GNSS-R for Land Bio-Geophysical Parameters Monitoring: the LEiMON Project

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Presentation's Outline

- Introduction
  - Motivation
  - Fundamentals
- The LEiMON project
  - Experimental campaign
  - Data Analysis
  - New Scenarios Simulations
- Outcomes/ Further work

Introduction

Motivation and fundamentals

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Introduction

-Why Soil Moisture and Vegetation?-

- Soil Moisture
  - primer parameter for the surface hydrologic cycle
  - keys for understanding interaction between continental surface and atmosphere (evapotranspiration)
  - SM affects heat storage, thermal conductivity
  - SM largely determines surface runoffs after rainfall

- Vegetation
  - critical for life support of humans and animals
  - key for understanding land resource management
  - climate variable
  - carbon cycle modelling
  - greenhouse gas emission inventories (C02 sequestration)
  - desertification control

Fundamentals of Soil Moisture and Vegetation Detection with GNSS-R

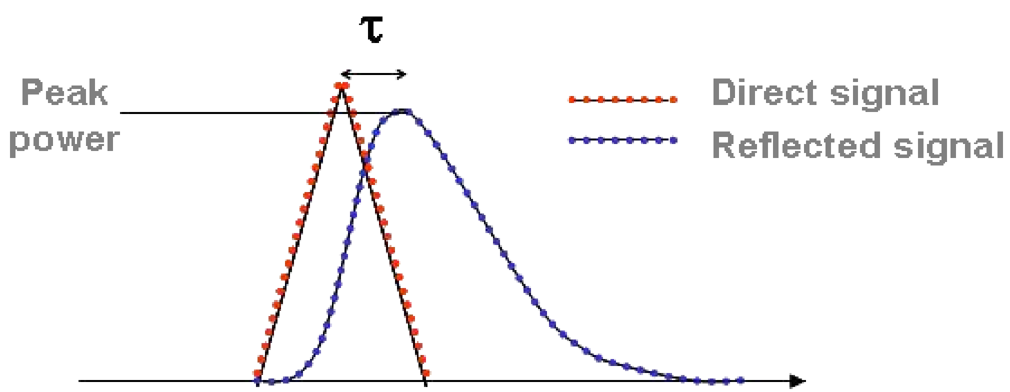
- Variability of ground dielectric properties with Soil Moisture:
  - Higher soil moisture volumetric content yields higher reflectivity

$$m_v \uparrow \;\longrightarrow\; \varepsilon_r \uparrow \;\longrightarrow\; \Gamma_{soil} \uparrow$$

- Variability of propagation properties with Vegetation:
  - Higher vegetation biomass leads to lower signal power due to attenuation

$$PWC \uparrow \;\longrightarrow\; L_v \uparrow \;\longrightarrow\; \Gamma_{soil} \downarrow$$

- GNSS-R waveform peaks depend on the CNR of the received signals



The LEiMON Project

Land Monitoring with Navigation Signals

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The LEiMON Project

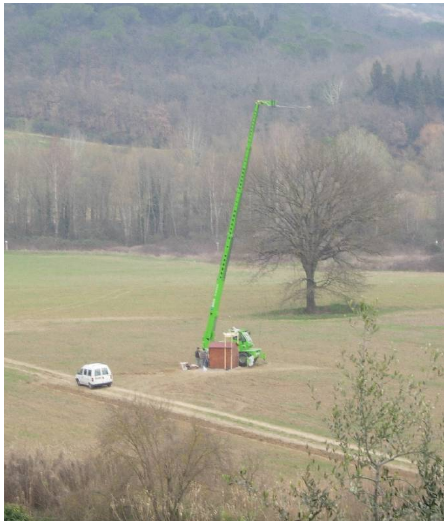
- ESA (ESTEC) funded project [from 2008 to 2010]
  – Main objective: To investigate the combined effects of soil moisture, surface roughness, and vegetation into GNSS reflections and to evaluate the prospects of GNSS-R as a consolidated technology for land remote sensing applications.
- The project tasks:
  – Long term experimental campaign
    - GNSS-R + ground truth measurements continuously recorded
    - Database preparation and browsing tool
  – Experimental campaign data processing
  – GNSS-R simulator development for land applications
    - Scattering model for GNSS signals
    - Simulator implementation
  – Simulator validation with GNSS-R experimental data
  – Simulations of other scenarios

LEiMON experimental campaign

Long Term experimental campaign

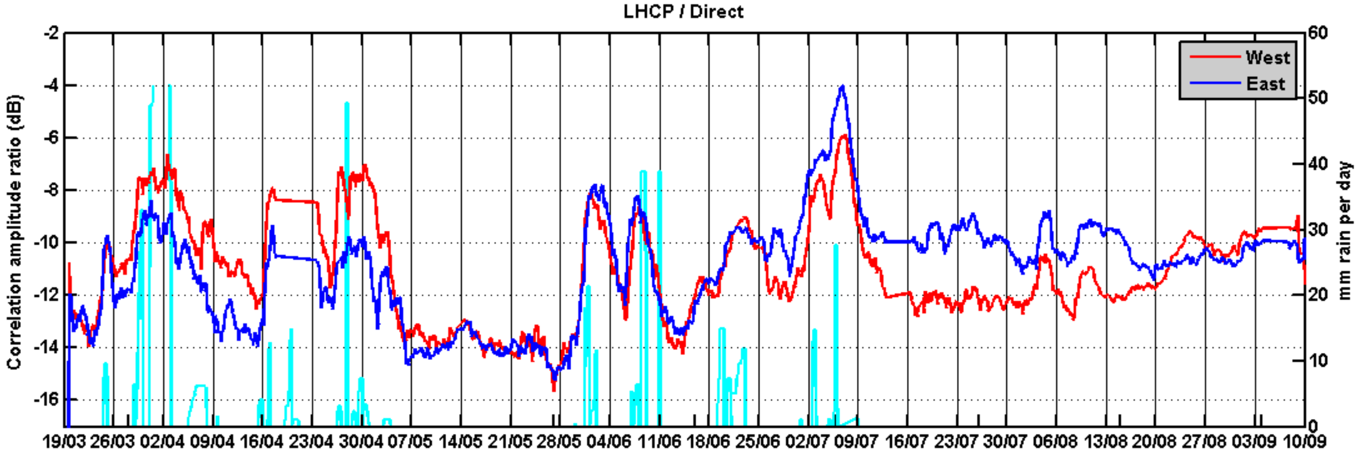
– Montespertoli Experiment, Florence, Italy (March 2009 - Sept 2009)
  - Test-site field separated in two sides (E/W) for maximum variability of soil parameters
  - Strong rain events
  - Different roughness conditions throughout the campaign
  - West field seeded with sunflowers (up to 7kg/m2 biomass)

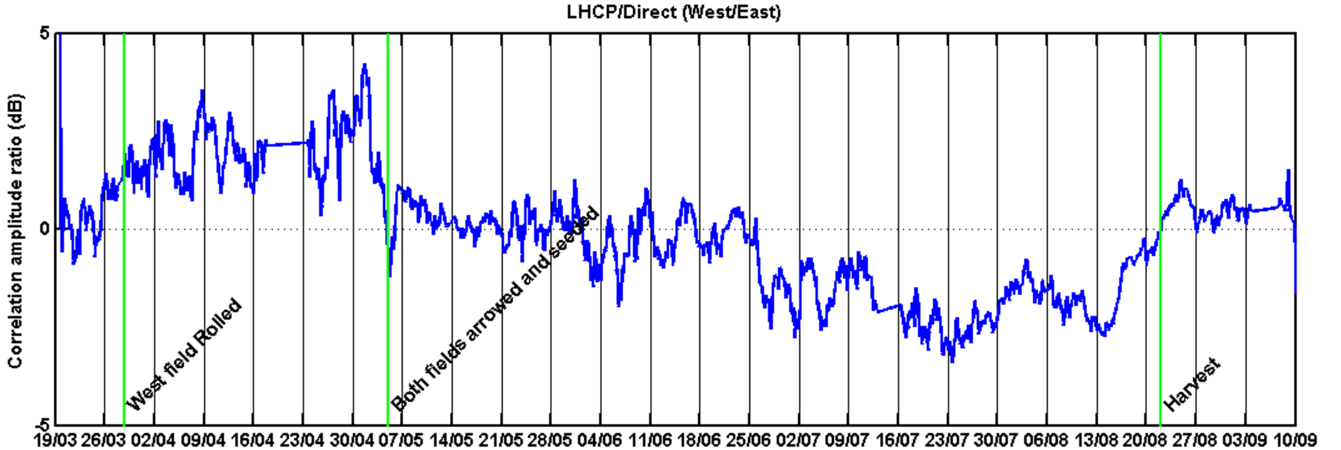
– Continuous recording of GNSS-R polarimetric data, and ground-truth measurements (soil moisture probes, meteo station, surface roughness, plant height, plant water



