

# Comparison of GRAS processing results obtained at EUMETSAT and UCAR

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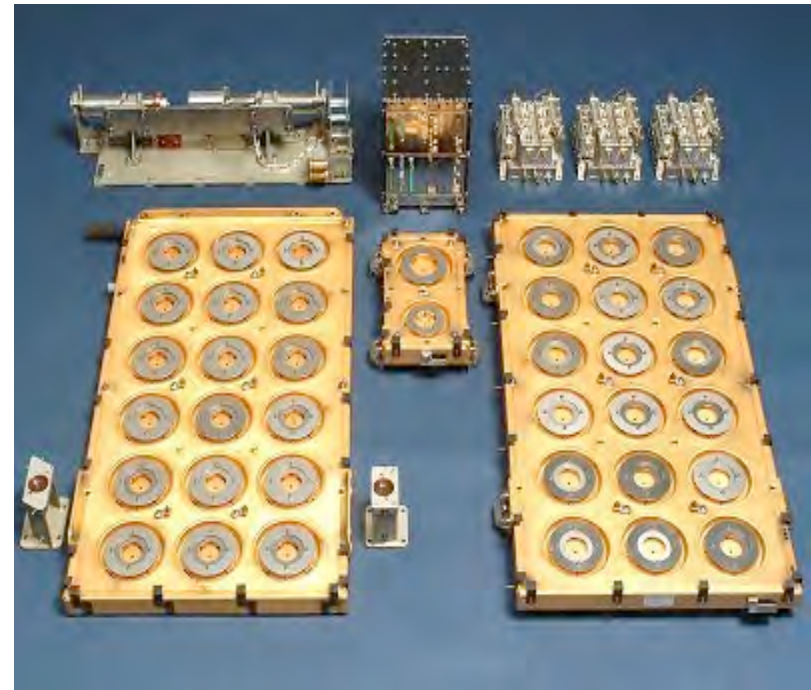
UCAR COSMIC Project

Axel v. Engeln, Christian Marquadt

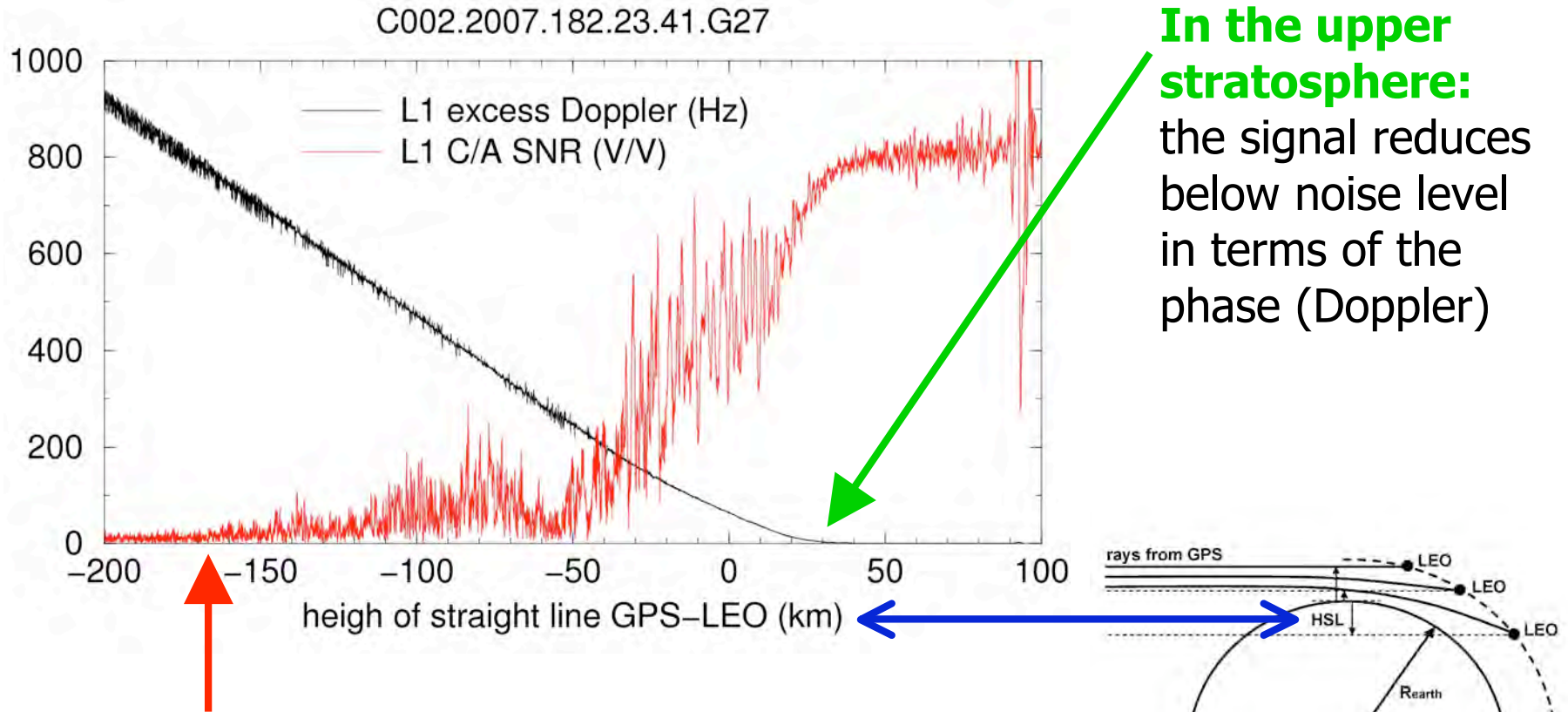
EUMETSAT

# Reasons for processing METOP/GRAS data

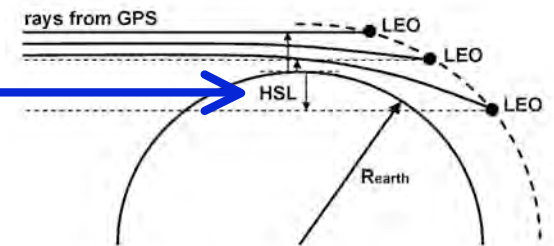
- EUMETSAT - funded structural uncertainty study
- CDAAC interested in routinely processing these data
- Technically Interesting because
  1. Well supported stable platform
  2. High gain antennas
  3. Ultra stable oscillator
  4. 1000Hz open loop data



Upper stratosphere and lower troposphere are regions of the maximum uncertainty of the GPS RO inversions

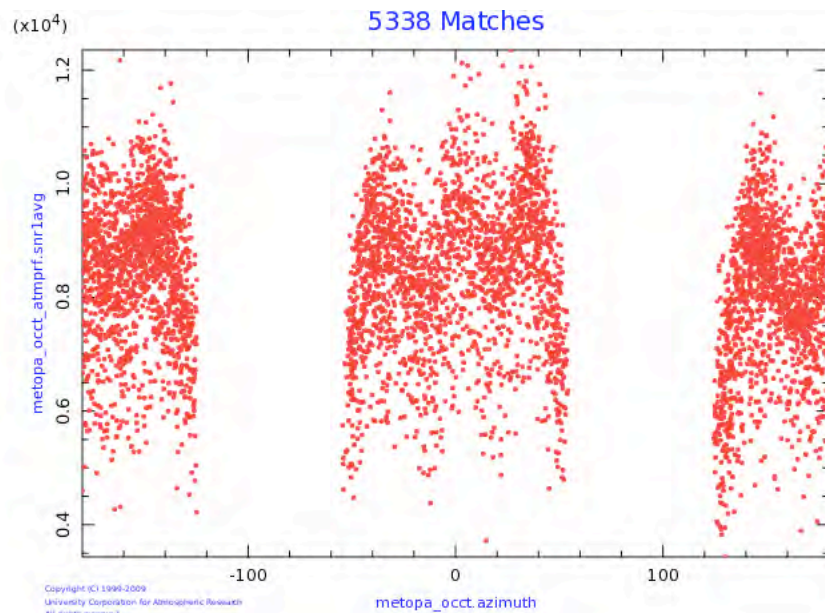


**In the lower troposphere:**  
the signal reduces below noise level in terms of the amplitude

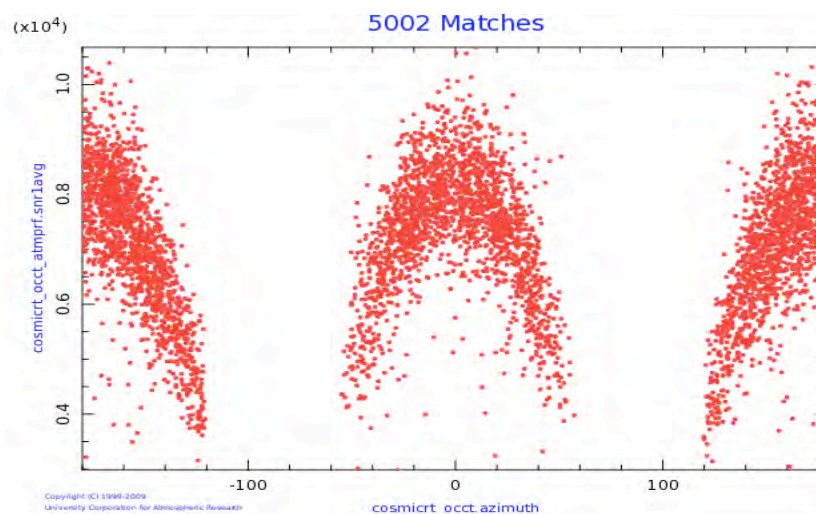


# GRAS - COSMIC SNR vs. AZIMUTH

## GRAS

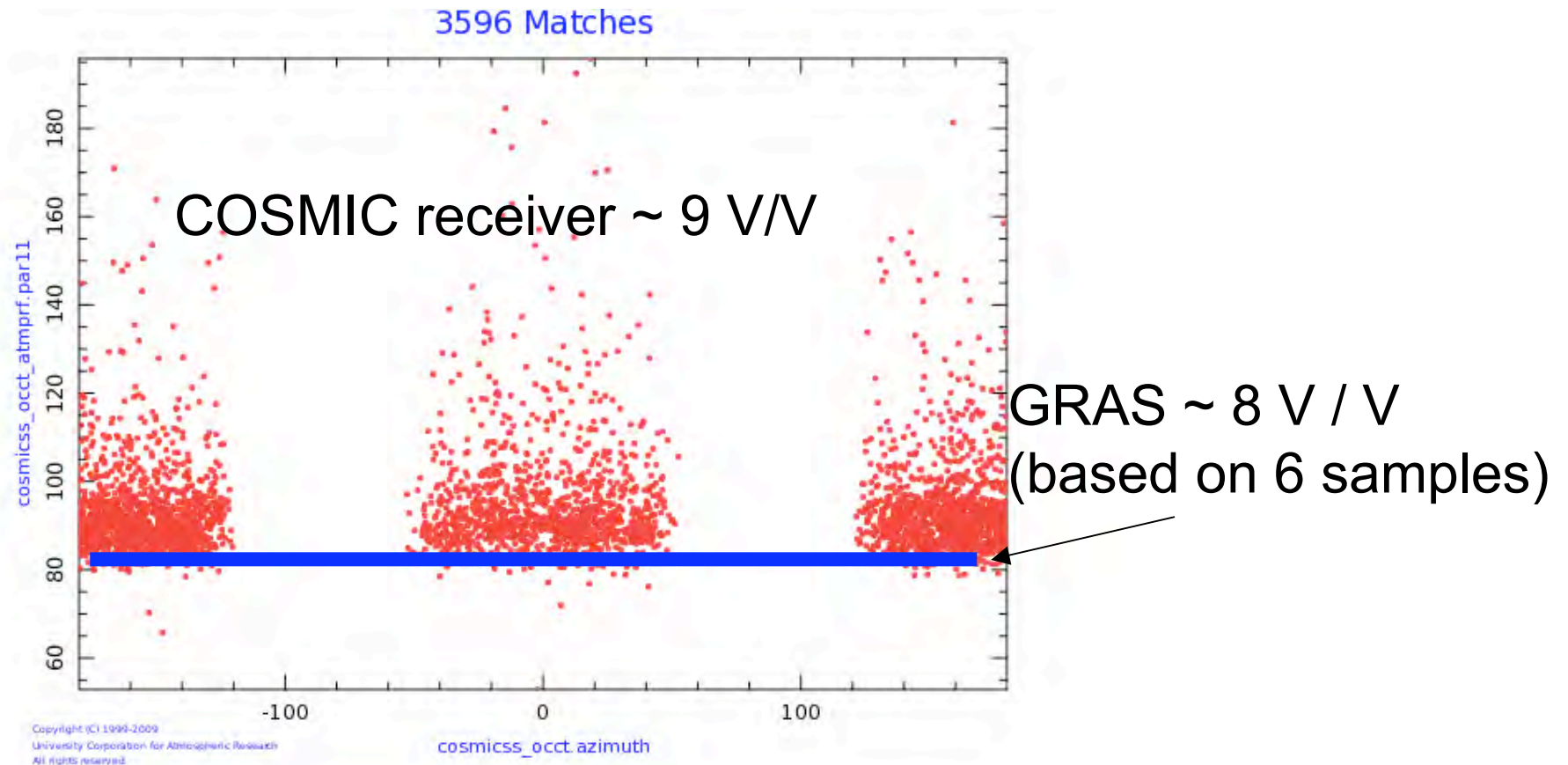


## COSMIC



The GRAS instrument has (a) more even gain pattern and (b) ~10% higher peak SNR, ~15% higher average SNR

# Background Noise level Comparison



Based on limited observation it appears that GRAS noise is slightly better (small statistics)

# Information / Data from EUMETSAT

EUMETSAT supplied slightly more than one month of level 0 data (**days 2007.272-305**) in single-orbit files. These files were in the form:

GRAS\_xxx\_00\_M02\_20070929005700Z\_20070929024159Z\_N\_O\_20070929023850Z

and were supplied in January 2009.

