Post-processing of COSMIC open-loop radio occultation signals at CDAAC

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1995: Problems of PLL in moist LT found

OL tracking (raw sampling) applied for planetary occultations used high sampling rate (50 kHz)

2001: Principles of model-aided RO OL tracking developed

   - sampling RO signal at minimal (Nyquist) rate;
   - reconstruction of RO signal from complex samples

2005: OL tracking of GPS RO L1 signal tested on SAC-C by Jet Propulsion Laboratory

2006: OL tracking applied routinely on six COSMIC satellites

This talk: Summary of the principles and their validation based on reconstruction of COSMC OL signals

   - validation of the two frequency models used in the OL PP;
   - validation of the two methods of removal of the NDM

Spectrum of RO signal
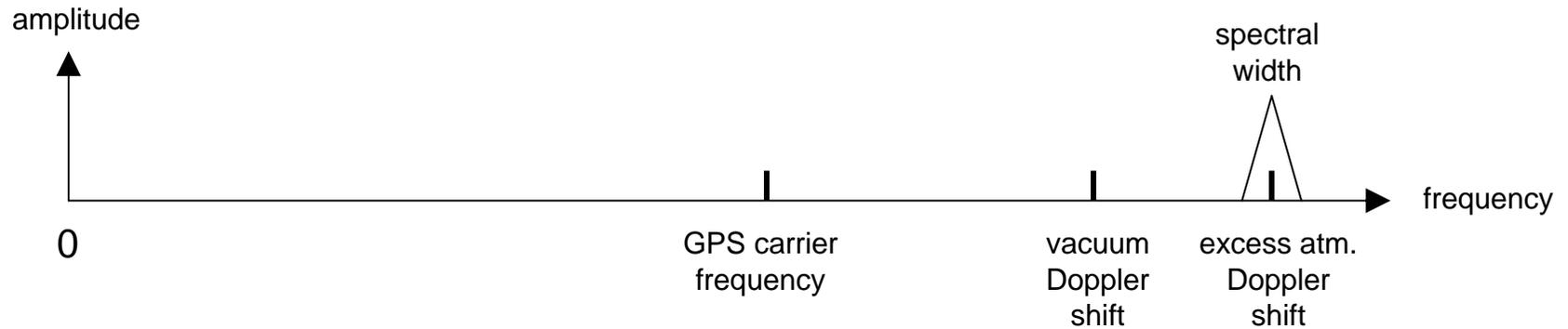
Minimal sampling rate is limited by the spectral width

Raw sampling at minimal rate:
Aliasing of the signal spectrum + aliasing of noise = low SNR

Needed: noise filtering before sampling; reduction of frequency; modeling of the frequency

Model-aided sampling rates:
modeling of carrier frequency ~ 50 kHz
modeling of Doppler shift in a vacuum ~ 3 kHz
modeling of excess Doppler shift in the atmosphere ~ 50 Hz

In receiver:

1) down-conversion (the phase model does not use feedback)

$$u_{down}(t) = u_{in}(t)\exp[-i\Phi_{rec\,mod}(t)]$$

2) low-pass filtering (integration)

$$I_{out}(t) = \Delta t^{-1}\int_{t}^{t+\Delta t}\mathrm{Re}[u_{down}(t')]dt'$$

$$Q_{out}(t) = \Delta t^{-1}\int_{t}^{t+\Delta t}\mathrm{Im}[u_{down}(t')]dt'$$

$$\Delta\Phi_{out} = \arctan 2(Q_{out}, I_{out})$$

3) output signal sampling

$$u(t) = A(t)\exp[i\Phi_{rec\,mod}(t) + \Delta\Phi_{out}(t)] = I(t) + iQ(t)$$

Important: output signal contains NDM; sampling intervals aligned with received NDM bit sequence, not with standard GPS time tags
Important: the only purpose of receiver model is noise filtering.
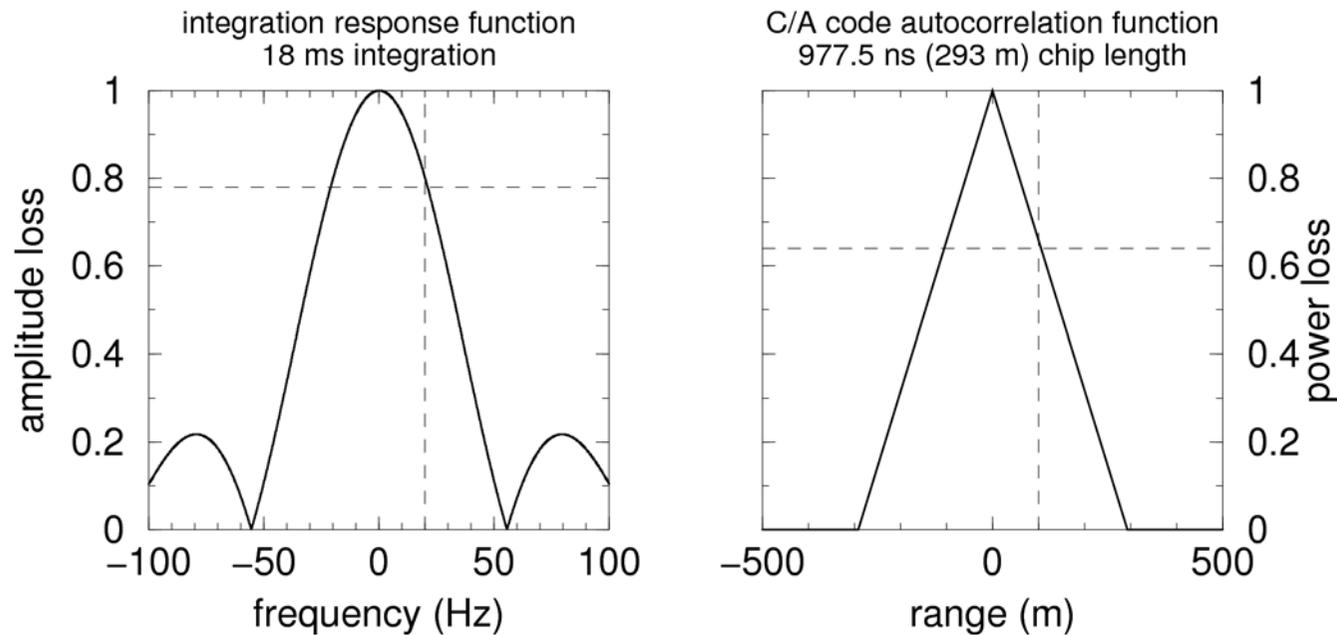The phase is connected between samples in the post-processing.

