FROM DELAY-DOPPLER MAP TO OCEAN SURFACE MAPPING

E. Valencia, A. Camps, N. Rodríguez-Álvarez,

I. Ramos-Perez, X. Bosch-Lluis, H. Park

Remote Sensing Lab, Dept. Teoria del Senyal i Comunicacions,

Universitat Politècnica de Catalunya

and IEEC-CRAE/UPC

Tel. +34 93 405 46 64, E-08034 Barcelona, Spain.

E-mail: valencia@tsc.upc.edu

Departament de Teoria del Senyal i Comunicacions
UNIVERSITAT POLITÈCNICA DE CATALUNYA

0. Outline

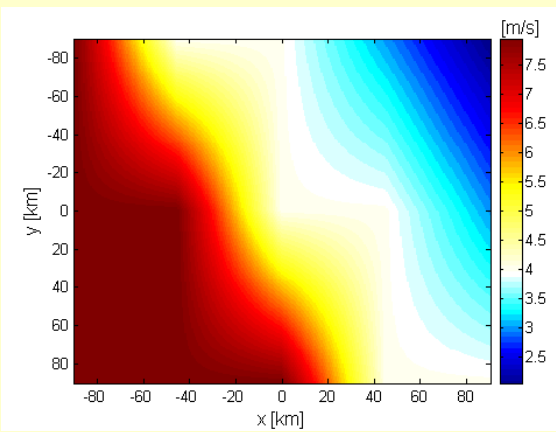
1. Introduction (1/3)

- GNSS-R has stood as a powerful remote sensing technique.
- In ocean applications, proposed to retrieve sea surface roughness (scatterometry).
- Current approaches use the delay waveform or the DDM:
    - Fit a model tuned by the desired parameter.
    - Use an empirical direct relationship among the desired parameter and a GNSS-R observable (e.g. scatterometric delay or volume of the normalized DDM).
- These approaches retrieve a single roughness descriptor for the whole glistening zone (averaged retrieval).

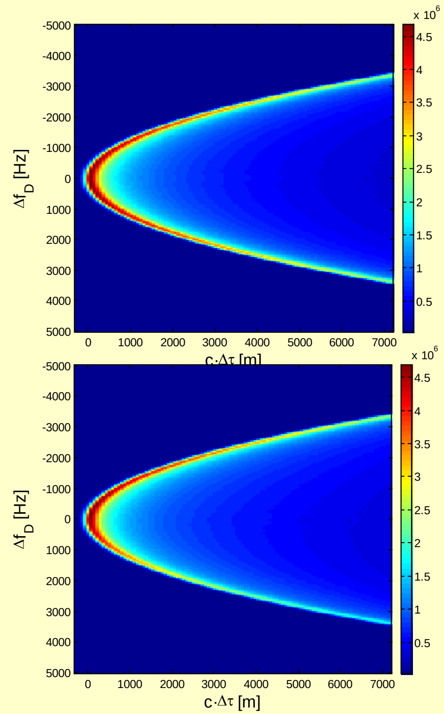
1. Introduction (2/3)

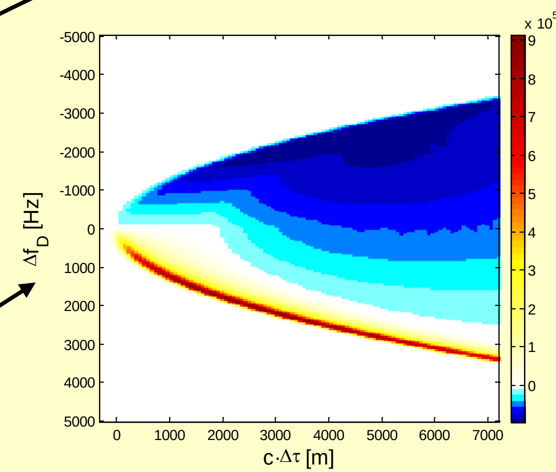
- Glistening zone size ≈ hundred of km from a LEO.
- Roughness may not be homogeneous within glistening zone.
- Example:

DDM computed considering homogeneous 4 m/s WS



WS distribution over the surface under observation





Non-homogeneities observable in the resulting DDM

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1. Introduction (3/3)

- DDM can be regarded as a blurred image of the scattering coefficient distribution in the Delay-Doppler (DD) domain.