IMT/GPS conversion files (imts\_200709-200710.tar.gz) and comparison orbits and clocks (orbits\_20070929-20071030.tar.gz) were supplied in March 2010. Comparison bending angle profiles, supplied in files of the form:

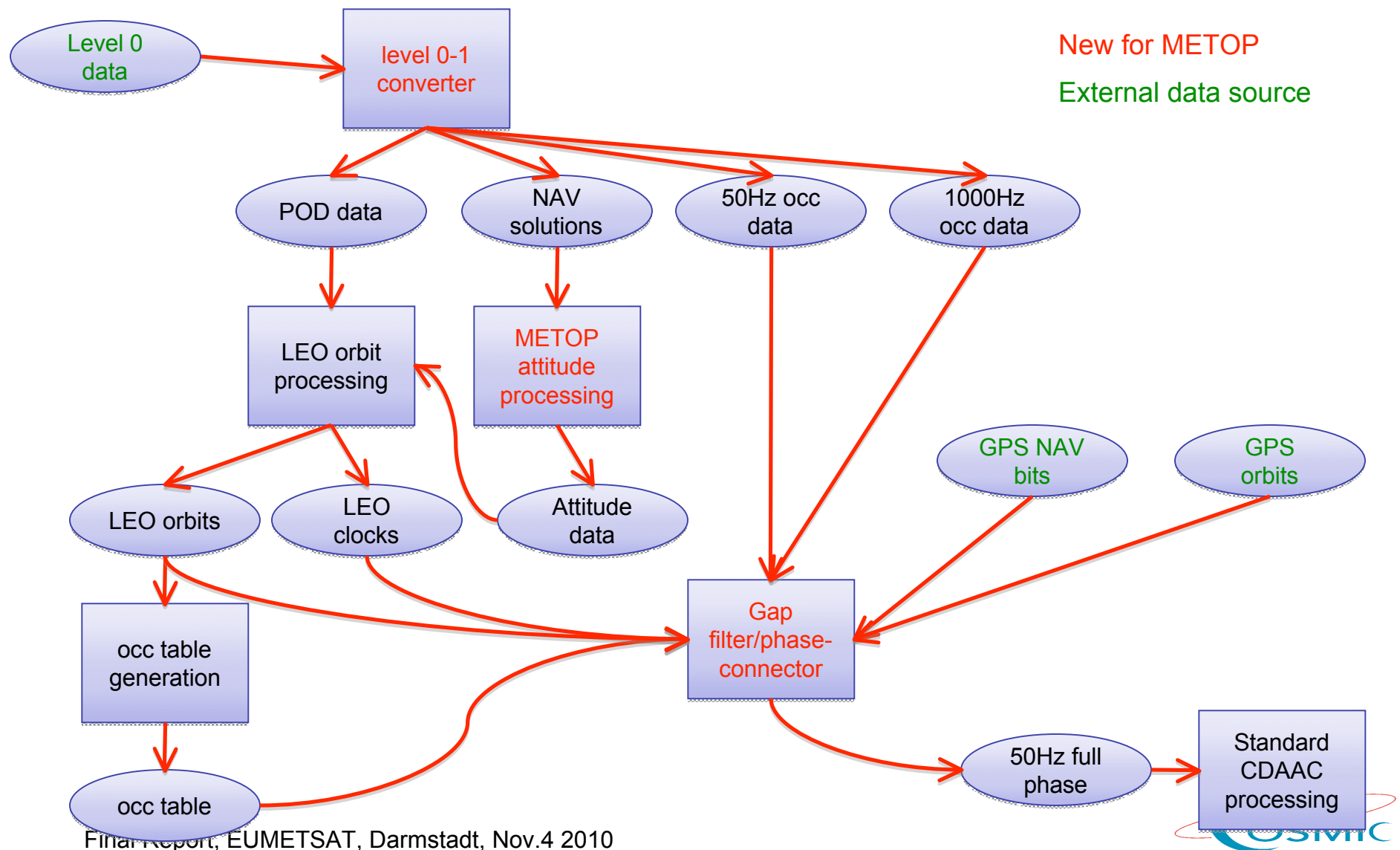
gras\_l1b\_occ\_m02\_20071001000051Z\_20071001000204Z\_20100715111252Z.nc

were provided in July 2010.

The PyGRAS reference translator code was supplied in Dec. 2008 and updated in March 2009.



# CDAAC processing of METOP data



# 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.



# Challenges and Differences that may contribute to structural uncertainty

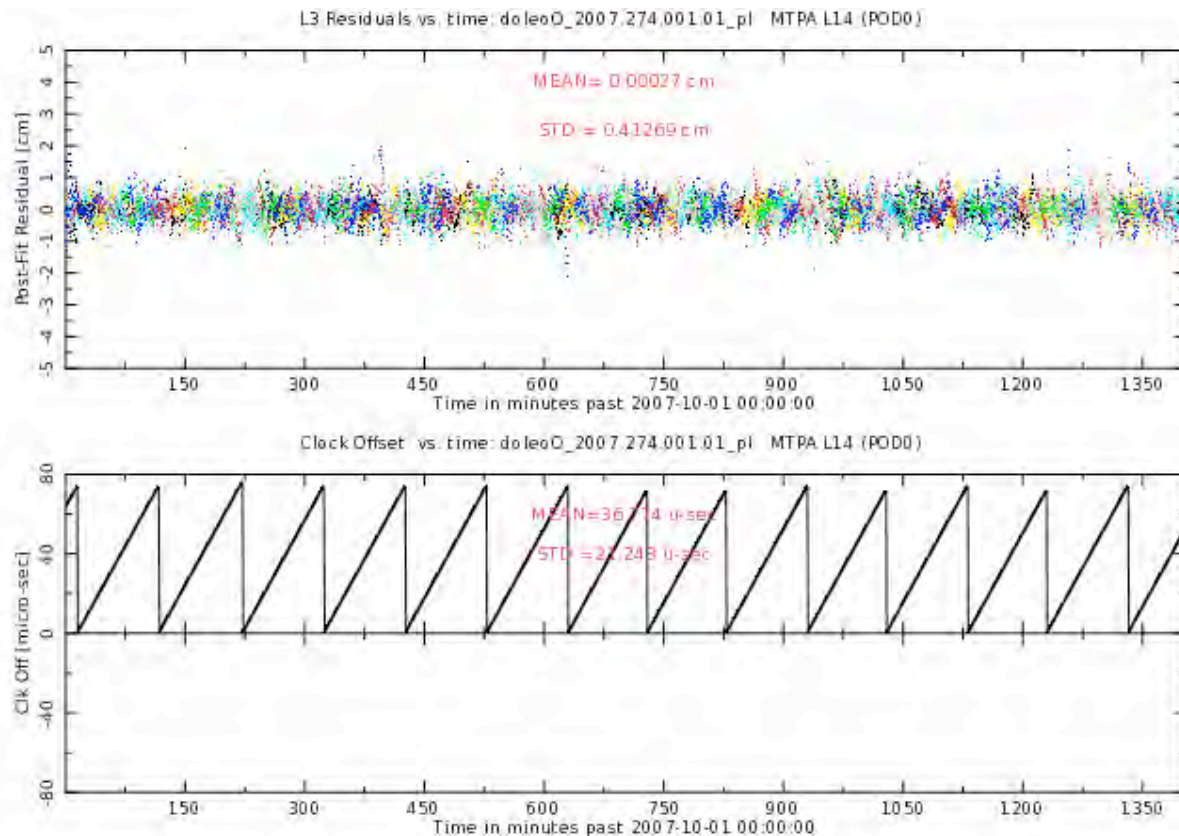
Processing METOP/GRAS data presents several challenges for one who is used to JPL heritage GPS RO receivers

- 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

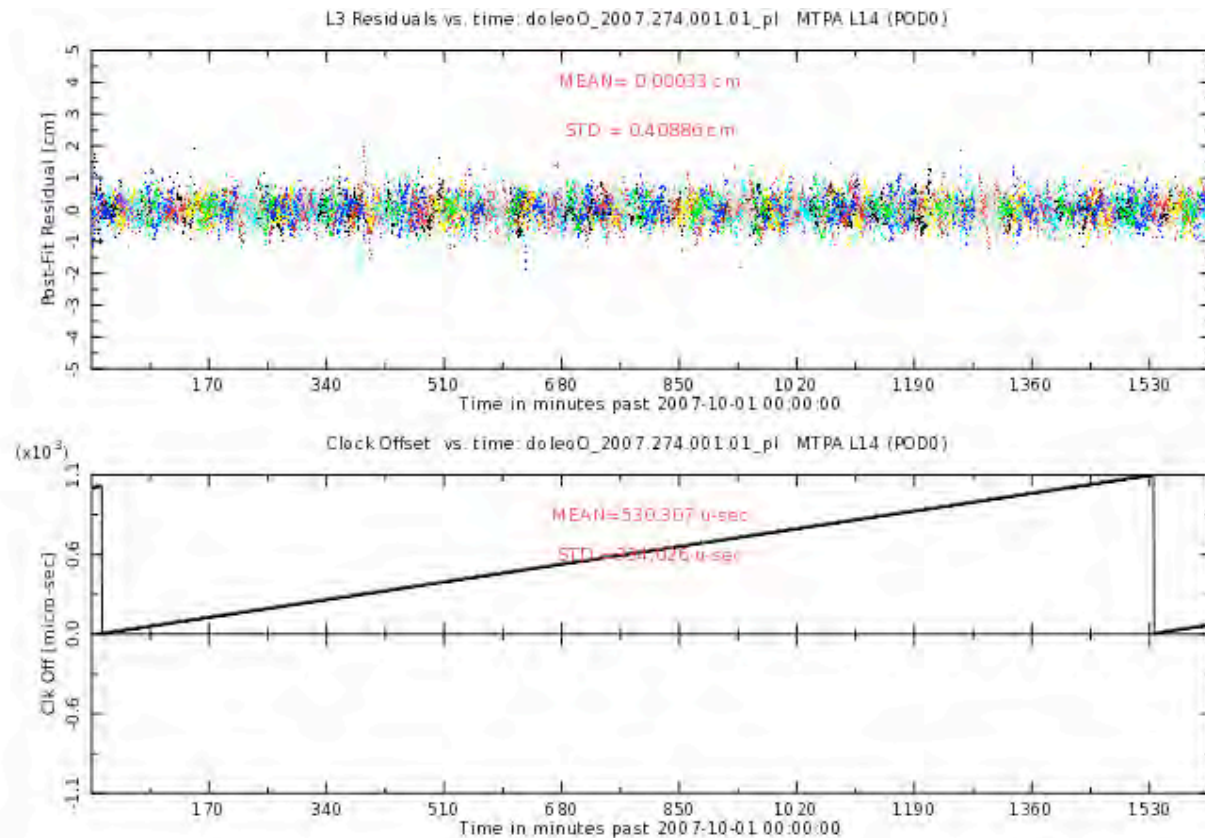
# Improvements in Translator software

- General cleanup, writing the code much more compactly
- In the raw sampling phase section of PyGRAS, atan3 was used to fix cycle slips. This seemed to cause problems near nav bit flips. I replaced this by atan2 correction with a simple phase connector that adds or subtracts full cycles to minimize the difference between adjacent samples.
- The ambiguity adjustment code, designed to keep the phase values close to the pseudorange values, was improved over that in PyGRAS.

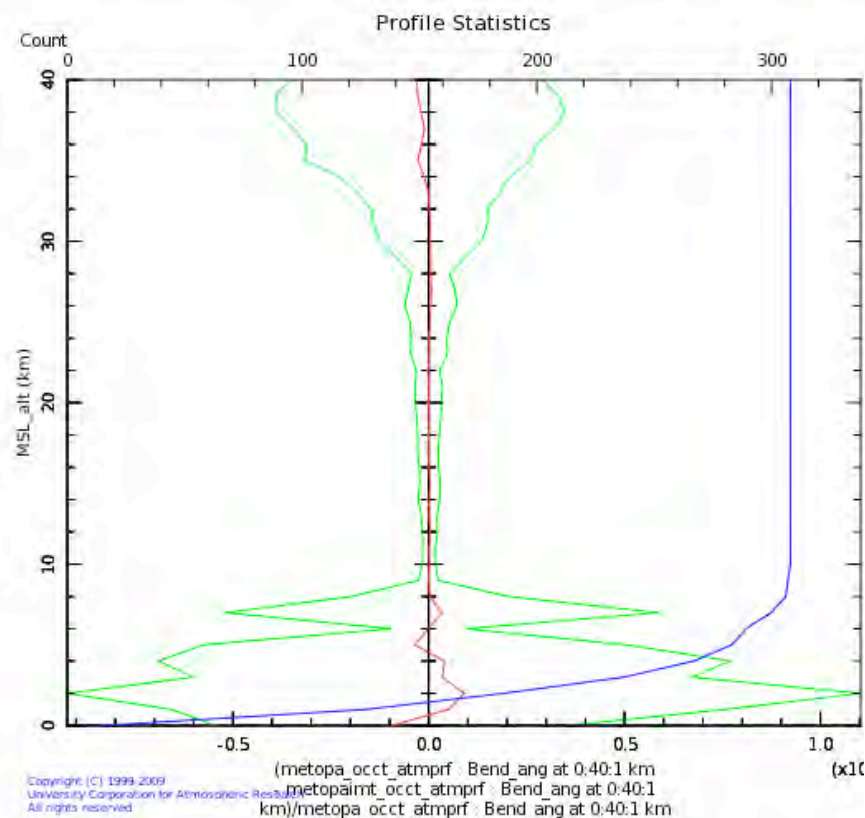
# Metop/GRAS clock error with “per-dump” IMT -> GPS time initialization



