GNSS-R for studies of the cryosphere

F. Fabra[1], E. Cardellach[1], O. Nogués-Correig[1], S. Oliveras[1], S. Ribó[1], J.C. Arco[1], A. Rius[1], M. Belmonte-Rivas[2], M. Semmling[3], G. Macelloni[4], S. Pettinato[4], R. Zasso[5] and S. D'Addio[6]

[1]ICE-CSIC/IEEC, Spain
[2]NCAR, CO, USA
[3]GFZ, Germany
[4]IFAC/CNR, Italy
[5]CVA-ARPAV, Italy
[6]ESTEC/ESA, The Netherlands

Workshop on GNSS-Reflectometry, Barcelona. Oct 22nd 2010

Outline

1. Introduction
   - GPS-SIDS project
   - GOLD-RTR
2. SI: Greenland
   - Scenario
   - Results
3. DS: Antarctica
   - Scenario
   - Models
   - Methodology
   - Preliminary results
4. Summary

The frame of this work

GPS Sea Ice - Dry Snow

- GOAL: to investigate the use of reflected GPS signals to study **sea ice** and **dry snow** properties from Space
- METHOD: to collect long term data sets from fixed platforms and then extrapolate the results
- CHALLENGE: experimental campaign under polar environmental conditions
- Many institutions involved: ICE-CSIC/IEEC, GFZ and IFAC/CNR (funded by ESA)

The instrument employed

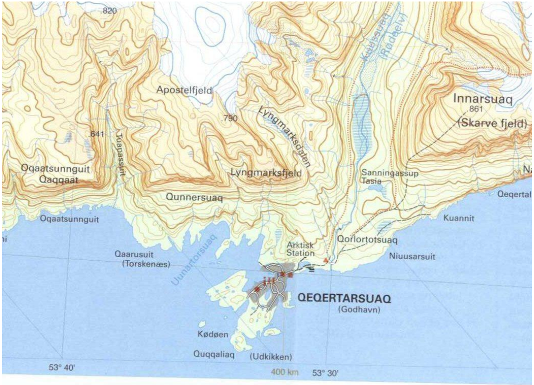
Main aspects

- GNSSR dedicated hardware receiver
- GPS L1 (1575.45 MHz) C/A code
- 10 channels compute cross-correlations (waveforms) of 64 lags every millisecond
- 50 ns lagspacing $\Rightarrow \sim$ 15 meters
- Scan the delay- and/or Doppler-space
- 3 radio front-ends
- One Up-looking antenna for reference signal (internal GPS receiver)
- Designed, manufactured, and tested at the ICE-CSIC/IEEC

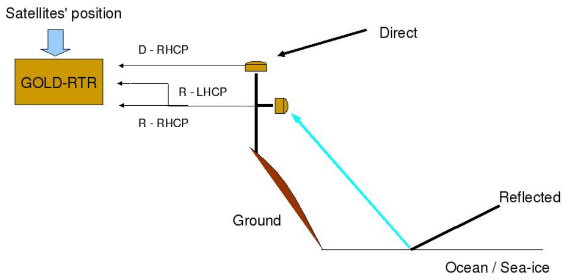
SEA ICE

Location

Godhavn (west coast in Greenland)



Basic setup


Satellites' position
GOLD-RTR
D - RHCP
R - LHCP
R - RHCP
Direct
Reflected
Ground
Ocean / Sea-ice

Main aspects

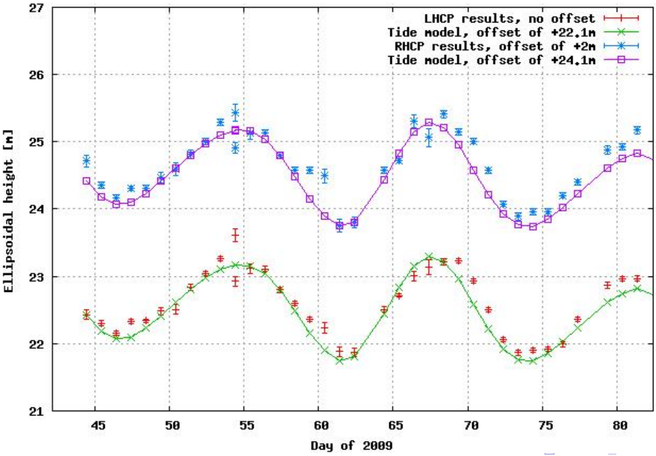
- Long term campaign: Nov 2008 $\rightarrow$ May 2009
- Formation, evolution and melting of sea ice confirmed from in situ Arctic Stations (DMI)
- Low elevation range due to coastline profile: 5 to 15 deg
- Presence of direct signal and near-multipath corrupts the shape of reflected waveforms

