Phase-Delay Altimetry from Low Elevation GPSR Measurements

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Overview

- Goal and justification
- Experimental setup
- Evidence of signal coherence at carrier level
- Identify error sources:
  - ray bending due to tropospheric gradients
  - roughness
- Inversion results: carrier phase altimetry at open sea with GPSR techniques
- Conclusions

Goal and Justification

- GPSR C/A group delay altimetry has limited precision and coarse space resolution.
- Improvement of precision by means of carrier phase (C.P.) observations appears difficult at open sea, with surface roughness of the order of several carrier wavelength: diffuse regime, non-coherence at carrier level.
- A possible way to avoid roughness' multipath is to constraint to observations at very grazing elevation angle, with apparent roughness diminished by 2*sin(el)
- At grazing angles, however, slight uncertainty in the slant delay yields to huge error in the vertical (altimetric) components, by a factor 1/(2 sin(el))
- IS IT WORTH TO DESCEND TO LOW ELEVATIONS TO GET CARRIER PHASE COHERENCE? Yes, 20 deg uncertainty for a single C.P. observation, at 1 deg elevation is 30 cm vertical error, better than C/A single observation error at nadir (~m)

Goal and Justifications

- The concept could be applied from air- and space-borne,
- but also powerful application from ground stations, for coastal monitoring:
  - indeed, the current monitoring system has poor coverage in the coastal areas
  - GPSR is a cheap technology and could be deployed wherever along the coast.

Experimental Setup

- Data gathered from a GPSR ground station located at ~85 m above the sea surface, Palos Verdes, CA, Sept. 2002
- GPSR equipment including:
  - RHCP antenna pointing to the horizon
  - LHCP antenna pointing to the horizon
  - RHCP antenna zenith-looking
  - standard and dedicated receivers

Evidence of coherence at carrier level

- The equipment collects binary data stream at 20.456 Mbps.
- After correlation with the PRN C/A code, and assuming a single specular reflection, the correlation function or waveform can be modeled as:

$$A(\tau_i) = e^{i\phi_0}[A_d\Lambda(\tau_i - \tau_0) + A_r e^{ik_0(r_r - r_d)}\Lambda(\tau_i - \tau_0 - \frac{r_r - r_d}{c})]$$

- r_r and r_d are not changing at the same rate (elevation dependent, variations in the altimetric range...), the interferometric phase is not constant: interferometric frequency. ⟶ AMPLITUDE BEATING