↓

- Proposal:

"Use the Delay-Doppler Map to retrieve the scattering coefficient distribution over the observed surface"

- A method to retrieve σ^0 from measured DDMs is presented and evaluated.

2. Theoretical background (1/2)

- Power DDM is expressed by (integral over the *xy* domain):

$$\left\langle \left| Y(\Delta\tau, \Delta f_D) \right|^2 \right\rangle = T^2_i \iint D^2\left(\vec{r}\right) \chi^2 \left[\Delta\tau\left(\vec{r}\right), \Delta f_D\left(\vec{r}\right) \right] g^2\left(\vec{r}\right) d^2\vec{r}$$

- Re-writable as 2D convolution:

$$\left\langle \left| Y(\Delta\tau, \Delta f_D) \right|^2 \right\rangle = \chi^2\left(\Delta\tau, \Delta f_D\right) ** \Sigma\left(\Delta\tau, \Delta f_D\right)$$

- The autocorrelation function of the PRN code convolves with a function that describes the geometry and the surface properties:

$$\Sigma\left(\Delta\tau, \Delta f_D\right) = T_i^2 \iint \frac{D^2\left(\vec{r}\right)\sigma^0\left(\vec{r}\right)}{4\pi R_0^2\left(\vec{r}\right) R^2\left(\vec{r}\right)} \delta(\Delta\tau)\delta(\Delta f_D) d^2\vec{r}$$

2. Theoretical background (2/2)

- Change of variables $(x,y) \longrightarrow (\Delta\tau,\Delta f_D)$:

$$d^2\vec{r} = \left|J\left(\Delta\tau,\Delta f_D\right)\right| \cdot d(\Delta\tau) \cdot d(\Delta f_D)$$

- 2D integral is avoided:

$$\Sigma\left(\Delta\tau,\Delta f_D\right) = T_i^2 \frac{D^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)\sigma^0\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)}{4\pi R_0^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)R^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)}\left|J\left(\Delta\tau,\Delta f_D\right)\right|$$

- DDM expressed as the 2D convolution of the WAF with a simple function (computationally inexpensive):

$$\left\langle\left|Y(\Delta\tau,\Delta f_D)\right|^2\right\rangle = \chi^2\left(\Delta\tau,\Delta f_D\right) ** \left[T_i^2 \frac{D^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)\sigma^0\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)}{4\pi R_0^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)R^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)}\left|J\left(\Delta\tau,\Delta f_D\right)\right|\right]$$

3. Scattering coefficient distribution retrieval (1/3)

- The first step to retrieve σ^0 is to remove the WAF effects on the measured DDM by deconvolution (conceptually):

$$\mathscr{F}\left[\tilde{\Sigma}(\Delta\tau,\Delta f_D)\right]=\frac{\mathscr{F}\left[\left\langle\left|Y(\Delta\tau,\Delta f_D)\right|^2\right\rangle\Big|_{measured}\right]}{\mathscr{F}\left[\chi^2(\Delta\tau,\Delta f_D)\right]}$$

- Inverse filter not suitable due to noise amplification effects.

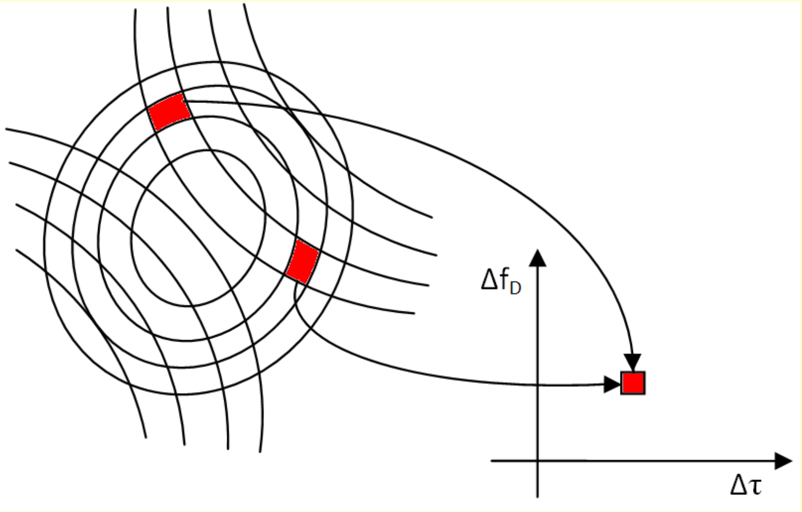
- Many deconvolution methods available in the image processing literature.

