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Spatial Coherence of GNSS-R Signals: A Numerical Investigation

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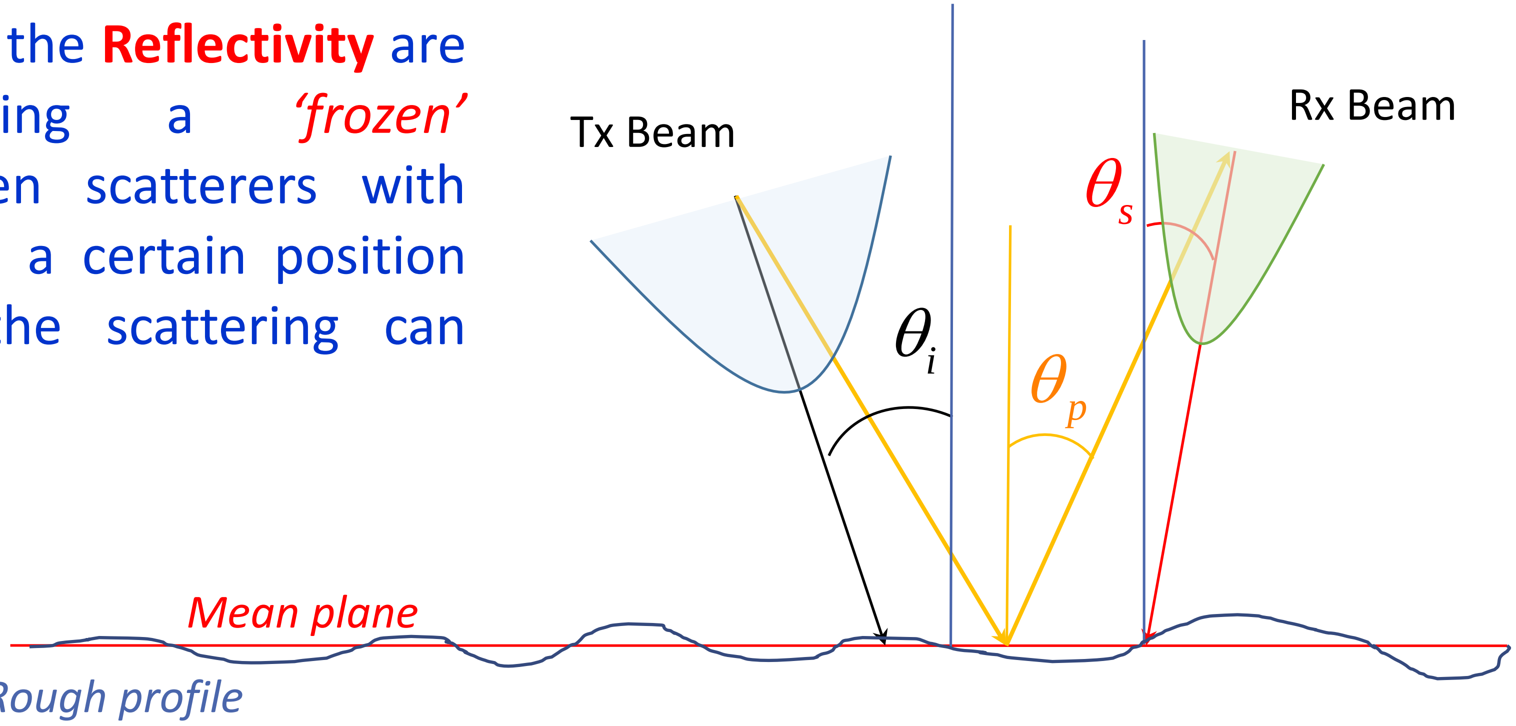
Introduction

- ✓ The scattered field is generated by the superimposition of an ***incoherent*** and a ***coherent*** field
  - ✓ The two contributions are generally represented by the ***Normalized Radar Cross Section*** **(NRCS)** and the ***Surface Reflectivity***
    - ✓ However if the ***NRCS*** and the **Reflectivity** are achieved by assuming a *'frozen' configuration,* i.e., frozen scatterers with both antennas placed in a certain position over the 2-D space, the scattering can present ***phase coherence***



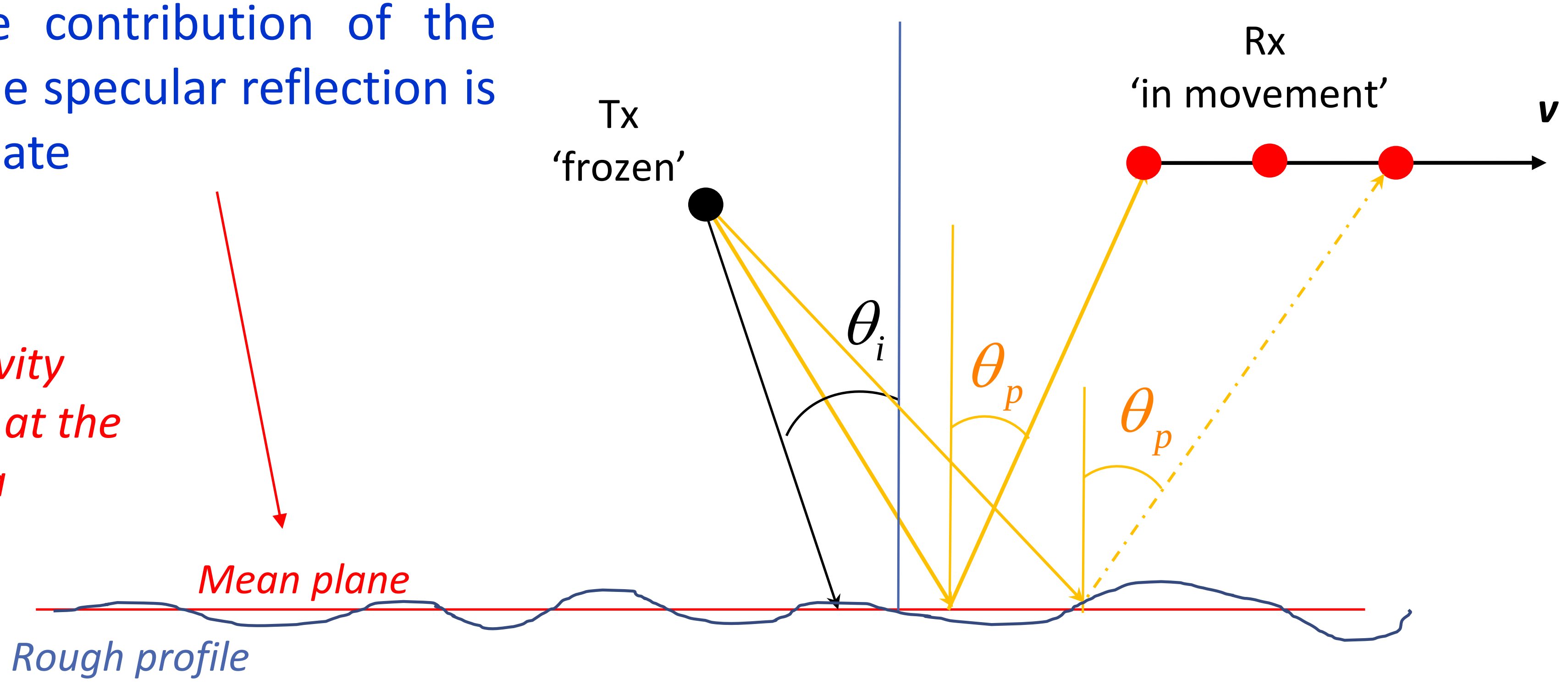
Coherence of the Scattered Field

- ✓ The ***relative movements*** of transmitter and receiver and the system resolution, combined with the random nature of the illuminated surface, affect the ***coherence*** of the ***scattered field***

