mathbf{K}_t, \mathbf{K}_i) d\theta_t.$$

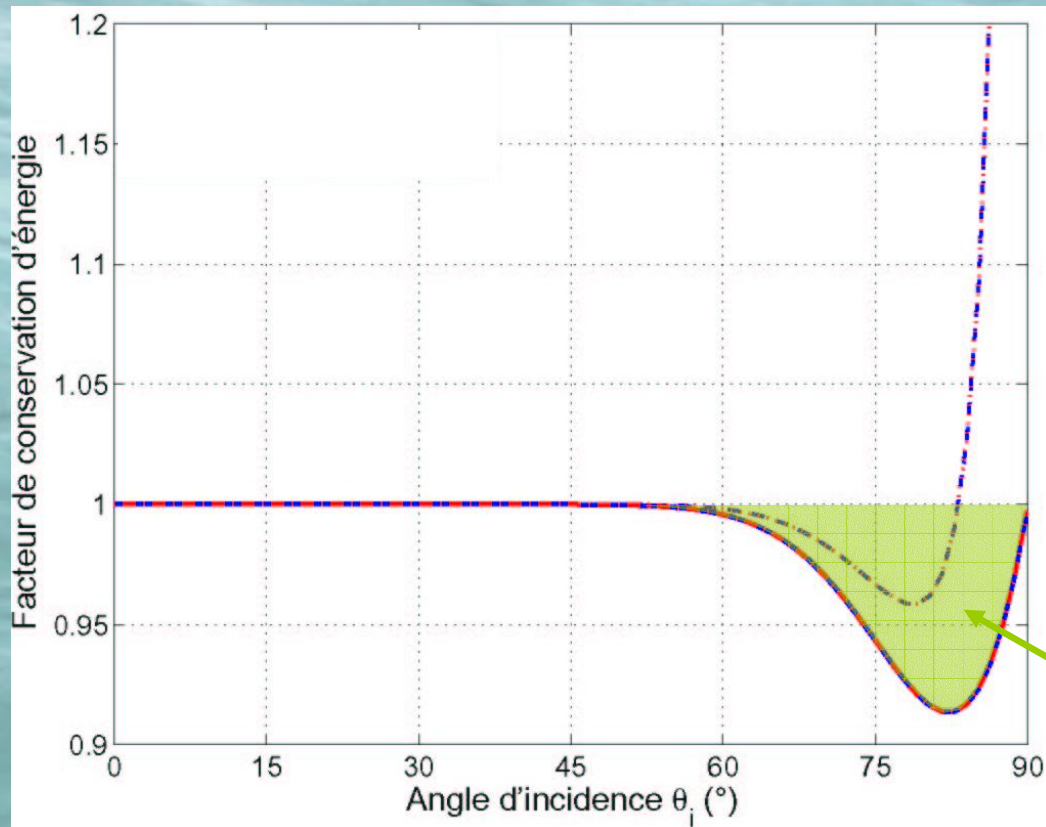
- In theory, one should have:

$$\eta(\theta_i) = \mathcal{R}(\theta_i) + \mathcal{T}(\theta_i) = 1$$

- Comparison of energy conservation factor $\eta(\theta_i)$ with 1:
 - => *Validate the numerical codes*
 - => Validate the shadowing functions
 - => Quantify the multiple scattering

III.3. Energy conservation of the model: Numerical results (2D)

Study of energy conservation factor $\eta(\theta_i)$: Perfectly Conducting case



rms slope $\sigma_s = 0.1$

- - V Polar (no shadow)
- ... H Polar (no shadow)
- . V Polar (shadow)
- .- H Polar (shadow)

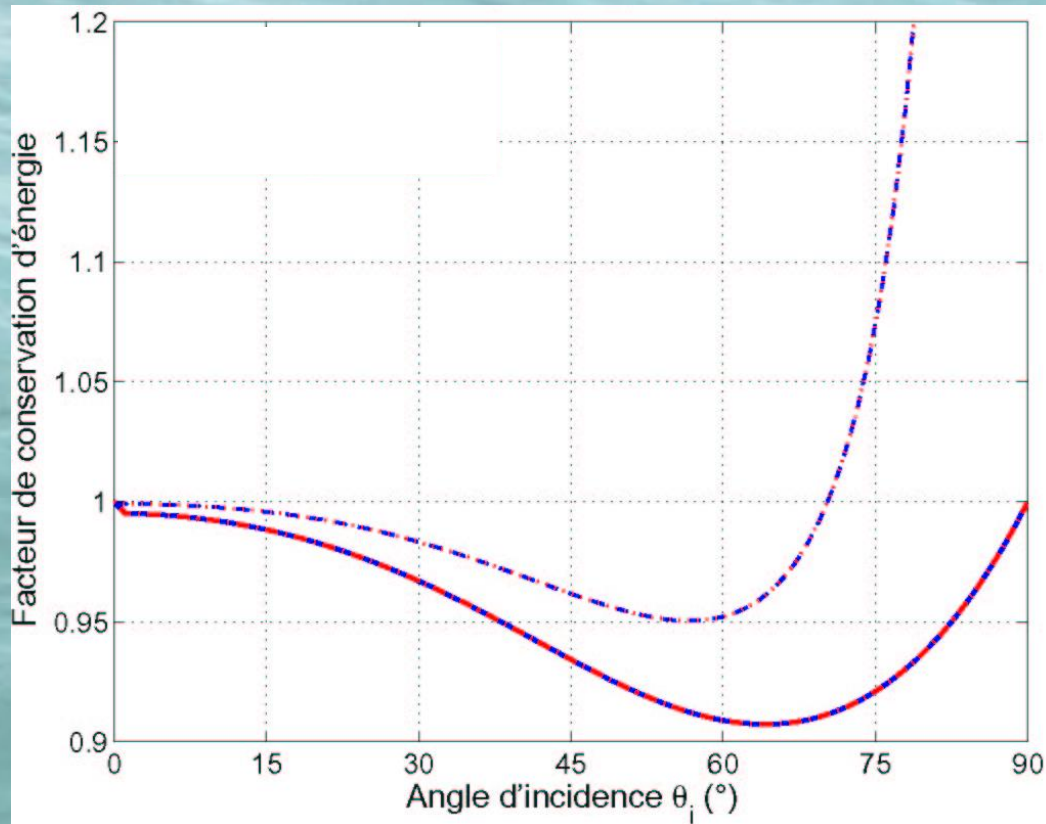
Model without shadow: diverges

Model with shadow: ≤ 1 . Difference \rightarrow Multiple scattering

Good energy conservation rate for moderate incidence angles

III.3. Energy conservation of the model: Numerical results (2D)

Study of energy conservation factor $\eta(\theta_i)$: Perfectly Conducting case



rms slope $\sigma_s = 0.3$

- V Polar (no shadow)
- ... H Polar (no shadow)
- . V Polar (shadow)
- . - H Polar (shadow)

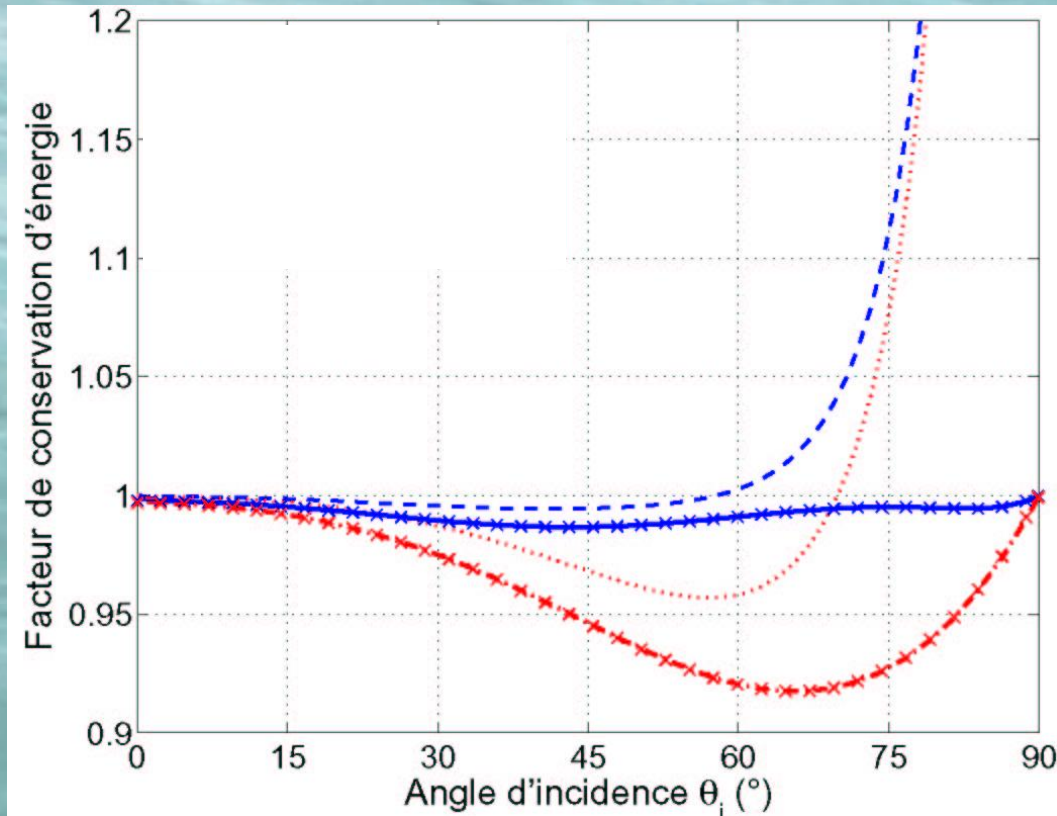
Model without shadow: diverges

Model with shadow: ≤ 1 . Difference \rightarrow Multiple scattering

Good energy conservation rate for low incidence angles

III.3. Energy conservation of the model: Numerical results (2D)