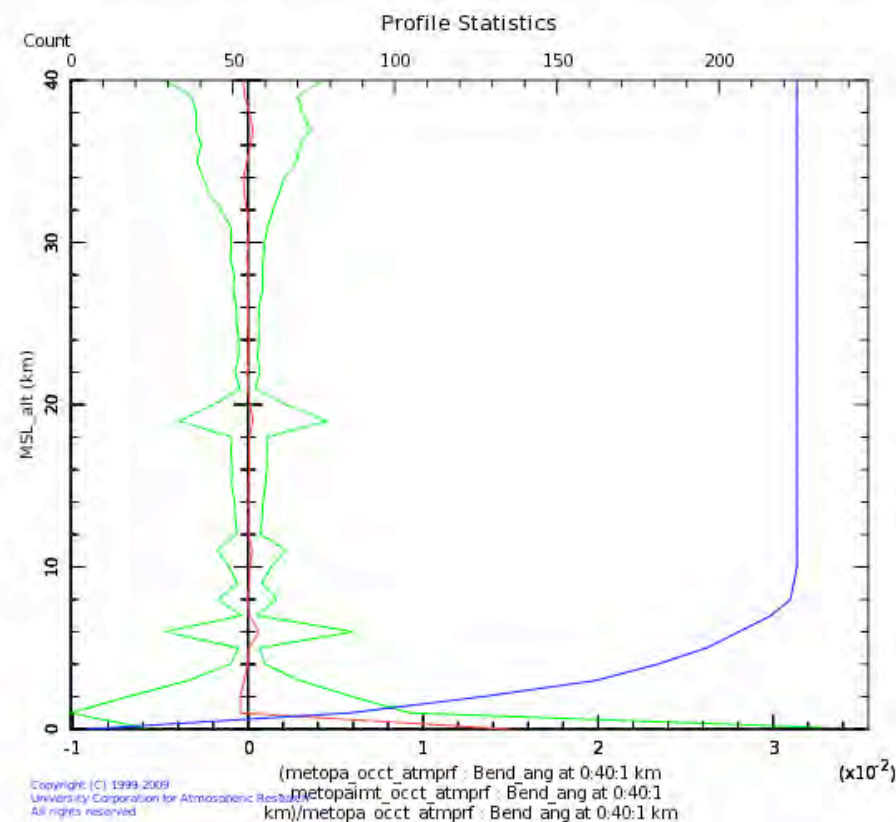
# Metop/GRAS clock error with “daily” IMT -> GPS time initialization



# Effect of Different IMT-GPS conversion on bending angle profiles

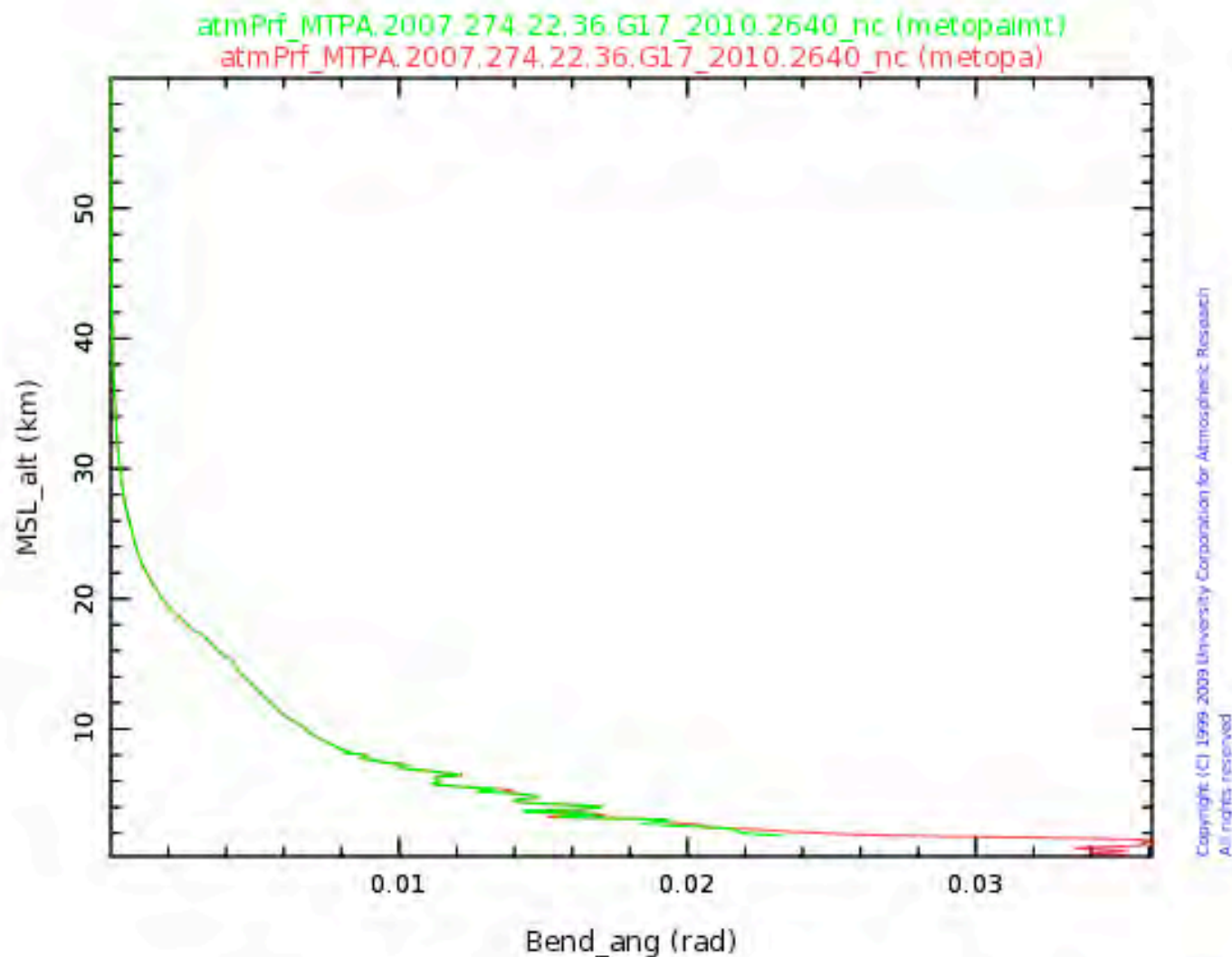


Setting



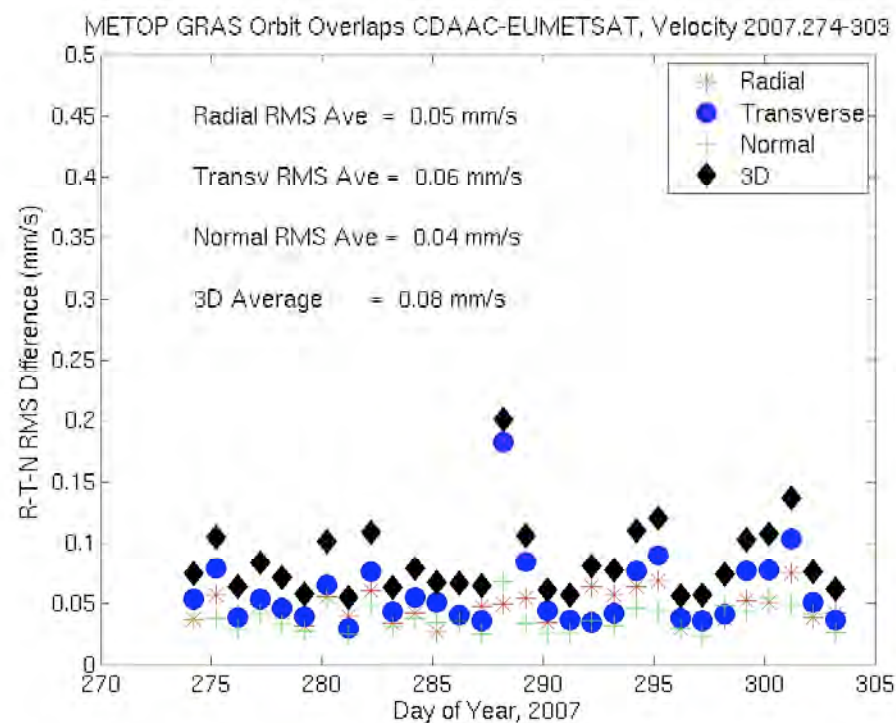
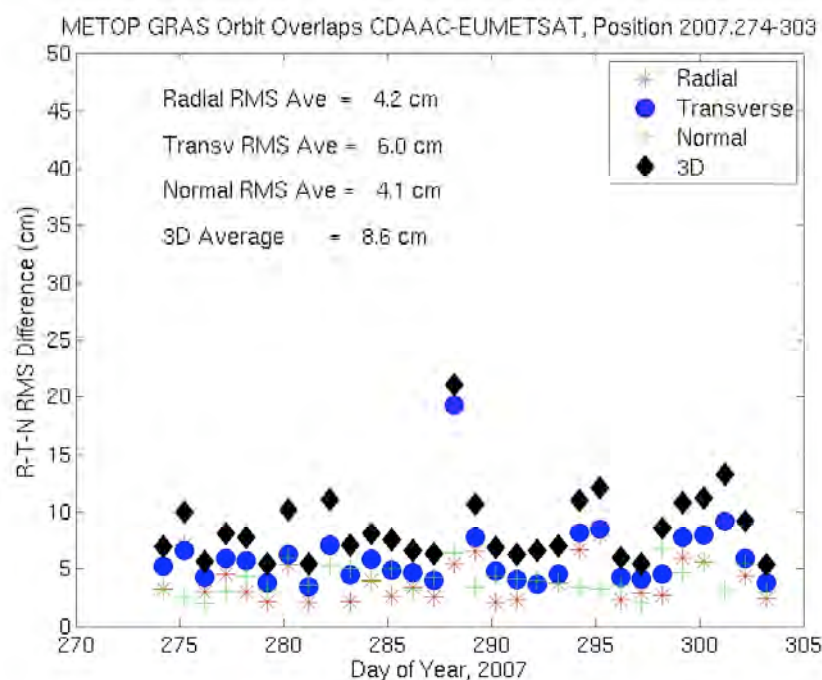
Rising

# Example BA Profile difference (IMT->GPS)





# Precision Orbit Determination



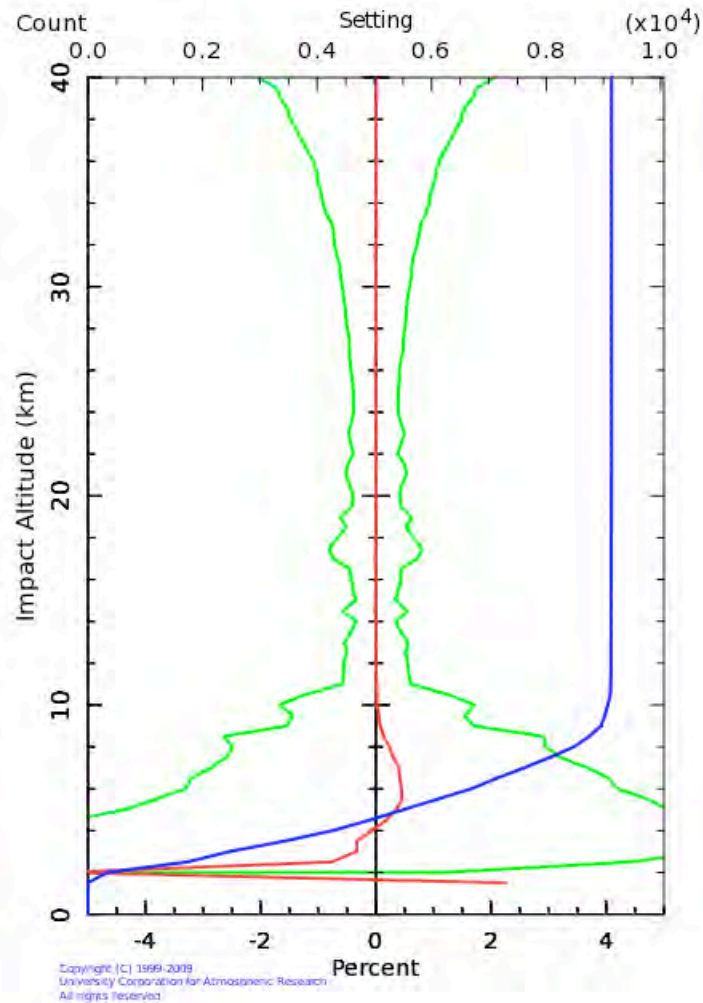
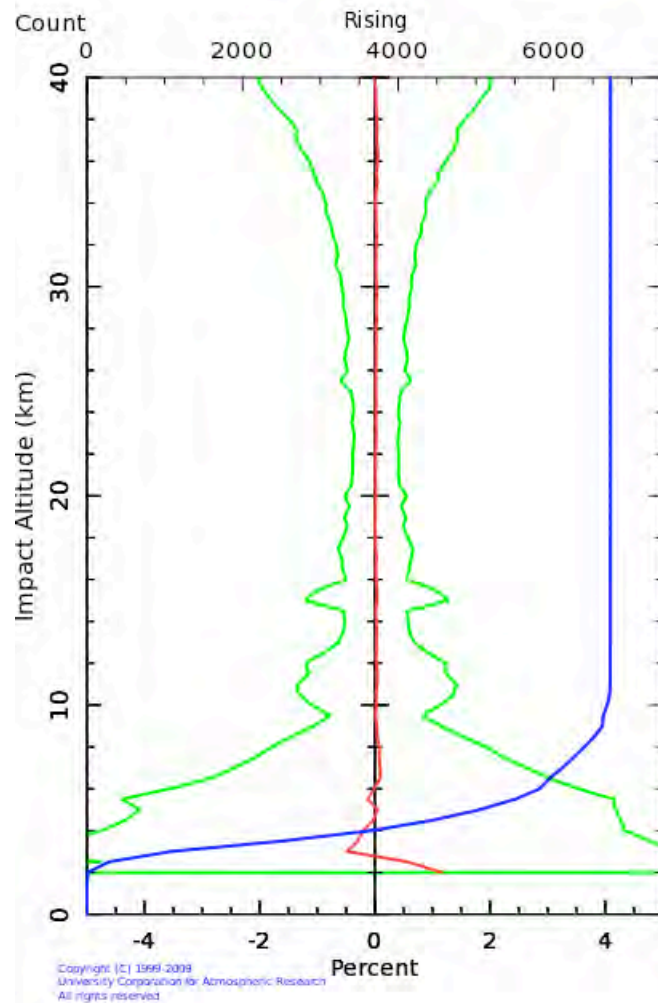
	MEAN Position Difference (cm)	STD Position Difference (cm)	MEAN Velocity Difference (mm/s)	STD Velocity Difference (mm/s)
Radial	0.7	4.2	-0.01	0.05
Transverse	0.9	6.0	-0.01	0.06
Normal	2.9	4.1	0.00	0.04
3D		8.6		0.08