- ✓ For a flat surface, the ***coherent component*** is, by definition, the contribution of the '*mean plane*'. Thus, the specular reflection is expected not to fluctuate

⇩

The surface reflectivity determines the power at the receiver antenna



Coherence of the Scattered Field

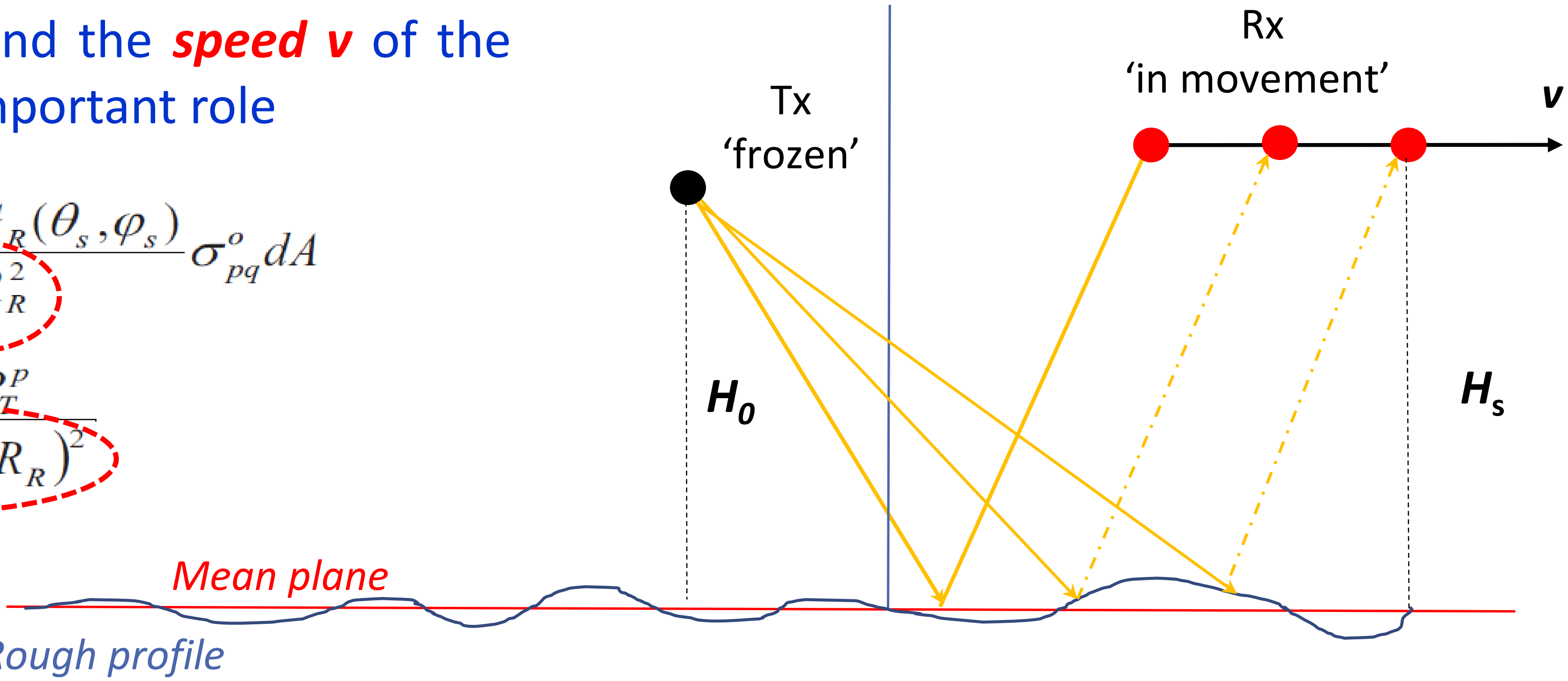
- ✓ A change in ***coherence*** can have a detrimental effect on the coherent and incoherent ***integration*** of the radar echoes at the receiver

  - ✓ ***Long term fluctuations*** would not be mitigated by incoherent integration (fewer independent samples)

    - ✓ Both the ***height*** and the ***speed v*** of the receiver play an important role

$$P_r^{q(incoh)} = \frac{P_T^p \lambda^2}{(4\pi)^3} \int \frac{G_T(\theta_i,\varphi_i)\, G_R(\theta_s,\varphi_s)}{R_T^2 R_R^2} \sigma^o_{pq}\, dA$$

$$P_r^{q(coh)} = \Gamma_{pq} \frac{\lambda^2 G_T G_T P_T^p}{(4\pi)^2 (R_T + R_R)^2}$$

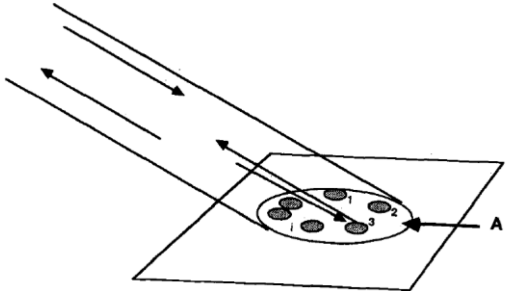


Spatial Decorrelation

- ✓ **In the literature, *the*** ***spatial coherence has mainly been characterized in the frame of SAR interferometry considering backscattering***

Li, Fuk K. and Richard M. Goldstein, "Studies of multibaseline spaceborne interferometric synthetic aperture radars." *IEEE TGRS* 28.1 (1990): 88-97.

Zebker, Howard A. and John Villasenor, "Decorrelation in interferometric radar echoes." *IEEE TGRS,* 30.5 (1992): 950-959.



Uncorrelated scatterers within the resolution cell

Simple expression provided for the correlation as a function of the *system baseline* assuming a 2-D distribution of *uncorrelated scatterers*

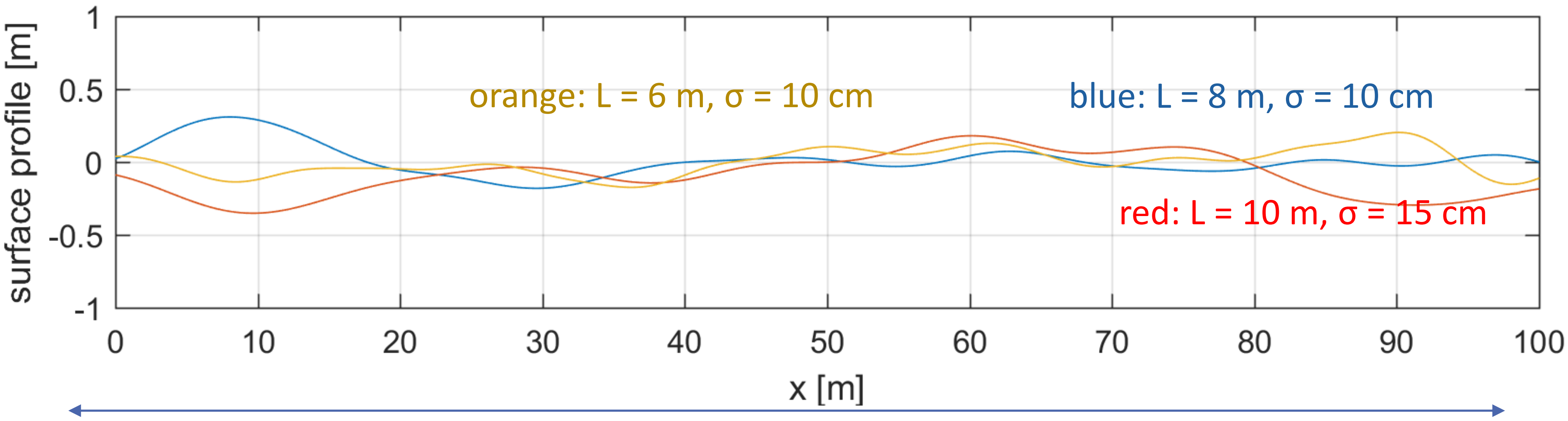
- ✓ **The effect of the local terrain slope was accounted for by *Franceschetti et. al.*, later in the frame of the Kirchhoff scattering theory**

Franceschetti, G., et al. "The effect of surface scattering on IFSAR baseline decorrelation." *JEWA* 11.3 (1997): 353-370.

