

Rough thin pavement thickness estimation by GPR



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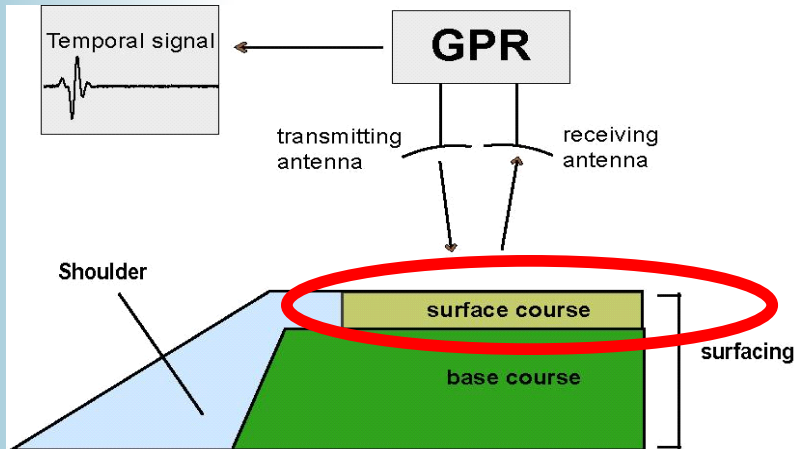
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- Pavement survey and control by NDT (Non destructive Testing) method
 ⇒ **To measure the thicknesses of the pavement layers**
- First layer of pavement : surface course (~5cm)



- ⇒ French standards : VTAS/UTAS
 (Very / Ultra Thin Asphalt Surfacing)
- ⇒ Tendency: reduction of the thickness
 → **Thickness : H ~ 2-3 cm**

- **Radar** NDT method for the pavement



Step frequency radar

GPR
(Ground Penetrating Radar)

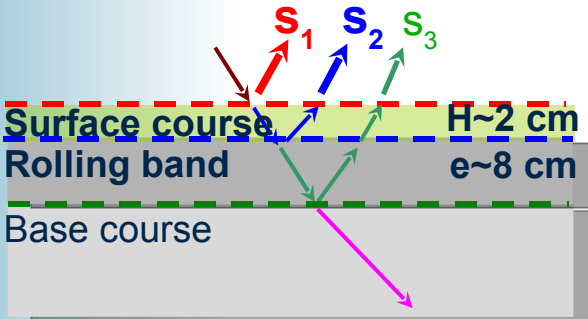


Pulse GPR

- **General context of the study:**

Electromagnetic wave scattering from *rough* thin layers in GPR context

Better pavement thickness estimation, as well as oil slick thickness evaluation
=> To reduce uncertainties

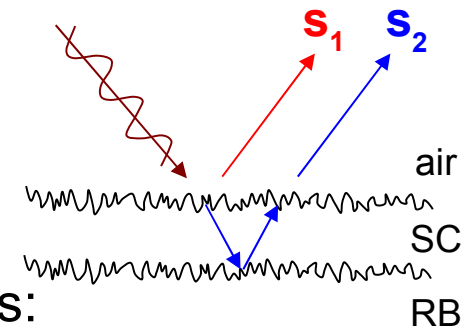


↳ Modeling of the EM scattering of GPR
from the rough thin SC pavement : s_1 , s_2

=> Integration in signal processing algorithms

- **EM scattering modeling (*rough* surfaces)**

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



- **Different possible approaches:**

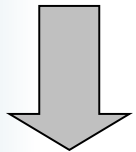


rigorous

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

asymptotic

- + fast
- restricted domain of validity



Method of Moments (MoM)
accelerated by PILE method
[Déchamps et al., JOSAA, 2006]

⇒ Description of the problem to be solved (Waves / Surfaces & Media)

- I. Introduction
- II. Configuration of the study**
- III. EM backscattering from the rough thin pavement
- IV. Application to pavement thickness estimation
- V. Conclusion & Future work

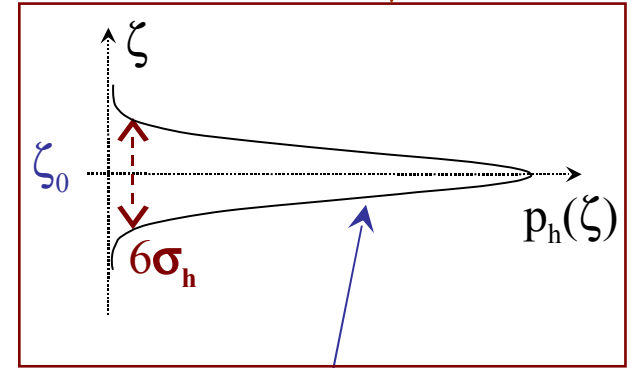
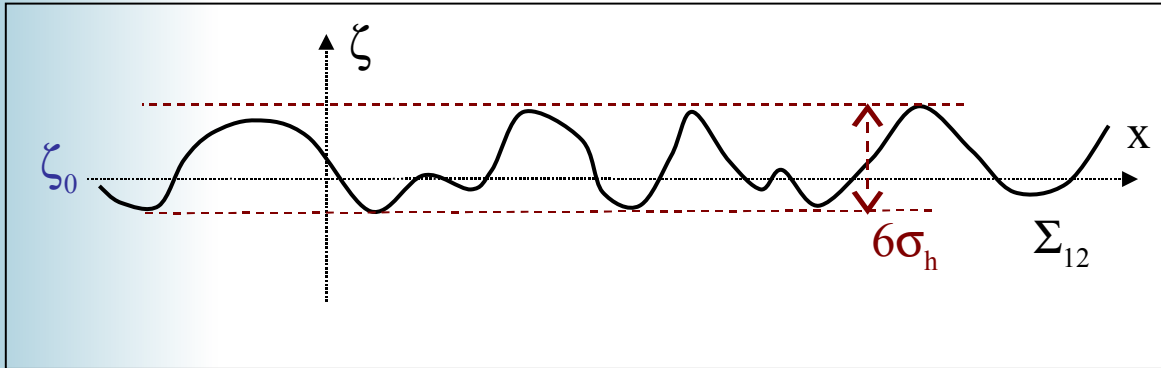
1. MEDIA & SURFACES:

- Hypothesis of homogeneous media (reasonable for this frequency range **[1]**)
- Knowledge of the relative permittivities ϵ_r and conductivities σ of the SC and the RB
- Statistical description of the rough surfaces => Realistic simulations
 - Height distribution
 - Height autocorrelation function

[1]: [Gentili and Spagnolini, TGRS, 2000]

2 main description tools:

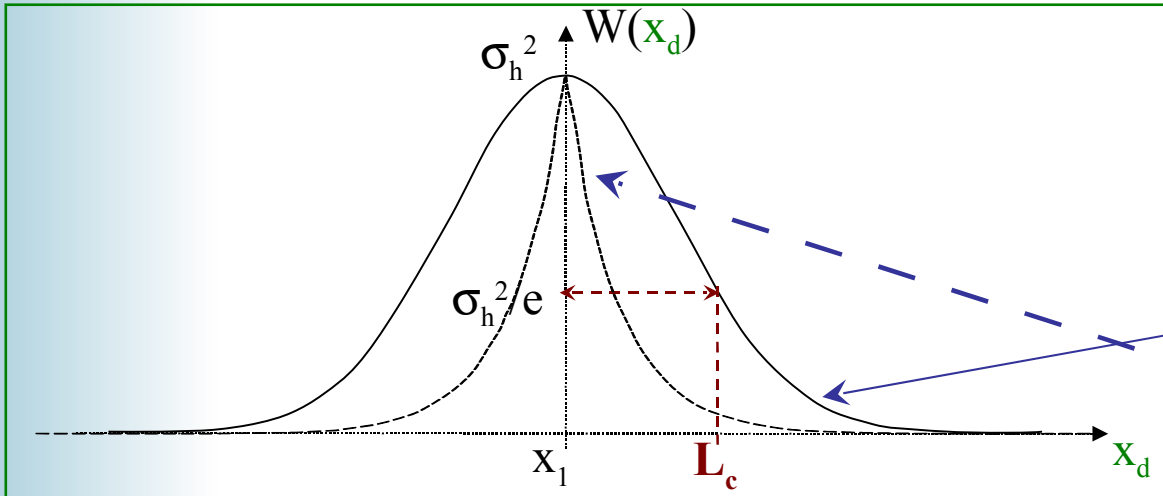
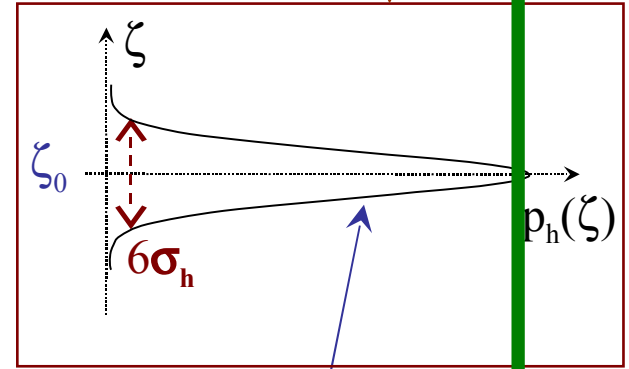
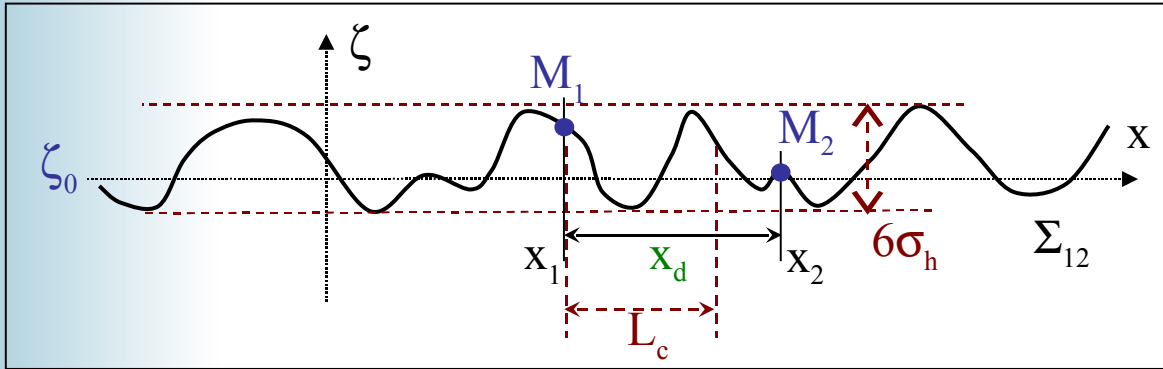
- Height distribution: $p_h(\zeta)$
- Height autocorrelation function: $W(x_d)$



usually
Gaussian

2 main description tools:

- Height distribution: $p_h(\zeta)$
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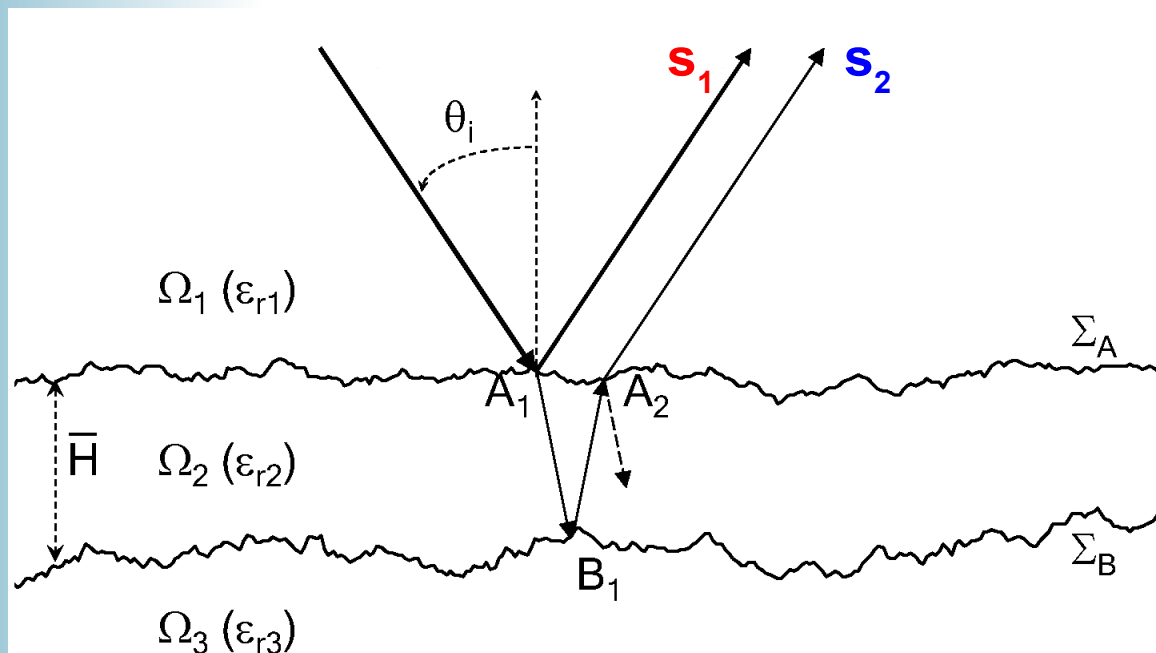
usually Gaussian

usually Gaussian

Pavement: exponential

1. MEDIA & SURFACES:

- Statistical description of the rough surfaces => Realistic simulations
 - Height distribution $p_h(\zeta)$
 - RMS height σ_h : $\sigma_{hA} \approx 1 \text{ mm}$ - $\sigma_{hB} \approx 2 \text{ mm}$
 - Height autocorrelation function $W(x_d)$
 - correlation length L_c : $L_{cA} \approx 5-10 \text{ mm}$ - $L_{cB} \approx 10-20 \text{ mm}$



Representation of
air/SC and SC/RB
surface heights

2. SENSORS (→GPR) & WAVES:

- Configuration: Monostatic (→ backscattering)
- Angular incidence: Normal incidence $\theta_i = 0$
- Frequency band: $B \approx 2 \text{ GHz}$ / Central frequency: $f_c \approx 2 \text{ GHz}$
- Polarization states: any → linear here
- Co-polarization mainly (VV & HH)
- Far-field zone from the pavement
- Type of incident wave: plane wave
(Gaussian beam)
- Illumination width: $\sim 10 \text{ cm}$
⇒ *Variability of the backscattered echoes*



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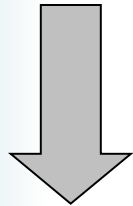
- Different possible approaches:

rigorous

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Needs to calculate the first two echoes s_1 and s_2

Method of Moments (MoM)
accelerated by PILE method
[Déchamps et al., JOSAA, 2006]

SPATIAL method which is able
to calculate **each** echo
backscattered from the rough pavement

- Simulation parameters :
 - Media permittivities ϵ_r and conductivities σ :

$$\left\{ \begin{array}{l} \epsilon_r^{SC} = 5 \quad - \quad \sigma^{SC} = 5 \times 10^{-3} \text{ S/m} \\ \epsilon_r^{RB} = 8 \quad - \quad \sigma^{RB} = 1 \times 10^{-2} \text{ S/m} \end{array} \right.$$
 - Rough surfaces Σ_A and Σ_B characteristic values (σ_h and L_c):

$$\left\{ \begin{array}{l} \sigma_h^A = 0.8 \text{ mm} \quad - \quad L_c^A = 10.0 \text{ mm} \\ \sigma_h^B = 1.6 \text{ mm} \quad - \quad L_c^B = 30.0 \text{ mm} \end{array} \right.$$
 - Mean layer thickness H :

