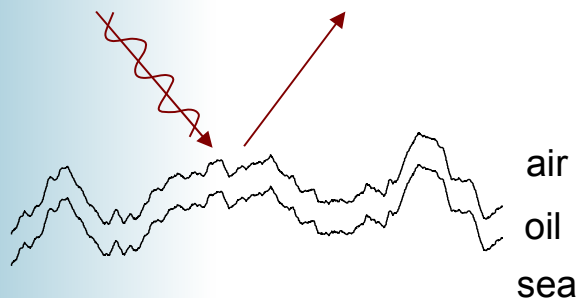


Modeling of radar scattering from oil films



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- **General context of the study:**
Remote sensing of oil slicks on sea surfaces

Better oil slick detection (& characterization and quantization)
⇒ More effective direction of oil spill countermeasures

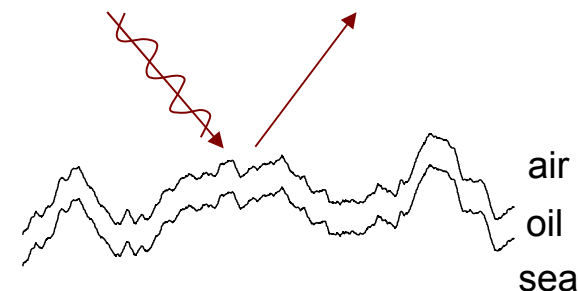


- ↳ Modeling of the EM scattering from oil slicks on sea surfaces
⇒ Integration in imagery simulators

- **EM scattering → Normalized Radar Cross Section (NRCS)**

$$\text{NRCS} \propto \frac{\text{scattered power}}{\text{incident power}}$$

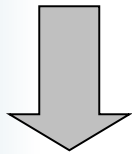
- one single interface → air/sea interface: relatively **well-known**
- **two interfaces** → air/oil and oil/sea interfaces: research in progress



- Different possible approaches:

rigorous

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



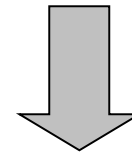
MoM accelerated by
PILE+FB+SA

[Déchamps et al., IEEE TAP, 2007]

asymptotic

- + fast
- restricted domain of validity

cf. oil slick detection



1. GOA (Geometric Optics Approx.)
+ intuitive approach (Thin Layer)
2. SSA-1 (Small Slope Approximation)
+ intuitive approach (Thin Layer)
3. etc.

⇒ Statistical description of studied natural surfaces (*hydrodynamic modeling*)

I. Introduction

II. Hydrodynamic modeling (surfaces)

1. Natural interfaces: Statistical description
2. Case of clean and contaminated sea surfaces
3. Spectrum of clean and contaminated surfaces

III. NRCS of clean and contaminated seas

IV. Conclusion & Future work

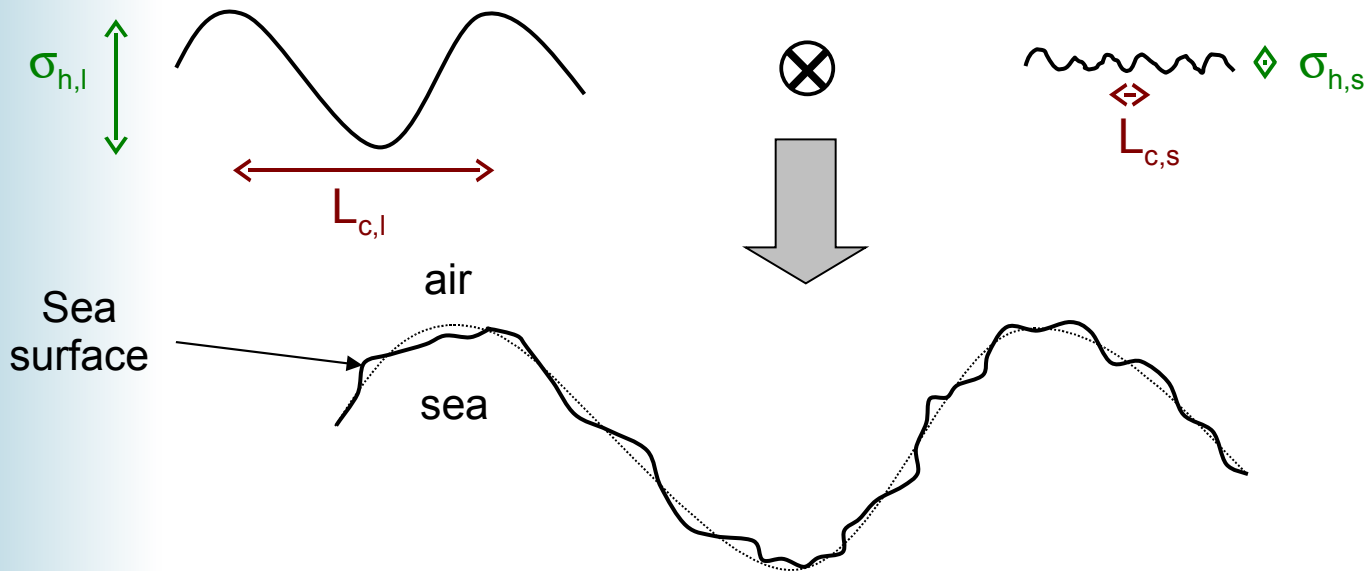
- Clean sea → Qualitative description:
Gravity and capillary waves:

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:

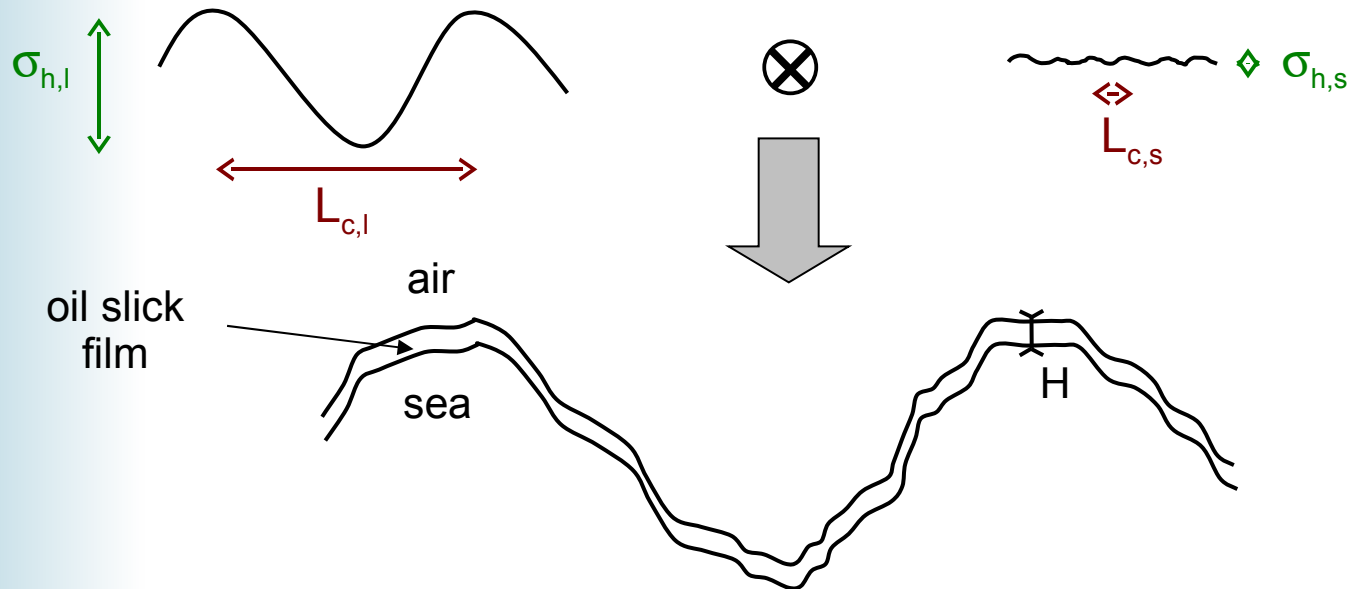
Damping of capillary waves
of both surfaces (air/oil and oil/sea)

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 $S(k=2\pi/x_d, \phi) \rightarrow$ 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]:

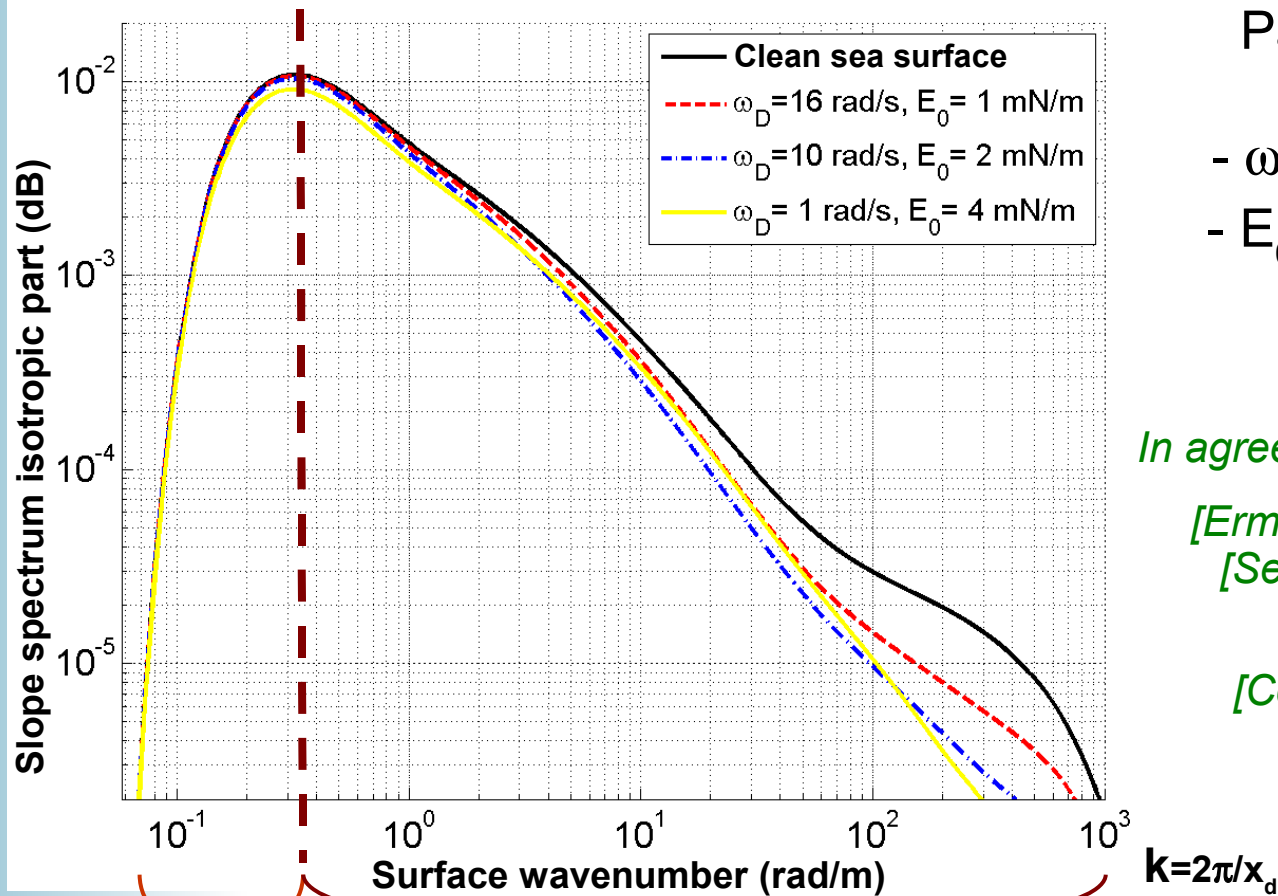
- Dependent on the oil film thickness H
- Harder to use: 8 hydrodynamic parameters (oil)

...