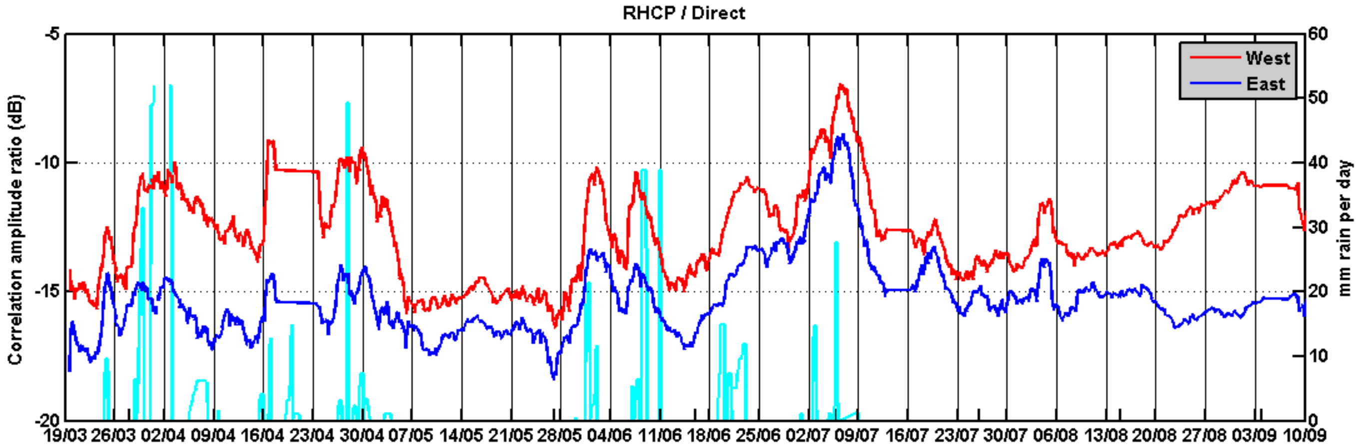
LEiMON experimental campaign

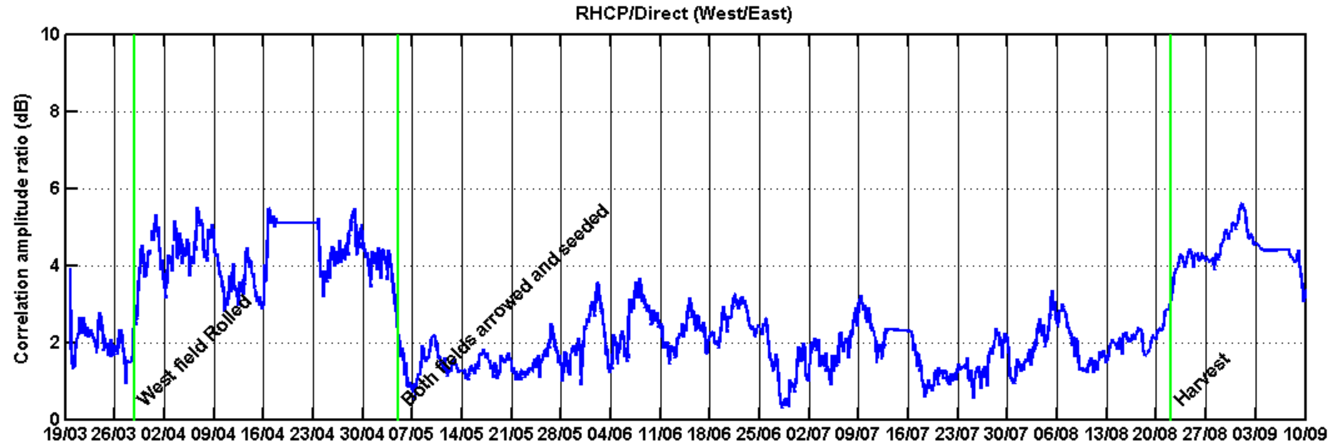
GNSS-R signals comparison with ancillary data



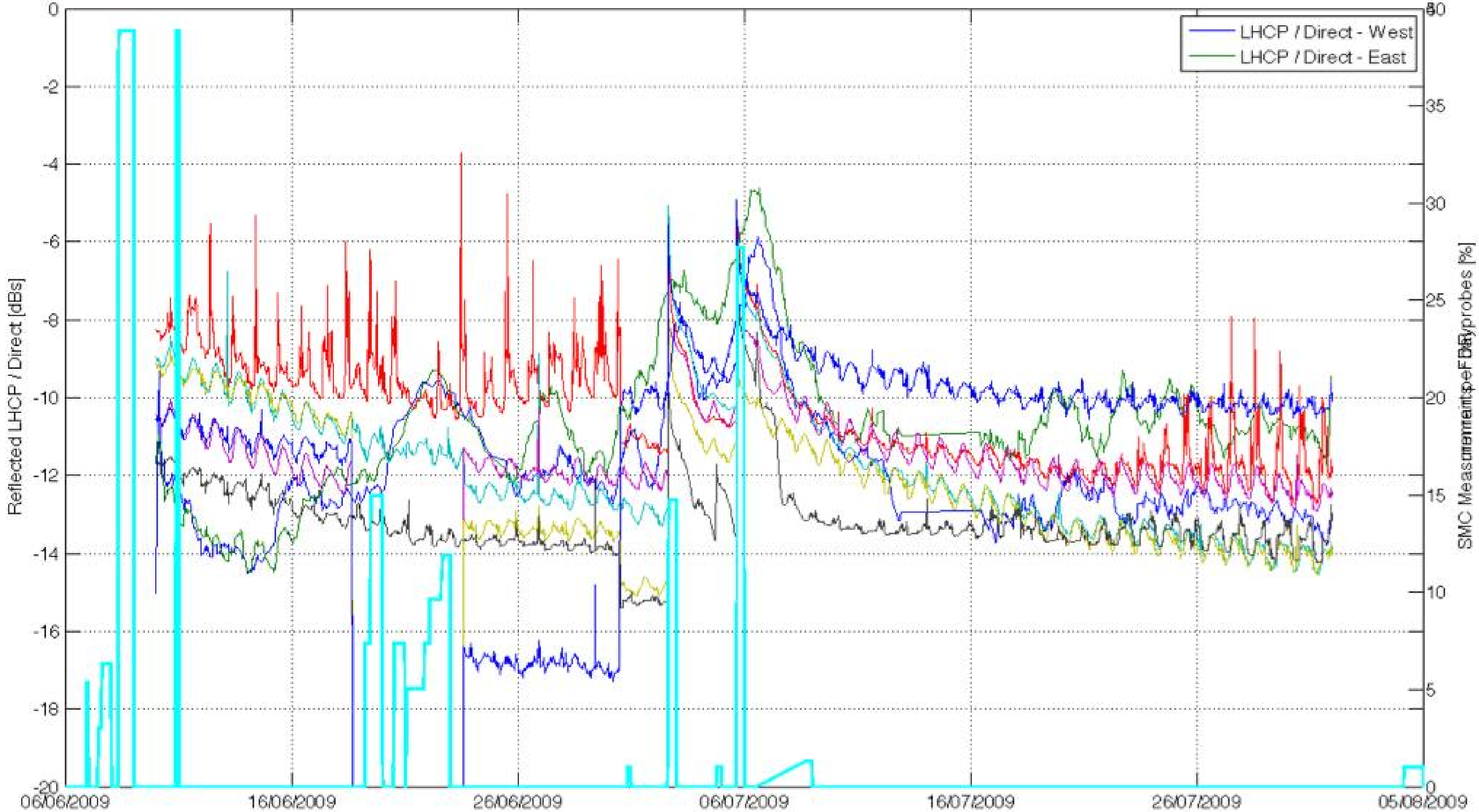


GNSS-R signals comparison with ancillary data

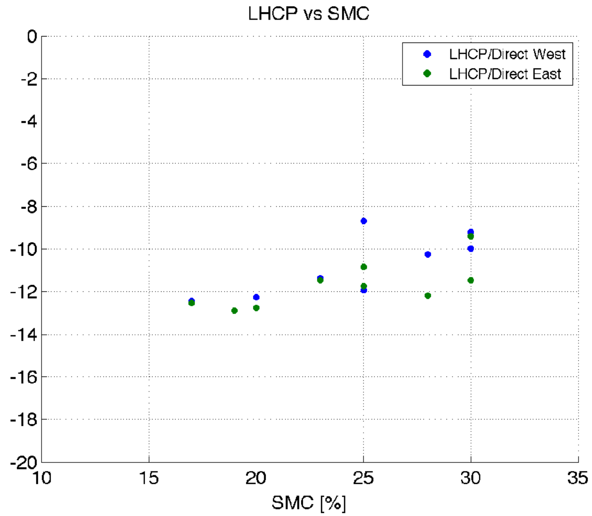


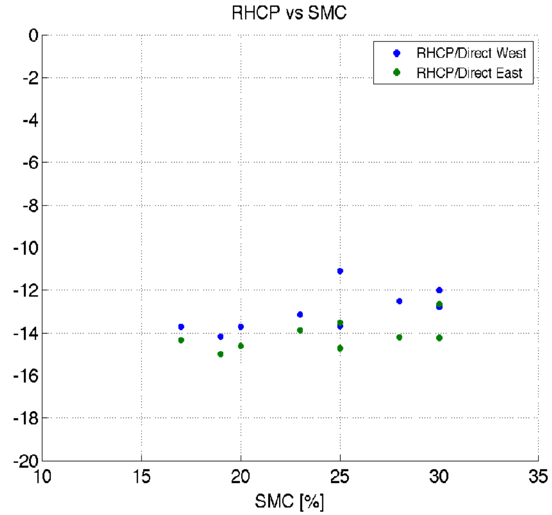


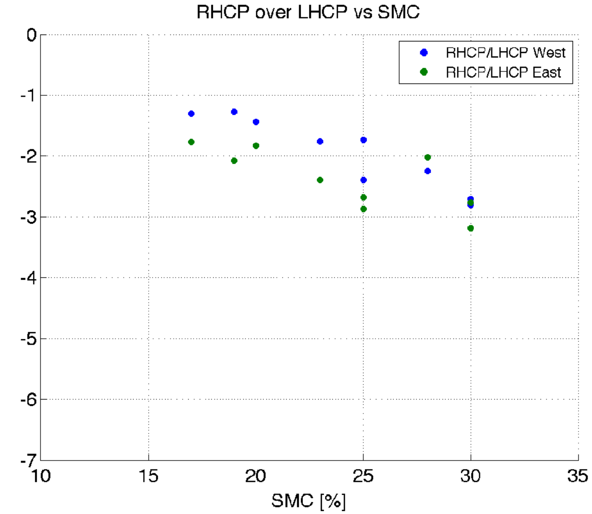
GNSS-R signals comparison with ancillary data (SM probes & Rain)



