

Processing of METOP/GRAS open loop radio occultation data at CDAAC



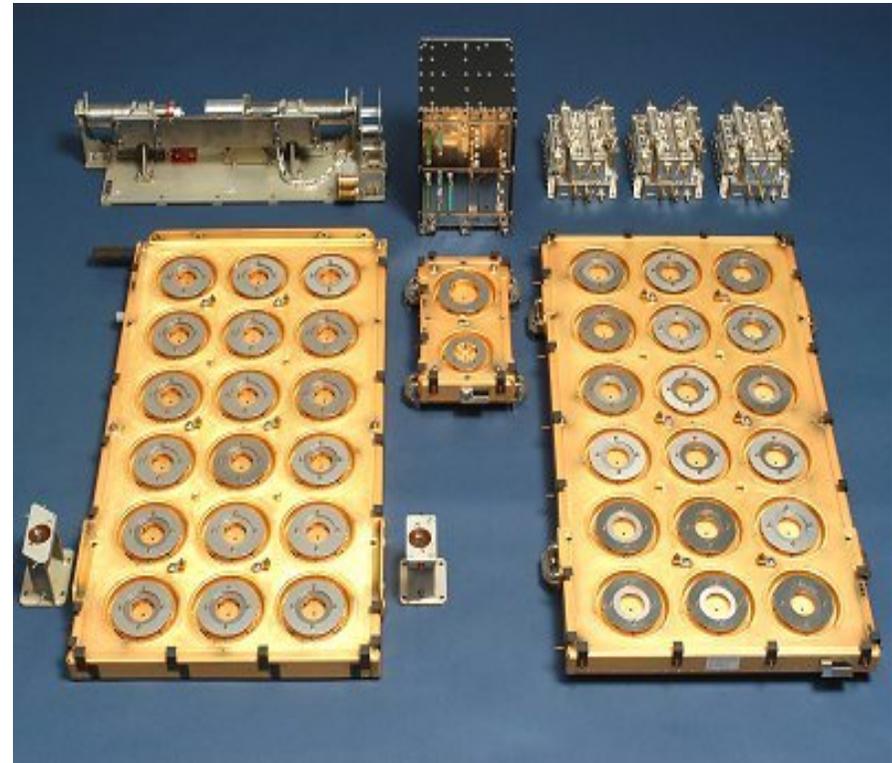
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UCAR / COSMIC

Overview

- UCAR/CDAAC is working towards routine processing of METOP/GRAS data, both closed- and open-loop
- Attraction of processing GRAS data
- Challenges involved in METOP/GRAS data processing
 - GRAS data examples for illustration
- Modifications to CDAAC data processing flow to accommodate METOP data
 - Methods for combining 1000Hz and 50Hz data
- Gap fixing methods and discussion
- Statistics of various methods
- Gap fixing study using COSMIC data
- 1000Hz vs. 50Hz inversions
- Conclusions

Reasons for processing METOP/GRAS data

- Well supported stable platform
- High gain antennas
- High occultation count
- Quality oscillator
- 1000Hz open loop data
- Operational mission with follow-ons envisioned



Challenges

Processing METOP/GRAS data presents several challenges for one who is used to JPL heritage GPS RO receivers

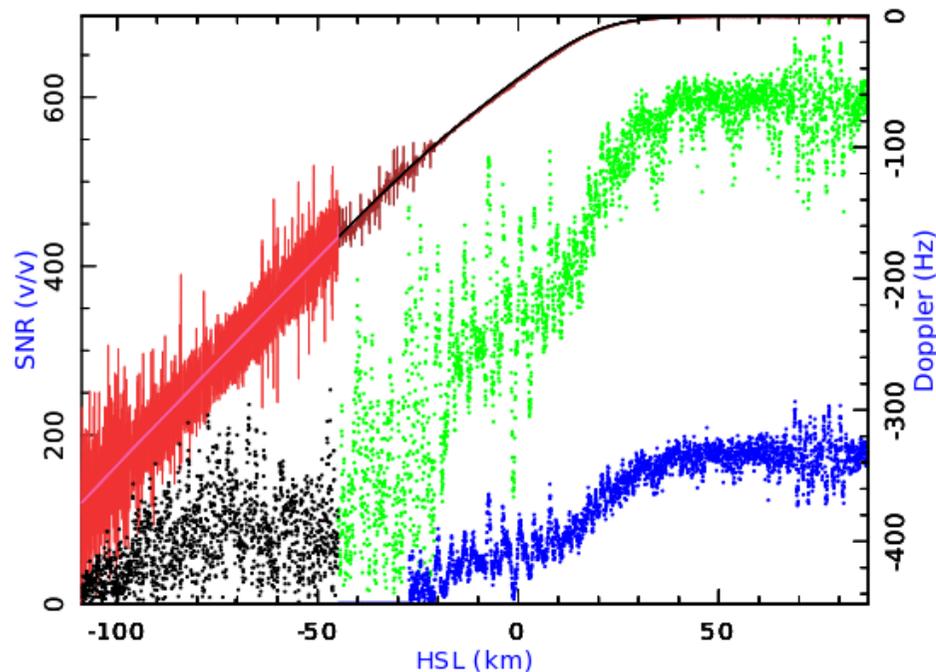
- Much lower level raw data:
 - Blackjack: Phase, Amplitude, times in GPS seconds
 - GRAS: Noise and Gain histograms, temperatures and voltages, phase I, Q and model, times in oscillator ticks
 - Code an order of magnitude more complex (used the PyGRAS software from EUMETSAT as a reference)
- Separate, overlapping packets for dual-frequency and single-frequency closed loop data in addition to open-loop data
- Gaps in both closed- and open-loop data
 - 52% of occultations have one or more closed-loop gaps
 - 65% of occultations with open loop data have one or more open-loop gaps
- Different data rates: 50Hz for closed-loop and 1000Hz for open-loop

Examples of METOP occultations

Good Setting occultation

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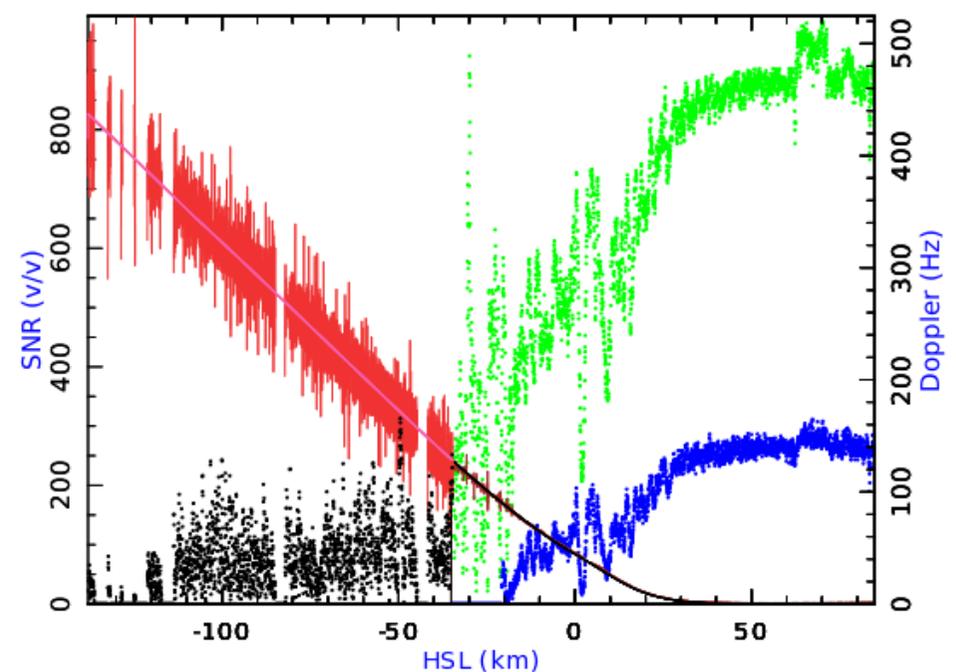
OL SNR L1 CL SNR L2 CL SNR L1
CL Doppler CL Dop. Mod. OL Doppler OL Dop. Mod.



Good Rising occultation

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OL SNR L1 CL SNR L2 CL SNR L1
CL Doppler CL Dop. Mod. OL Doppler OL Dop. Mod.