[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]

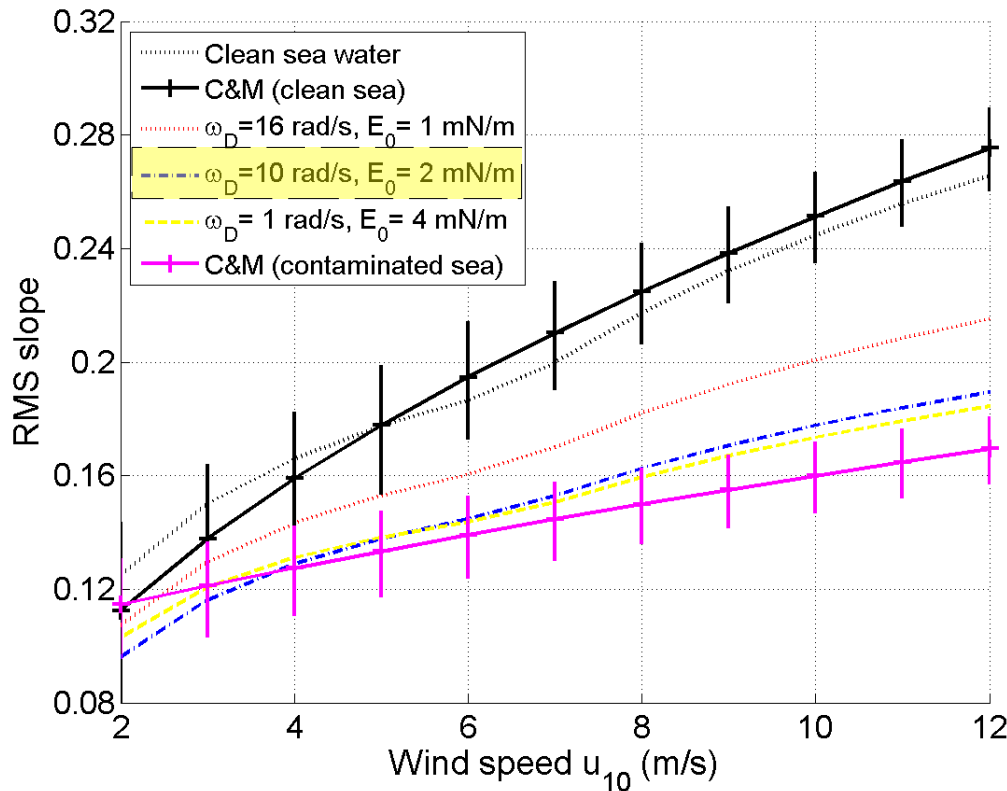
[Sergievsakaya and Ermakov, BIS Symposium, 2008]

[Cox and Munk, JOSA, 1954]

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

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

- **RMS slopes σ_s : Comparison with experiments [4]**
 - Cox & Munk model [4]: experiments conducted for $H \sim 0.02\text{mm}$
 - Lombardini *et al.* model



Oil Coxis & Munk model
of slopes
Lombardini et al. model:

Similar qualitative and
quantitative results

[4]: [Cox and Munk, JOSA, 1954]

I. Introduction

II. Hydrodynamic modeling (surfaces)

III. NRCS of clean and contaminated seas

1. Contaminated sea: Thin film of identical parallel interfaces
2. Numerical results: Validation of the thin-film approach
3. Thin-film approach: Validity domain study

IV. Conclusion & Future work

- At radar frequencies:

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

- Sea relative permittivity ϵ_r^{sea} : relatively well-known
- Oil relative permittivity ϵ_r^{oil} : only a few results of the literature, but...
at radar frequencies f : ϵ_r^{oil} only weakly varying with f , as well as with T

⇒ OK for EM modeling / Pb. for oil type characterization (→ optical frequencies)

- Homogeneous oil slicks (not emulsions):

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

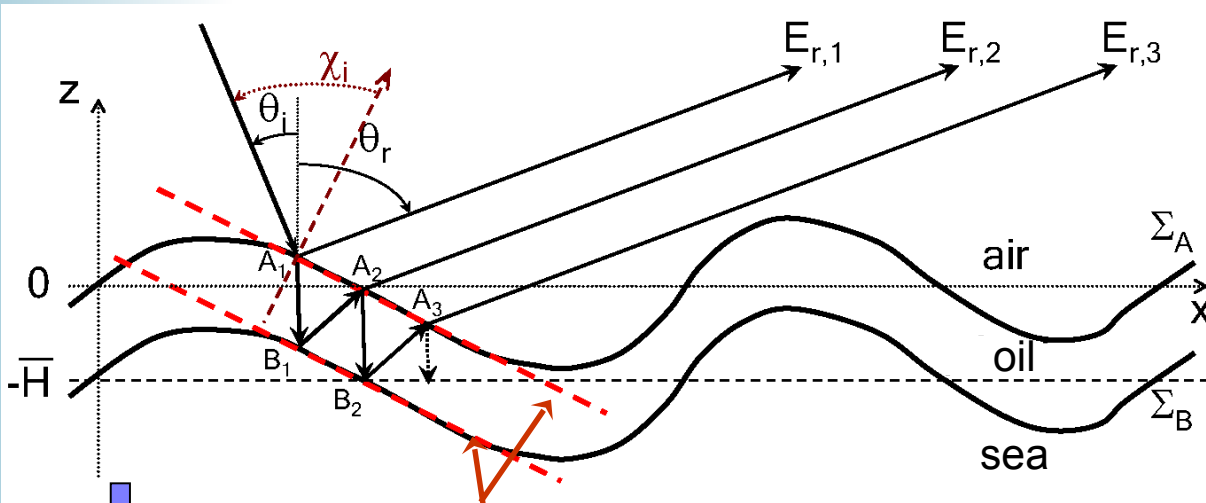
- Use of the Lombardini *et al.* damping model:

Surfaces assumed to be identical and parallel:



- Use of the height spectrum $S(k)$ for an EM model:

Comparison between a rigorous method [5] (MoM+PILE+FB+SA) and an asymptotic method using an **intuitive approach**



Oil films:

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

Locally flat parallel interfaces (\leftarrow **capillary wave damping**):

From a double interface problem to a single interface problem:

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

Application of the thin-layer (“TL”) approach to an asymptotic model:
GOA-TL, then SSA1-TL, ...

[5]: [Déchamps et al., IEEE TAP, 2007]

- Simulation parameters:

- Radar frequency f :

$$f = 1 \text{ GHz} \Rightarrow \begin{cases} \epsilon_r^{\text{sea}} = 70 + 41j \\ \epsilon_r^{\text{oil}} = 2.25 + 0.01j \end{cases}$$

$(\lambda_0 = 30 \text{ cm})$

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

$$u_{10} = 5 \text{ m/s} \quad (\text{Beaufort scale 3–4: light breeze – gentle breeze})$$

- Incidence angle θ_i :

$$\theta_i = \{0; -20\} \text{ deg.}$$

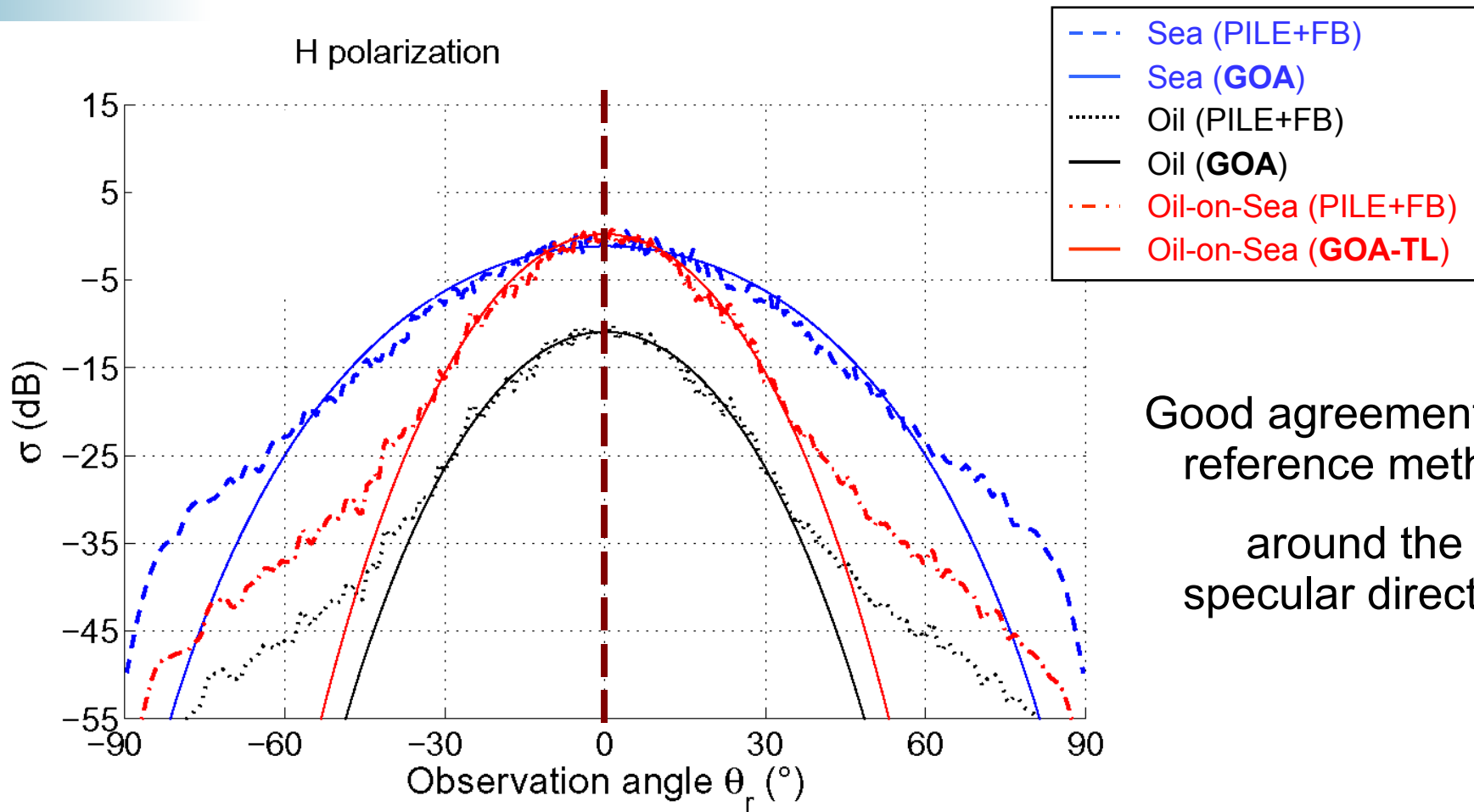
- Oil film ($\omega_D = 6 \text{ rad/s}$, $E_0 = 9 \text{ mN/m}$) of thickness H :

$$H = \{10; 1\} \text{ mm}$$

- Monte-Carlo process (PILE+FB): $N = 50$ realizations:

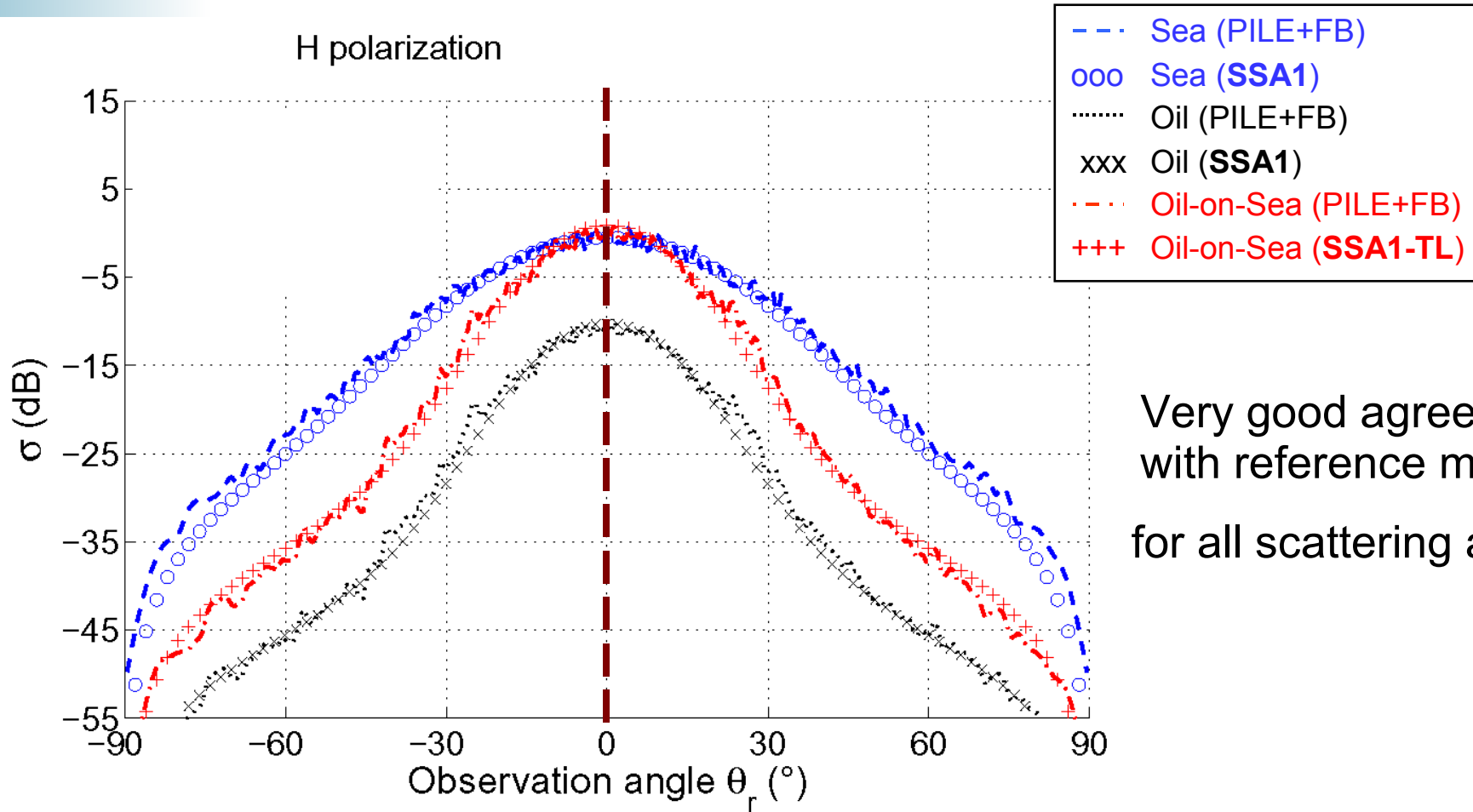
$$\left\{ \begin{array}{l} \text{Surface length: } L = 250 \lambda_0 \\ \text{Sampling step: } \Delta x = \lambda/10 \end{array} \right.$$

- Oil film thickness $H=10\text{mm}$ – rigorous (PILE+FB) vs. GOA



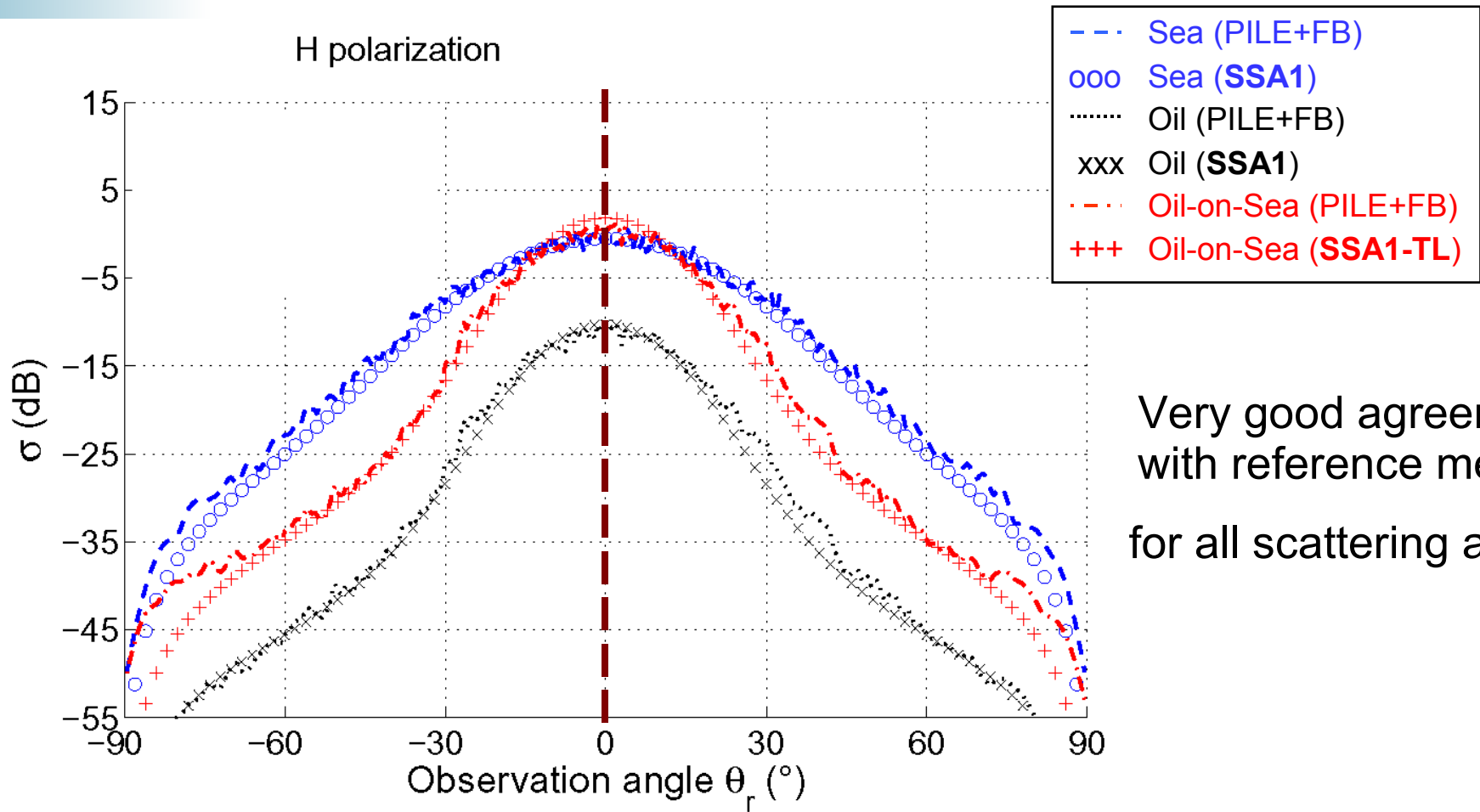
Good agreement with
reference method
around the
specular direction

- Oil film thickness $H=10\text{mm}$ – rigorous (PILE+FB) vs. SSA1



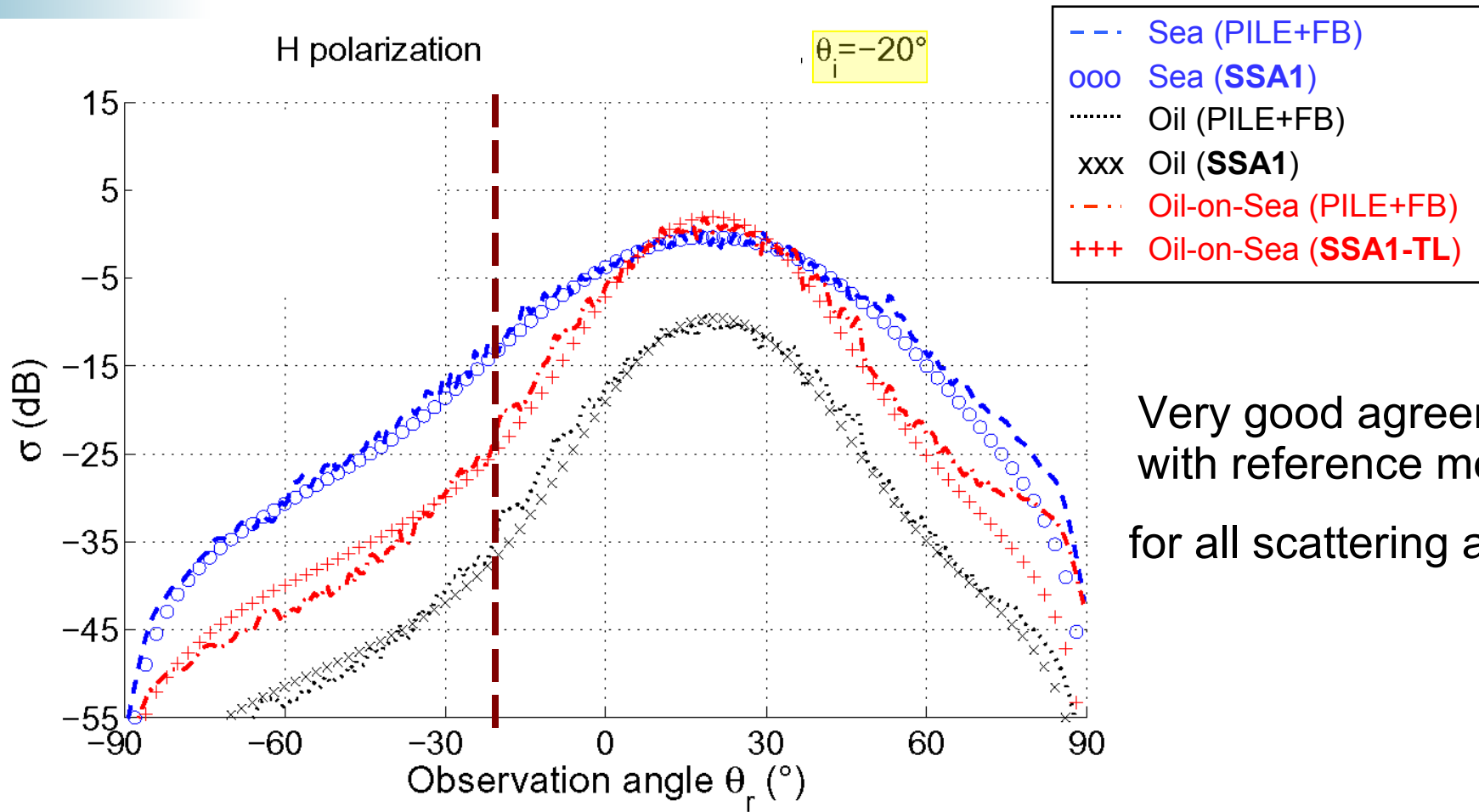
Very good agreement
with reference method
for all scattering angles

- Oil film thickness $H=1\text{mm}$ – rigorous (PILE+FB) vs. SSA1



Very good agreement
with reference method
for all scattering angles

- Oil film thickness $H=1\text{mm}$ – rigorous (PILE+FB) vs. SSA1; $\theta_i=-20\text{deg}$.