Sensitivity of GNSS-R signals to SMC





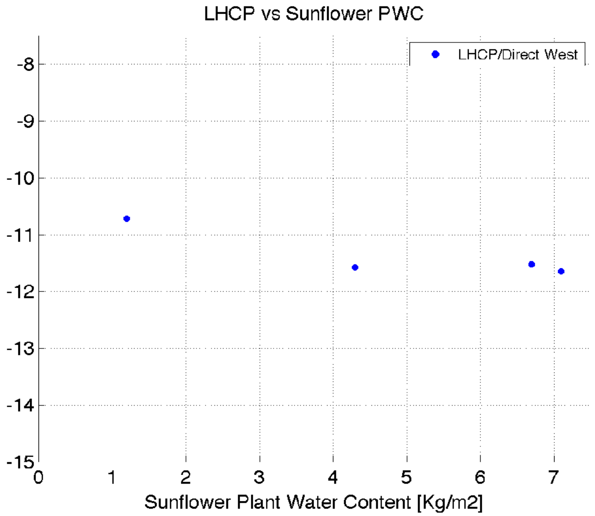


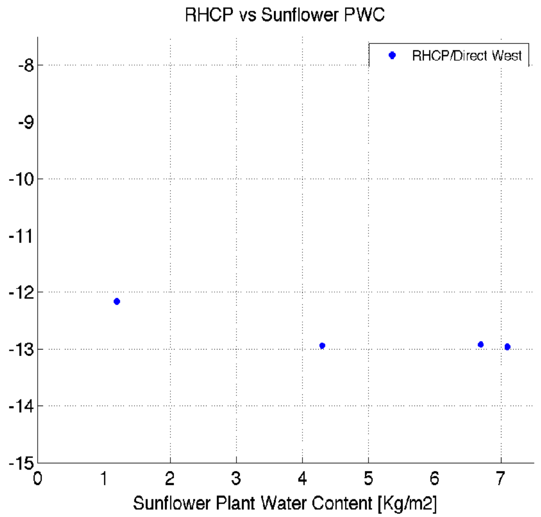
- LHCP
  - East field
    - CorrCoeff (R^2) = 0.7
    - Sensitivity = 0.18 dB/SMC
    - RMSE = 4.6 %
  - West field
    - CorrCoef (R^2) = 0.77,
    - Sensitivity = 0.24 dB/SMC
    - RMSE = 3.66%

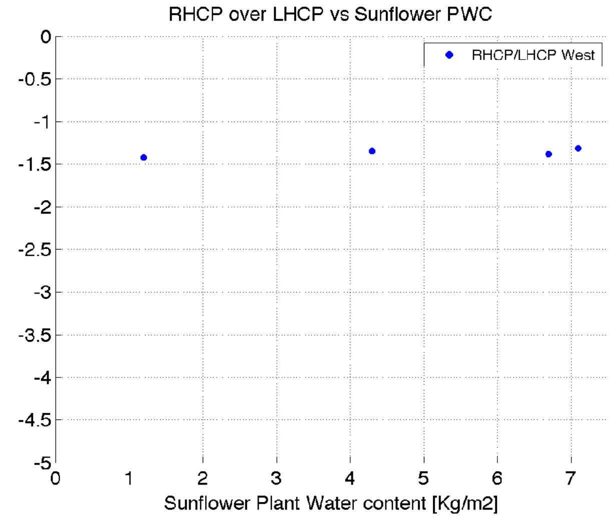
- RHCP
  - East field
    - CorrCoeff (R^2) = 0.57
    - Sensitivity = 0.09 dB/SMC
    - RMSE = 6.5 %
  - West field
    - CorrCoef (R^2) = 0.62,
    - Sensitivity = 0.13 dB/SMC
    - RMSE = 5.66%

- RHCP / LHCP
  - East field
    - CorrCoeff (R^2) = 0.76
    - Sensitivity = 0.08 dB/SMC
    - RMSE = 3.9 %
  - West field
    - CorrCoef (R^2) = 0.92,
    - Sensitivity = 0.12 dB/SMC
    - RMSE = 1.55%

Sensitivity of GNSS-R signals to PWC







- LHCP
  - West field
    - CorrCoef (R^2) = 0.9,
    - Sensitivity = 0.14 dB/(Kg/m2)
    - RMSE = 1.16 Kg/m2

- RHCP
  - West field
    - CorrCoef (R^2) = 0.9,
    - Sensitivity = 0.13 dB/(Kg/m2)
    - RMSE = 1.2 Kg/m2

- RHCP / LHCP
  - West field
    - CorrCoef (R^2) = 0.71,
    - Sensitivity = 0.02 dB/(Kg/m2)
    - RMSE = 2.4 Kg/m2

GNSS-R Data Analysis Outcomes

- The general trends in the data match the behaviour predicted by theoretical models
  - LHCP and RHCP reflected signal components sensitive to Soil Moisture and Roughness
    - ↑ Soil Moisture ↔ ↑ RHCP (~1dB/10% SMC), ↑ LHCP (~2dB/10% SMC)
    - ↑ Soil Roughness ↔ ↓ RHCP, ↓ LHCP
  - RHCP over LHCP ratio sensitive to soil moisture
    - ↑ Soil Moisture ↔ ↓ RHCP/LHCP (~1dB/10% SMC)
  - RHCP over LHCP ratio quite insensitive to soil roughness
  - LHCP and RHCP signals little sensitive to vegetation
    - ↑ Vegetation ↔ ↓ LHCP, ↓ RHCP (~0.1dB/(kg/m2))
- GNSS-R signals sensitive to light rain events that soil moisture FDR probes do not detect

Moving towards space

- Simulations performed with developed software to determine the sensitivity of GNSS-R signals to soil parameters from airborne/spaceborne platforms
- Model validated with GNSS-R experimental data
- Several land conditions selected in order to perform the analysis for several scenarios

Soil Moisture Conditions	**#**	**1**	**2**	**3**
	State	Dry	Mid	Wet
	Value (VSM)	5.00%	20.00%	40.00%
Roughness Conditions	**#**	**1**	**2**	**3**
	State	Smooth	Mid	Rough
	Value (s_Z)	0.5cm	1.5cm	2.5cm
Vegetation Conditions	**#**	**1**	**2**	**3**
	State	Bare	Mid	Developed
	Value (H)	0cm	60cm	150cm

Scenario	SoilMoisture	Roughness	Vegetation
1	2	1	1
2	1	2	1
3	2	2	1
4	3	2	1
5	2	3	1
6	2	2	2
7	2	2	3
8	3	2	3

- Selected plaforms characteristics:

Airborne

Parameter	Value
Platform Height	5000m
Platform Speed	200m/s
Antenna HPBW	40º
Integration Time	1 ms

Spaceborne

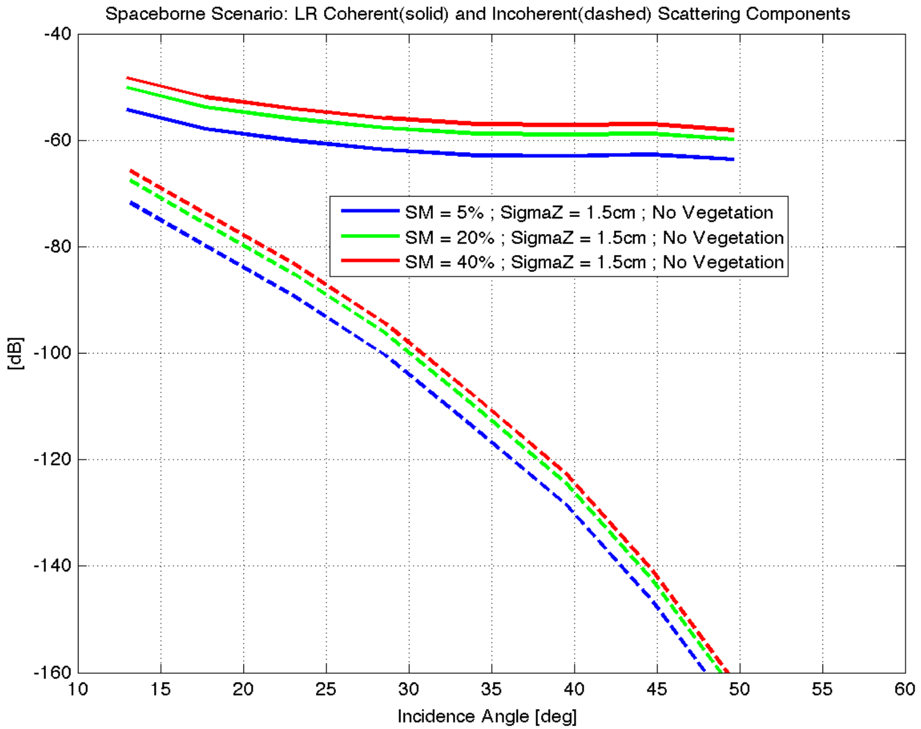
Parameter	Value
Platform Height	750Km
Platform Speed	7Km/s
Antenna HPBW	20º
Integration Time	1 ms