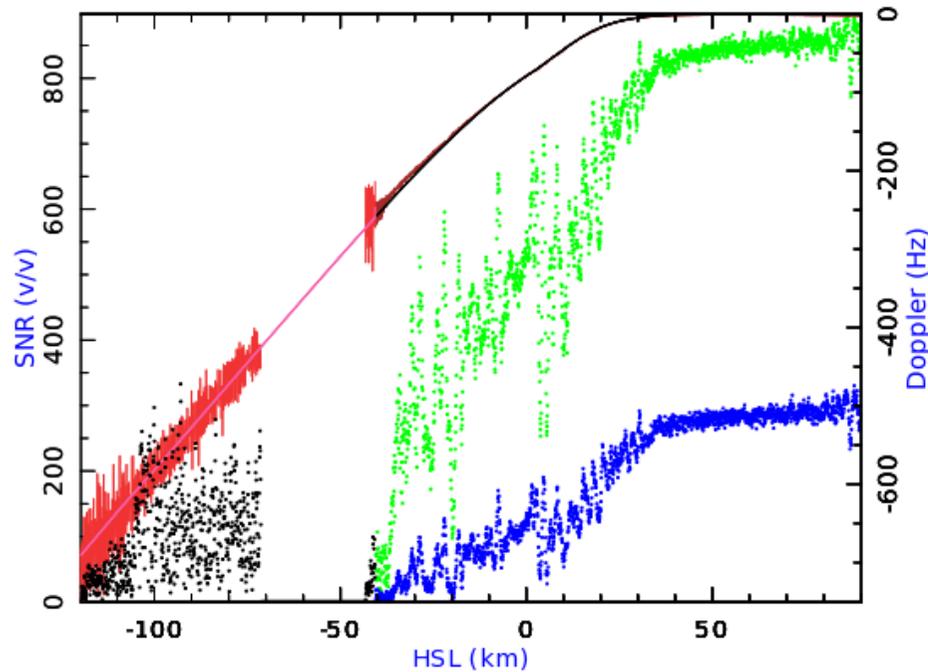


Examples of METOP occultations

Setting occultation with gap

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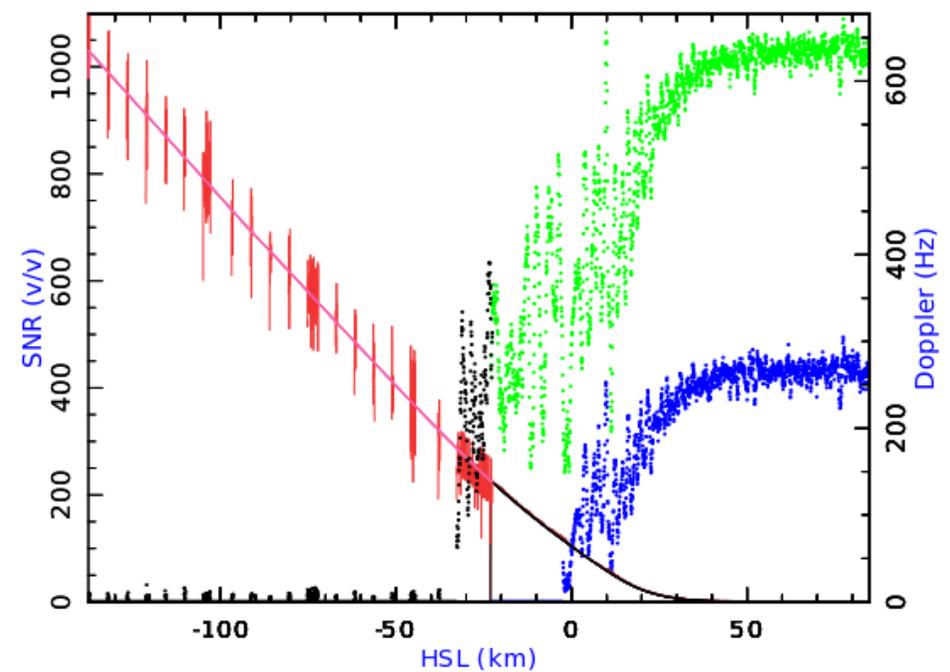
OL SNR L1 CL SNR L2 CL SNR L1
CL Doppler CL Dop. Mod. OL Doppler OL Dop. Mod.



Rising occultation, lots of gaps!

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OL SNR L1 CL SNR L2 CL SNR L1
CL Doppler CL Dop. Mod. OL Doppler OL Dop. Mod.

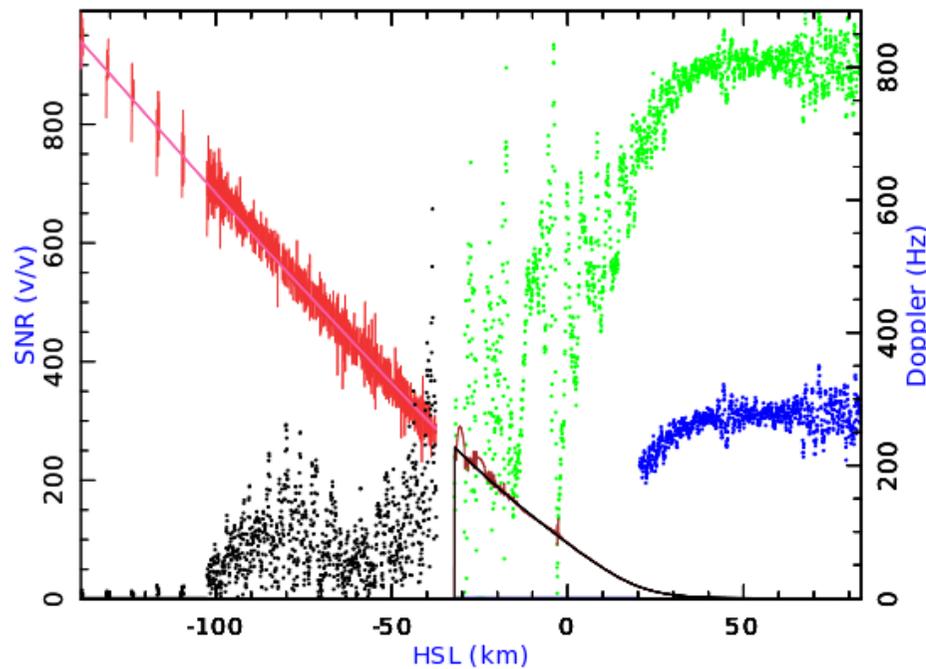


Examples of METOP occultations

Rising, late L2

[mtpPst_2007.274.01.G06.016482.png](#)

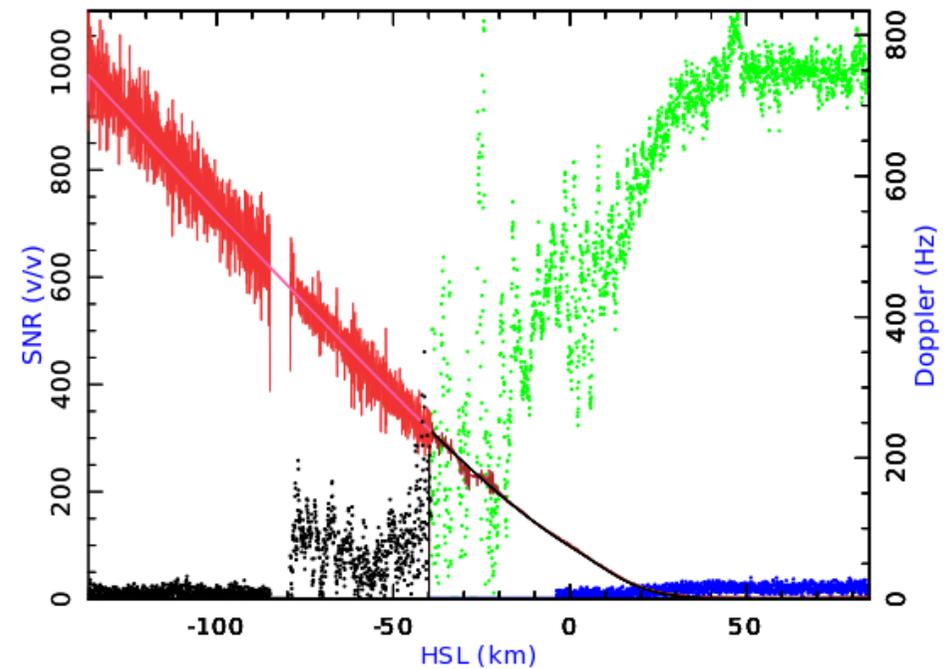
OL SNR L1 CL SNR L2 CL SNR L1
CL Doppler CL Dop. Mod. OL Doppler OL Dop. Mod.



Rising, low L2 SNR

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OL SNR L1 CL SNR L2 CL SNR L1
CL Doppler CL Dop. Mod. OL Doppler OL Dop. Mod.