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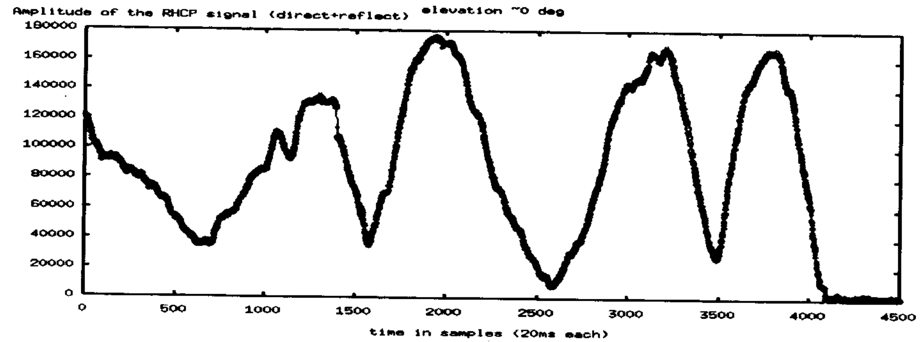
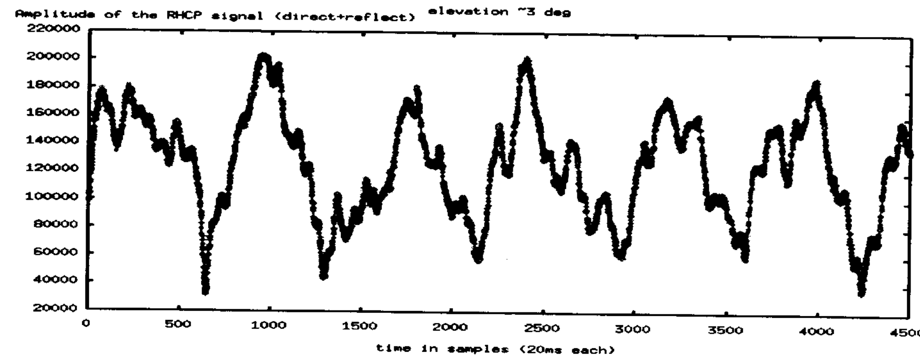
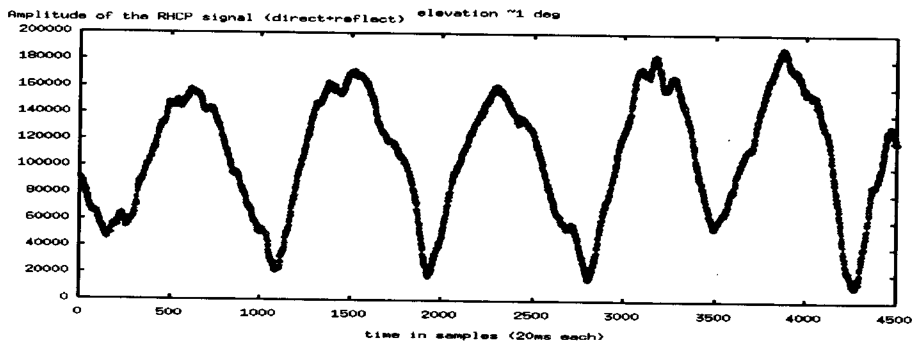
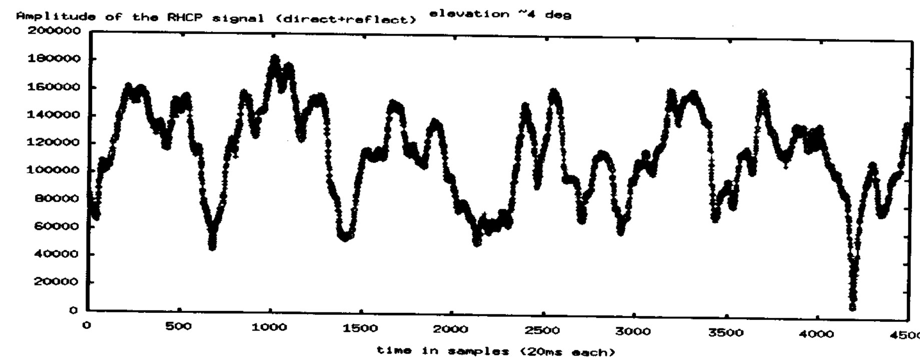
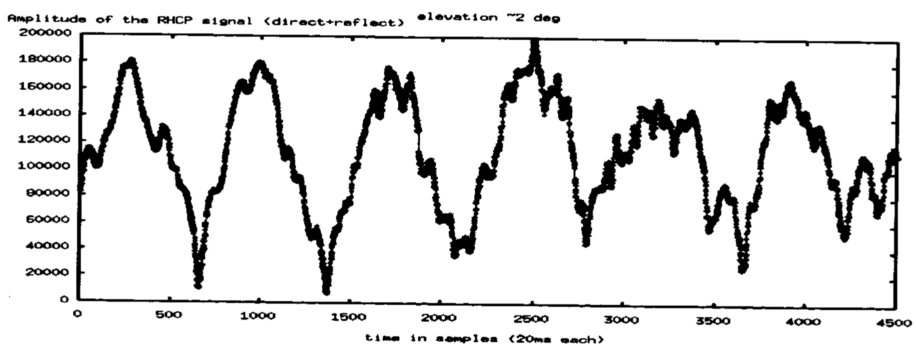
Evidence of coherence at carrier level