In receiver: two models run in real time <u>without a feedback</u>

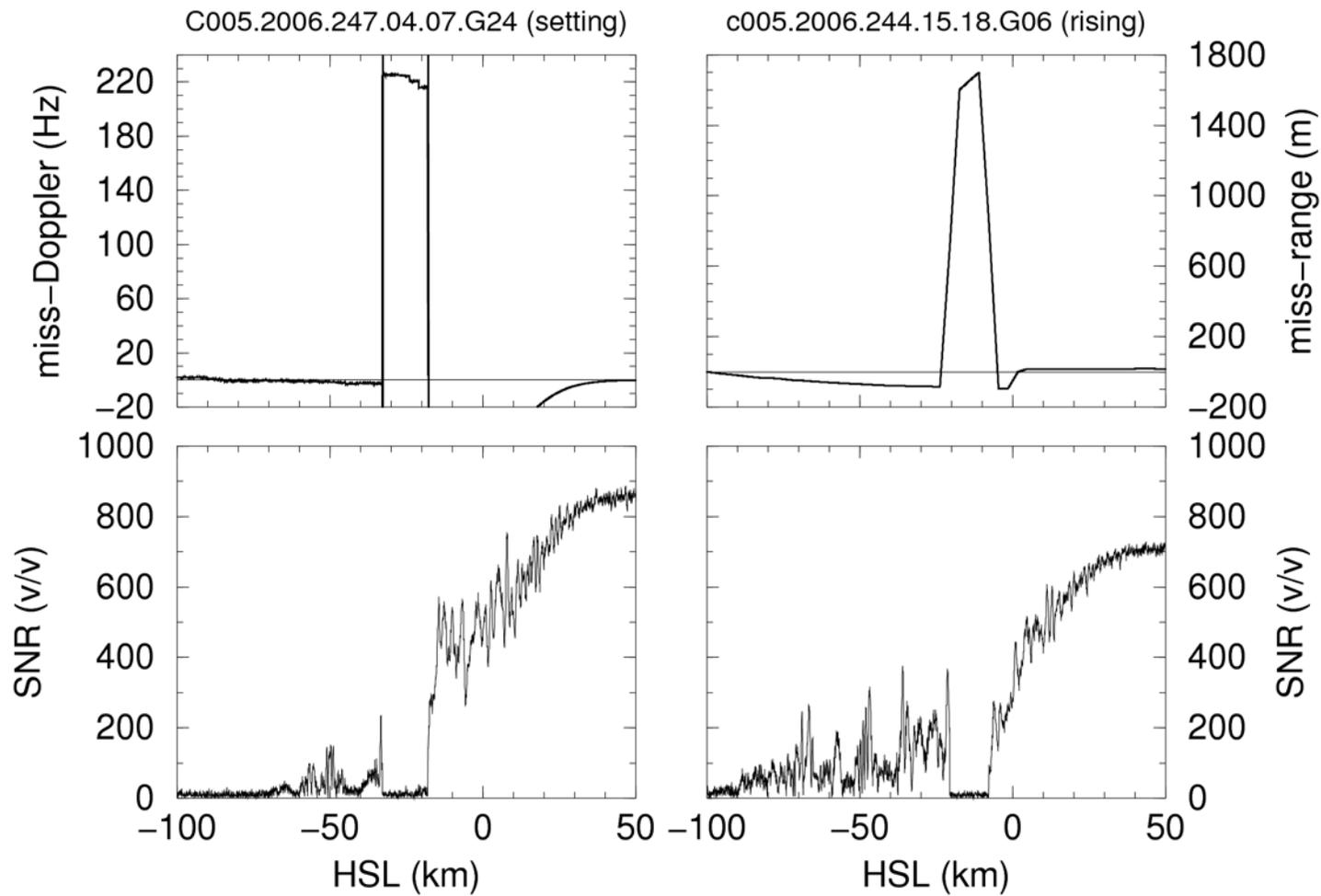Phase (frequency) model – frequency reduction for noise filtering

Range model – C/A code demodulation

Miss-modeling results in reduction of SNR (OL SNR lower than PLL)

Examples of large frequency and range miss-modeling

HSL – height of straight line between GPS and LEO

C005.2006.247.04.07.G24 (setting)　　c005.2006.244.15.18.G06 (rising)

<u>In the post-processing:</u> OL RO signal is considered as the sequence of complex samples with un-connected phase.

Important: receiver model is not used in the post-processing

1) down-conversion (frequency model discussed later)

$$u_{down}(t) = u(t)\exp[-i\Phi_{mod}(t)]$$

2) removal of the NDM (discussed later)

3) connection of the phase between samples

$$\Delta\Phi = \arctan 2(Q, I)$$

$$\Delta\Phi_i = \Delta\Phi_i + 0 \quad \text{or} \quad +2\pi \quad \text{or} \quad -2\pi$$

$$\text{whichever minimizes} \quad |\Delta\Phi_i - \Delta\Phi_{i-1}|$$

$$\Phi = \Phi_{mod} + \Delta\Phi$$

Frequency model 0 – based on the post-processed orbits and clock and the bending angle model (impact height, latitude, month).

The bending angle model is calculated from refractivity model based on CIRA+Q climatology [Kirchengast et al., 1999].

1) given: radii of the GPS and LEO;
                   central angle between the GPS and LEO;
                   bending angle (impact height);
    solve for: zenith angles of a ray at GPS and LEO

2) given: zenith angles of a ray at GPS and LEO;
                   velocities of the GPS and LEO
    calculate: frequency

Frequency model 1 – Frequency model 0 adjusted by use of the feedback from RO signal reconstructed with the use of the model 0

Internal removal of NDM (similar to that in PLL) requires
phase lapse between samples (atmospheric modulation +
+ residual frequency + noise) < 1/4 cycle

$$\text{If } (I_i I_{i-1} + Q_i Q_{i-1}) < 0 \text{ then } I_i = -I_i \text{ and } Q_i = -Q_i$$

- results in 2-quadrant phase extraction;
- works well for high-latitude occultations;
- results in errors for tropical occultations in LT
- these errors contribute to unstable operation of PLL in LT

External removal of NDM by aligning the externally recorded
NDM bit sequence with RO signal samples by accounting
for the propagation time between GPS and LEO.

- results in 4-quadrant phase extraction

COSMIC deployed a netwrok of the ground-based receivers for
collection of the NDM bit sequences (USA (Boulder), Germany
(Potsdam), Taiwan, New Zeland, South Africa, Brazil).

