Open loop tracking of radio occultation signals in the lower troposphere

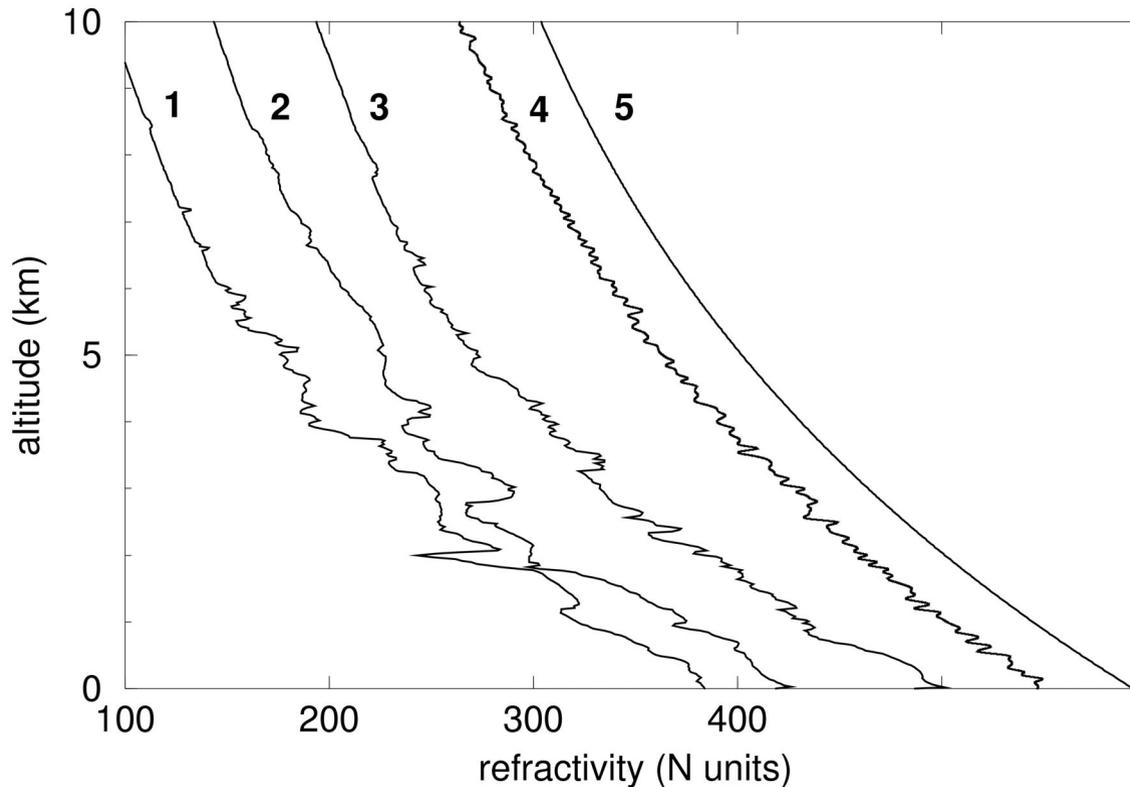*S. Sokolovskiy*

University Corporation for Atmospheric Research
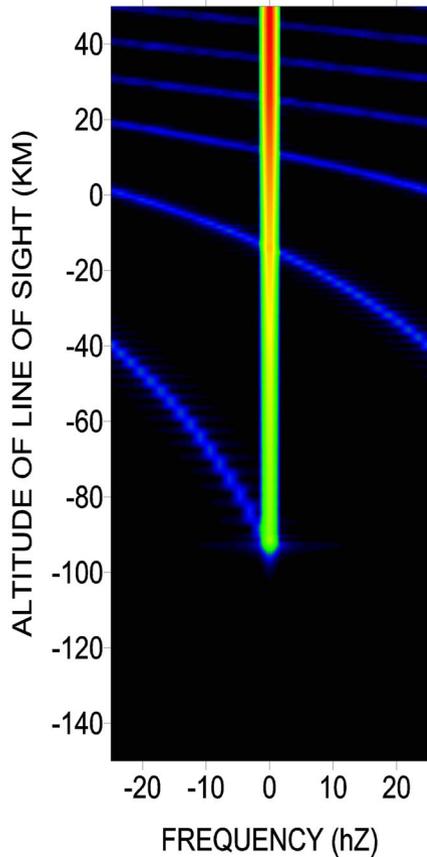
Boulder, CO

Refractivity profiles used for simulations

(1-3) high resolution radiosondes, 7.1N, 171.4W, Oct.1,9,19, 1995, 12UTC
(4,5) models (model 4 is used with different horizontal/vertical aspect ratio
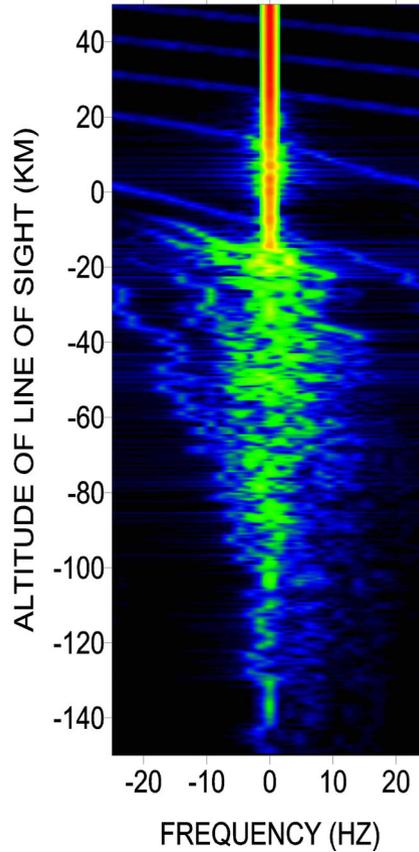   of the irregularities)

Examples of sliding spectrograms of the simulated RO signals
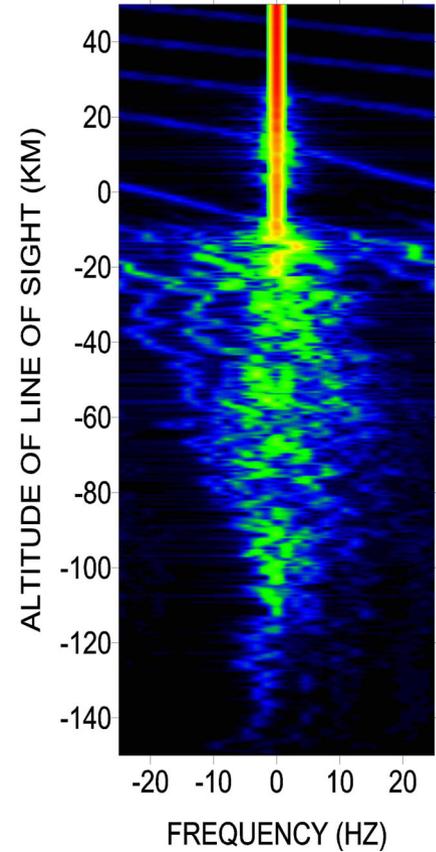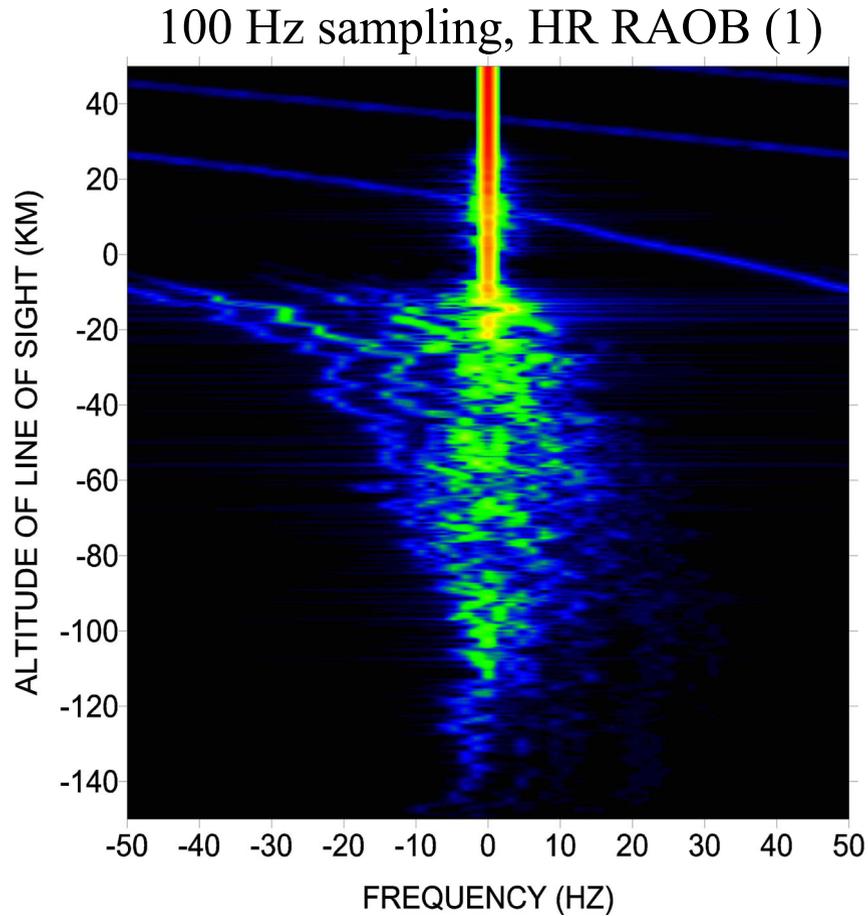## (50 Hz sampling)