No statistically significant velocity biases



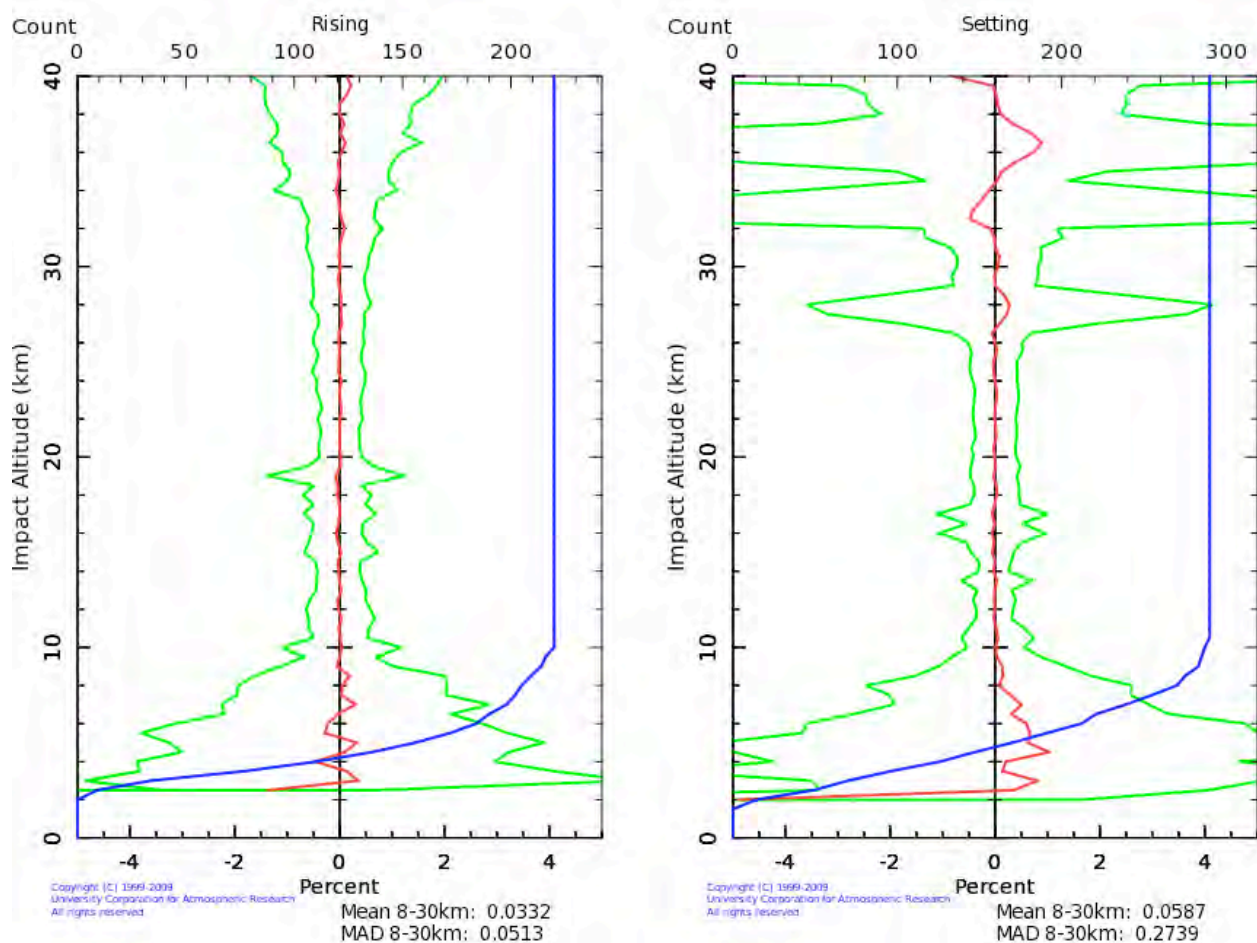
# GRAS Global Bending Angle Comparison

UCAR minus EUMETSAT 2007.274-304



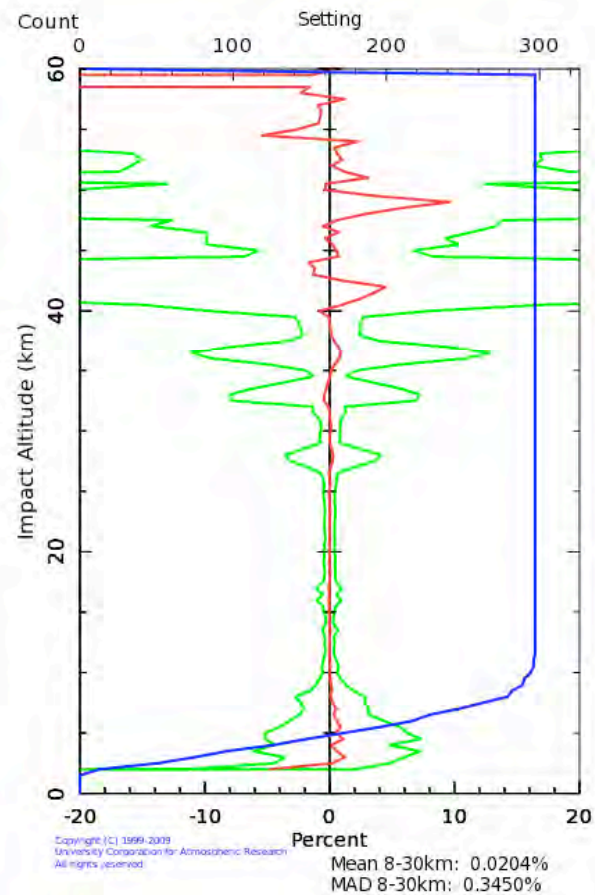
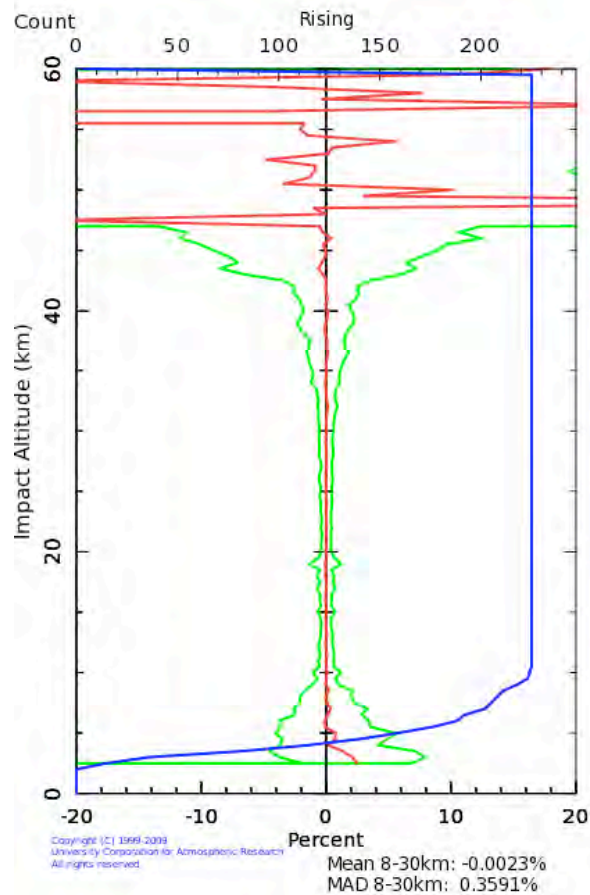
# GRAS Global Bending Angle Comparison

