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What do reflected GPS signals tell us about the ocean waves?
A numerical study

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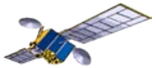
22/10/2010

Outline

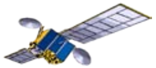


- Introduction
  - GNSS-R: Oceanography applications
  - First encouraging results

- GNSS-R Simulator
  - Motivation
  - Sea Surface Simulations
  - Scattering Model
  - Results

- Conclusions and Future Work

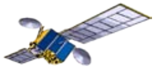
GNSS-R & Oceanography



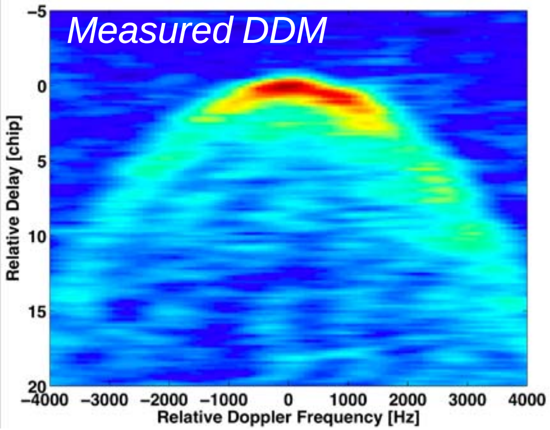
o The signal scattered from the sea surface contains primarily information on directional ocean roughness (wind and waves), but also sea surface height (altimetry).

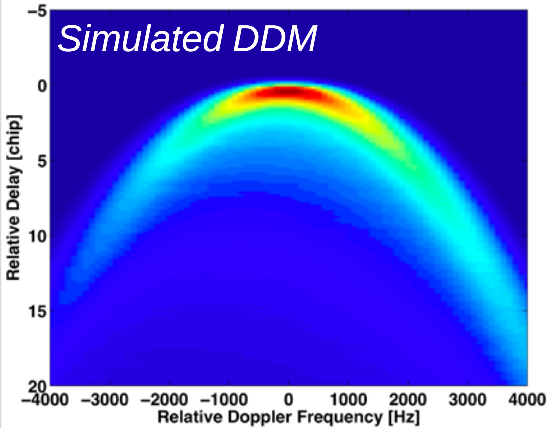
o GNSS-R can provide *high density global measurements of ocean roughness*, useful for operational oceanography, scientific purposes and supporting role for Earth Observation missions such as SMOS.

Retrieval of Ocean Roughness using GNSS-R



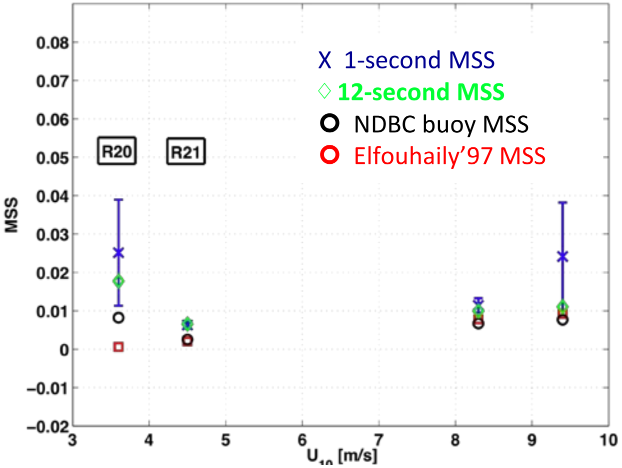
- Data were collected onboard by the UK-DMC satellite, and represented as **Delay-Doppler Maps (DDM)**, namely scattered power in the delay-Doppler frequency domain
- DDMs were simulated using a theoretical Zavorotny-Voronovich (Z-V) model, and *least-square fitted* to measured DDM to retrieve the optimal *Mean Square Slopes (MSS)* and *Surface Slope Directions*.



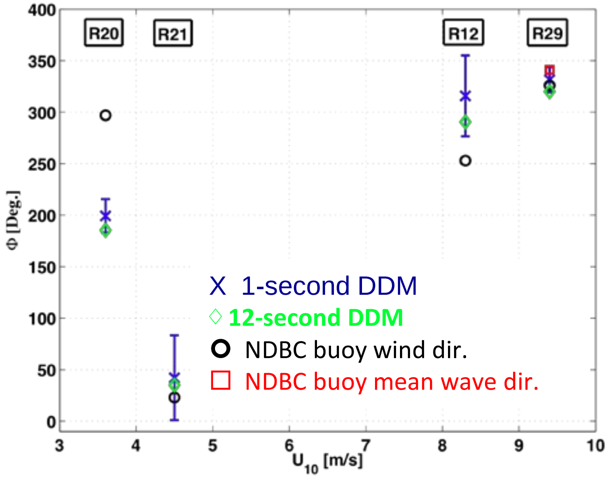


Results were validated against theoretical calculations of MSS, and in situ measurements from NDBC buoys.

Mean Square Slopes

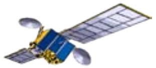


Sea Surface Slope Direction



From Clarizia et al., "*Analysis of GNSS-R delay-Doppler Maps from the UK-DMC Satellite over the Ocean*", Geophys. Res. Let., 2009.