- Deconvolution is the key step of the proposed method.

3. Scattering coefficient distribution retrieval (2/3)

- After deconvolution, the scattering coefficient distribution can be retrieved from Σ by simple operations using known terms.
- However, 2 *xy* coordinates contribute to each DD point.

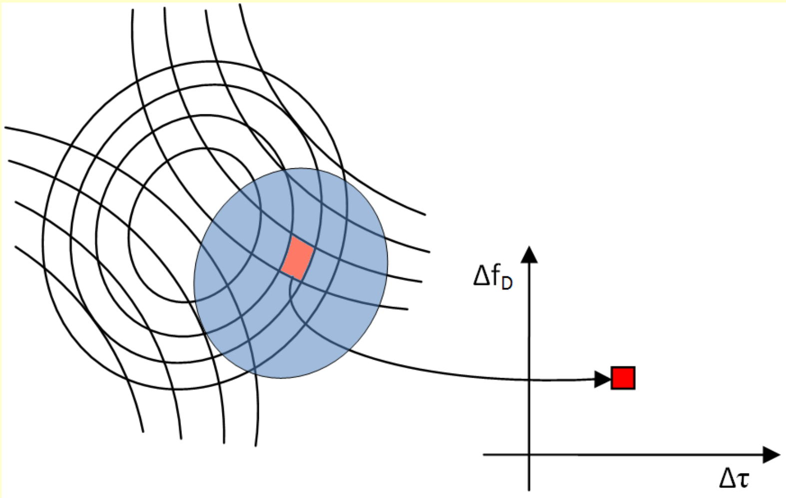
→ 2 ambiguous spatial regions.



- Function Σ is a linear combination of both regions' contributions.
- Each region has an associated Jacobian function: J_1 and J_2.
- Ambiguity has to be resolved, presented approach based on the measurement setup.
- Other approaches are possible to resolve the ambiguity.

3. Scattering coefficient distribution retrieval (3/3)

- Spatial filtering of only one of the ambiguous zones is proposed by antenna beam pointing away from the specular point .
  → SAR-like setup.
- A beam-forming system is needed
  → planned in future missions (PARIS-IoD).
- Using this spatial filtering scheme, Σ is only contributed by a single space region with an associated Jacobian.



- At this point σ^0 in the DD domain can be derived:

$$\tilde{\sigma}^0\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)=\frac{\tilde{\Sigma}\left(\Delta\tau,\Delta f_D\right)}{\left|J\left(\Delta\tau,\Delta f_D\right)\right|}\frac{1}{T_i^2}\frac{4\pi R_0^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)R^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)}{D^2\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)}$$

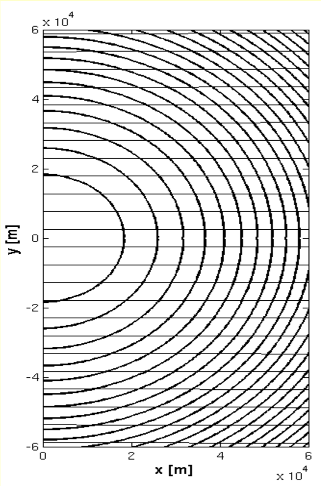
- The final distribution over the *xy* surface domain is obtained by direct coordinates correspondence:

$$\tilde{\sigma}^0\left(\vec{r}\left(\Delta\tau,\Delta f_D\right)\right)\rightarrow\tilde{\sigma}^0\left(\vec{r}\right)$$