Observables

- Amplitude and **phase** at 1 msec during **limited** daily periods
- 1 second **non-coherent** integrated waveforms stored continuously
- Waveform shape **not used**, only values at lag from specular position

Phase altimetry with cm precision

- Agreement with AOTIM-5 and between polarizations (LHCP and RHCP)
- Potential determination of sea ice free-board level, linked to **thickness** (stage of development)

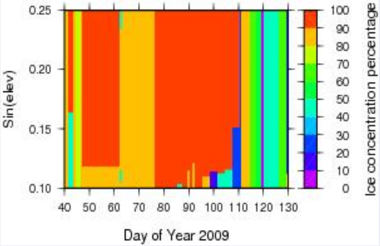


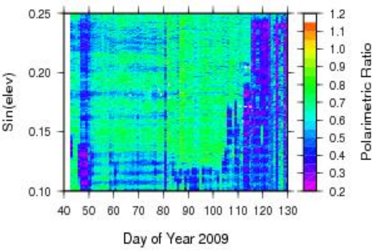
Characterization of sea ice

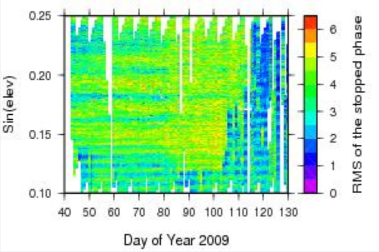
- **Polarimetric ratio** between co- and cross-polar components relates to **permittivity**
- **RMS** of the phase (coherence) relates to **roughness**

⇒ Helpful retrievals towards **sea ice classification** [Belmonte et al. 2009]

Ground-truth



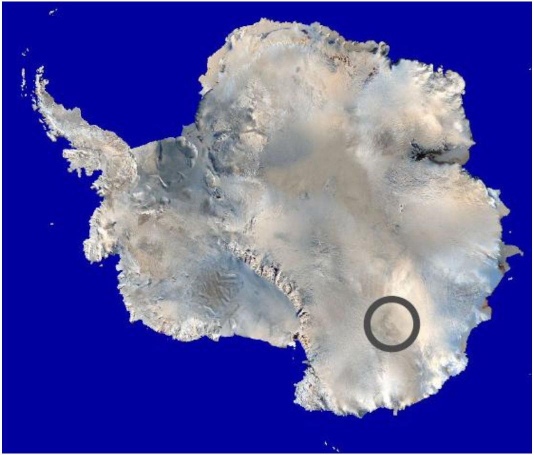




DRY SNOW

Location

Dome Concordia



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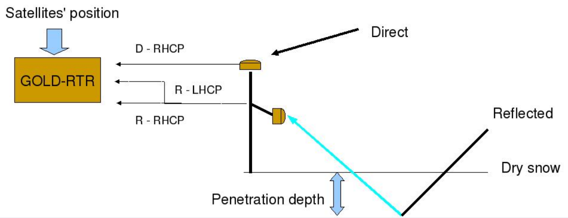
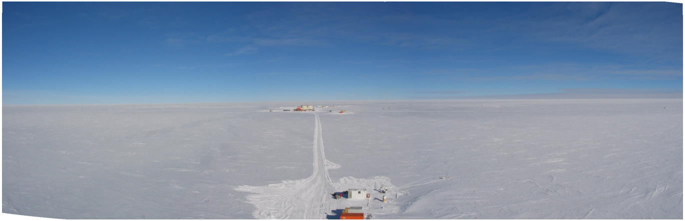

Satellites' position
GOLD-RTR
D - RHCP
R - LHCP
R - RHCP
Direct
Reflected
Dry snow
Penetration depth



Main aspects

- Shorter campaign due to **stability** (DOMEX experiment, Macelloni et al. 2005) of the dry snow cover: 10^{th} to 21^{st} January 2010
- Clean visibility, large range of elevations (5 to 65 deg) and absence of near-multipath
- Validation area for remote sensing: availability of ancillary data
- 45 m vertical distance: overlap of direct and reflected signal for several lags
- Not a single "surface": reflected signal as a contribution from different layers

Observables

- 1 msec **coherent** integrated waveforms (amplitude and phase) stored continuously
- Waveform shape **not used**, a different approach has to be followed...