Fluctuation over *Almost Flat* Areas

- ✓ **Over a very flat area one would not expect fluctuations from satellite height, as diffuse component is greatly attenuated** (due to free space losses)
- ✓ **Instead fluctuations can be very high, larger than from an airborne receiver (Disomogeneity? Instrument? others?)**
  - ✓ **The question is: a «*flat area*» is *really flat*?**
  - ✓ **What about the presence of water bodies?**

- ✓ Gentle ondulations may occur at large scale, i.e., low height **(~5-15 cm)** and long correlation length **(~6-10 m)**
- ✓ Validity limits scalar KA almost always ok for a general assessment:



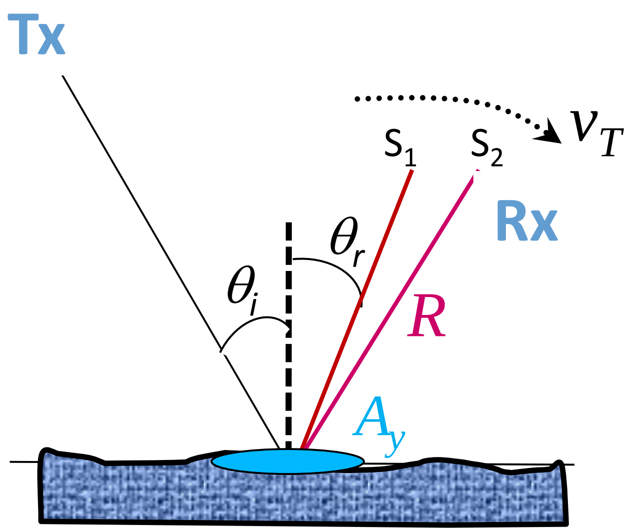
$(qz*\sigma)^2 >> 10 \quad k_0*\sigma >> 2$

Surface profile over 100 m

Correlation Time

- ✓ For an *incoherent* scattering the signal fluctuates (speckle "noise").

  - ✓ When Rx moves from S1 to S2, if the *target A_y consists of uniformly distributed uncorrelated scattering centers*, the *decorrelation time* (see e.g., Zuffada et al., 2003, RSoEnv, Zebcker,1992, TGRS) is given by



$$T_C = \frac{\lambda R}{2 v_T A_y \cos^2 \vartheta_i}$$

for a plane 100 m high, **v_T = 60 m/sec**, **15° incidence**, **T_C = 2.4 msec**

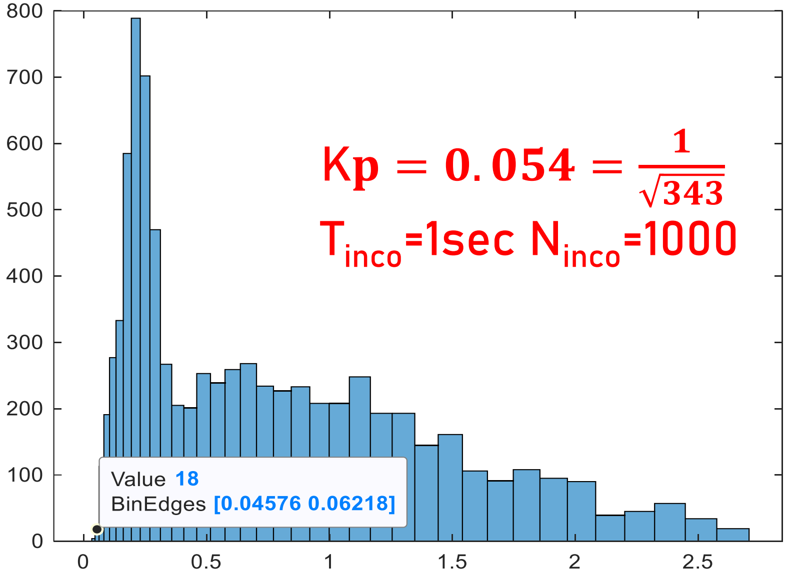
- ✓ **How the coherent signal is expected to fluctuate?**

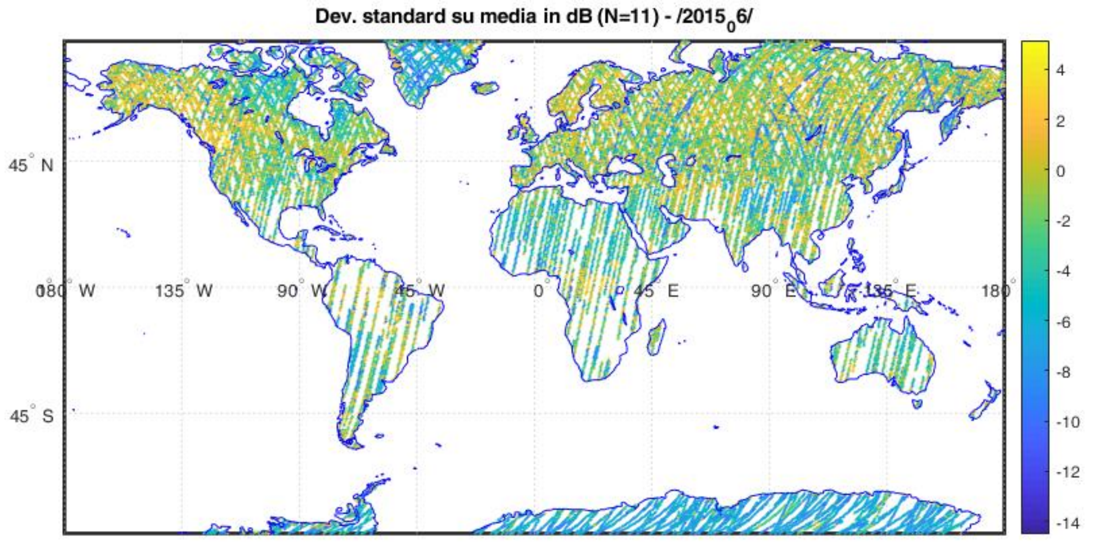
Limit case: the variability determined by a ***pure coherent reflection*** from a flat infinite surface should be zero

- ✓ **The presence of water bodies is expected to generate coherent signals…**

Spaceborne Fluctuations

Histogram of *the coefficient of variation* (Kp=std/mean) of TDS reflectivity within 11 samples, i.e., over 11 secs (70 km).