exponential
N-profile

HR RAOB (3)

HR RAOB (1)

Strong sub-refraction may cause the additional broadening of the spectrum of RO signal

100 Hz sampling, HR RAOB (1)

PLL   # OL

Downconversion by use of <u>phase model</u> (for the purpose of noise filtering).

The phase model is calculated in real time, <u>by extrapolating the previously extracted phase</u>.

The phase model is calculated in advance. <u>No feedback</u> from received signal.

Low-pass filtering (integrating), sampling, and transmitting the results.

The phase must be extracted in real time for updating the phase model.

The phase can be extracted in the post-processing from the transmitted I and Q samples. <u>Resampling to higher rate allows to reduce the number of the cycle slips.</u>

- An optimal noise filter for single tone signals.
- May provide unstable results for multi-tone signals (the results may depend on method of the projecting the phase model ahead).
- Needs time and large enough SNR to lock-on.

- Applicable for multi-tone signals.
- Applicable for rising occultations.
- Capable of tracking signals with any low SNR.
- Needs the pre-calculated phase model.

Why PLL tracking is not stable in the lower troposphere?

Because large random phase acceleration of the tropospheric RO signal may result in large deviation of the phase from the model projected ahead from the previously extracted phase.

RO signals simulated for *N*-profiles with irregularities, $\delta z \sim 50m, \delta N/N \sim 1\%$

spherically symmetric case   hor./vert. aspect ratio 4:1
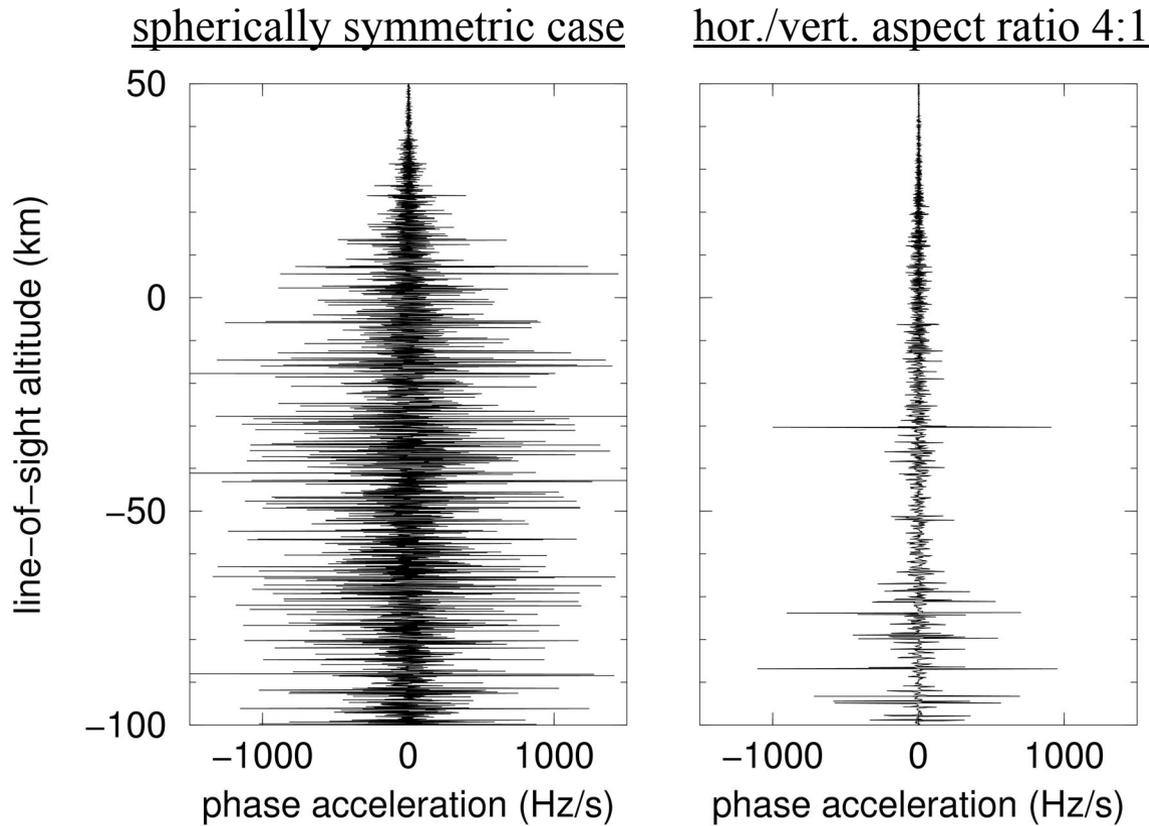
Note: for stable operation of a generic GPS receiver the phase acceleration must be within +/-300 Hz/s

Evidence of instability of PLL tracking in the troposphere

Sensitivity of inversion results (penetration, negative N-bias) to method
of the projection of the phase model ahead.
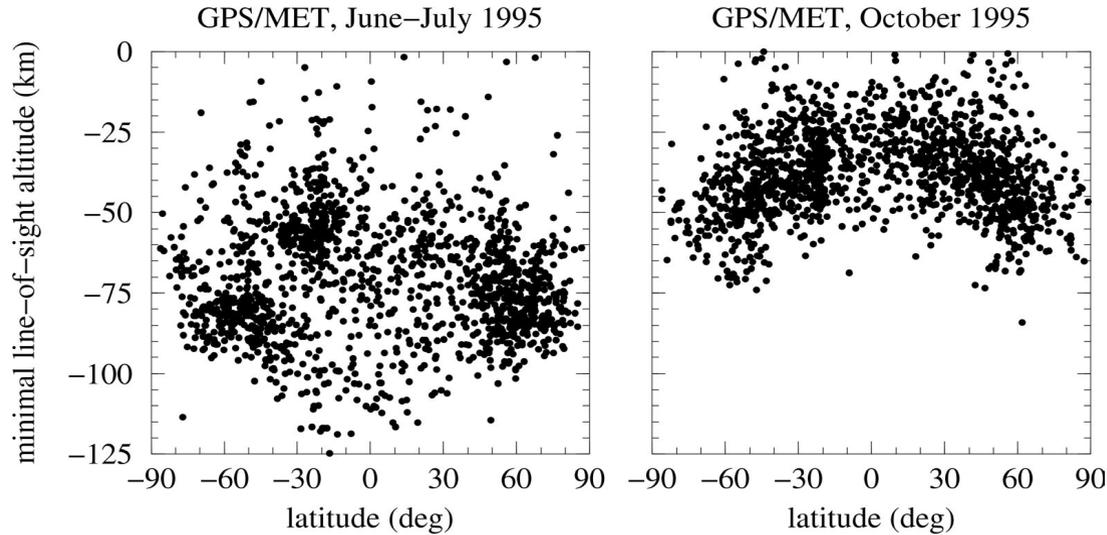
"Flywheeling" (increased time interval and
amount of previously extracted data used
for the projection of phase model ahead).

