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Interferometry with GPS Low Earth Orbiters Occultations

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Atmospheric irregularities and reflection off the Earth surface generate interfering signals. This talk presents the analysis of the interference fringes to infer geophysical information. Because this technique is based on the analysis of the amplitude and phase of the received field, and because it focus on the features produced by a set of phenomena that usually hinders performance of the close loop, the open loop approach seems a good candidate to enhance the potential use of the concept presented here:

GPS signals reflected off the Earth surface can be detected by receivers aboard occulting Low Earth Orbiters (LEO). After calibration, the occultation geometry and the troposphere have the main contributions to the relative delay between direct and reflected signal. The reflected-to-direct relative delay is a function of the location of the reflecting surface as well as the different effect of the lower troposphere on both ray paths. Geophysical information can be obtained from precise measurements of the interferometric delay, and by separating the geometric from the atmospheric effect. This talk presents results with centrimetric precision in carrier-phase reflected-to-direct relative delay from GPS to LEO occultations. The separation techniques will be discussed and potential applications of the interferometric delay to Ice surface topography, super-refractivity layer determination, or marine boundary layer height detection will be given.

Interferometry with GPS Low Earth Orbiters occultations: a technique to analyze GPS-R/Occ

Based on work conducted at NASA/JPL, *Cardellach, E.; Ao, C. O.; de la Torre Juárez, M.; Hajj, G. A*

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OVERVIEW

- **Introduction**
- **Interferometric technique to infere multi-path relative delay**
- **Inversion: topography**
- **Open questions**
- **Validation plan: Antarctica Snow Dunes Field**
- **Conclusions**

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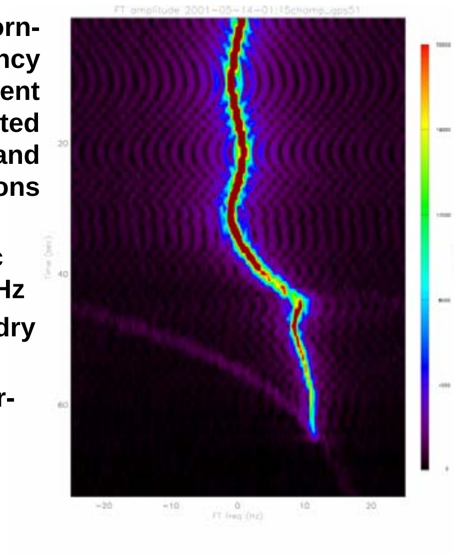
REFLECTIONS IN GPS-LEO OCCULTATIONS

- **Beyerle et al. 2002 proved that horn-like signatures in the frequency domain of the Occultation event correspond to GPS signal reflected off the Earth (ice/ocean) surface and collected in the Occultations antenna**
- **They estimated radio-holographic altimetric performance of 220m/1Hz**
- **Most reflection events are Polar (dry atmosphere)**
- **Wet atmosphere (multipath, super-refractivity, …) hinders signal tracking--> loss of signal before reflection occurs**
- **OPEN LOOP: may help finding reflection events in wet conditions**



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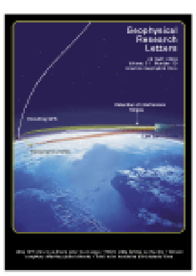
INTERFEROMETRIC TECHNIQUE

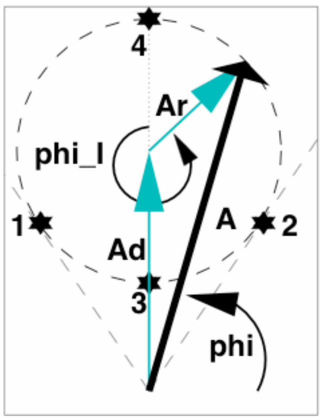
1. **Signals beating because of the interference**
2. **Search of beating cycles (interferometric cycles)**
3. **Convert them to relative delay between signal branches**
4. **Invert the relative delay to geophysical parameters**
   - **location of reflection layer;**
   - **[refractivity corrections at lower troposphere?]**



Cardellach, E.; Ao, C. O.; de la Torre Juárez, M.; Hajj, G. A.
Carrier phase delay altimetry with GPS-reflection/occultation interferometry from low Earth orbiters*Geophys. Res. Lett.*, Vol. 31, No. 10, L1040210.1029/2004GL019775

