SIMULATIONS OF SPACEBORNE GNSS-R SIGNAL OVER LAND

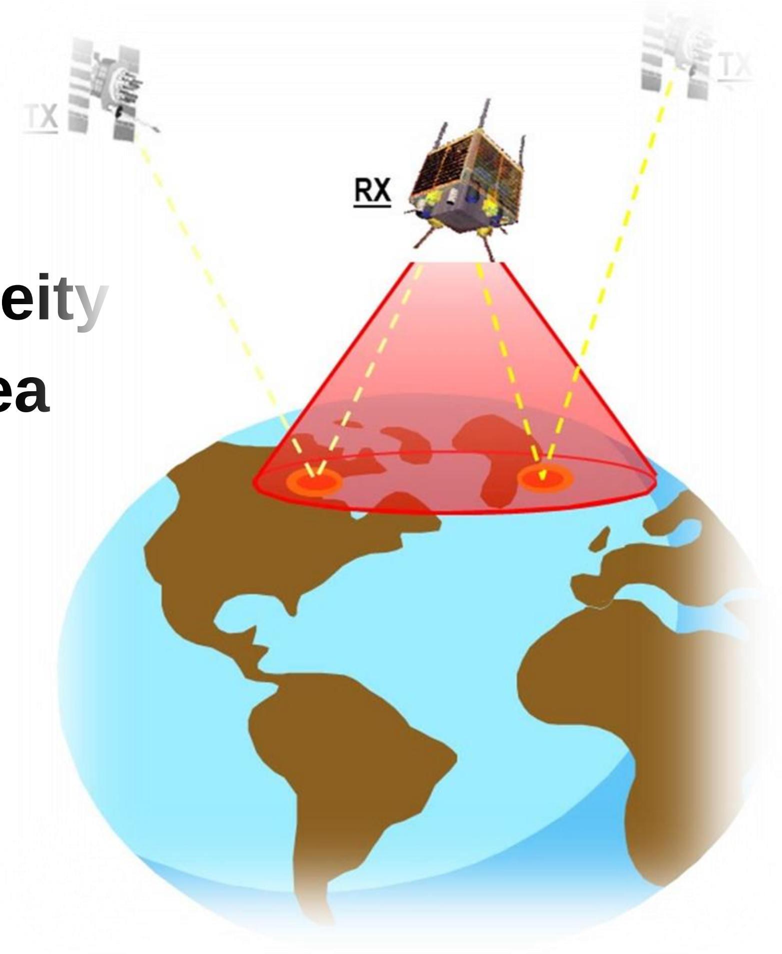
L. Guerriero[1], L. Dente[1], D. Comite[2], N. Pierdicca[2]

[1] DICII, Tor Vergata University, Rome, Italy

[2] DIET, Sapienza University of Rome, Rome, Italy

Content

- Introduction
- The modelling framework
- Topography and inhomogeneity
- Validation over mountain area
- Validation over forest
- Conclusions



Introduction and motivations

- Ground based receivers are already operationally exploited for land but airborne and especially spaceborne data are still to be fully understood
- Although the dependence from the main land parameters is known, the real land signal is particularly “variable”, noisy, sometime difficult to explain
- A combination of data analysis and modelling interpretation is important to progress further in this field

Work supported by ESA/ESTEC CONTRACT n. 4000120299/17/NL/AF/hh,”Potential of Spaceborne GNSS-R for Land Applications”.

A bit of ‘history’

Soil And VEgetation Reflection Simulator (SAVERS)

LEiMON: Land Monitoring with Navigation Signals
ESA/ESTEC Contract No. AO/1-5830/08/NL/AF

Ground

Airborne

Pierdicca, N., L. Guerriero, R. Giusto, M. Brogioni, A. Egido, (2014), "SAVERS: A Simulator of GNSS Reflections from Bare and Vegetated Soils", ***IEEE Transactions on Geoscience and Remote Sensing*****, Vol. 52, pp. 6542-6554.**

GRASS: GNSS Reflectometry Analysis for biomaSS monitoring. ESA Contract No: 4000103329/11/NL/CVG

Potential of Spaceborne GNSS-R for Land Applications.
ESA/ESTEC Contract n. 4000120299/17/NL/AF/hh

GNSS+R InLab

SAVERS v2

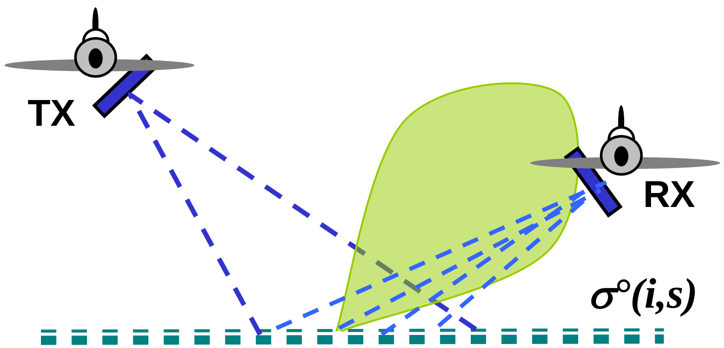
A consolidate (a bit simplistic) view

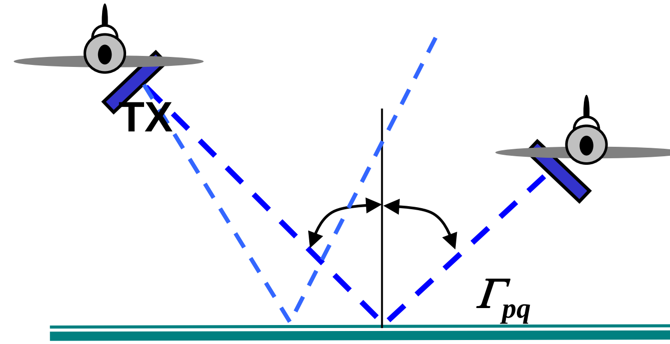
Incoherent scattering diffused in any direction

$E^{incoh}=E-\langle E\rangle$

$$W_r^{inco} = \sigma^\circ \frac{W_t \lambda^2}{(4\pi)^3 R_r^2 R_t^2} G_r G_t A_S$$

Bistatic scattering coefficient σ°





Coherent reflection along specular direction

$E^{coh}=\langle E\rangle$

Specular reflectivity Γ

$$W_r^{cohe} = \Gamma \frac{\lambda^2 W_t}{(4\pi)^2 (R_r + R_t)^2} G_r G_t$$

- **Different dependence on ranges (R_t and R_r) and resolution (A_S) makes the relative magnitude of inco and cohe components varies with receiver height, being in general $W_r^{inco} \ll W_r^{cohe}$ over flat land from satellite**