Even with the "flywheeling" a significant percentage of occultations
show abnormally large deviation of Doppler from that predicted from
climatology (Hajj et al., COSMIC Workshop, Aug. 2002)

Why OL tracking is needed?

1) To minimize tracking errors in the lower troposphere.
2) To track rising occultations.

Why OL tracking is feasible?

Because the small weather-related spread of Doppler frequency shift of RO signals observed from LEO (+/-15Hz) allows downconversion close to mean zero frequency by use of the frequency model based on predicted orbits and refractivity climatology.
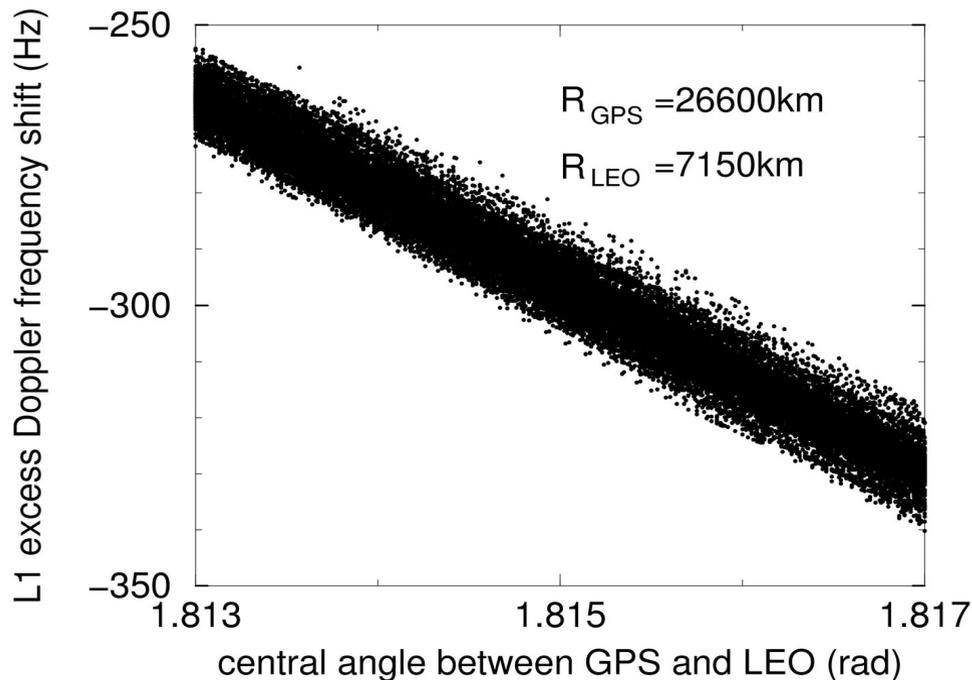
The excess Doppler frequency shift for 768 refractivity profiles produced by NCEP T62 NWP model at 0-75deg N. Maximal spread is observed at ~3-4km.

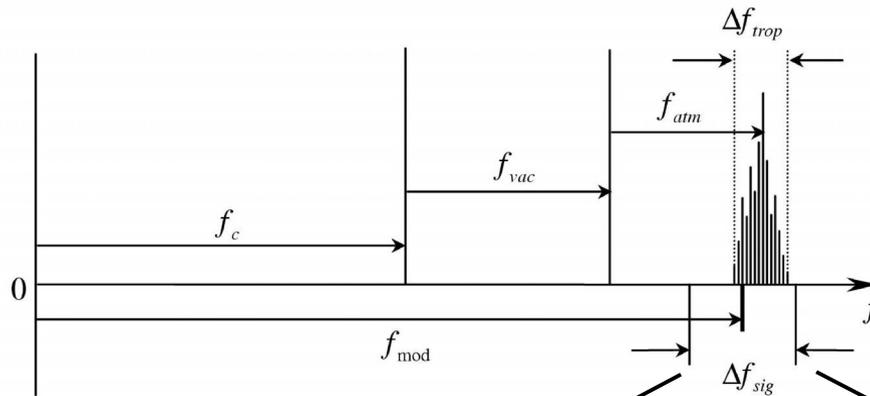# Layout of RO signal in frequency domain
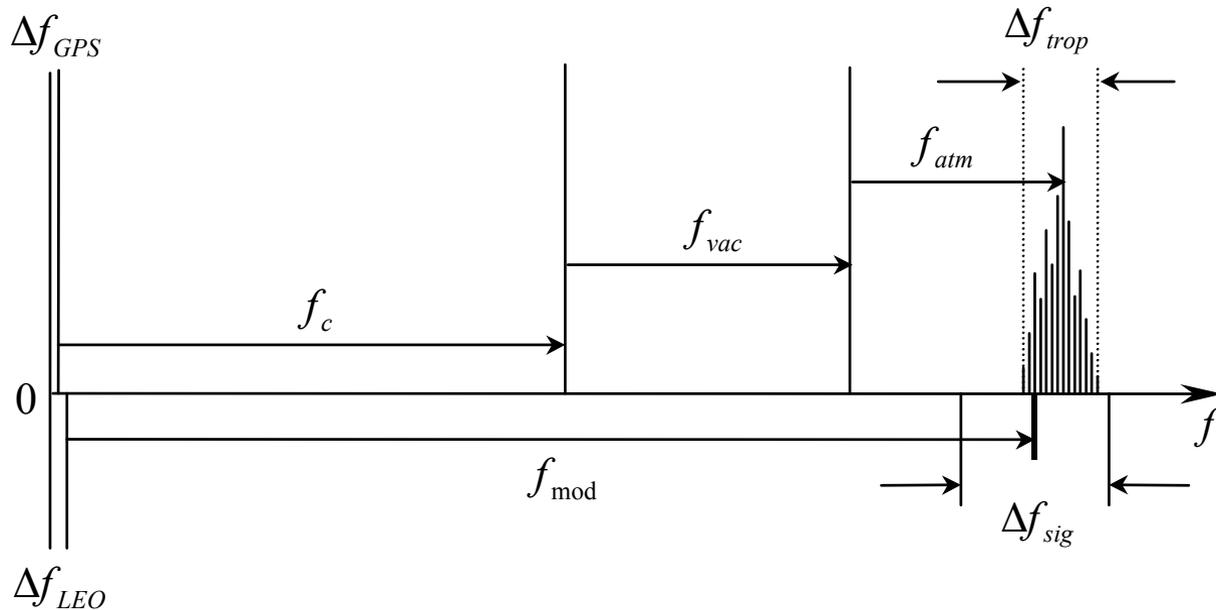
$$f_c \sim 1.5\,GHz$$
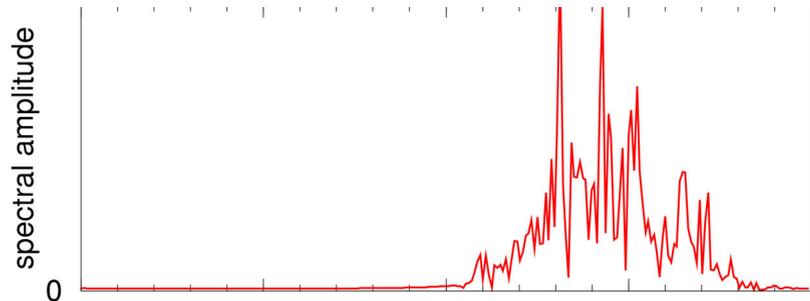$$f_{vac} \sim 0 - 30\,kHz$$
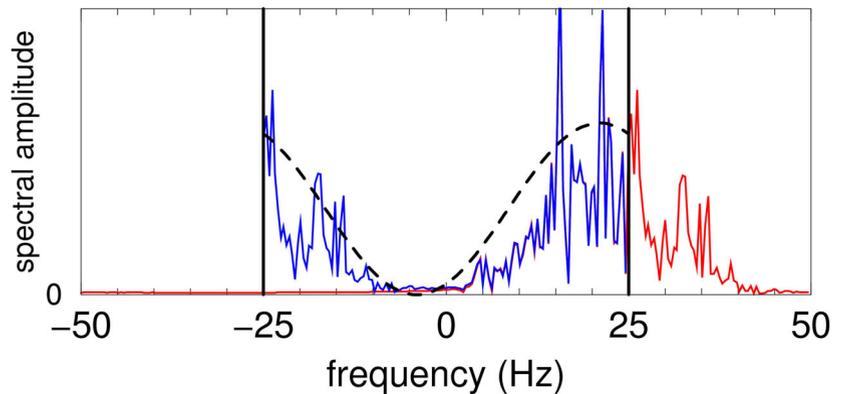$$f_{atm} \sim 0 - 1kHz$$
$$\Delta f_{trop} < 50\,Hz$$

True spectrum of the downconverted signal (100 Hz sampling).