GNSS-R Simulator: Motivation



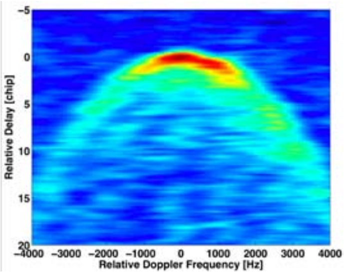
- Surface Roughness can be successfully retrieved from GNSS-R data at spaceborne

- There are some **differences** between measured and simulated DDM, probably linked to the Z-V model, which:

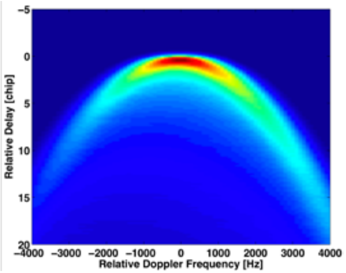
    1. Uses the Geometrical Optics (GO) limit for the scattering
    2. Describes the sea surface through a gaussian Probability Density Function (PDF) of the slopes
    3. Does not account for Polarization

Solution: end-to end simulator of the GPS signal scattering from realistic sea surfaces

DATA



MODEL



Explicit Simulations of sea surfaces

Improved Scattering Model

Delay-Doppler Processing of the scattered GPS signal

- **Wind Wave Surfaces**
- **Wind Waves+Swell**

- Scattering calculated using **a model different from GO**
- Vector formulation, to explore **polarization**

Simulation of Wind Wave Surfaces

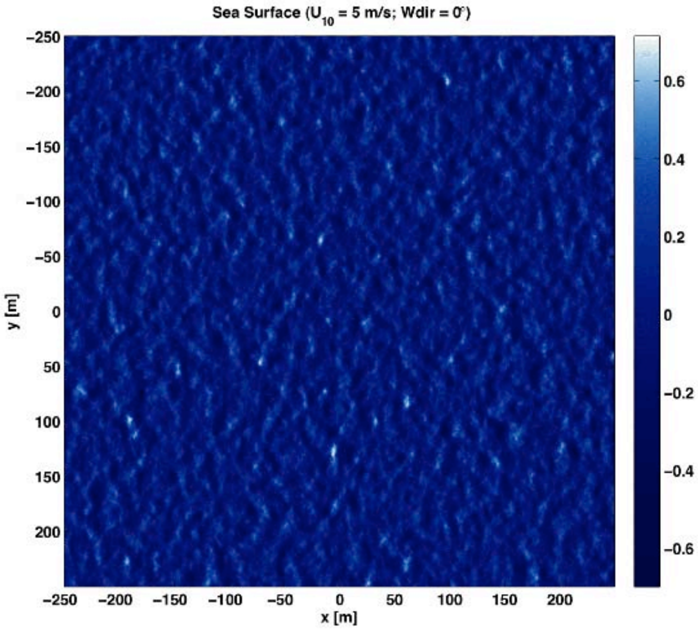
Method: a Gaussian white noise is filtered with a surface wave spectrum, function of **wind speed** and **wind direction**

- In our case, we use the Elfouhaily et al. 1997 spectrum.

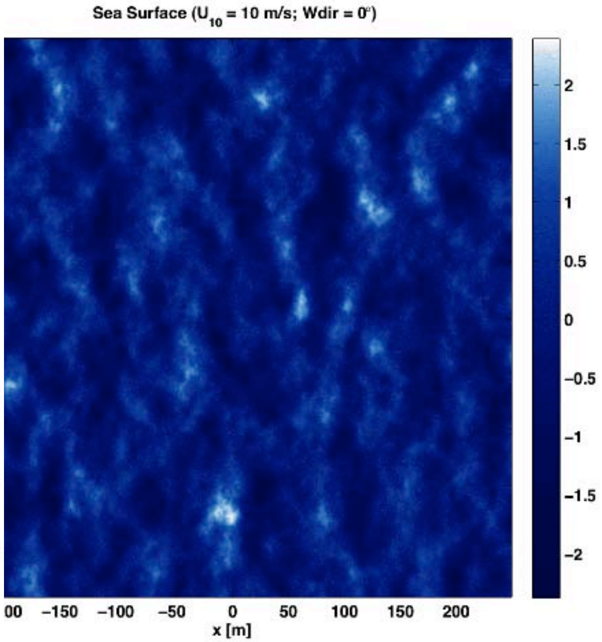
A **wavenumber cutoff** has been defined and only the part of the spectrum up to the cut-off has been used for the filtering, in order to simulate only the large-scale components

- In our case, the cutoff is $5\lambda_{GPS}$ (λ_{GPS} = 19 cm).

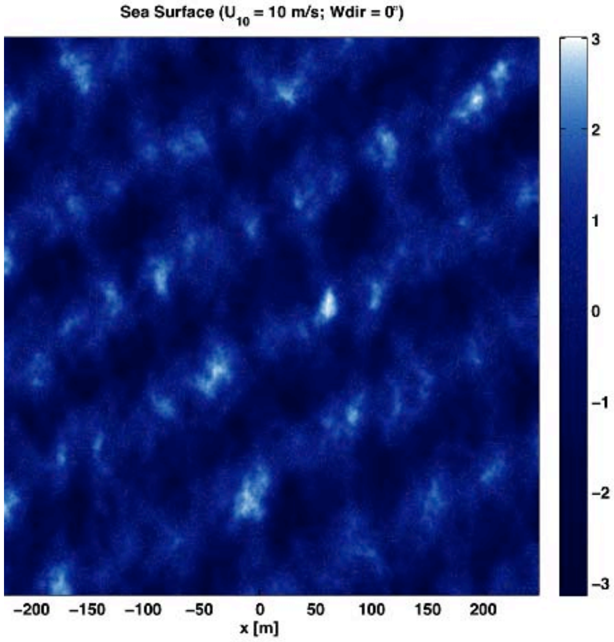
Wind Sea (U_{10} = 5 m/s)



Wind Sea (U_{10} = 10 m/s)