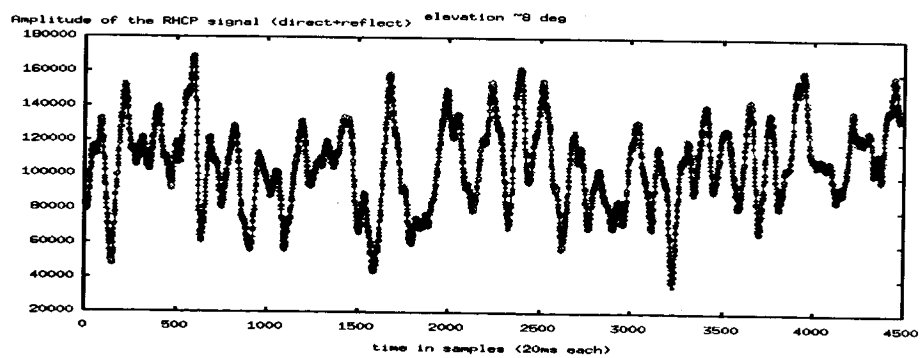












Evidence of coherence at carrier level

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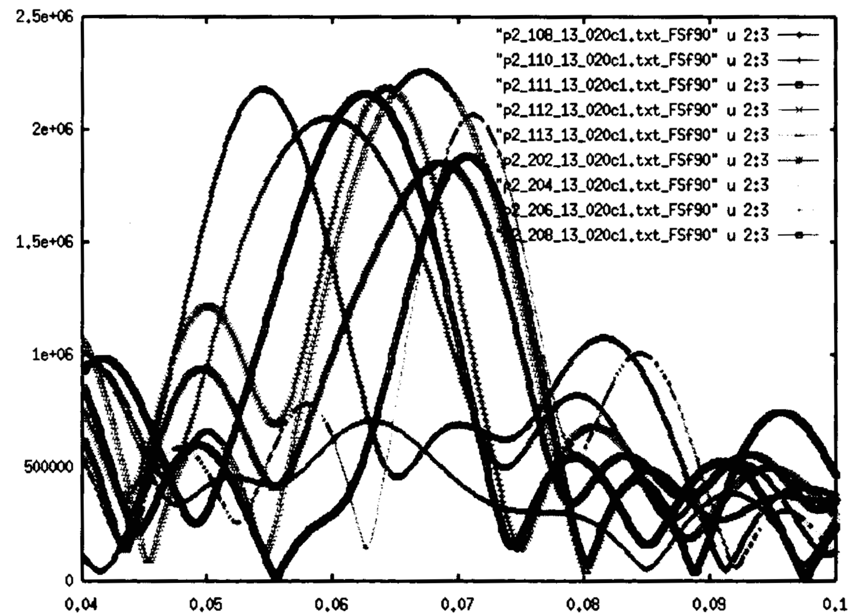
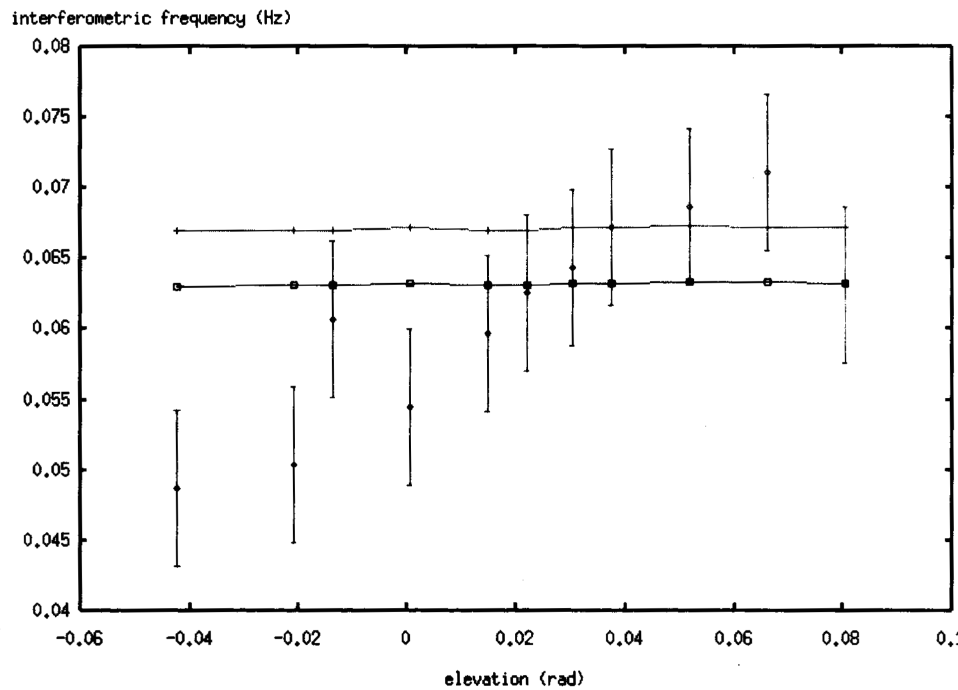
- **Assuming that the relative delay between the reflected and the direct link can be modeled as:**

phi= 2 Hr sin(el)/lambda + Err [cycles]

- **Then, the interferometric frequency should behave as**

f= d phi/dt = 2 Hr/lambda [cos(el) d el/dt + sin(el) d Hr/dt] + d Err/dt



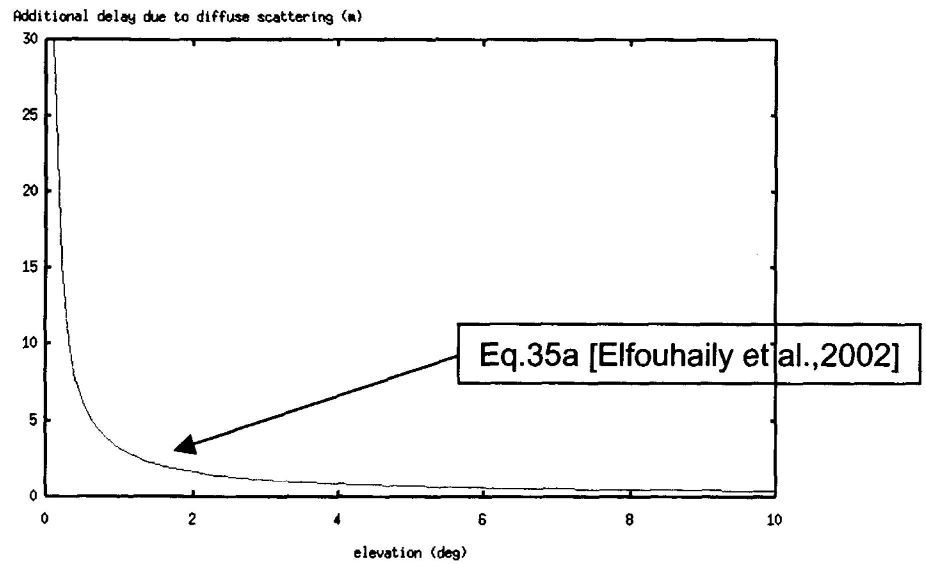


Identifying error sources

- Something is affecting the interferometric phase, besides the geometrical relative delay. What?