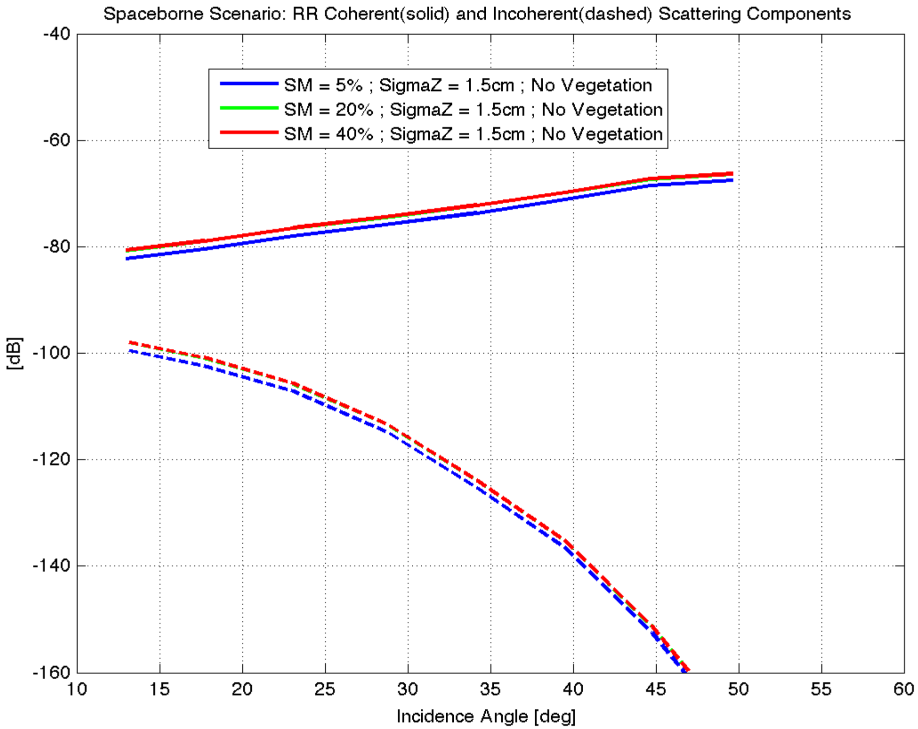
Spaceborne Platform

-Soil Moisture Sensitivity-

Varying Soil Moisture, s_z = 1.5cm, No Vegetation

- LHCP and RHCP coherent and incoherent scattering components





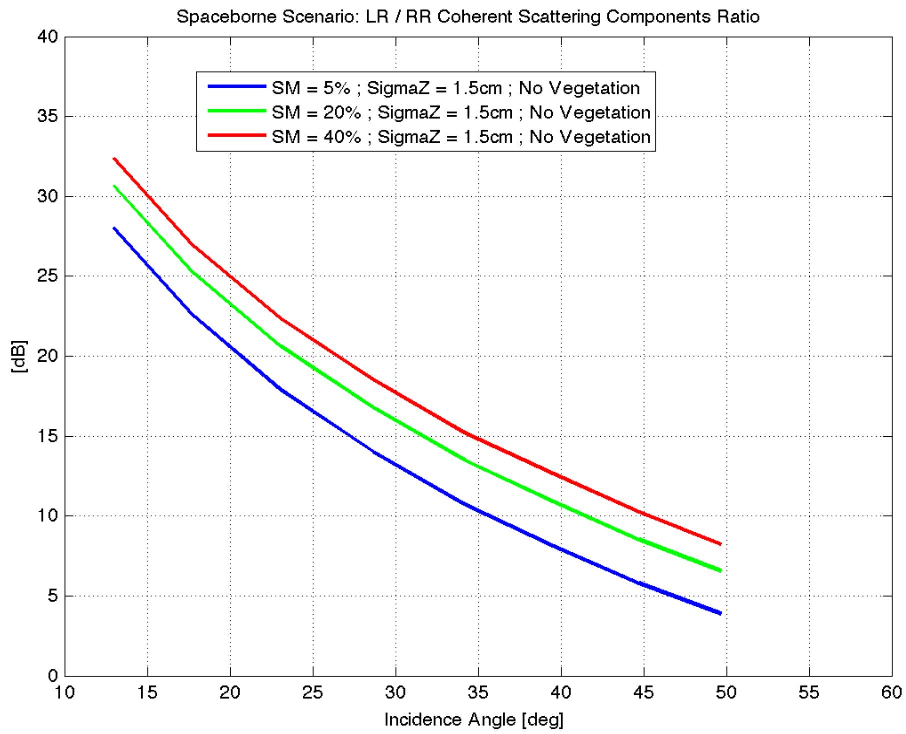
- Good sensitivity in LHCP polarization; over 6dB between dry and wet case

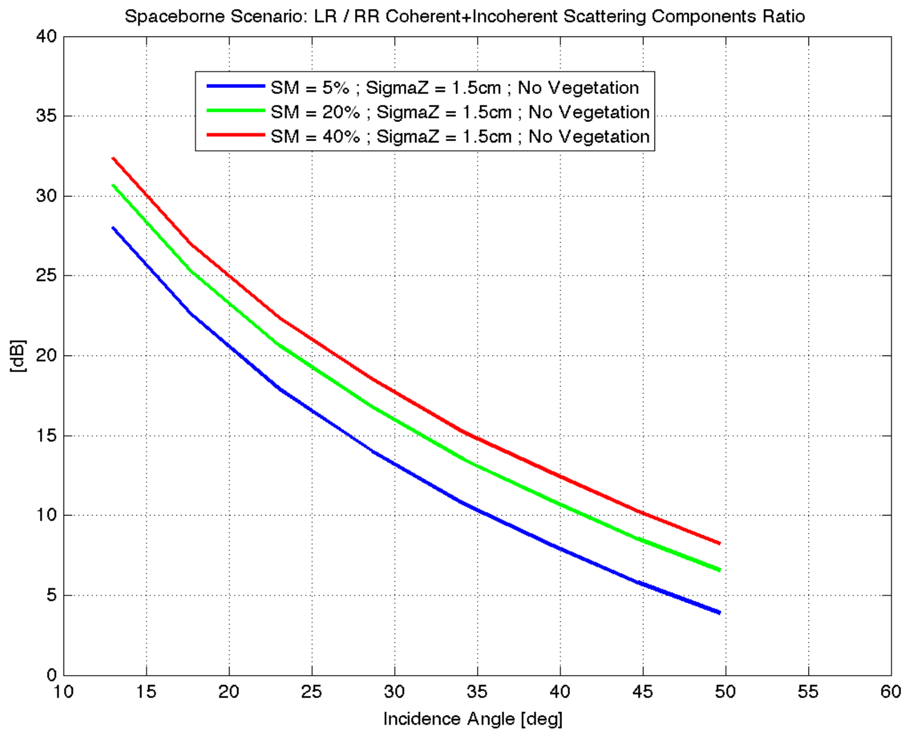
Spaceborne Platform

-Soil Moisture Sensitivity-

Varying Soil Moisture, s_z = 1.5cm, No Vegetation

- LHCP over RHCP coherent components ratio and complete fields ratio





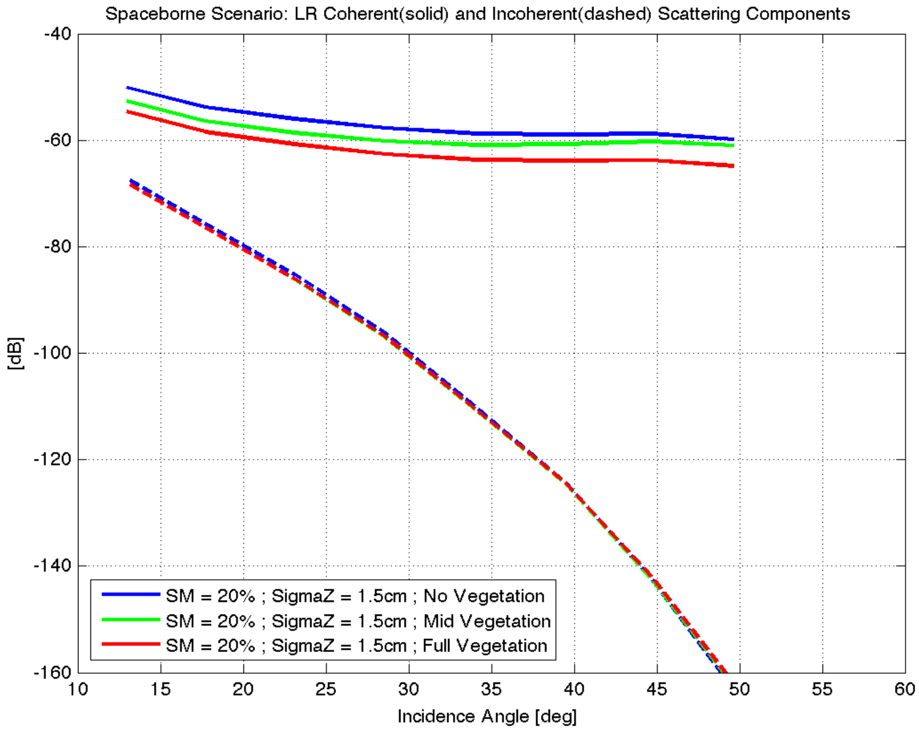
- Incoherent component is almost negligible
- Good sensitivity to soil moisture; 4dB difference among dry to wet soil condition