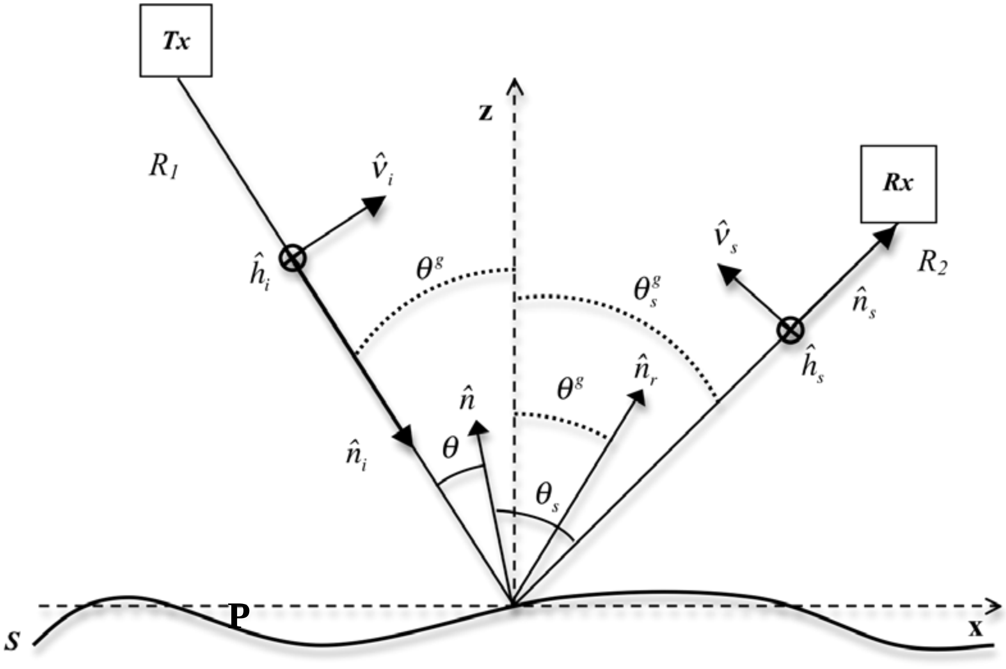
Wind Sea + Swell



Electromagnetic Scattering: Kirchhoff Approximation

Kirchhoff Approximation (KA) or Physical Optics (PO) describes the scattering from the **Large-Scale surface components** (Radius of curvature > λ_{GPS} (19 cm))
The Incident Radiation is **a Right-Hand Circularly Polarized (RHCP) spherical wave E_i**

$$\boldsymbol{E}_i = \hat{a}E_0 \frac{\exp\left(-jk_0R_1\right)}{4\pi R_1}\exp(-jk_0\hat{n}_i \cdot \boldsymbol{r})$$



EQUATION FOR THE SCATTERED ELECTRIC FIELD

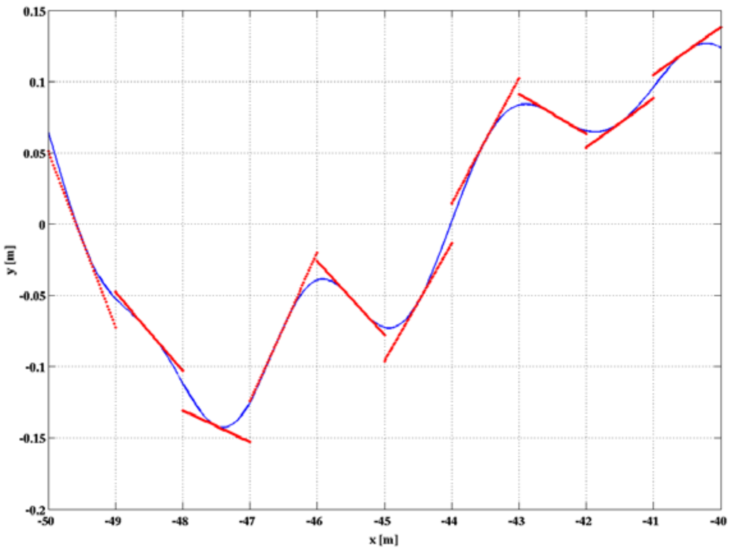
From Ulaby, Moore and Fung, *Microwave Remote Sensing, Active and Passive, Vol. II, Artech House, Inc., 1986*

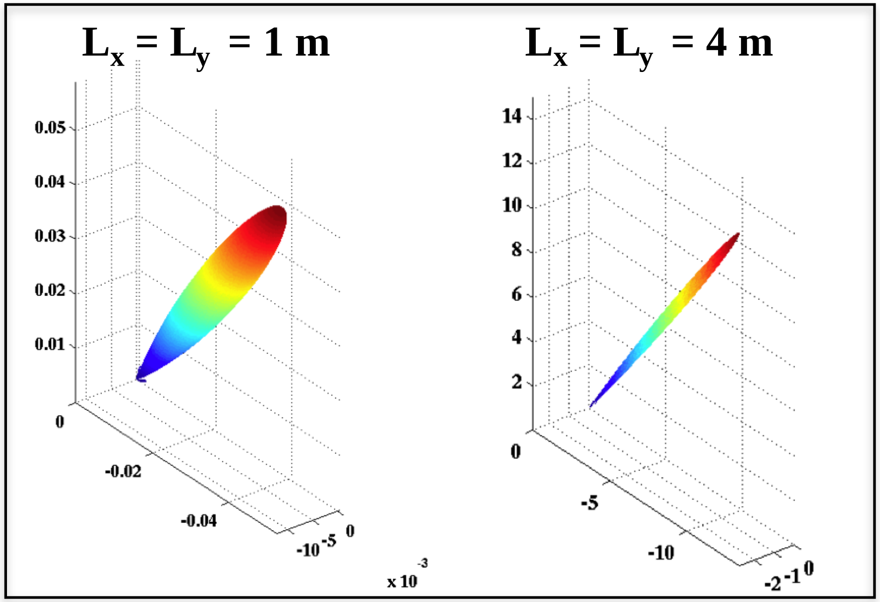
$$\boldsymbol{E}_s = -jk_0 \frac{exp\left[-jk_0\left(R_1+R_2\right)\right]}{\left(4\pi\right)^2 R_1R_2}\hat{n}_s \times \iint \boldsymbol{p} \cdot \; exp\left[j\left(\hat{n}_s - \hat{n}_i\right)\cdot \boldsymbol{r}\right]dS$$

where $\boldsymbol{p} = \hat{n}\times\boldsymbol{E} - \eta_s\hat{n}_s\times(\hat{n}\times\boldsymbol{H})$

- The KA allows to write the scattered electric and magnetic fields ***E*** and ***H*** on the surface *S* explicitly, but we are still left with an integral that must be solved numerically…..