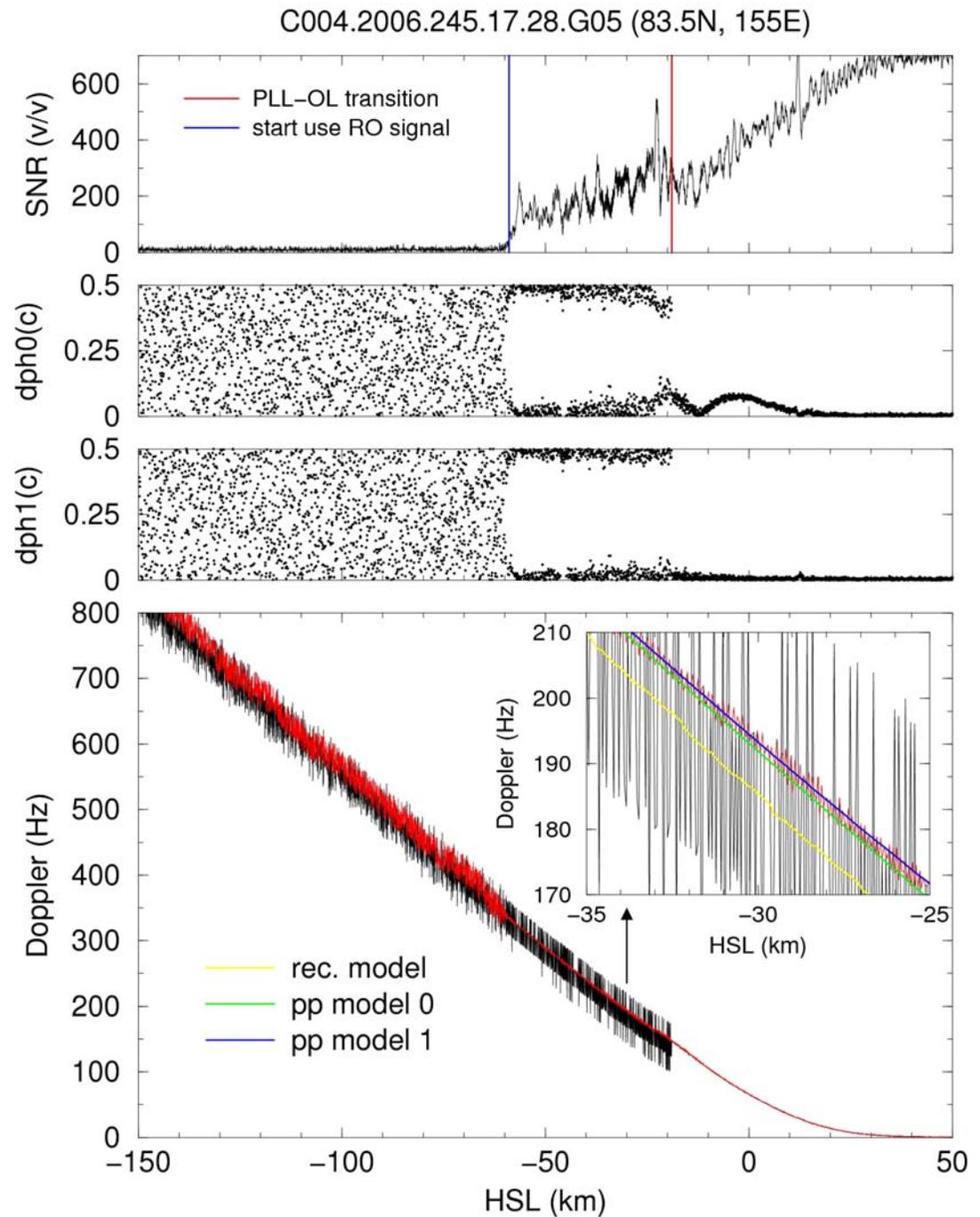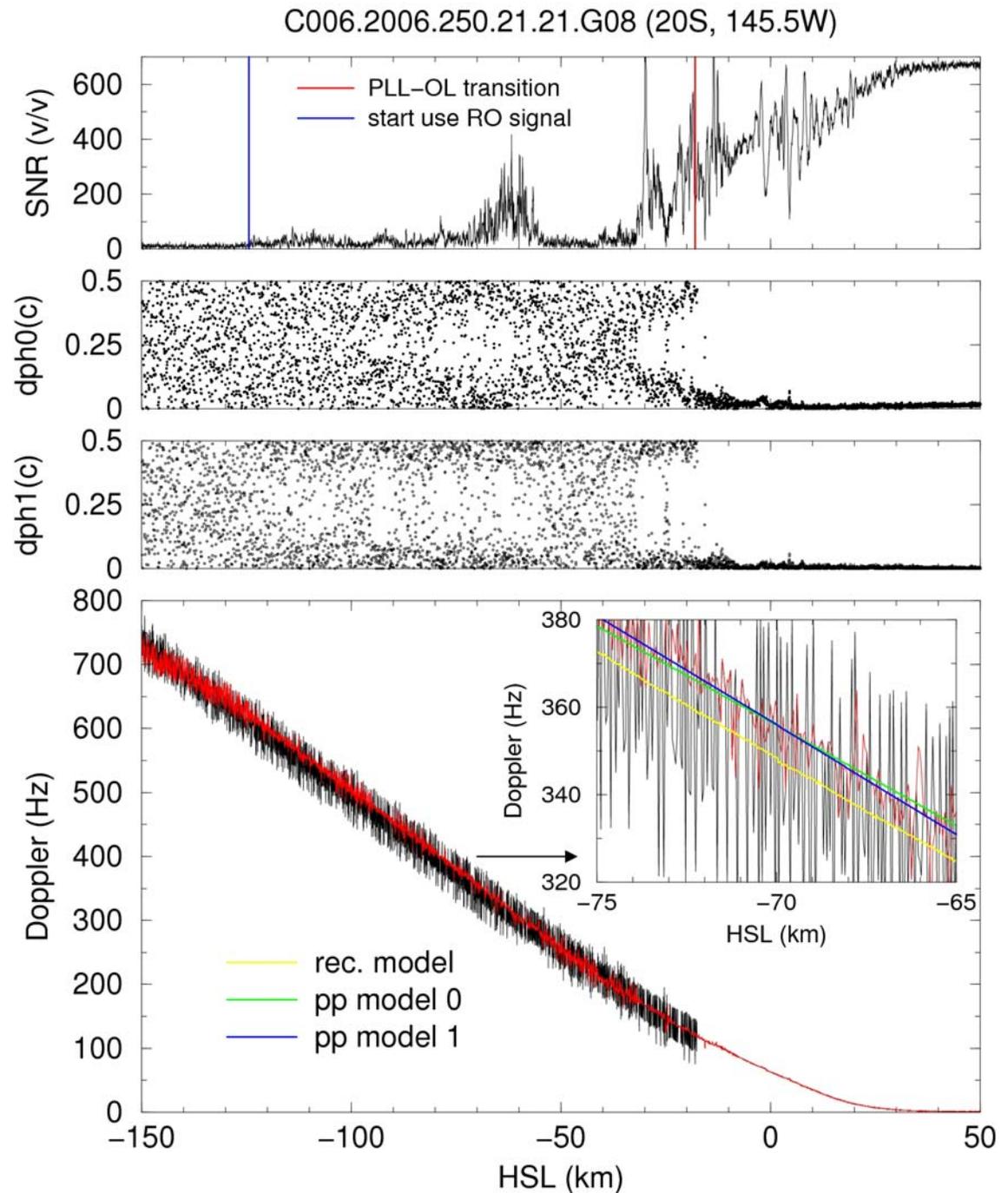# High-latitude occultation

Noise level: 3 s averaged
SNR at the end

Start use RO signal:
1s-averaged SNR exceeds
noise level by 50%

Phase lapse (atmosphere-
-induced modulation +
+ residual frequency +
+ noise) < 1/4 cycle

NDM clearly distinguishable

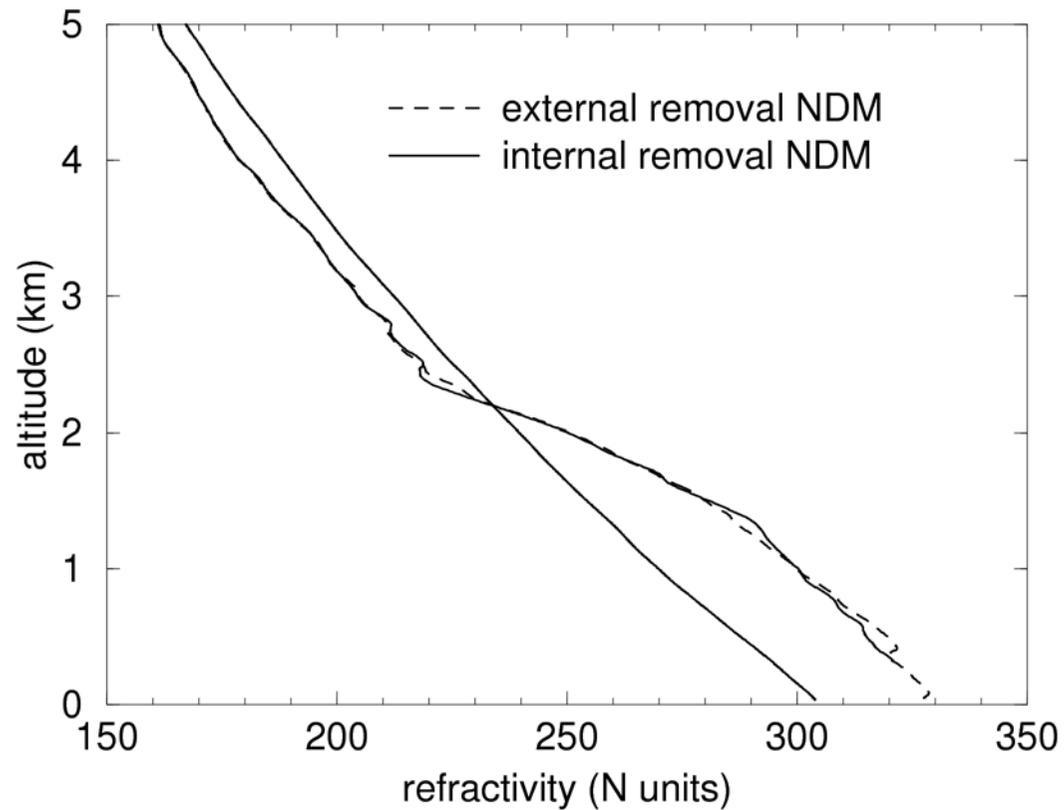internal NDM removal
does not result in errors