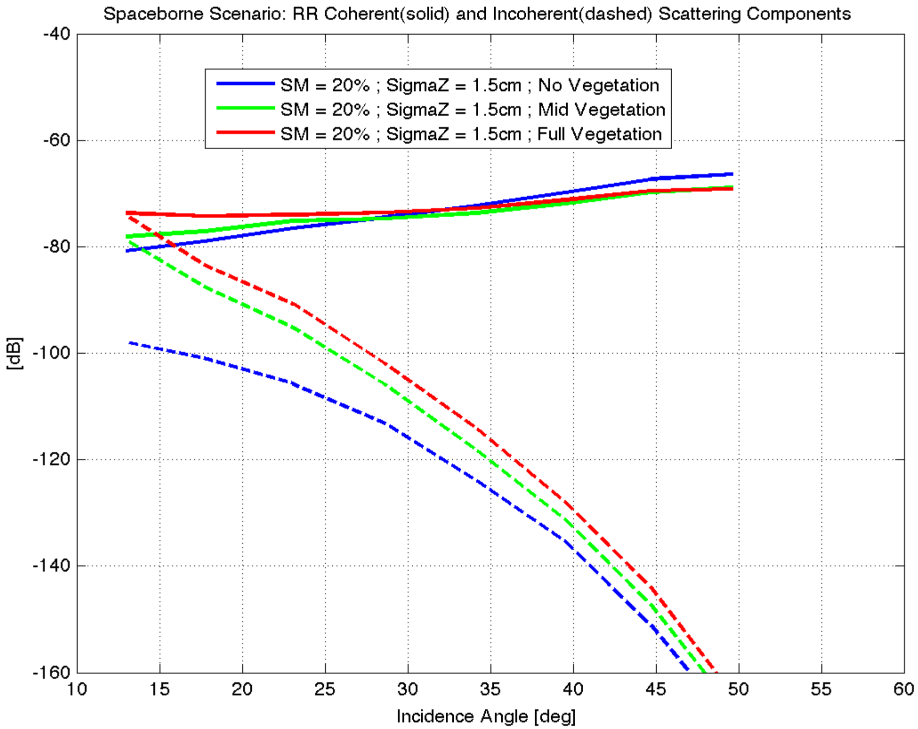
Spaceborne Platform

-Vegetation development Sensitivity-

Varying Vegetation, SMC= 20%, s_z = 1.5cm

- LHCP and RHCP coherent and incoherent scattering components





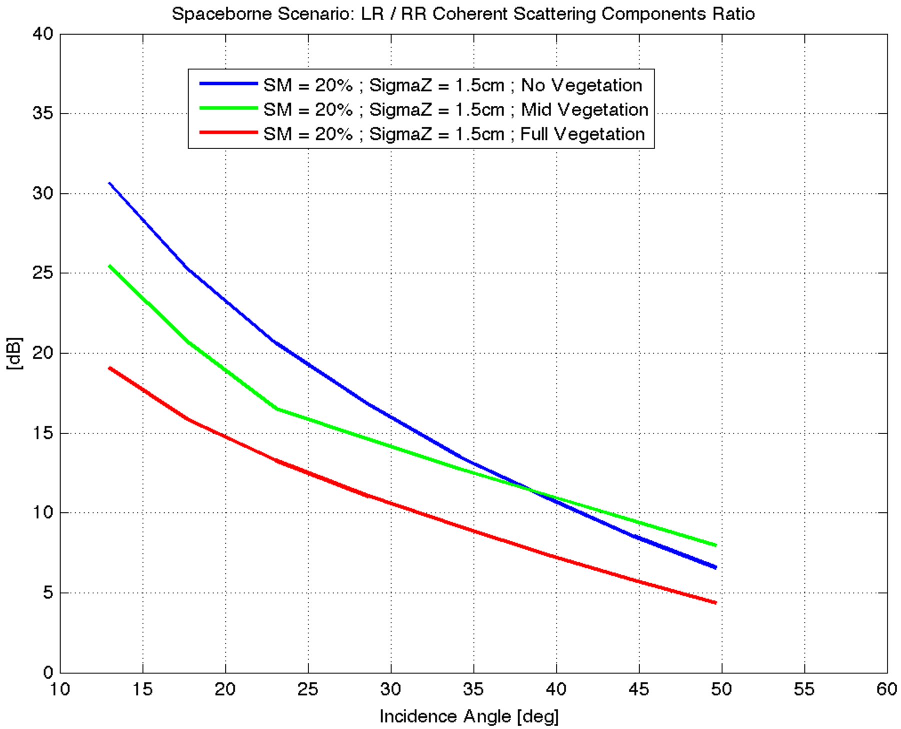
- Good sensitivity for LHCP, and RHCP coherent components at low incidence angles; 5dB difference from bare to fully developed vegetation
- RHCP incoherent component; big increase with vegetation development

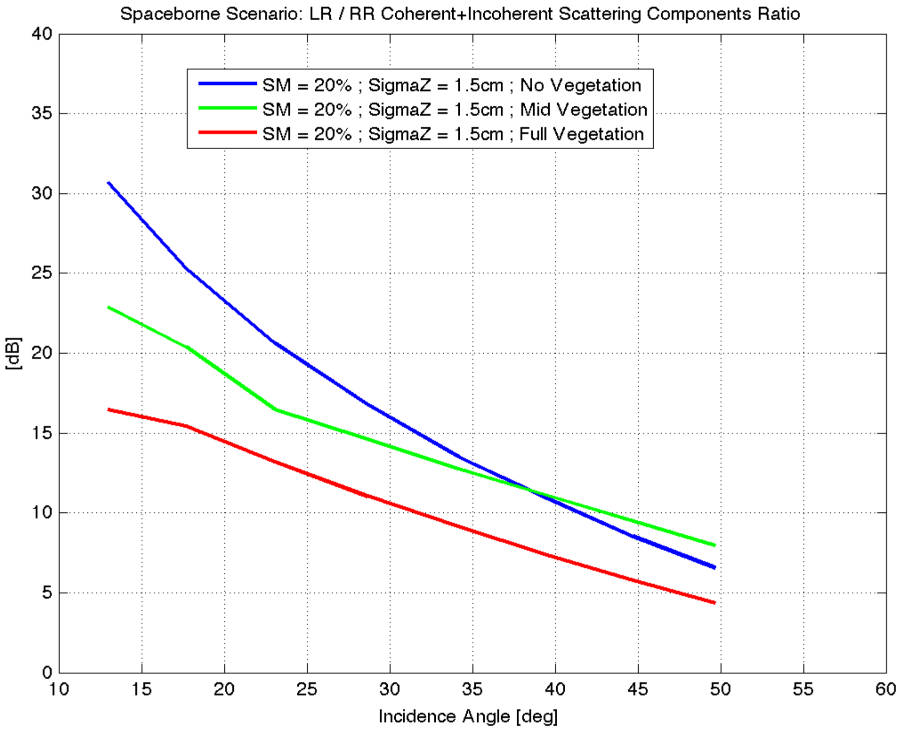
Spaceborne Platform

-Vegetation development Sensitivity-

Varying Vegetation, SMC= 20%, s_z = 1.5cm

- LHCP over RHCP coherent components ratio; complete fields ratio





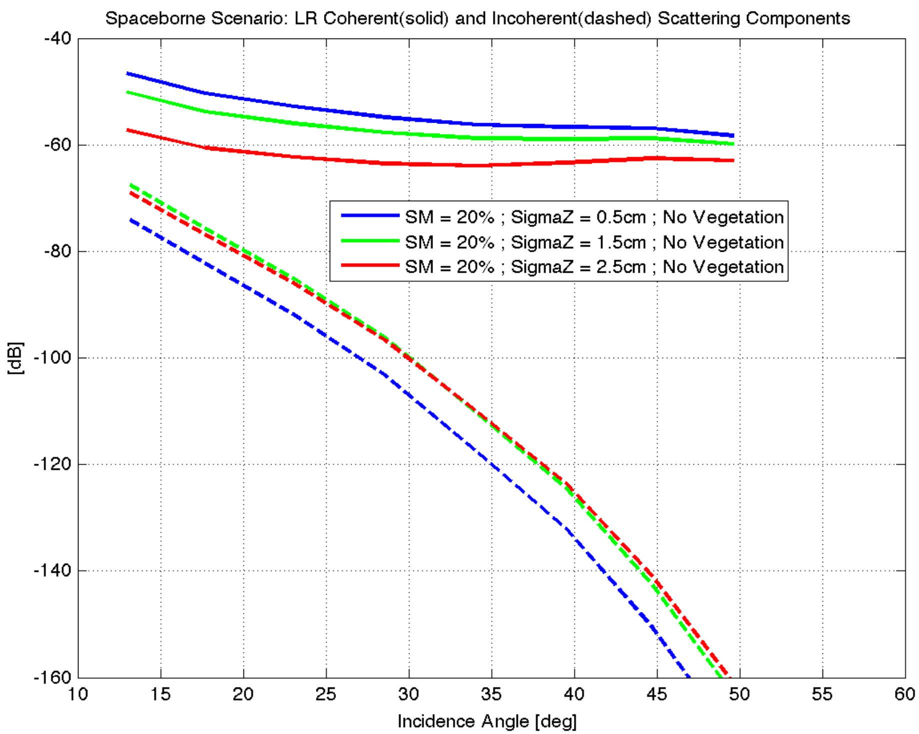
- Good sensitivity both for coherent component and complete field at low incidences