UCAR minus EUMETSAT One day 2007.274



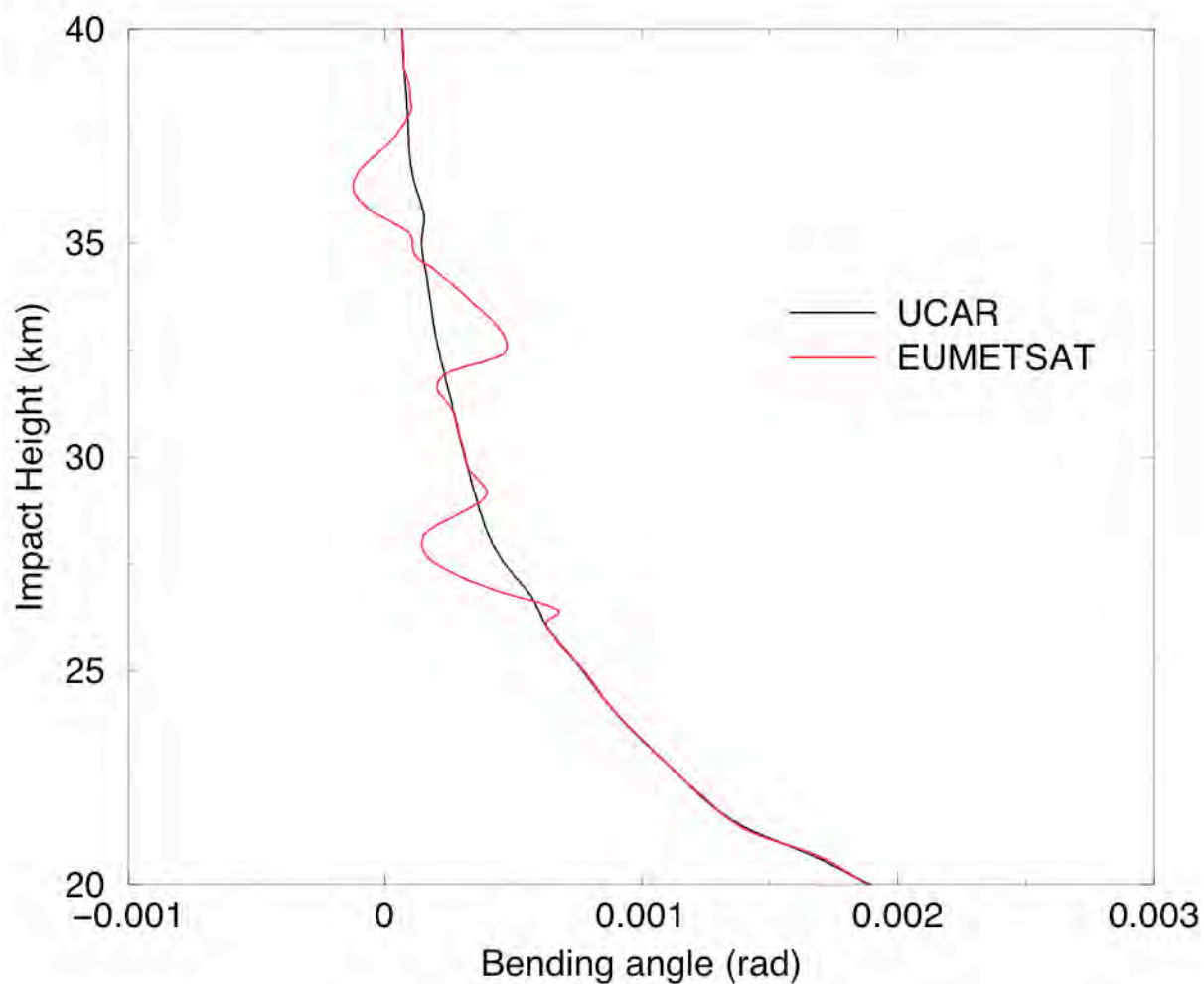
Setting Occultations Show Outliers

... the same comparison up to 60 km



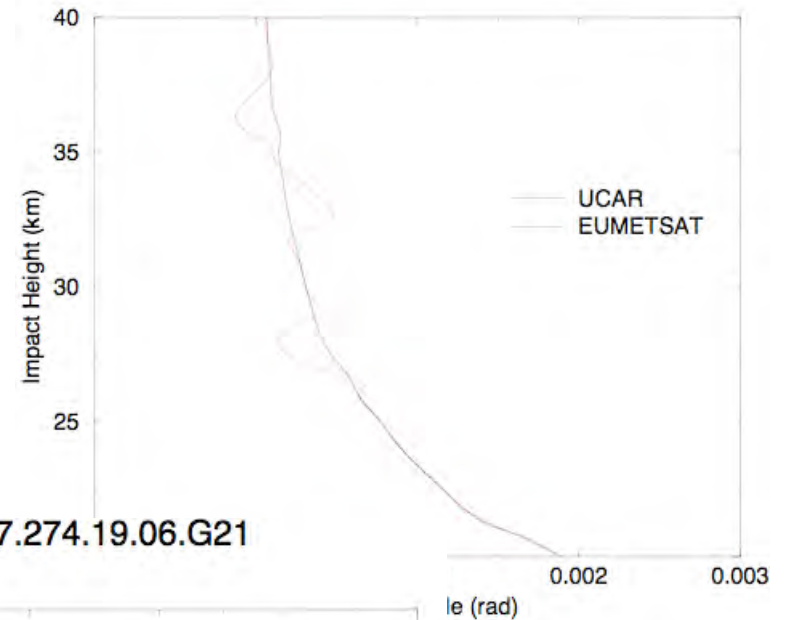
# Example Profile comparison

2007.274.20.06.G30

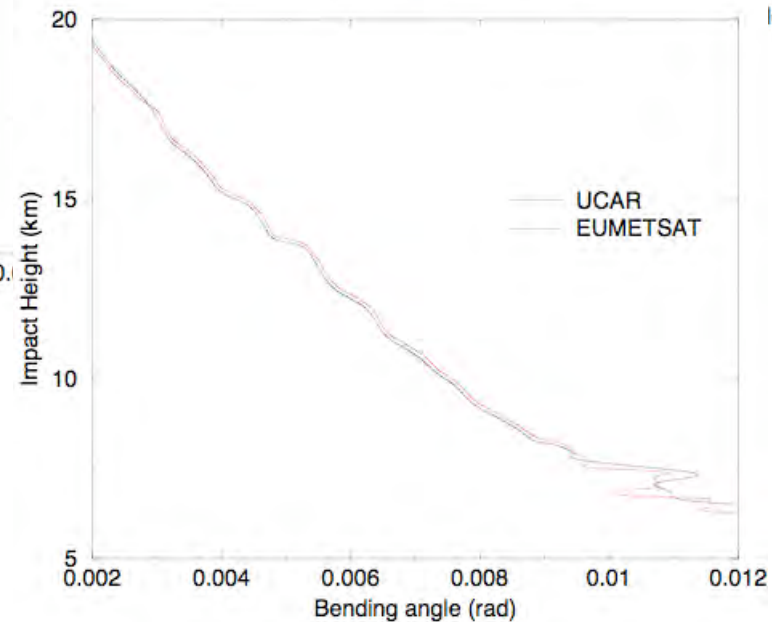


# A few examples for day 274

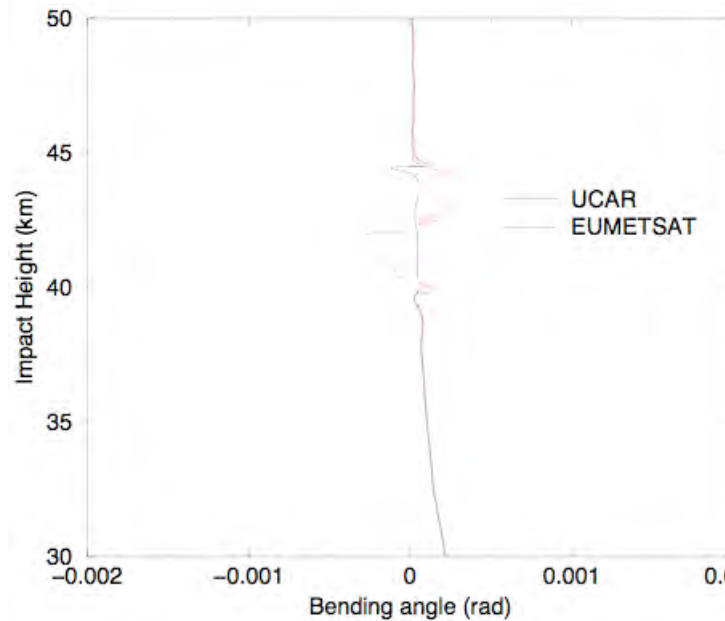
2007.274.20.06.G30



2007.274.19.06.G21



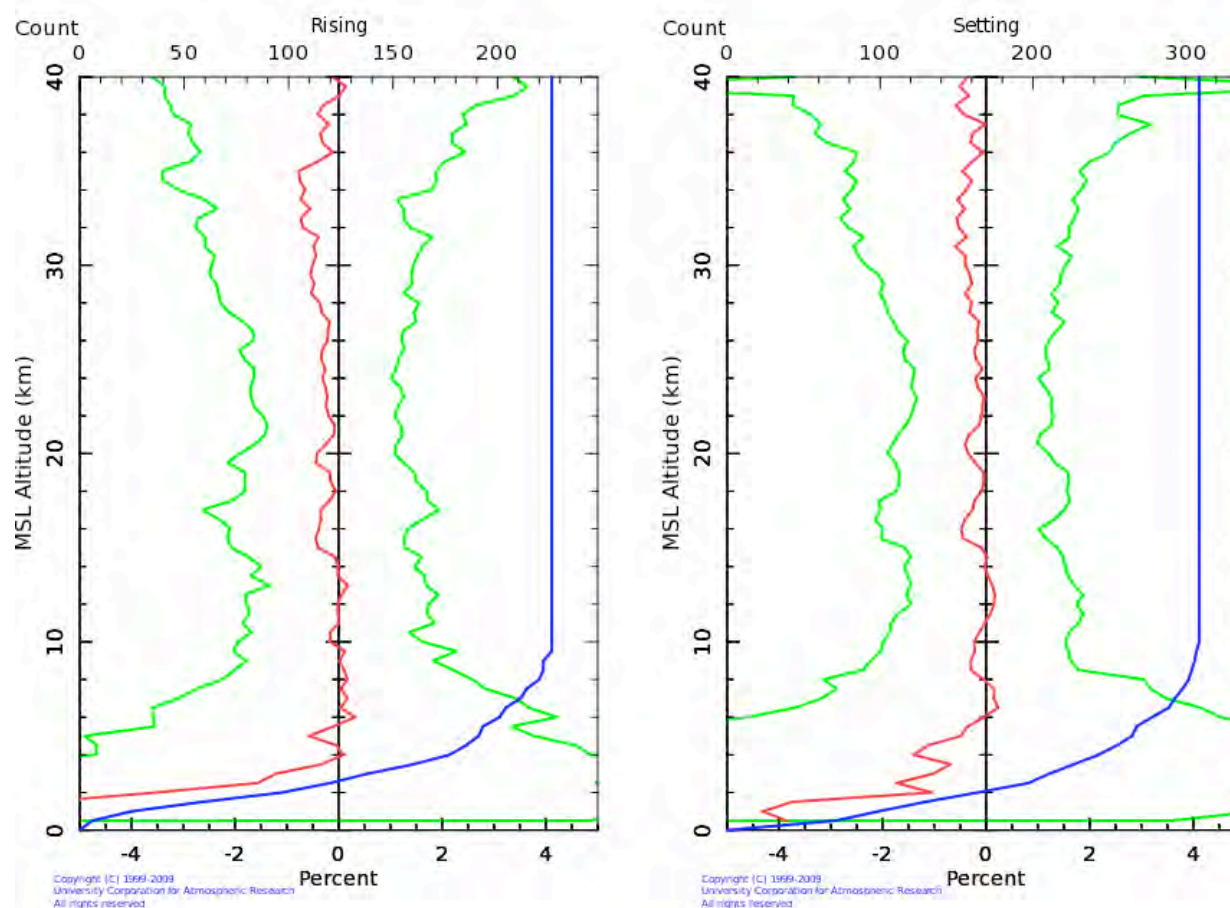
2007.274.14.43.G14





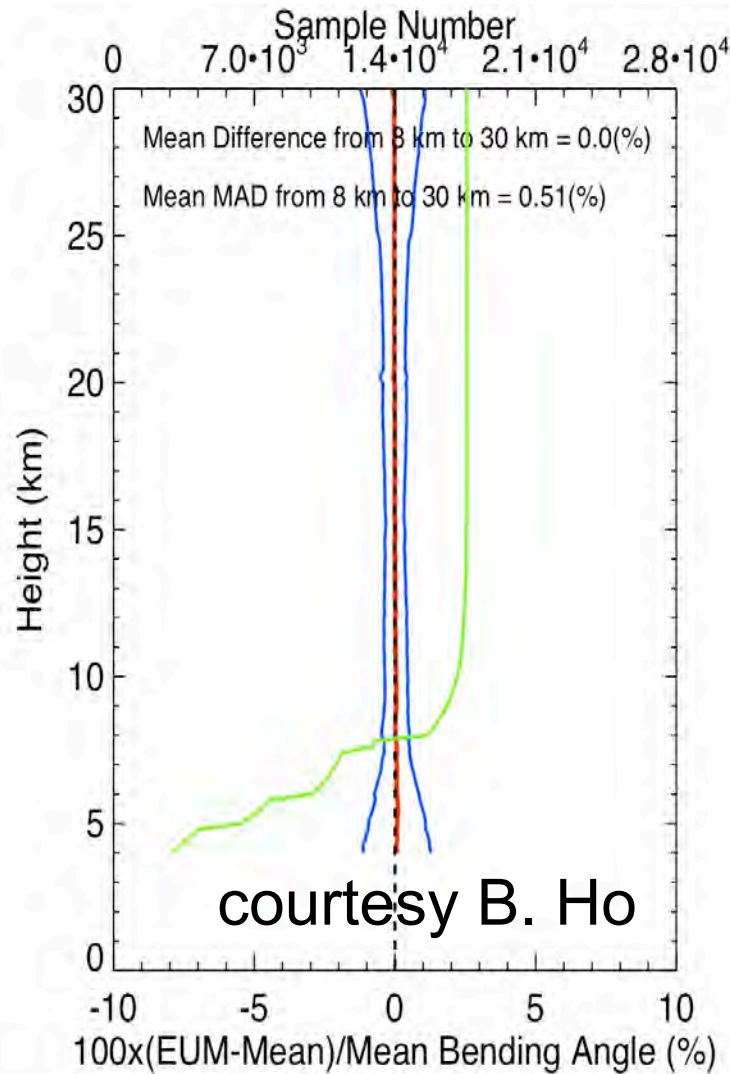
# GRAS Global Bending Angle Comparison

UCAR minus ECMWF One day 2007.274



No apparent outliers in UCAR profiles

# Comparison of CHAMP EUMETSAT vs. Multi-Center profiles



$$MAD = \frac{\left( \sum_{i=1}^N \frac{|a_i - b_i|}{a_i} * 100 \right)}{N}$$

compute MAD for every height layer  
 $a_i$ : EUMETSAT profile  $i$ ,  
 $b_i$ : average of several centers profile  
 $N$ : number of profiles (~16000)  
 Mean MAD is average over all layers

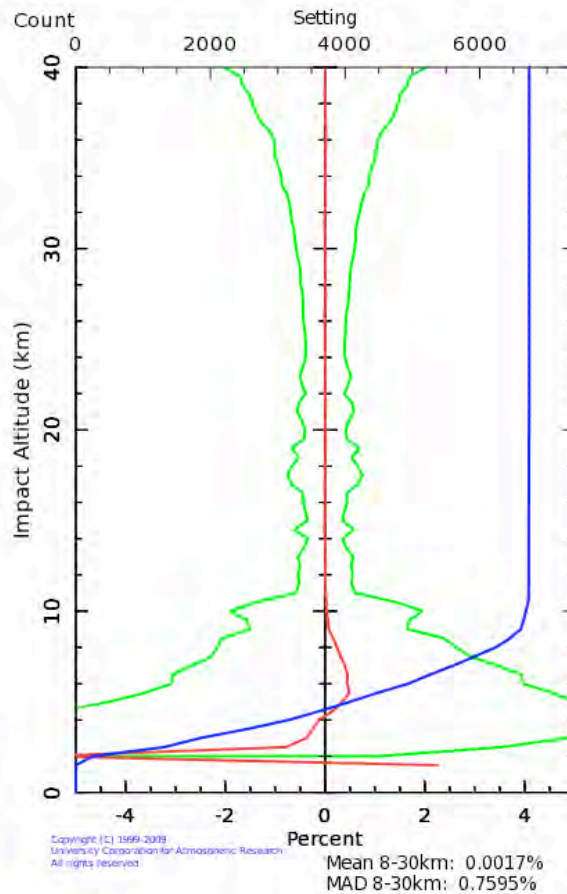
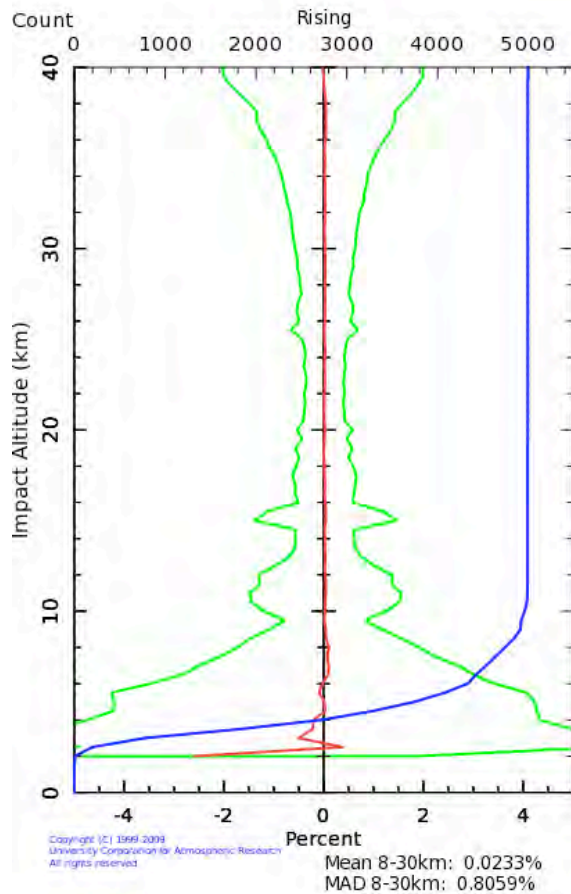
8-30 km

Mean Difference: 0.00 %

Mean MAD : 0.51 %



# Comparison of GRAS UCAR and EUMETSAT profiles



8-30 km rising  
Mean Difference: 0.02 %  
Mean MAD : 0.81 %

8-30 km setting  
Mean Difference: 0.00 %  
Mean MAD : 0.76 %

# Structural Uncertainty Results Overview

CHAMP comparison  
(EUMETSAT vs. average  
of 4 processing centers)

Mean Difference: 0.00 %  
Mean MAD : 0.51 %

GRAS comparison  
(EUMETSAT vs. UCAR  
setting only)

Mean Difference: 0.00 %  
Mean MAD : 0.76 %

These results are consistent because Ho et al. compare EUMETSAT CHAMP results against an average of 4 centers which is expected to be a factor of two less noisy than the results from any individual center.