INTERFERENCE FRINGE

- **Hypothesis: since both signals have similar Doppler frequencies, changing along the event, they should interfere with each other, as detected from coastal experiments…**



… providing the total received field with interferometric fringes, both in the total amplitude (minimum/maximum at points 3/4) and total phase (or phase delay) (min/max at points 1/2). The phase fringe should be in ***skewed quadrature*** **w.r.t. amplitude fringes.**

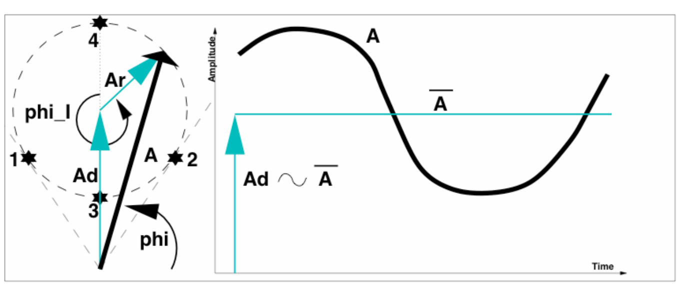
REFLECTED-TO-DIRECT DELAY

- **When the direct and the reflected fields reach the antenna, the total field may be modeled as sum of two fields:**

$$A e^{i\phi} = A_d e^{i\phi_d} + A_r e^{i\phi_r} = e^{i\phi_d}[A_d + A_r e^{i(\phi_r - \phi_d)}]$$

- **As first approach, the averaged value of the amplitude within the oscillation corresponds to the direct field:**

$$A_d \sim \overline{A}$$



…same for the phase:

$$\phi_d \sim \overline{\phi}$$

REFLECTED-TO-DIRECT DELAY

The model for the complex received signal, thus, becomes:

$$Ae^{i\phi} = e^{i\overline{\phi}}[\overline{A} + A_r e^{i\phi_I}]$$

System of 2 equations with 2 unknowns (amplitude of reflected signal and interferometric phase).

The interferometric phase is:

$$\phi_I = (\phi_r - \phi_d) = \vec{k} \cdot (\vec{r}_r - \vec{r}_d)$$

- Possibility of extracting the interferometric phase
- Each cycle in the interferometric phase is 1 GPS-L1 wavelength difference between the reflected and the direct signals (approx. 19 cm)

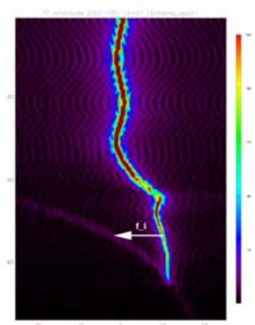
REFLECTED-TO-DIRECT DELAY

… writing the equation in their Real and Imaginary components…

$$tan(\phi_I) = \frac{\overline{\mathcal{R}}\mathcal{I} - \overline{\mathcal{I}}\mathcal{R}}{\overline{\mathcal{R}}(\mathcal{R} - \overline{\mathcal{R}}) + \overline{\mathcal{I}}(\mathcal{I} - \overline{\mathcal{I}})}$$

The smoothed values are taken over running windows of variable size, because the interferometric frequency, and so the fringe, slow down as both signals approach each other. The size is set to two times the interferometric period, roughly estimated from the frequency domain:

T_w = 2 T_I = 2 / f_I = 2 / (f_direct – f_reflected)



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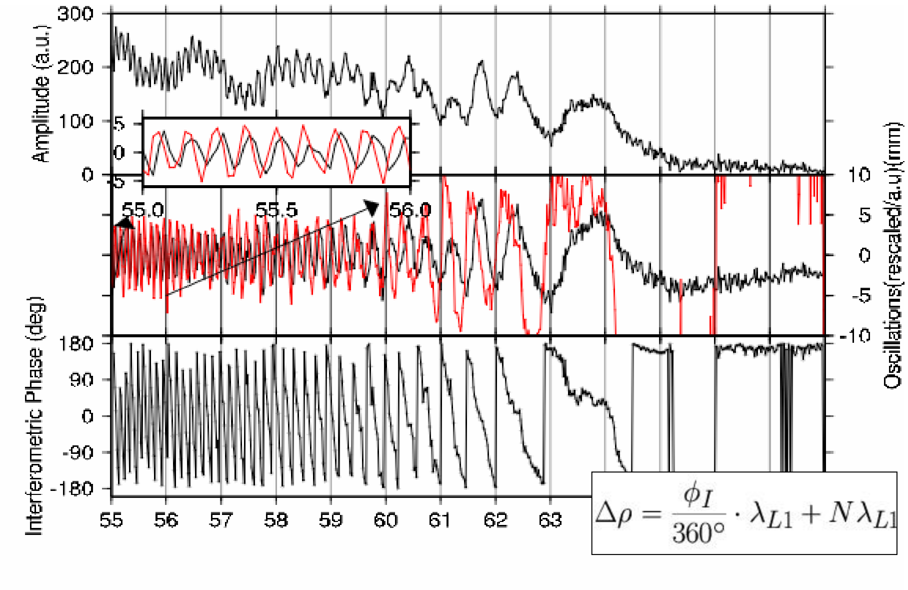
REFLECTED-TO-DIRECT DELAY