- **Guess 1:** At low elevation, the ray path may be strongly affected by the tropospheric gradients, bending the trajectory:
- The simple 2hsin(el) model may not be valid any more.
- Simulations for ray-tracing have been performed to investigate its impact on the interferometric phase and thus altimetric products

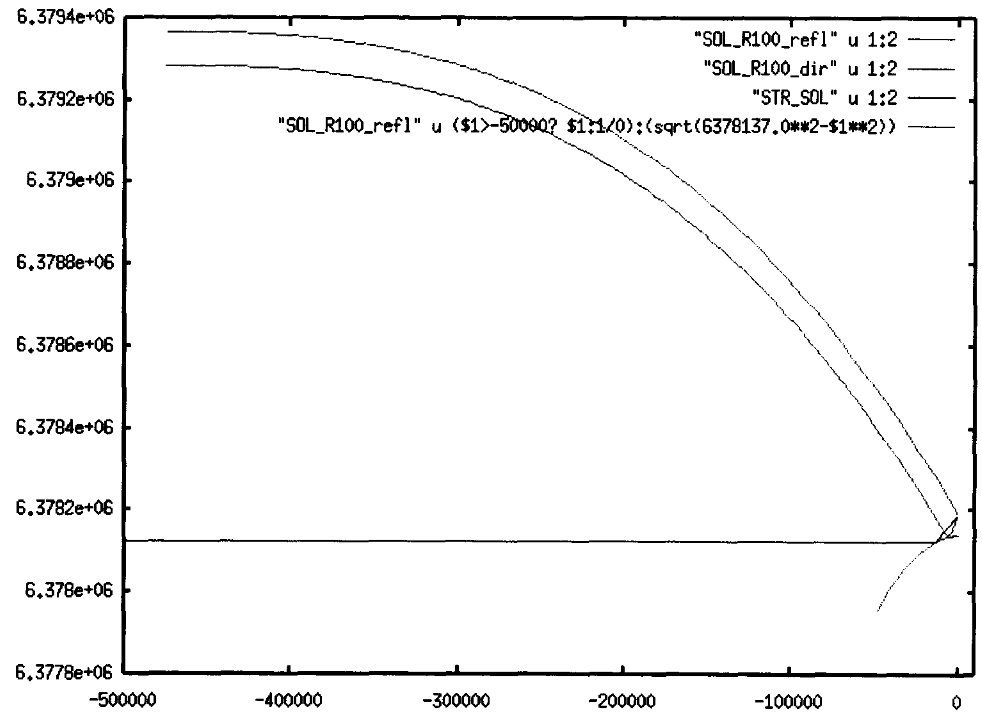
- **Guess 2:** Roughness adding some more non-accounted reflections, transition to diffuse regime.



- Work on simulations to find out about the transition between the diffuse to the coherent regime and its effect on the relative delay and interferometric phase.

Bending troposhere

- Simultions based on an exponential refractivity profile: Xo*exp(-h/H).
- The parameters used are X0=250e-6 and H=10 km. Variabilities of 20% in X0 give differences in the relative delay of the order of 5-20 cm (elevation dependent).
- Hr set at 85 m. A variation of 5 m in the altitude results in differences of ~5 cm in the relative delay.
- 2000 layers of 10 m each have been used, except for the lowest part, below receiver altitude layers of thickness Hr/100.



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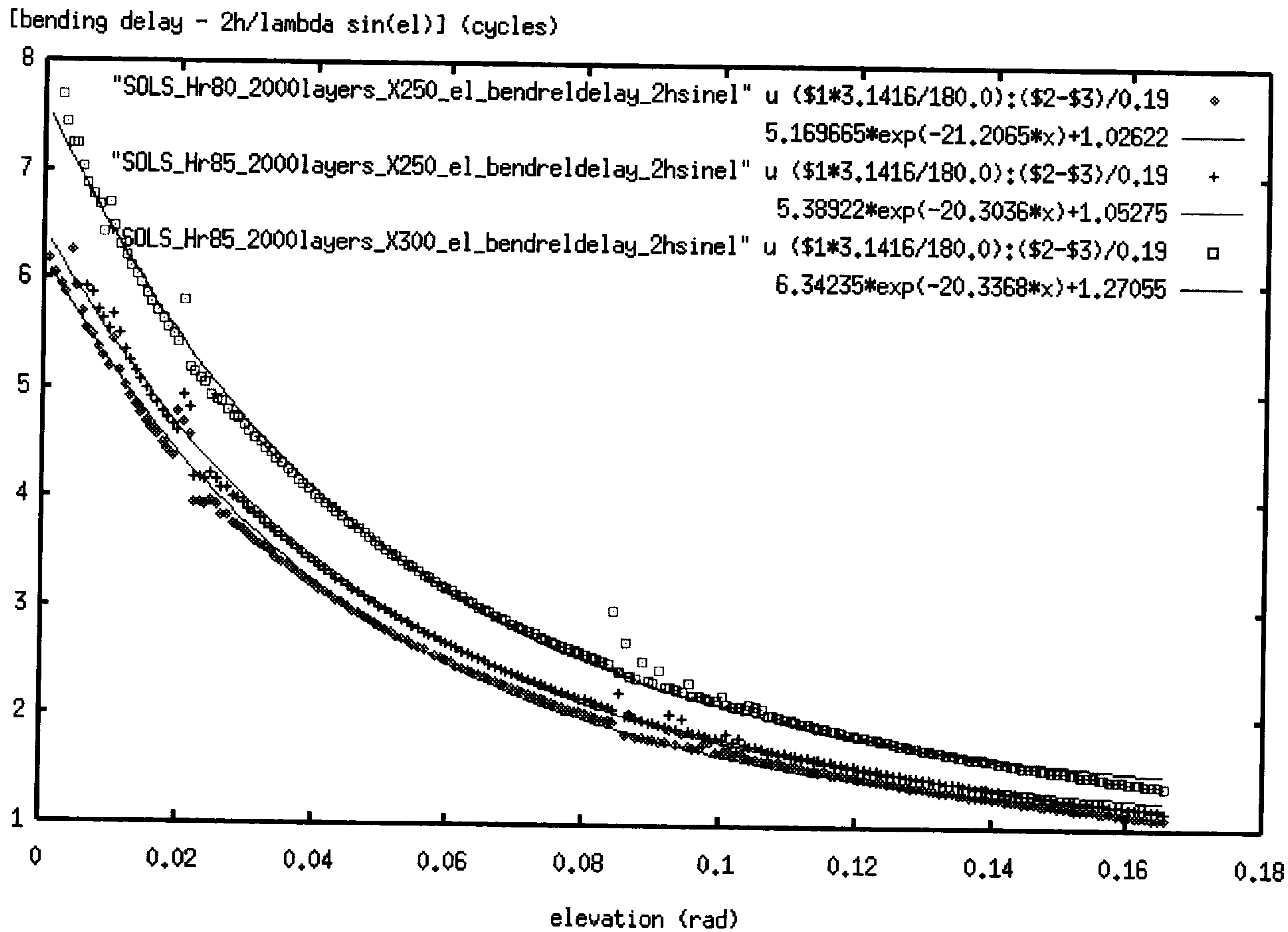
Bending troposphere