Very good agreement
with reference method
for all scattering angles

[Pinel et al., TGRS, 02/2008]

- Simulation parameters (H polarization):
 - Radar frequency f:

$$f = 1 \text{ GHz} \Rightarrow \begin{cases} \epsilon_r^{\text{sea}} = 76 + 70j \\ \epsilon_r^{\text{oil}} = 2.25 + 0.01j \end{cases}$$

$$(\lambda_0 = 30 \text{ cm})$$
 - Wind speed (at 10 meters above the surface) u_{10} :

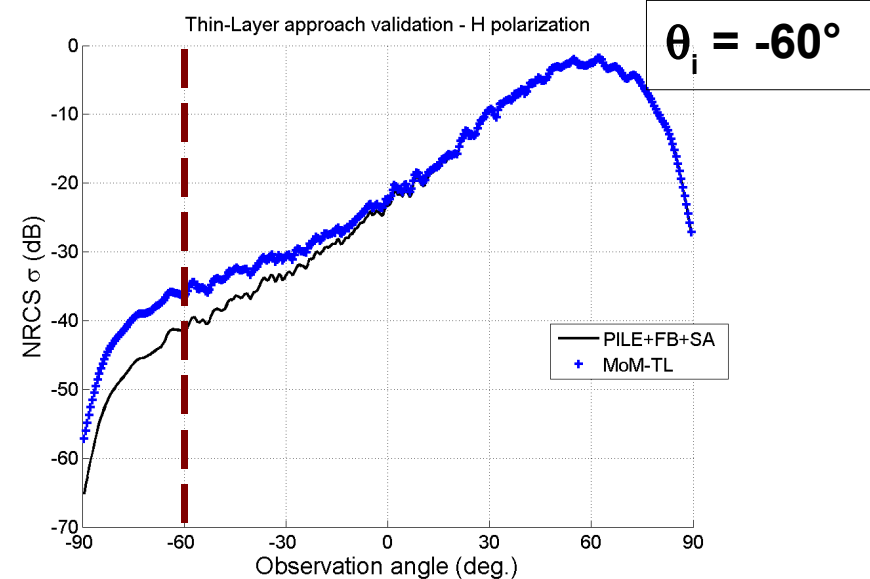
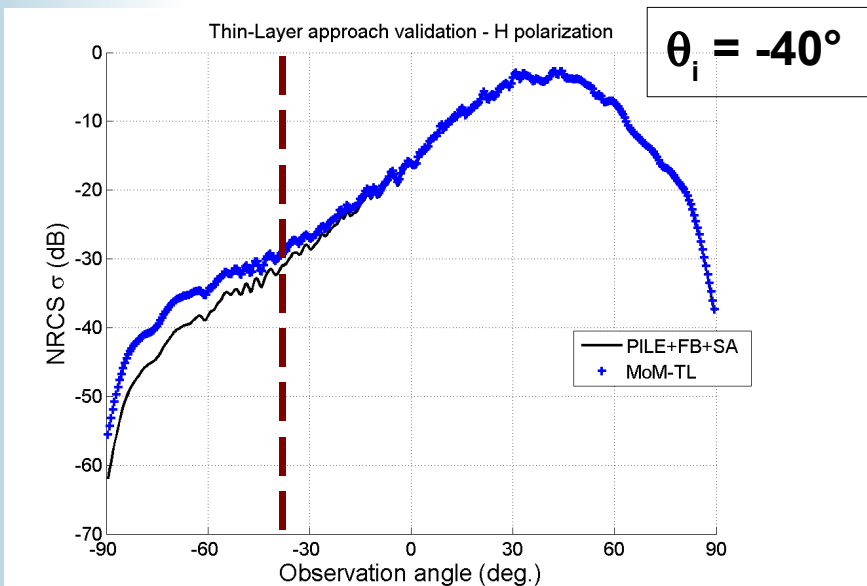
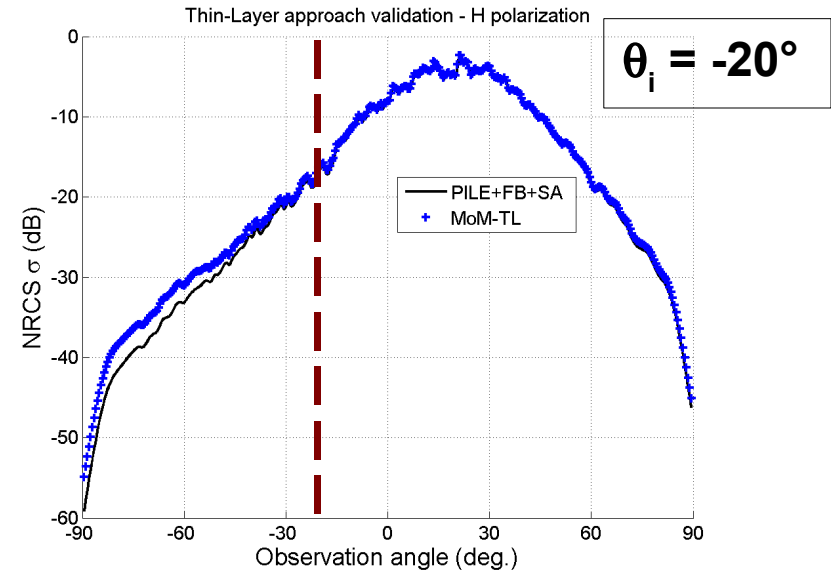
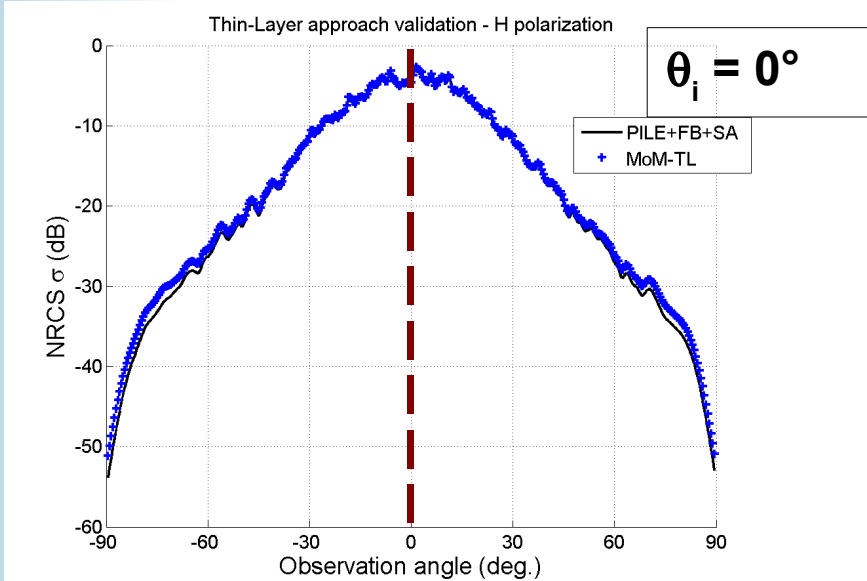
$$u_{10} = 6 \text{ m/s} \quad (\text{Beaufort scale 4: gentle breeze})$$
 - Incidence angle θ_i :

$$\theta_i = \{0; -20; -40; -60\} \text{ deg.}$$
 - Oil film ($\omega_D = 10 \text{ rad/s}$, $E_0 = 2 \text{ mN/m}$) of thickness H:

$$H = \{15\} \text{ mm}$$

$$\Rightarrow H \approx \{\lambda_{\text{oil}}/13\}$$
 - Monte-Carlo process (PILE+FB+SA): N = 70 realizations:

$$\left\{ \begin{array}{l} \text{Surface length: } L = 137 \lambda_0 \\ \text{Sampling step: } \Delta x = \lambda/10 \end{array} \right.$$



- Simulation parameters (H polarization):
 - Radar frequency f:

$$f = 1 \text{ GHz} \Rightarrow \begin{cases} \epsilon_r^{\text{sea}} = 76 + 70j \\ \epsilon_r^{\text{oil}} = 2.25 + 0.01j \end{cases}$$

$$(\lambda_0 = 30 \text{ cm})$$
 - Wind speed (at 10 meters above the surface) u_{10} :

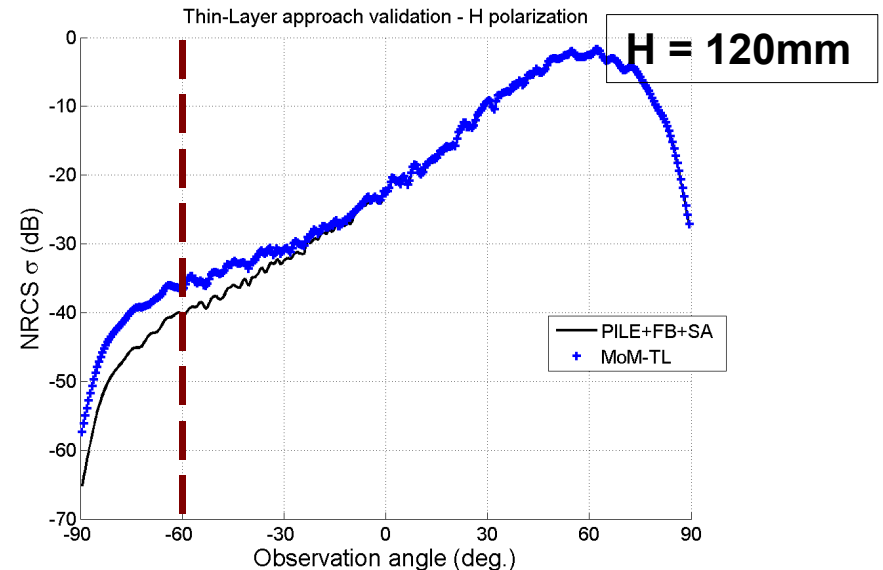
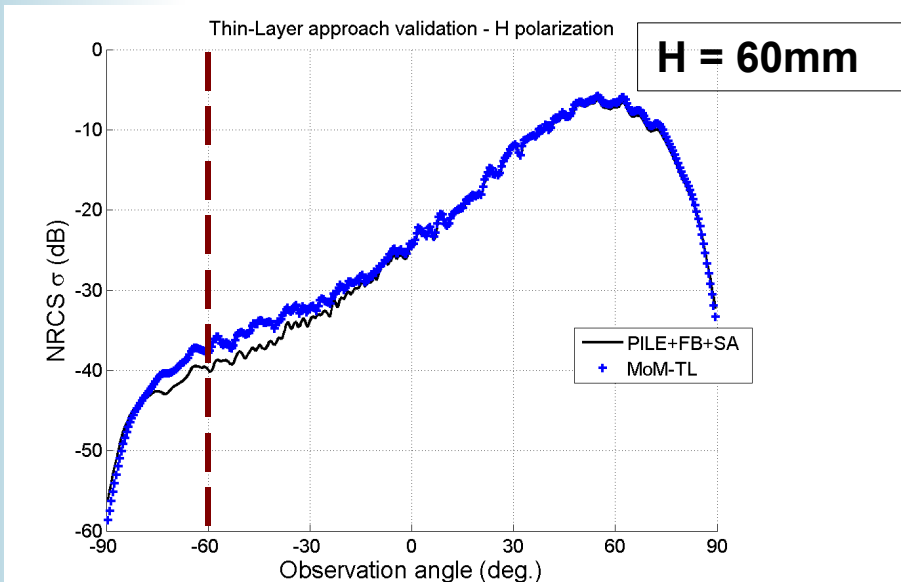
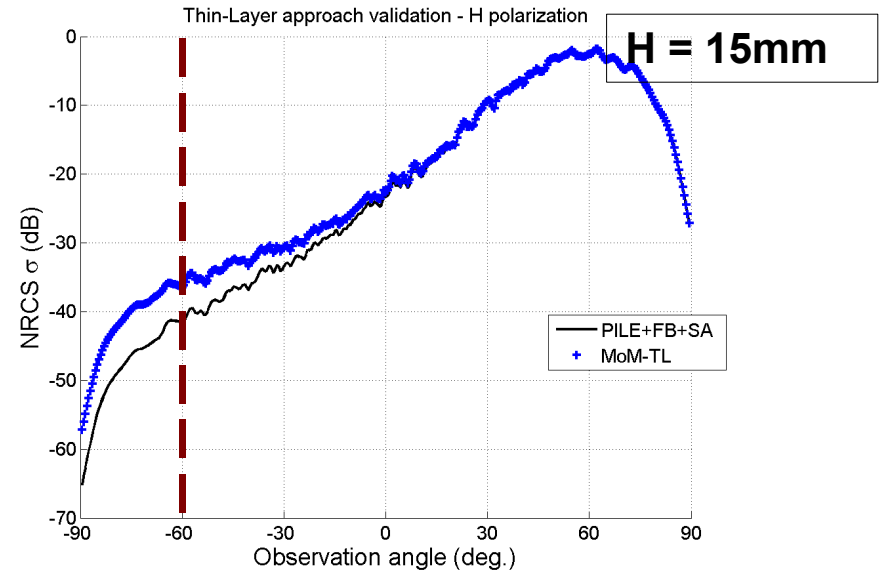
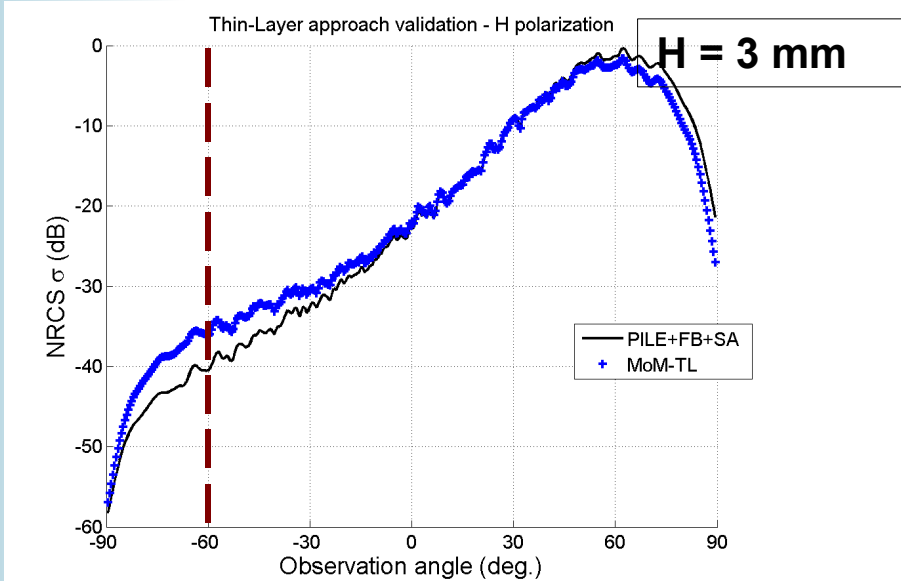
$$u_{10} = 6 \text{ m/s} \quad (\text{Beaufort scale 4: gentle breeze})$$
 - Incidence angle θ_i :