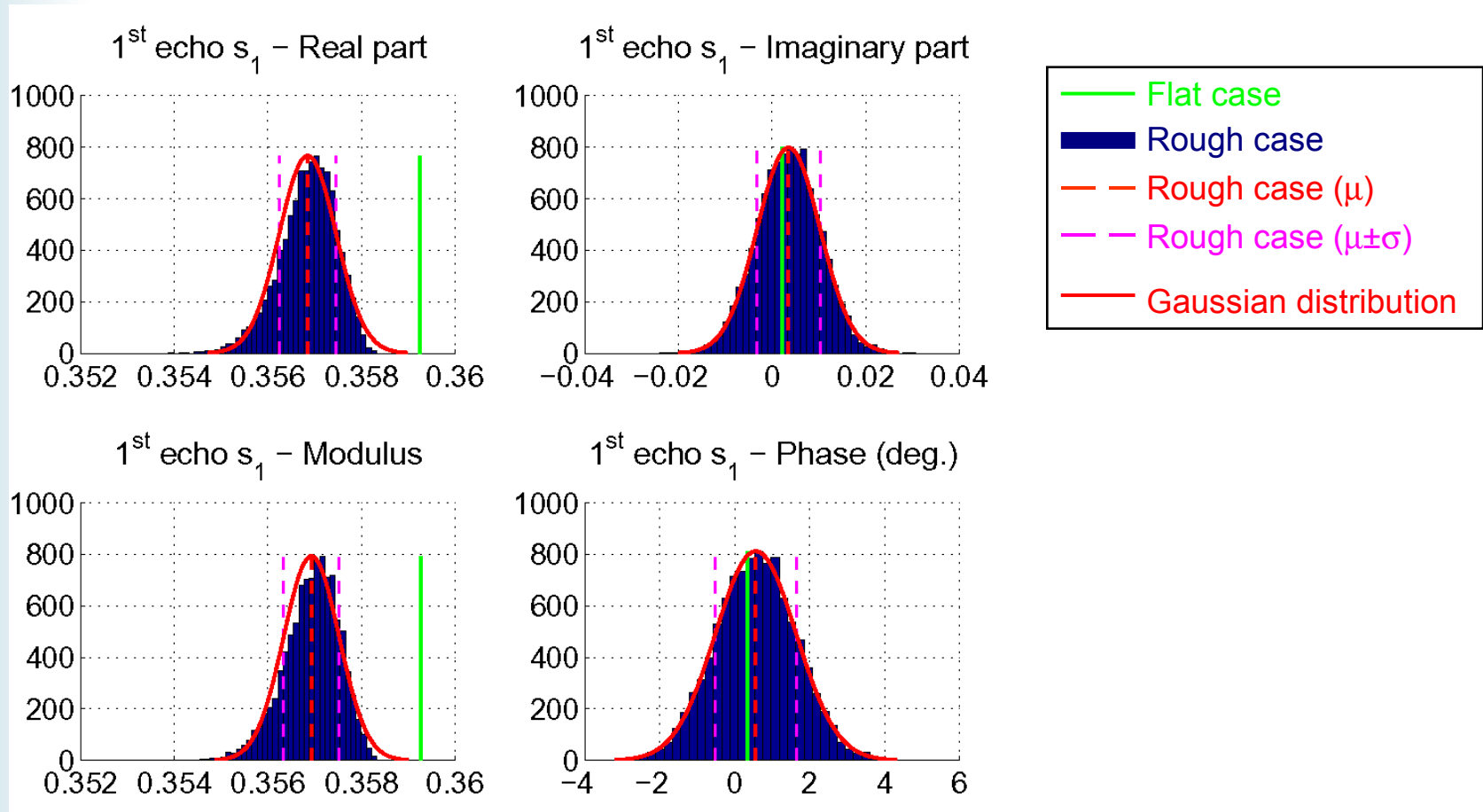
$$H = 20 \text{ mm}$$
 - Radar central frequency f_0 and bandwidth B :

$$f_0 = 2 \text{ GHz} \quad - \quad B = 2 \text{ GHz}$$
 - Incidence angle θ_i and polarization:

$$\theta_i = 0 \text{ deg.} \quad - \quad \text{VV polarization}$$
 - Monte-Carlo process: $N = 1000$ realizations

$$\text{Sampling step } \Delta x = \lambda_2 / 10$$

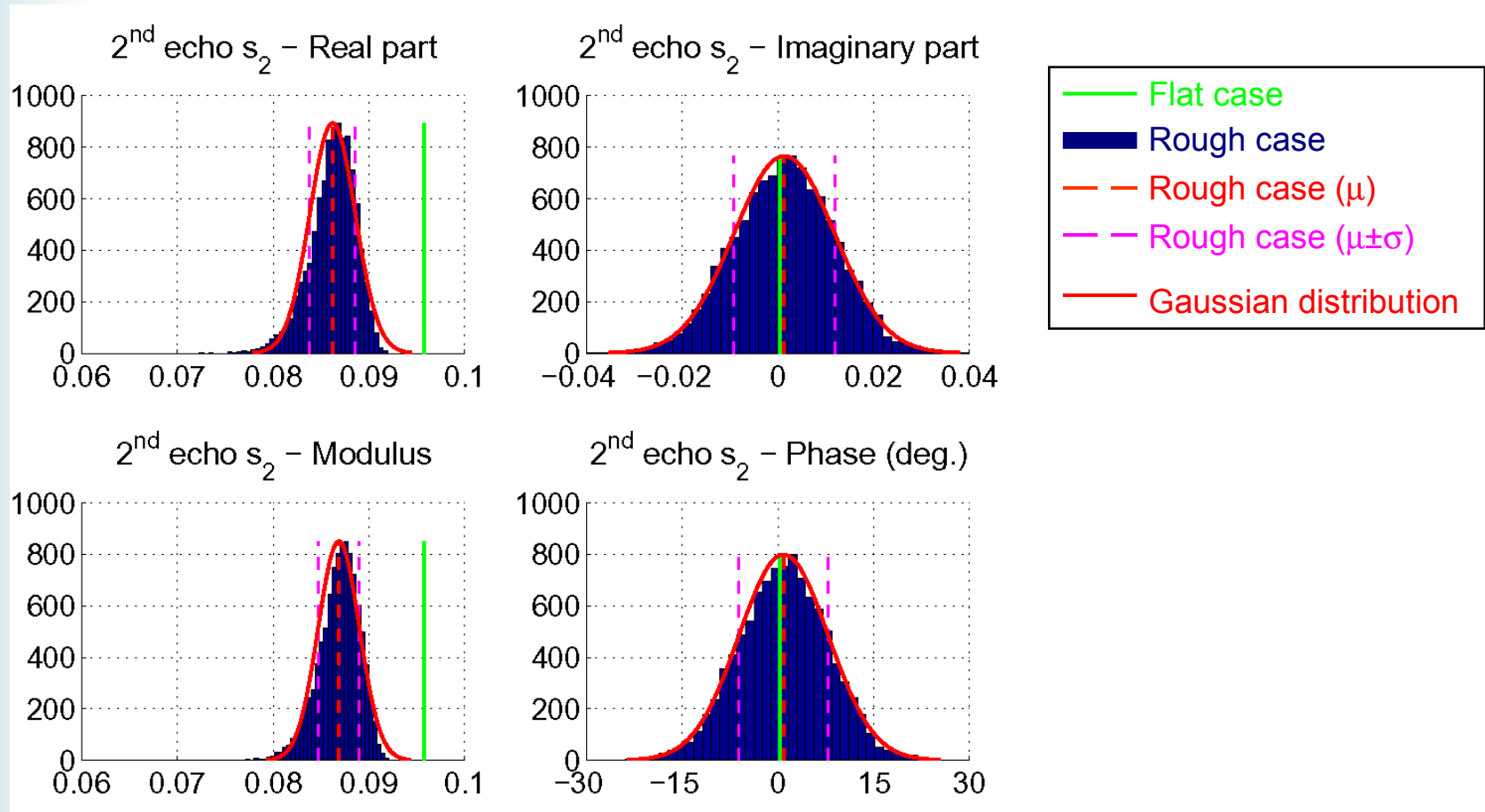
Statistical distribution of the backscattered echoes ($f = 2$ GHz): 1st echo s_1