Study of energy conservation factor $\eta(\theta_i)$: Dielectric case ($\epsilon_{r2}=53$)



rms slope $\sigma_s = 0.3$

- - V Polar (no shadow)
- ... H Polar (no shadow)
- . V Polar (shadow)
- . - H Polar (shadow)
- x- V Polar (shadow [7])
- .x- H Polar (shadow [7])

[7]: [Tsang & Kong, Wiley, 2001]

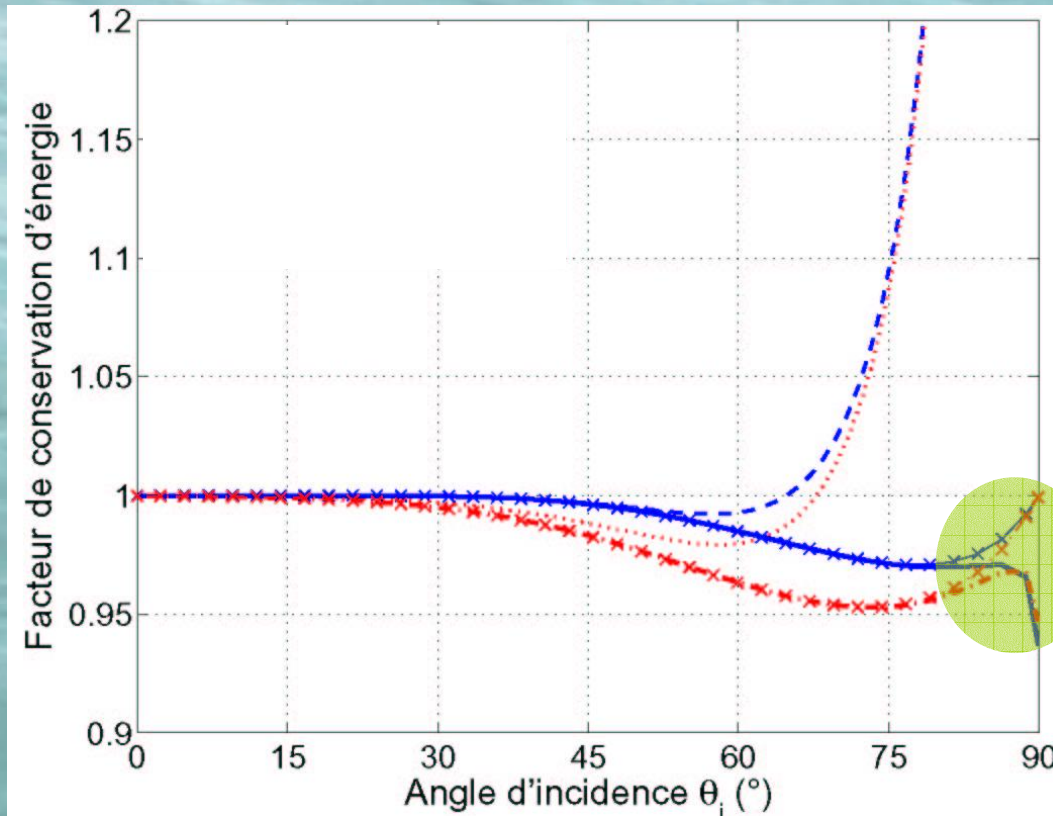
Same conclusions as PC

V Polar > H Polar

Brewster angle effect ($\theta_i^B \sim 82.2^\circ$)

III.3. Energy conservation of the model: Numerical results (2D)

Study of energy conservation factor $\eta(\theta_i)$: Dielectric case ($\epsilon_{r2}=2$)



rms slope $\sigma_s = 0.3$

- - V Polar (no shadow)
- ... H Polar (no shadow)
- . V Polar (shadow)
- . - H Polar (shadow)
- x- V Polar (shadow [7])
- .x- H Polar (shadow [7])

[7]: [Tsang & Kong, Wiley, 2001]

Same conclusions as PC; V Polar > H Polar

Transmission shadowing functions differ (only) for $\theta_i \rightarrow 90^\circ$

=> *More detailed study of the transmission shadowing functions for $\theta_i \rightarrow 90^\circ$*

III.3. Energy conservation of the model: Extension to the 3D case

Study of energy conservation factor $\eta(\theta_i, \phi_i)$

2D case:

In agreement with results of the literature:

[Lynch and Wagner, JMP, 1970]

3D case:

- Same conclusions as 2D case
- Lower levels
- In agreement with results of the literature:
[Eom, AO, 1985], [Tsang and Kong, Wiley, 2001]

Outline

I. Introduction

II. Scattering from natural interfaces: Generalities

III. Scattering from a very rough interface

IV. Scattering from a very rough layer

1. Analytic methods: State of the art
2. Presentation of the new model developed
3. Numerical results

V. Conclusion & Prospects

two
rough interfaces



IV.1. Analytic (asymptotic) methods: State of the art (1/2)

Small Perturbation Method ($\sigma_h \ll \lambda$) [Fuks & Voronovich, WRM, 2000]

Reduced Rayleigh Equations ($\sigma_h \ll \lambda$) [Soubret et al., PRB, 2001]

Kirchhoff Approximation ($R_c > \lambda$)

↳ Scalar Kirchhoff Approximation ($R_c > \lambda + \sigma_h \ll \lambda$) [Ohlidal et al., PO, 1995]

Full Wave Model [Bahar et al., TAP, 1999]

two
rough interfaces



IV.1. Analytic (asymptotic) methods: State of the art (2/2)

Small Perturbation Method ($\sigma_h \ll \lambda$)
Reduced Rayleigh Equations ($\sigma_h \ll \lambda$)

*Low Frequency
approximations*

Kirchhoff Approximation ($R_c > \lambda$)

↳ Scalar Kirchhoff Approximation ($R_c > \lambda + \sigma_h \ll \lambda$)

new: ↳ Geometric Optics approximation ($R_c > \lambda + \sigma_h > \lambda/2$)

*High Frequency
approximations*

Full Wave Model

*Unified
approximations*

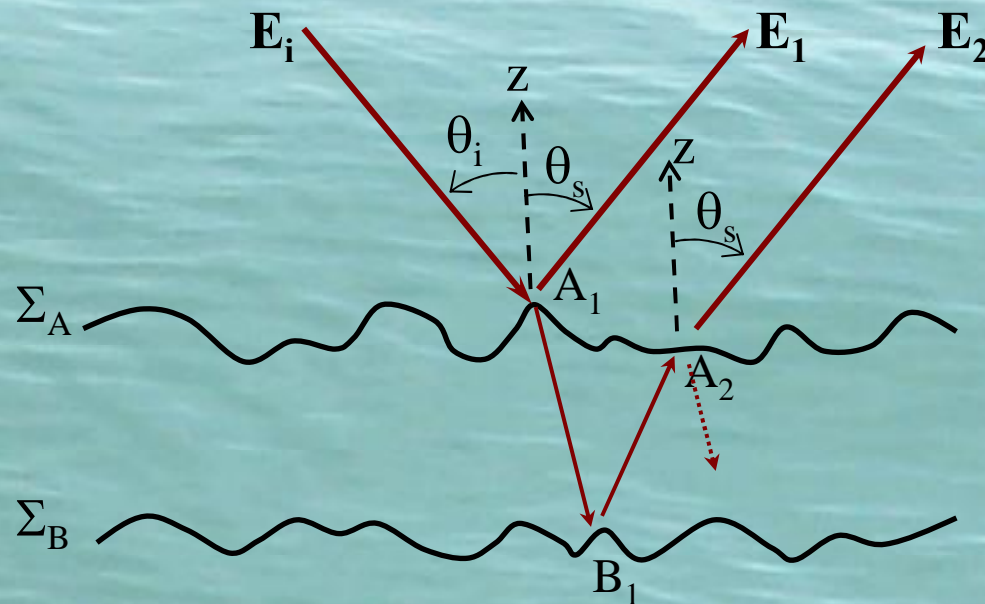
**Extension of the Kirchhoff Approximation ($R_c > \lambda$)
to the case of 2 rough interfaces**