Roughness: simulations

- Kirchhoff integral (not stationary phase approximation)

$$E = \frac{ie^{ikR_0}}{4\pi R_0}\int_S [R\vec{v} - \vec{p}] \cdot \hat{n} e^{i\vec{v}\cdot\vec{r}} dS \qquad \vec{v} = \vec{k}_{inc} - \vec{k}_{sct} \qquad \vec{p} = \vec{k}_{inc} + \vec{k}_{sct}$$

- Where the surface has been generated with the 2D anisotropic spectrum in [Elfouhaily et al., 1997], for developed seas.
- Surface 2000 m along the transmitter-receiver direction and 100 m across it.
- Integration in 10 cm X 10 cm grid spacing.
- Validation:
  - surface z=0 should recover 2h sin(el) from the interferometric phase. DONE
  - use of longer surfaces to check stable solutions. ON THE WAY
- Generation of a large population of different surfaces of equal roughness to separate particular features from statistical ones. ON THE WAY
- Shadowing. ON THE WAY

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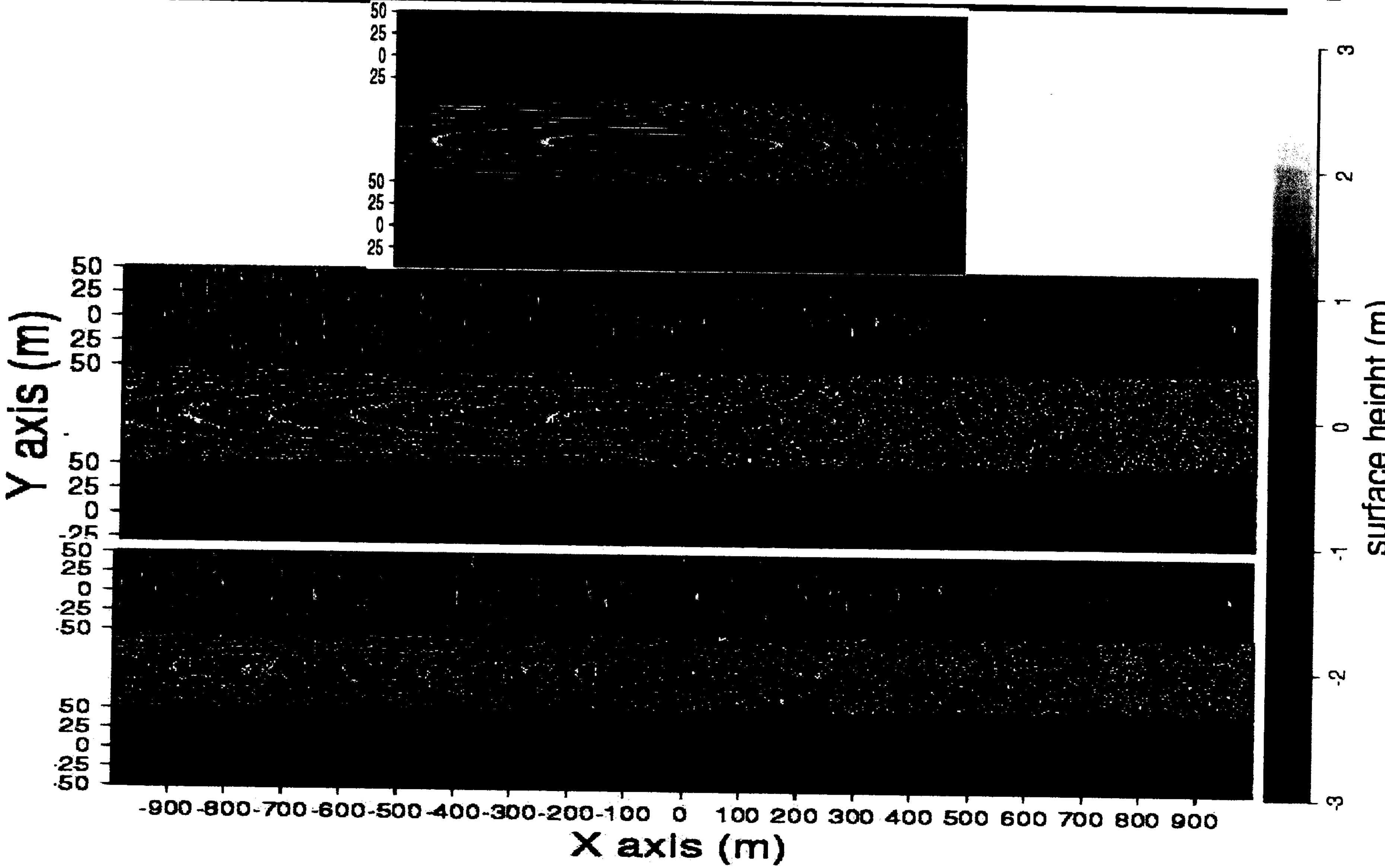
Roughness: simulations