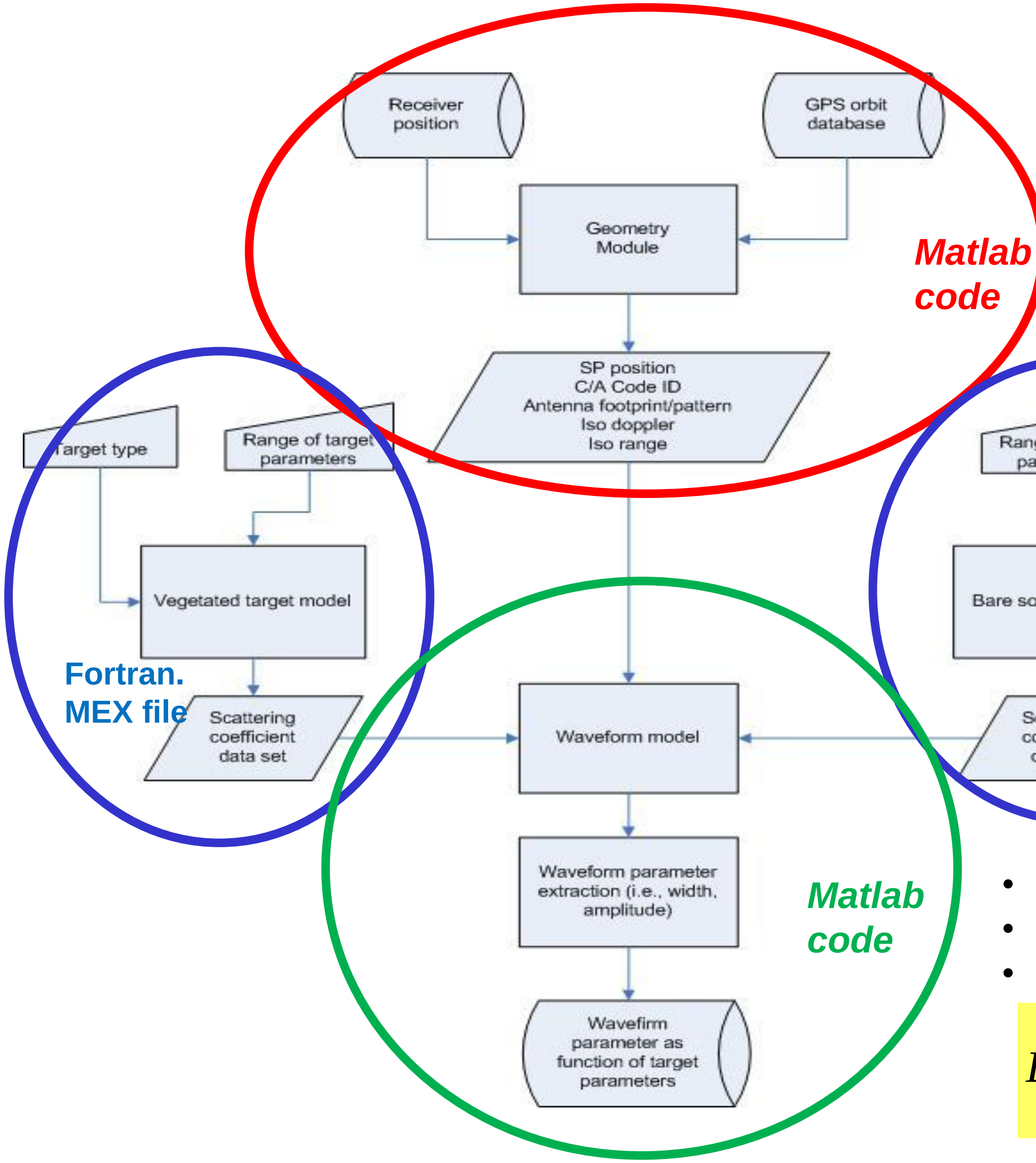
The Bistatic Radar Equation

- The mean power of received signal vs. delay τ and frequency f is modeled by the Bistatic Radar Equation which integrates the bistatic scattering coefficient $\sigma°$ of each surface element (Zavorotny and Voronovich, 2000).

$$\left\langle \left| Y(\hat{\tau}, \hat{f}) \right|^2 \right\rangle = \frac{T_i^2 P_T \lambda^2}{(4\pi)^3} \int \frac{G_T G_R \Lambda^2(\tau' - \tau) S^2(f' - f)}{R_R^2 R_T^2} \sigma^0(x, y) dA$$

$\|Y\|^2$	**Processed signal power at the receiver vs. delay τ and frequency f.**
P_T	**The transmitted power of the GPS satellite.**
G_T, G_R	**The antenna gains of the transmitting and the receiving instrument.**
R_R, R_T	**The distance from target to receiving and transmitting antennas.**
T_i	**The coherent integration time used in signal processing.**
$\sigma°$	**Bistatic scattering coefficient**
Λ^2	**Time domain system response (GPS C/A correlation triangle function)**
S^2	**Doppler domain system response (sinc function)**
dA	**Differential area within scattering surface area A (the glistening zone).**

SAVERS architecture



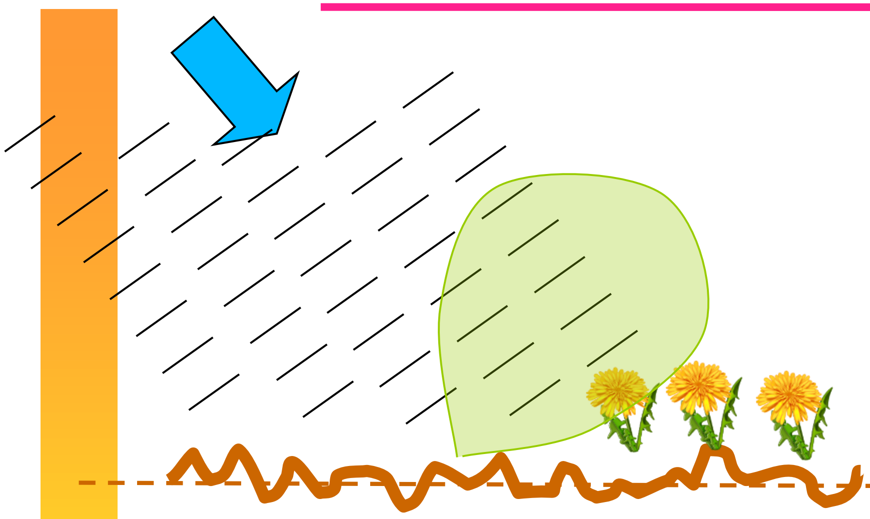
- Input target parameters
- TX Position, PRN
- SP Position
- Isodopppler isorange
- Antenna patterns
- Bistatic angles

- Rough soil σ°, RL & RR
- Vegetated soil σ°, RL & RR

- Antenna mismatch & cross-talk
- Radar equation
- DDM parameters

$$DDM(\tau, f) = \frac{W_r^{inco+cohe}}{W_r^{dir}}(\tau, f)$$

Electromagnetic modelling



INCOHERENT

Horizontally homogeneous vegetation cover above a soil surface with roughness at wavelength scale.

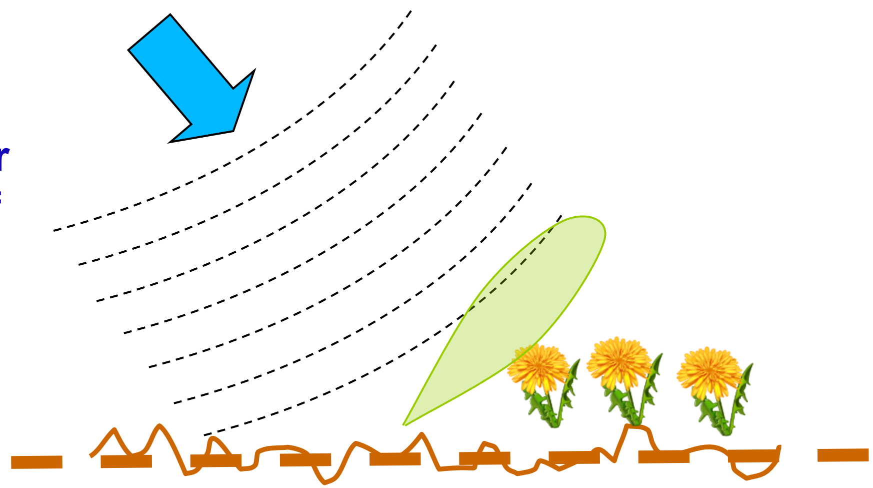
Bistatic scattering coefficient of locally incident plane waves by AIEM

Attenuation and multiple scattering by a discrete medium RTE solution (Tor Vergata). Allometric equation to convert lump vegetation parameters (crop height, forest biomass) into detailed geometric and electrical vegetation description

COHERENT

Scattering of a spherical wave impinging on an infinite surface

A 'scattering coefficient' is introduced for coeherent term reproducing the Kirchoff approximation and image theory for a conductive plane (extention of Fung & Eom, 1988 – submitted to TGARS)



GNSS-R observable

Reflectivity Γ (assuming prevalent coherent signal)

$$P_r = \Gamma(\theta)\frac{\lambda^2}{(4\pi)^2}\frac{G^t G^r P_t G_D G L_S}{(R_r + Rt)^2} \qquad EIRP = G^t P_t$$