$$\theta_i = \{-60\} \text{ deg.}$$
 - Oil film ($\omega_D = 10 \text{ rad/s}$, $E_0 = 2 \text{ mN/m}$) of thickness H:

$$H = \{3; 15; 60; 120\} \text{ mm}$$

$$\Rightarrow H \approx \{\lambda_{\text{oil}}/67; \lambda_{\text{oil}}/13; \lambda_{\text{oil}}/3; \lambda_{\text{oil}}/1.7\}$$
 - Monte-Carlo process (PILE+FB+SA): N = 70 realizations:

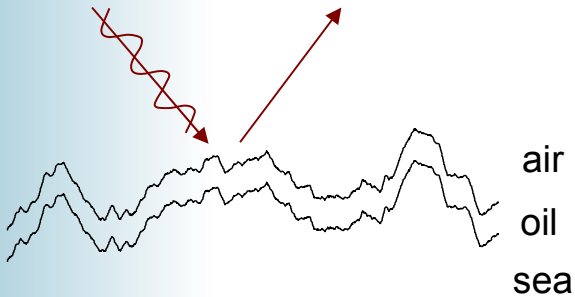
$$\left\{ \begin{array}{l} \text{Surface length: } L = 137 \lambda_0 \\ \text{Sampling step: } \Delta x = \lambda/10 \end{array} \right.$$



- I. Introduction
- II. Hydrodynamic modeling (surfaces)
- III. NRCS of clean and contaminated seas
- IV. Conclusion & Future work**

- **Hydrodynamic modeling** → Surfaces 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)
 - ✓ Radar NRCS: Application of this approach → GOA, SSA1; MoM
 - ✓ Validation by comparison with a reference numerical method
[Déchamps et al., JOSAA, 2006]
 - ✓ Oil slick detection possible (characterization and quantization: hard)
 - ✓ Thin-layer approach: Validity domain study
- **Future work:**
 - More investigations of the thin-layer approach validity domain
 - Extension of the method to a 3D problem
 - Use of a more physical damping model for oil films

Modeling of radar scattering from oil films



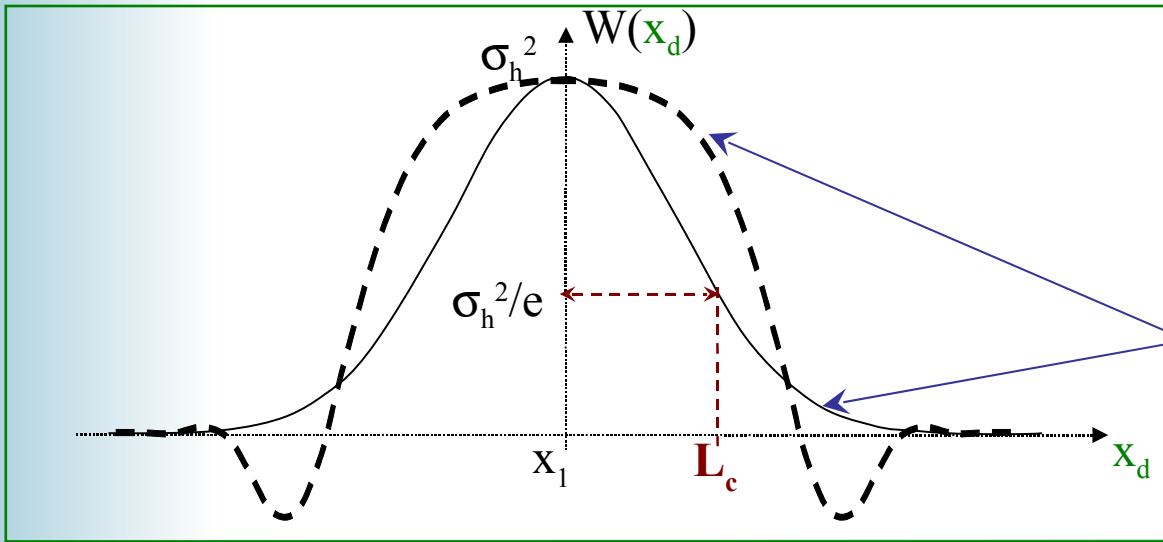
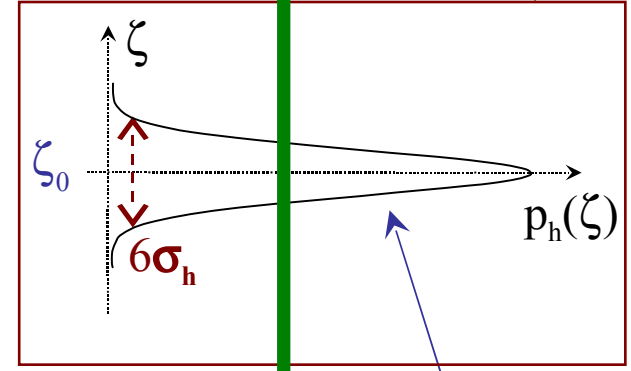
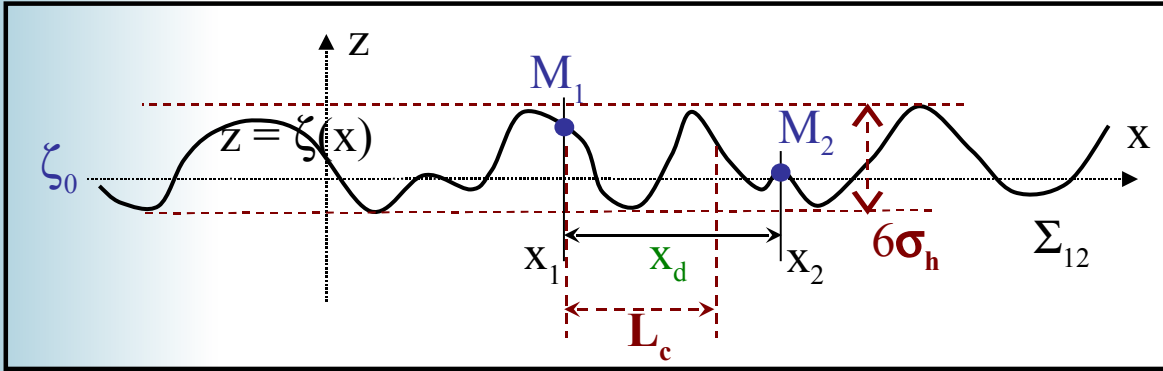
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Nantes, France

*E-mail: nicolas.pinel@univ-nantes.fr

2 main description tools:

- Height distribution (PDF): $p_h(\zeta)$
- Height spectrum: $S(k=2\pi/x_d, \phi)$

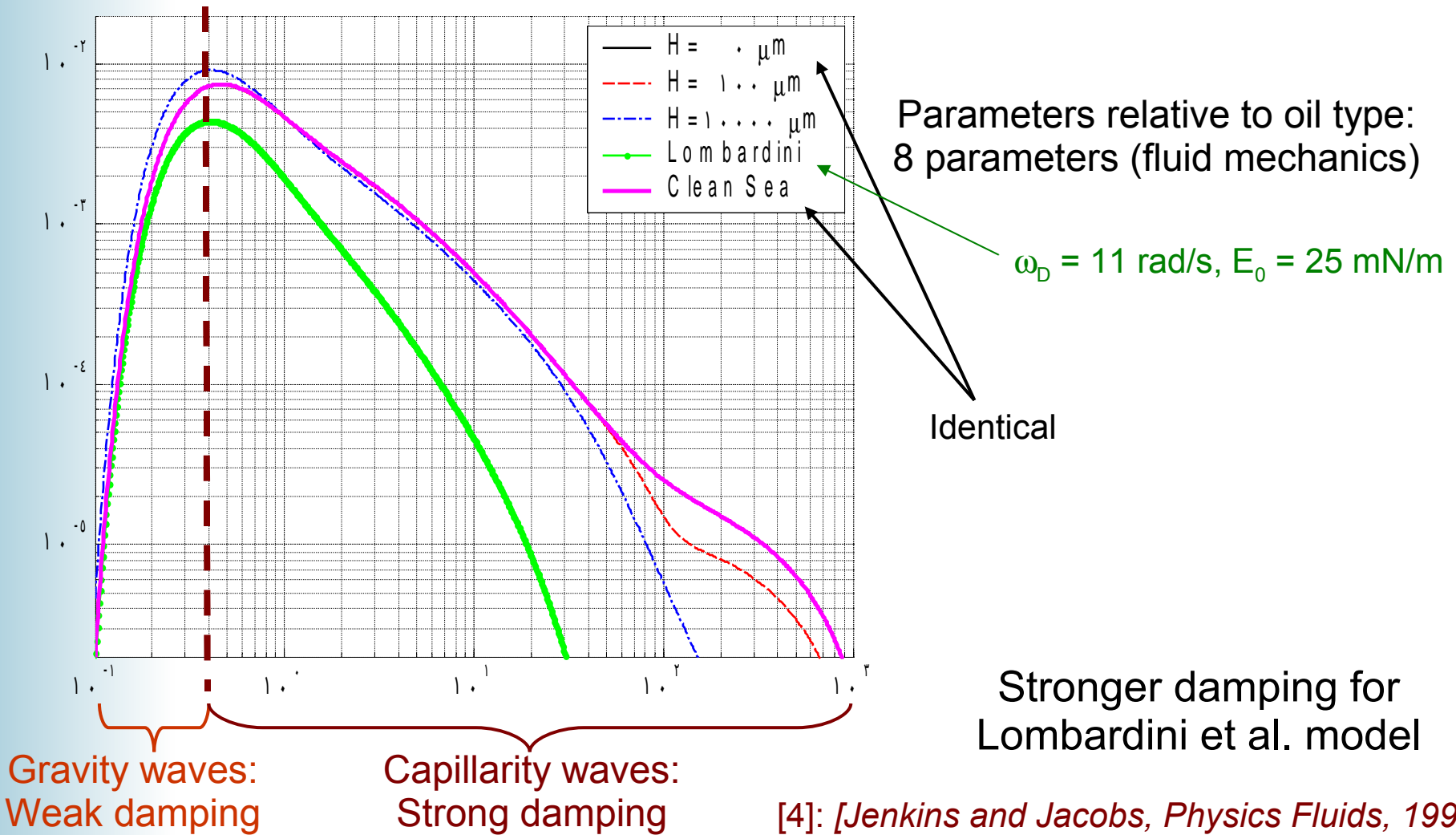


generally Gaussian

Gaussian

Sea: much more complex...