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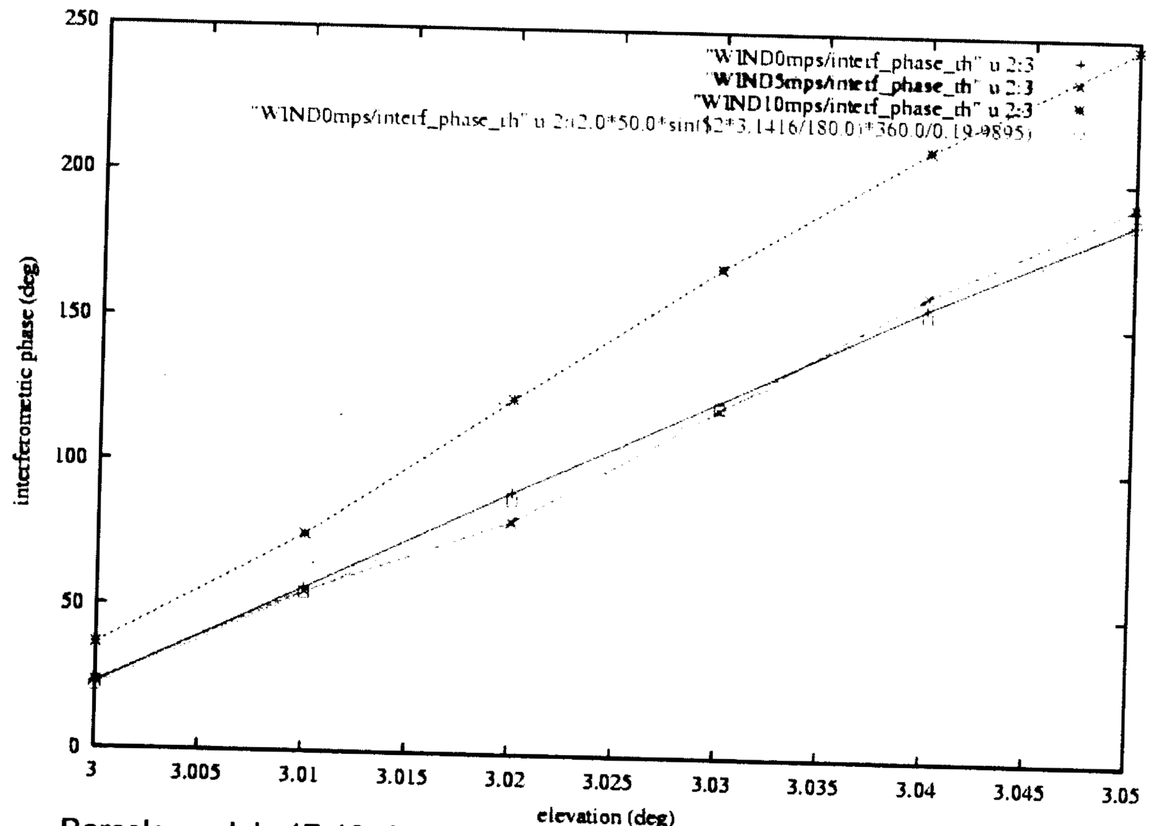
Roughness: preliminary results

- Example at 3 deg:
  - SWH of 2.6 m would have an extra delay of ~50deg=2.6cm (~0.5 m vertical) while elevation changing 0.05 deg (~ 6 sec).
  - SWH of 0.6 m would have deviations of the order of ~10deg=0.5cm (10cm vertical), both positive and negative.