Facet Approach (FA) to the Kirchhoff Approximation





$L_x = L_y = 1$ m

$L_x = L_y = 4$ m

- …however, if we approximate the sea surface as an ensemble of *n* facets, the integral can be solved easily

$$\boldsymbol{E}_s = \sum_{k=1}^{n} \boldsymbol{E}_s^k \qquad \boldsymbol{E}_s^k = K\sqrt{1+\alpha_k^2+\beta_k^2}\, e^{-jq\cdot r_k} L_x L_y\, sinc\left[\left(q_x + q_z\alpha_k\right)L_x/2\right] sinc\left[\left(q_y + q_z\beta_k\right)L_y/2\right] \boldsymbol{p}_k$$

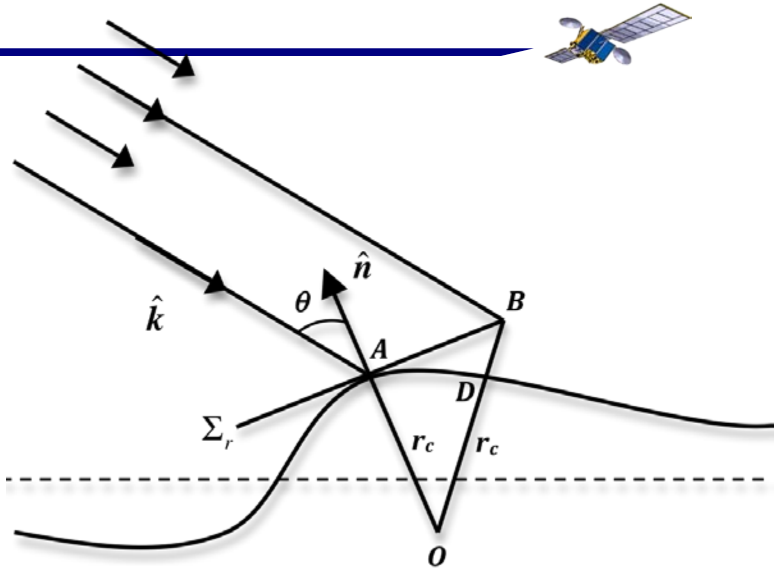
- In essence, each facet behaves like a radiating antenna, and the width of the radiating lobe depends on the size of the facet (L_x and L_y)

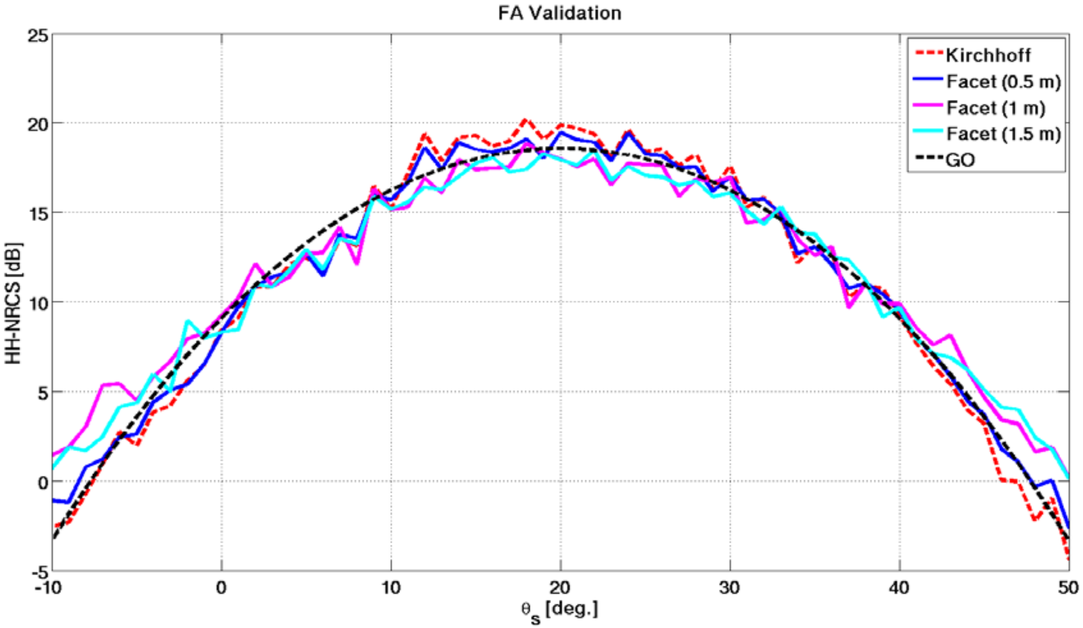
Facet Approach (FA) to the Kirchhoff Approximation (2)

- The choice of the facet size is governed by specific criteria

$$AB \gg \frac{1}{k_0 \cos(\theta)}$$

$$BD \ll \frac{k_0}{\cos(\theta)} \quad \Rightarrow \quad AB \ll \sqrt{\left[\frac{\cos(\theta)}{k_0}\right]^2 + 2\frac{r_c \cos(\theta)}{k_0}}$$