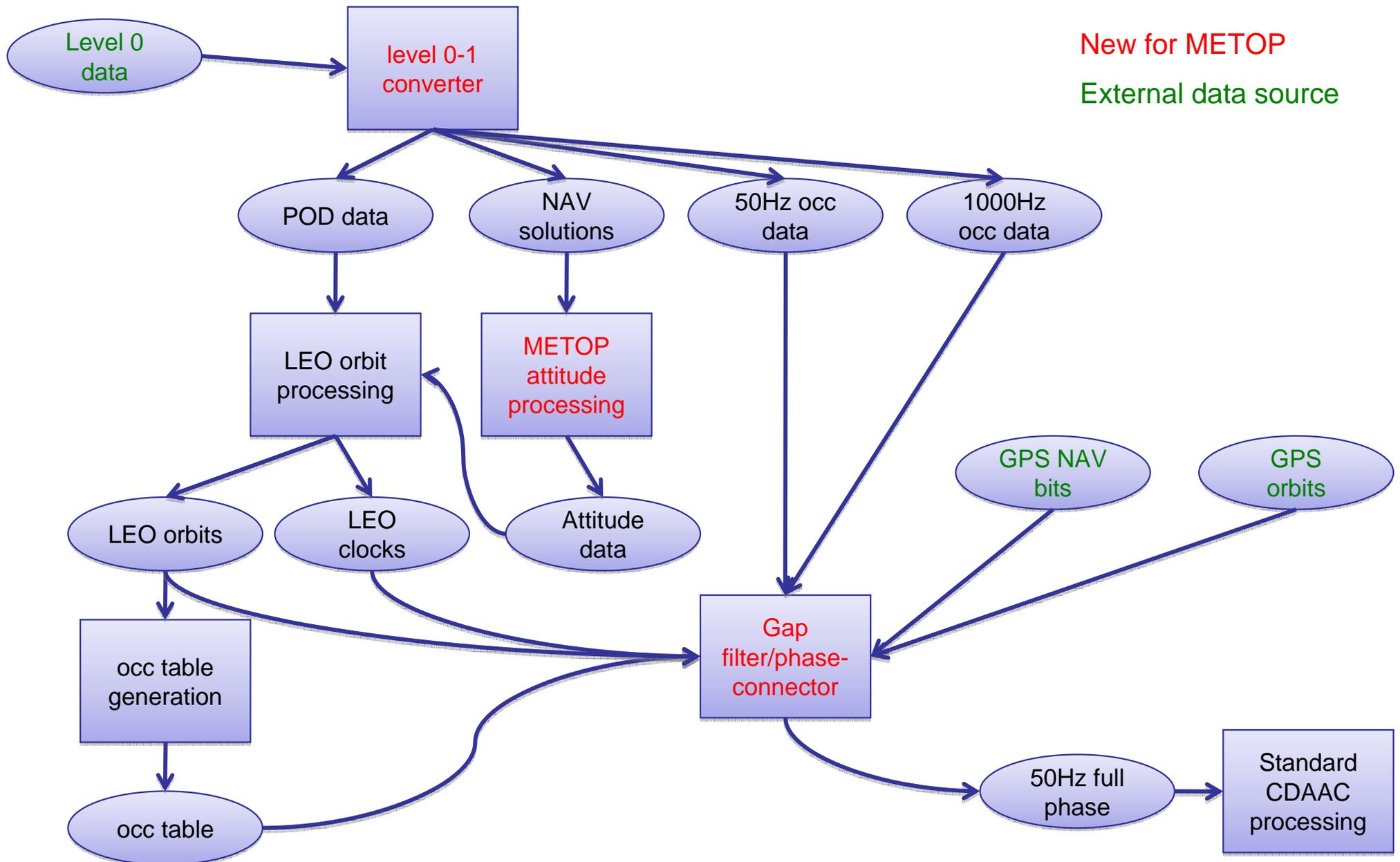


Approach to processing GRAS data

1. Pre-process all the different packet types into one uniform, gap-filled 50Hz phase-connected file per occultation
2. Push these through CDAAC's standard closed-loop excess phase and inversion processing

Our investigation has shown that it makes more sense to down-sample the 1000Hz data to 50Hz to reduce noise rather than to process the 1000Hz data separately at full resolution. This also makes it easier to use the existing CDAAC processing stream.

CDAAC processing of METOP data



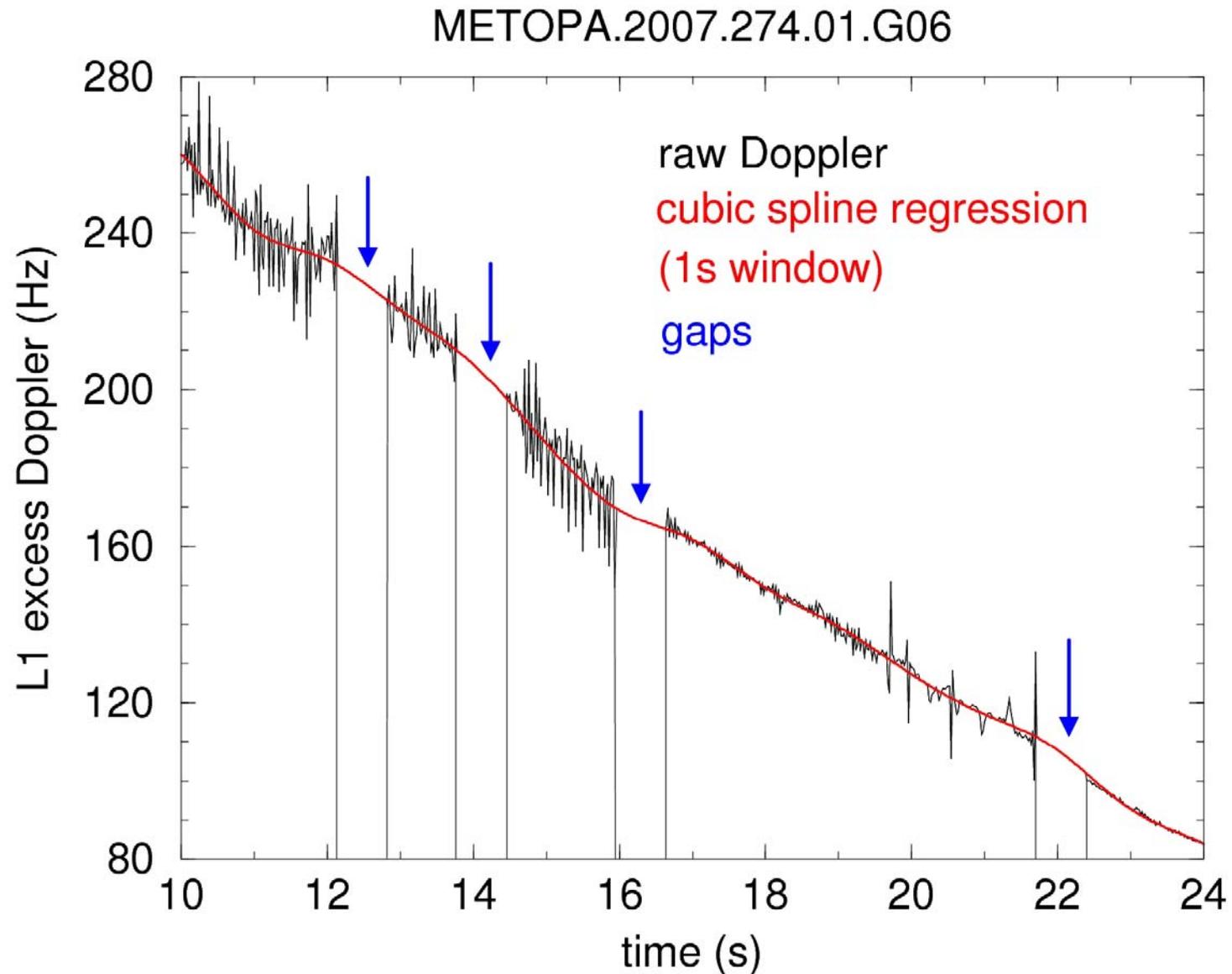
Gap filler: Closed loop data

Closed-loop data are processed normally, but gaps must be filled in to work with the rest of the CDAAC processing string:

1. Generate continuous phase and SNR profiles by filling in gaps with 'missing' values
2. Compute excess phase from full phase (subtract out satellite motion and LEO clock errors)
3. Compute Doppler by differentiating excess phase
4. Fill in gaps (maximum of one second) in Doppler with cubic spline regression
5. Reconstruct full phase from gap-filled Doppler
6. Fill in gaps in SNR with an average of SNRs near the gap

Filling gaps in Doppler by **cubic spline regression** (least squares fit by spline)