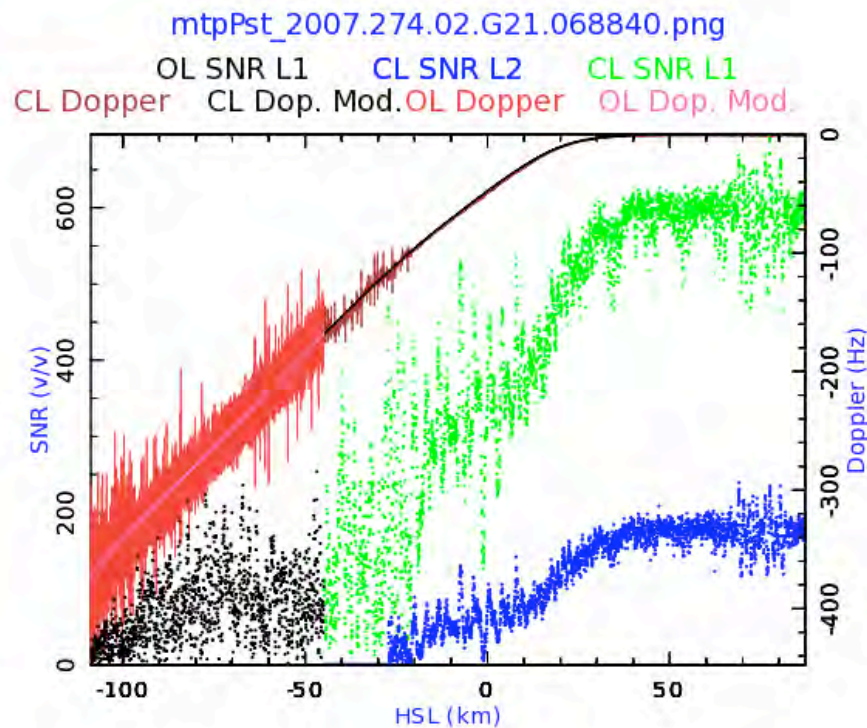
# Initial Conclusion

- Structural uncertainty of GRAS Metop data is comparable to “JPL-type” receiver data in the height range  $\sim 8\text{-}30$  km and thus suitable for climate monitoring
- There are several sources of structural uncertainty that do not affect our processing of JPL - type receivers
  - Conversion of IMT - GPS-time
  - High Quality oscillator
  - Data Gaps
  - 1000 Hz data
  - “Early” end of tracking in the lower troposphere

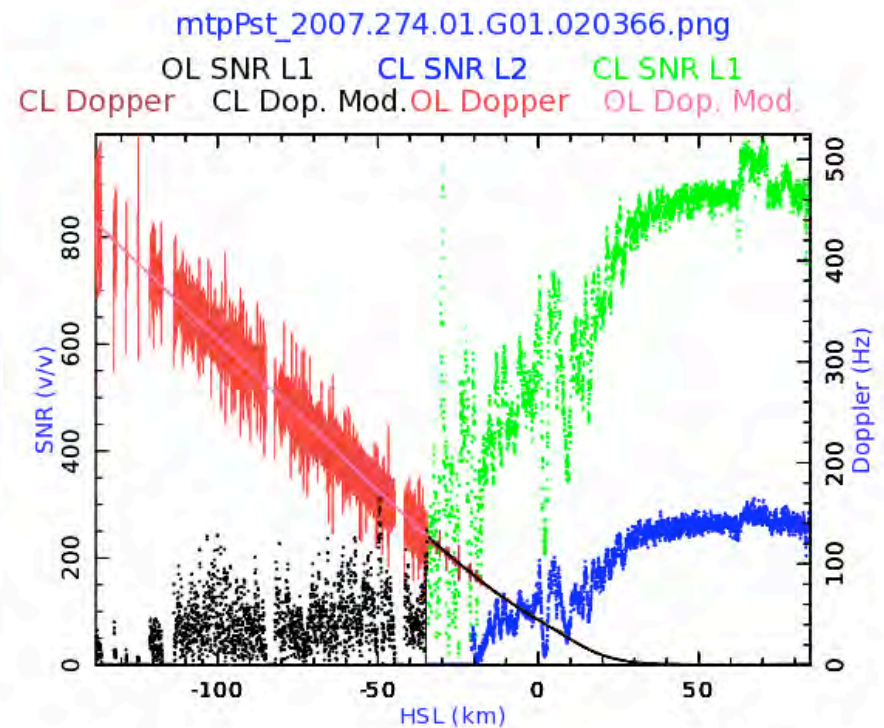
# Discussion of GAPS in Metop / GRAS data

# Examples of METOP occultations

## Good Setting occultation

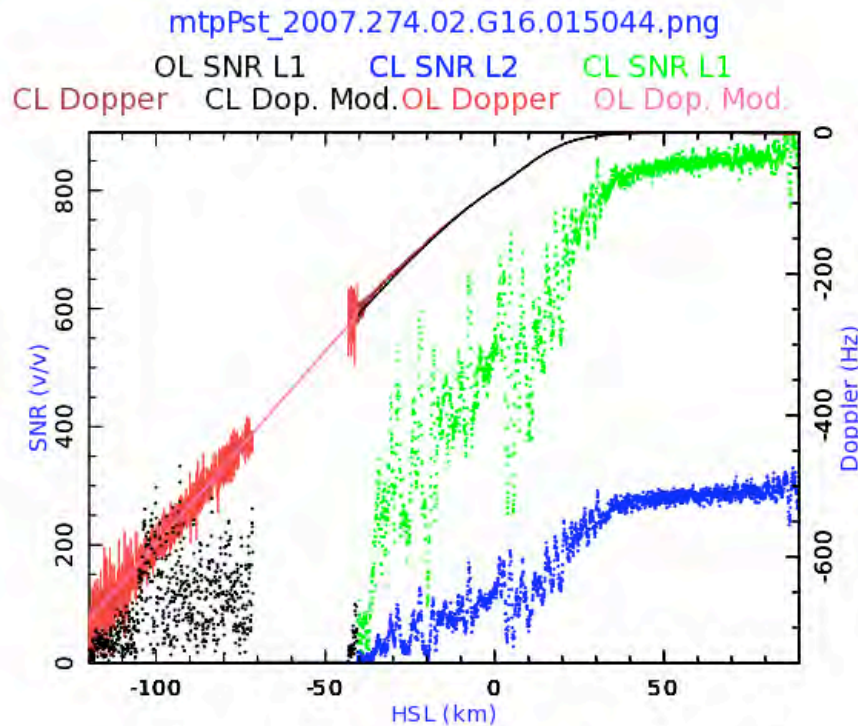


## Good Rising occultation

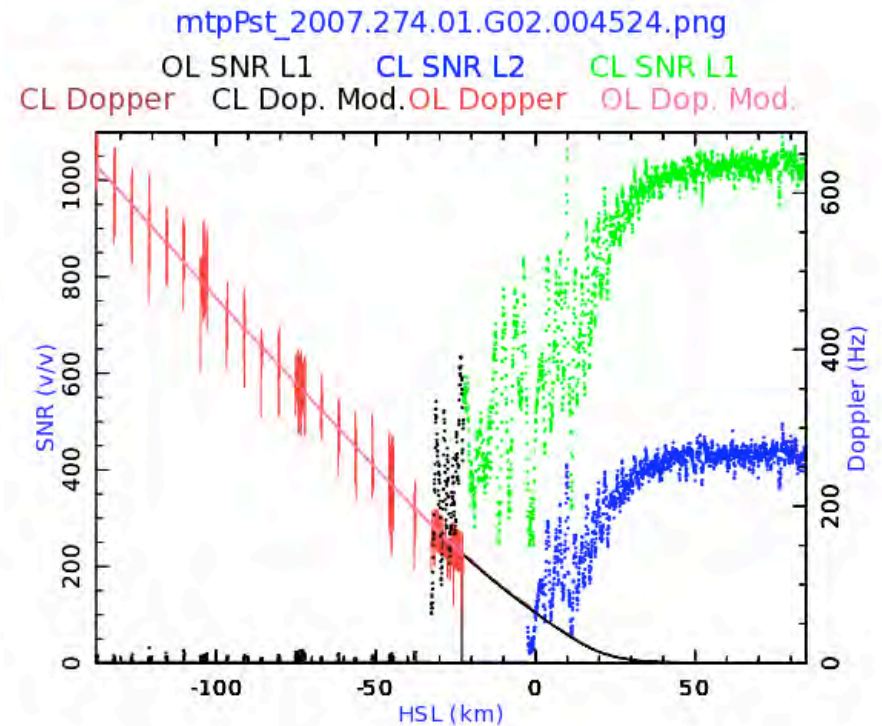


# Examples of METOP occultations

Setting occultation with gap



Rising occultation, lots of gaps!

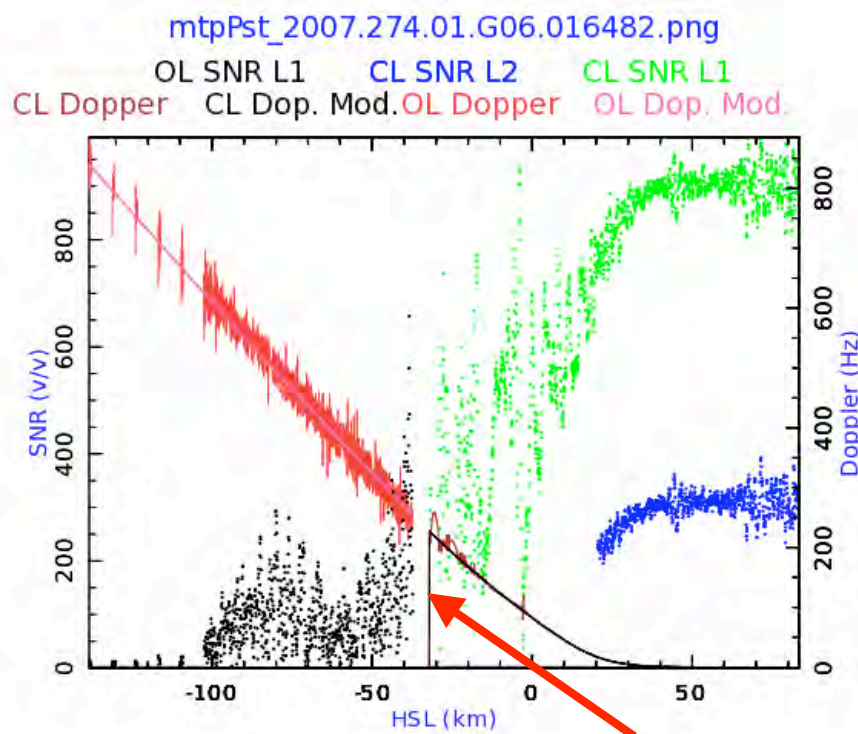


On day 274 **547 out of 712** occultations had closed loop Gaps!

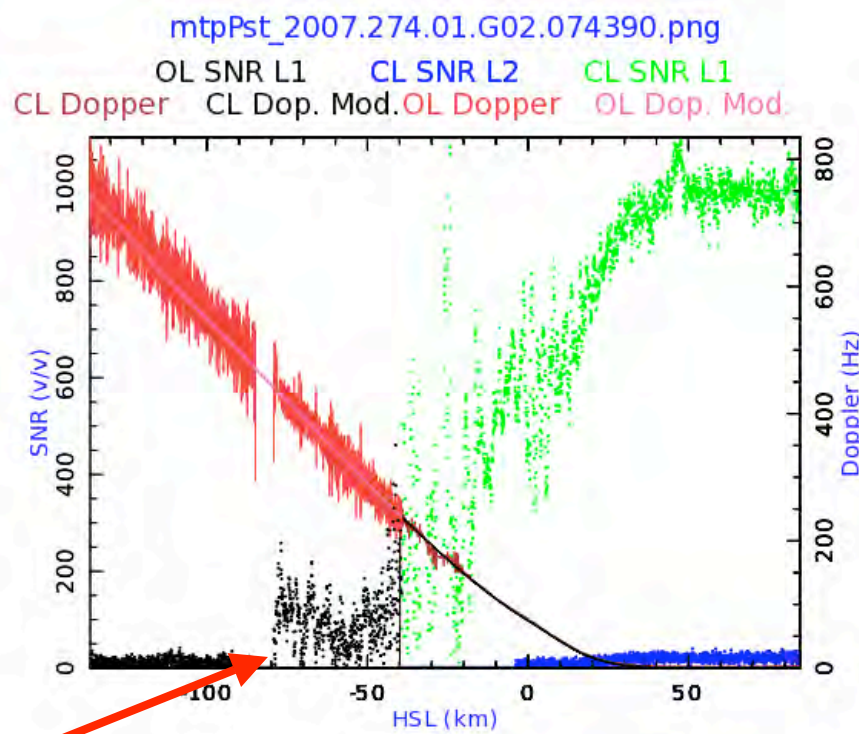


# Examples of METOP occultations

Rising, late L2



Rising, low L2 SNR



These are examples with gaps where the signal should be well above the noise level



# 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. (transition when raw L2 Doppler (exceeds 6 cm / sample) and the deviation of smoothed L1 from L2 Dopplers (exceeds 0.5 cm / sample - if this happens > 20 km occultation is discarded)