C004.2006.245.17.28.G05 (83.5N, 155E)

Low-latitude occultation

Noise level: 3 s averaged SNR at the end

Start use RO signal: 1s-averaged SNR exceeds noise level by 50%

Phase lapse (atmosphere--induced modulation + + residual frequency + + noise) > 1/4 cycle

NDM not clearly distinguishable

internal NDM removal does result in errors

C006.2006.250.21.21.G08 (20S, 145.5W)

Refractivity profiles retrieved with internal and external removal of NDM for the two COSMIC occultations

High-latitude occultation - no difference

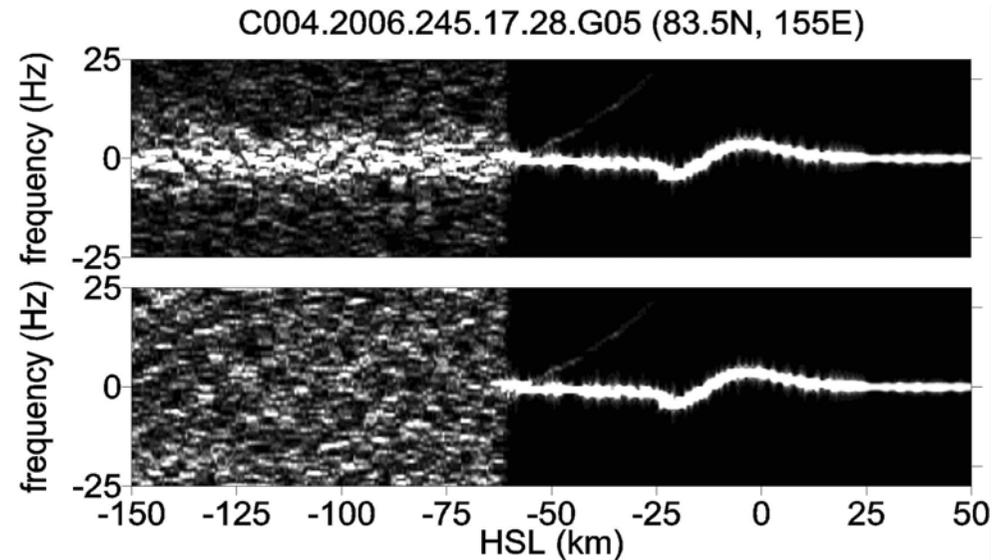## Low-latitude occultation - some difference

From Model 0 to Model 1

Sliding spectrograms of RO signals. Down-conversion with Model 0.

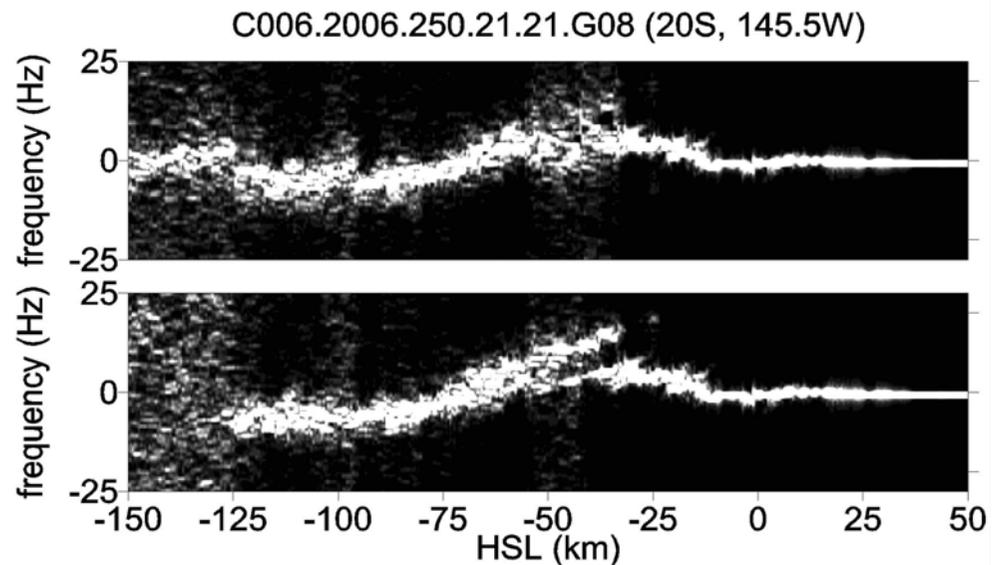**High-latitude occultation**

- internal NDM removal

- external NDM removal
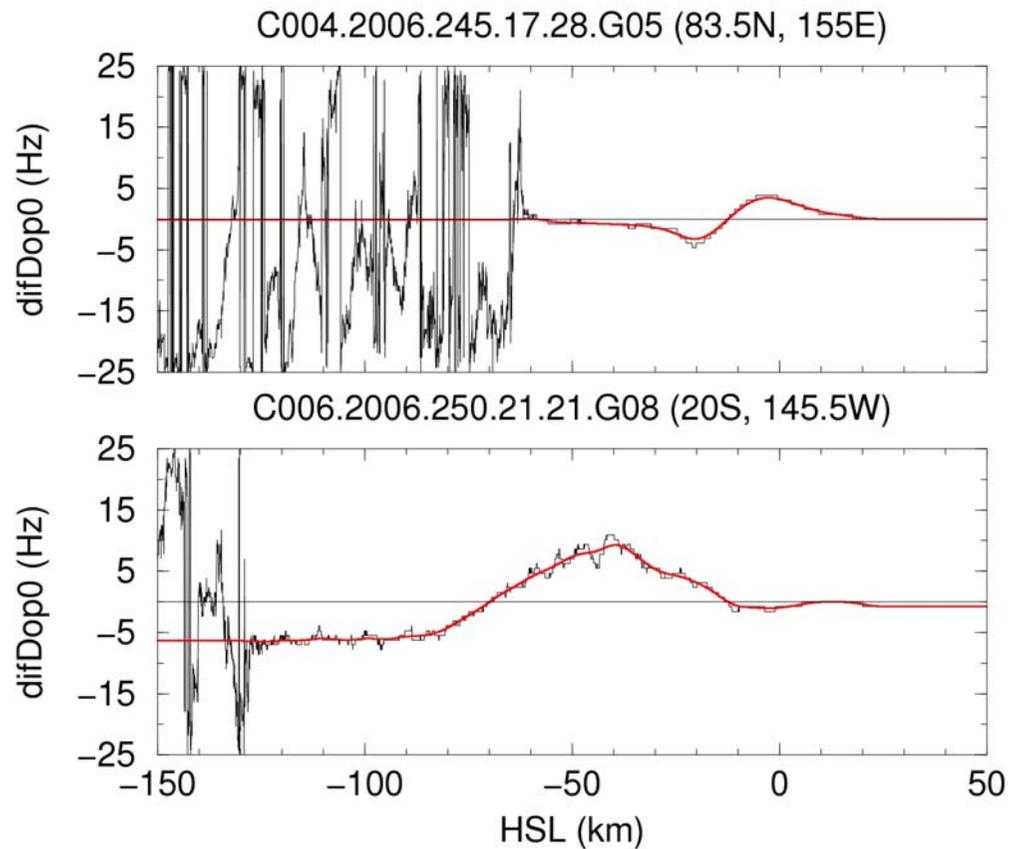
Low-latitude occultation