Applied in the closed-loop (CL) mode for the gaps < 1 sec

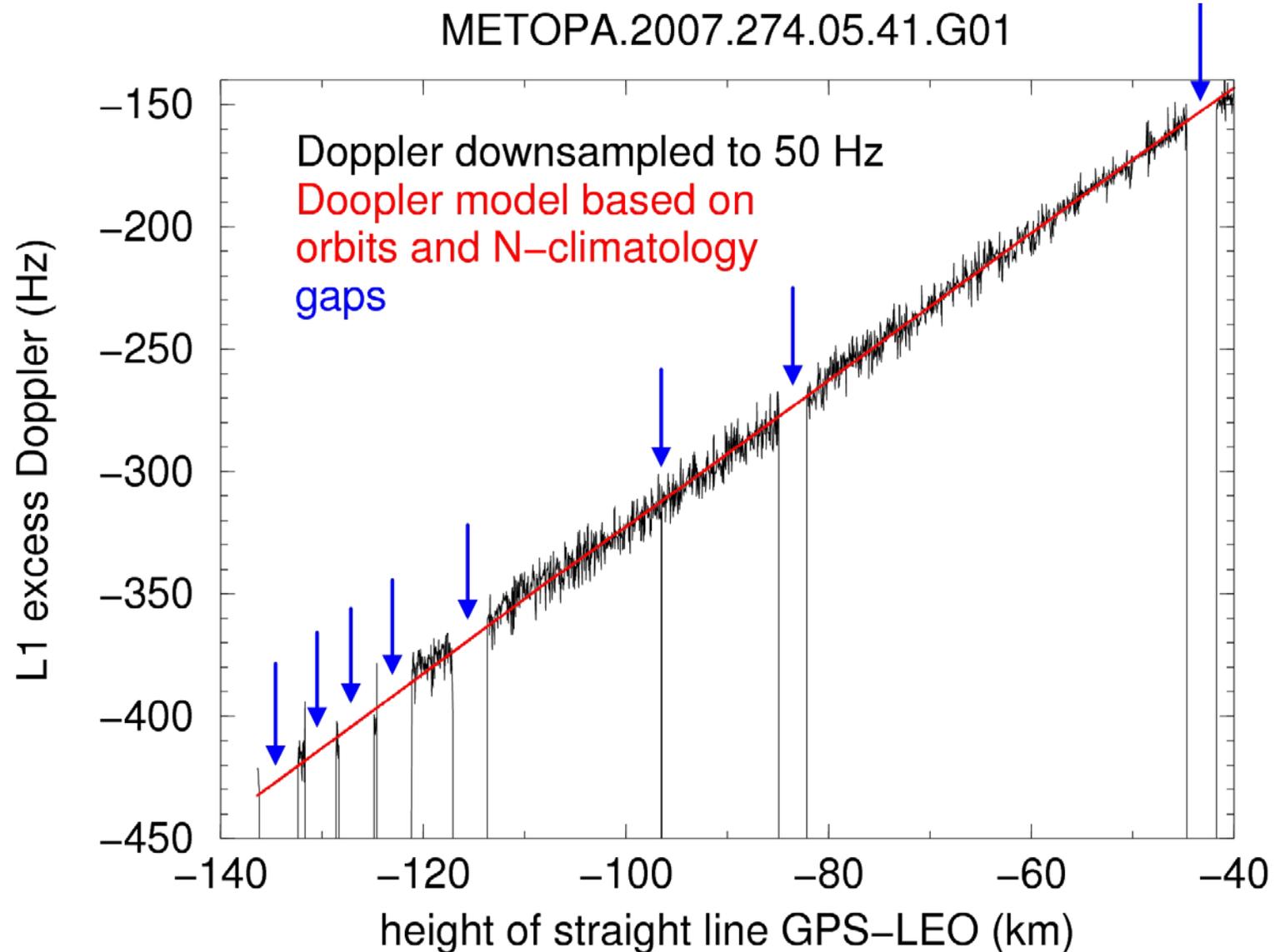


Open loop data: Gap filling and down-sampling

1. Generate missing time tags (for which we must determine SNR and phase in the following steps)
2. Compute 1000 Hz excess phase from full phase (subtract out satellite motion and LEO clock errors)
3. Compute a Doppler model from N-climatology and satellite motion
4. Compute a phase model by integrating the Doppler model
5. Difference the excess phase with the phase model. Where gaps are present, just fill in the phase model.
6. Compute I and Q from this model difference and the SNRs:
$$I = \text{SNR} * \cos(\text{delta_phase})$$
$$Q = \text{SNR} * \sin(\text{delta_phase})$$
7. Apply the raw GPS navigation bits to I and Q. Align the NAV bits using time tags and the CA pseudorange.
8. Down-sample I and Q to 50 Hz by averaging sets of 20 samples.
9. Compute connected excess phase and SNR from the down-sampled I and Q.
10. Reconstruct full 50 Hz phase by adding satellite motion and clock errors back in.

Filling gaps in Doppler by **model** (based on orbits and N-climatology)

Applied in the open-loop (OL) mode



Processing types used for this study

We processed one day of GRAS data using several strategies:

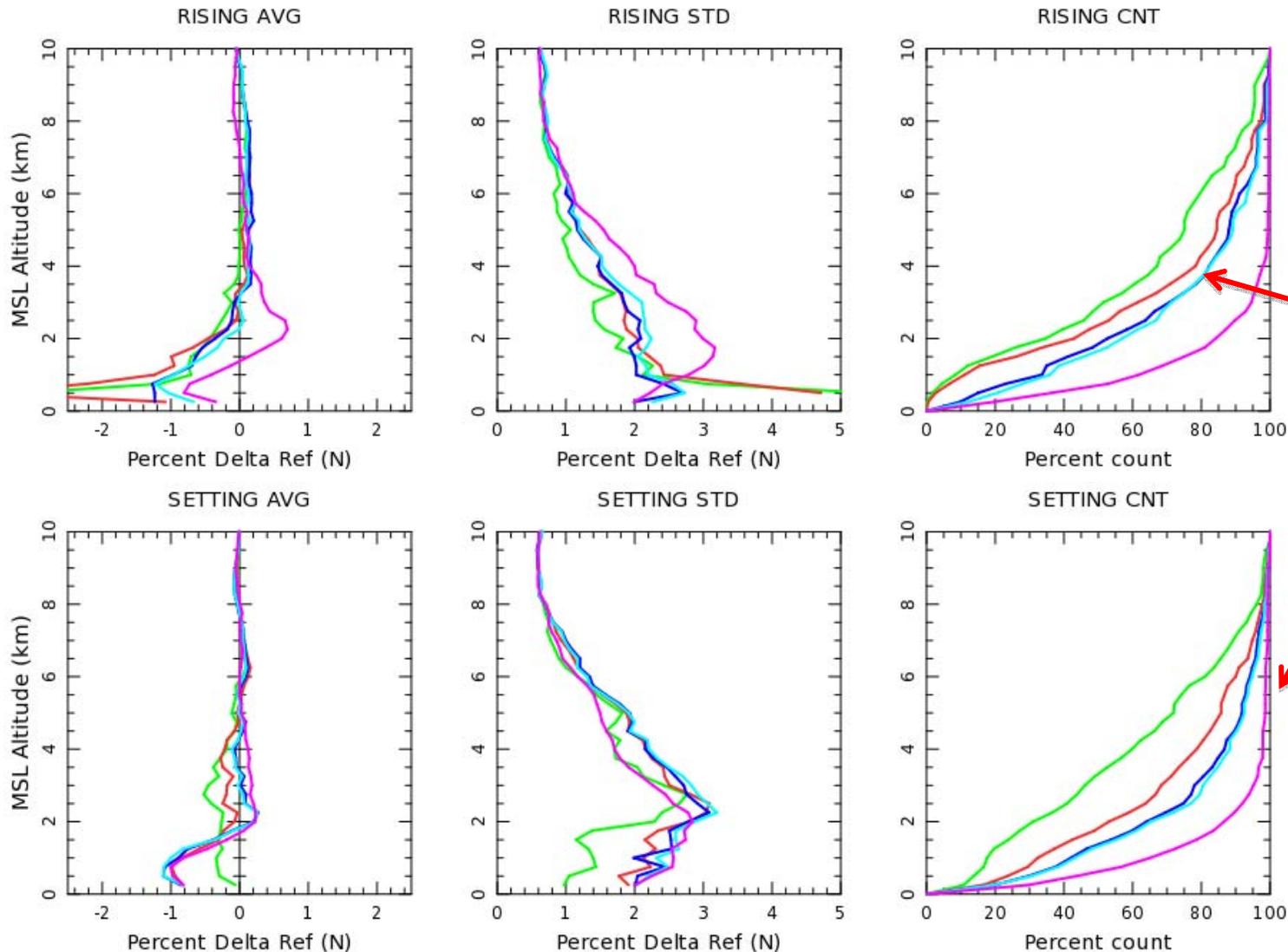
- Closed-loop data only, use the largest contiguous data section—no gap filling
- Closed-loop data only, fixing gaps less than 1 second long
- Closed-loop data with gaps fixed, plus open-loop data down to the first gap
- Closed-loop data with gaps fixed, plus open-loop data with gaps of any length filled with model data

Comparison of processing types

Comparisons with ECMWF: 2007.274

METOP CL to first gap
METOP CL with gap fixing
METOP CL+OL to first gap

METOP CL+OL with gap fixing
cosmic



Each successive improvement yields deeper penetration and yet the bias and standard deviation remain reasonable.

Processing of the occultations with gaps (intervals of missing data)

CDAAC dynamically determines where to use GO and WO processing for each occultation. Gaps in METOP data can occur in both GO and WO areas.

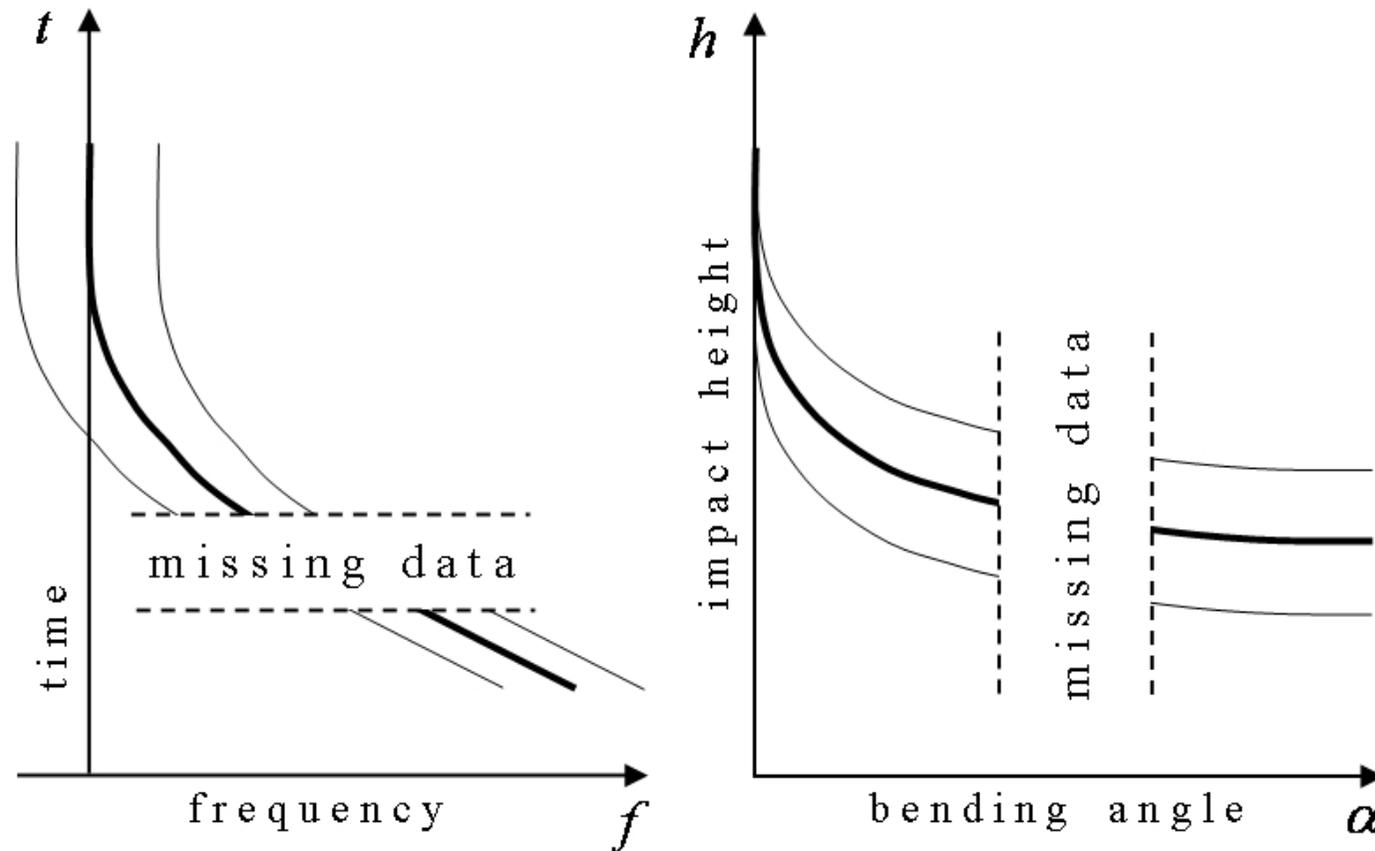
Geometric optical processing:

- interpolation through gaps may be done before or after inversion (calculation of the bending angles)
- only interpolation of Doppler is needed, amplitude does not matter

Wave optical processing:

- methods based on FFT (FSI, CT2) need interpolation through gaps before the inversion
 - phase Matching (PM) does not need interpolation
 - processing of the signals with gaps by PM without interpolation is equivalent to applying interpolation with zero amplitude through the gaps
 - inversion results depend on the interpolation of both Doppler and amplitude
- Processing strategy at CDAAC: always interpolate data before the inversion
- Interpolation method may depend on the size of gaps, the noisiness and the amount of data between the gaps

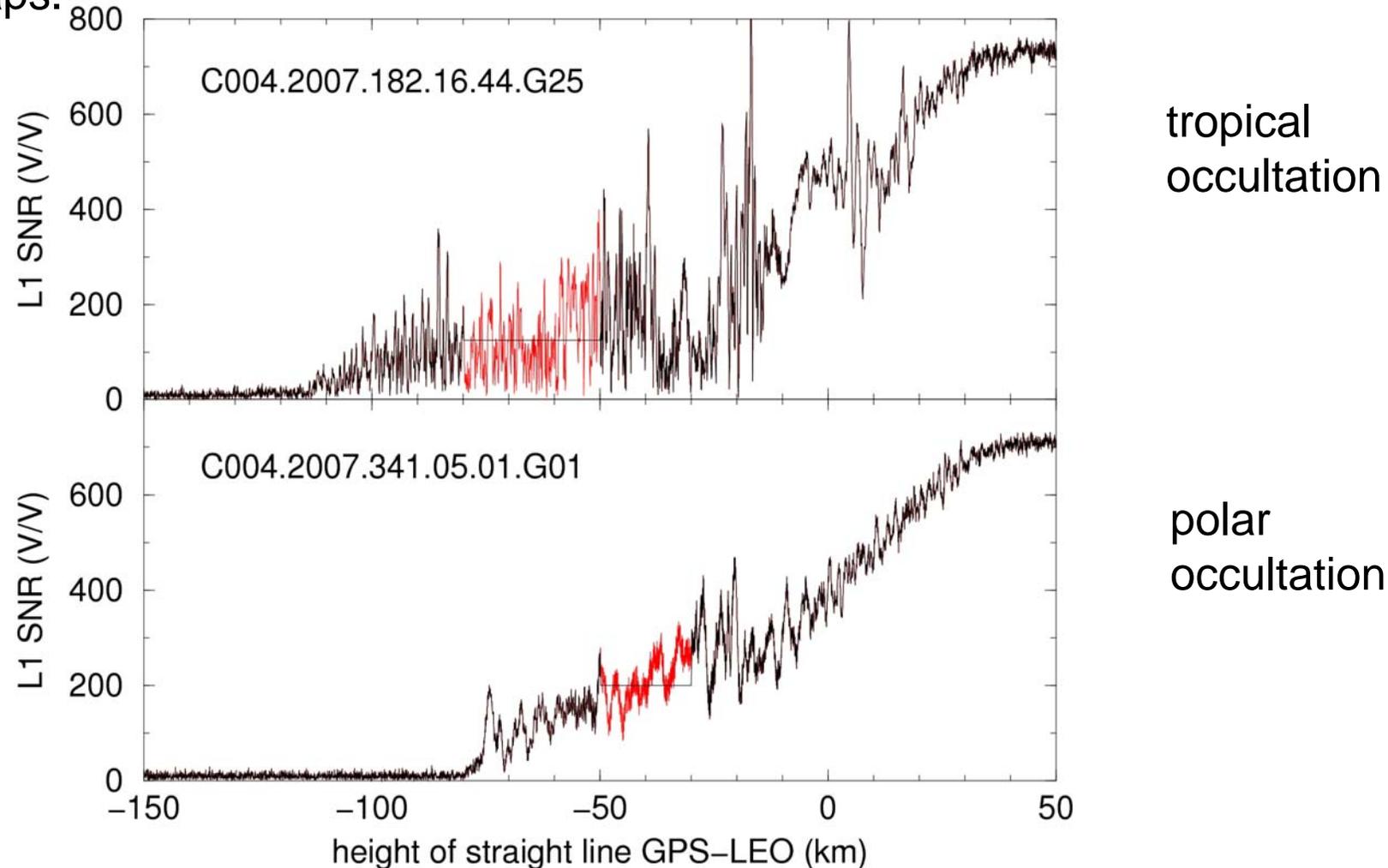
Transformation of RO signal by WO methods from time - frequency to impact parameter - bending angle representations results in a gap in time mapping into a gap in bending angle.



Bending angle retrieved in the gap by differentiation of the phase of the WO-transformed signal depends on the distribution of local spectra of signal and noise and on the phase and amplitude used for filling the gap.

To investigate the effect of data gaps on WO inversions, **artificial gaps** were introduced in COSMIC RO signals, processed with the Phase Matching method.

The results depend on the structure and local spectral width of the transformed signal, which are different for polar, tropical and sub-tropical (sharp ABL top) occultations. This size of gap was chosen as typical of GRAS setting occultation gaps.

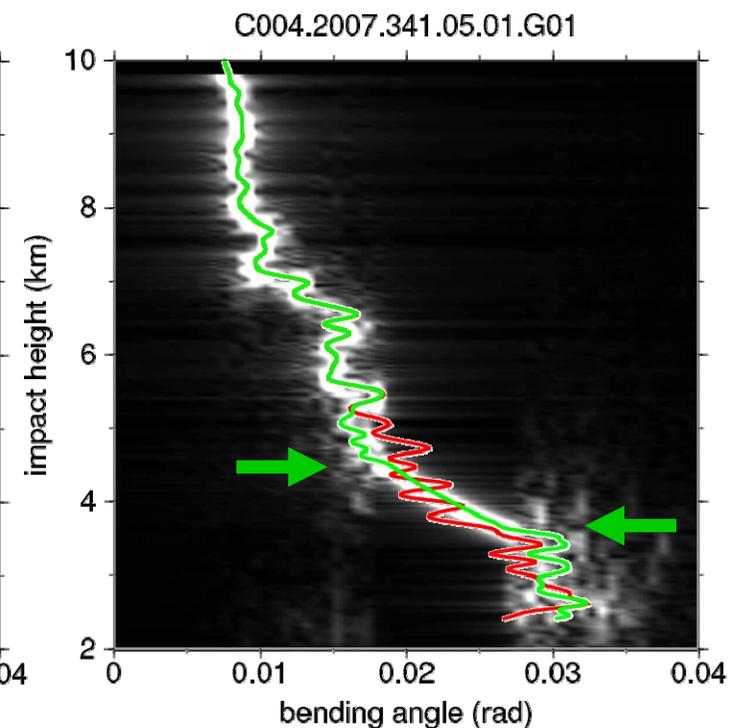
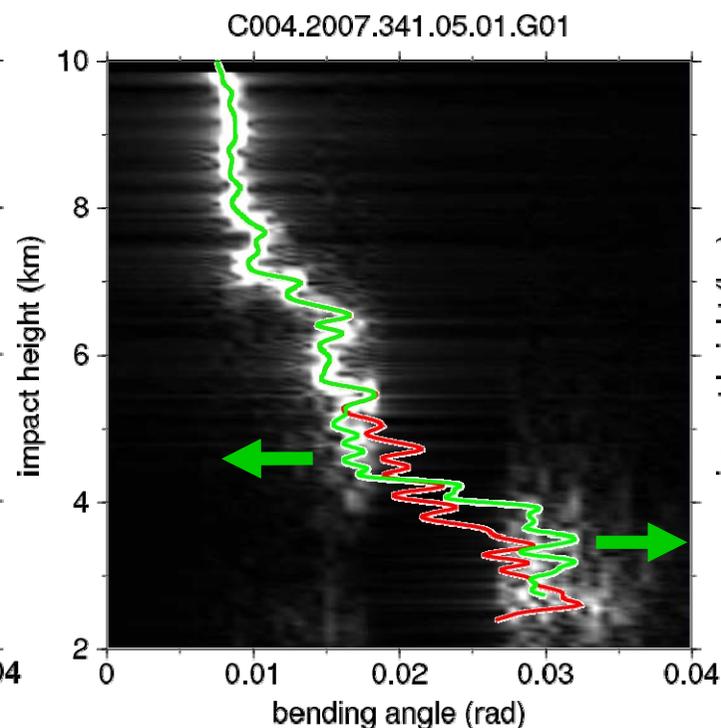
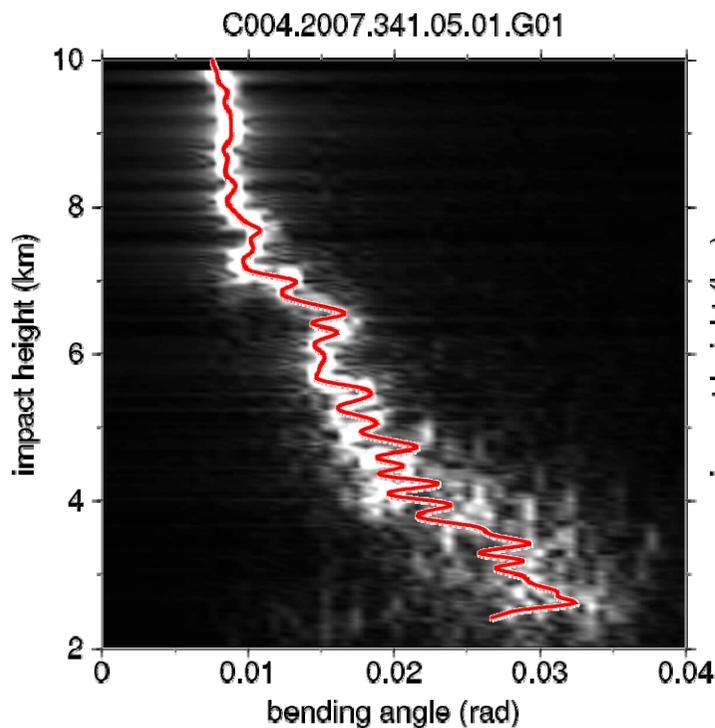