Most homogenous areas is Antarctica

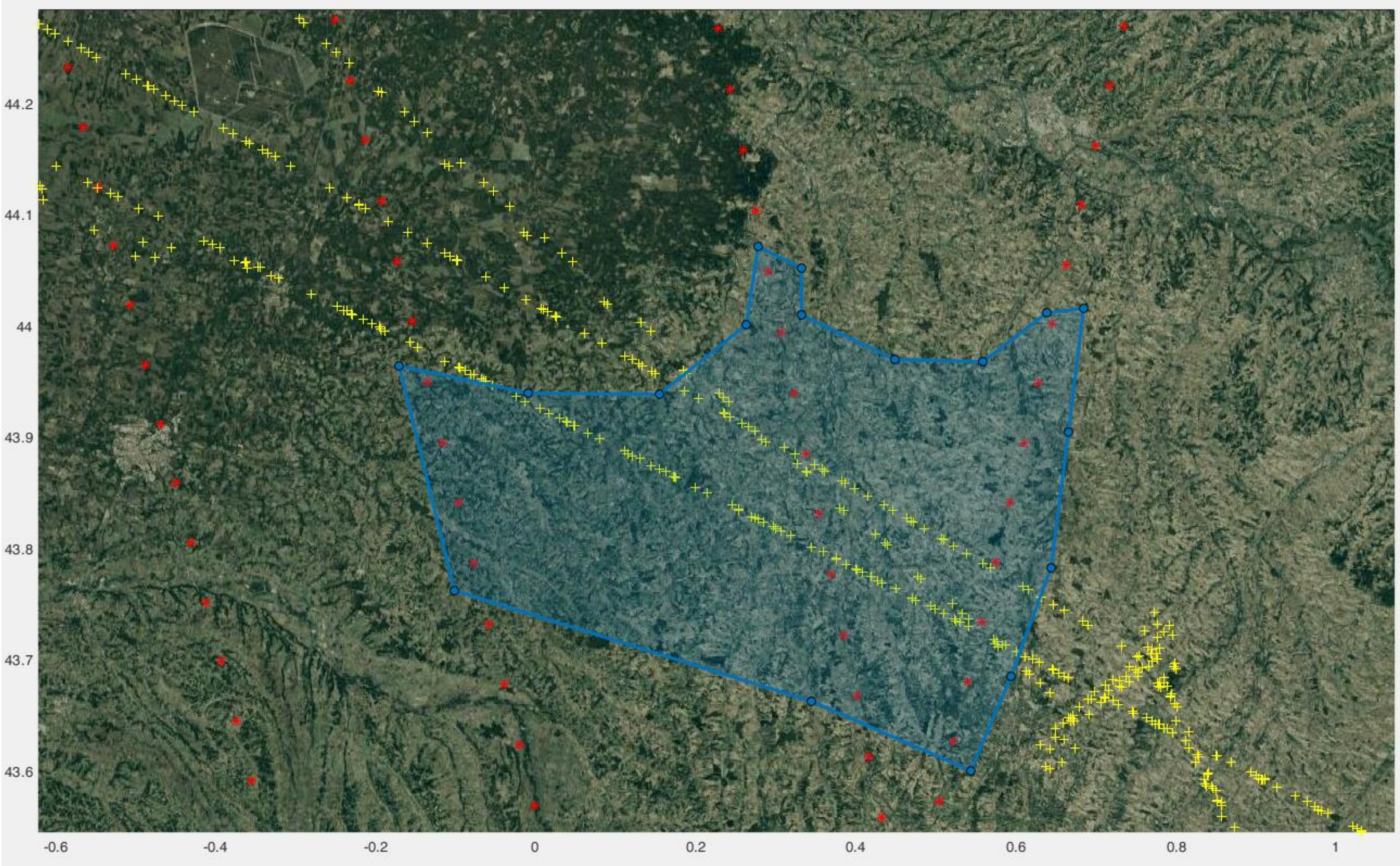
- Minimum value (i.e., mostly homogenous areas) ~0.05. **In Antarctica the scattering should not be assumed completely coherent**
- It corresponds to 340 looks ($kp=1/\sqrt{340}=0.054$) as compared to 1000 samples average (1 sec incoherent, 1 msec coherent integration). **Therefore, as expected, there is a certain degree of correlation between samples…**

Airborne Fluctuations

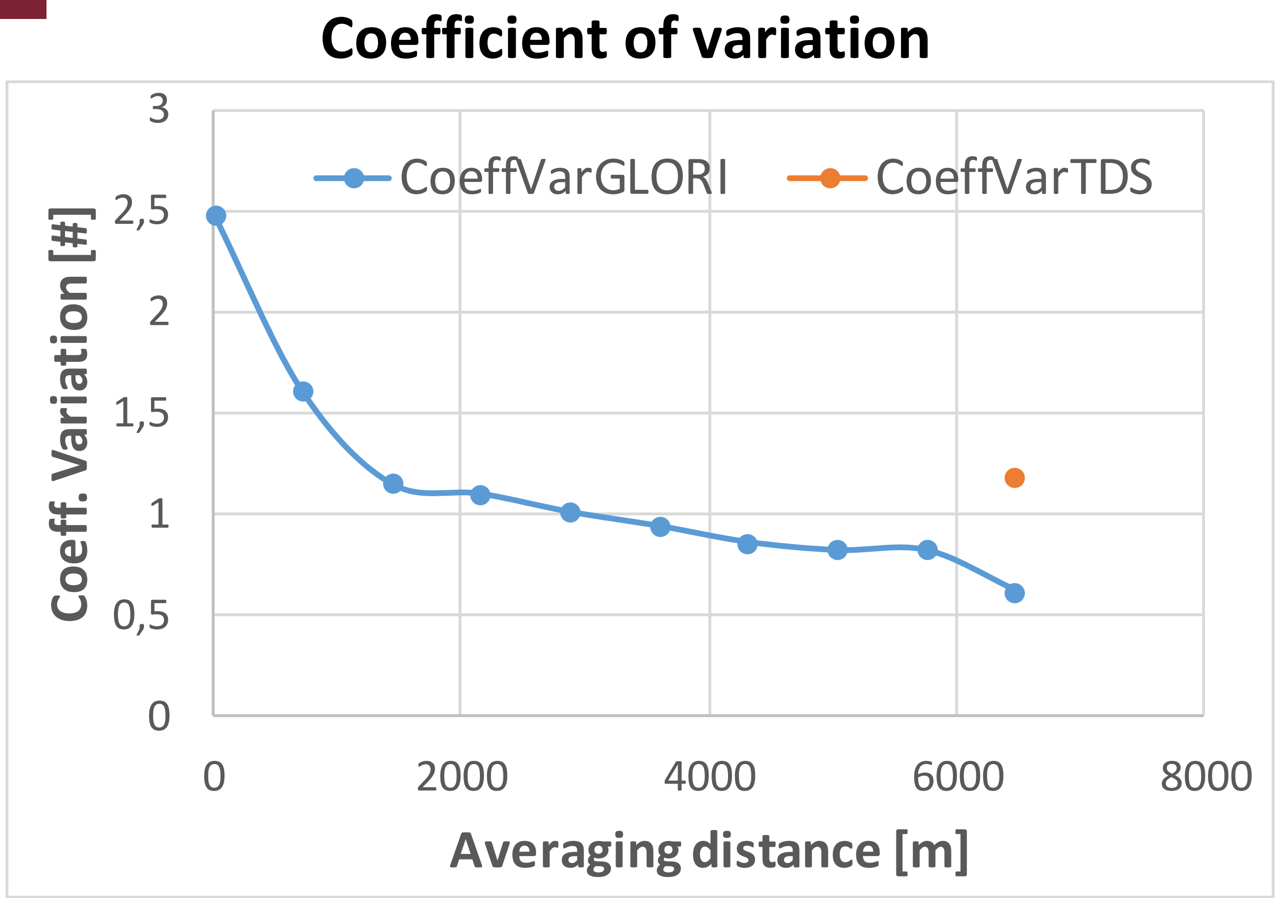
TDS-1 data (red, 1 ms coherent) at 1 sec (incoh, 6.5 km distance made) and GLORI data (yellow, 20 ms coherent) averaged incoherently over different distances (**from 15 m to 6.5 km**) were analysed on a common quite homogeneous agricultural area

GLORI data: kindly provided by Dr. Zribi (CESBIO), in the frame of an ESA project.

Thanks!!