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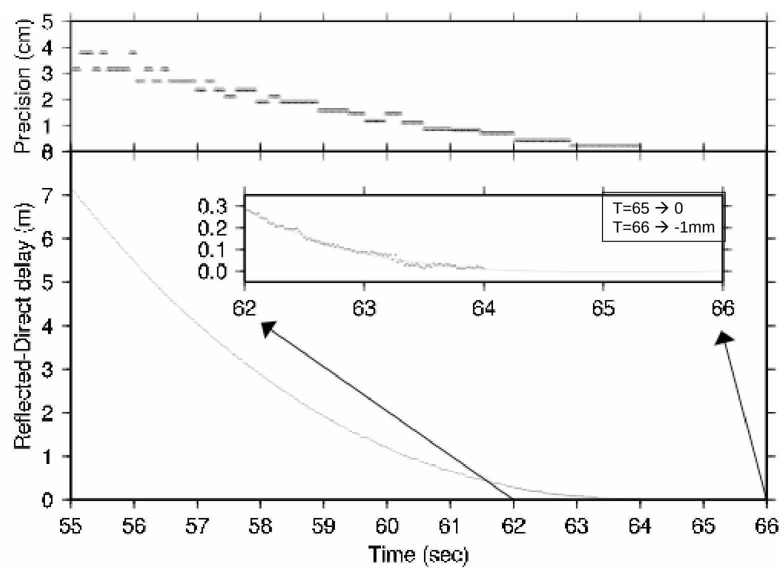
REFLECTED-TO-DIRECT DELAY



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GEOPHYSICAL CONTENT

- **NORTH POLE EVENT:**
  - **Observation located at ~89.75 deg latitude N:**

REFLECTION ON POLAR ICE

Dry troposphere expected

User Requirement for ice topography: 0.5 m precision

Current observation system: lack of coverage over extreme polar latitudes (ICESat since 2003)
GPS-R/Occ: most coverage on the poles.

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GEOPHYSICAL CONTENT

$$
\begin{aligned}
\Delta\rho &= \rho^R - \rho^D \\
&= (\rho^R_{geo} + \rho^R_{trop} + \rho^R_{rough} + \rho^R_{iono} + \rho^R_{instr} + n) \\
&\quad -(\rho^D_{geo} + \rho^D_{trop} + \rho^D_{iono} + \rho^D_{instr} + n) \\
&= \Delta\rho_{geo}(\vec{R}, \vec{T}, \vec{S}) + \Delta\rho_{trop}(\vec{R}, \vec{T}, \vec{S}, N) + \cancel{\rho^R_{rough}} + n
\end{aligned}
$$

R and T known from P.O.D

Specular point: unknown

Refractivity profile already known

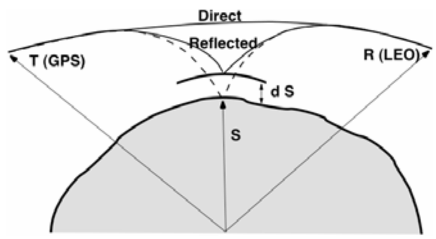
- **Ionosphere and instruments assumed to perturb the reflected and direct signals in the same way**
- **Roughness effects neglected (could introduce offsets, left as future work)**
- **Geometric (altimetry) and tropospheric (crossing atmosphere through different altitudes) are modeled by means of a ray tracing tool**

GEOPHYSICAL CONTENT

GENERAL APPROACH:

- **For given**
  - **R and T locations (Precise Orbit Determination),**
  - **N, refractivity profile (solution of Occultation),**
  - **and S, a-priori surface model (ellipsoid or geoid),**

the ray tracing tool generates the model of the interferometric delay



- **the ray tracing tool only needs to correct the surface's altitude to fit the data:**