Existing Model, (Wiehl et al. 2003): sub-surface contribution essentially given by volumetric scattering

- But we consider **volume scattering negligible** compared to absorption loss
- Motivation: data shows **clear interference fringes**, better explained by multiple-layer reflections

$\Rightarrow$ Need to develop our own model

Multi-layer Single-reflection model: MLSR

- Multiple infinite parallel layers
- 1 single reflection per layer is considered
- Only LHCP reflections reach the receiver

$$\rho_i = \rho_0 + \sum_{k=1}^{k=i} 2n_k \frac{H_k}{cos(\theta_k)} - (\sum_{k=1}^{k=i} D_k) sin(\theta_0)$$

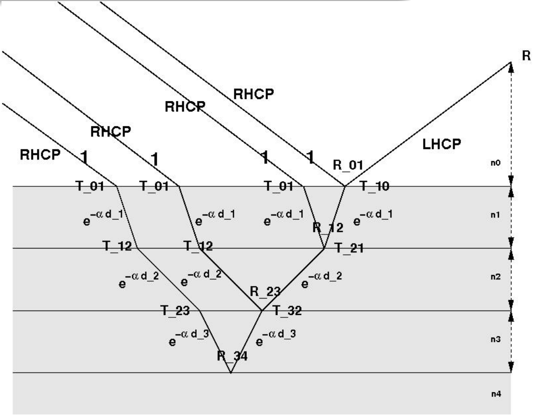
$$D_k = 2H_k tan(\theta_k)$$

$$U_k = R_{k,k+1} \Pi_{i=1}^{i=k} T_{i-1i} T_{ii-1} \exp -2\alpha d_i$$

$$T_{co} = \frac{1}{2}(T_{\parallel} + T_{\perp})$$

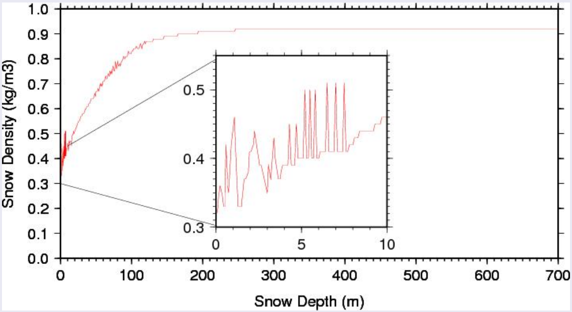
$$R_{cross} = \frac{1}{2}(R_{\parallel} - R_{\perp})$$

$$\alpha = \frac{2\pi}{\lambda} |Ima\{\sqrt{\epsilon}\}|$$



Input of the forward model (MLSR)

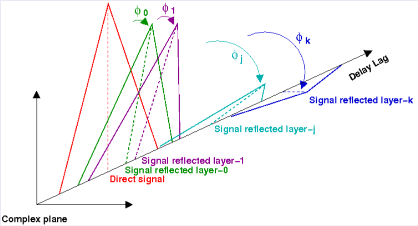
- Depths and permittivity of the dry snow layers are needed
- Retrieved from in situ measurements of snow density



Complex waveform generated

- Incident signal at surface with A=1
- Direct signal set to lag 22 (RHCP to LHCP leakage with A=0.1)
- Frequency of direct signal as a reference