→ a model with strongly rough interfaces ($\sigma_h > \lambda/2$)

Presentation of the 2D case => Extension to 3D case

IV.2. Approach of the method

- Use of KA-1 on the upper interface Σ_A (A_1)
=> reflected & transmitted fields at the point A_1
- Huygens' principle (Green function \rightarrow Weyl representation)
=> E_1 & incident field on Σ_B (B_1)
- Use of KA-1 on the lower interface Σ_B (B_1)
- *etc.*

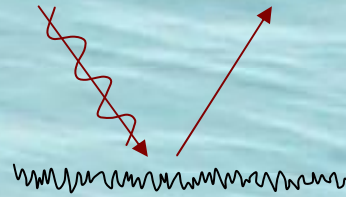


IV.2. Approximations of the method (2D problem)

Within the 1st-order Kirchhoff approximation ($\sigma_s < 0.5$, $R_c > \lambda$):

- calculus of the 1st-order SC:

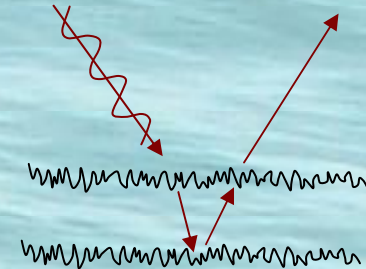
Simple



- calculus of the nth-order SC ($n \geq 2$):



Too much complicated



Method of Stationary Phase:

main contribution comes from regions around the specular direction



Still too much complicated

Geometric Optics approximation: $P_{s,coh} \ll P_{s,inc} \Rightarrow \sigma_h > 0.5 \lambda$

main contribution comes from closely-located correlated points



2D problem: $\left\{ \begin{array}{l} 2(n-1) \text{ numerical integrations (rough lower interface)} \\ (n-1) \text{ numerical integrations (plane lower interface)} \end{array} \right.$

IV.2. Analytic expression of $\sigma_{r,2}$ (2D problem)

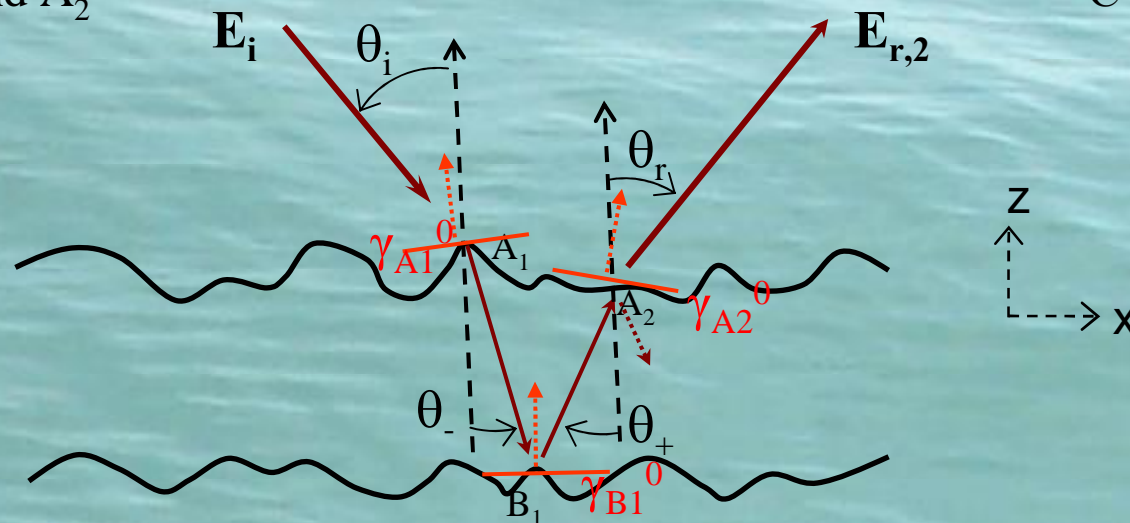
Second-order Scattering Coefficient $\sigma_{r,2} \sim \langle |E_{r,2}|^2 \rangle$:

$$\sigma_{r,2} = \int_{-\pi/2}^{+\pi/2} \int_{-\pi/2}^{+\pi/2} d\theta_- d\theta_+ f_2(\theta_i, \theta_-, \theta_+, \theta_r) \times p_s(\gamma_{A1}^0) p_s(\gamma_{B1}^0) p_s(\gamma_{A2}^0) \times S(\theta_i, \theta_-, \theta_+, \theta_r)$$

depends on the Fresnel reflection and transmission coefficients at A_1 , B_1 , and A_2

probability density functions (give the specular directions)

average shadowing function $\in [0,1]$



↳ This expression can be generalized to any order $\sigma_{s,n}$ (R & T)

IV.3. Numerical results (2D)

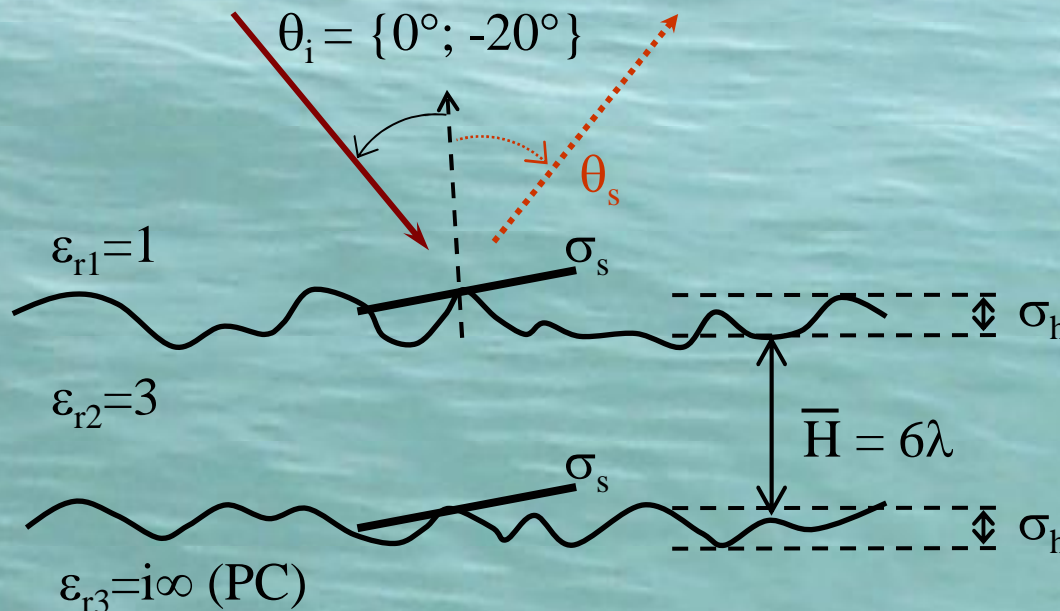
Bistatic SC σ_1 & σ_2 : **Comparison with a reference numerical method...**

... based on the Method of Moments [*Déchamps et al., JOSAA, Feb. 2006*]