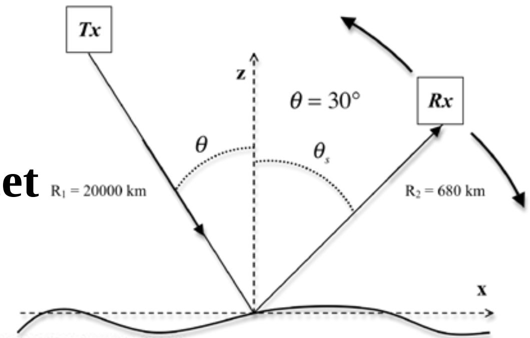
The FA is:

1) **Close to the full KA**, but it's **computationally faster** than the standard numerical integration of the Kirchhoff integral

2**) More flexible than GO**, as it is based on scattering calculation from **explicit surfaces**

Results: Normalized Radar Cross Section (NRCS)

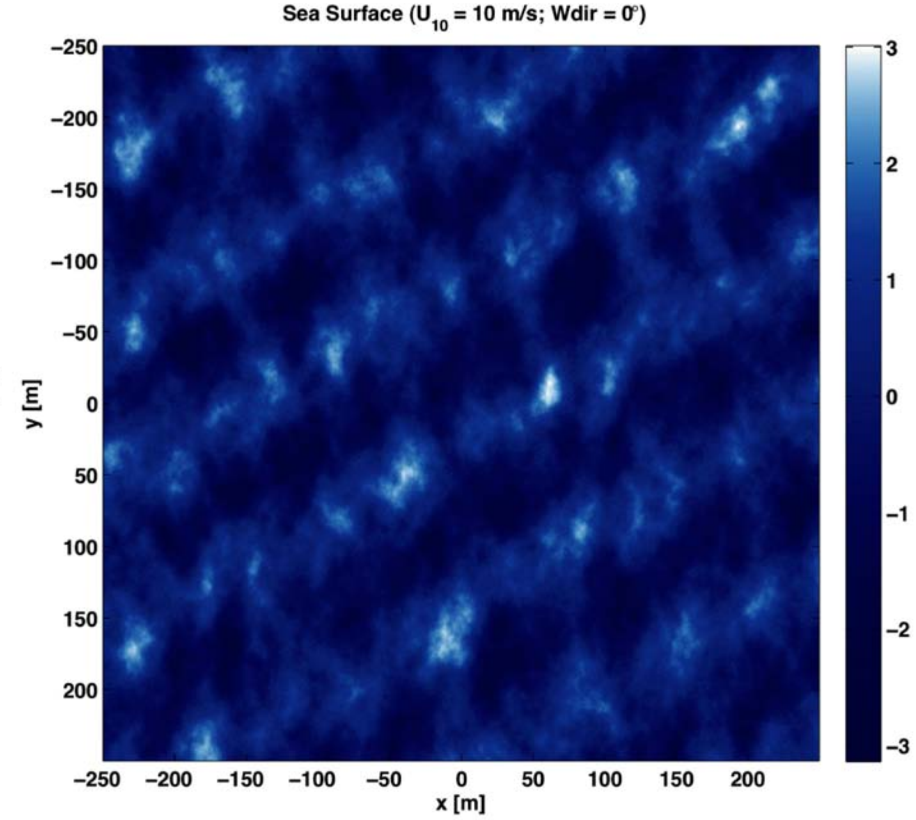
Spaceborne Config.

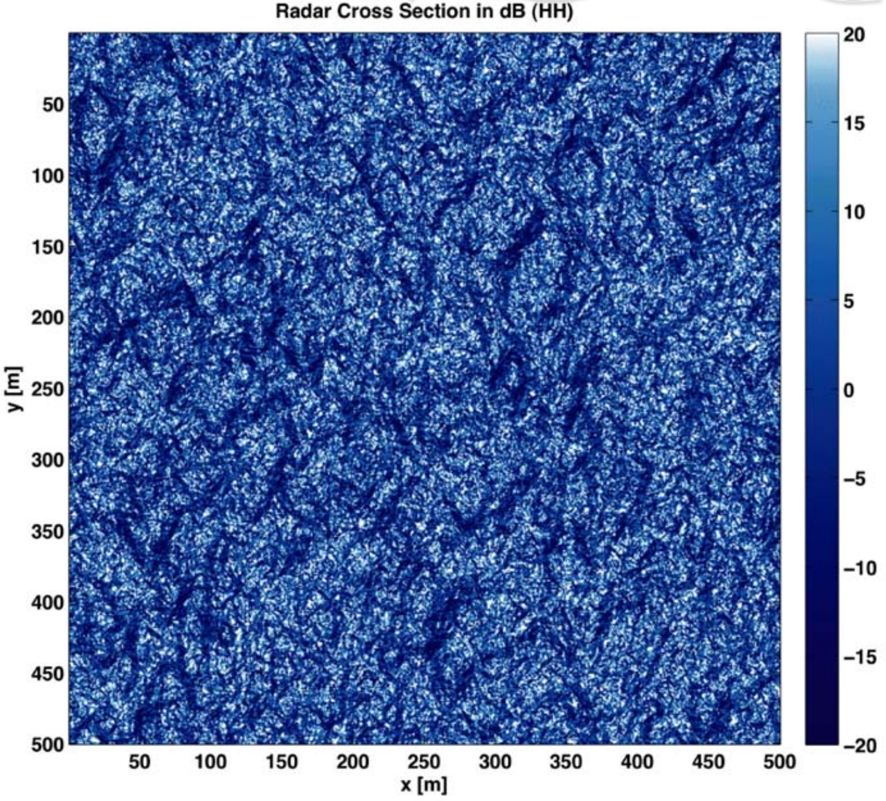


Defined in the bistatic case as: $\sigma_0^{pq} = \dfrac{4\pi R_2^2 \left|\boldsymbol{E}_s^{pq}\right|^2}{S\left|\boldsymbol{E}_i^{p}\right|^2}$