- *Jenkins and Jacobs* [4,5]: dependent on layer mean thickness H :



[4]: [*Jenkins and Jacobs, Physics Fluids, 1997*]
[5]: [*Pinel et al., TGRS, to be published, 03/2008*]

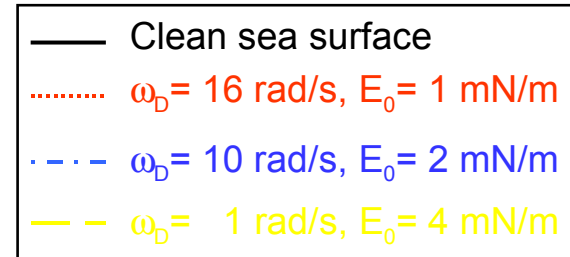
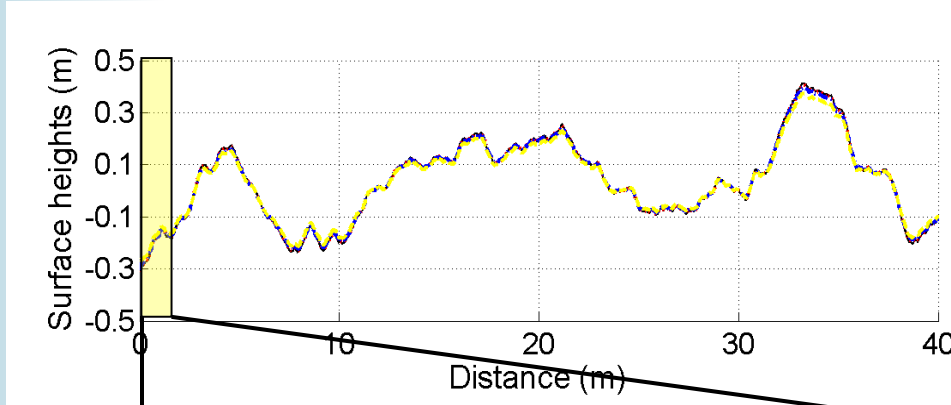
- Other statistical description tools:
 - Slope distribution $p_s(\gamma)$
 - Autocorrelation function $W(x_d)$ (=FT⁻¹ of surface height spectrum $S(k, \phi)$)
 - Slope spectrum $k^2 S(k, \phi)$
 - etc. (other derivatives of height spectrum)

Different types of distributions:

- Simple distributions: Gaussian, etc.
- Natural interfaces \Rightarrow more complex descriptions in general:
Clean / Contaminated sea surface \rightarrow Statistical description:
 - Height distribution function $p_h(\zeta)$: \approx Gaussian
 - Height spectrum: \rightarrow much more complex...

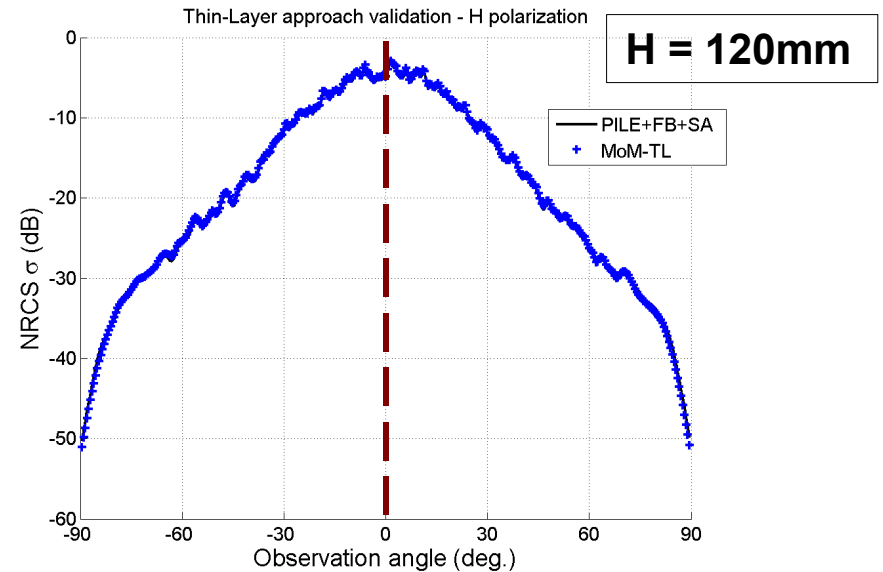
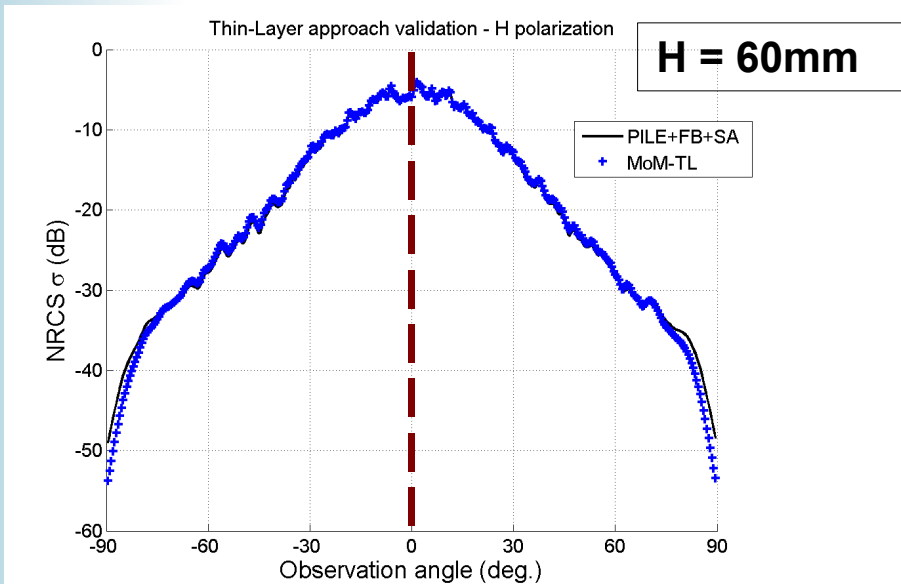
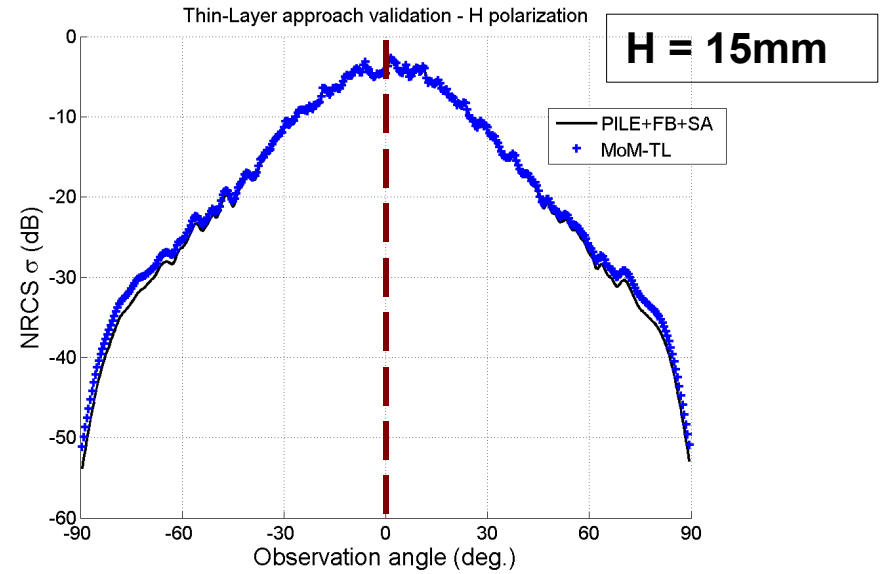
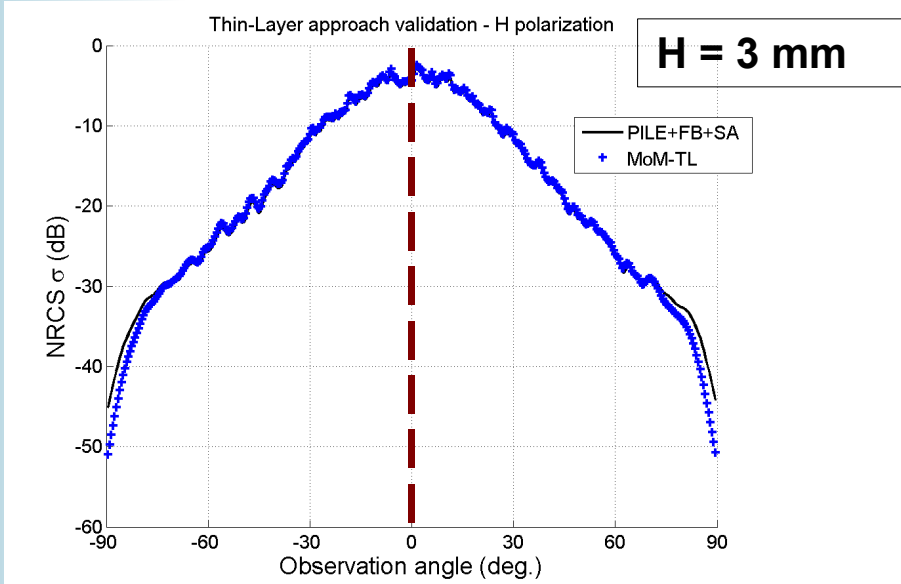
- Sea covered in oil → Choice for height spectrum $S(k)$: Lombardini *et al.* model: Independent of H