$$\begin{aligned} \sigma_h &= 0.5 \lambda \\ \sigma_s &= 0.1 \end{aligned}$$



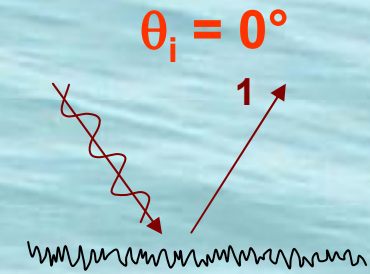
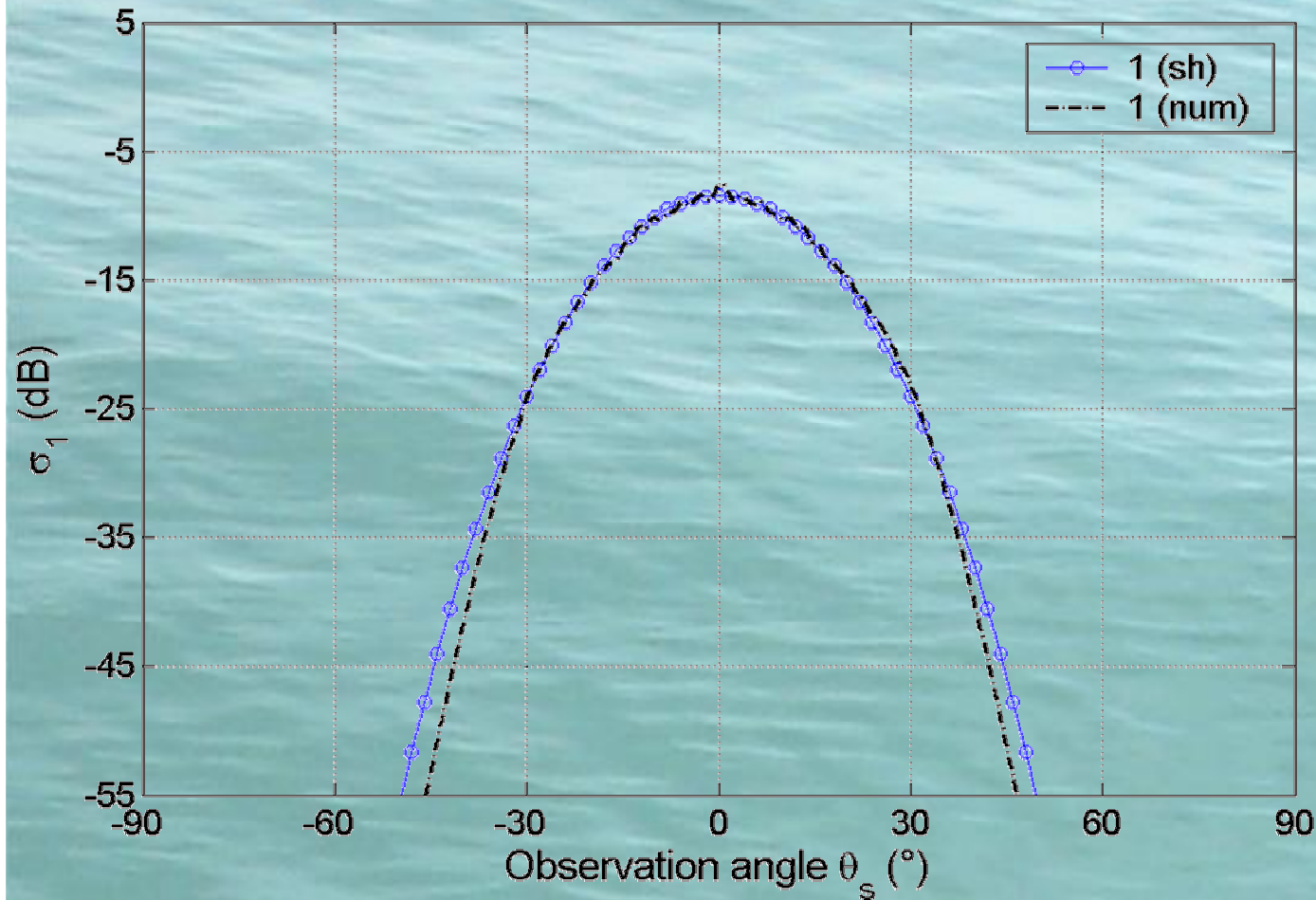
Geometric Optics
validity domain



V polarization

IV.3. Numerical results (2D)

1st-order SC σ_1 : Comparison with a reference numerical method

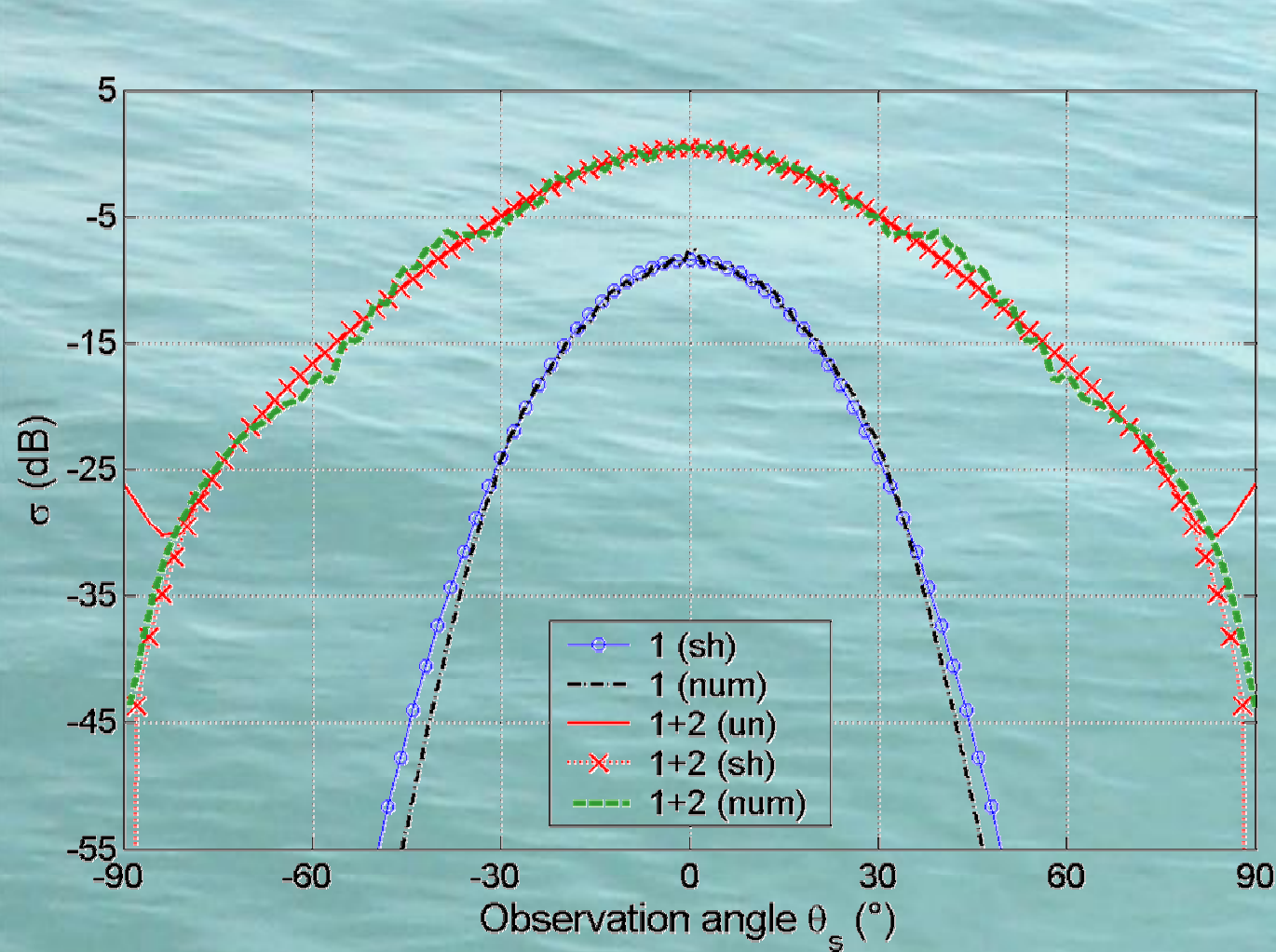


The shadow can be neglected

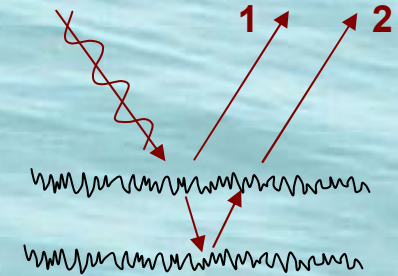
Good agreement with reference method

IV.3. Numerical results (2D)