- internal NDM removal

- external NDM removal
  (reveals multipath)

Frequency miss-modeling determined from the sliding spectrograms
after down-conversion with Model 0 can be used for adjustment
of the frequency model
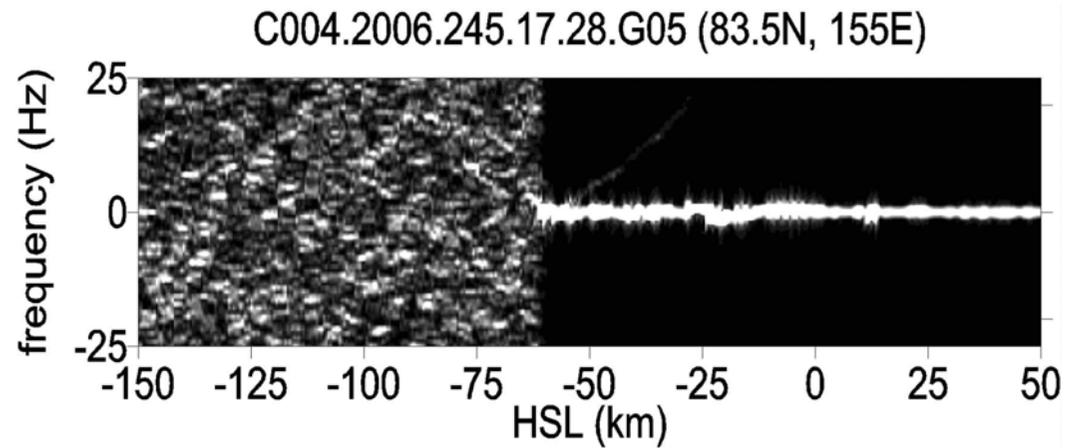
$$f^1_{\text{mod}} = f^0_{\text{mod}} + \Delta f$$
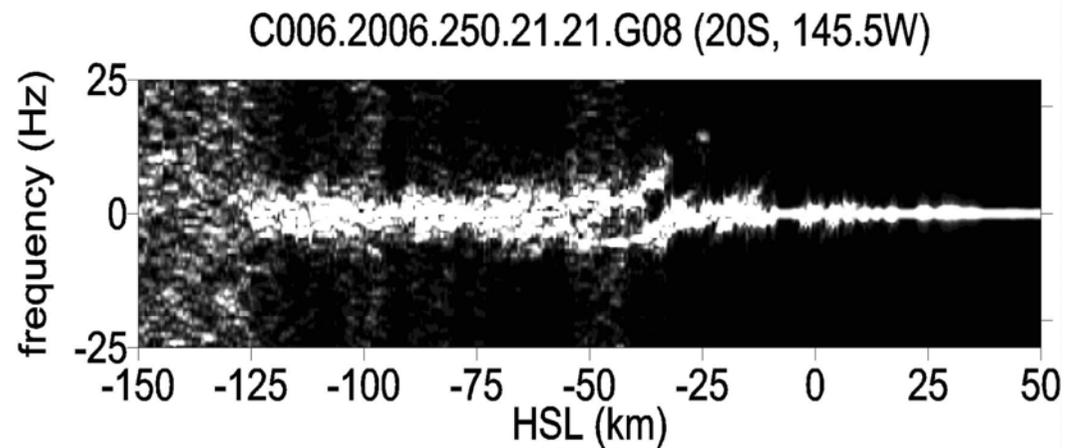
High-latitude occultation
external NDM removal

Low-latitude occultation
external NDM removal

C004.2006.245.17.28.G05 (83.5N, 155E)

C006.2006.250.21.21.G08 (20S, 145.5W)

Sliding spectrograms of RO signals after down-conversion with Model 1

High-latitude occultation
external NDM removal

Low-latitude occultation
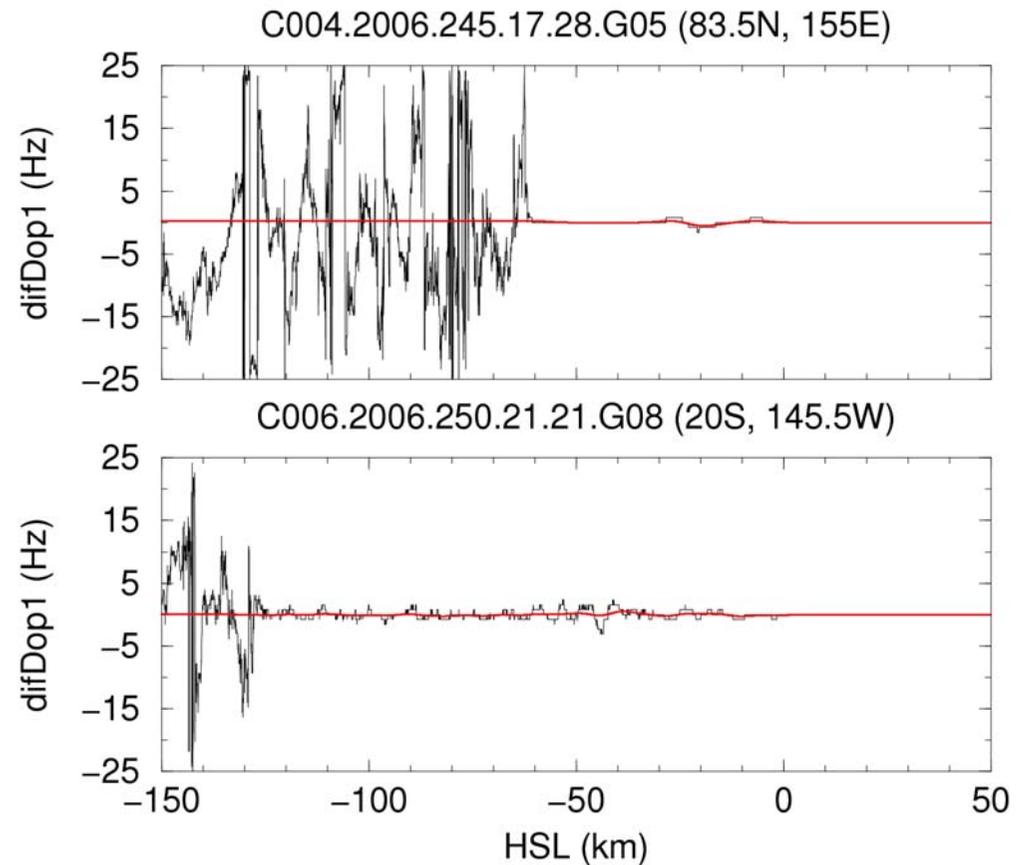external NDM removal

C004.2006.245.17.28.G05 (83.5N, 155E)

C006.2006.250.21.21.G08 (20S, 145.5W)

The residual frequency miss-modeling after down-conversion with Model 1 is substantially reduced