Here we look at spatial maps, showing the scattering for each facet

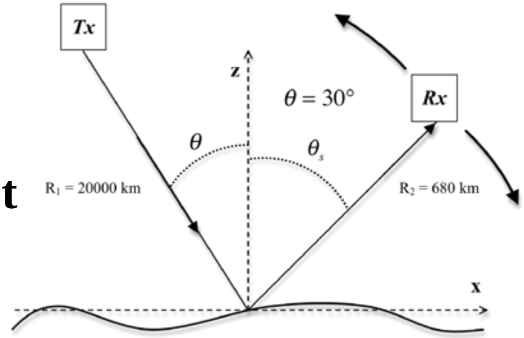
Wind Sea + Swell





Results: Polarization Ratio (PR)

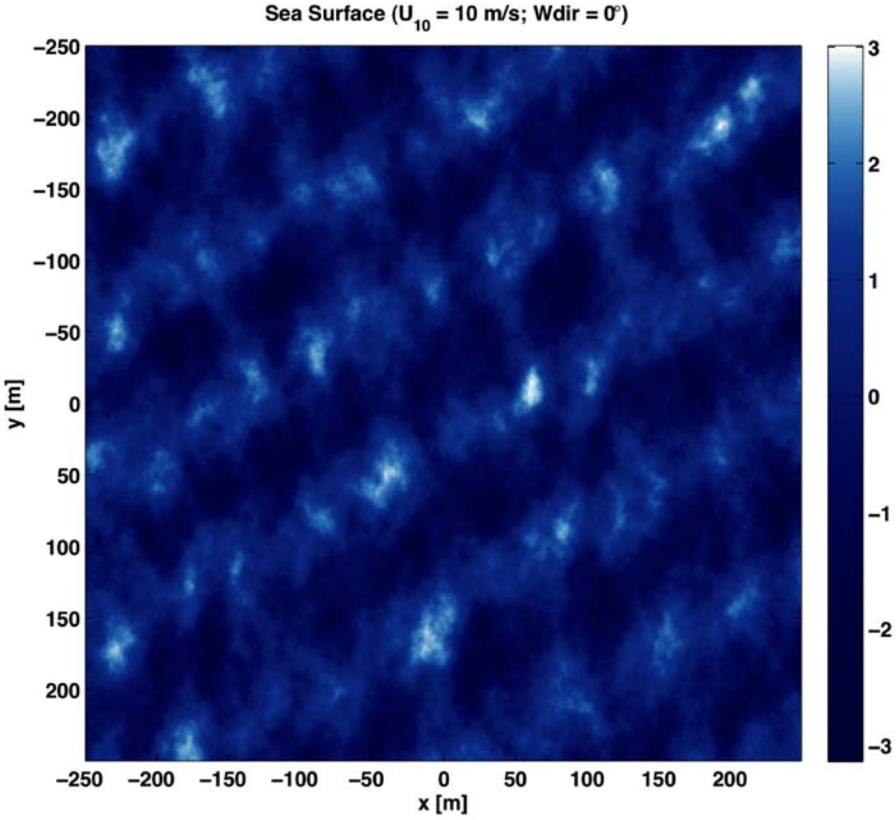
Spaceborne Config.