2nd-order contribution σ_2 : Comparison with a reference numerical method



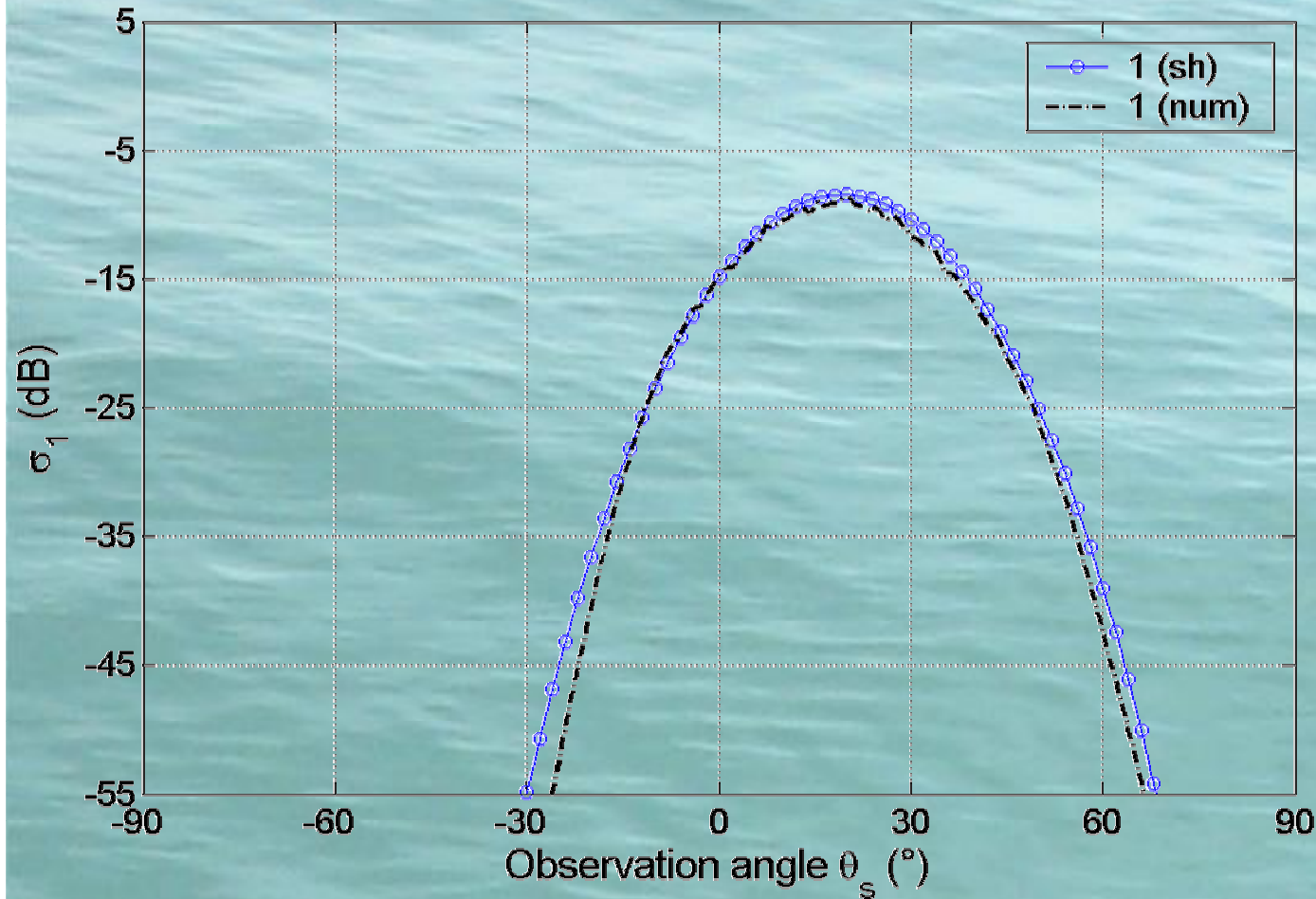
$\theta_i = 0^\circ$



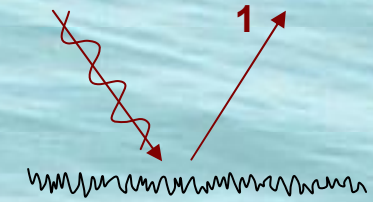
**Good agreement with
reference method
(model with shadow)**

IV.3. Numerical results (2D)

1st-order SC σ_1 : Comparison with a reference numerical method



$$\theta_i = -20^\circ$$

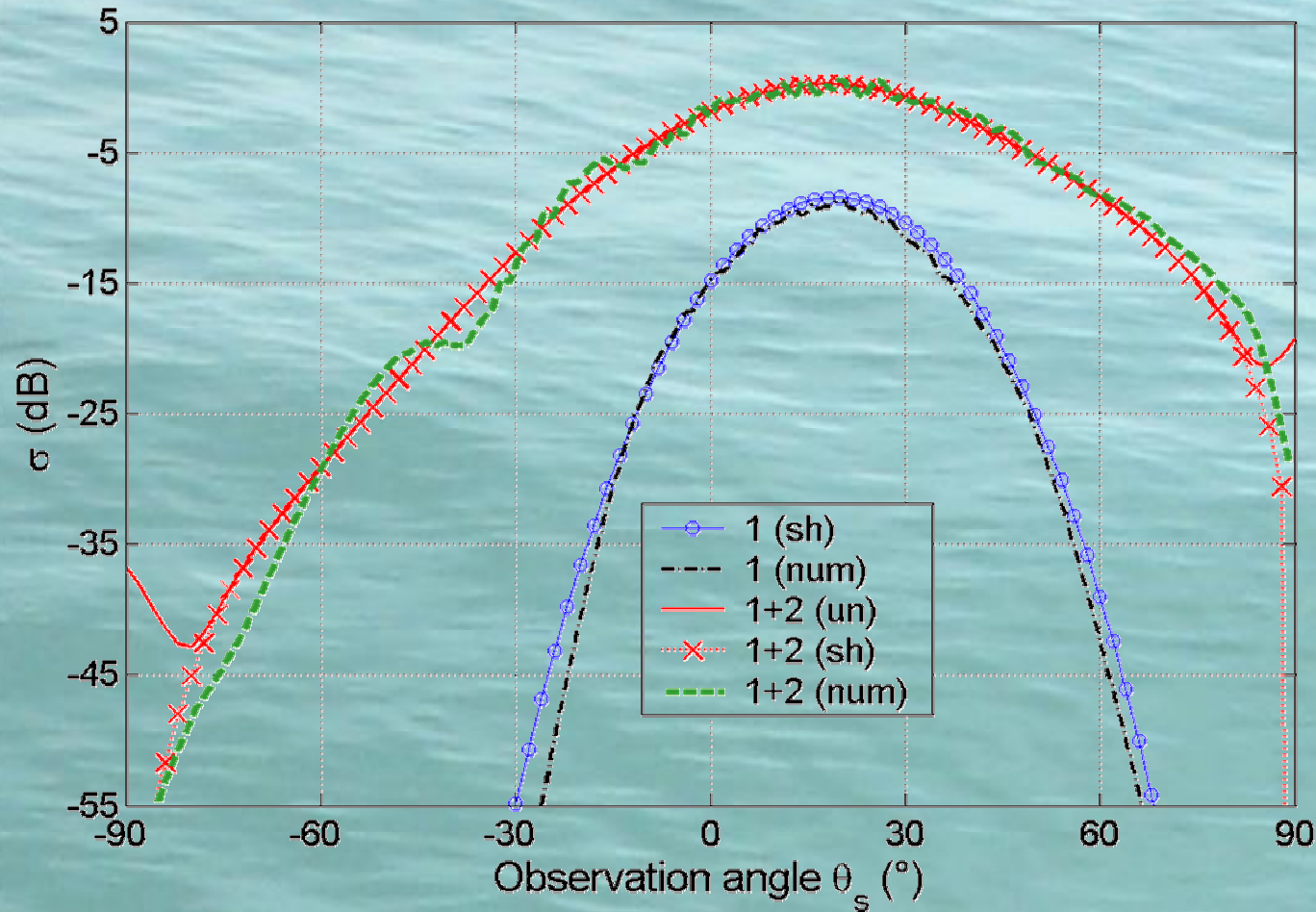


The shadow can be neglected

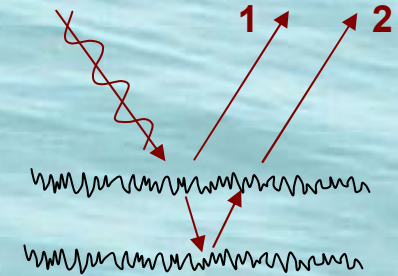
Good agreement with reference method

IV.3. Numerical results (2D)

2nd-order contribution σ_2 : Comparison with a reference numerical method



$\theta_i = -20^\circ$



Good agreement with reference method (model with shadow)



Validation of the developed model in the high-frequency limit

IV.3. Monostatic SC (dB): oil slick detection (2D)