Aliased spectrum of the downconverted signal (50 Hz sampling). The shift of the center can be estimated in the postprocessing.

Extraction of the continuous (accumulated) phase from the sampled I and Q

Why the accumulated phase is necessary?

1) for calculation of the bending angles directly from Doppler;
2) for propagation of the complex EM field from curved
   to straight-line trajectory:
-   in wave optics, by calculating Fresnel integrals;
-   in geometric optics, by continuation of rays normal to phase fronts
   (valid for short distance, to avoid caustics).

Resampling to higher rate allows to reduce the number of cycle slips.
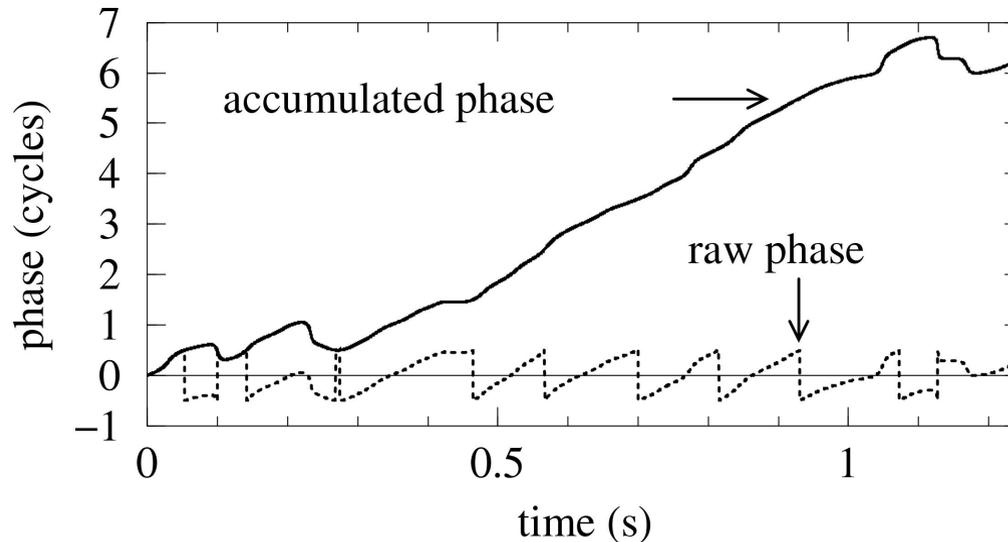
Inversions of RO signals

1) Calculation of bending angles from the complex RO signal:
canonical transform method by M.Gorbunov, 2001,2002

2) Abel inversion.

HR RAOB, 7.1N, 171.4W, 12 UTC
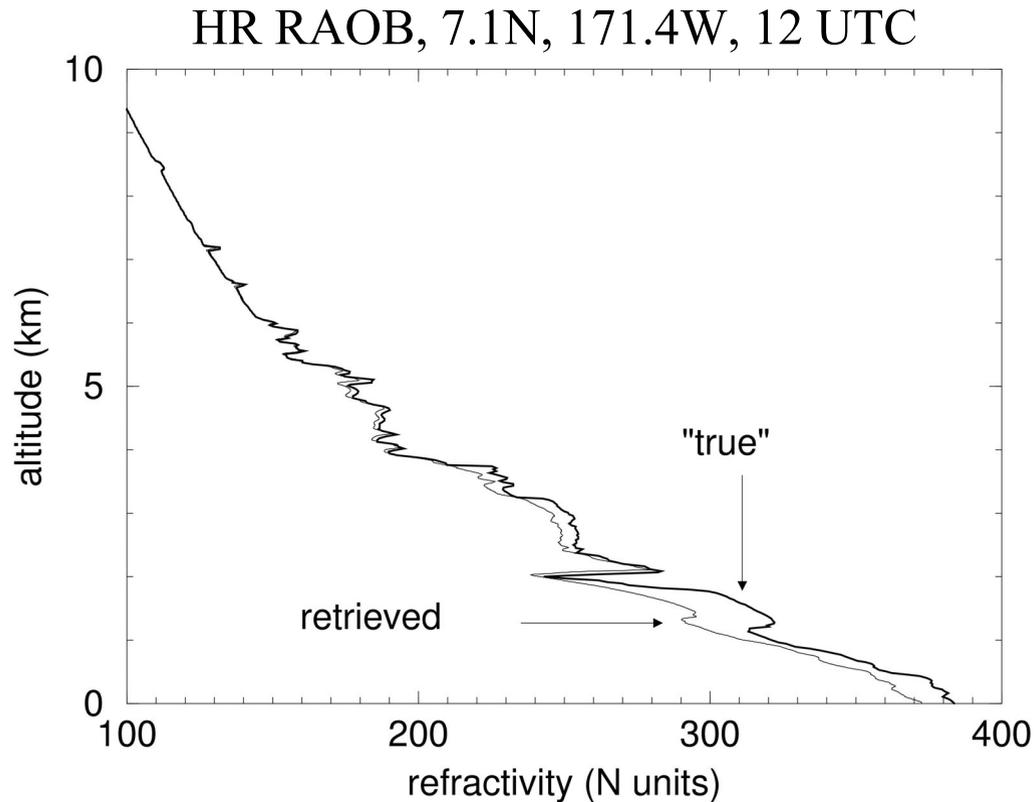
The profile inverted from RO signal sampled at 3.2 kHz on straight line
(even though affected by the super-refraction) will be used as the reference