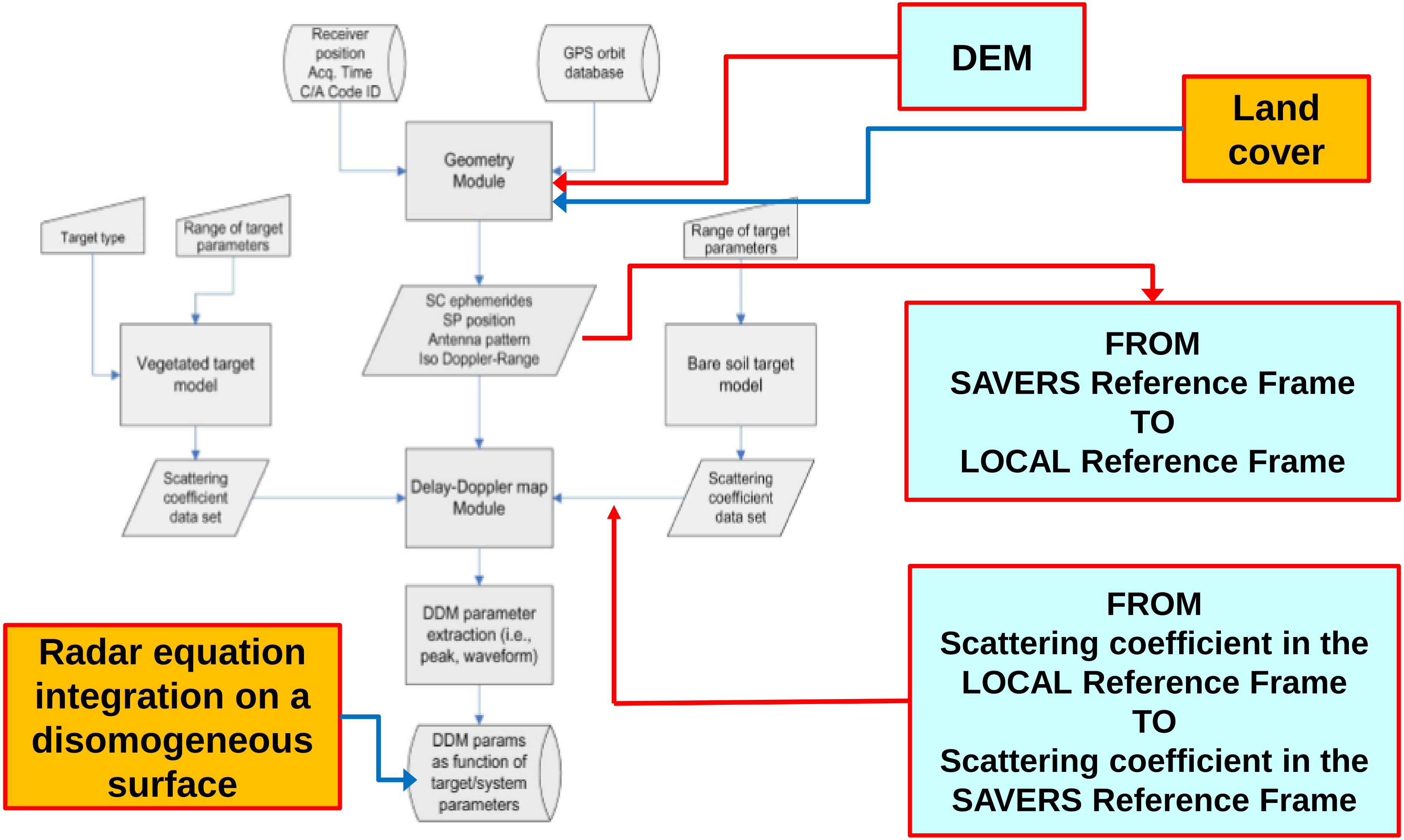
✓**From data: retrieved from downward antenna received power (minus estimated noise) with EIRP retrieved from measured direct power minus estimated noise ($G^r{}_{UP}$ is in the order of 3.5-4.7 dB)**

$$\Gamma(\theta) = \frac{(4\pi)^2 (R_r + Rt)^2}{\lambda^2 G^r\, EIRP}\frac{P_r^* - N^*}{G_D G L_S} \qquad EIRP = \frac{P_d^* - N_d^*}{G_D G L_S} R_{rt}^2 \frac{(4\pi)^2}{\lambda^2 G_{UP}^r}$$

✓**From SAVERS:**

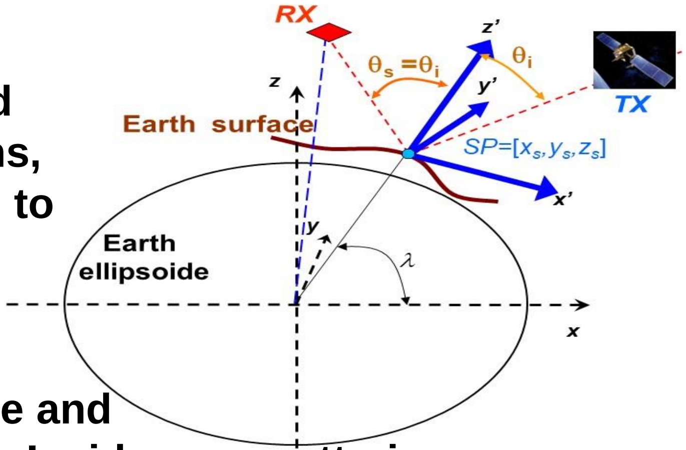
$$\frac{P_r^{coh+inc}}{P_d} = \Gamma \frac{R_{rt}^2}{(R_r + Rt)^2}\frac{G^r\, G^t}{G_{UP}^r G^{t\prime}} \approx \Gamma$$

SAVERS v2 upgrades

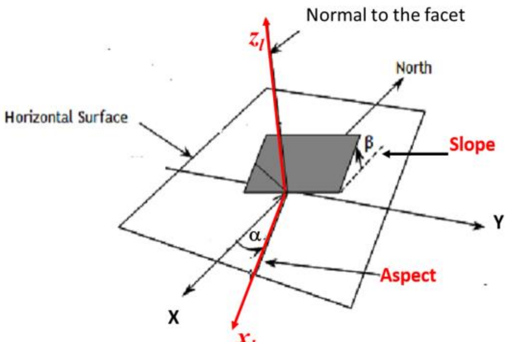


Topography

- **From SAVERS to local ref. frame**
  - **SAVERS Reference Frame (XYZ) is a rotated ENU system. Incidence, scattering directions, polarization unit vectors must be converted to the local frame** $\vartheta_{il}, \varphi_{il}, \vartheta_{sl}, \varphi_{sl}, \ \widehat{v_l}, \widehat{h_l}, \ \widehat{v_{sl}}, \widehat{h_{sl}}$.



- **EM model in the local frame**



  - **For each facet distance and Doppler are computed. Incidence, scattering directions, polarization unit vectors must be converted to the local frame. Scattering amplitude is then compute in the Local Frame**