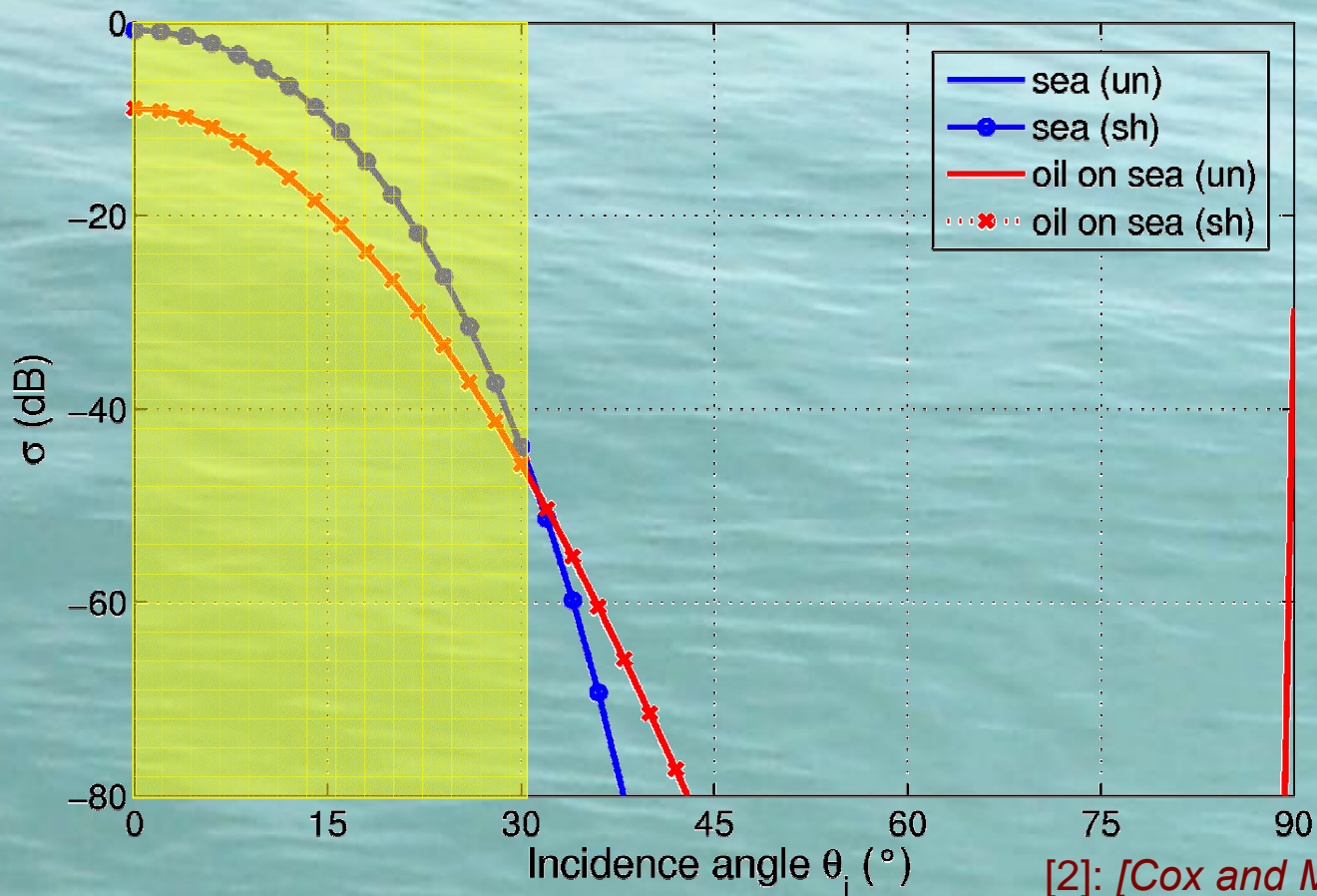
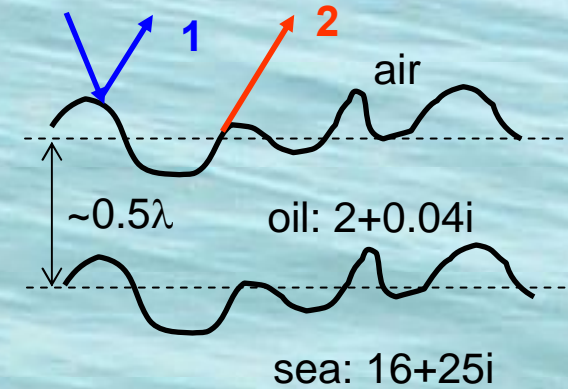
$\theta_s = -\theta_i$ (backscattering)

$f = 35 \text{ GHz} \Rightarrow \lambda = 8.6 \text{ mm}$

Beaufort scale: 4:

- sea: $\sigma_s = 0.126$ [2]

- oil on sea: $\sigma_s = 0.094$ [2]



For $\theta_i \in [0^\circ, 30^\circ]$:
detection of oil slick possible

[2]: [Cox and Munk, J. Opt. Soc. Am., 1954]

IV.3. Extension of the model to the 3D case

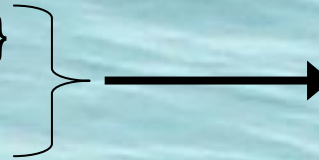
- Exactly the same methodology as the 2D case
- Number of numerical integrations: multiplied by 2:
 - { 4(n-1) numerical integrations (**rough** lower interface)
 - { 2(n-1) numerical integrations (**plane** lower interface)
- ⇒ Increase of numerical complexity
- Interest: Quantify the cross-polarizations
- *N.B.: No numerical or experimental validation:
Complexity of numerical implementation ($\sigma_h > \lambda/2$: MoM not well adapted to high frequencies)*

IV.3. Numerical results (3D)

Bistatic SC σ_1 & σ_2 for a **plane** lower interface

$$\theta_i = \{0^\circ; 20^\circ\}$$

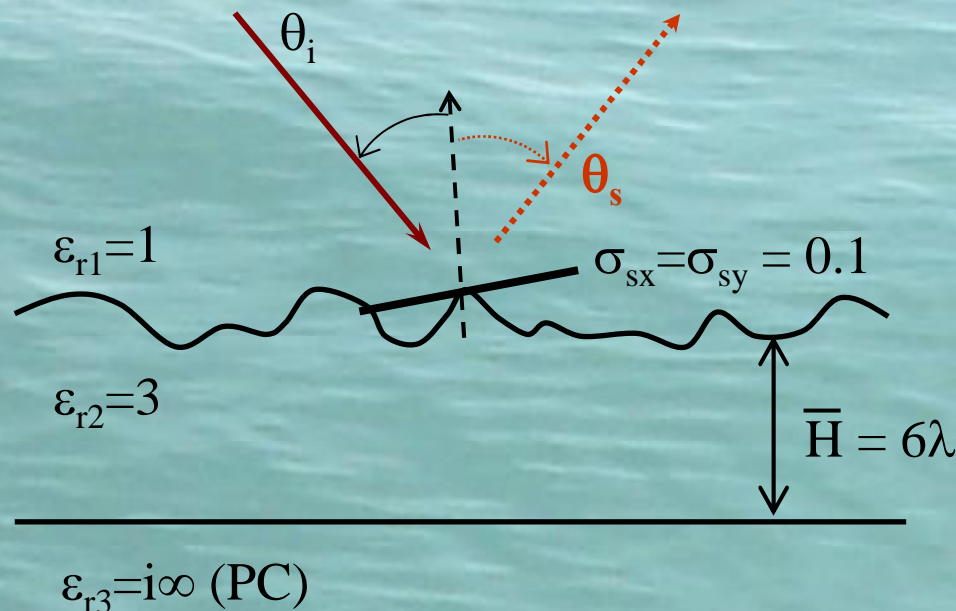
$$\phi_i = 0^\circ$$



In the plane of incidence $\phi_s = 0^\circ$:

Study of the co- and cross-polarizations

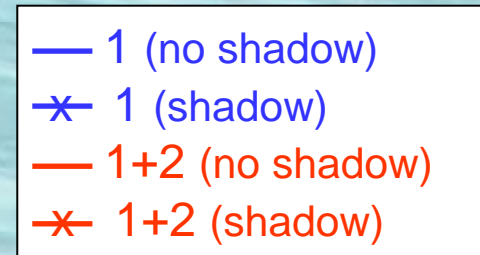
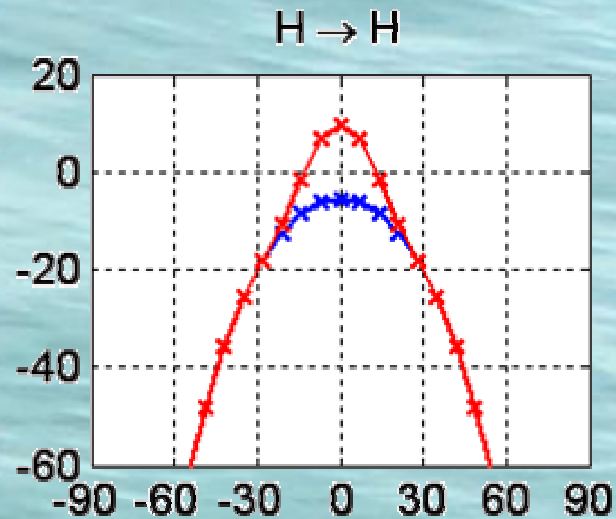
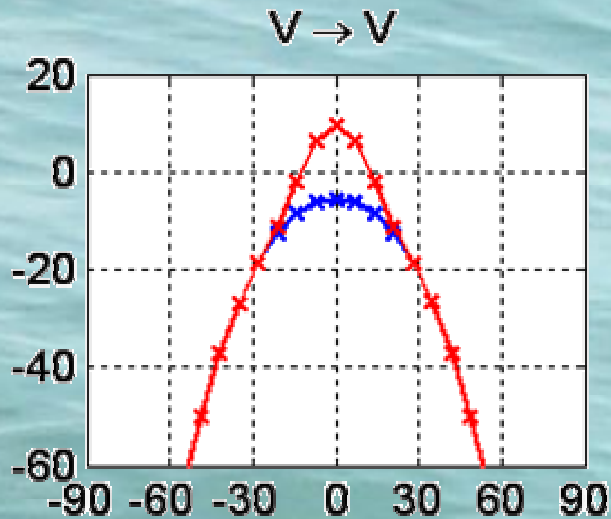
with respect to θ_s