Tropical occultation: broad local spectrum of the WO-transformed signal (due to the effect of moist convection)

Sliding spectrogram of
WO-transformed signal.
Retrieved BA.

Artificially introduced gap
at $-80 < \text{HSL} < -50$ km; filled
with Doppler model,
amplitude set to zero.
**Retrieved BA inside the
gap is affected by the
spectral density of the
signal outside the gap.
The Doppler model has
no weight.**

The gap is filled with the
Doppler model and the
interpolated amplitude
(from around the gap).
**Retrieved BA inside the
gap is "pulled" toward
the Doppler model.**

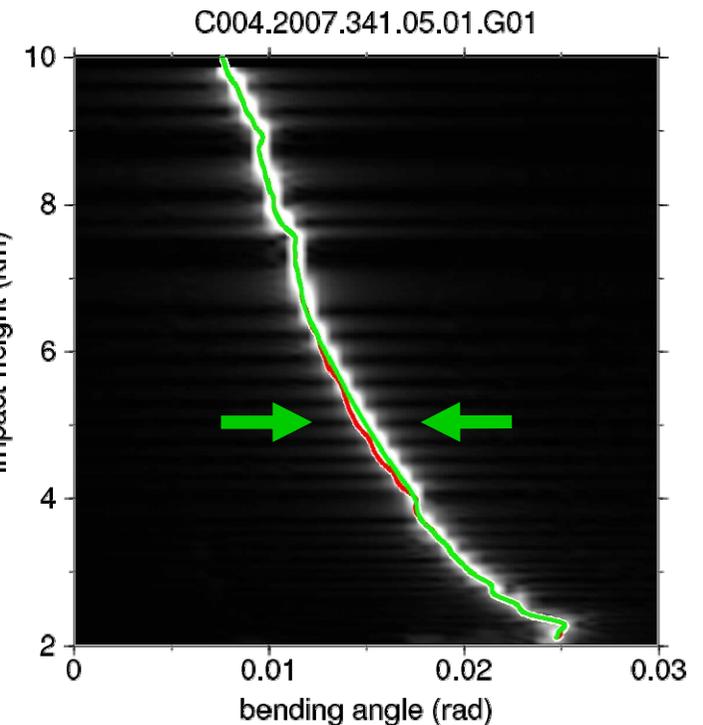
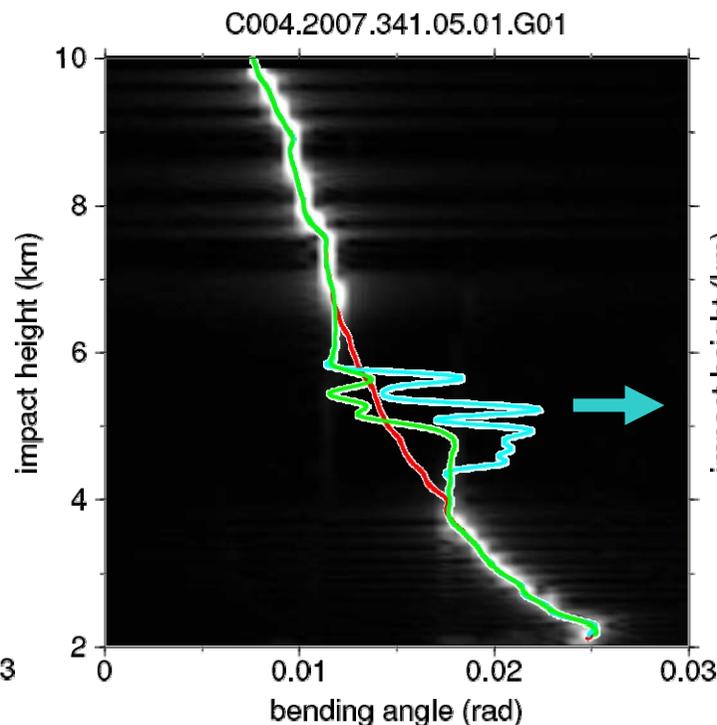
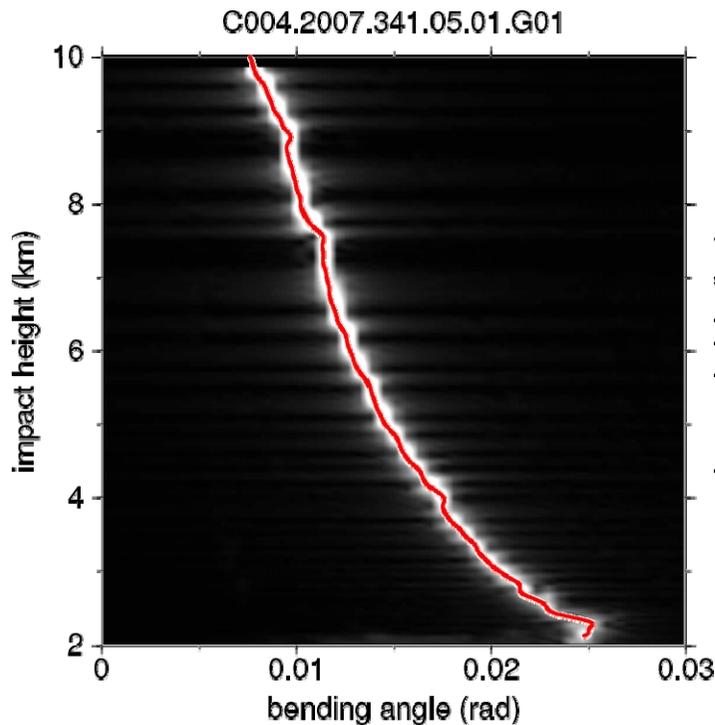


Polar occultation: narrow local spectrum of the WO-transformed signal

Sliding spectrogram of WO-transformed signal.
Retrieved BA.

Artificially introduced gap at $-50 < \text{HSL} < -30$ km; filled with Doppler model, amplitude set to zero.
Retrieved BA inside the gap is affected by the asymmetric distribution of the spectral density of noise. RO signal is used down to: $\text{HSL} = -80$ km; $\text{HSL} = -150$ km
(Sokolovskiy et al., JGR, 2010)

The gap is filled with the Doppler model and the interpolated amplitude (from around the gap).
Retrieved BA inside the gap is "pulled" toward the Doppler model.