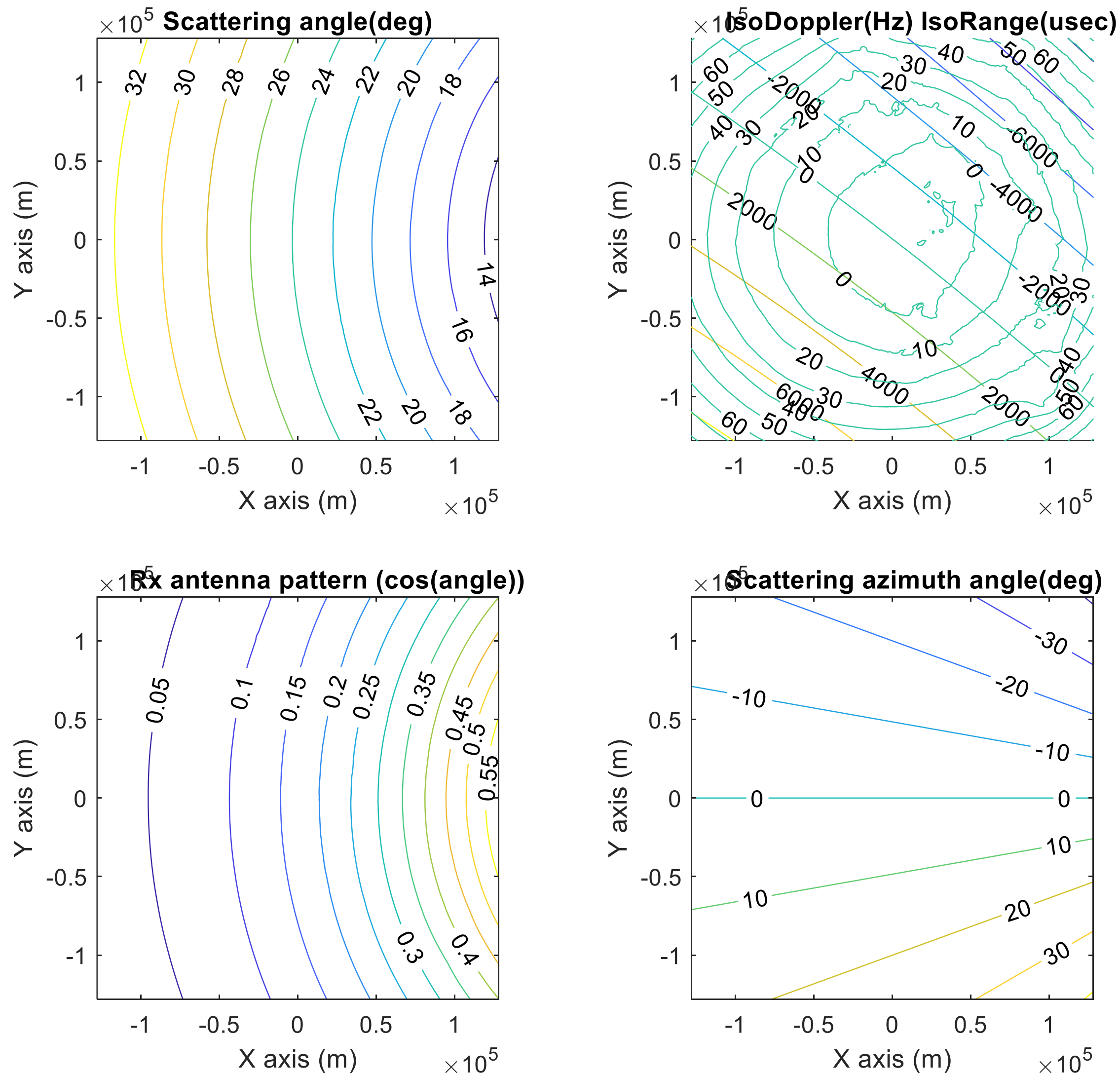
$$f_l' = \begin{bmatrix} f'_{v_l v_l} & f'_{v_l h_l} \\ f'_{h_l v_l} & f'_{h_l h_l} \end{bmatrix}$$

- **From local to SAVERS: polarization**
  - **The scattering amplitude should be converted back in the SAVERS frame in order to combine LHCP and RHCP scattering of each cell in the radar equation**

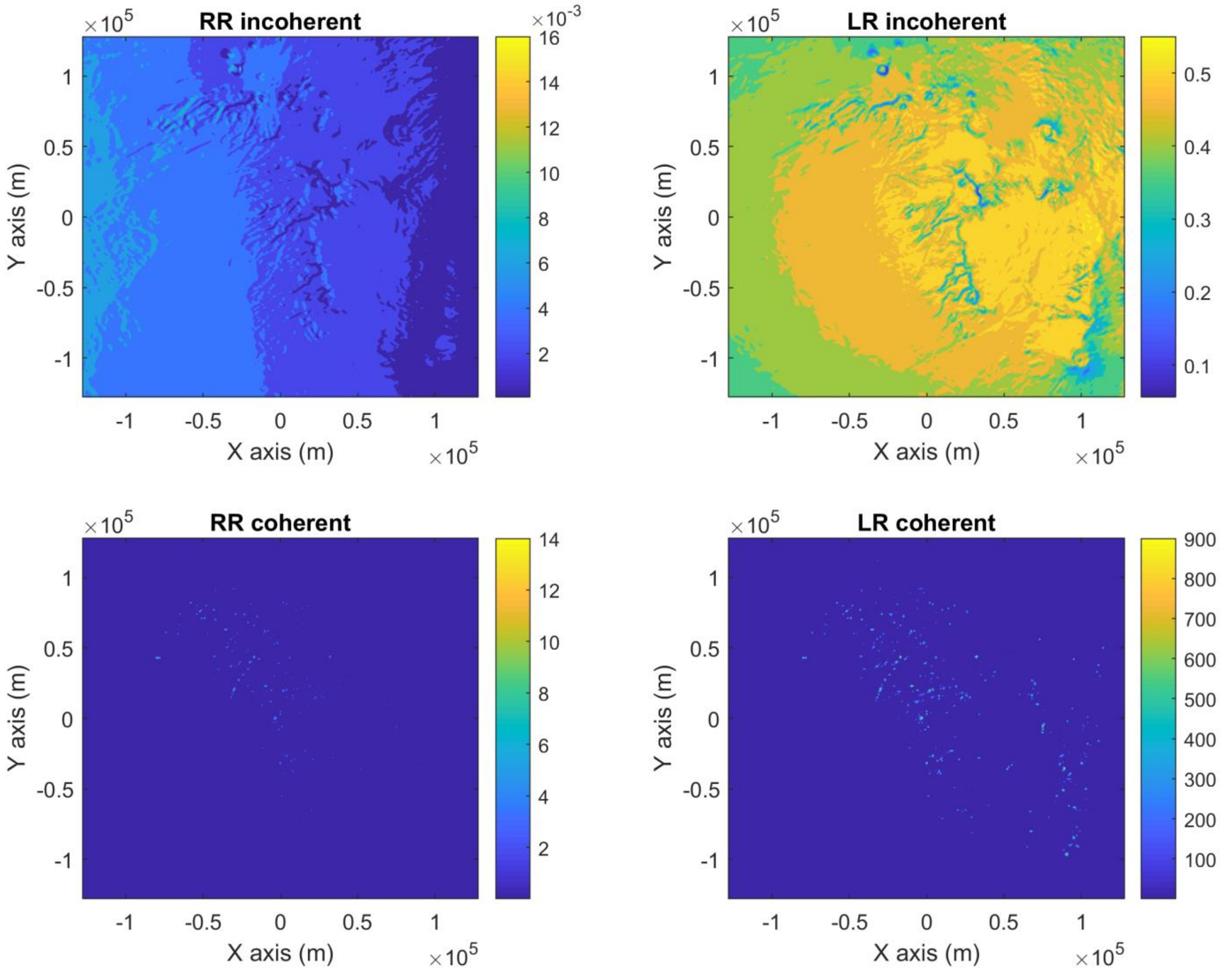
$$F_{pq} = \sum_{p_{sl}} \sum_{q_{il}} f'_{psl,qil} \, (p_s \cdot p_{sl})(q_i \cdot q_{il})$$

  - **Then it is possible to compute the LR and RR bistatic scattering coefficient of each cell in the SAVERS frame and then integrate the radar equation.**