•Need to find out whether these are features due to particular surface roughness (ripple related to scanning of SWH) or there is a net effect (multipath-like).

•Extend simulations to other ranges of elevations.

•Use of different surfaces of equal statistical roughness properties.



Inversion

- Bit data stream processed to obtain the complex waveform, which contains both direct and reflected signal.
- Assuming specular reflection, we model the waveform as the sum of two "triangle functions",

$$A(\tau_i) = e^{i\phi_0}[A_d\Lambda(\tau_i - \tau_0) + A_r e^{ik_0(r_r - r_d)}\Lambda(\tau_i - \tau_0 - \frac{r_r - r_d}{c})]$$

- Fit to parameters Ad,Ar,interferometric phase
- We can infer the altimetric range from the interferometric phase except for the phase ambiguity. Need to model the errors:

Phi = K + 2 H/lambda * sin(ele) + Err.

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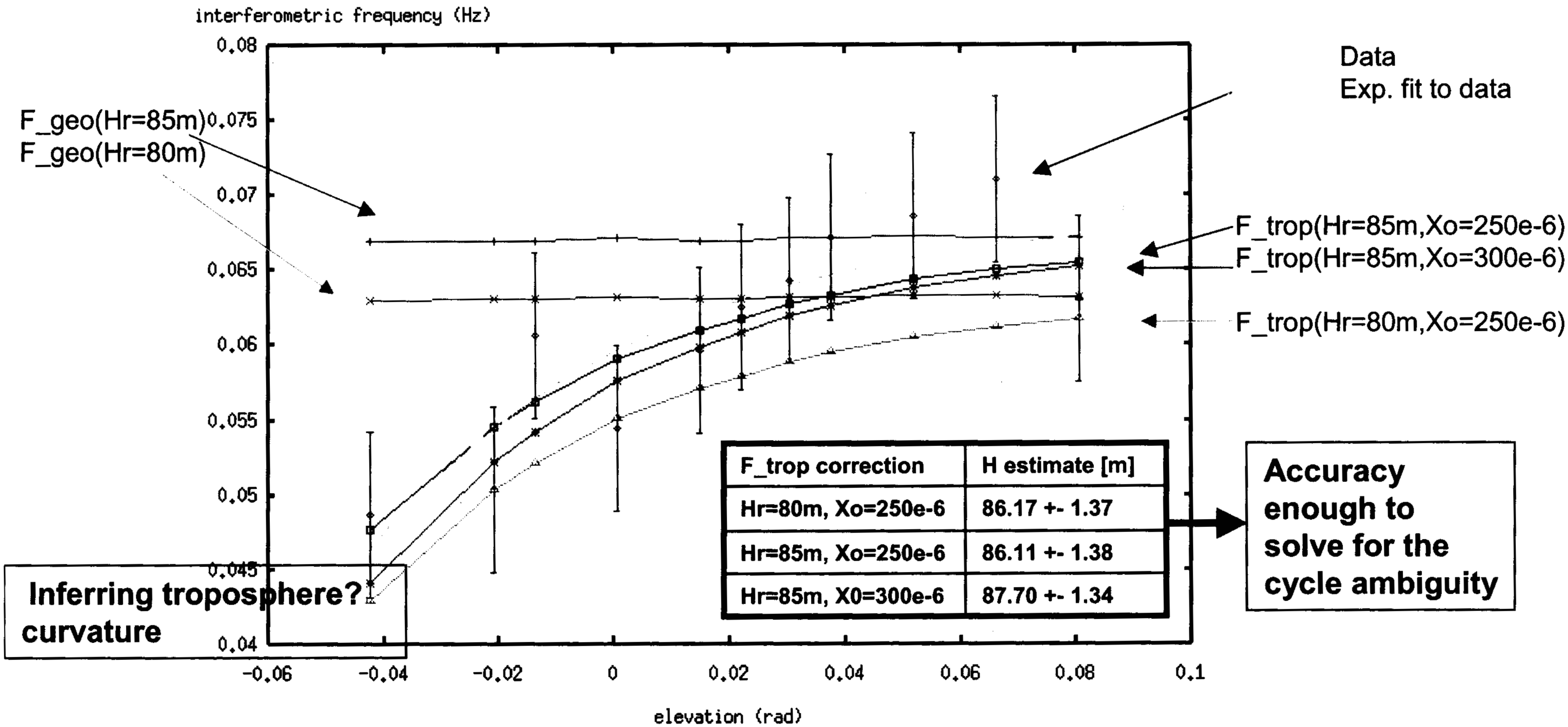
Inversion

- **First, coarse altimetric range estimation by analysis of the amplitude's beats:**
  - **when we including d Err/dt as from fit on tropospheric effect**



F_trop correction	H estimate [m]
Hr=80m, Xo=250e-6	86.17 +- 1.37
Hr=85m, Xo=250e-6	86.11 +- 1.38
Hr=85m, X0=300e-6	87.70 +- 1.34

Inversion: method

- STEP 1: coarse estimation of Hr and troposphere by frequency analysis (effect of the roughness yet to be known, may also change the curvature/slope).
- STEP 2: generate tropospheric corrections (and roughness?)
- STEP 3: inversion by carrier interferometric phase
- STEP 4: cycle ambiguity resolution by coarse estimate.