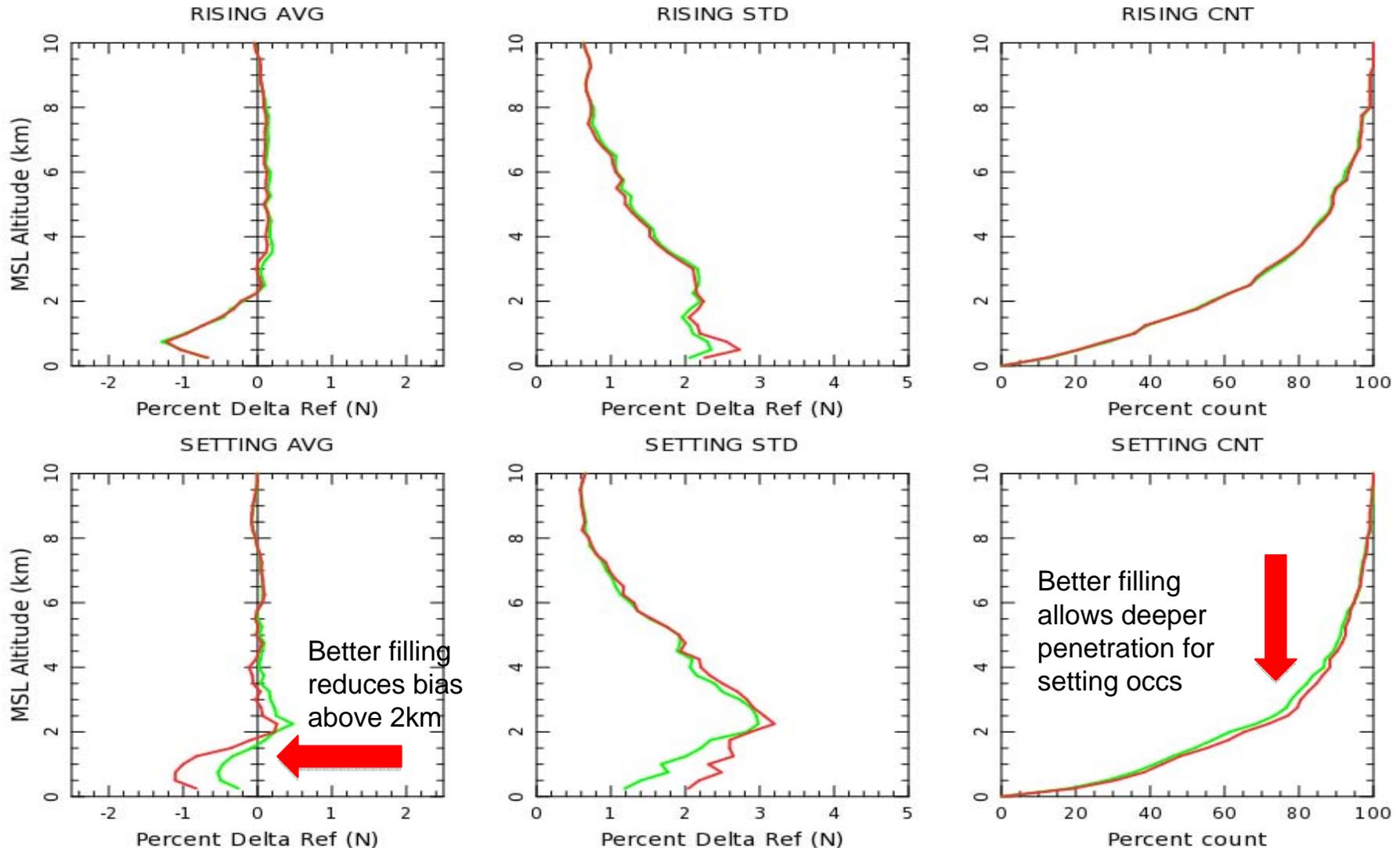


Statistical comparison of two methods of SNR gap filling

Comparisons with ECMWF: 2007.274

METOP CL+OL (gaps zero filled)

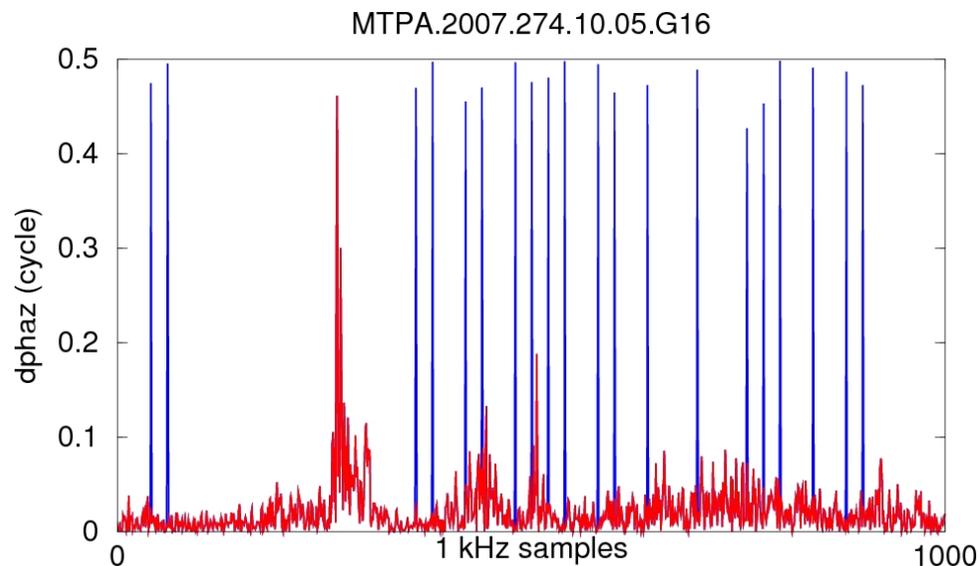
METOP CL+OL with gap fixing (neighboring SNR fill)



Processing of the METOP OL data with and without downsampling (I)

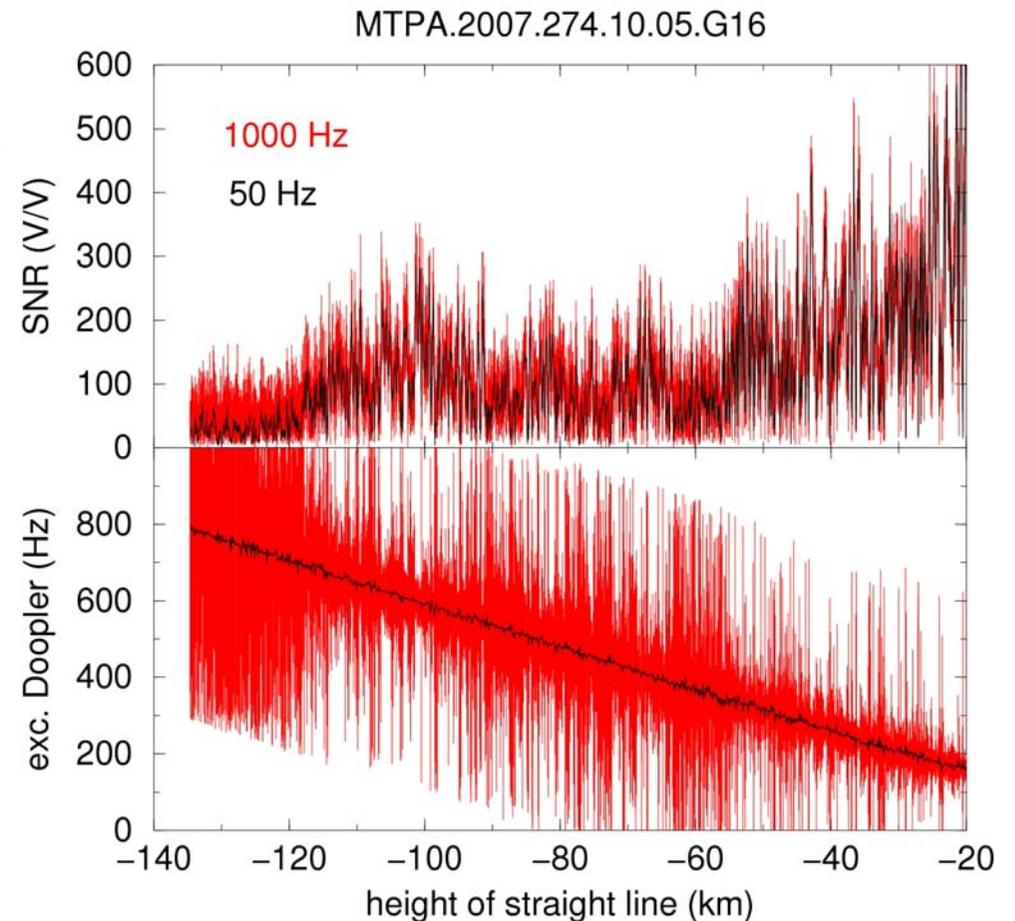
Raw signal downconverted with the reference frequency (phase) model based on orbits and N-climatology.

Phasor rotation between 1 kHz samples (NAV data bit flips are visible):



Phasor rotation between 1 kHz samples with the NAV data modulation removed.

Amplitude and Doppler from 1 KHz samples:

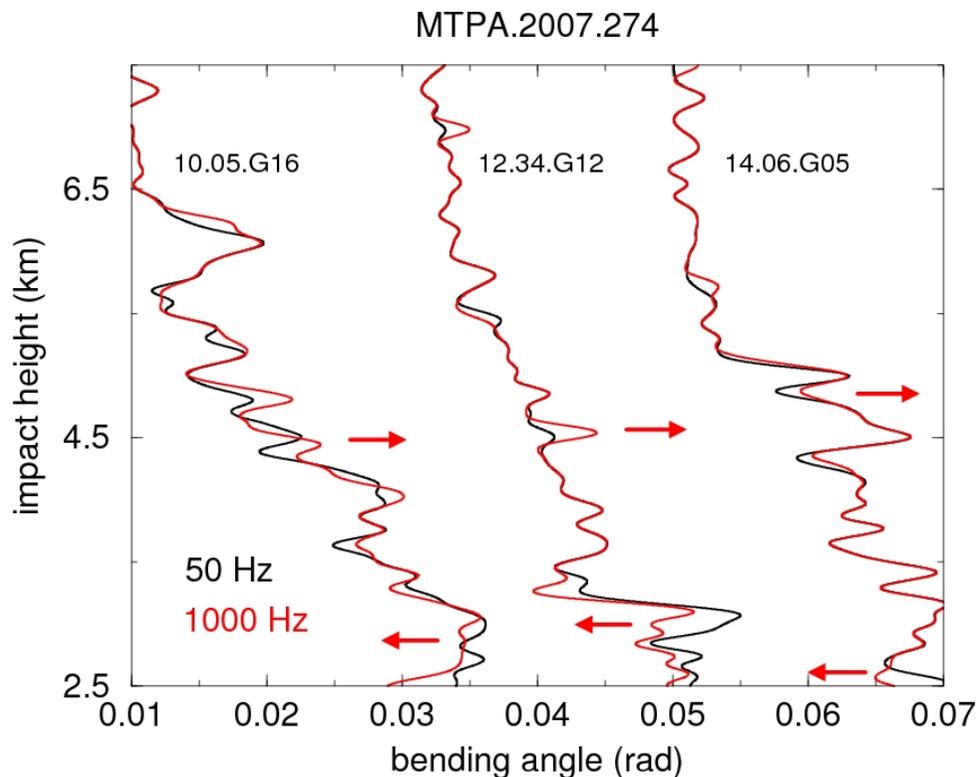


and from the signal down-sampled to 50 Hz by 20 ms integration of the I and Q and up-conversion.