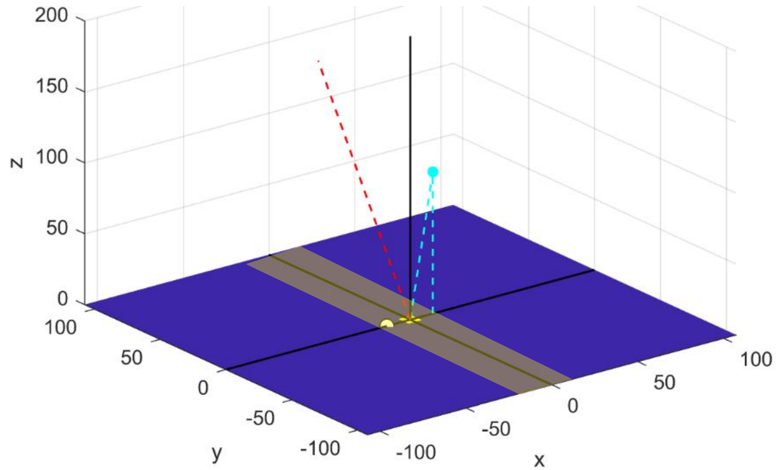
Output of geometry module



Map of σ° in the main frame



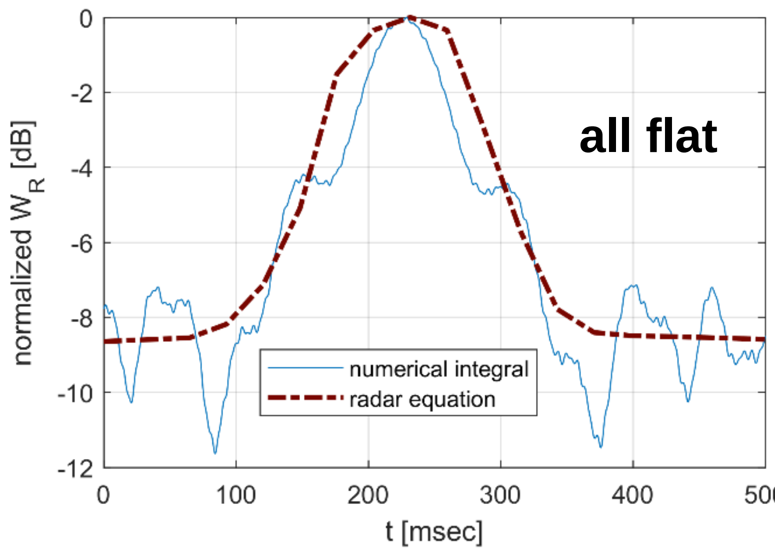
A note on coherent model in SAVERS



- **A flat surface with a conductive PEC strip (Yellow) in between a dielectric (Blue, epsr = 4)**

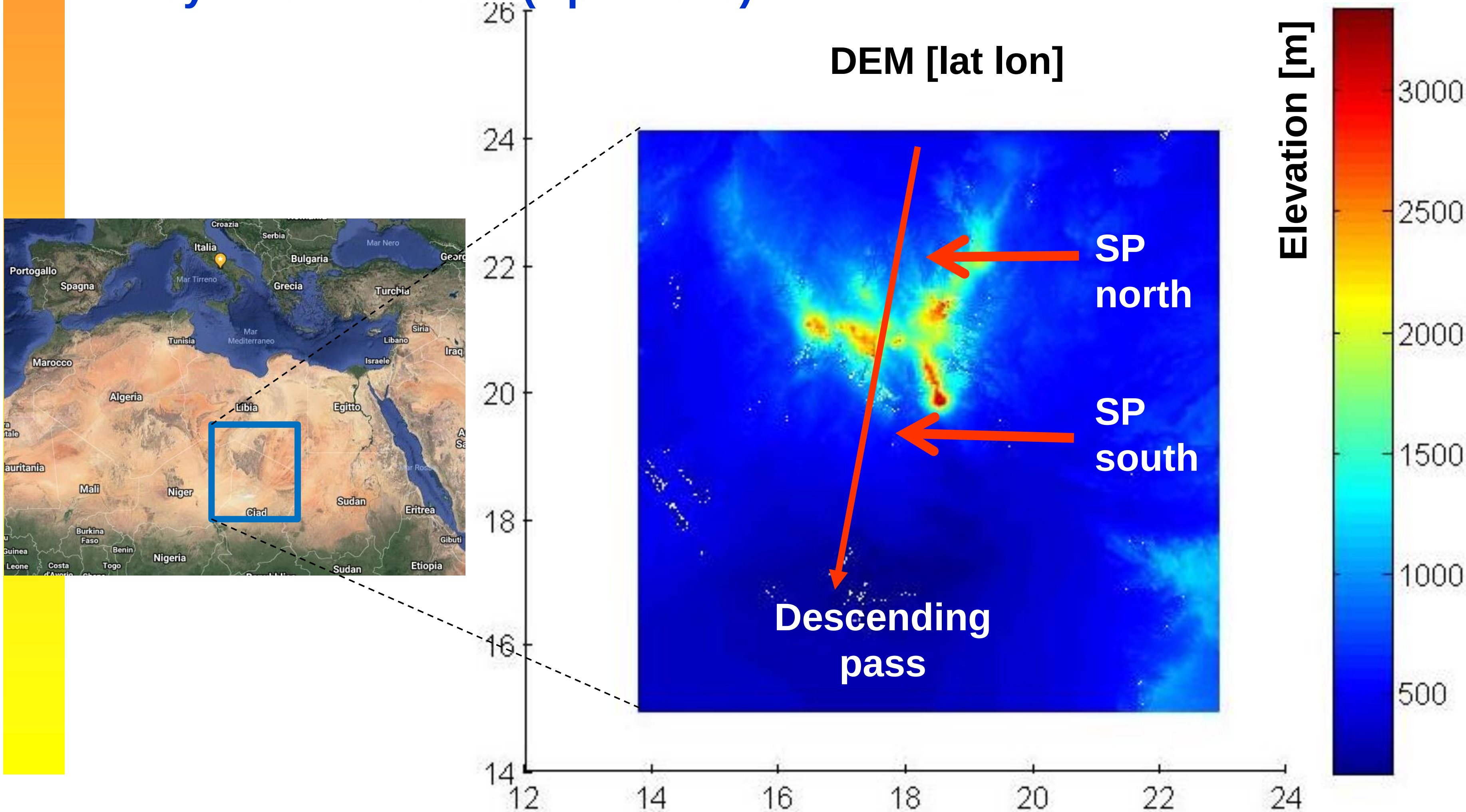
H0 = 20e6;
Hs = 100e0;
R0 = H0./cos(θ_0);
v = 60; %m/s

- **Comparison of received power (normalized) versus time for an airborne receiver using a Kirchhoff "coherent" formulation and the $\sigma^{\circ coh}$ model in SAVERS**
- **Transition through boundary is progressive, with oscillations due to Fresnel zone interferences**
- **Oscillations are not reproduced by the $\sigma^{\circ coh}$ model but transition is fairly reproduced**