## 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

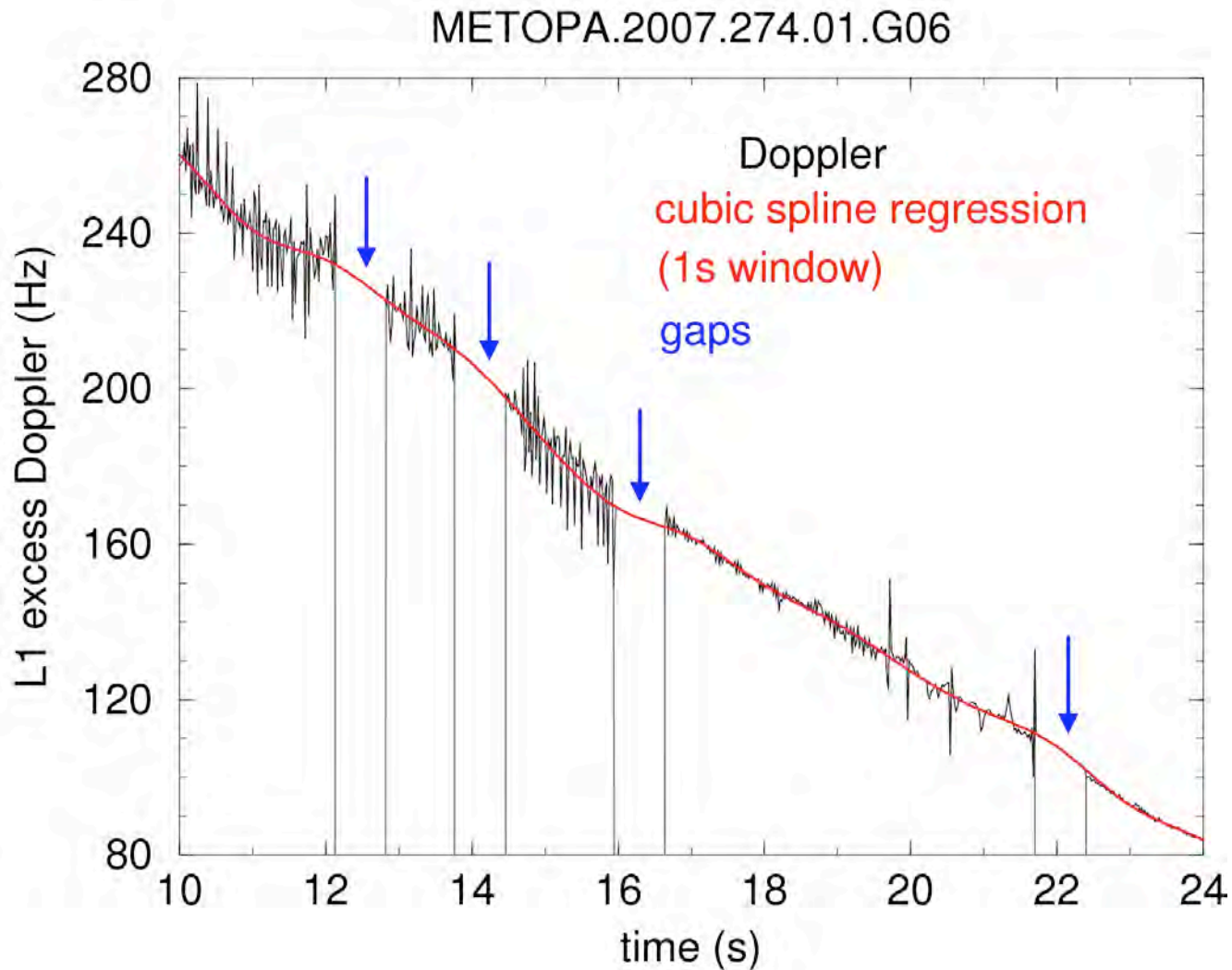
# Gap filler: Closed loop data

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

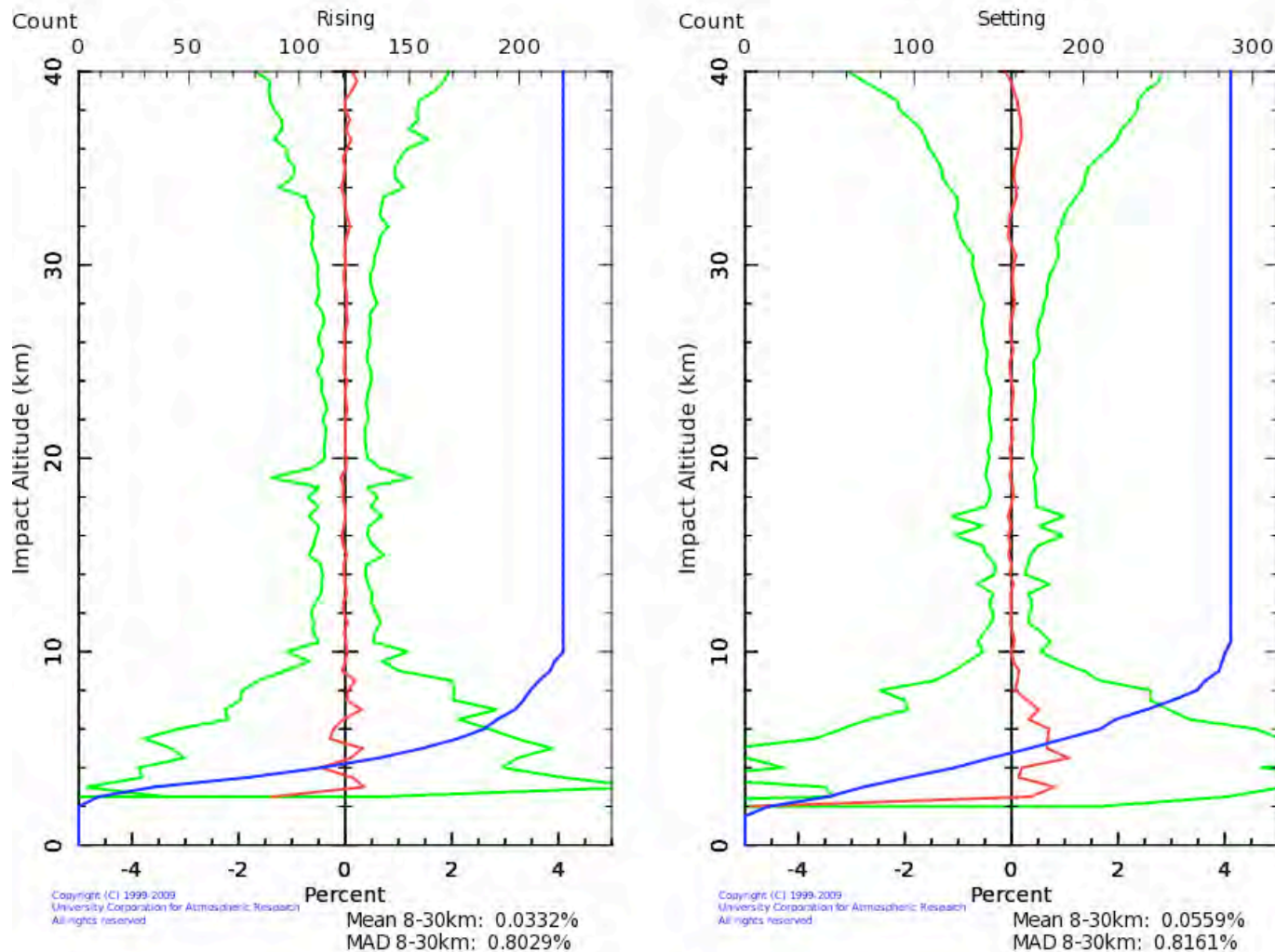
1. Generate continuous phase and SNR profiles by filling in gaps with 'missing' values
2. Compute excess phase from full phase (subtract out satellite motion and LEO clock errors)
3. Compute Doppler by differentiating excess phase
4. Fill in gaps (maximum of one second) in Doppler with cubic spline regression
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

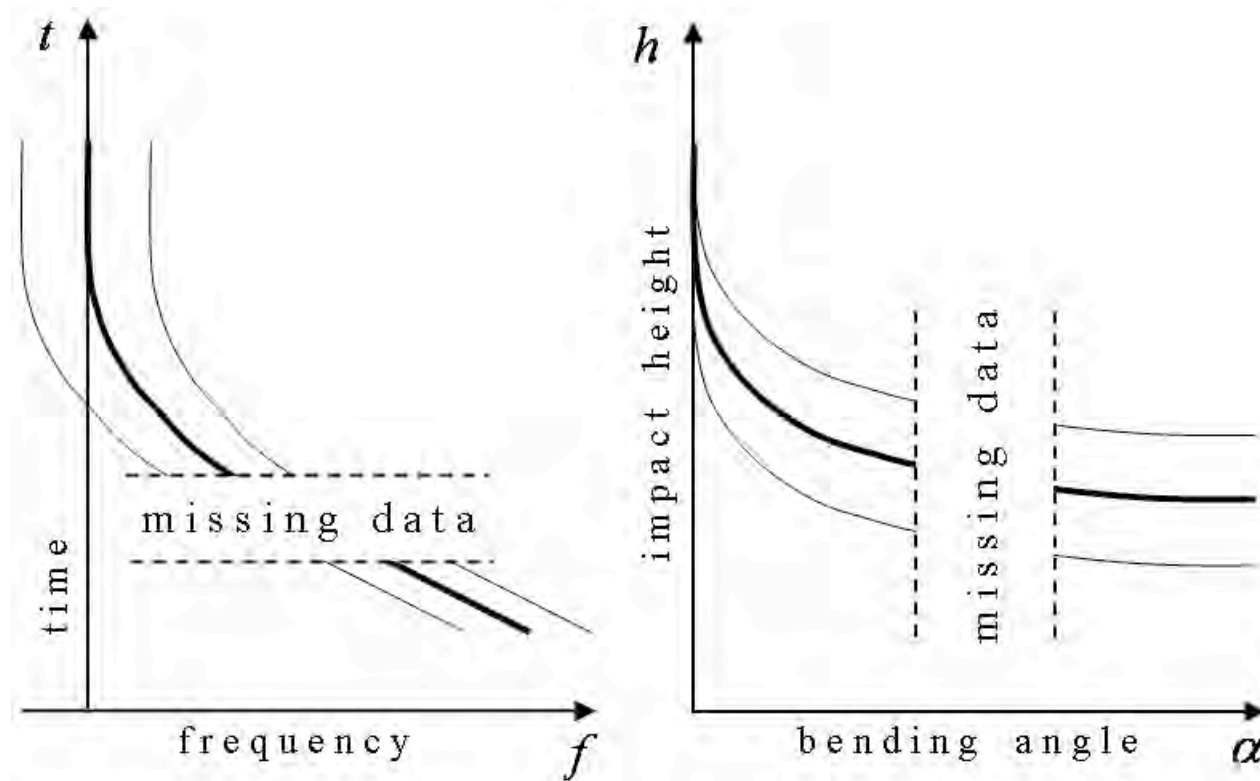


# Effect of GAP Fixing



Transparent curves show UCAR vs. EUMETSAT BA comparison excluding profiles affected by gaps. Thicker lines show comparison that include gap fixed data. No difference above 10 km - Differences below 10 km will be discussed

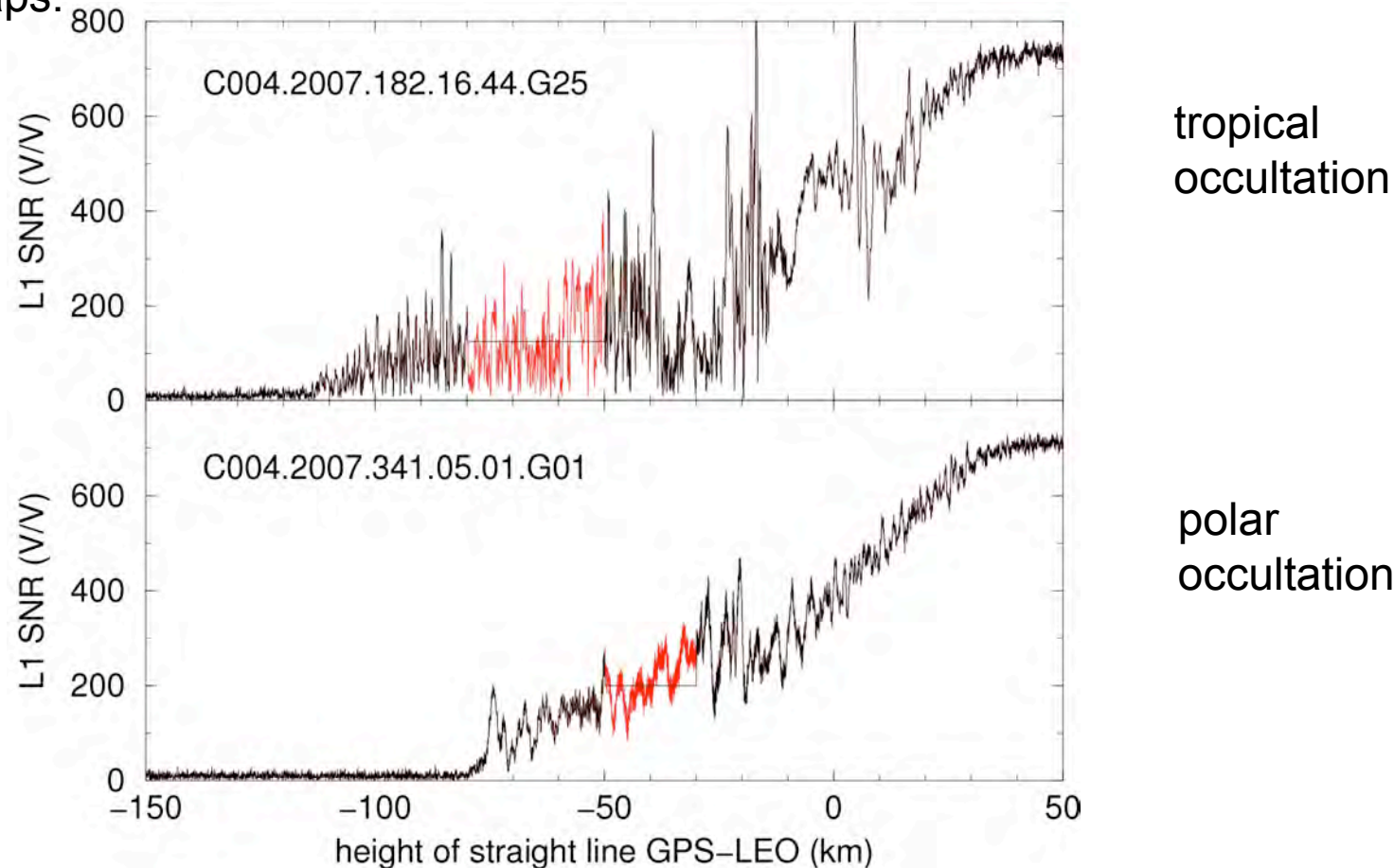
Transformation of RO signal by WO methods from time - frequency to impact parameter - bending angle representations results in a gap in time mapping into a gap in bending angle.



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.