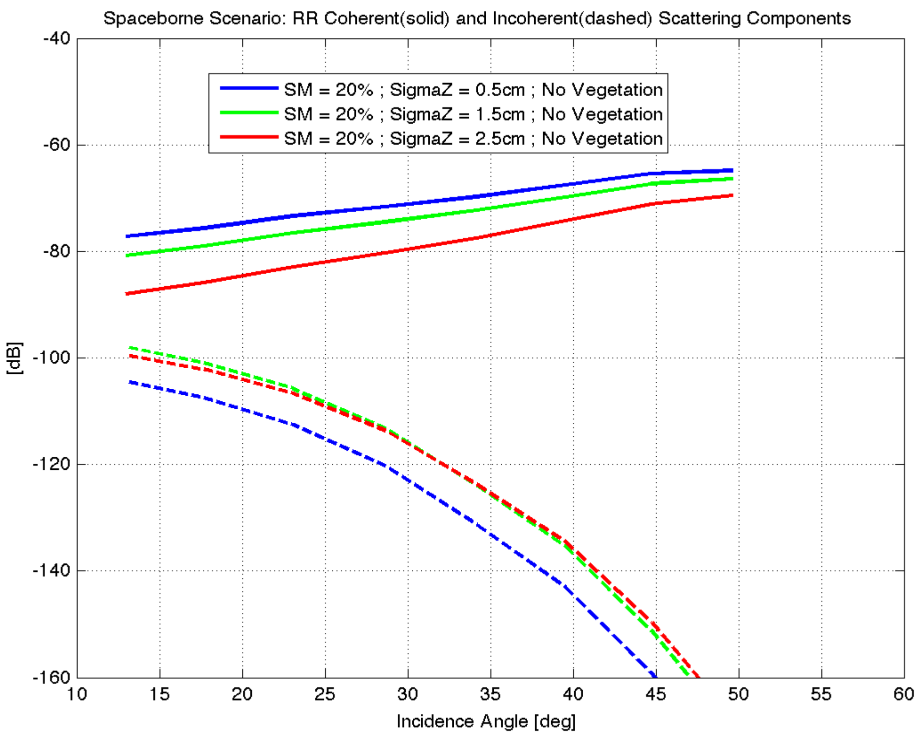
Spaceborne Platform

-The effect of Surface Roughness-

Varying Roughness, SMC= 20%, No Vegetation

- LHCP and RHCP coherent and incoherent scattering components





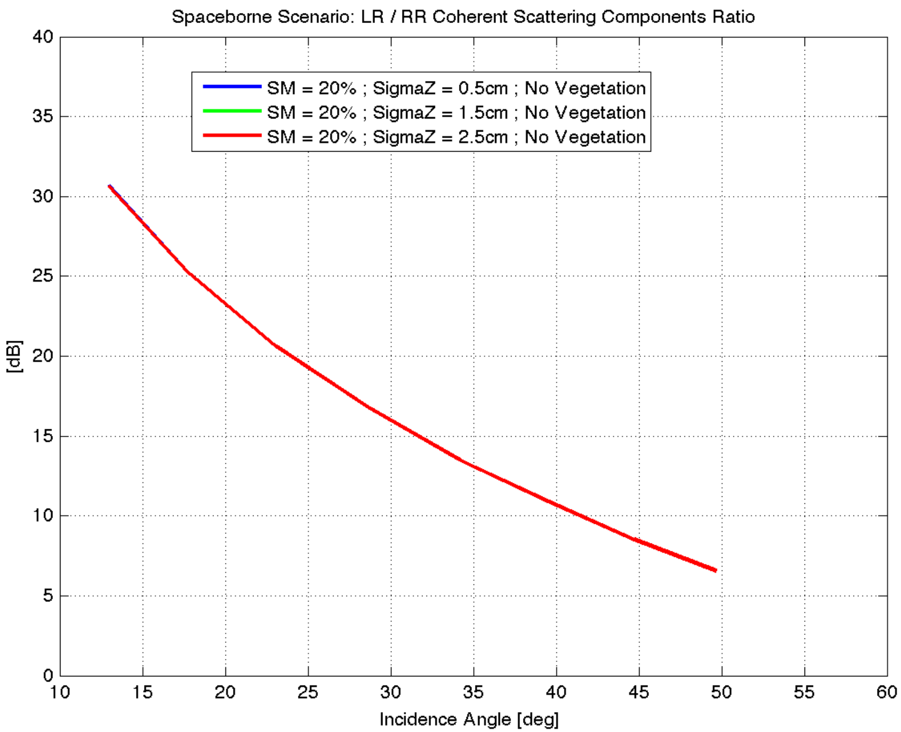
- Rapid decrease of LHCP and RHCP coherent scattering components with roughness, and increase of the incoherent component
- Surface roughness main parameter driving coherency in the scattering process

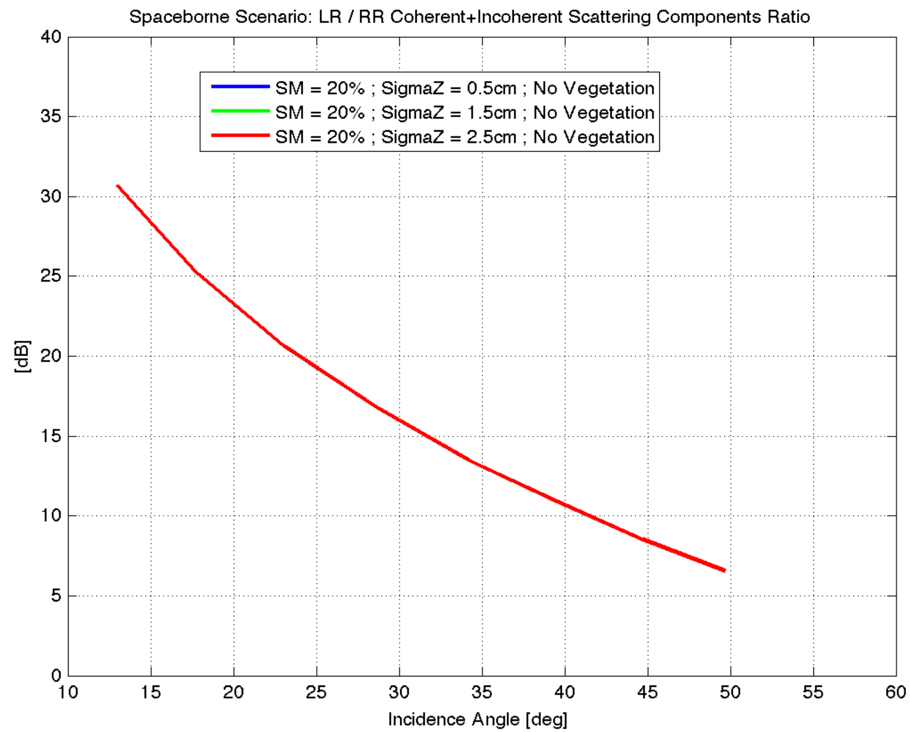
Spaceborne Platform

-The effect of Surface Roughness-

Varying Roughness, SMC= 20%, No Vegetation

- LHCP over RHCP coherent components ratio and complete fields ratio





- Ratio LHCP over RHCP, of both coherent scattering components and complete fields is not sensitive to roughness. (result observed in experimental campaign data)
- This makes this parameter an optimum observable for soil moisture measurements over bare soil.

Summary

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Summary of outcomes

- Long Term Experimental campaign performed
  - 6 months continuous acquisition of GNSS-R data + ancillary data
  - High variability of soil bio-geophysical parameters
- Experimental campaign data processing
  - Signals correlate to events on the field (rain, roughness, vegetation)
  - GNSS-R signals sensitive to soil parameters
    - Good sensitivity(>0.2dB/m_v) and high correlation(>0.8) with soil moisture
    - Low sensitivity to vegetation (~0.14dB/(kg/m2))
- Space scenario simulations
  - GNSS-R signals show good sensitivity to soil moisture and vegetation parameters from airborne and spaceborne platforms (Coherent scattering predominant)
  - LHCP/RHCP ratio confirms to be a good candidate to measure SM on bare soil

Further work

Towards a GNSS-R spaceborne mission for land remote sensing applications:

- Changes in the local incidence and scattering angles to be considered by the simulator
- Diffraction effects on coherent reflections due to topography variation within the first Fresnel zone
- Precise SNR budget to be included
- Mixed pixel effect
- …

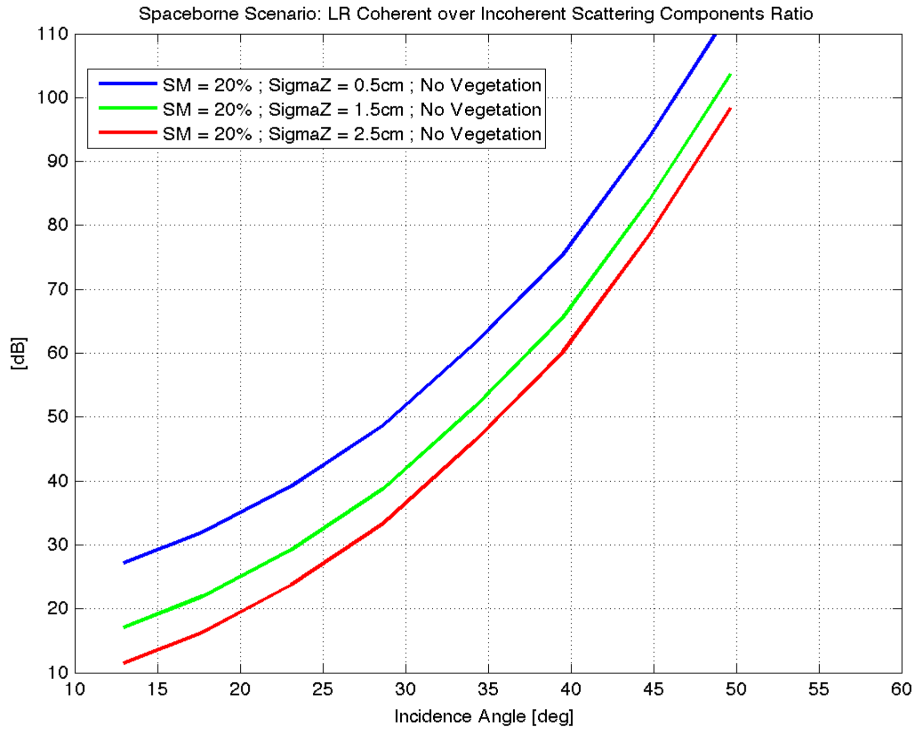
Thank you

Spaceborne Platform

-The effect of Surface Roughness-

Varying Roughness, SMC= 20%, No Vegetation

- LHCP coherent over incoherent scattering components ratio



- Ratio decreases both in LHCP and RHCP polarizations
- Over 15dB difference between smooth and rough surfaces