Effect of sampling (I)
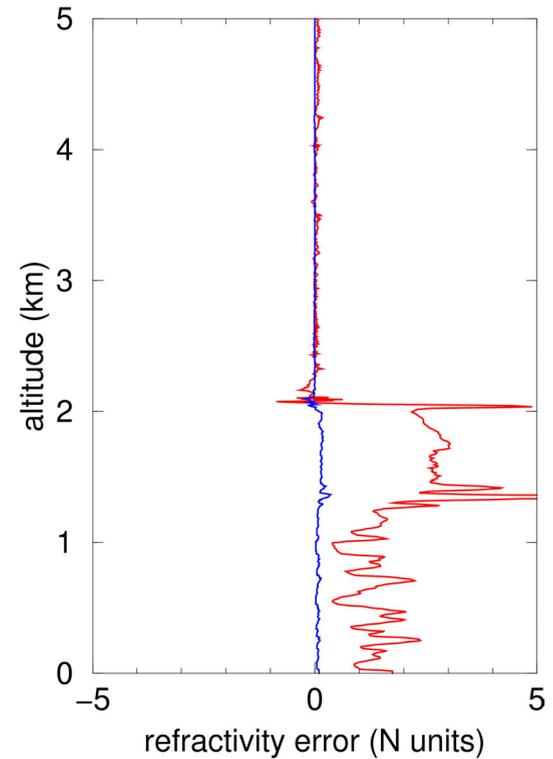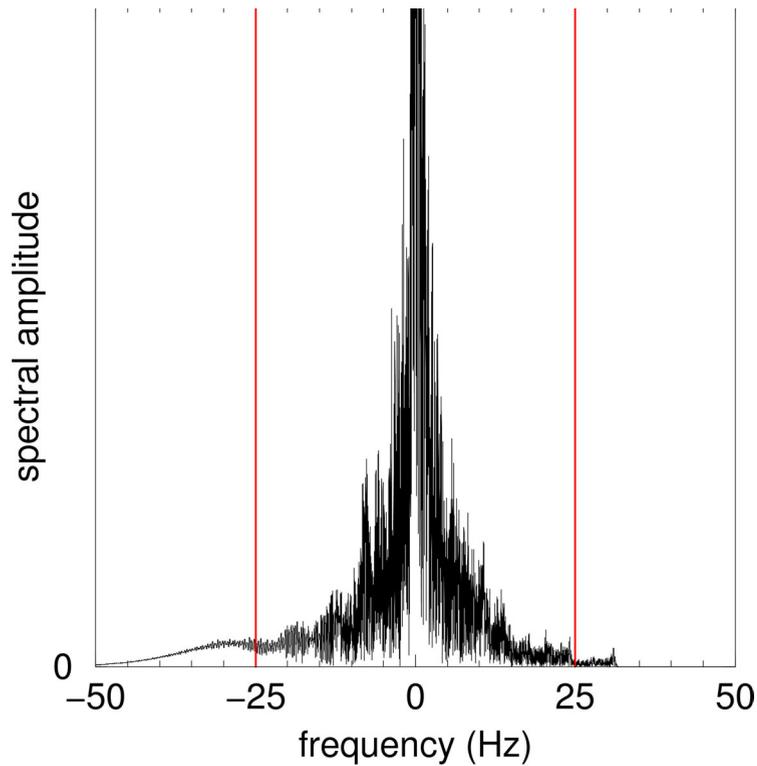(the spectral content outside is aliased inside the sampling band)
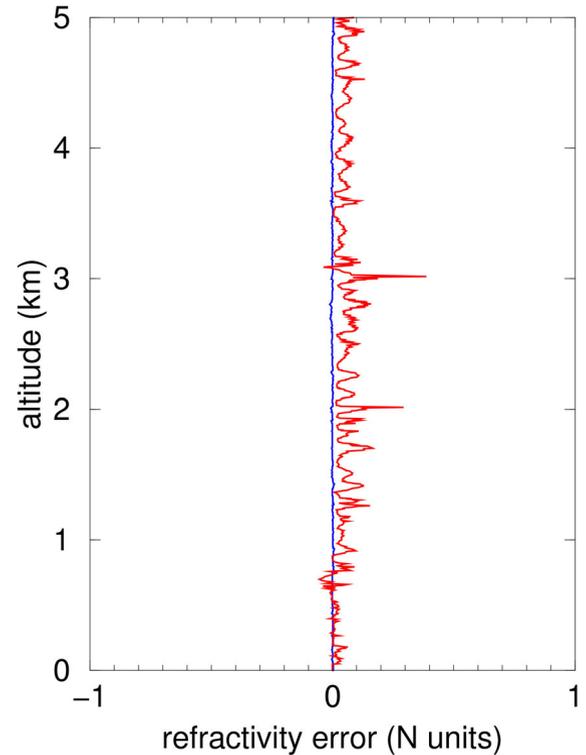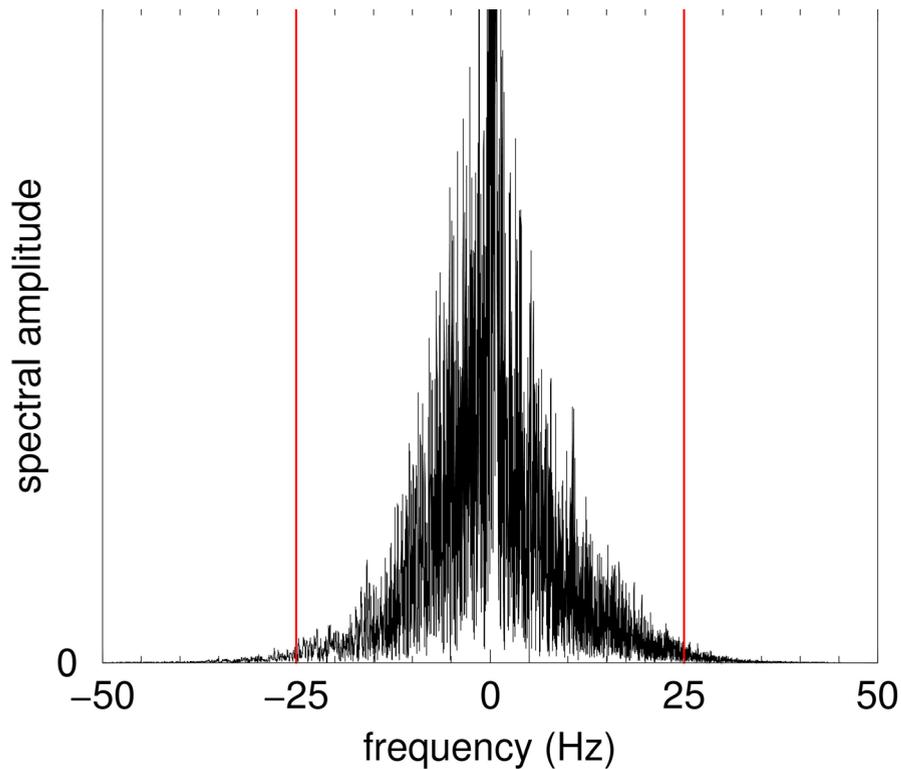
50 Hz sampling
100 Hz sampling

Effect of sampling (II)
(in the case of strong sub-refraction)
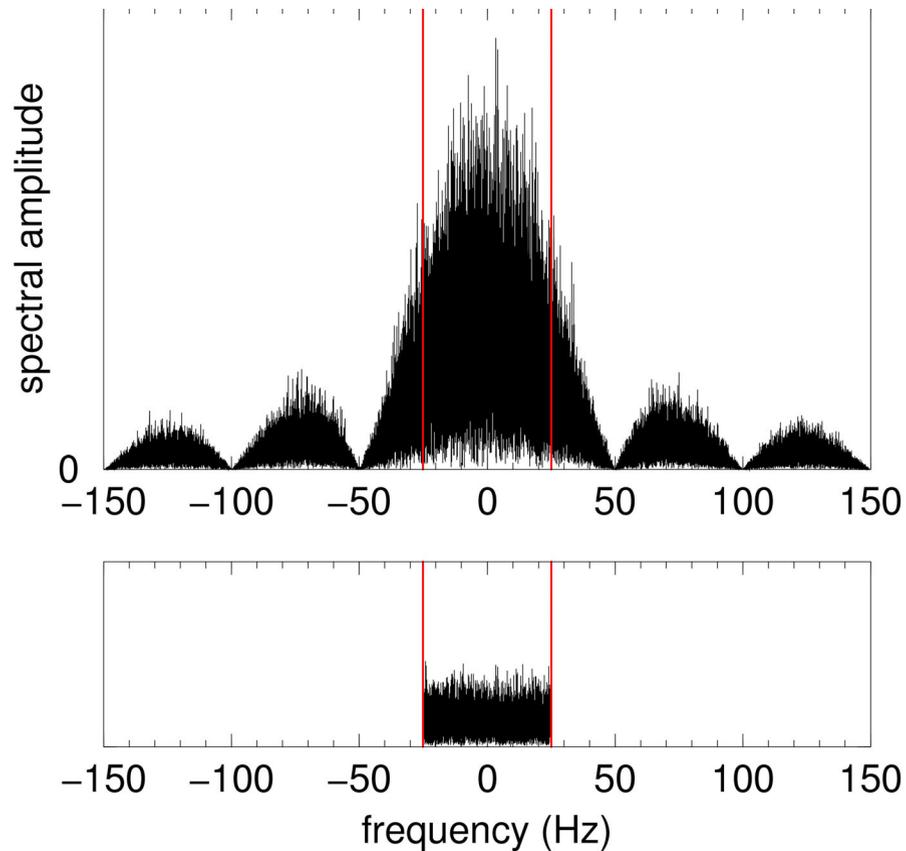
HR RAOB (1)

50 Hz sampling
100 Hz sampling

Effect of noise and filtering (integration)