Several contributions



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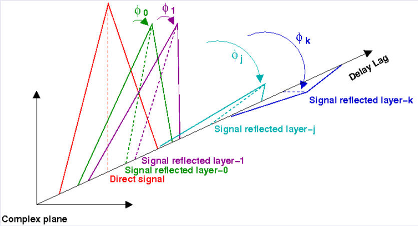
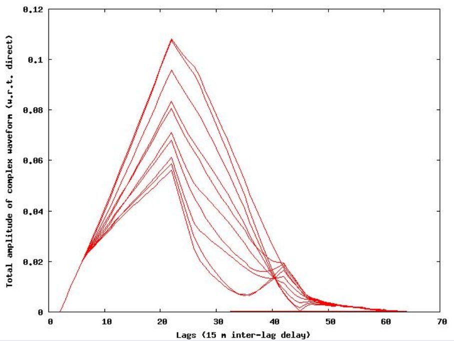
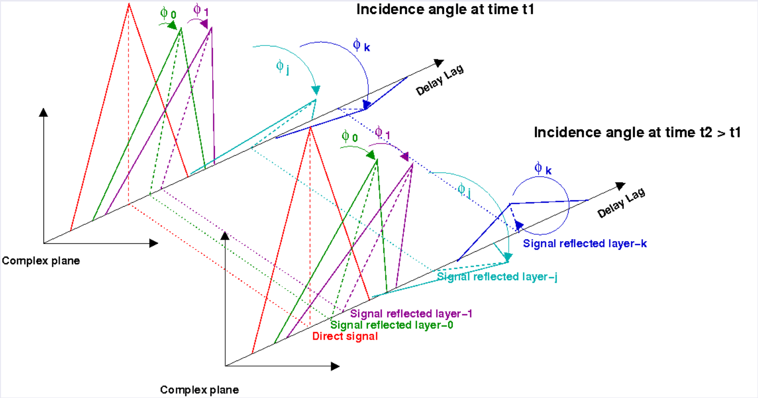


Example: elevation from 44.884 to 44.955 deg (128 samples)



Evolution of the different contributions wrt incidence angle



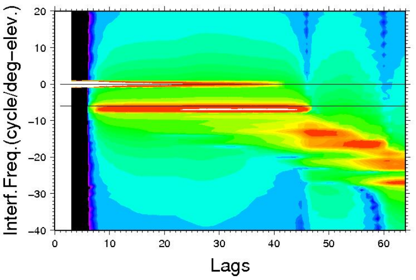
$\Rightarrow$ Interferometric frequency relates to depth of the layer

How do we retrieve information?

- FFT to each of the lag-time series → elevation domain (cycles/deg)
- Several bands of main contributions below the surface level appear, corresponding to depths with stronger gradients of snow density/permittivity

⇒ Proper **inversion** might determine **dominant layers** of L-band reflections

Lag-hologram from previous example



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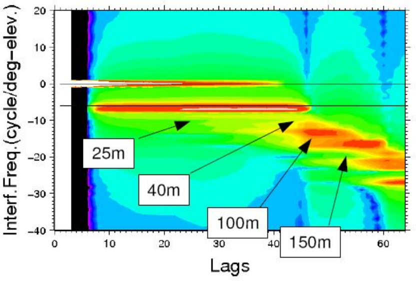
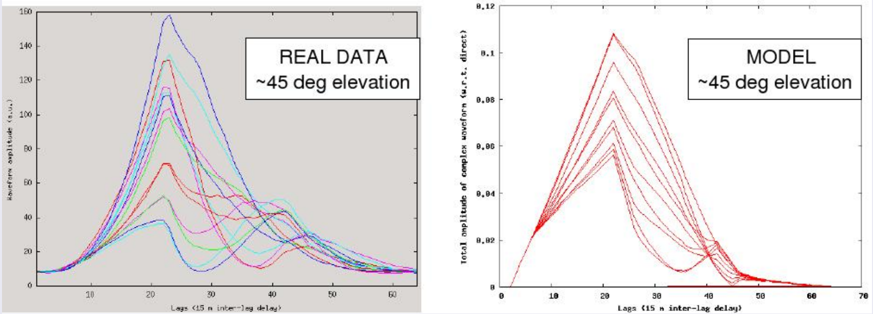