Observed Fluctuations



GLORI:

$$T = \frac{space}{velocity} = \frac{6.5\ km}{60\ m/sec} = 108sec$$

$$Nc = \frac{time\ span}{T_{coheren}} = \frac{108\ sec}{20\ msec} = \mathbf{5400\ samples}$$

TDS:

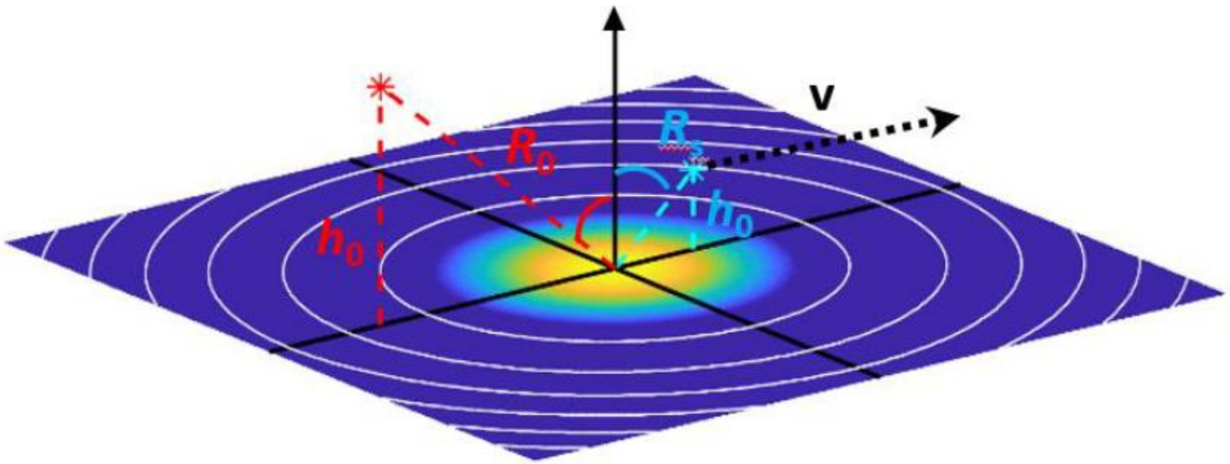
$$Nc = \frac{1\ sec}{1\ msec} = \mathbf{1000\ samples}$$

- ✓ Kp not zero, the scattering should not be considered fully coherent
  - ✓ Integrating more samples with GLORI, Kp gets smaller…

✓ **Both the Spaceborne and the Airborne case generally suggest the scattering cannot be fully coherent, neither incoherent….**

Field Fluctuations vs Target Corr. Length

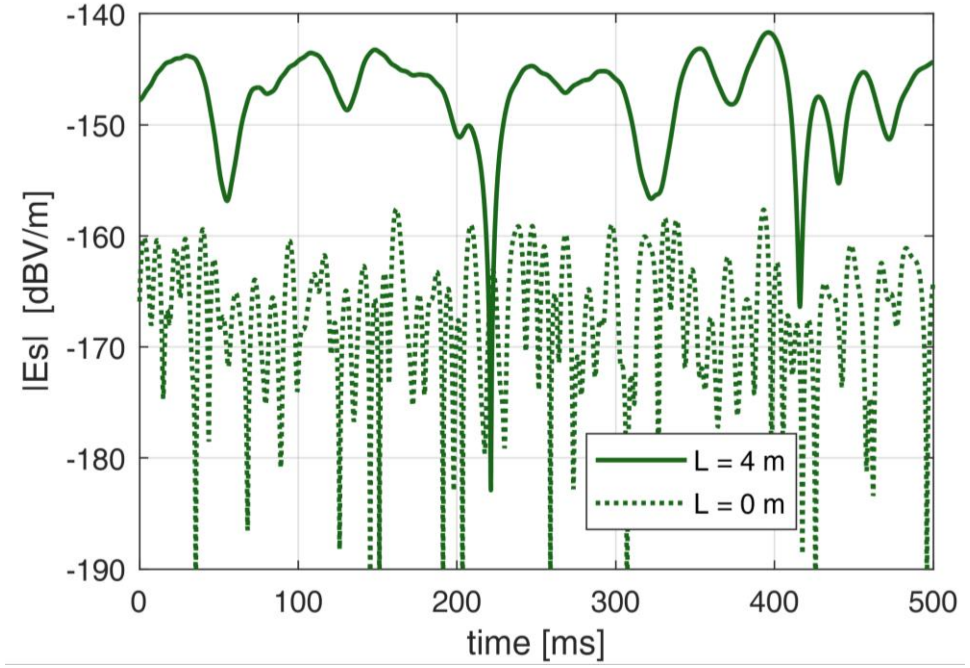
- ✓ Simulation of 2-D Gaussian surfaces with different correlation lengths: ***H*=100 m, *v*=60 m/sec, 15° beam**
  - ✓ Kirchhoff scalar solution versus time/position for a moving RX



Full-wave numerical solution of the KA integral including Sphericity and Antennas Gains:

$$E_s = -\frac{jk_0 a_0}{4\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\frac{e^{-jk_0(R_1+R_2)}}{R_1 R_2}e^{-g_0^2\left(\cos^2\theta_0 x^2+y^2\right)-g_s^2\left(\cos^2\theta_s x^2+y^2\right)}dxdy$$

E-field versus time/position for σ = 6 cm (rms h.)



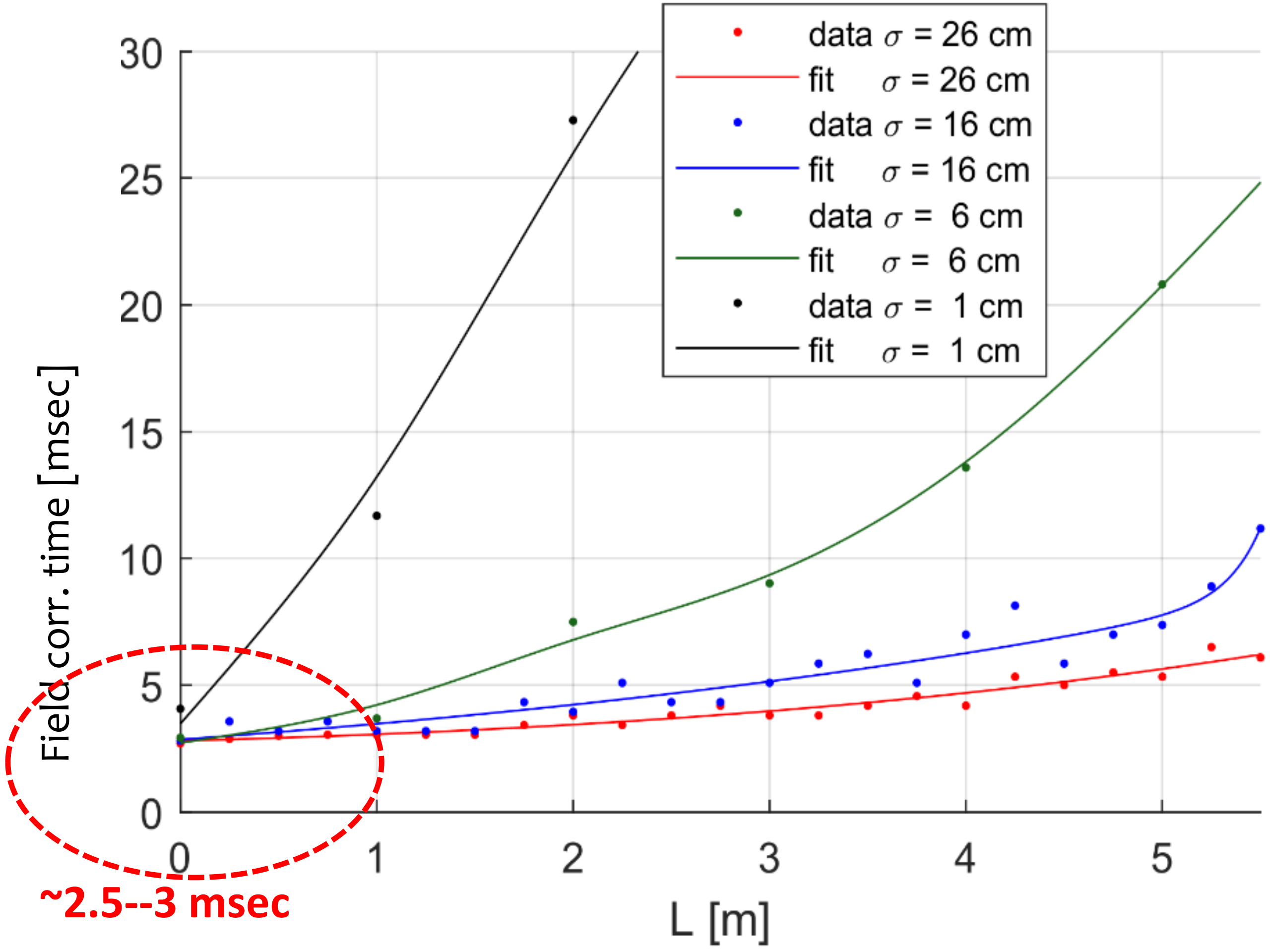
Strong dependence of the E-field profiles on *L*…