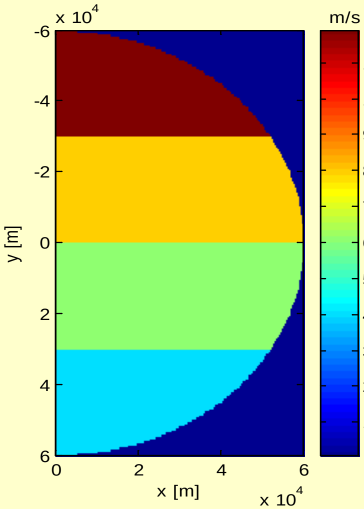
4. Method evaluation (1/4)

- A first evaluation of the method has been performed by setting a LEO receiver simple scenario (without loss of generality).
- Hardware effects not considered and D = 1 within the region of interest an 0 outside.

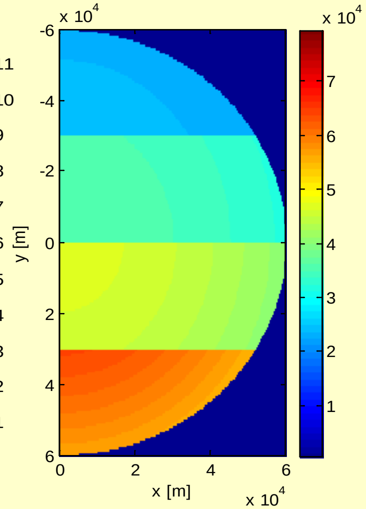
Receiver height	700 km
Receiver velocity (Vty)	5000 m/s
Transmitter velocity (Vty)	3000 m/s
Elevation angle	90º (nadir reflection)
Observation surface x direction	[0 60] km
Observation surface y direction	[-60 60] km
Maximum considered delay (Δτ)	10 chips (C/A code)
Maximum considered Doppler shift (ΔfD)	[-2500 2500] Hz
Coherent/incoherent integration times	10 ms / 1 s