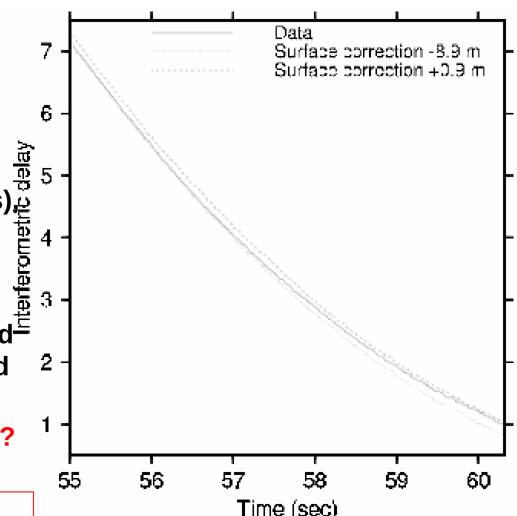
$$\Delta\rho_{rtt}(\delta S; S, \vec{R}, \vec{T}, N) \longleftrightarrow \Delta\rho_{data}$$

GEOPHYSICAL CONTENT

EXAMPLES:

- **Data (solid line), ray tracing tool model for reference surface – 8.9 m (long dashes), ray tracing tool output for reference surface + 0.9 m (short dashes)**
- **Data prefers –8.9 m corrected surface at the beginning, and +0.9 correction at the end**
- **Topography or mismodeling?**

RAY-TRACING mismodeling? inaccuracies in the refractivity profile?



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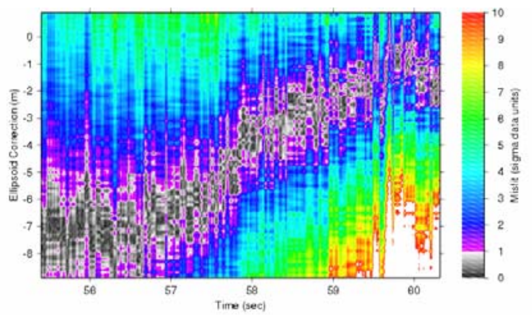
ALTIMETRY

- **Find best fit at every data point (20 ms, 50Hz):**
  - **For each data point in the time series, we define the solution as the surface correction that minimizes:**

$$M^2(t, \delta S) = \frac{(\Delta\rho_{data(t)} - \Delta\rho_{RTT}(\delta S; S, \vec{R}(t), \vec{T}(t), N))^2}{\sigma^2_{data(t)}}$$



20ms/50Hz-uncertainty ~ 2m

20ms/50Hz-time spacing ~20 ms

20ms/50Hz-horizontal spacing ~83 m

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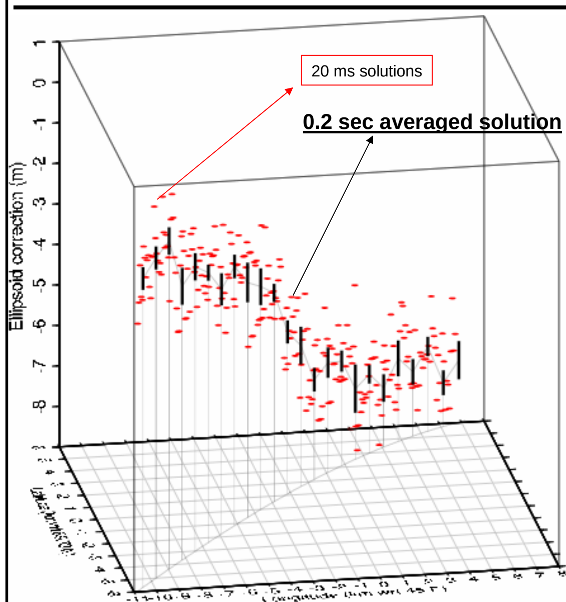
ALTIMETRY: averaged solution



0.2 sec averages:	
Solution:	**Topographic profile, max grad ~ 5cm/100m**
Precision, <RMS>:	**0.70 m**
Horizontal sampling:	**~ 1 km**

•Polar ice: smooth topography expected
•Close to user requirements on ice
•Event not validated (NO DATA)
•Event on Greenland showed capability to detect stronger terrain gradients (validated)

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OPEN QUESTIONS

- The Fresnel zone extends several km:

QUESTION 1: Is it possible to solve for smaller topographic features?