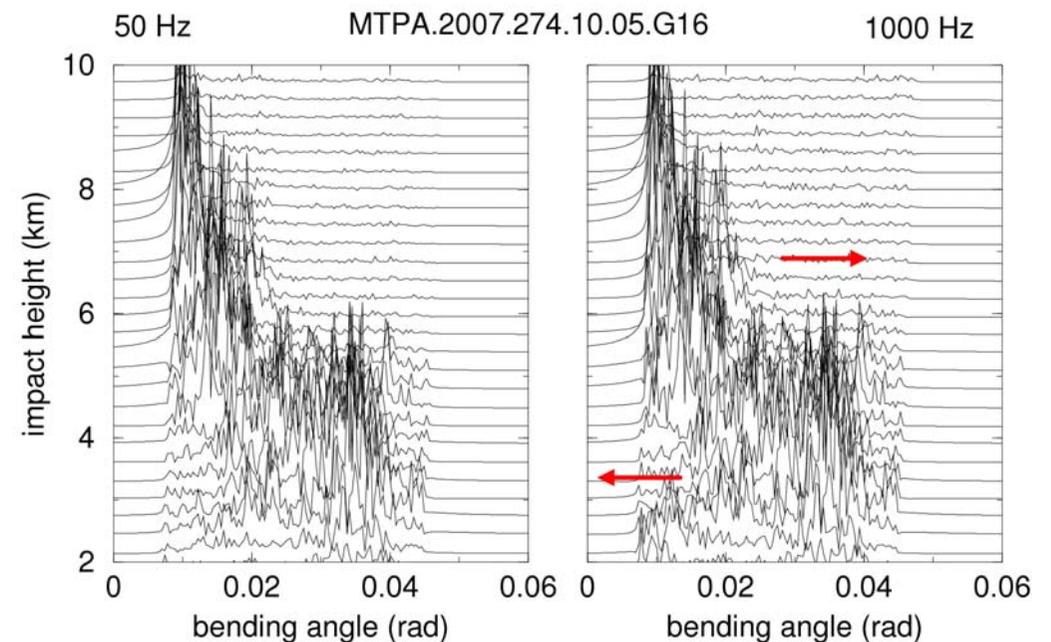
1 kHz and 50 Hz downsampled RO signals look very different, but: (see next slide) =>

Processing of the METOP OL data with and without downsampling

Bending angles (BA) calculated from **1 kHz** and 50 Hz signals by Phase Matching (PM) for selected tropical occultations without gaps are not very different. This is because the 50 Hz sampling in most cases is sufficient for capturing the spectral content of multi-tone RO signals propagating through the moist troposphere (except for the case of strong sub-refraction). Small negative and positive biases of 1 kHz compared to 50 Hz inverted BA can be explained by the effect of noise in the local spectrum of the PM-transformed signal (which is larger for 1 kHz).



Sliding spectrograms of the RO signal transformed by Phase Matching



The applied down-sampling is equivalent to noise filtering in the time domain. Recording 1 kHz OL RO signal in a larger time interval would broaden the distribution of noise of the PM-transformed signal and allow more efficient application of noise filtering in the impact parameter domain, i.e. the "RH-filtering" (Gorbunov, Lauritsen, et al. OPAC-2, JGR 2006).

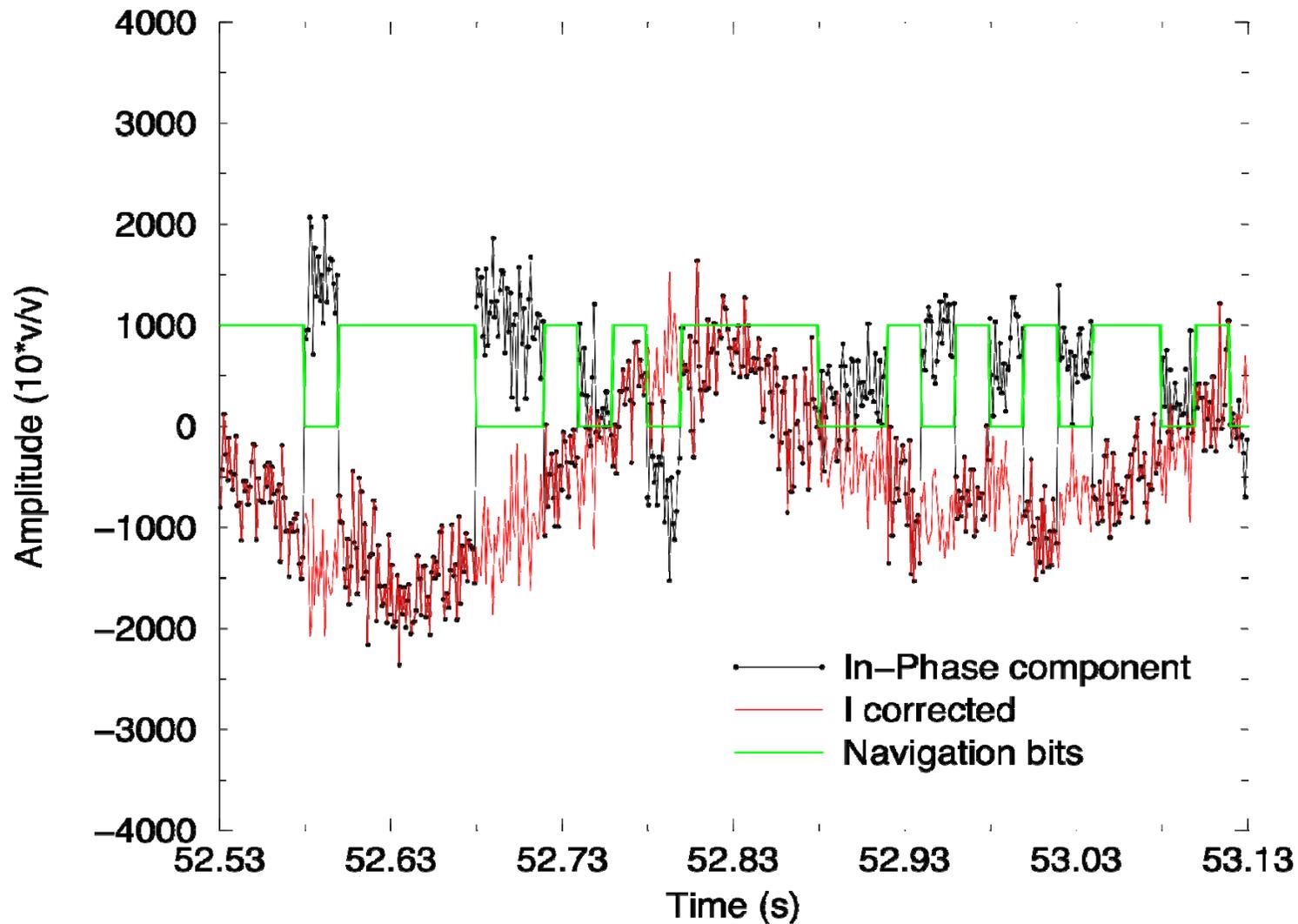
Conclusions

- UCAR/CDAAC is planning on processing METOP/GRAS data routinely
- Adding raw sampling/open-loop data to inversions improves penetration depth
- Useful profiles can be computed with good penetration depth provided one carefully fills gaps in both closed-loop and open-loop sections
- Filling gaps in SNR with neighboring values is a better approach than filling gaps with zeroes for WO inversions
- Down-sampling from 1000Hz to 50Hz to reduce noise and ease combination of closed- and open-loop data yields good results when compared with direct inversion of 1000Hz data

Thanks to EUMETSAT for funding for the closed-loop portion of this study!

Applying GPS navigation bits

NAV bit correction of I and Q



Filling SNR gaps

Open loop gaps in phase are filled with a climatological model. The question is “how to weight this filled section of data?” I.E. how to fill in the gap in SNRs?

- Fill in SNR gaps with zeros
- Fill in SNR gaps with a large SNR value (say 1000 v/v)
 - This helps in specific cases, but ruins the statistics
- Fill in SNR gaps with an average neighboring value
 - This was the approach we selected
- It is important to handle this is a way which works for both Geometric Optics processing and Radio Holographic processing, since CDAAC switches dynamically between these two approaches