High-latitude occultation
external NDM removal

Low-latitude occultation
external NDM removal

Another method for determining
frequency miss-modeling based
on smoothed frequency after
down-conversion with Model 0

- computationally more simple
  than the spectrograms
- may need more iterations
- affected by cycle slips
- does not allow detection
  of the multipath

C004.2006.245.17.28.G05 (83.5N, 155E)

C006.2006.250.21.21.G08 (20S, 145.5W)
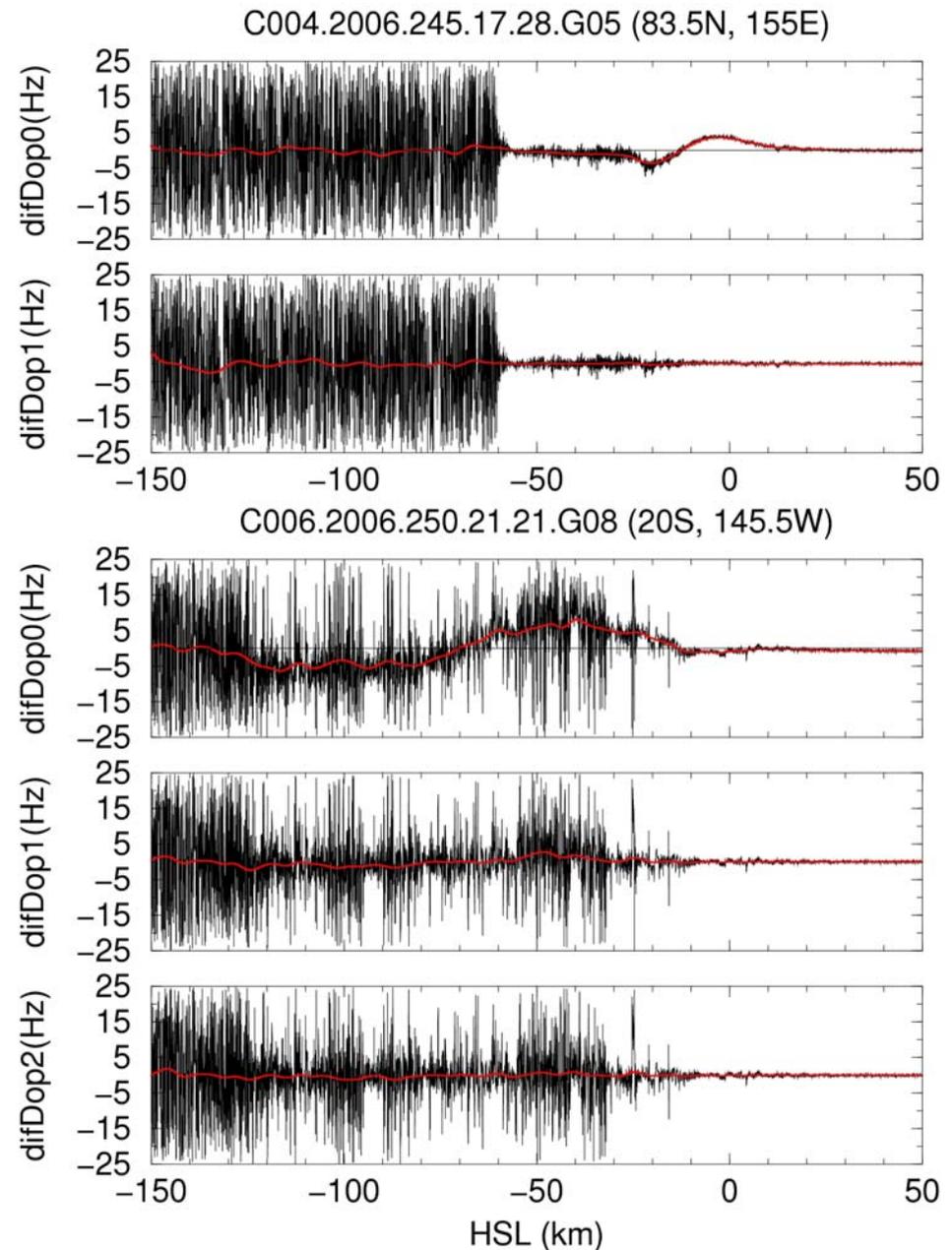
Important: when accuracy of first guess (Model 0) is within +/- 25 Hz, the results of the post-processing after adjustment of the model do not depend on the first guess (Model 0).

Maximal frequency miss-modeling after down-conversion with Model 0

Maximal frequency miss-modeling after down-conversion with Model 1
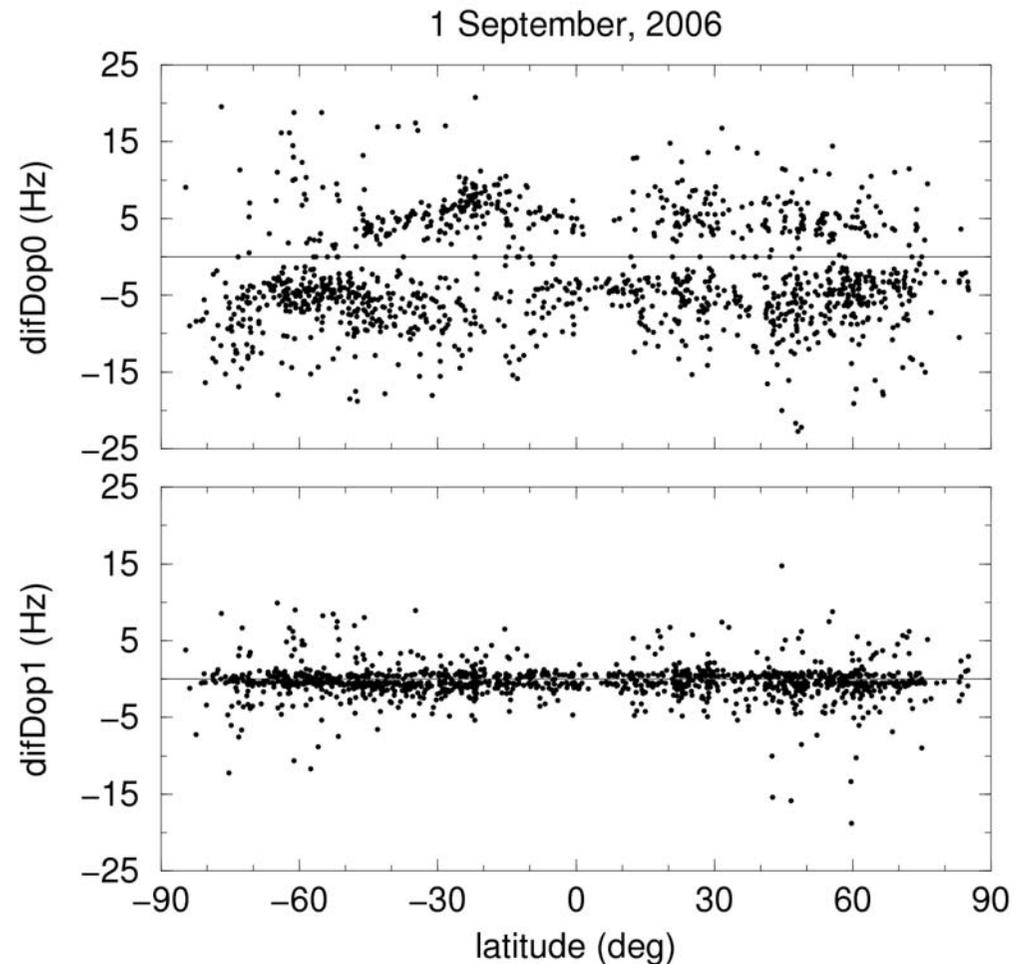
1 September, 2006