Results obtained with real data and comparison with the model



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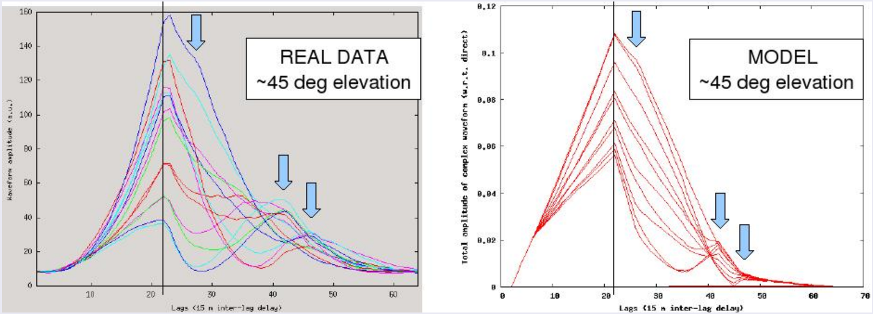
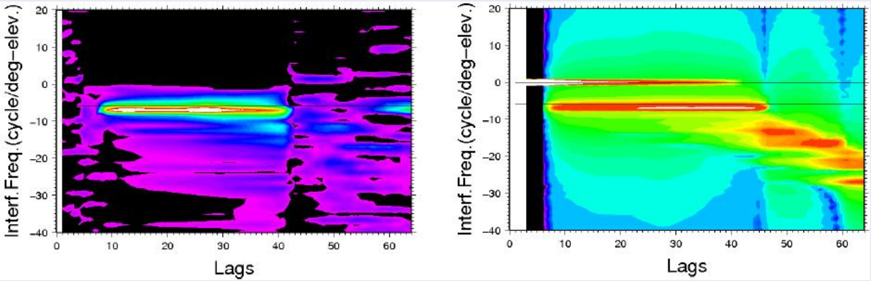


Comparison between lag-holograms



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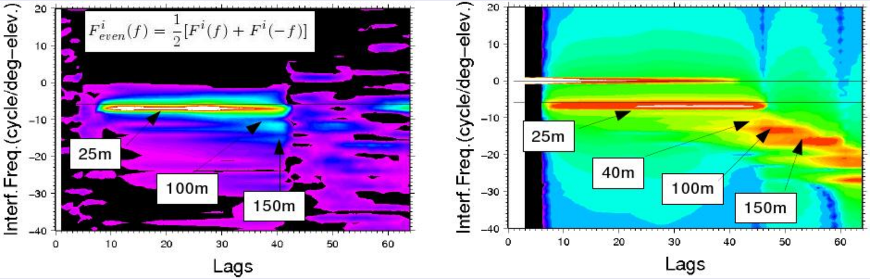


SUMMARY

SEA ICE

- Phase altimetry with cm precision at two polarizations
- ⇒ Potential determination of the ice **thickness** (related to free-board level)
- Polarimetric and RMS-phase measurements matches with ice percentage
- ⇒ **Permittivity** and **roughness** can be used for sea ice classification

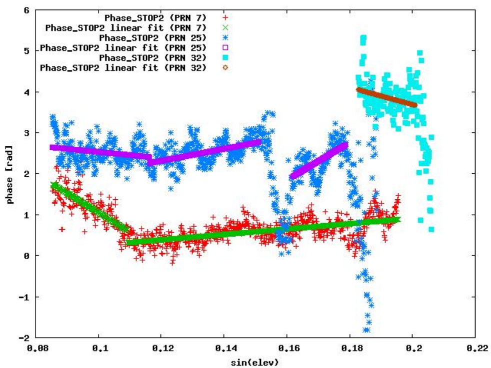
DRY SNOW

- A model with multiple layers has been tested
- Lag by lag FFT series separates information from different contributions and enables to remove other effects with symmetrical interferometric frequency
- Preliminary results show good agreement
- Proper inversion could determine **dominant layers** of the dry snow profile at L-band

Thank you for your attention

Phase Altimetry

$$H_v = \frac{1}{2}\frac{\partial \rho}{\partial \sin(e)} = \frac{m}{2}$$



Polarimetric ratio

Radar equation [Zavorotny and Voronovich, 2000]

$$\chi_{\text{scat}}(\tau_r, mss) = \iint \frac{\sigma^0(\vec{r}; \Re_{\text{RL}}, mss)\chi\left[\tau_r - \tau(\vec{r})\right]}{4\pi R^2(\vec{r})} d^2 r$$

$$\sigma^0(\vec{r}; \Re_{\text{RL}}, mss) = |\Re_{\text{RL}}|^2 \frac{(q/q_z)^4}{2\ mss} e^{-\frac{(q_\perp/q_z)^2}{2\ mss}}$$