Rather small variability of the echo s_1 – Similar to Gaussian distribution

Small differences with the flat case

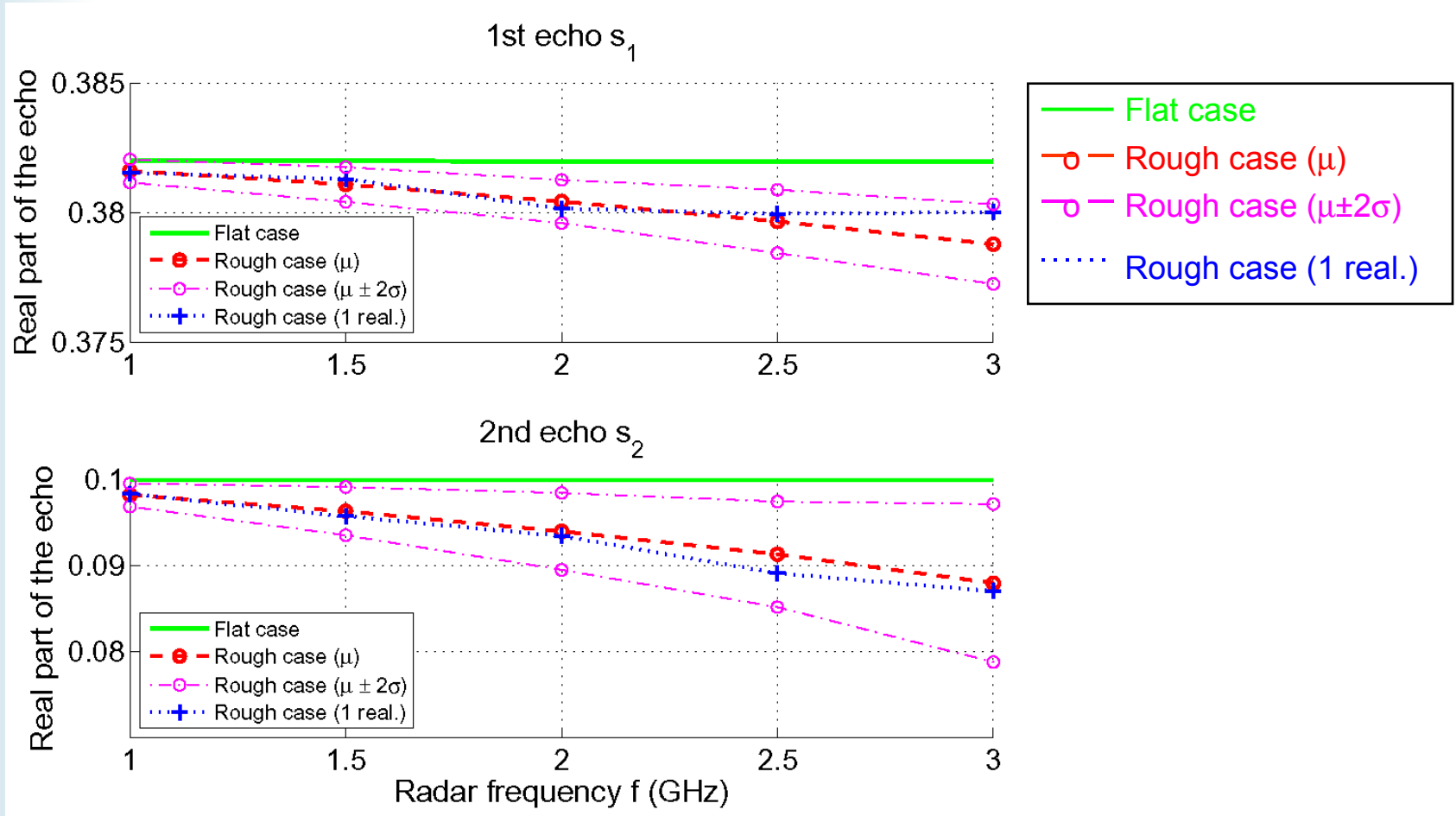
Statistical distribution of the backscattered echoes ($f = 2$ GHz): 2nd echo s_2