Statistical comparison of inverted COSMIC refractivities
in LT in tropics (30S – 30N) for September 2006

10490 occultations:
7077 - externally recorded NDM bit sequences available
3413 - externally recorded NDM bit sequences <u>not</u> available

Only the occultations with available NDM were processed:
- with internal and external removal of NDM;
- with Model 0 and Model 1 for down-conversion

ECMWF 21-level analysis is used as the reference

- the differences between RO and ECMWF analysis
  (caused by different factors) are not considered;
- only the differences between different processing
  modes are considered;
- important: when a difference is found it is known
  which processing mode is responsible for the error

The first guess Model 0 (based on CIRA+Q) is sufficient when externally recorded NDM bit sequence is available
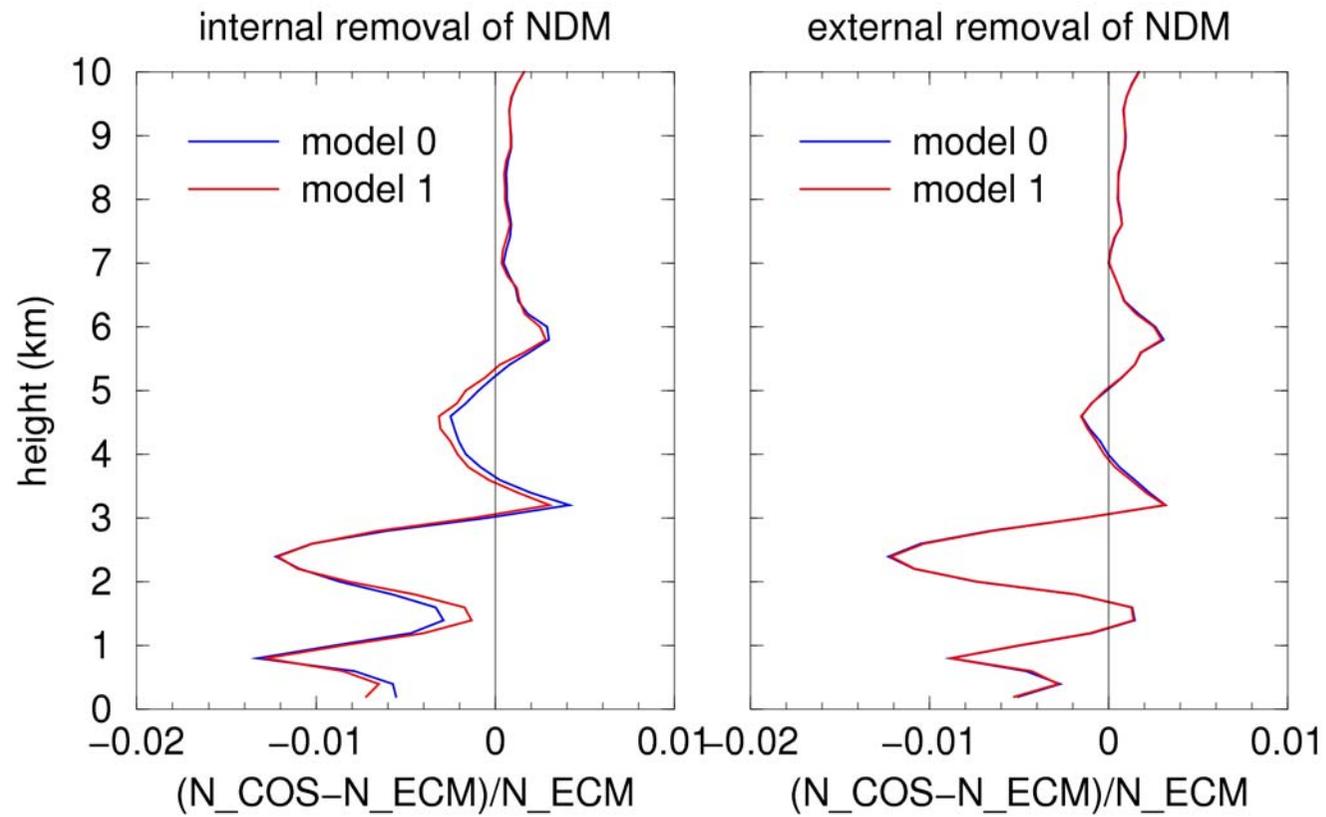
External removal of NDM results in reduction of the errors of the post-processing, even with the adjustment of the frequency model.
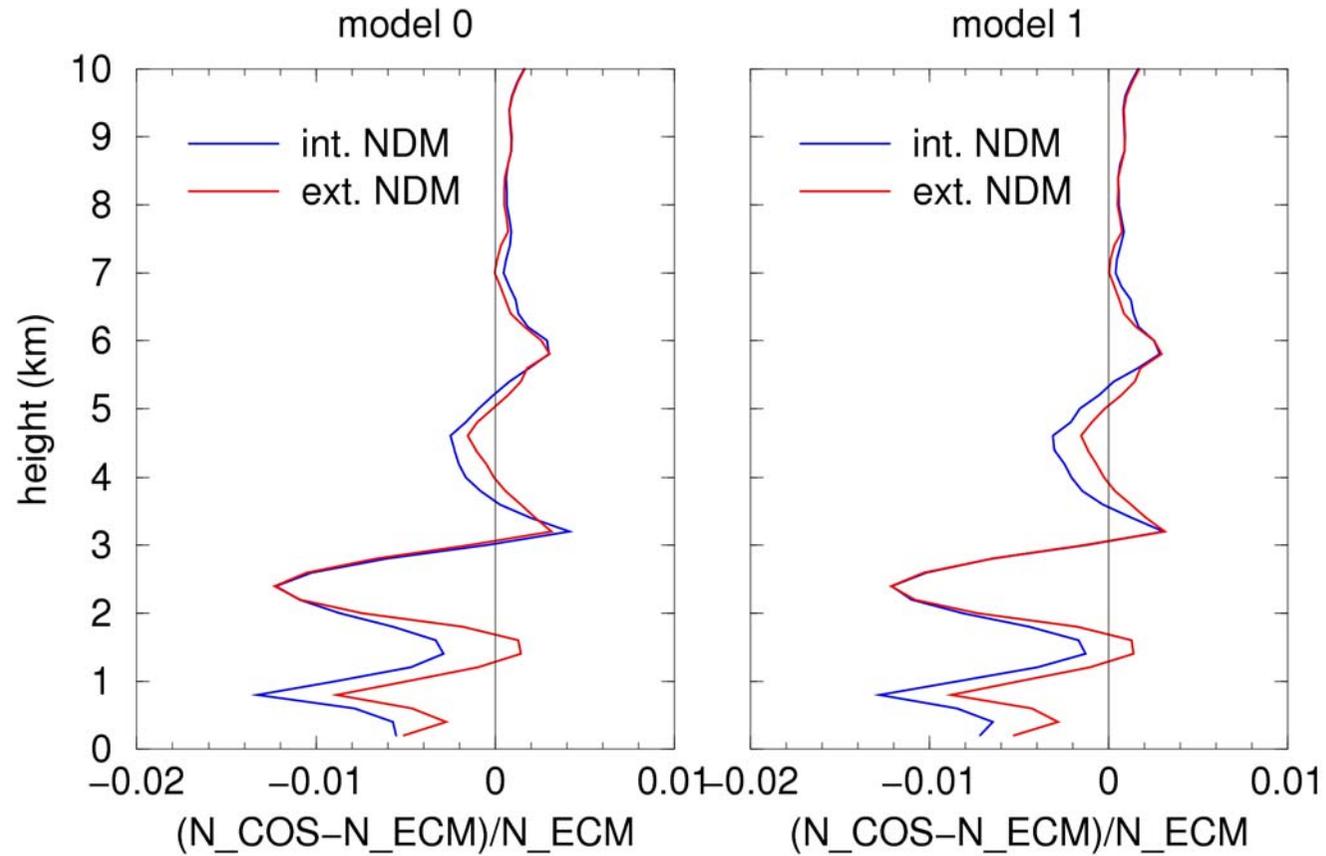
In tropical LT, RO signals propagate deep, at HSL<-100 km due to
diffraction by N-structures caused by WV. Due to the multipath, the
relation between RO signal and retrieved profile becomes non-local.
When RO signal is tracked not deep enough (truncated), this results in:
- loss of penetration (higher cut-off);
- inversion errors (bias) above the cut-off