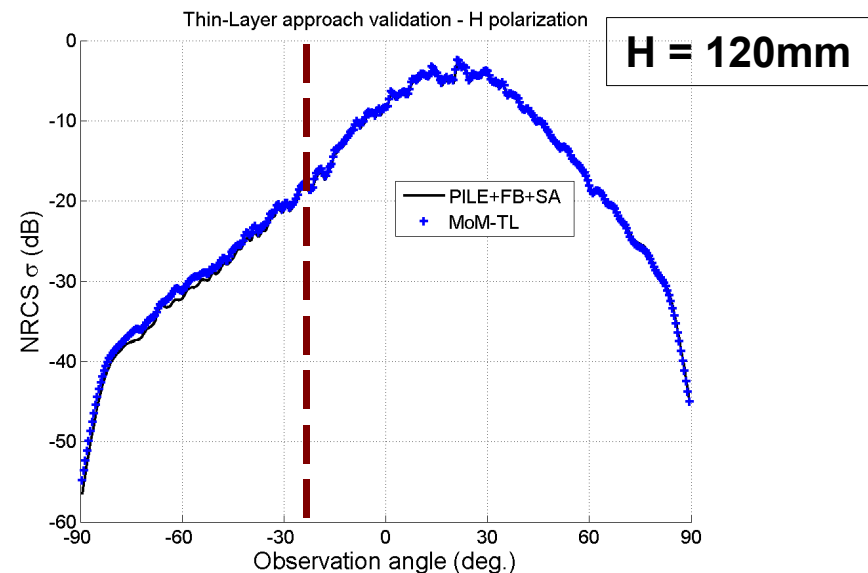
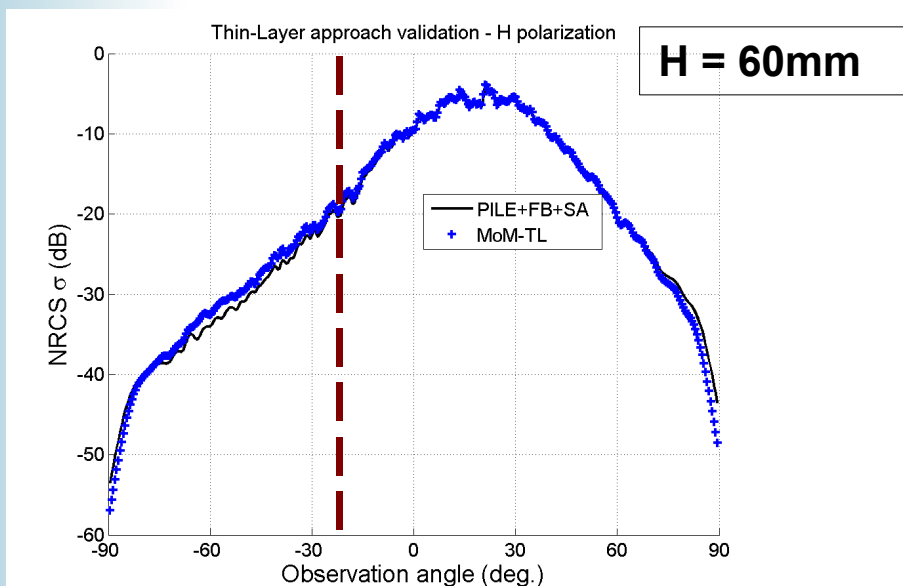
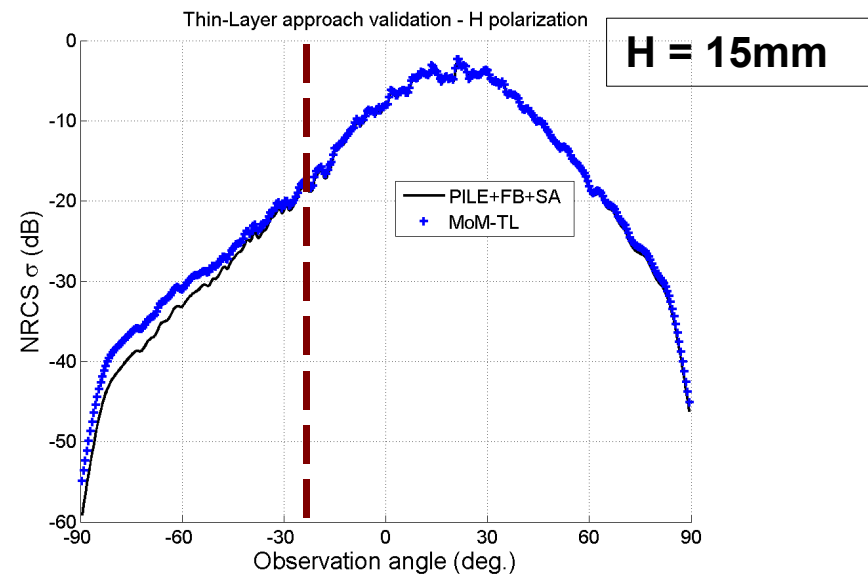
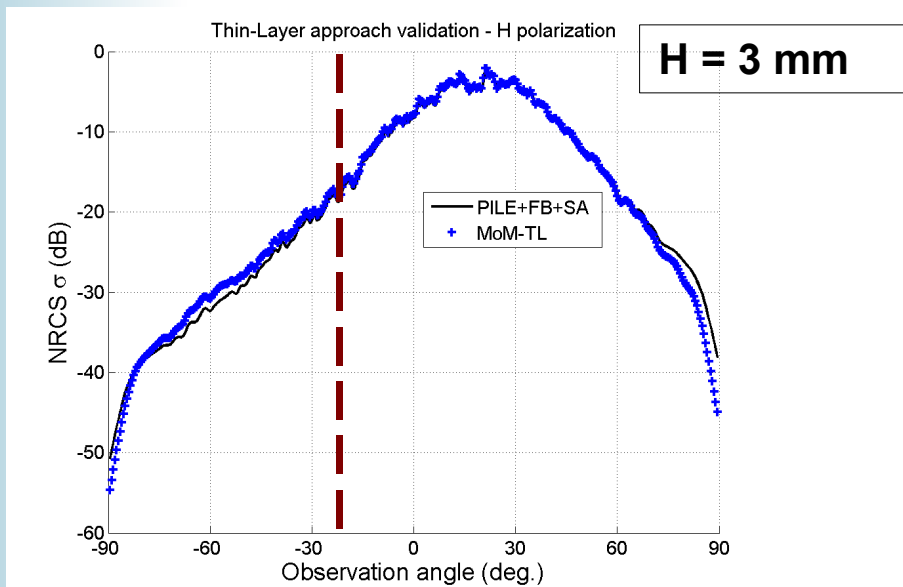
Representation of air/oil and oil/sea surface heights and slopes:

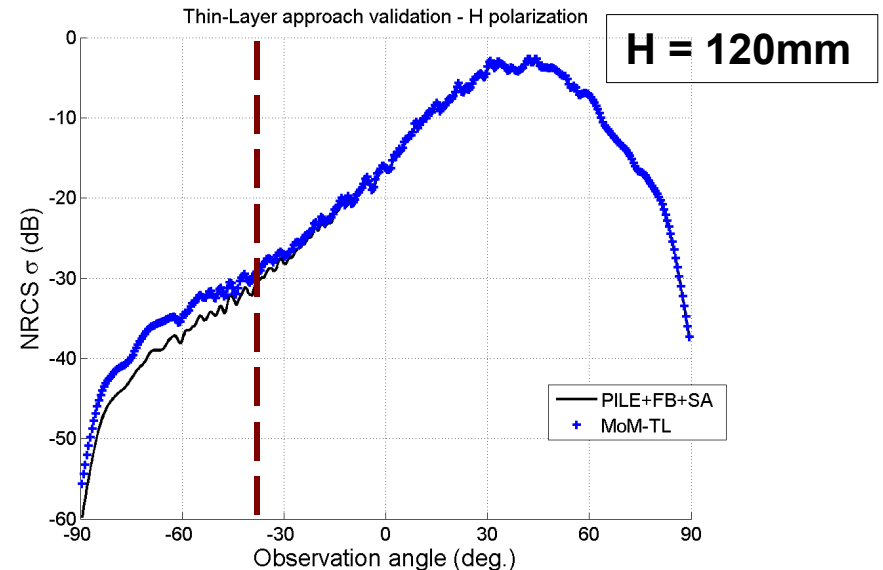
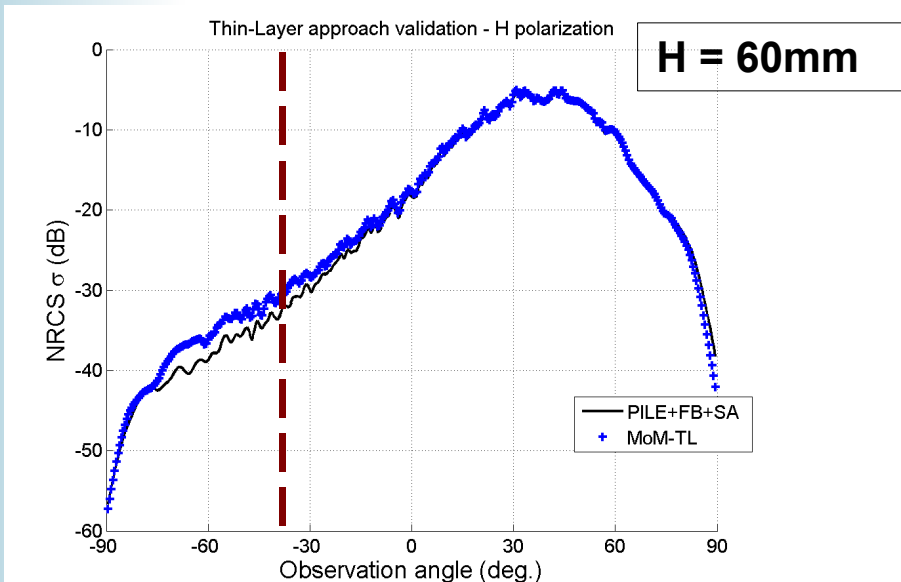
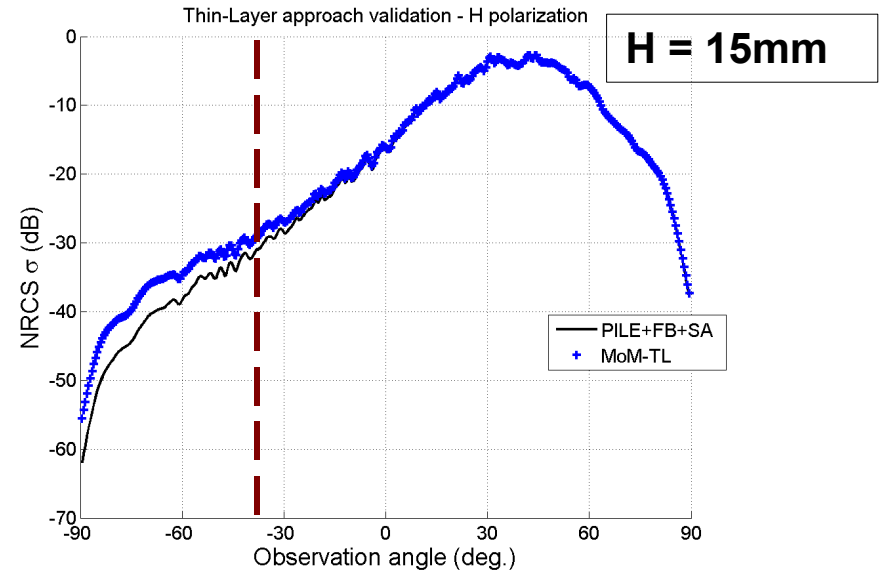
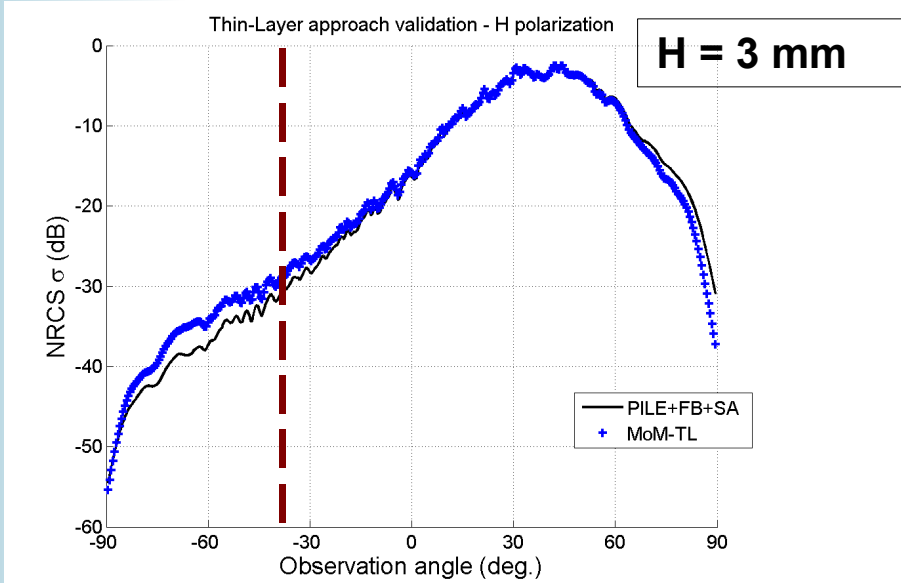