Higher variability of the echo s_2 – Similar to Gaussian distribution

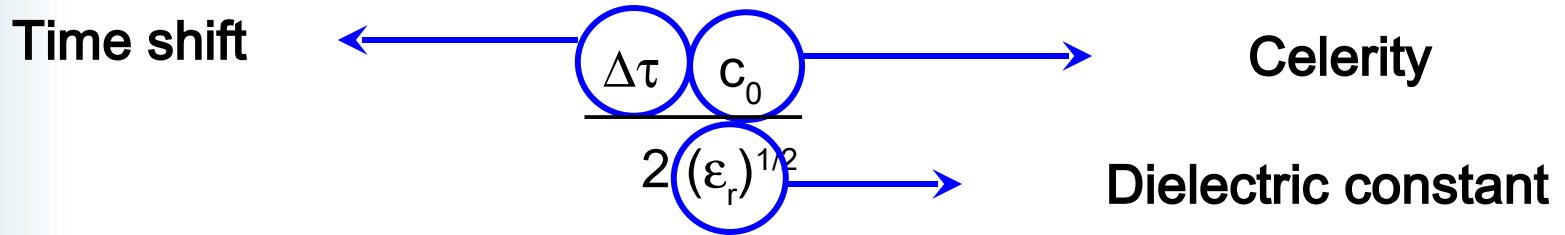
Rather small differences with the flat case

Frequency behavior of the backscattered echoes (f in [1.0; 3.0] GHz): Real part:



Frequency decrease of the rough case: significant especially for s_2

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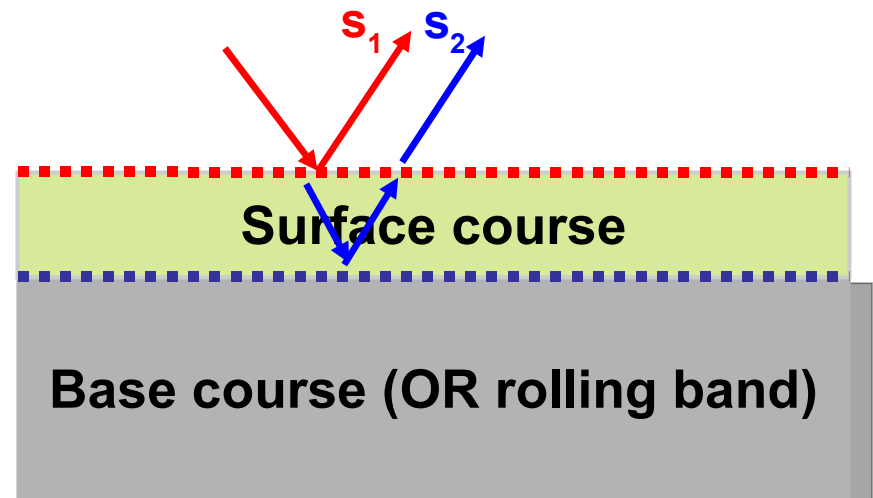
Principle

1. Estimation of time delay $\Delta\tau$ ($=t_2 - t_1$)
2. Estimation of dielectric constant ϵ_r

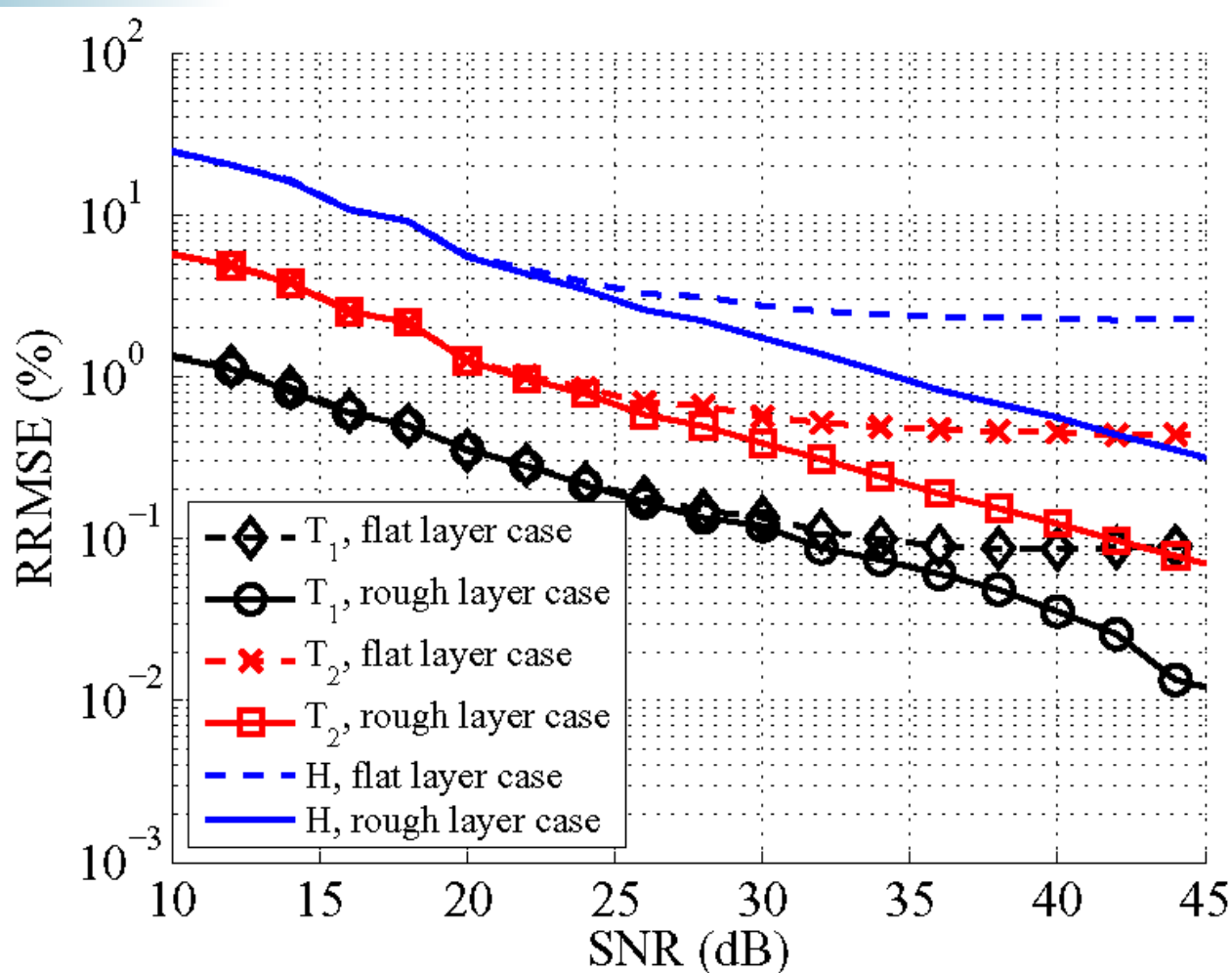
Thickness: function of $(\Delta\tau, \epsilon_r)$