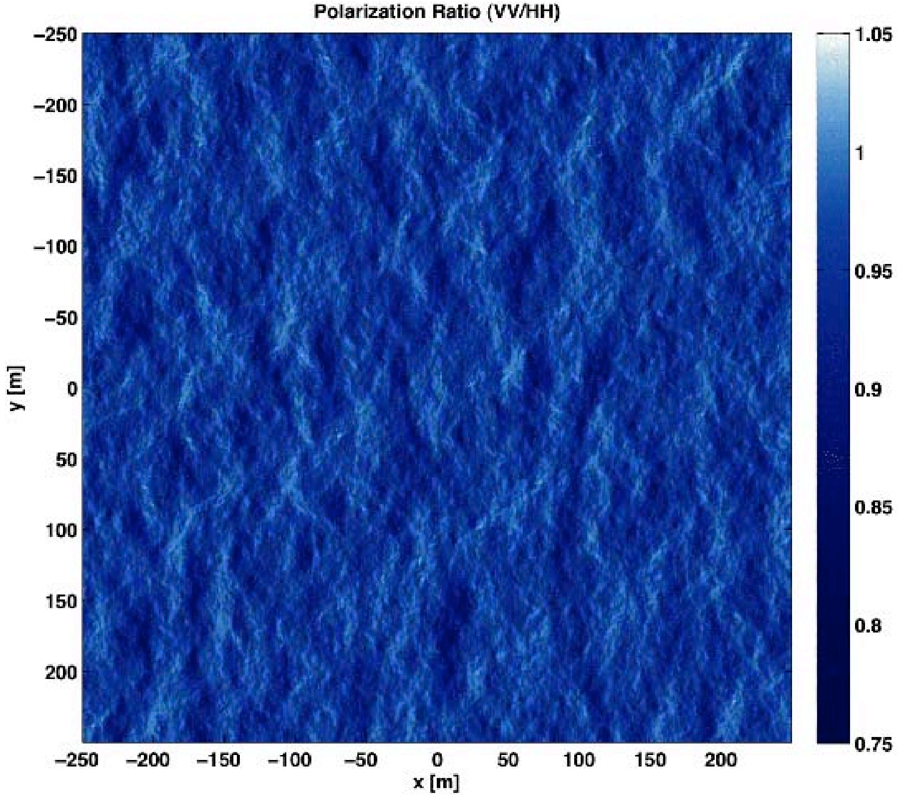


Defined as: $PR = \dfrac{\sigma_0^{VV}}{\sigma_0^{HH}}$

Here we look at spatial maps, showing the scattering for each facet

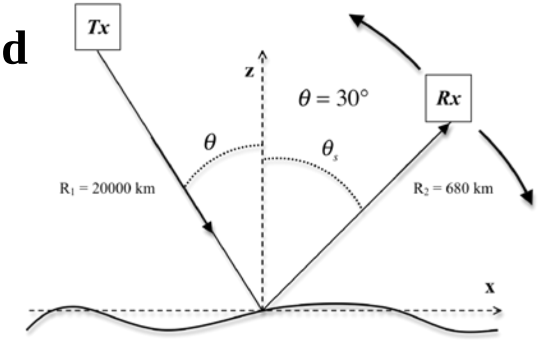
Wind Sea + Swell





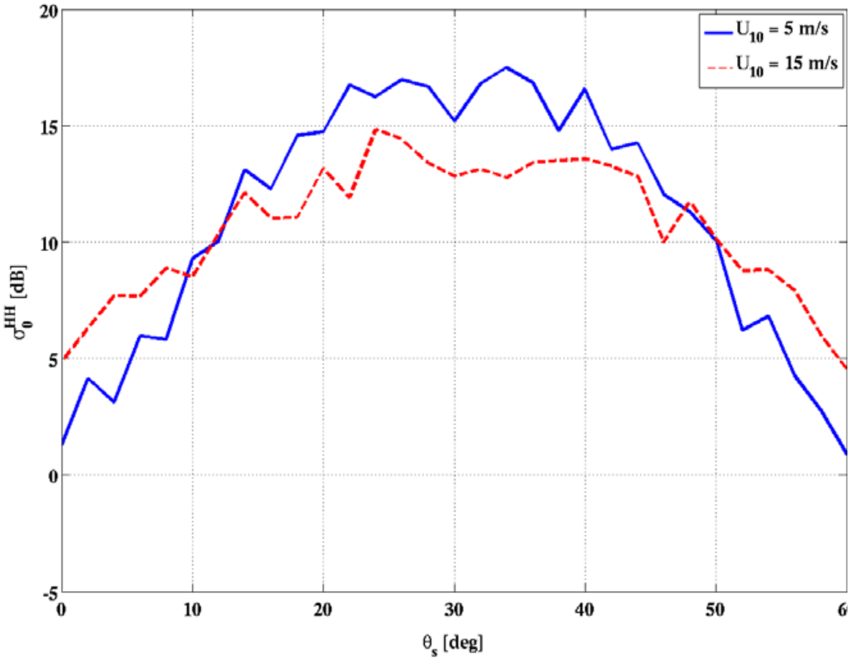
Results: NRCS and PR with varying θ_s

Spaceborne Config.

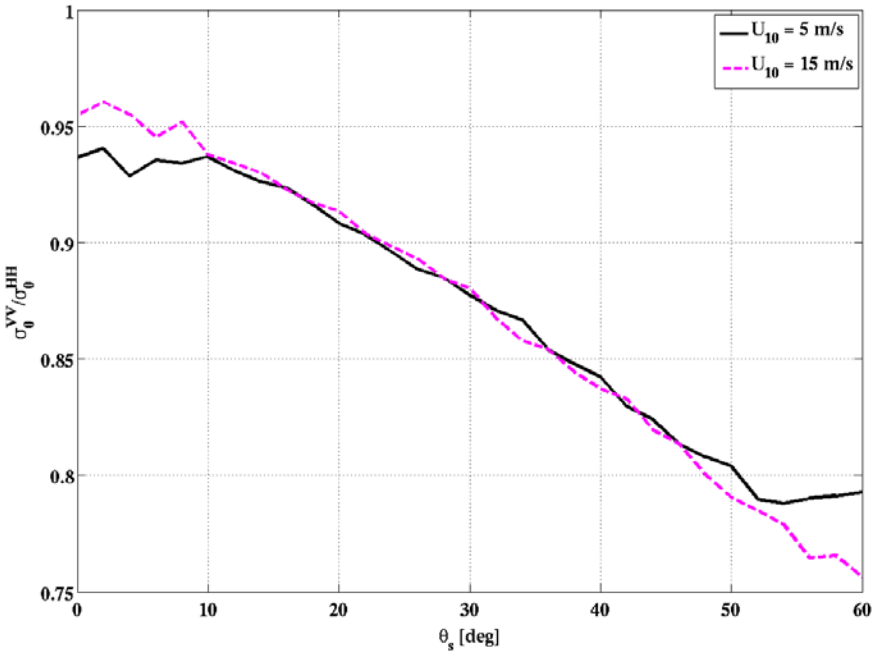


Here we look at the scattering from the whole surface, calculated as the summation of the contributions from all the facets, with varying elevation of the receiver (θ_s)