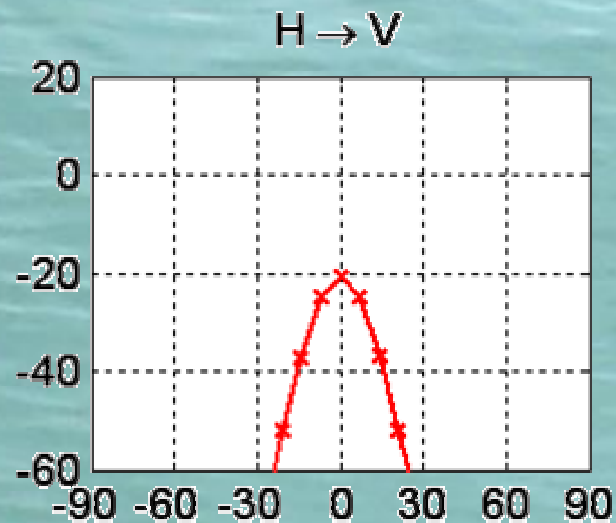
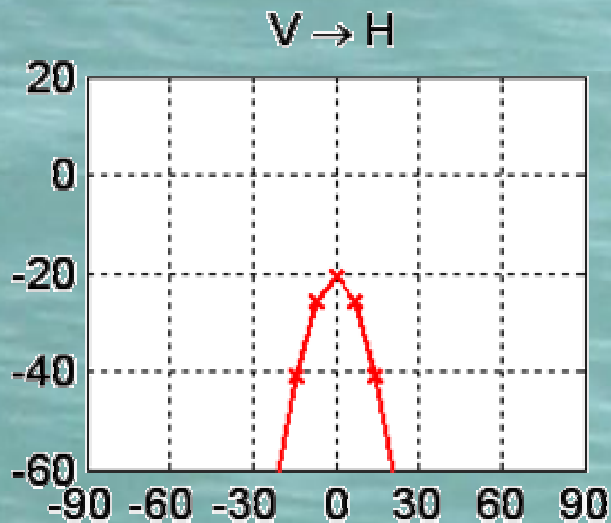
IV.3. Numerical results: 3D generalization

2nd-order contribution σ_2 (dB)

$\theta_i = 0^\circ$



The shadow can be neglected

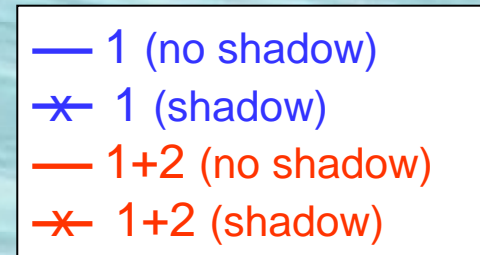
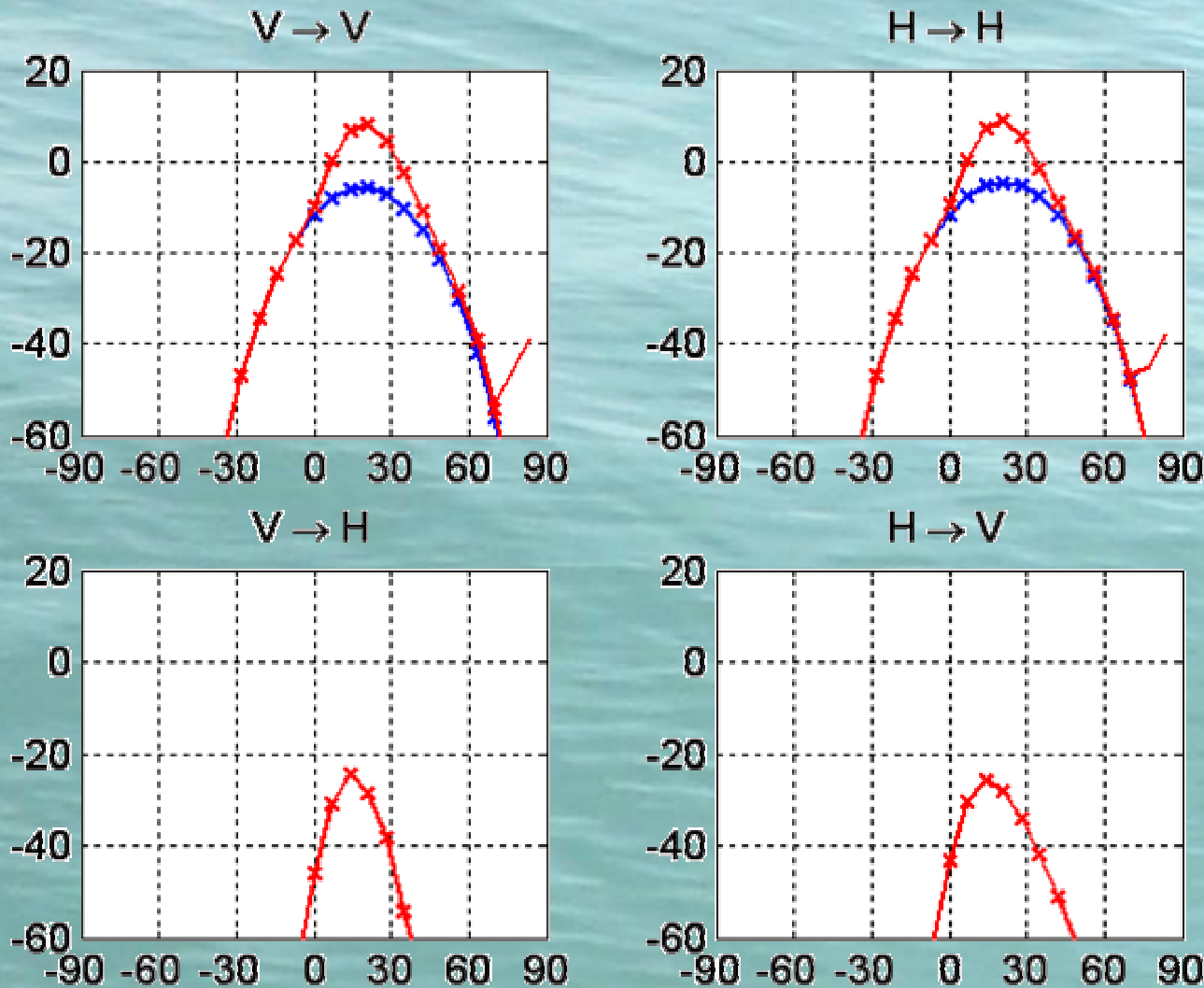


Contribution of the cross-polarization

IV.3. Numerical results: 3D generalization

2nd-order contribution σ_2 (dB)

$\theta_i = -20^\circ$



The shadow contributes for grazing angles

Contribution of the cross-polarization



Interesting means to detect oil slicks

Outline

- I. Introduction
- II. Scattering from natural interfaces: Generalities
- III. Scattering from a very rough interface
- IV. Scattering from a very rough layer
- V. Conclusion & Prospects**

Conclusions & Prospects

- A **fast** approximate method developed (valid in the high-frequency limit):
2D problem: Office PC (1GHz, 256Mo RAM): $\left\{ \begin{array}{l} \sim 5'' \text{ (approximate)} \\ \sim 4\text{h}10' \text{ (exact, } N=50) \end{array} \right.$
- Numerical validation (2D problem)
[Déchamps et al., JOSAA, Feb. 2006]
- Disposal of a fast method for two strongly rough interfaces (2D problem)
=> Laboratory: 2 rough surfaces:
 - a numerical method
 - an asymptotic method
- Extension of the fast asymptotic method to a 3D problem (valid in the high-frequency limit)

Conclusions & Prospects

Prospects:

- Extension of the formulation to a 3D problem:
 - Numerical results for **rough** lower interfaces (general case)
 - *Numerical / Experimental validation?*
- Extension to more than 2 interfaces
- More detailed study of transmission shadowing function
- Correlation between interfaces
- Taking into account of double scattering from the same interface => Extension of validity to higher rms slopes σ_s

Conclusions & Prospects

Publications:

- 1 published journal article (Optics Letters, Aug. 2005)
- 1 journal article in minor revision (Waves in Random and Complex Media)

- 5 international communications with selection committee:
3 as first author (Radar 2004, EuRAD 2005, APS/URSI 2006) ,
2 as second author (EuCAP 2006)

- 2 national communications with selection committee (JNM 2005, GdR Ondes 2005)

Conclusions & Prospects

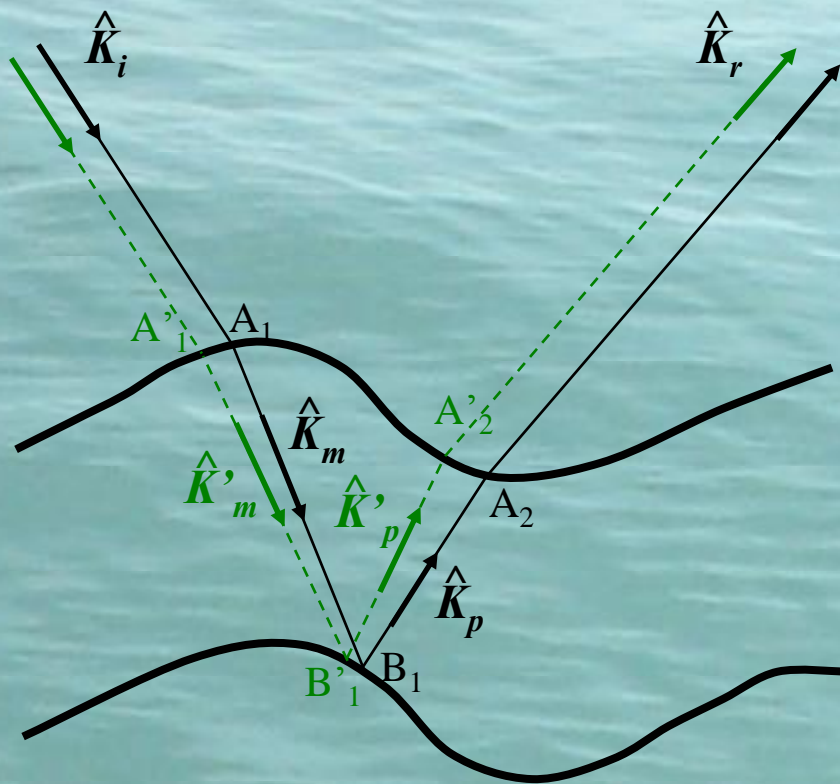
QUESTIONS?