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Spaceborne Platform

-Soil Moisture Sensitivity-

Varying Soil Moisture, s_z = 1.5cm, No Vegetation

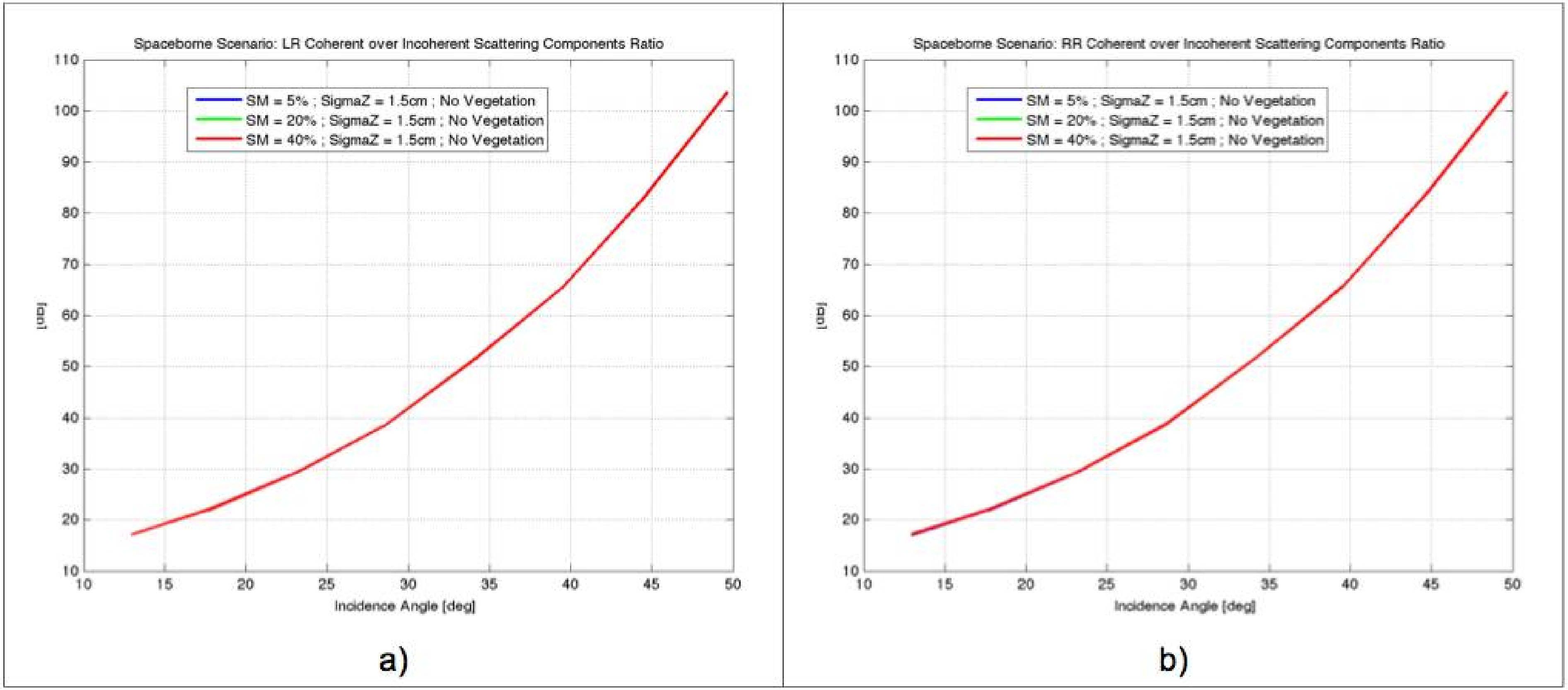


Figure 14: a) LR, and b) RR, ratio of coherent and incoherent scattering components for three different soil moisture situations; In blue Soil Moisture = 5%, in green 20%, and in red 40%.

Spaceborne Platform

-Vegetation development Sensitivity-

Varying Vegetation, SMC= 20%, s_z = 1.5cm

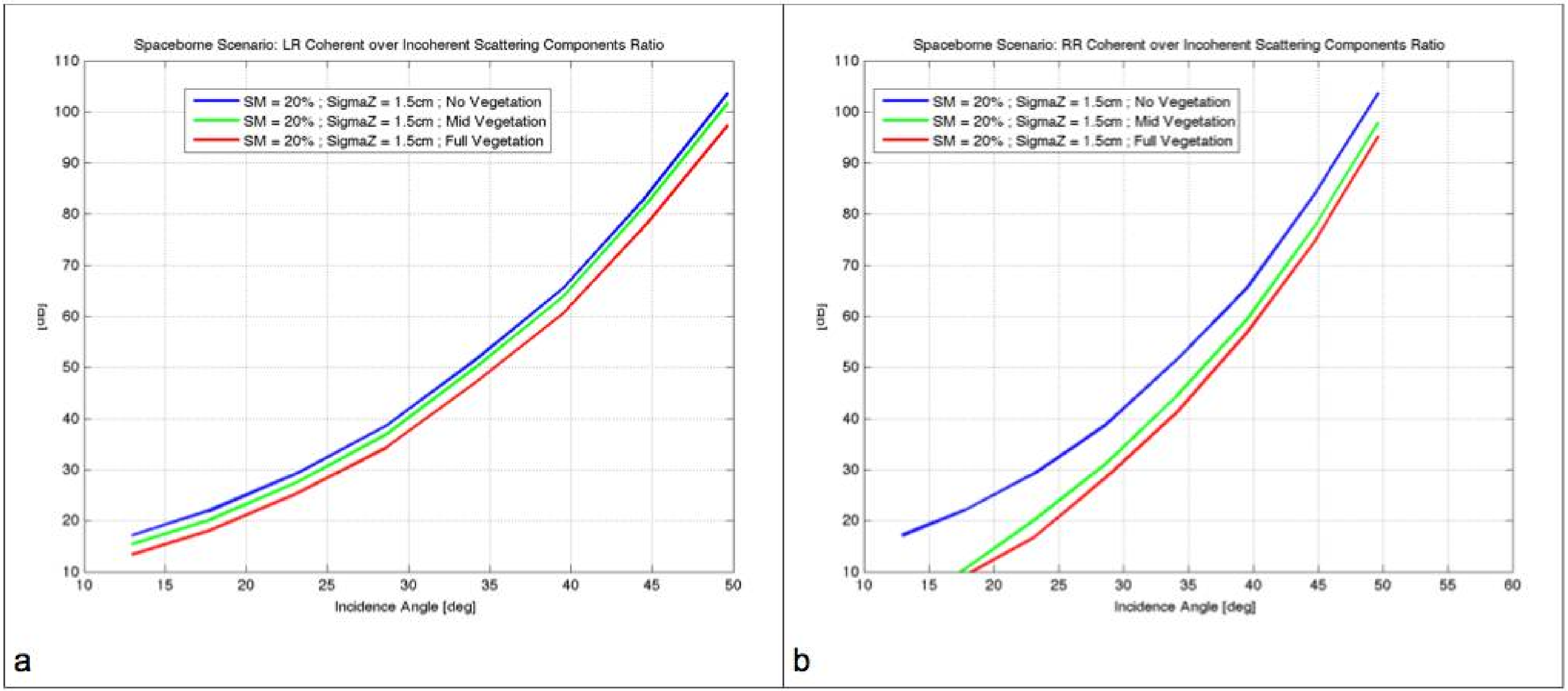
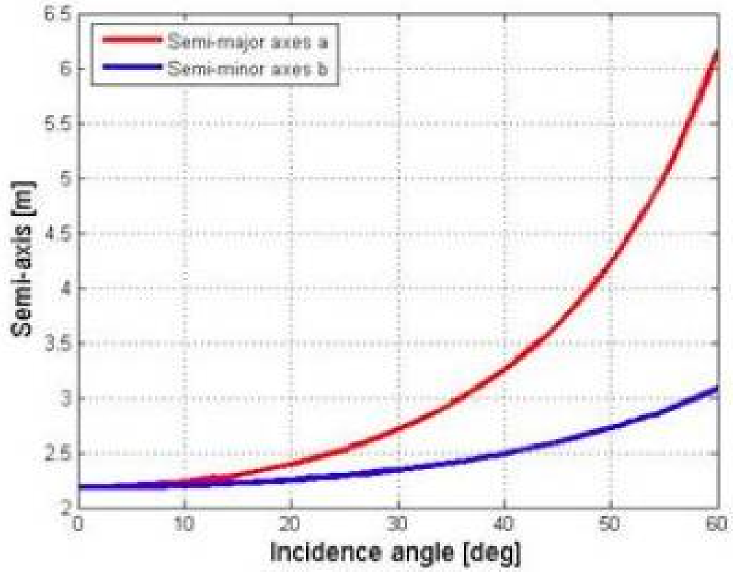


Figure 17: a) LR, and b) RR, ratio of coherent and incoherent scattering components for three different vegetation development stages; In blue no vegetation, in green partially developed vegetation, and in red fully developed vegetation.

1st Fresnel zone vs 1st chip zone



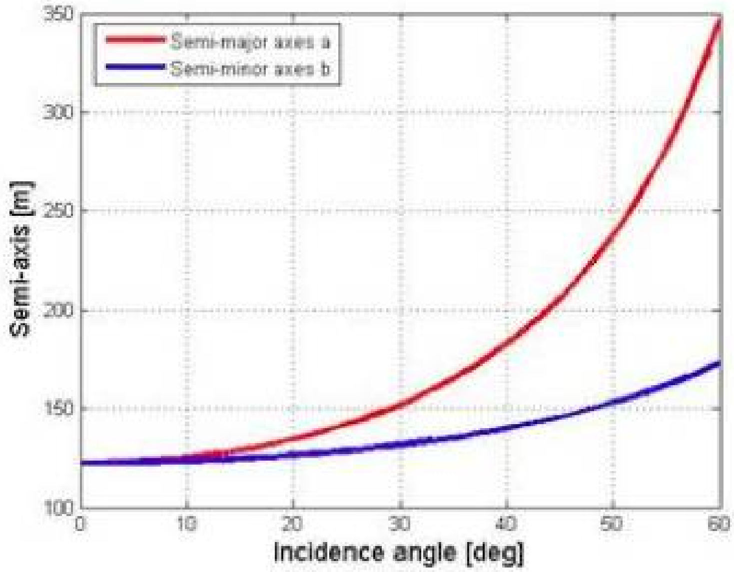


Figure 3: Dimensions of the First Fresnel zone (on the left) and of the first equidelay ellipse (on the right) corresponding to the C/A chip length of 300m, for a receiver at 25m height