- Inversion relays on given reference surface (geoid):

QUESTION 2: Sensitivity to reference surface? Geolocation of specular?

- The refractivity profile provided by the direct occultation technique is less reliable in the lowest part of the troposphere.

QUESTION 3: Is the technique sensitive to tropospheric inaccuracies?

QUESTION 4: Is it possible to separate the tropospheric from the geometric effects?

- OTHER APPLICATIONS?

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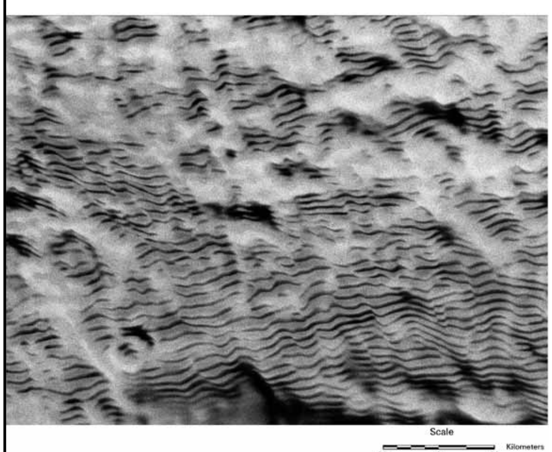
VALIDATION PLAN: snow dunes



- Field of snow dunes in Antarctica, carved out by the unrelenting katabatic winds
- Different ice-type at up/down wind side
- The dunes are a few meters high and a few kilometers apart

Images from nsidc

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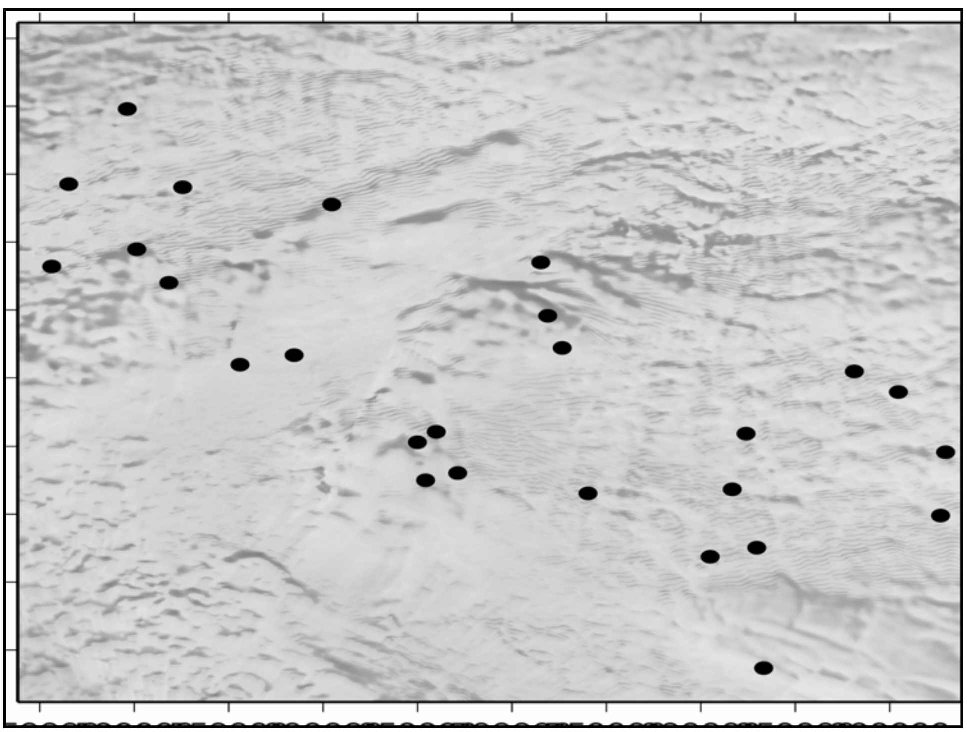
STATUS

- Identified of the order of 30 CHAMP reflection events in a snow dunes area
- Semi-automatic process to extract interferometric delay
- Developing algorithms for automatic detection of reflected signal (secondary peaks in the frequency spectrum) [required for full automatic processing]
- Bureaucratic issues regarding use of NASA/JPL ray tracing tool