Field Fluctuations vs Target Corr. Length

- ✓ ***H*=100 m, *v*=60 m/sec, 15° beam**

Coherence time evaluated as:

$$\tau \text{ so that } \left\langle E_s(t+\tau)E_s^*(t)\right\rangle \Big/ \left\langle \left|E_s(t)\right|^2 \right\rangle = 1/e$$

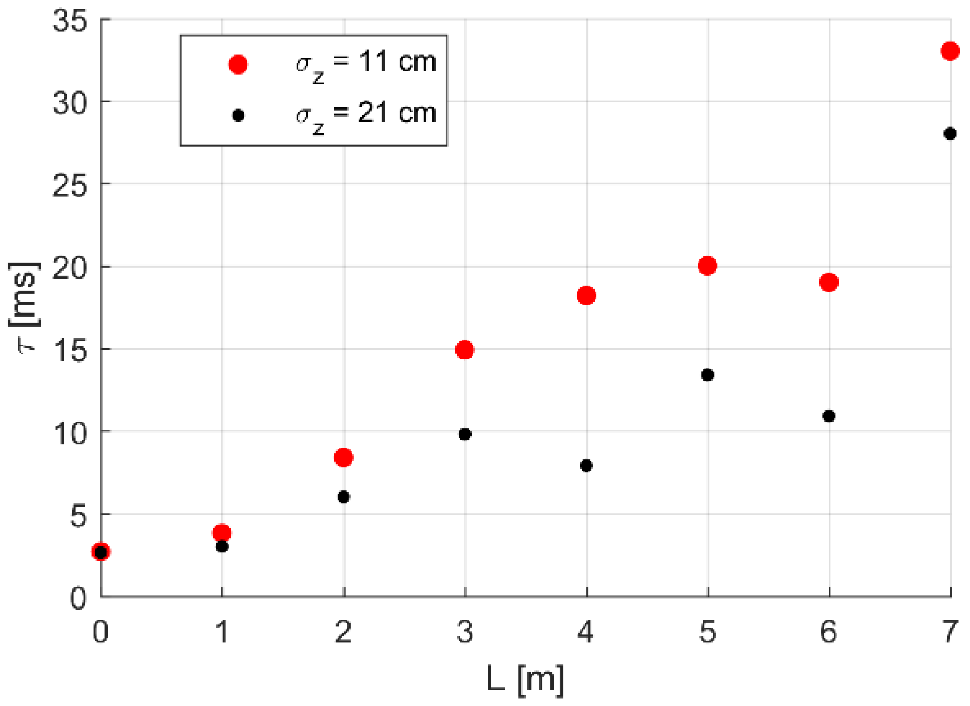


- ✓ The correlation **increases** with *L*, **decreases** with *σ*
  - ✓ Curves fitted with exponential functions
    - ✓ Values achieved for *L* tending to zero in agreement with theory

Field Fluctuations vs Target Corr. Length

Numerical solution for higher receiver but same speed

***H* = 200 m, *v* = 60 m/sec, 15° beam**



Note: to limit the computation time we consider here just one surface realization (Frequency averaging and/or Monte Carlo are in progress…)

Note: Antennas area directed along the specular point

- ✓ Increasing the receiver height, **larger coherence time** can be expected, but the speed also generally increases…
  - ✓ As is visible, larger **rms heights** are responsible for a reduction of the **coherence time**

The field coherence is strongly related to both *L* and the surface σ (rms h).

Statistics + Inhomogeneities Fluctuations

- ✓ Yellow: flat PEC
- ✓ Blue dielectric with $\varepsilon_r = 4$ (flat or rough)

Tx, Rx beams = 45°, 67° ;

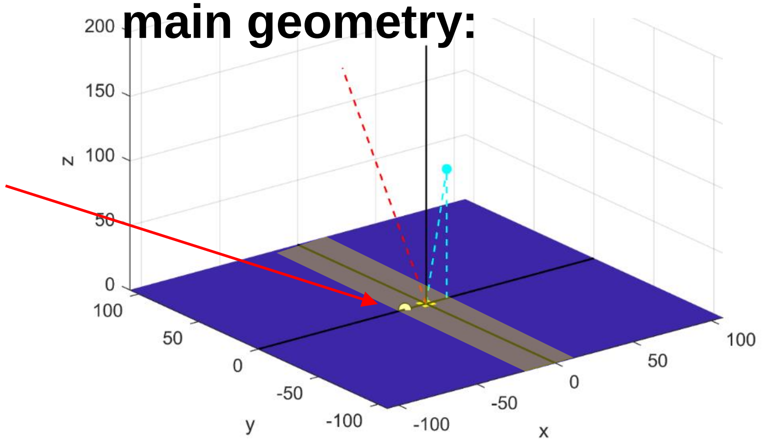
Rx =100 m, Tx = 20 000 km

Rx -3B footprint = 100 m

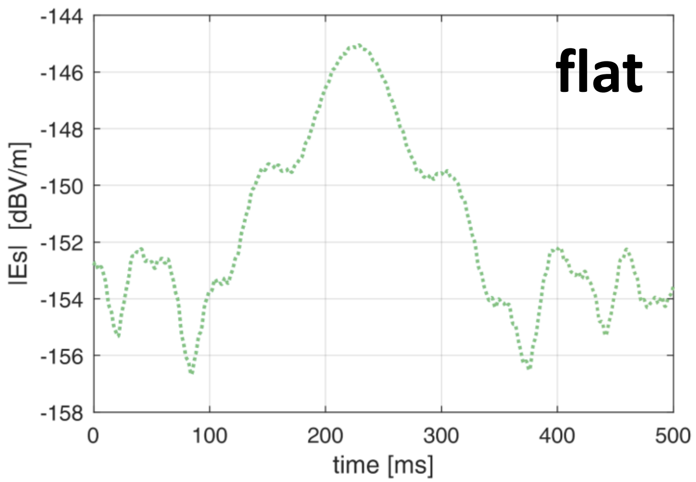
PEC side 10 m (comparable with FFz)