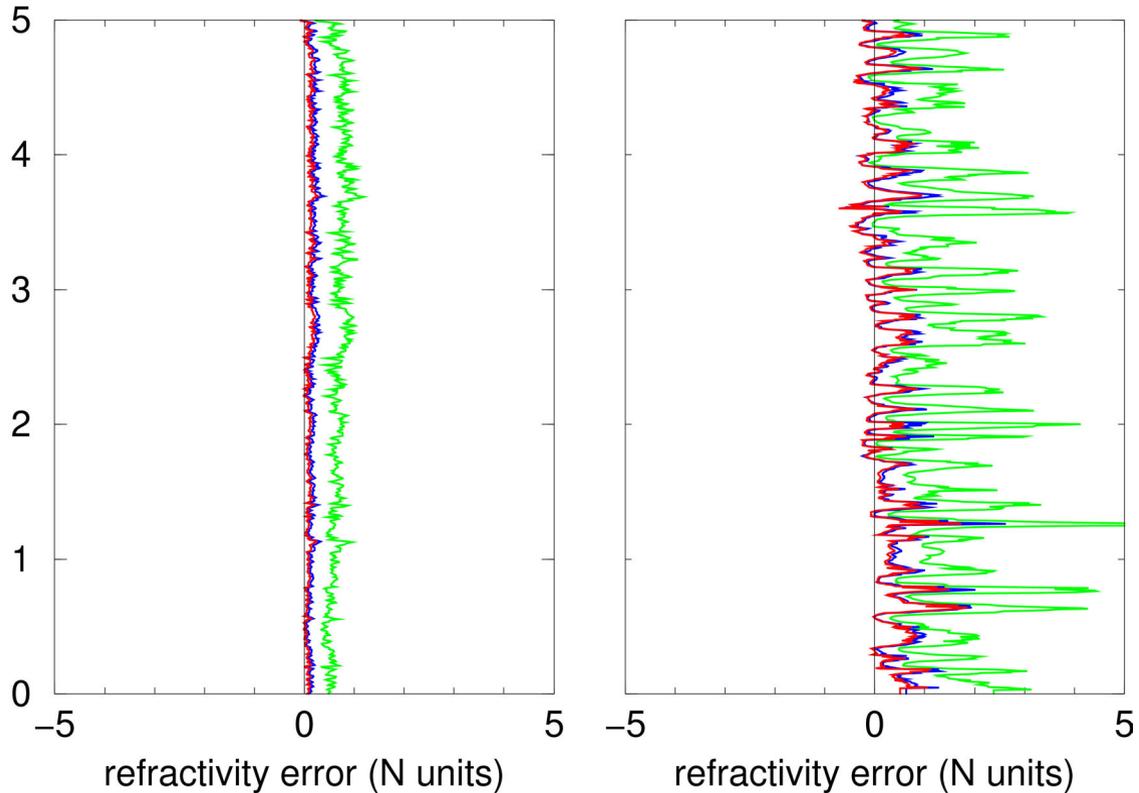20 ms integration time, 3.2 kHz sampling (white noise)

50 Hz sampling (unfiltered noise outside is aliased inside the sampling band)

Effect of noise on inversions

smooth *N*-profile   *N*-profile with irregularities

SNR~350 (GPS/MET, 4dB antenna?)
SNR~700 (CHAMP, 10dB antenna?)
SNR~900 (………., 12dB antenna?)

Effect of <u>wave optic</u> and <u>geometric optic</u> propagation to auxiliary trajectory (by use of interpolation of the accumulated phase)

WO back propagation -2000 km (calculation of Fresnel integrals)
GO forward propagation +1 km (continuation of rays normal to phase fronts)
WO back propagation -2000 km **by resampling to higher rate**
GO forward propagation +1 km **by resampling to higher rate**

smooth *N*-profile   *N*-profile with irregularities
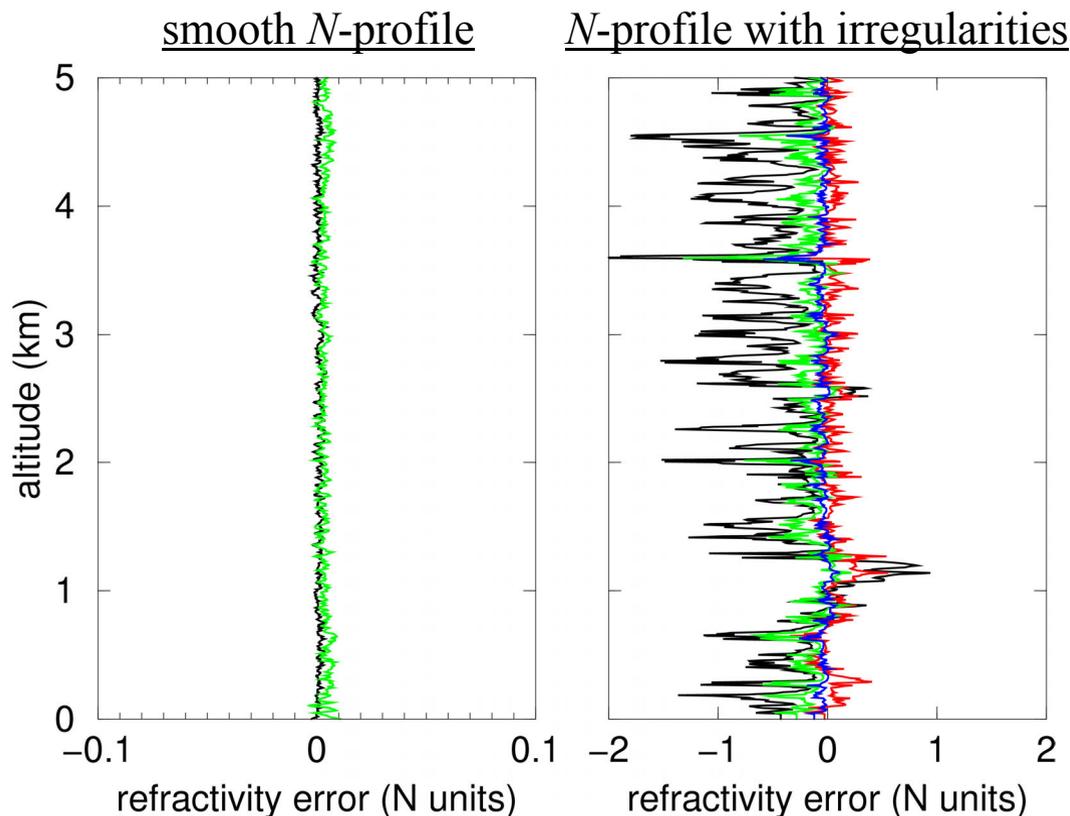
Effect of mean frequency mismodeling

Two error sources:
1) spectral aliasing (more significant)
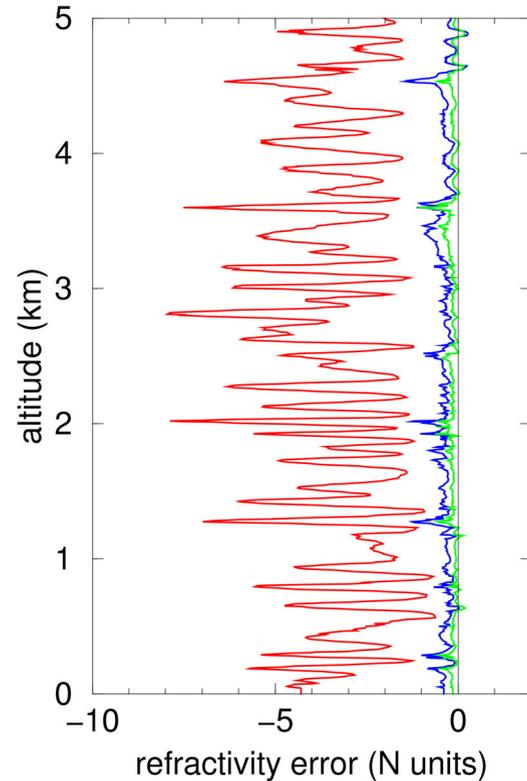2) damping of the aliased spectrum due
to integration (less significant)