Iso-range and iso-Doppler lines



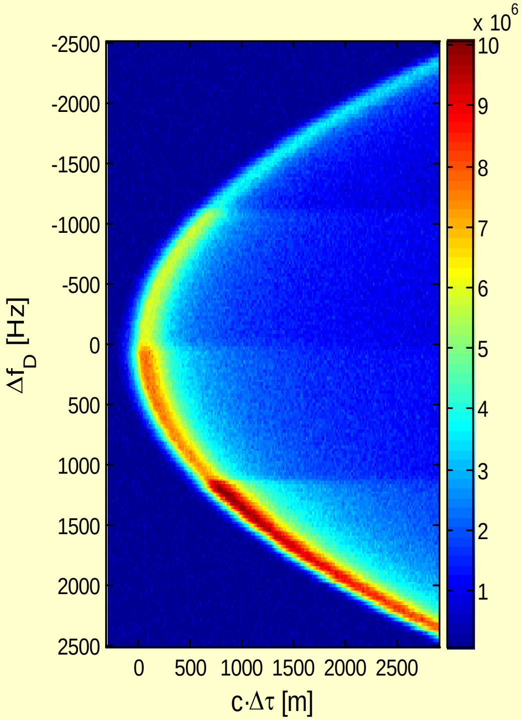
WS distribution over the surface

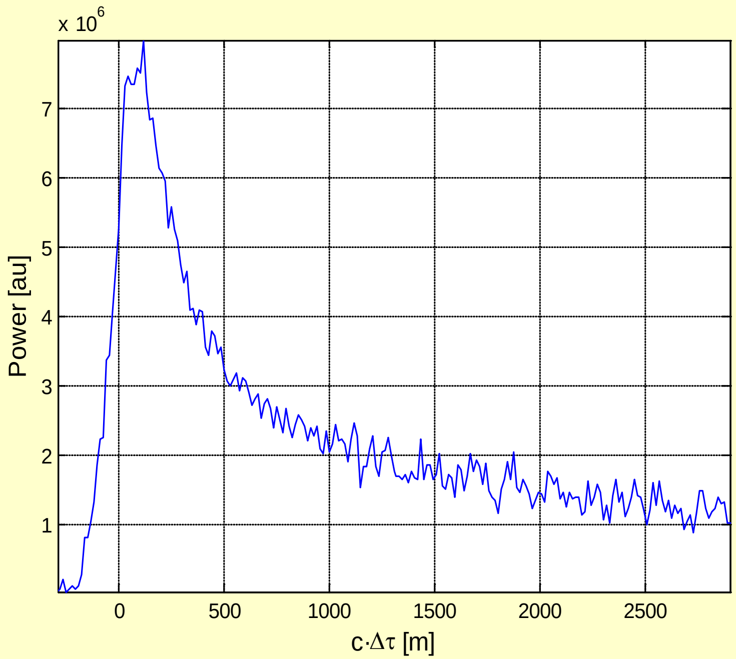


Corresponding σ^0 distribution (Z-V model)

4. Method evaluation (2/4)

- With the defined scenario and scattering coefficient distribution, a reference DDM_{xy} has been computed by the classical double integration over the surface *xy* domain.
- To further validate the method, noise has been added with a SNR similar to that of available space measurements (UK-DMC).





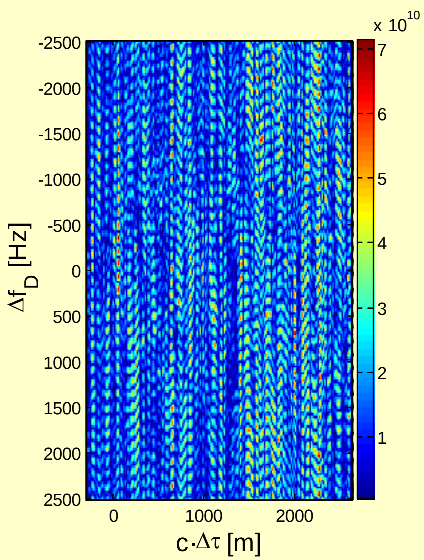
Obtained waveform similar in noise terms to the ones presented in TGARS Gleason et al. 2005.

4. Method evaluation (3/4)

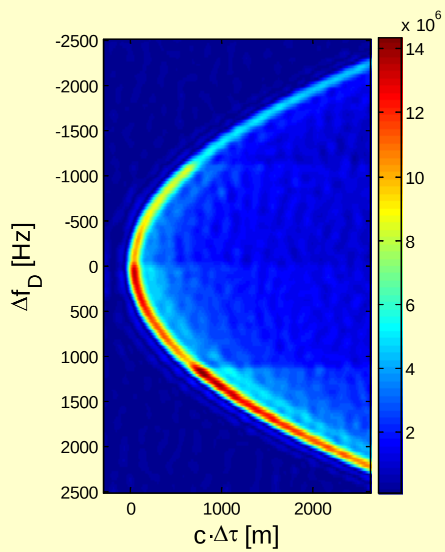
- A CLS frequency-based method has been used for deconvolution:

$$\mathscr{F}\left[\tilde{\Sigma}(\Delta\tau, \Delta f_D)\right] = K_{cls} \cdot \mathscr{F}\left[DDM_{xy}\right] \qquad K_{cls} = \frac{\mathscr{F}[\chi^2]^*}{\left|\mathscr{F}[\chi^2]\right|^2 + \gamma P}$$

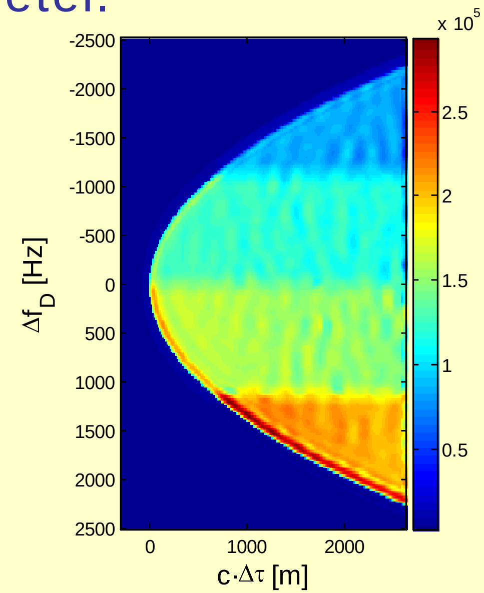
- P : Fourier transform of the smoothing criterion function.
- Trade-off definition/noise by tuning the γ parameter.