- Time delay estimation (TDE)
- Resolution: $B\Delta\tau$ product
 - ✓ B: frequency bandwidth
 - ✓ $\Delta\tau = t_2 - t_1$: minimal time shift between echoes s_1 and s_2
- Requirements for UTAS/VTAS survey ($H \sim 2$ cm):
 - ✓ Larger bandwidth: $B > 7$ GHz (with constant $B\Delta\tau > 1$)
 - ✓ Better resolution: $B\Delta\tau < 0.6$ (with constant bandwidth: 2 GHz)
- Solution: To increase the time resolution by high resolution signal processing
 - => Maximum Likelihood Method (MLM)

- Monte Carlo process: 500 independent runs, $B = 2$ GHz, $f_c = 2.0$ GHz
- Correlation matrix: 200 snapshots
- 2 echoes \mathbf{s}_1 and \mathbf{s}_2
- The powers of the two sources are fixed to 0 and -6 dB
- Dielectric constant: known
- $B\Delta\tau = 0.3$
- White noise
- Pulse: ricker
- $\text{SNR} \in [0; 30]$



- Relative Root Mean Square Error (RRMSE, %) vs. SNR (dB)



RRMSE decreases
when SNR increases

For high SNR,
significant difference
between flat and rough
cases

Increased performance
for high SNR

but small gain in
pavement thickness
estimation (~1%)

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- Electromagnetic modeling:
 - Quantification of the backscattered echoes from the rough pavement and comparison with the flat case
 - Variability of the backscattered echoes
 - Significant frequency decrease of the echoes (especially for s_2)
- Signal processing: Application to pavement thickness estimation
 - Improvement of the RRMSE for high SNR
 - Small gain in pavement thickness estimation ($\sim 1\%$)
 - => Considering flat interfaces is reasonable in this context