Inversion of the signal
with 15 Hz mean
frequency mismodeling
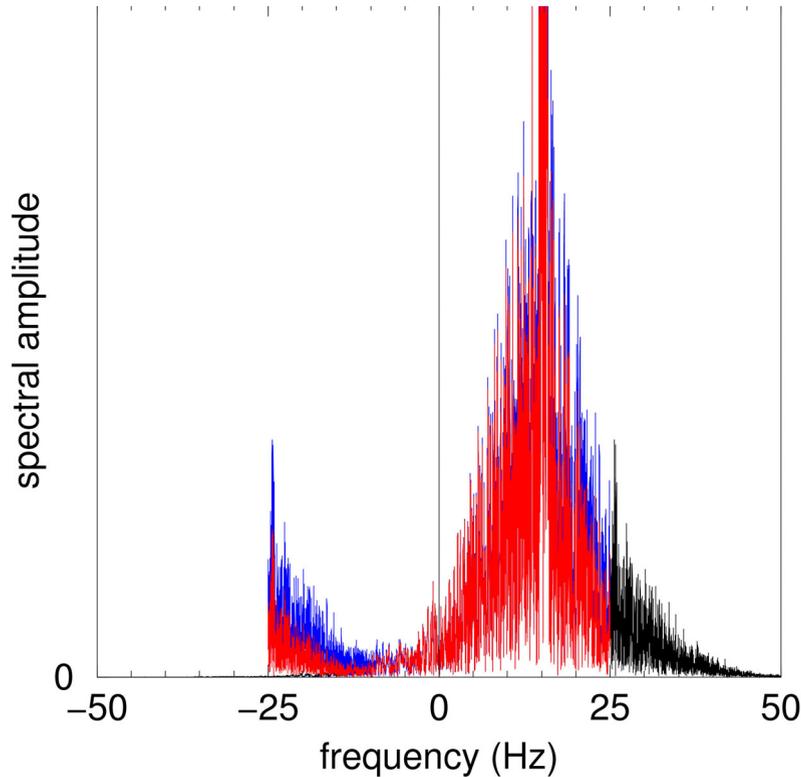
true spectrum
aliased spectrum (50 Hz sampling, 0 ms int.)
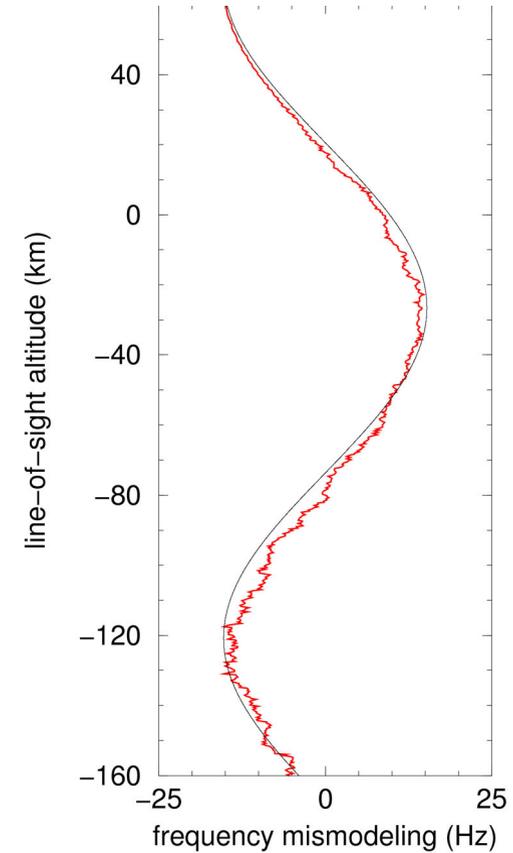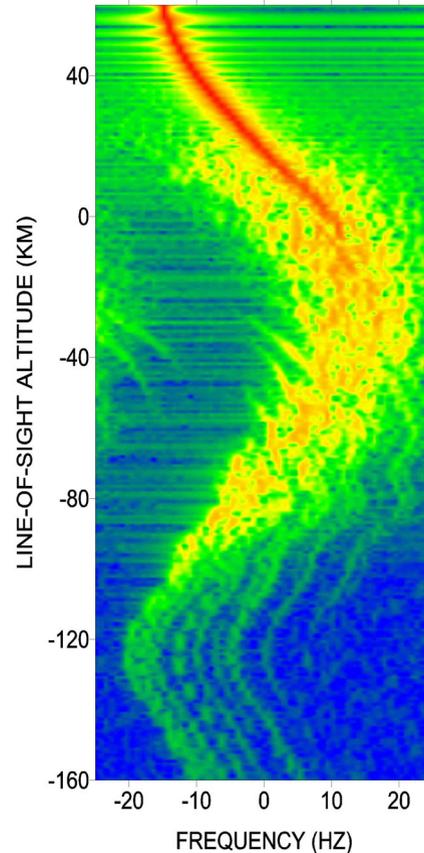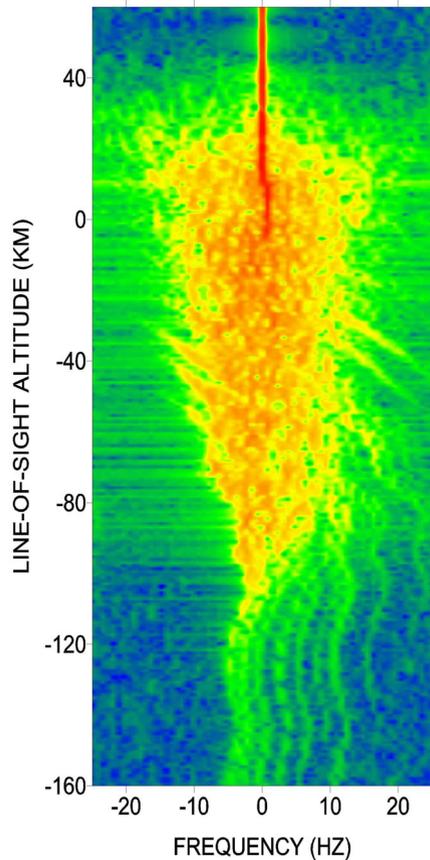aliased spectrum (50 Hz sampling, 20 ms int.)

50 Hz sampling
50 Hz sampling + frequency
correction before the inversion
100 Hz sampling

Estimation of mean frequency shift by the sliding window spectral analysis

____ an artificially introduced frequency shift
____ the frequency shift estimated based on the estimation of the center of spectrum in the sliding window

1 MHz C/A code demodulation

C/A code replica in receiver can be controlled by phase model generated similar to the Doppler model.
Accuracy of the neutral atmospheric model ~+/-15 m
Ionospheric group delay at 1.5 GHz can be as large as ~300 ns (~100 m)
Misphasing of the signal and replica is ~+/-65 m (~20% of C/A code chip)
This may result in 20% power loss (equivalent ~1dB loss of antenna gain).
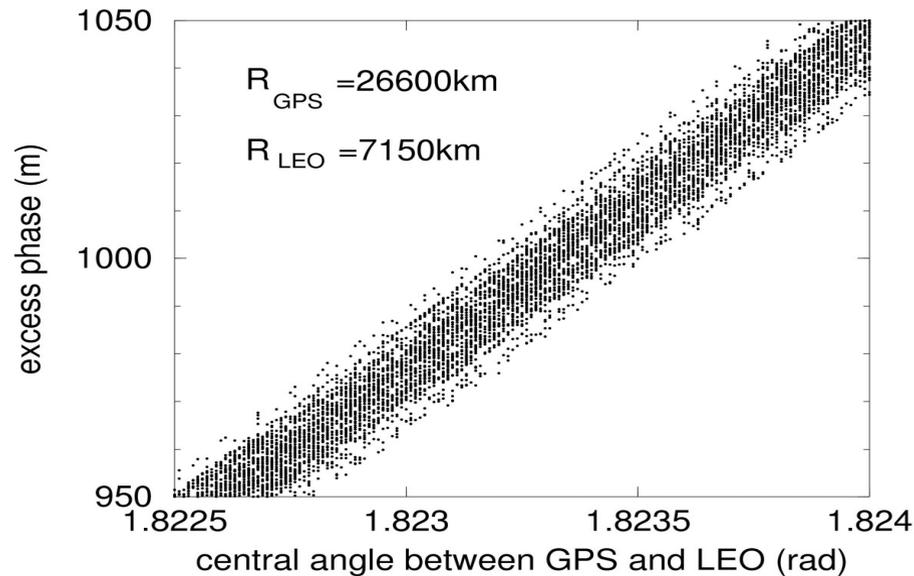
The excess phase delay for 768 refractivity profiles produced by NCEP T62 NWP model at 0-75deg N.