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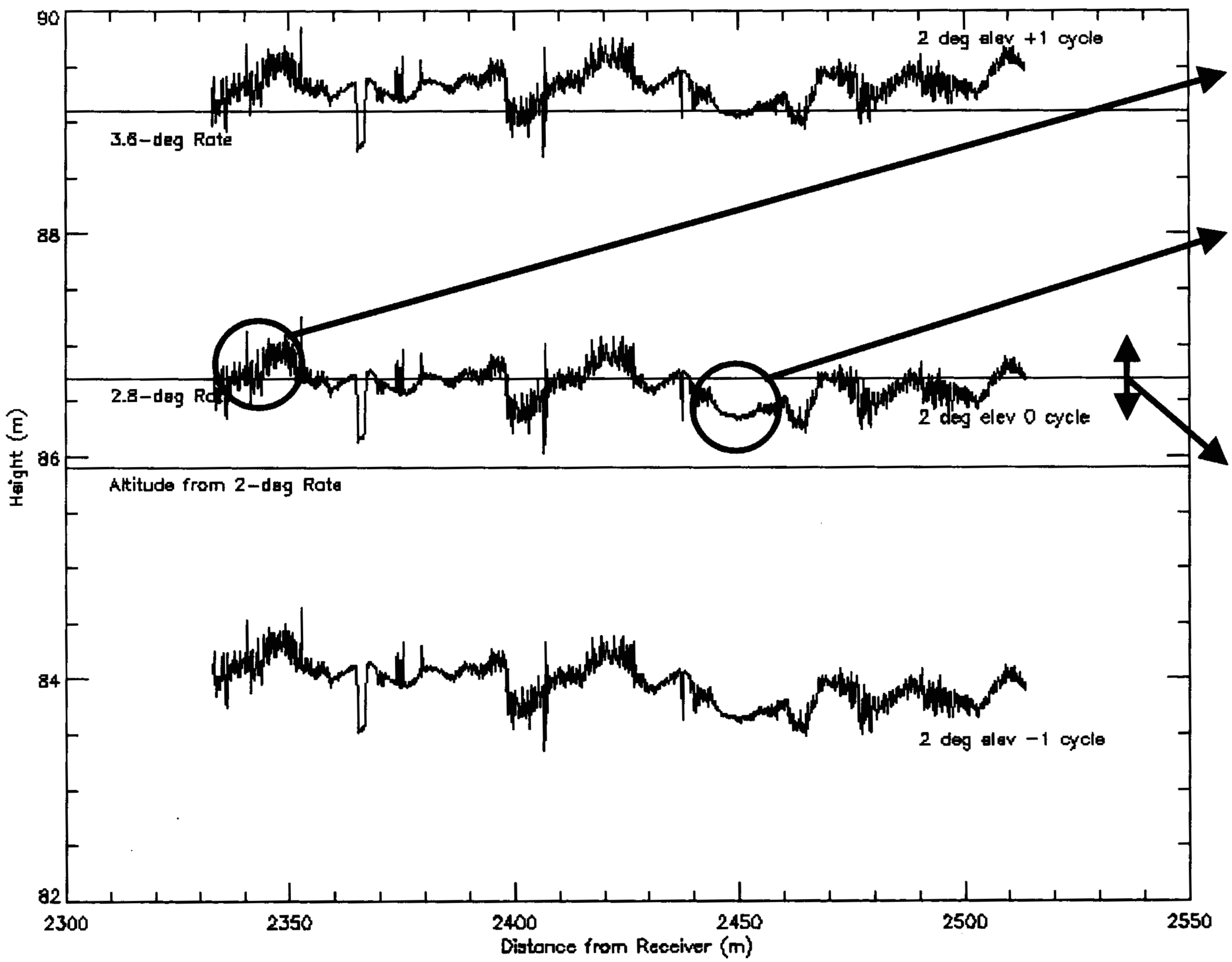
Inversion: precision

- **Inversion of 30 seconds of data by tracking of the carrier interferometric phase (elevation ~2 deg), sample every 20 ms:**



RMS=15cm; sigma<1cm

RMS,<2cm
sigma~1mm

100 meters scan average:

RMS=16cm
sigma<1cm

CONCLUSIONS

- It is possible to do altimetry with GPSR carrier measurements at open sea using low grazing angles of observation.
- The precision we have obtained is of the order of 16 cm RMS, sigma ~< 1cm, in 100 m horizontal scanning.
- Bending effect of the tropospheric refractivity profile may add biases and trends of the order of cycles (elevation dependent). Up to 1.5 m in slant delay.
- Biases and trends due to the roughness are being investigated.
- A method to solve for the cycle ambiguity has been identified, using the frequency of the amplitude beats. This improves the accuracy.
- Final accuracy will depend on the capability to infer/model the tropospheric and roughness effects. In any case within 1 cycle.