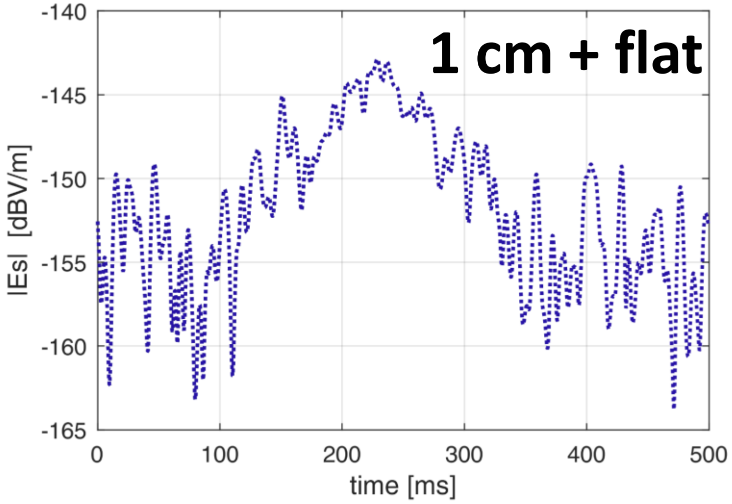
main geometry:

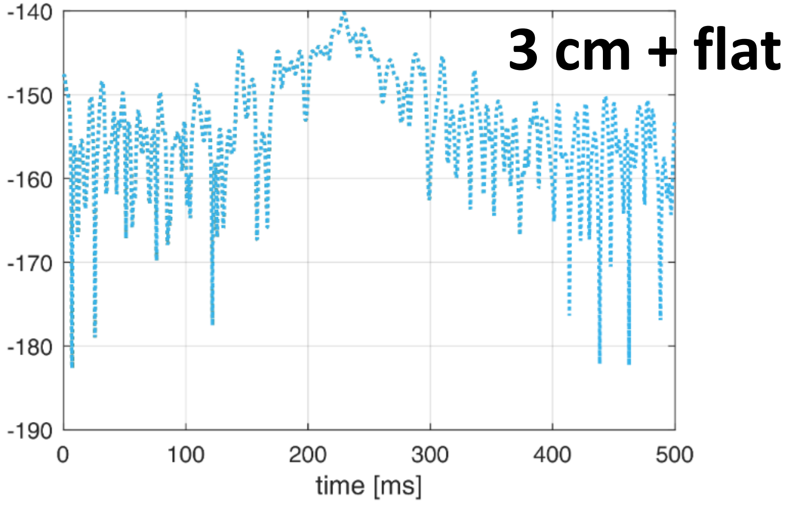
Starting position of the specular point



- ✓ Electric field versus time|position for an airborne Rx
- ✓ Transition through boundary is progressive with oscillations due to Fresnel zone interferences.
- ✓ When relatively small water bodies are considered, Fresnel oscillations can be masked in case of rough surfaces

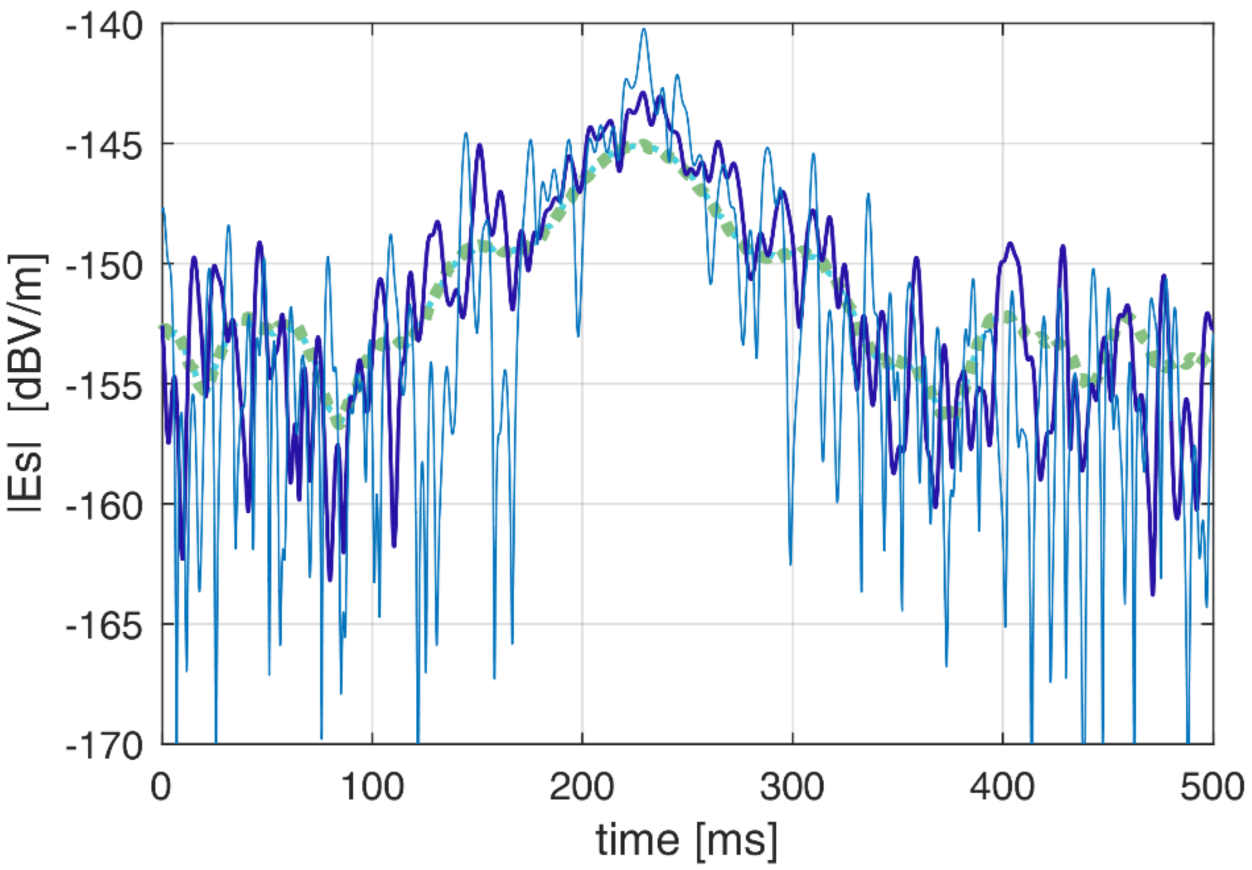






Statistics + Inhomogeneities Fluctuations

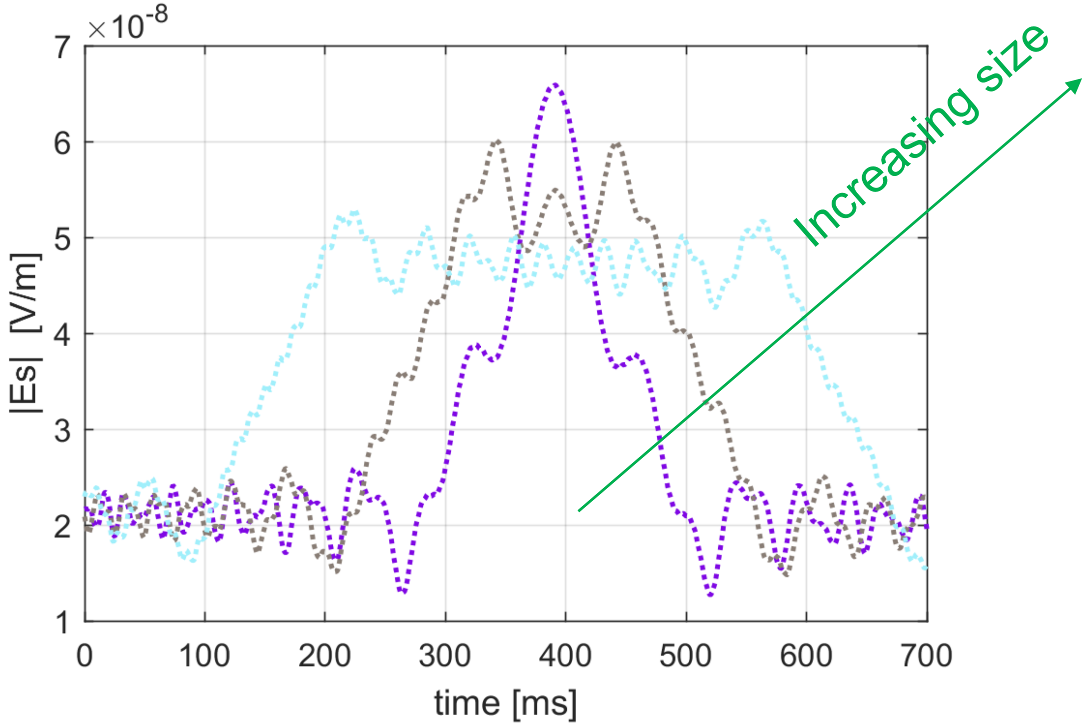
Comparison over the same figure frame:



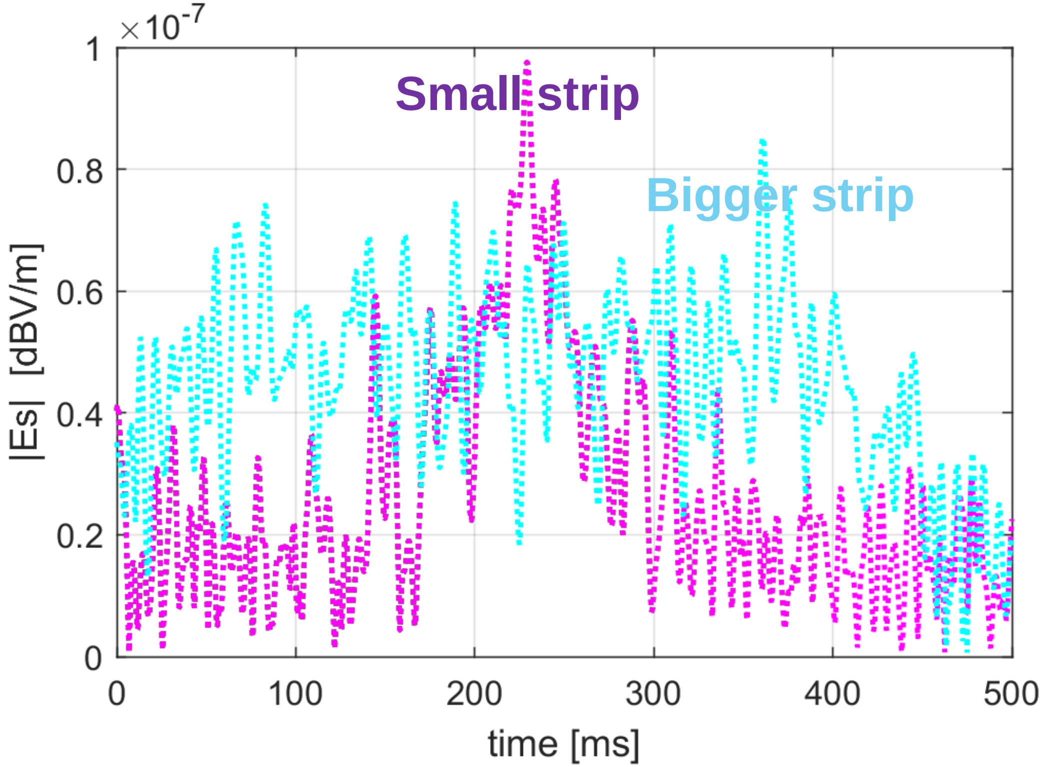
- ✓ Note: the field at the receiver is equal to 1 V/m
  - ✓ The ***statistical fluctuation*** are superimposed to the gentle ones related to the ***Fresnel oscillations*** determined by the presence of a ***clear reflector***, which can be potentially masked

Statistics + Inhomogeneities Fluctuations

✓ All the flat



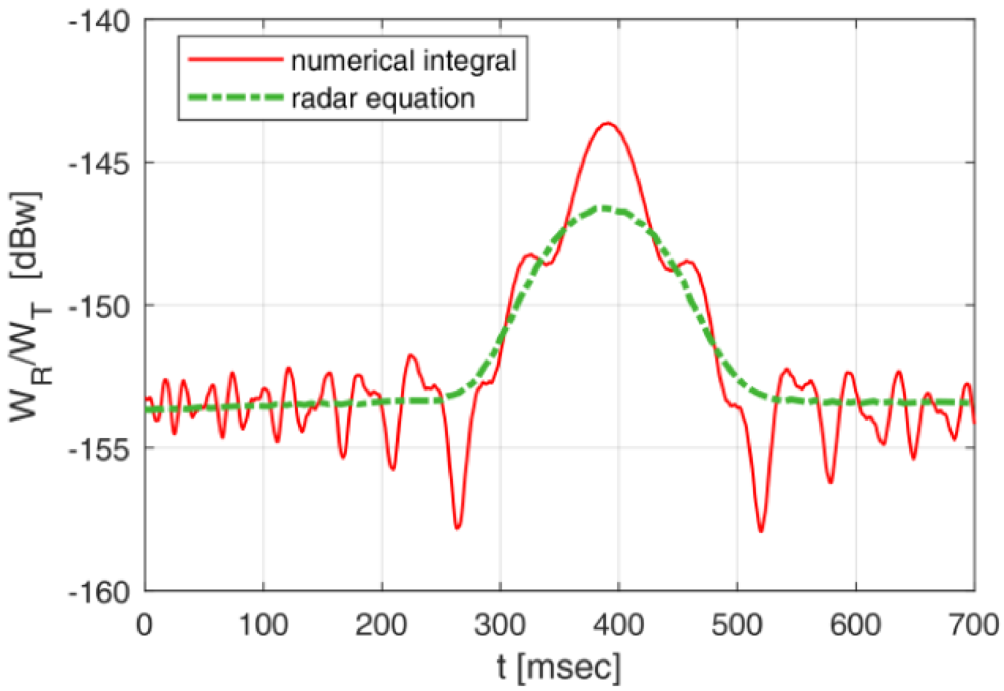
✓ Flat + 3 cm



✓ As expected, changing the size the fluctuation patterns vary

✓ The masking effect can be very strong in the presence of roughness

SAVERS: Approximate Modeling



- ✓ To model the power at the receiver for the spaceborne case we developed an **approximate model** for the coherent scattering
  - ✓ Based on the definition of a '*true*' NRCS associated to the coherent component

F. T. Ulaby, C. T. Allen, and A. K. Fung, "Method for retrieving the true backscattering coefficient from measurements with a real antenna," *IEEE Trans. Geosci. Remote Sens.*, vol. GE-21, no. 3, pp. 308-313, Jul. 1983.

- ✓ The solution is more convenient and allows for including bot the ***incoherent*** and '***coherent***' scattering in the bistatic radar equation…

More details during the inLab Session…

Conclusion

- ✓ We have numerically analyzed the signal fluctuations with respect to the surface parameters
- ✓ 1msec (spaceborne) to 20msec (airborne) coherent integration do not filter out those fluctuations. Incoherent integration smooth them according to number of independent samples Nc…
- ✓ We observed that the ***specular component*** (coherent in what extent?) ***fluctuates*** with long correlation time
- ✓ A significant dependence of the correlation time of *L and σ* has been observed…

Work in progress as regards the spaceborne configuration….

Useful information could be achieved to help selecting the incoherent integration time

Thanks!!

[redacted]

Field Fluctuations vs Target Corr. Length