$\gamma = 0$, inverse filter



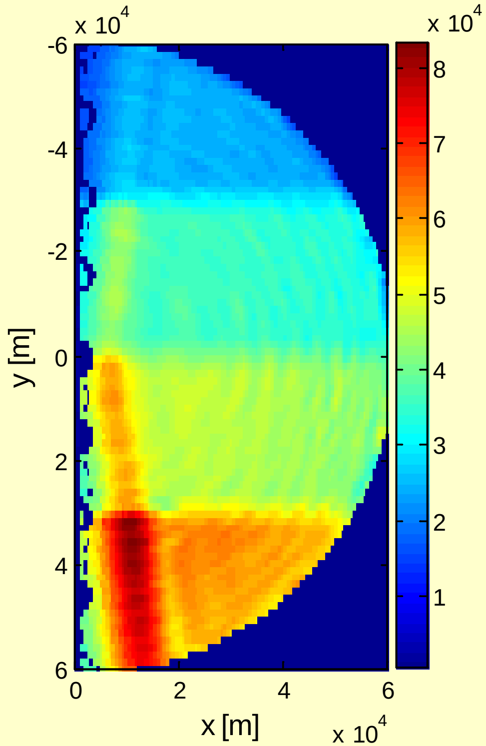
$\gamma = 0.05$, Σ function retrieved



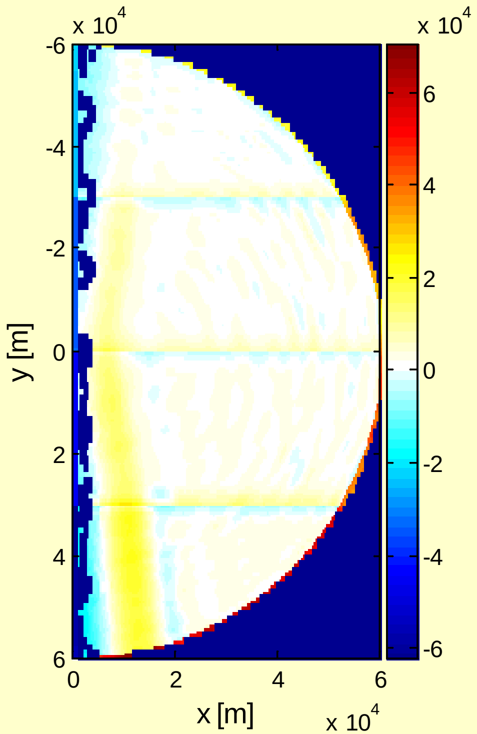
σ^0 retrieved in the DD domain

4. Method evaluation (4/4)

- The last step of the method is to map from the DD to *xy* domain by direct coordinates correspondence (spatial ambiguity overcome by spatial filtering in the measurement).



σ^0 retrieved in the *xy* domain



Error map w.r.t. the input distribution

- Scattering coefficient distribution retrieved with low error.
- Main error due to deconvolution artifacts.
- Deconvolution process identified as the key step of the proposed method.

5. Conclusions

- GNSS-R powerful remote sensing technique suitable for ocean scatterometry.
- Current approaches retrieve one single averaged sea state descriptor over the whole glistening zone.
- Glistening zone large enough so that it can not be considered homogeneous (specially in space observations).
- DDM deconvolution proposed to σ^0 mapping within the glistening zone:
  - Antenna beam steering to eliminate the mapping ambiguity.
  - WAF deconvolution needed.
  - Compensation for the Jacobian and other known terms.
- Proposed method successfully evaluated with a simulation example for a LEO receiver, including noise.
- Deconvolution process identified as the key step of the method and further work is required.

Thank you for your attention