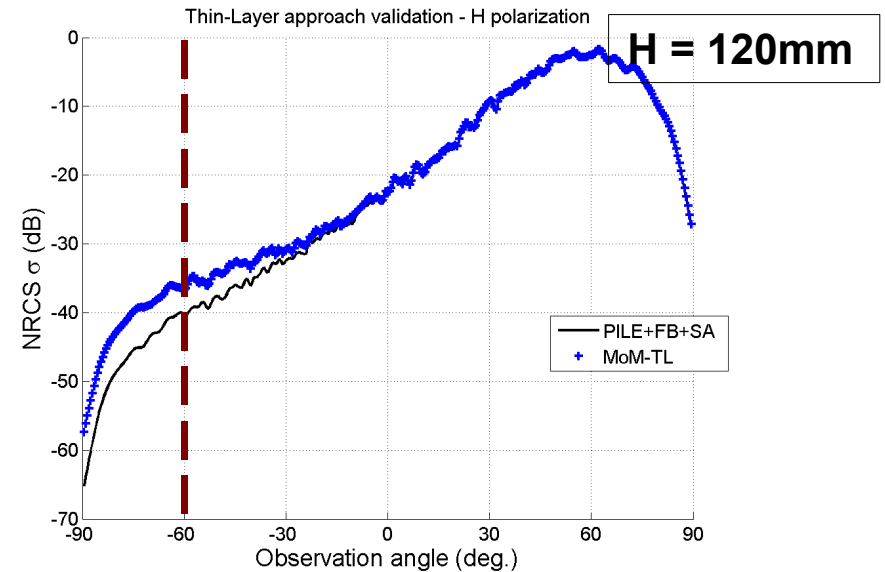
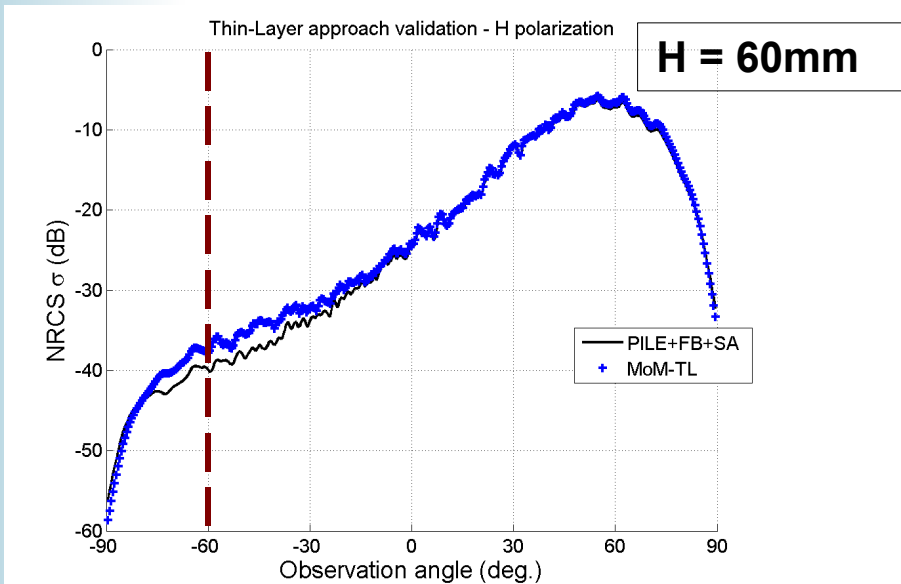
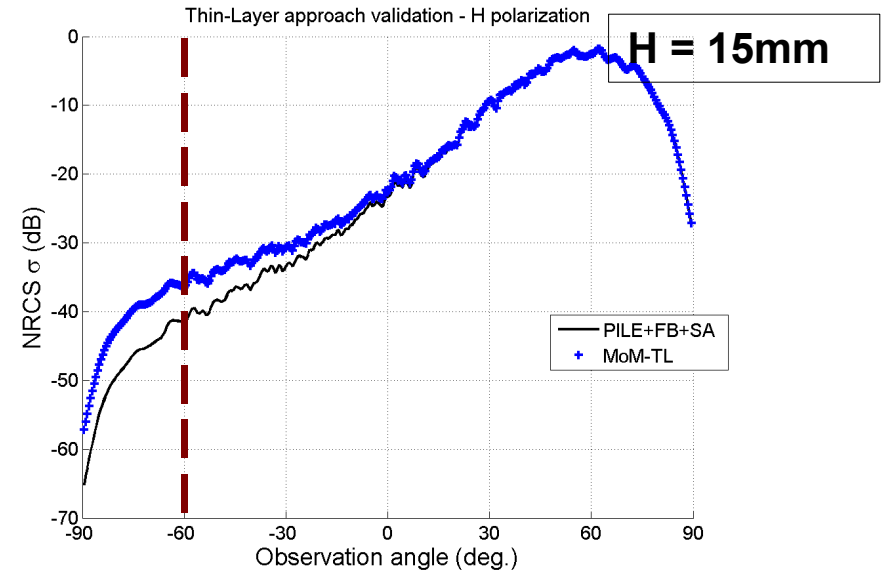
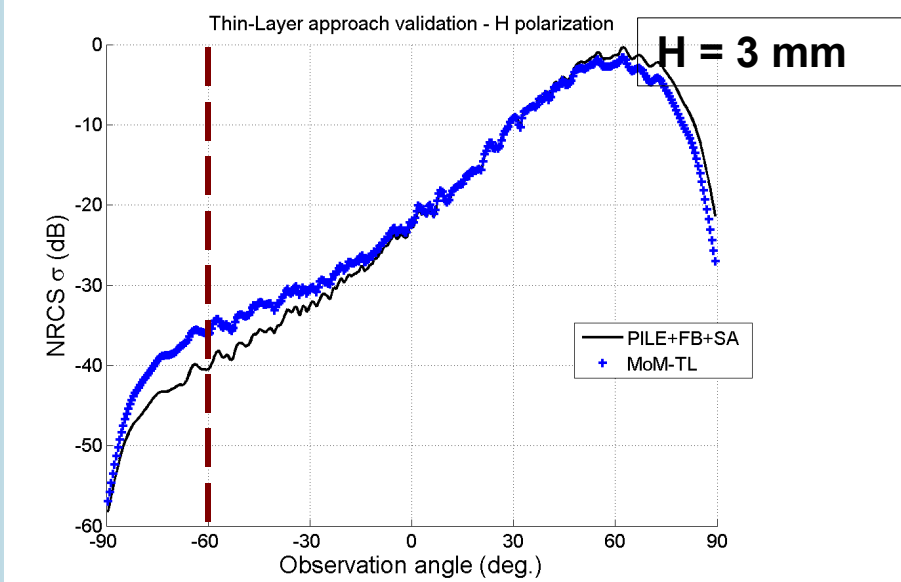
Confirmation of damping of small-scale height parts of $S(k)$

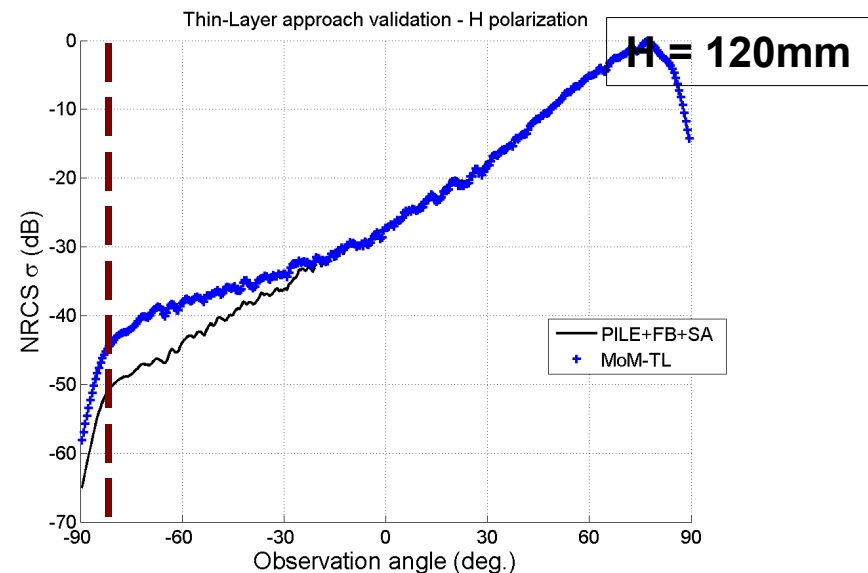
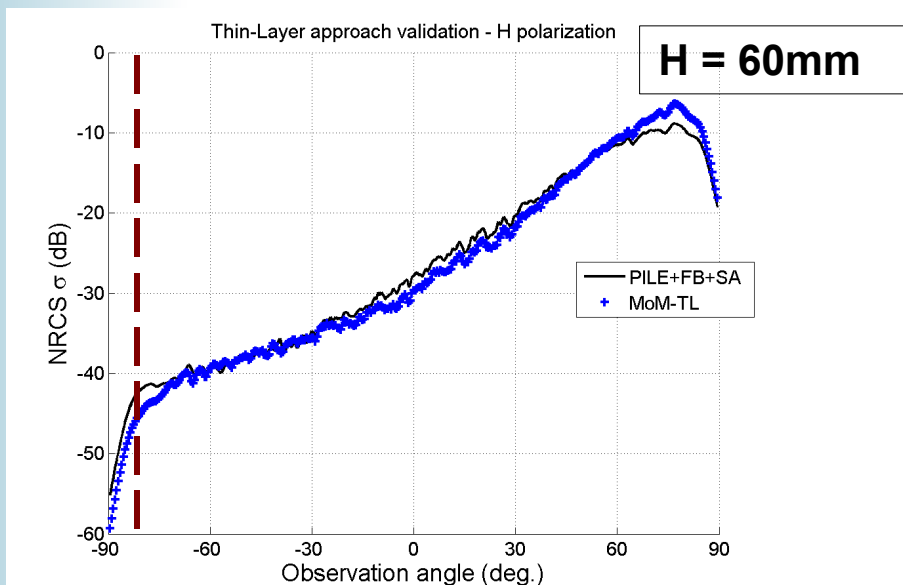
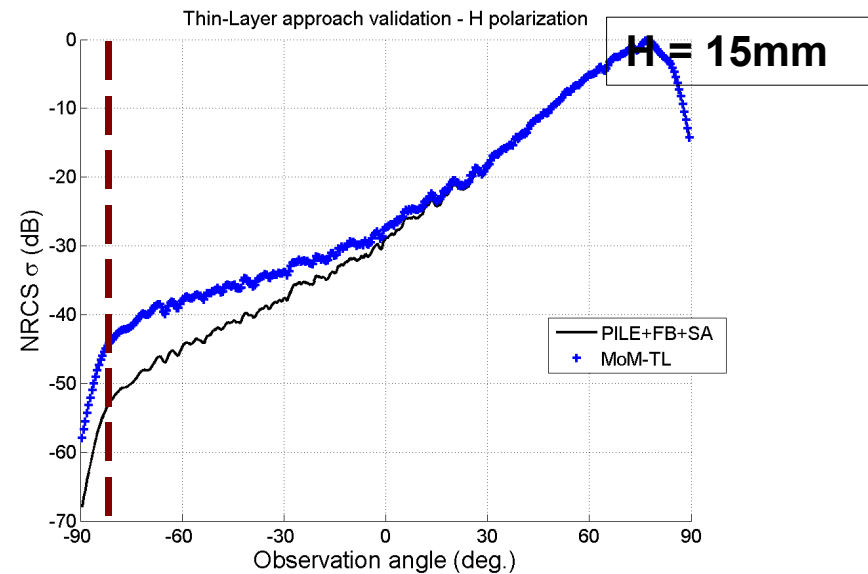
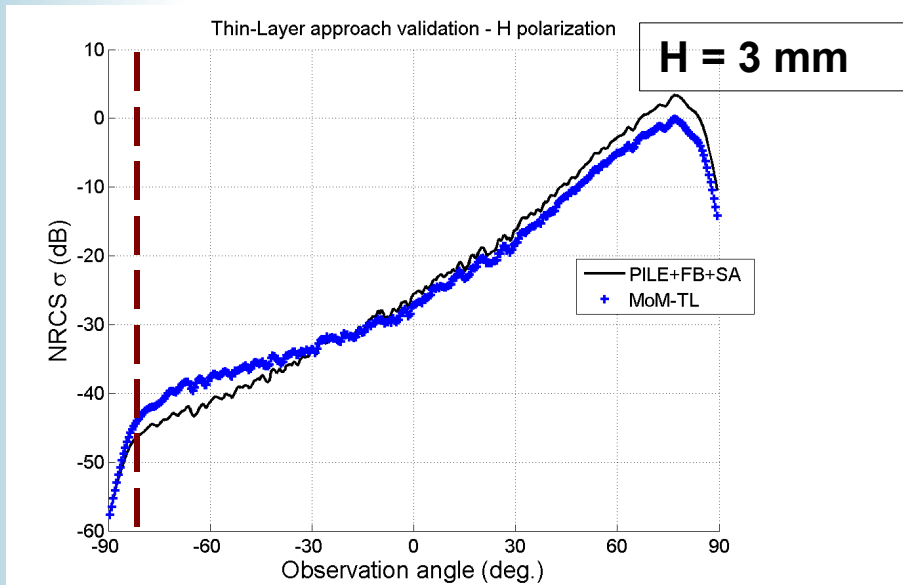
Significant damping of slopes $k^2 S(k)$











V POLARIZATION