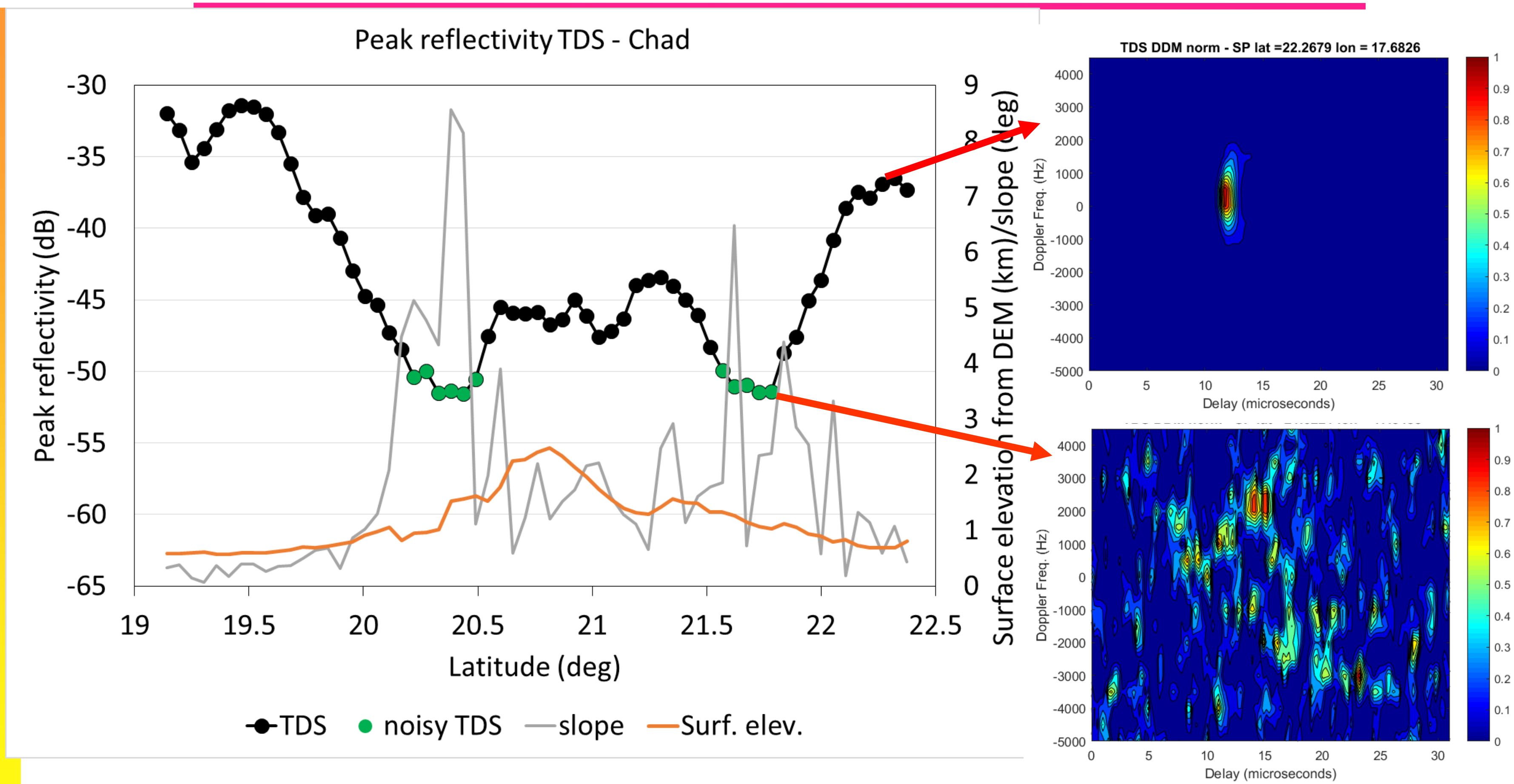


Volcanic area in Chad

- ✓ **SAVERS test of DDM's and Γ_{peak} along a SP track collected by TDS-1 in Chad (April 2016)**

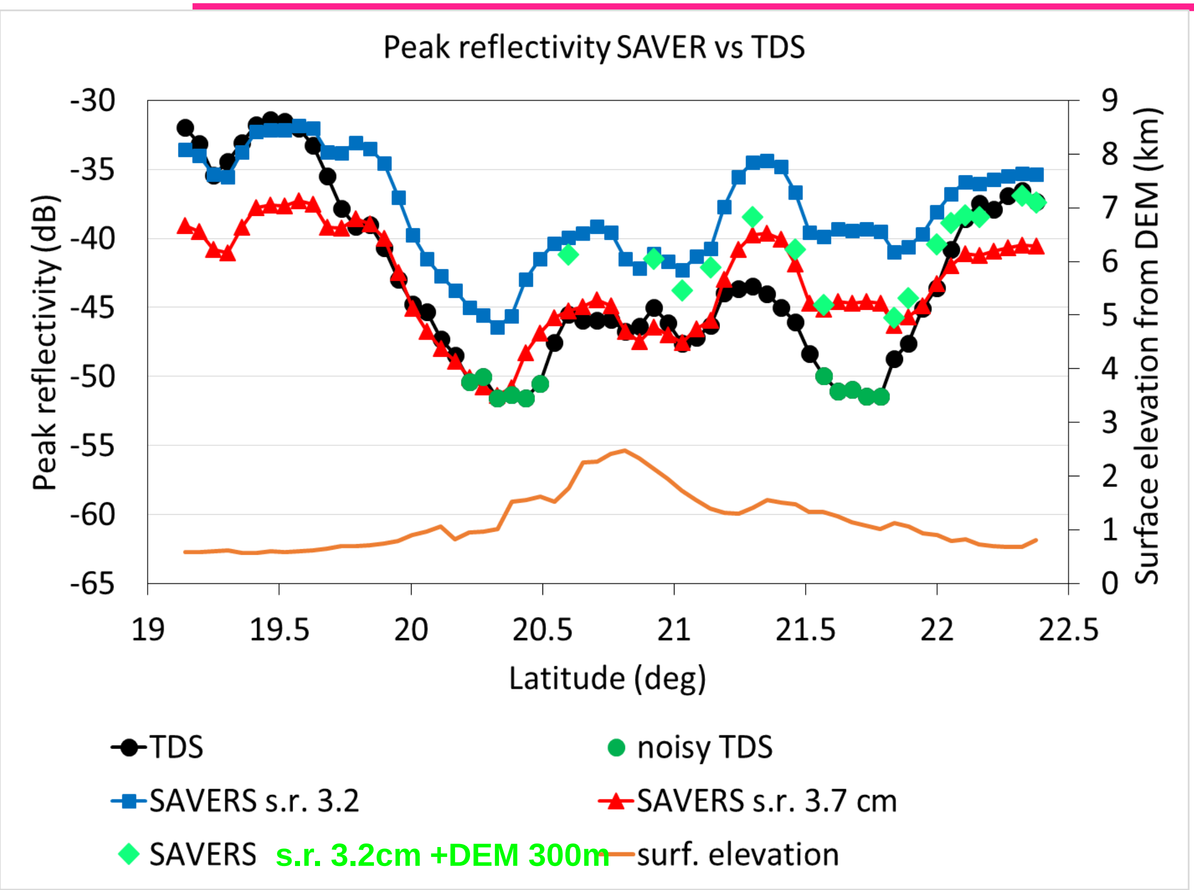


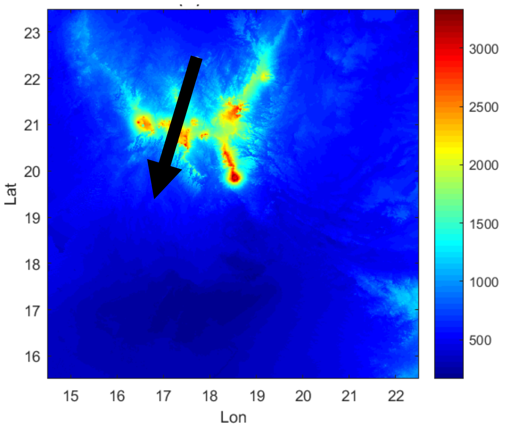
CHAD case study – TDS data



- Strong dependence on topography, **slope** and roughness.
- Lower values correspond to data where the signal is close to the noise, i.e. $10\log_{10}$ (DDM_peak/noise) < 1.0 and slope variation is high.

SAVERS simulations vs data





- 1 km and 300 m DEM included in SAVERS
- Soil moisture 5%
- Soil roughness 3.2 cm and 3.7 cm

- High DEM resolution increases the variability range of the simulated reflectivity for a certain roughness. However, there are memory space and simulation time issues!!
- The agreement would improve if a higher roughness is assumed over the mountains.

TDS-1 DDM vs SAVERS DDM

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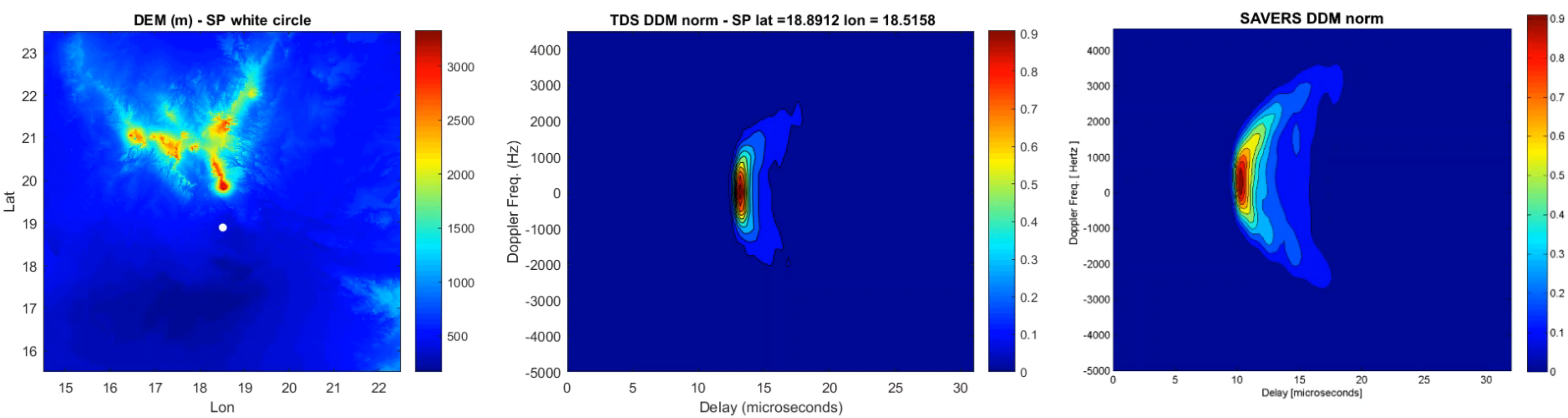