Effect of the duration of tracking (I)

Diffraction by small-scale irregularities spreads information about *N*-profile over longer section of LEO orbit than in case of the smooth *N*-profile. Failure to include that information in RH inversion may result in errors.
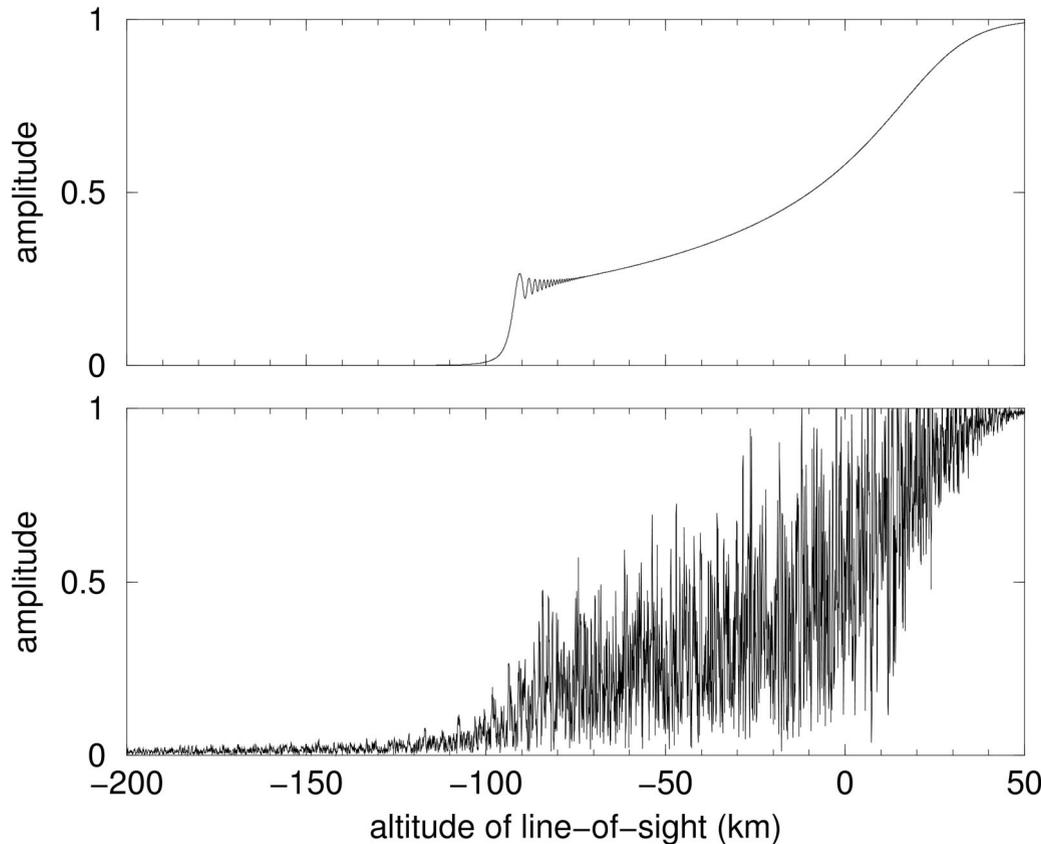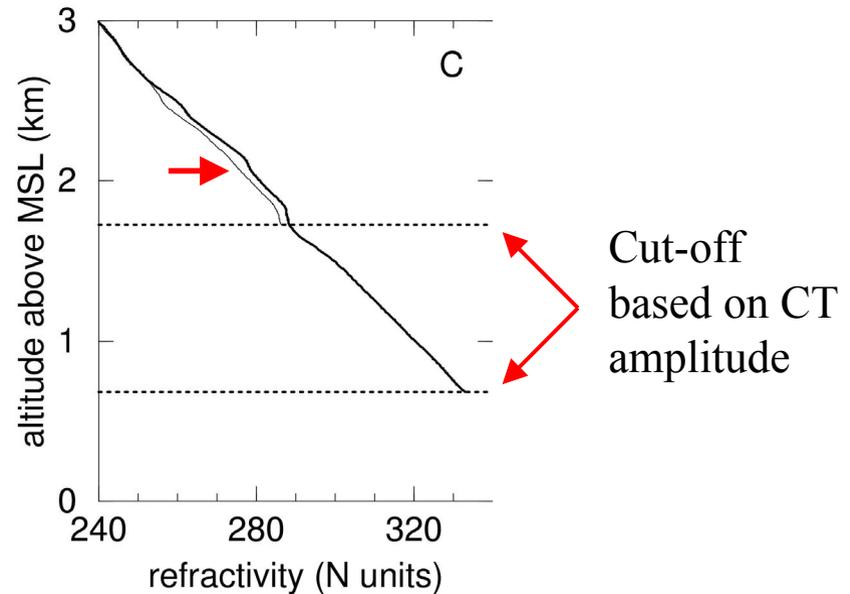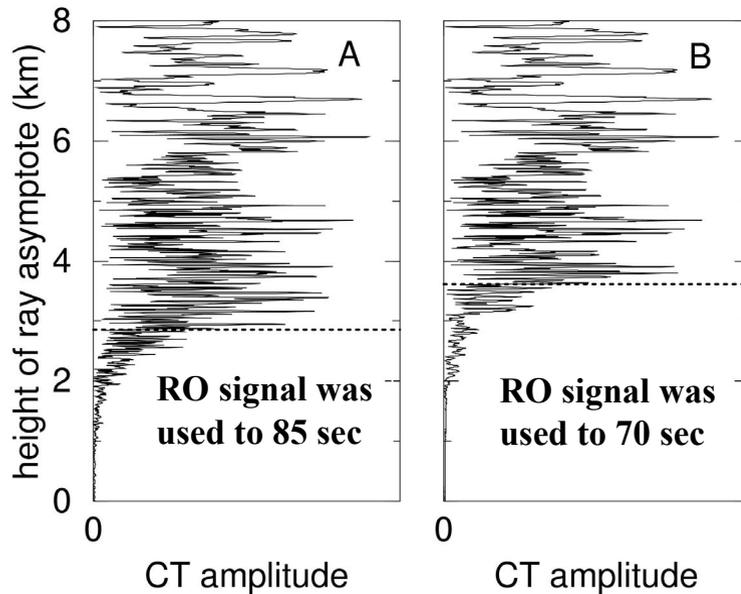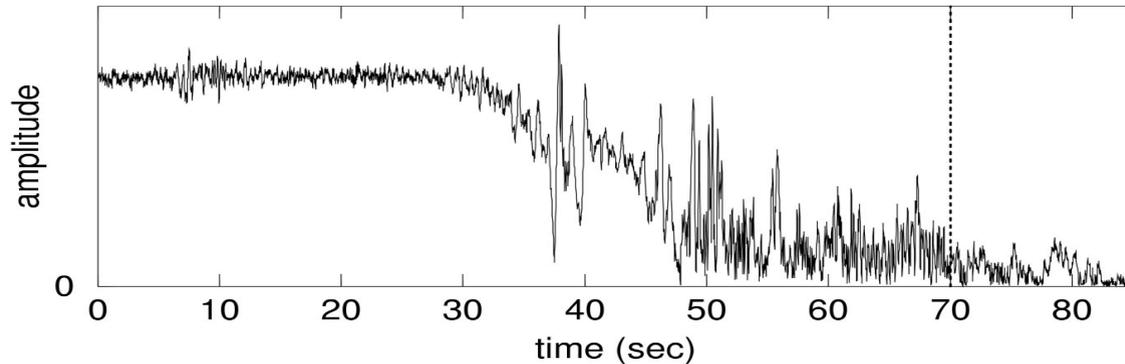

smooth (exponential) *N*-profile

N-profile with irregularities

Effect of the duration of tracking (II)

GPS/MET, June 23, 1995, 1:56 UTC, 16.7S, 171.1E

In the presence of the small-scale irregularities the concept of RO "penetration" looses clear physical sense (the errors appear above the cut-off altitude).
It is important to track RO signals down to low enough LS altitude.

Summary

Tracking RO signals, modulated by A/C code, without a feedback, by use of pre-calculated phase model, is feasible in the lower troposphere. Also, this will allow tracking rising occultations.

Thermal noise with ~10dB antenna is not a dominant error source ($<1N$)

The largest errors (~$5N$) can be introduced at 50Hz sampling due to:
1) large mean frequency mismodeling $\Delta f_{mis\,mod} + \Delta f_{spread}/2 > f_{samp}/2$ but this error can be corrected in the postprocessing.;
2) strong sub-refraction (how often it happens in the atmosphere ???).

Conclusion

It is feasible to keep both 50 and 100 Hz sampling rates. During test period to apply 100 Hz sampling and to process data in two modes:
1) as 100 Hz data;
2) as 50 Hz data (by applying additional integration and decimation).
To compare the results and to conclude about the sufficient rate.