Conclusions & Prospects

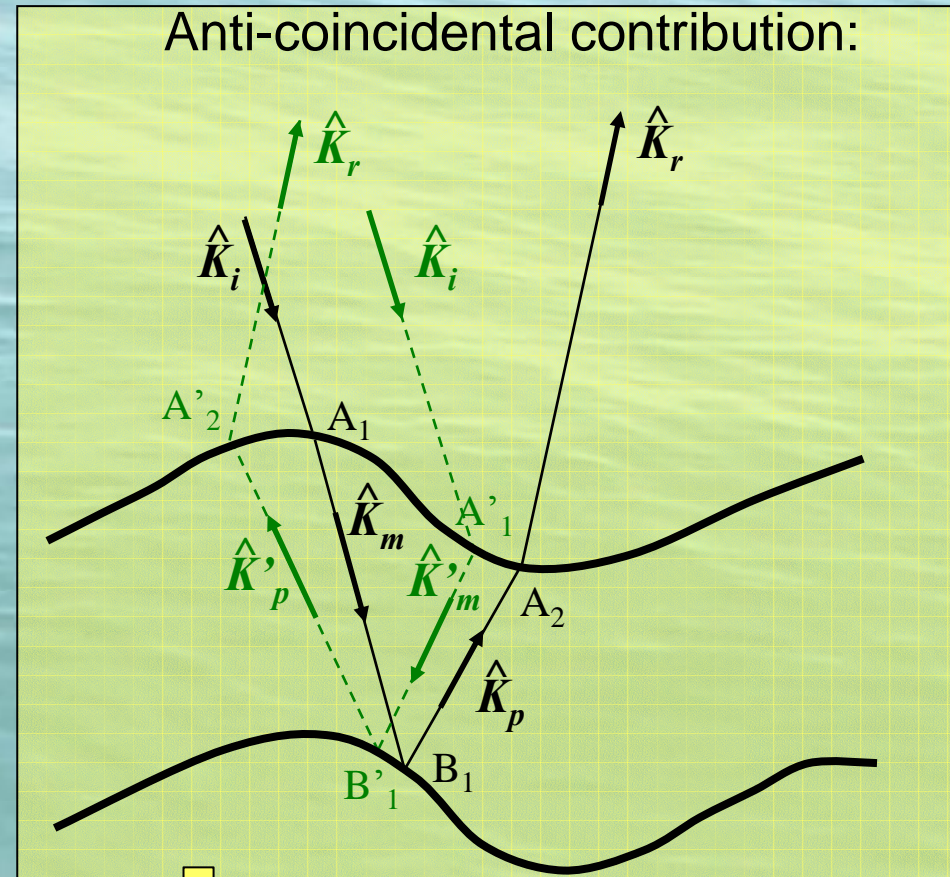
Prospects (2):

- Second-order scattered power $P_{r,2} = \langle E_{r,2} E_{r,2}^{*} \rangle$:

Coincidental contribution:



Anti-coincidental contribution:

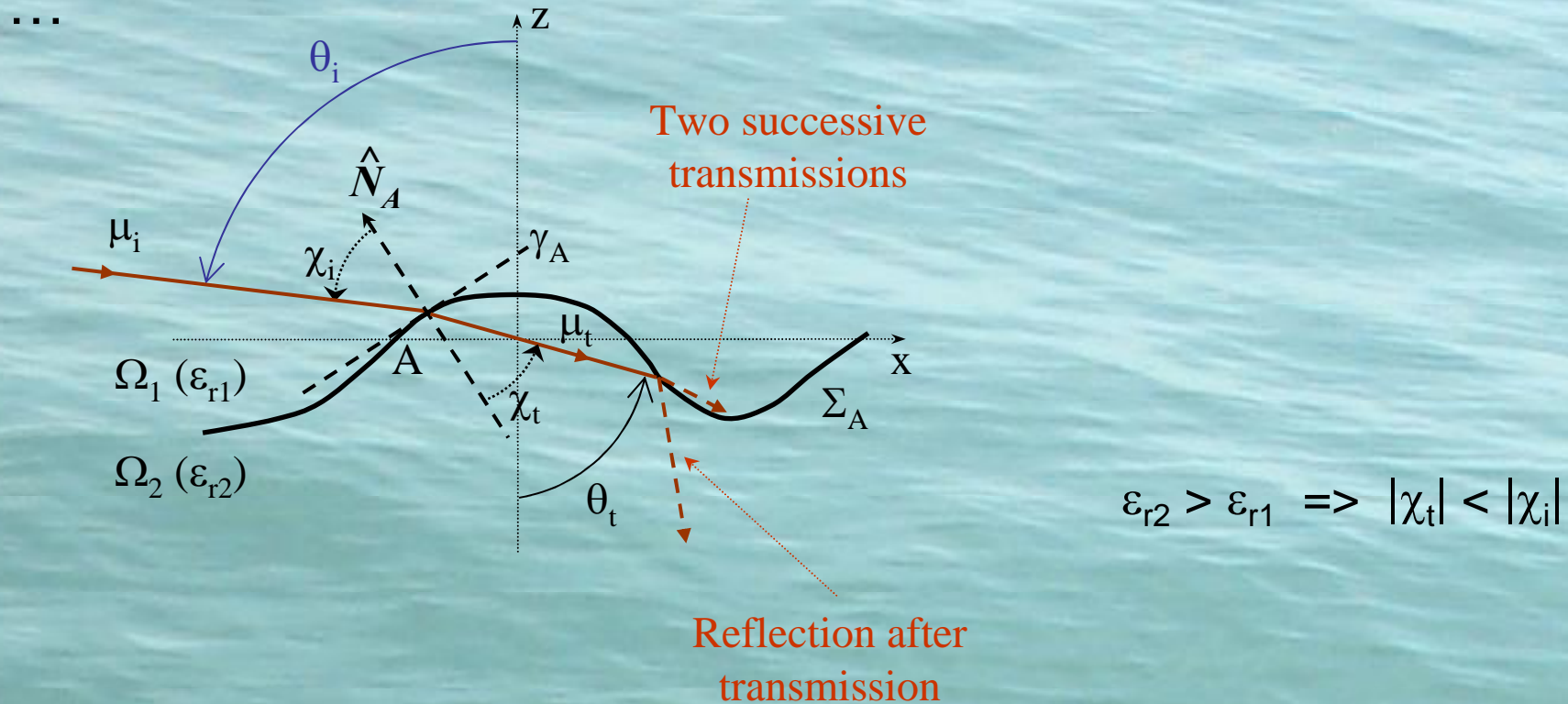


Numerical validation

Outline

- I. Introduction
- II. Scattering from natural interfaces: Generalities
- III. Scattering from a very rough interface
- IV. Scattering from a very rough layer
- V. Conclusion & Prospects

Multiple scattering phenomenon: Case of transmission for $\epsilon_{r2} > \epsilon_{r1}$



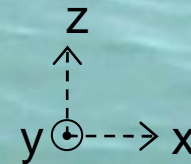
May occur for:

- Grazing incidence angles: $\theta_i \rightarrow 90^\circ$
- Relative permittivities of the inner medium ϵ_{r2} close to ϵ_{r1}

Contributes for moderate to high rms slopes σ_s

Analytic expression of σ_2 (3D problem)

Second-order Scattering Coefficient $\sigma_2 \sim \langle E_2 E_2'^* \rangle$:



↳ This expression can be generalized to any order σ_n

Results & Consequences

Method of stationary phase (MSP) :

The main contribution comes from regions around the specular direction:

$\gamma_A \rightarrow \gamma_A^0$ determined by k_{inc} and k_{s1}

$\Rightarrow E_2: \{ x_{A1}, x_{A2}, z_{A1}, z_{A2} \}$: 4 variables... still too much!