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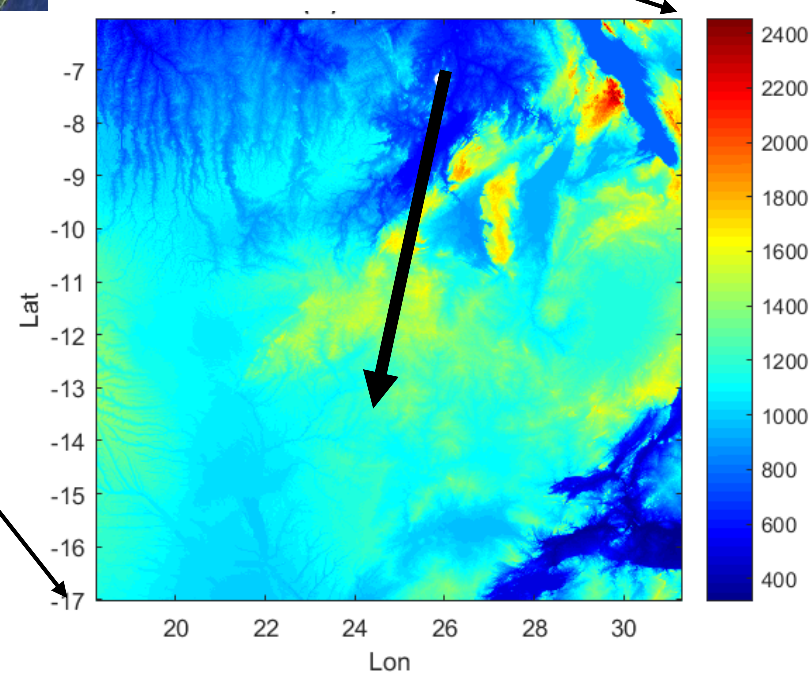
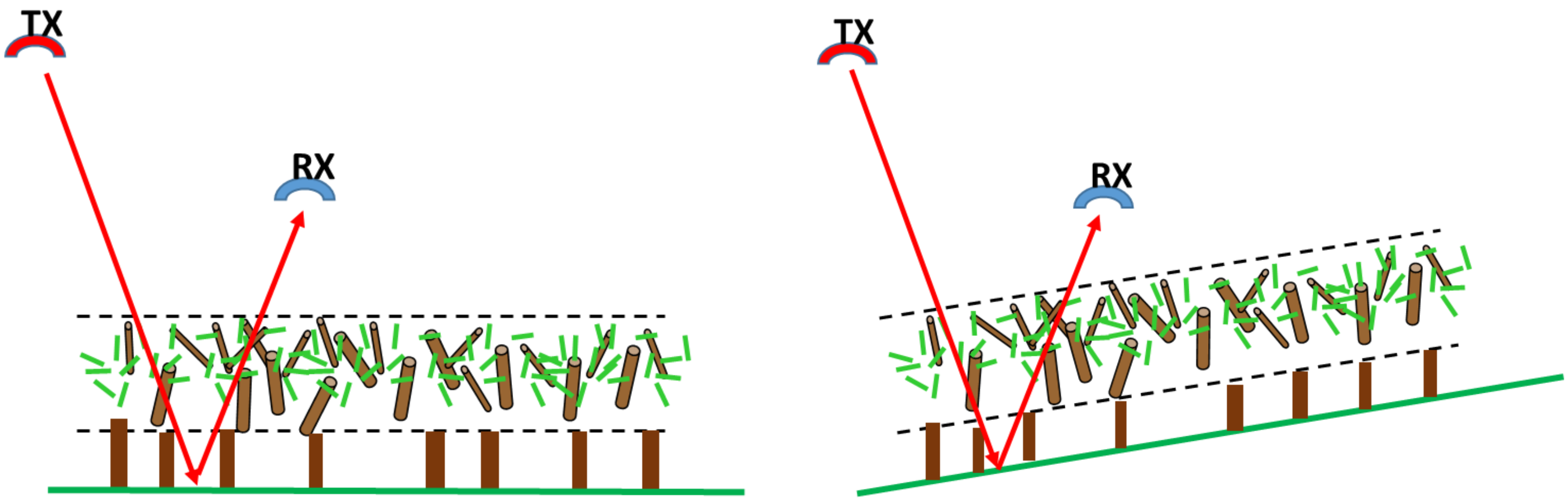
SAVERS over woodland

CONGO
Woodland
Above ground biomass:
30-70 tons/ha (Bouvet 2018)
Rainy season: Nov-Apr



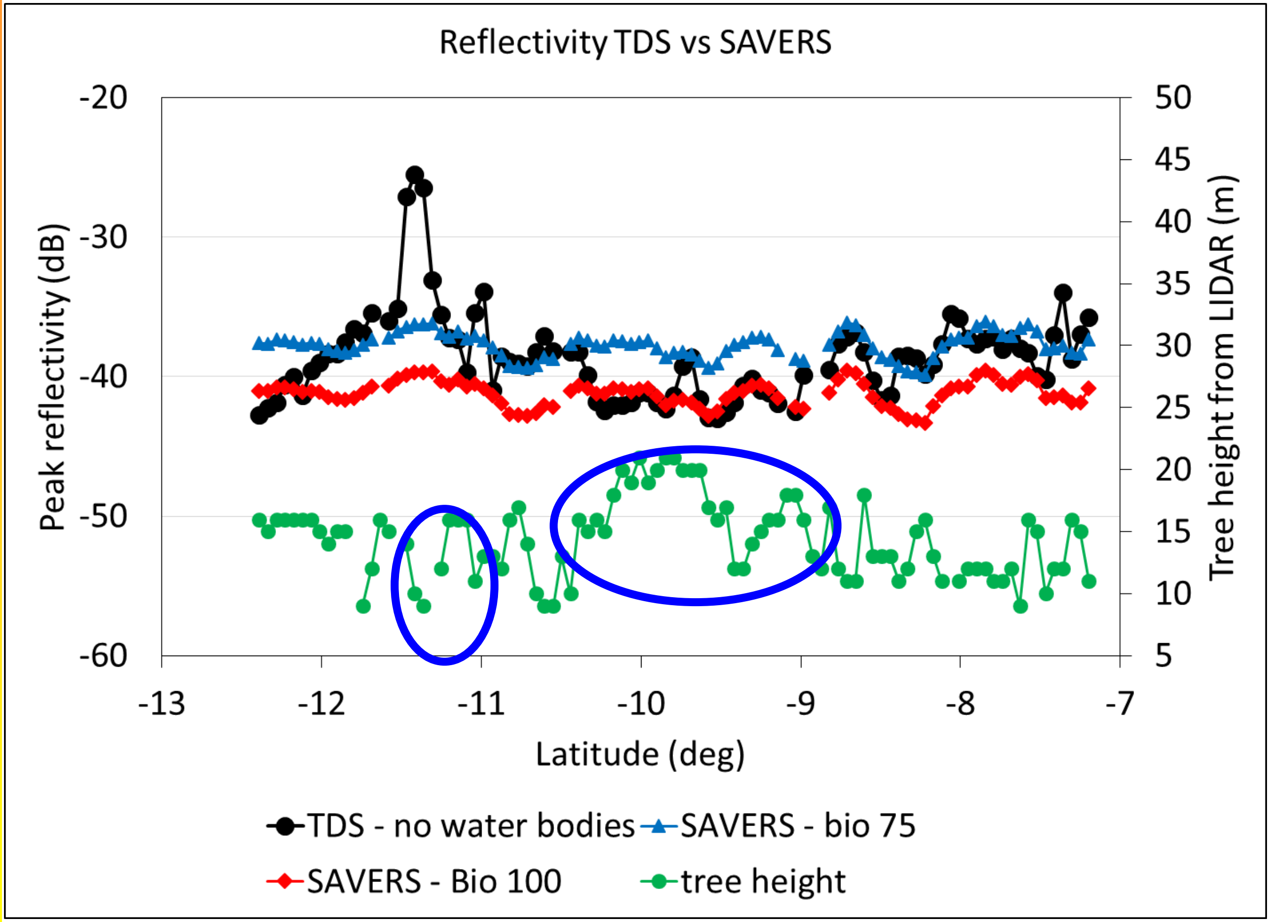
Descending pass in Feb 2017

SAVERS over forest



- When the slope under the forest is introduced, then the path length inside the crown changes. And consequently attenuation as well.
- In the current version of the forest model, slope effect has been introduced in the loss factor only.
- Incoherent scattering is computed for a «flat forest»