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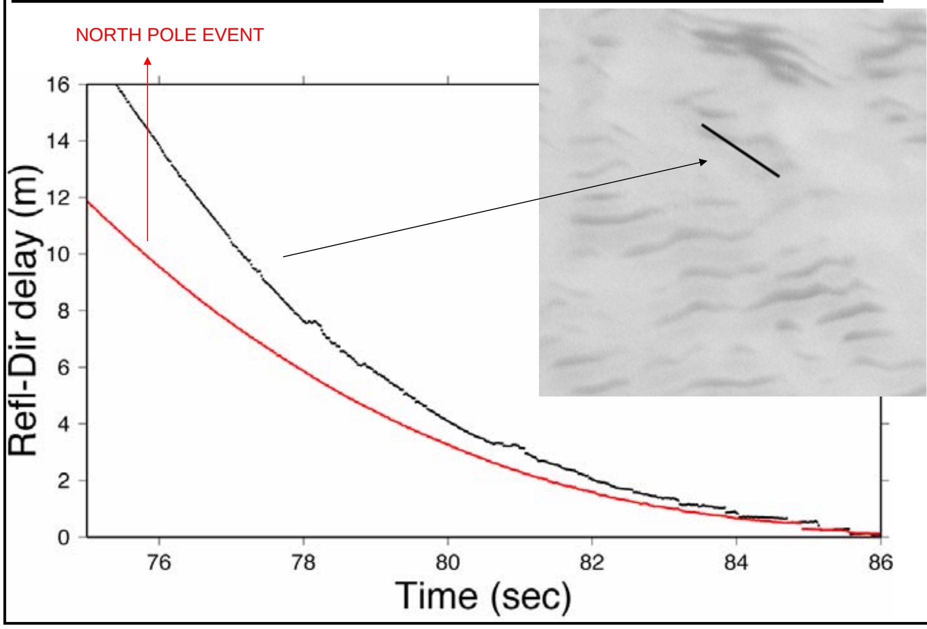
DUNE EXAMPLE



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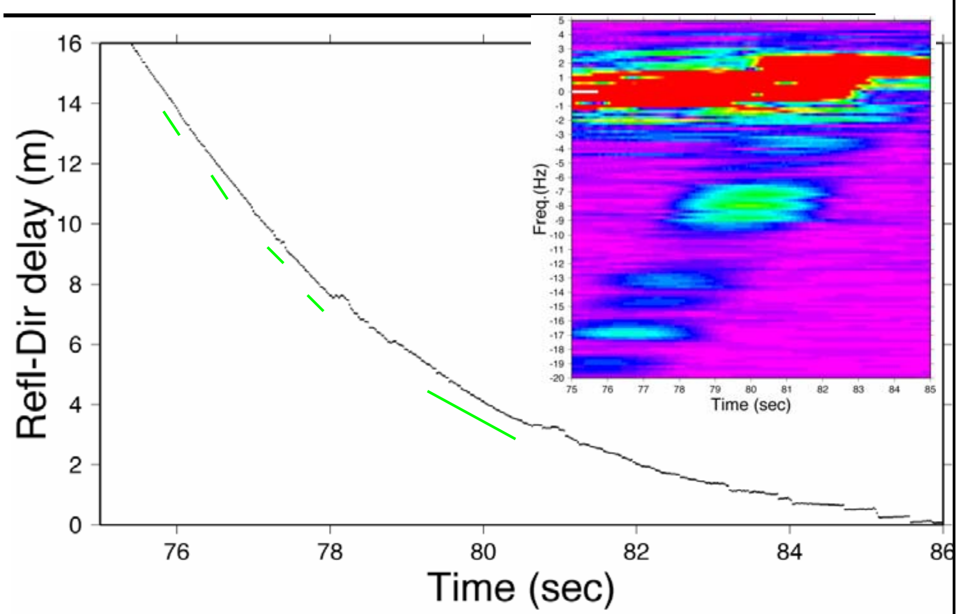
DUNE EXAMPLE



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SUMMARY

- The new technique to extract geophysical information from the interference fringe in GPS LEO Occultations has been presented
- APPLICATION TO Polar Ice Topography at 0.70 m vertical resolution on polar ice, 1 km horizontal spacing.
- The concept has been partially validated (capability to detect topographic gradients)
- Still many open questions
- A validation plan is being conducted on Antarctic Snow Dunes
- OPEN LOOP product may extent the use of the technique to other areas (ocean) and also other applications (helping solving for tropospheric multipath?)