Rough thin pavement thickness estimation by GPR



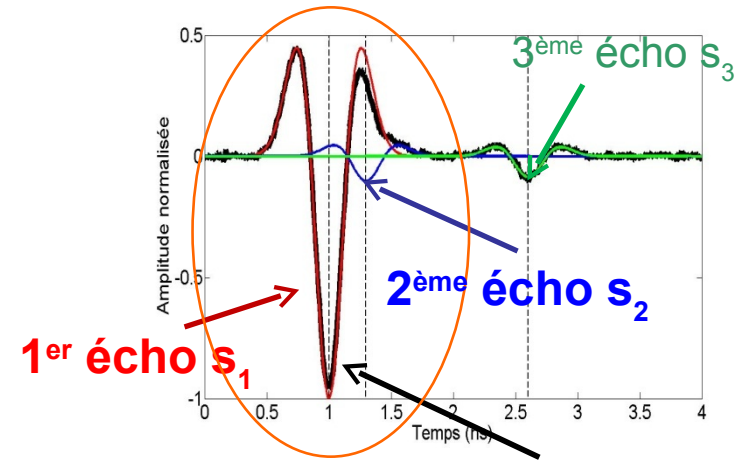
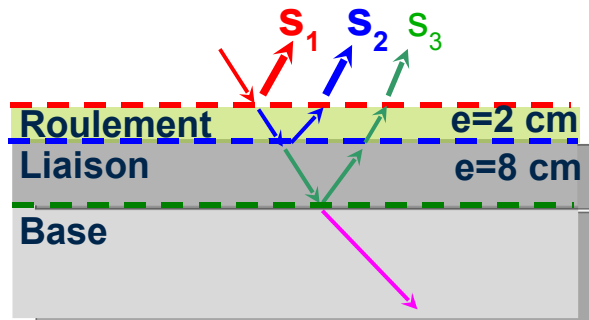
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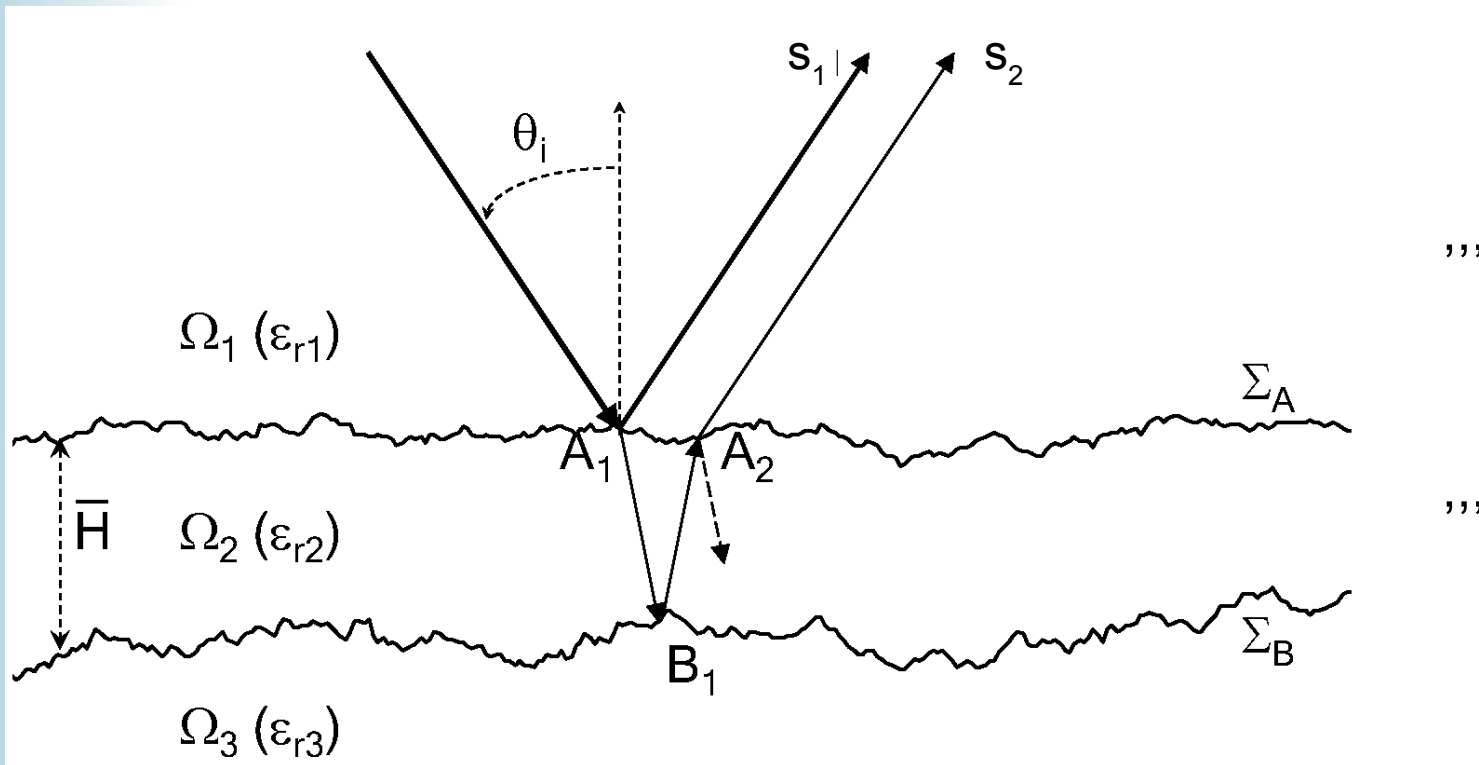
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Signal reçu par le GPR

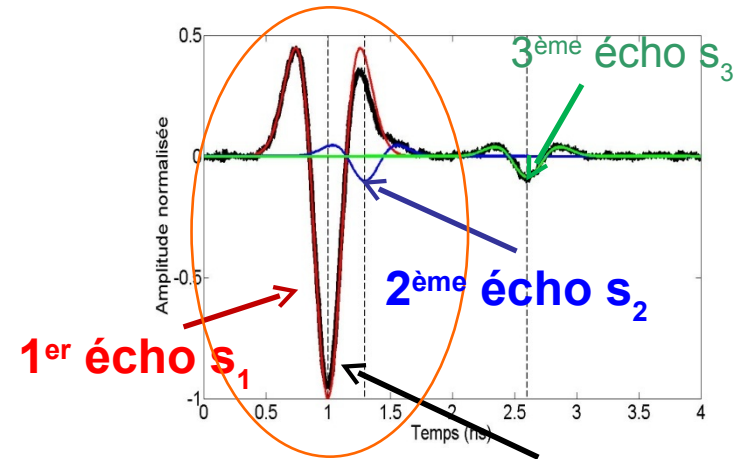
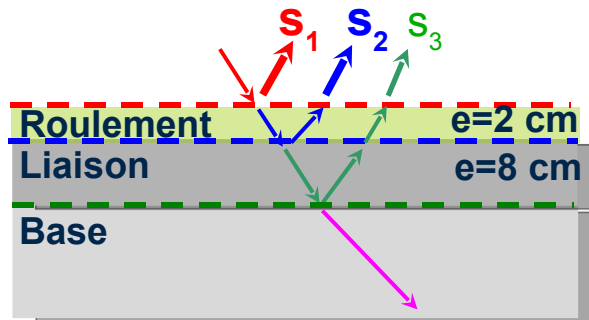
- Gaussian height PDF
- Exponential autocorrelation function

Representation of air/SC and SC/RB surface heights:



Thématique : Apport de techniques de traitement du signal super et haute résolution à l'amélioration des performances du radar-chaussée

- Problématique : estimation d'épaisseur de couches minces de chaussées par GPR



Signal reçu par le GPR

- Objectif : améliorer la résolution temporelle
- Moyens : Estimation de retards de propagation
 → algorithmes de traitement du signal « Haute résolution » (MUSIC, ...)