RHCP and LHCP reflected signals components power

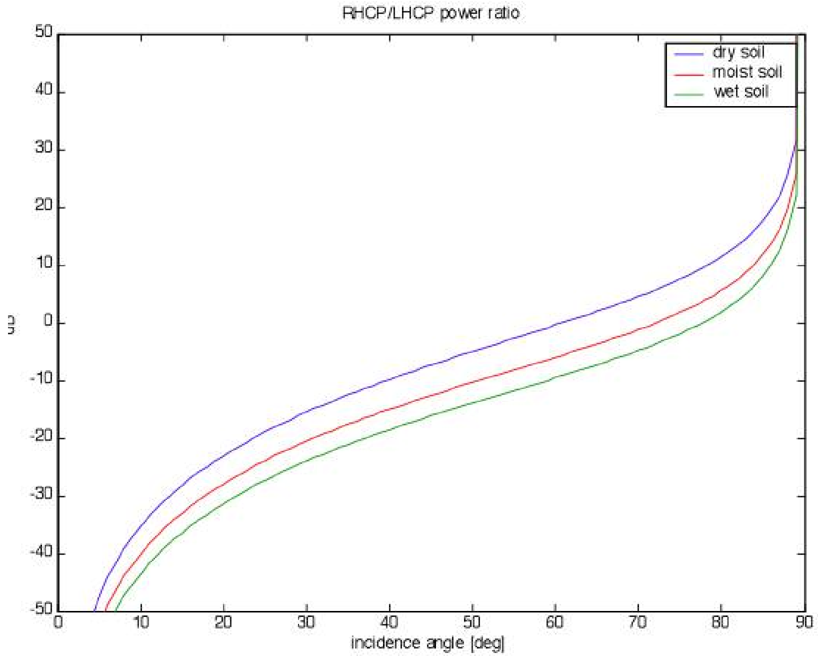


Figure 5: RHCP and LHCP reflected signals components power ratio

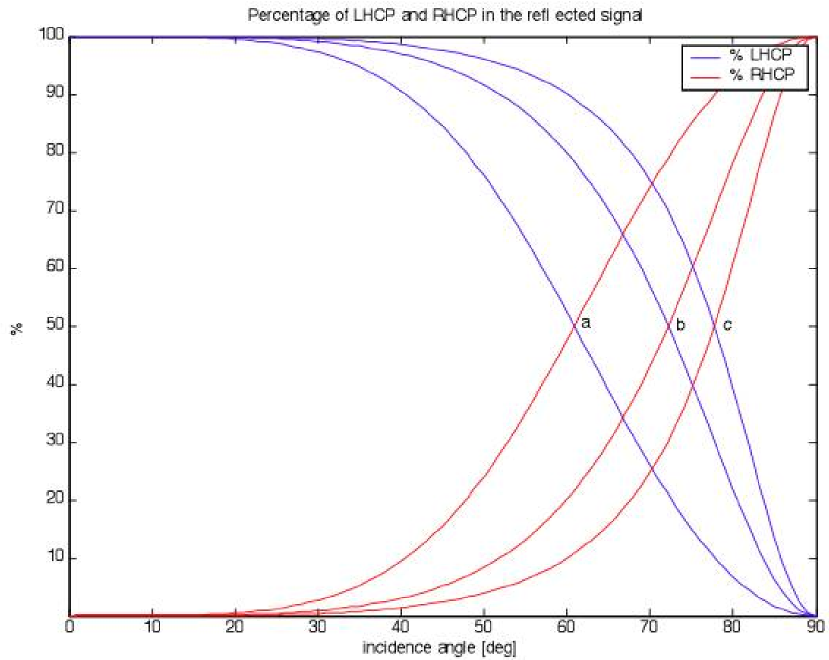


Figure 4: Percentage of LHC and RHC polarization components in the reflected signal; a) dry soil, $\varepsilon_r = 3.2\text{-}0.33i$, b) moist soil, $\varepsilon_r = 9.5\text{-}1.8i$, c) wet soil, $\varepsilon_r = 20.8\text{-}3.75i$

Soil's reflectivity for 3 different soil moisture conditions

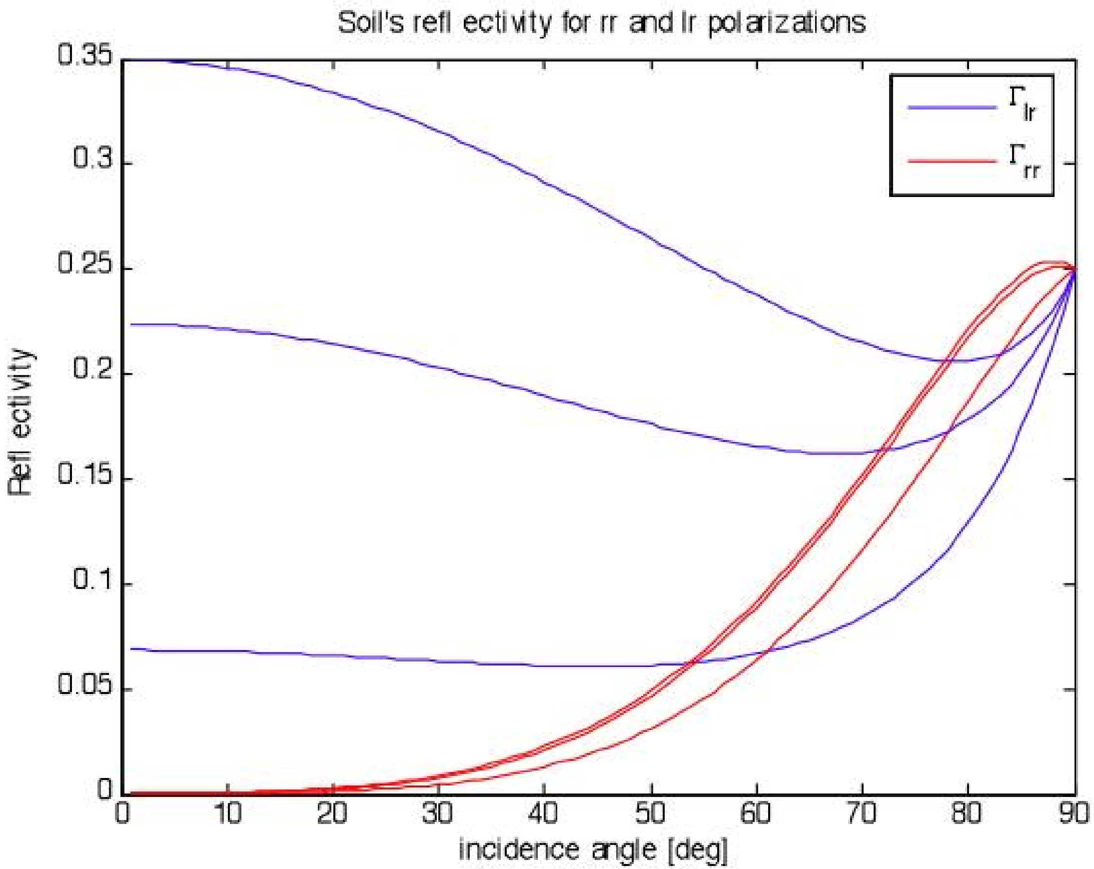
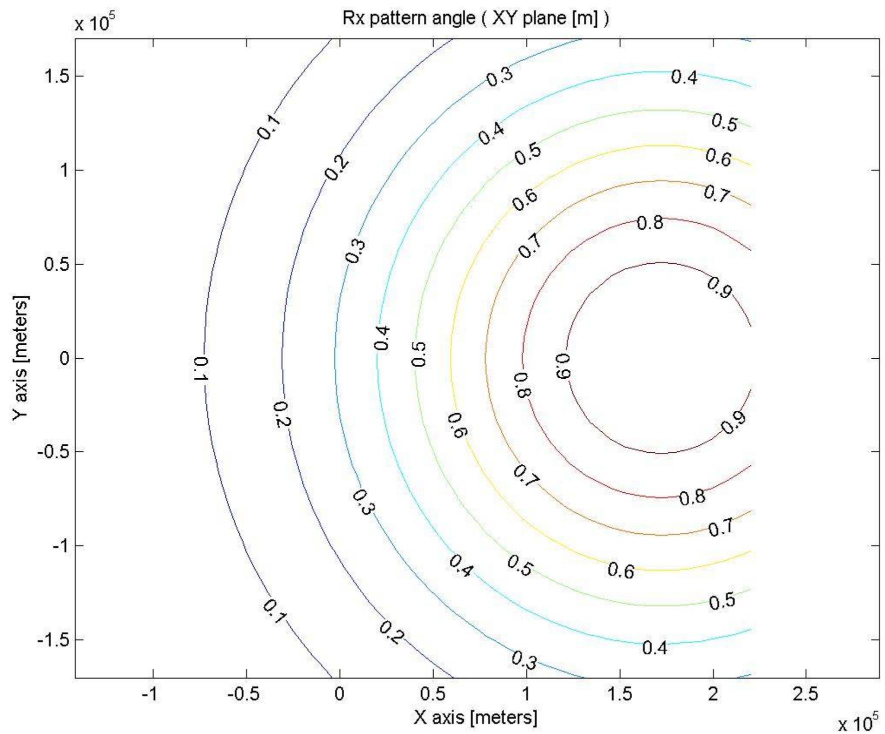
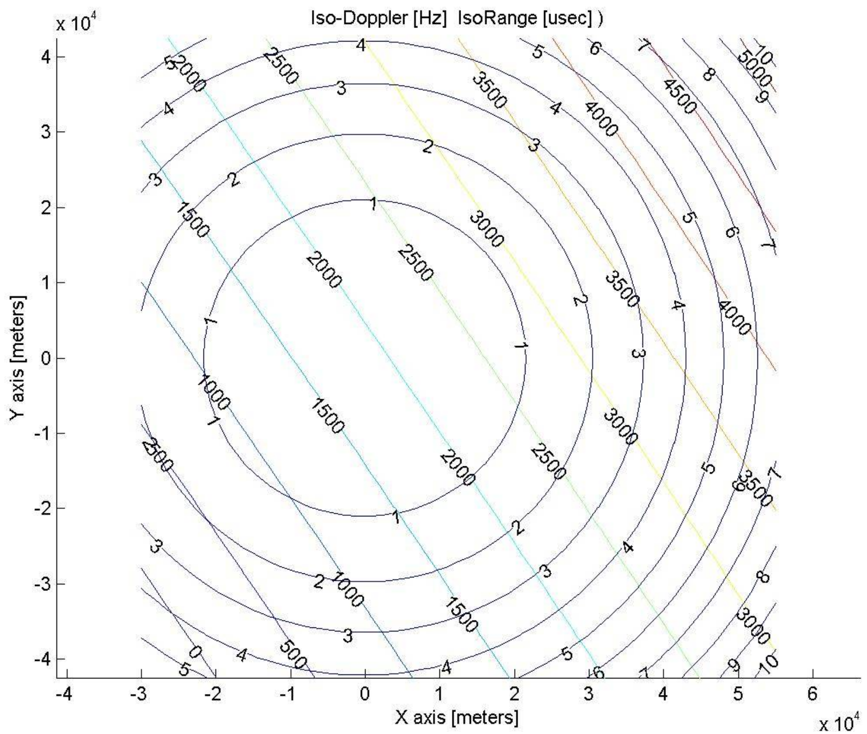


Figure 7: Soil's reflectivity for 3 different soil moisture conditions

Spaceborne Platform
-Resolution Calculation-

- Antenna Rx Pattern (Left); Iso-Delay and Iso-Doppler lines (right)





- Antenna Half Power Beam Width > First chip zone
- Resolution Cell from space platform CA-code ~ 40Km