NRCS



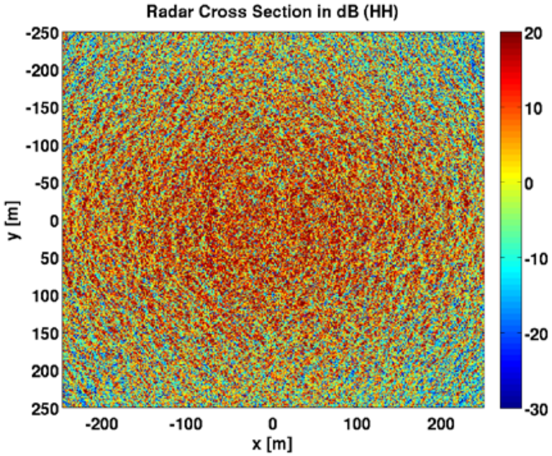
PR

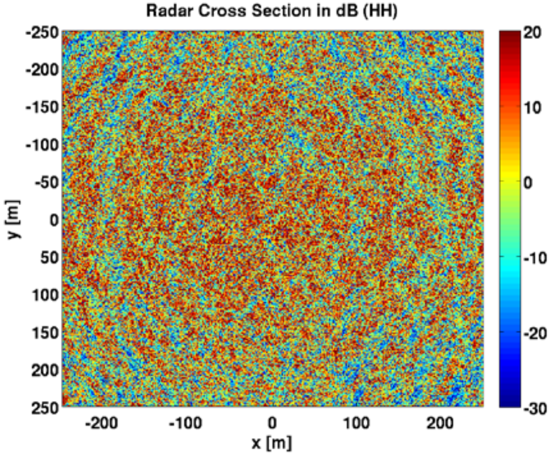


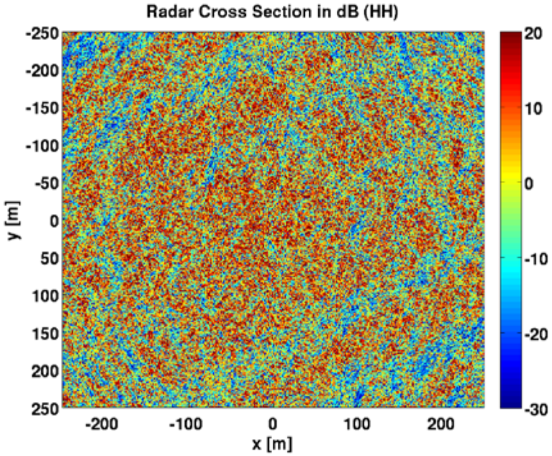
Examples of Delay-Doppler Mapping of NRCS

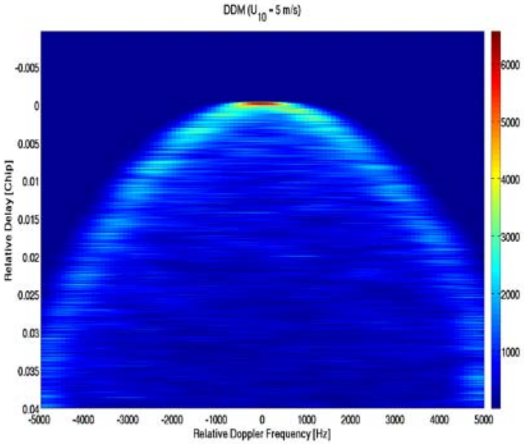
Tx and Rx are in an airborne configuration

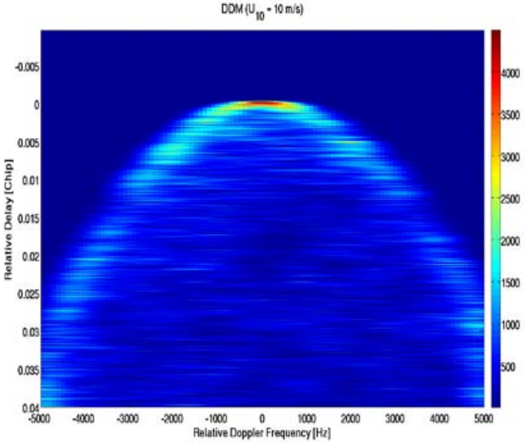
Tx and Rx velocities are test velocities taken from a GPS satellite and the UK-DMC satellite

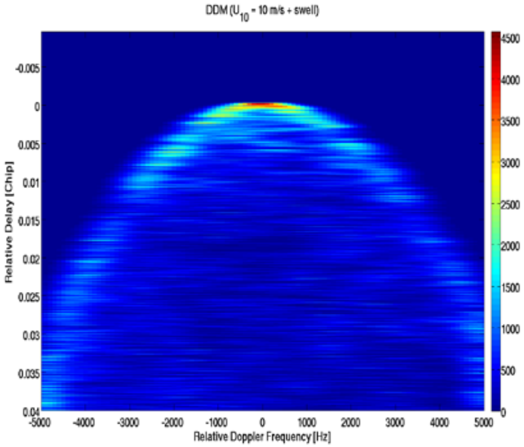




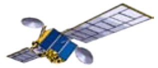








Conclusions



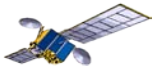
- The scattering of signals at L-band has been simulated using **explicit realization of wind wave surfaces with or w/o swell**, and **an improved facet-based implementation of the KA**

- The results expressed as NRCS and PR, and as spatial distributions of the scattered power show **some dependence upon the roughness of the sea surface (wind speed) and directionality of the waves (presence of a swell)**.

- Variations of NRCS for the whole surface with respect to the wind speed are consistent with what we would expect from physical arguments. Instead, they do not appear very significant for PR.

- A simple DD mapping of the NRCS is already able to show patterns more similar to real data. Sensitivity of these DDMs with respect to sea state still needs to be investigated.

Future Work



Completion of the GPS Scattering Simulator

- The scattering model will be completed by adding the small-scale contribution, and the two contributions will be combined

- The full scattering model will be tested over both linear and non-linear sea surfaces
  - Do non-linearities of the sea surface have a distinctive signature in the scattering?

- An improved Delay-Doppler processing of the scattered GPS signal will be implemented

Testing and Validation of the Simulator

- Analysis of the sensitivity of the simulated DDMs with respect to different wind/wave conditions
- Comparison of simulated DDMs with DDMs from real data