C006.2006.250.21.21.G08 (20S, 145.5W)
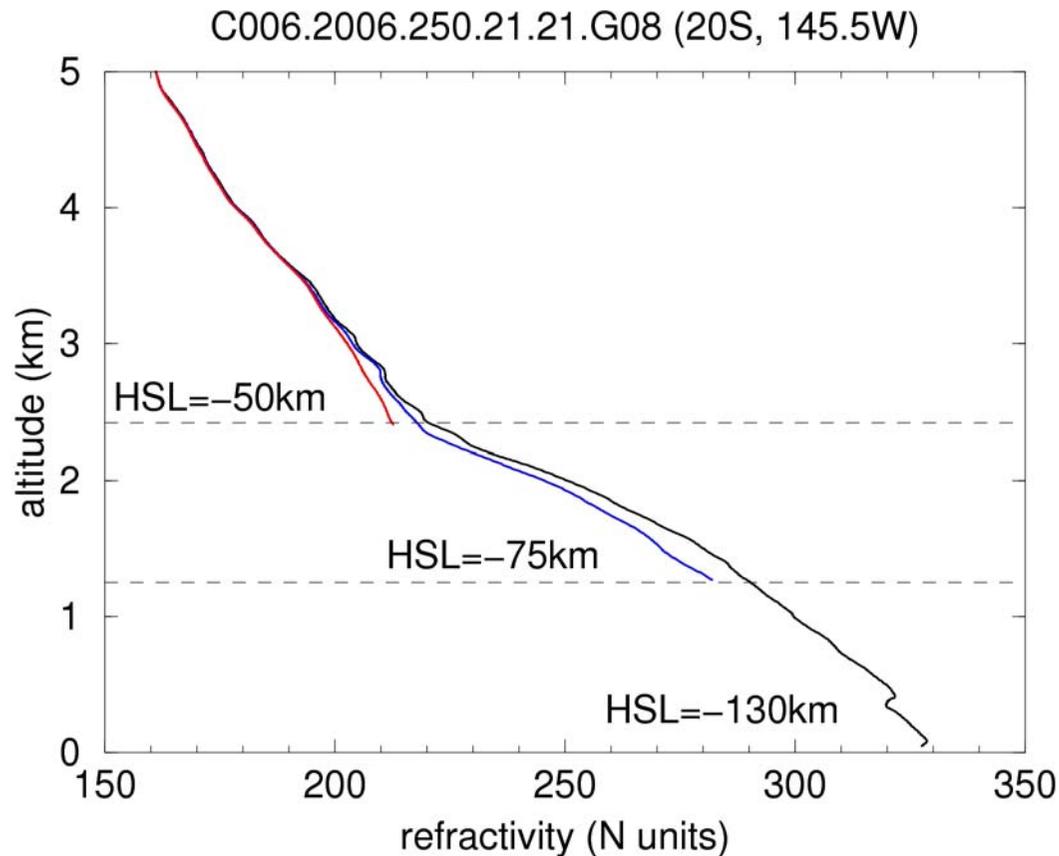
Statistical validation of the effect of tracking depth in tropics (30S-30N)
6634 occultations SNR exceeds noise level by 50% at HSL < -100 km
3856 occultations SNR exceeds noise level by 50% at HSL > -100 km
among possible reasons: loss of SNR due to errors of receiver models
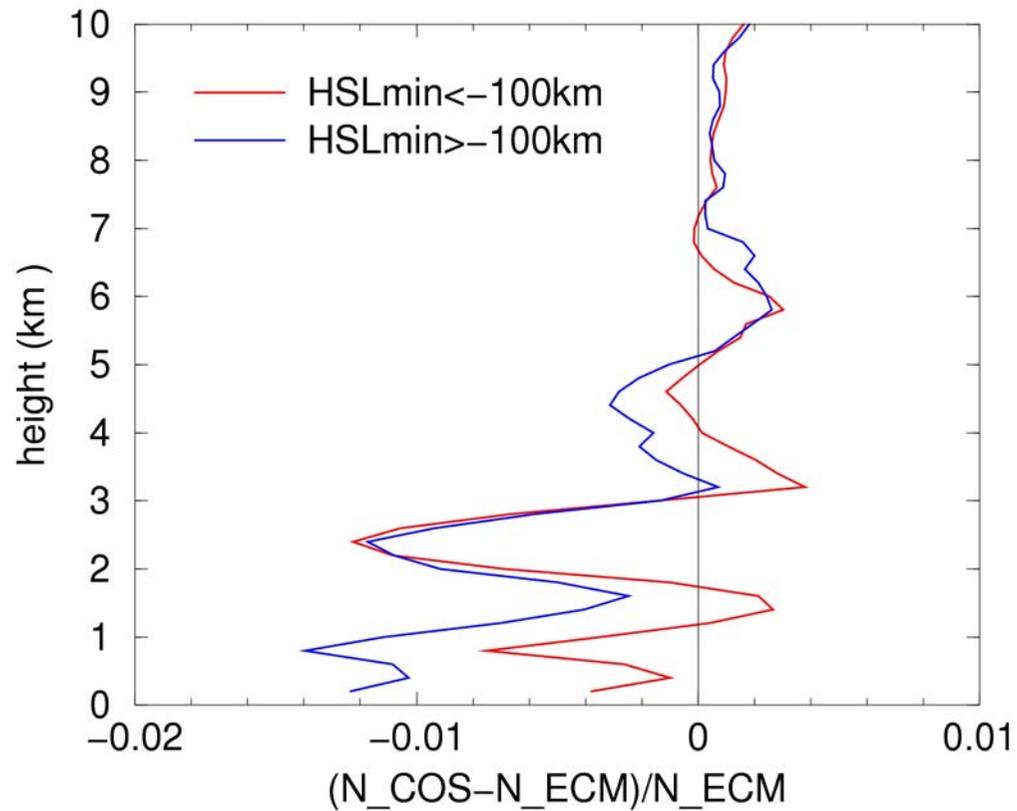
Conclusions

- receiver phase model is <u>not used</u> in the post-processing of OL signals

- adjustment of the frequency model (closing the loop) in the post-
  processing makes the results <u>independent</u> on the first guess
  when the first guess model is accurate within +/-25 Hz

- with the external removal of NDM, the phase model based on CIRA+Q
  is sufficient for the post-processing of all occultations

- with the internal removal of NDM the phase model based on CIRA+Q
  is sufficient for high-latitude occultations and sufficient as the first
  guess with the following adjustment for tropical occultations

- all COSMIC occultations are processed with the adjustment of the
  phase model (NDM bit sequences not available for all occultations)

- reduction of the errors due to insufficient tracking depth in tropics
  needs better accuracy of receiver models