SAVERS vs TDS: constant biomass

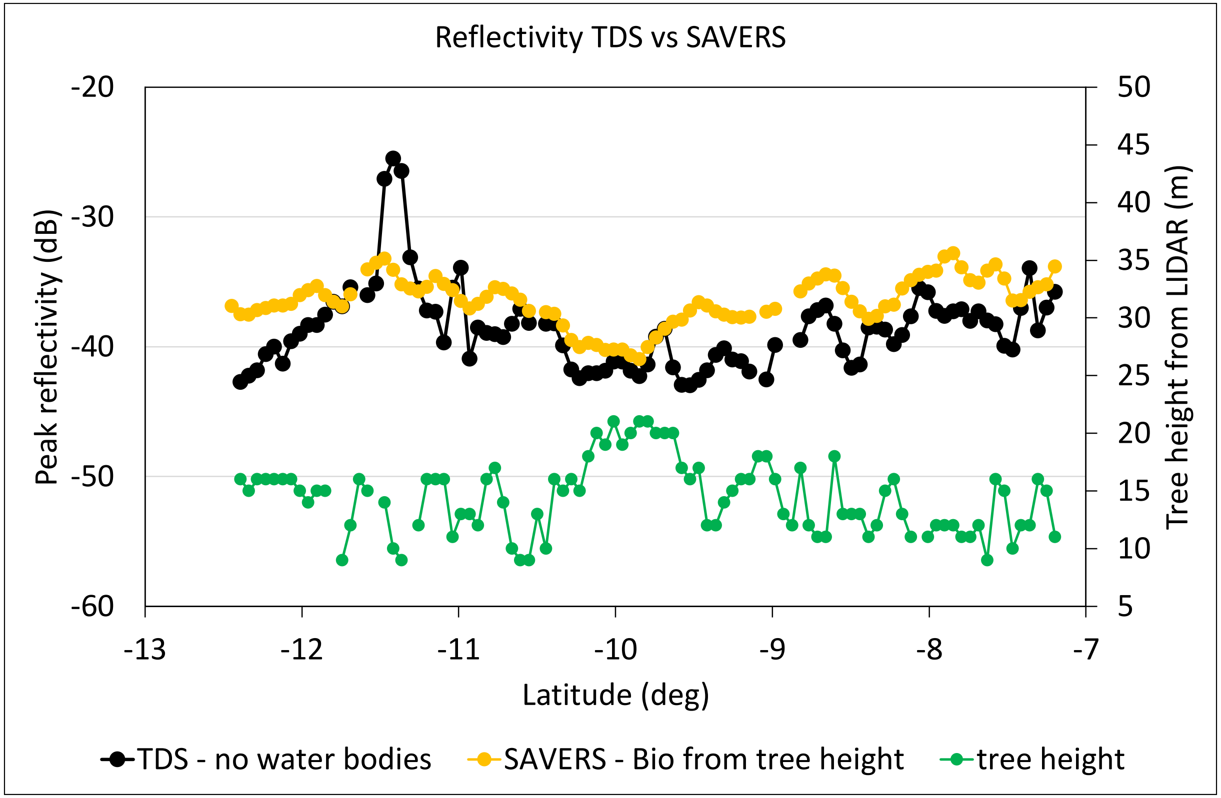


Higher biomass between -10.3° and -9.3° lat. and probably lower biomass at -11.4° as showed by the tree height estimated from LIDAR data

SAVERS simulations with constant biomass along the track of 75 t/ha and 100 t/ha

- **Partially good agreement, assuming a spatially constant biomass**
- **Some long scale variability seems to be related to tree height changes**

Variable biomass from Lidar

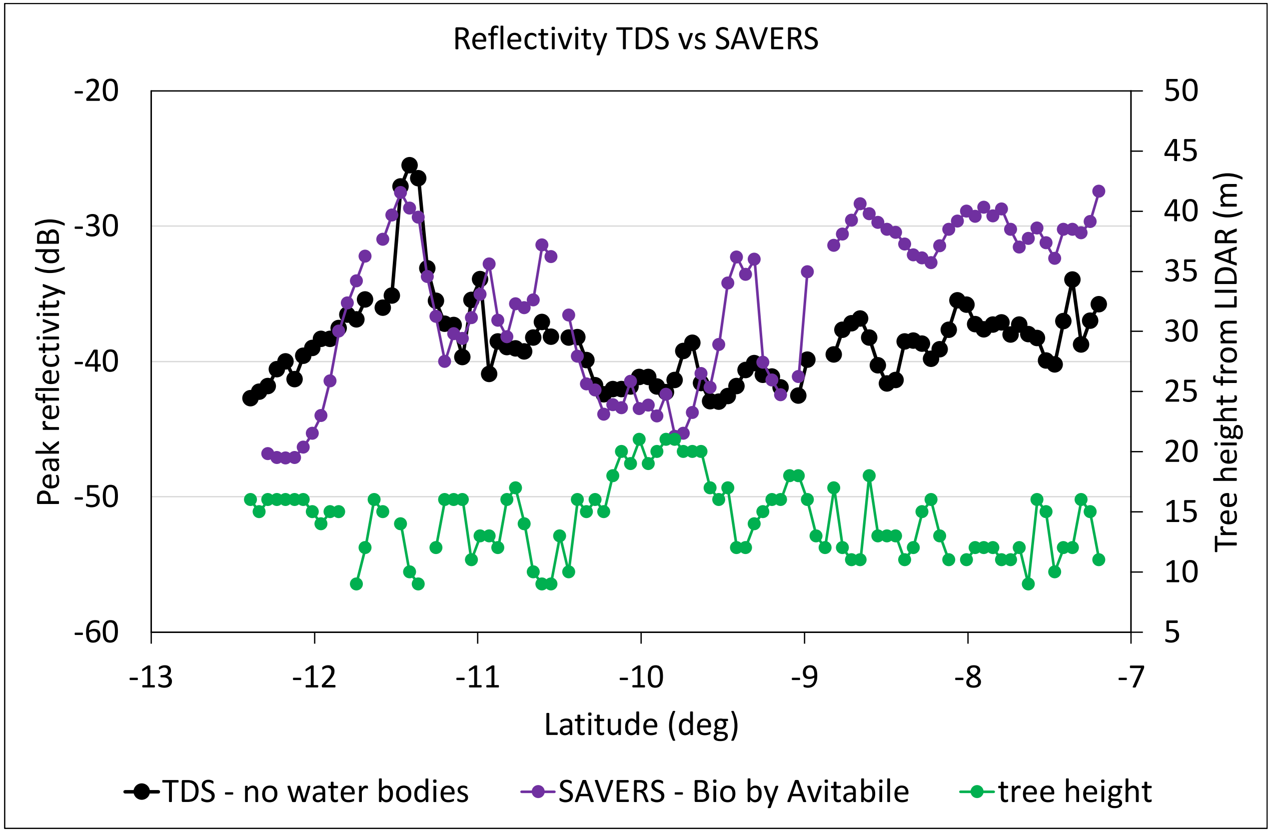


SAVERS simulations with <u>variable</u> biomass along the track.

Biomass estimated from LIDAR tree height and allometric equations by Jenkins et al. 2004

- **Improved match of variability range and pattern of SAVERS simulations with the TDS data.**
- **Underestimation around -11.5 deg latitude**

Variabile biomass from Avitabile et al.



SAVERS simulations with <u>variable</u> biomass along the track.

Biomass from map by Avitabile et al. 2015. The map uses 2010 data.

- **No more underestimation around -11.5 deg where there are not trees according to Avitabile data.**
- **Large overestimation between -9 deg and -7 deg latitude**

Conclusions

- SAVERS simulator has been upgraded to account for topography
- Topography has a big impact on the DDM's
- SAVERS seems to reproduce reflectivity and DDM shape variability observed by TDS-1
- The effect of variable biomass is also fairly reproduced
- The simulator can be usefule to investigate sensitivity to targete parameters and interpret any weird behavior of the data


Thank you