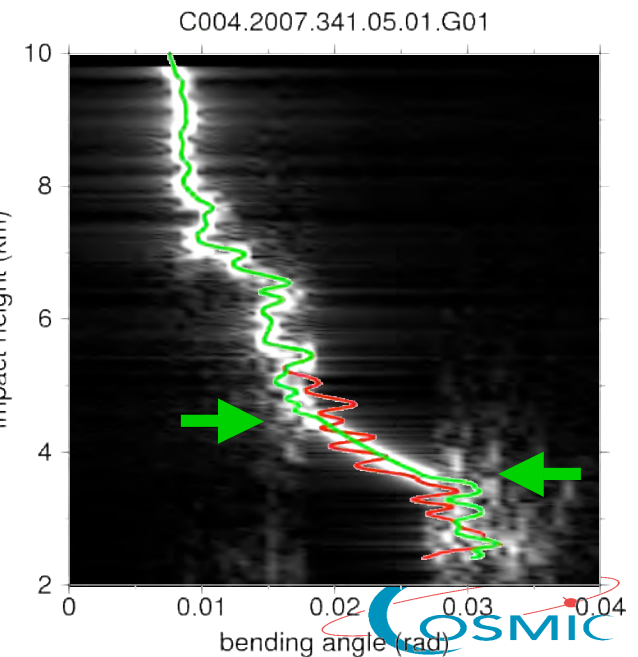
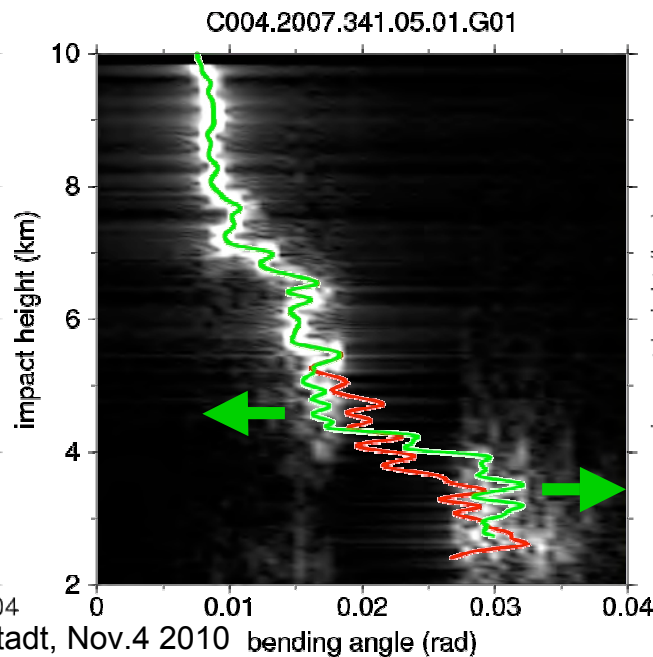
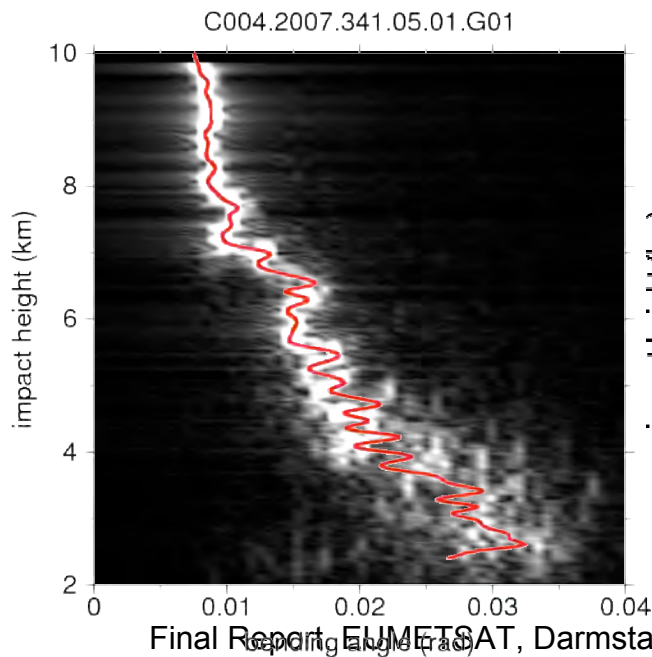


Tropical occultation: broad local spectrum of the WO-transformed signal  
(due to the effect of moist convection)

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.**

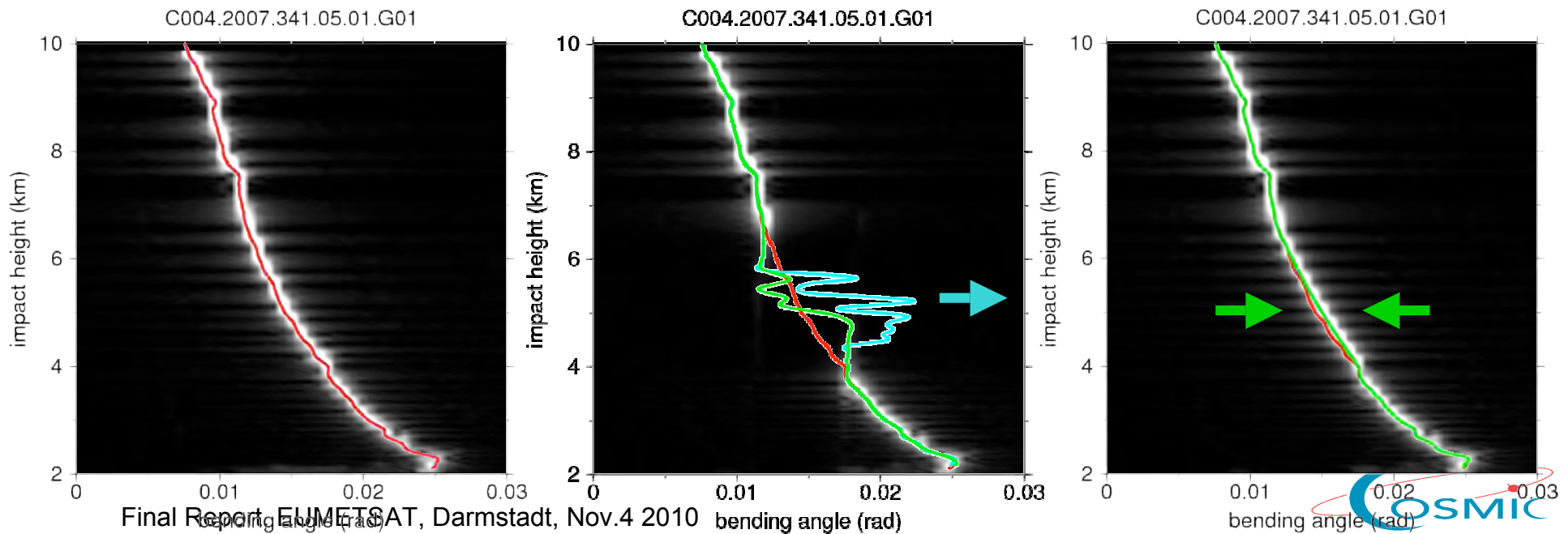


## Polar occultation: narrow local spectrum of the WO-transformed signal

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: **HSL=-80km;**  
**HSL=-150km**  
(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.



# 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

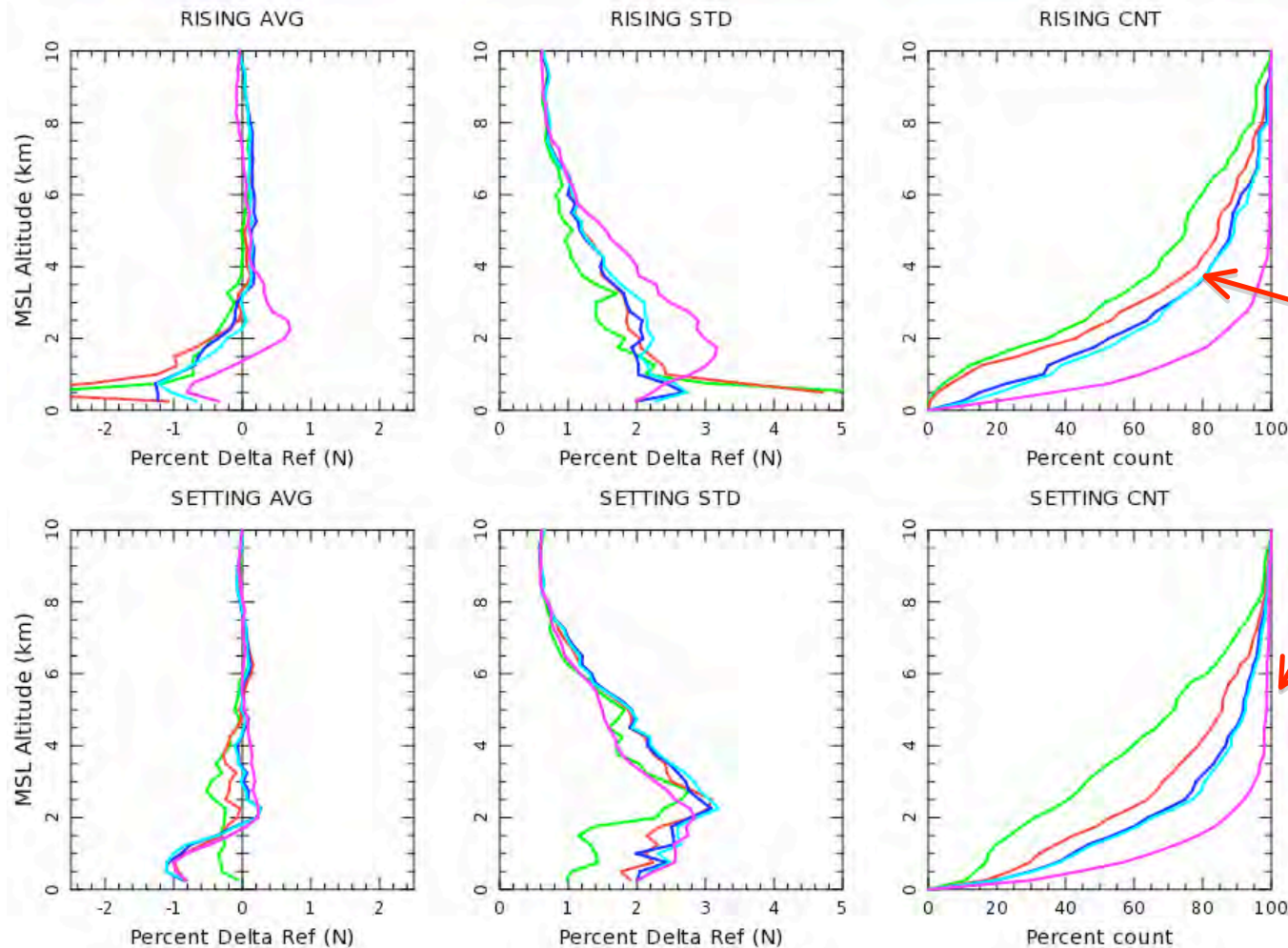
METOP CL to first gap

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.

# The Advantage of the GRAS Ultra Stable Oscillator

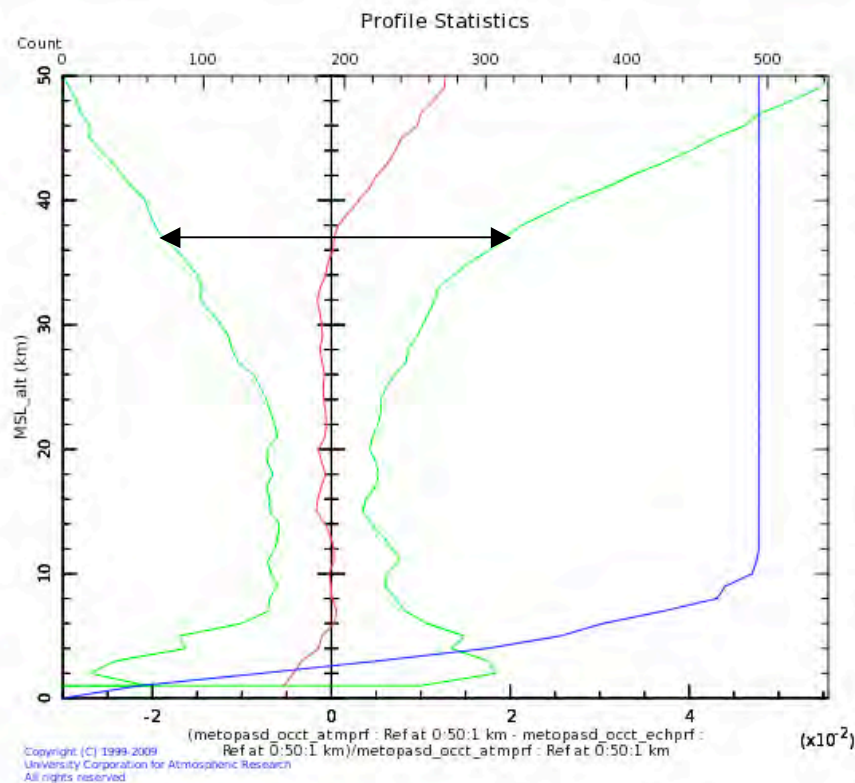
GRAS has a USO - allowing for processing of undifferenced RO observations

COSMIC does not have a USO and must process single or double differenced observation

We compared single difference and zero difference processing of GRAS - to help decide whether to consider a USO for “COSMIC II / Formosat7”

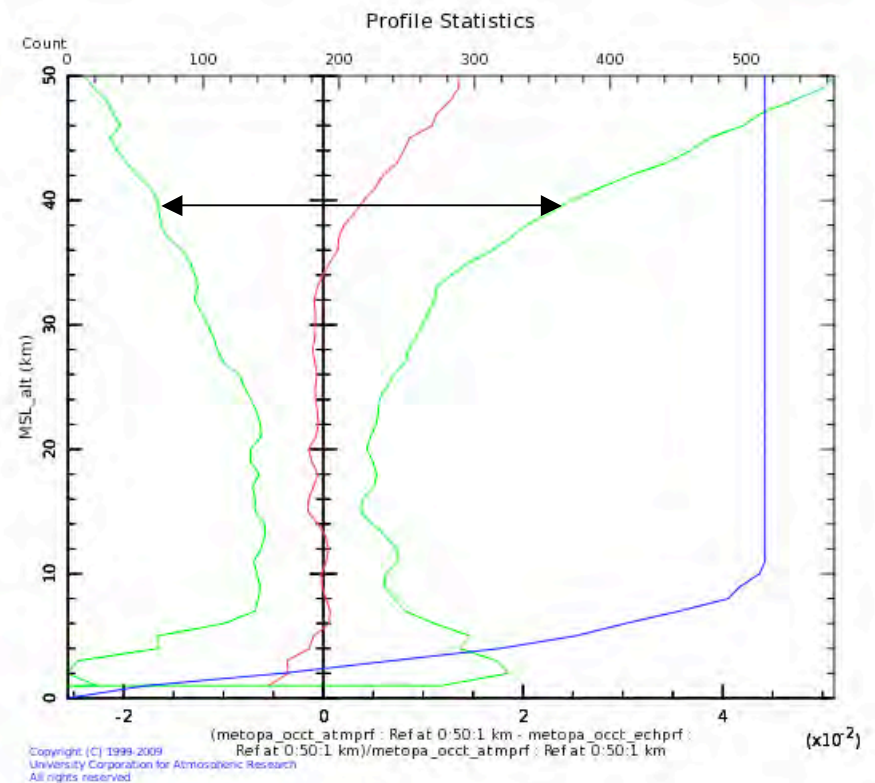
# Single Difference vs. Zero Difference

## UCAR GRAS refractivity statistics compared to ECMWF



single difference

+/- 2% stdev at ~37 km

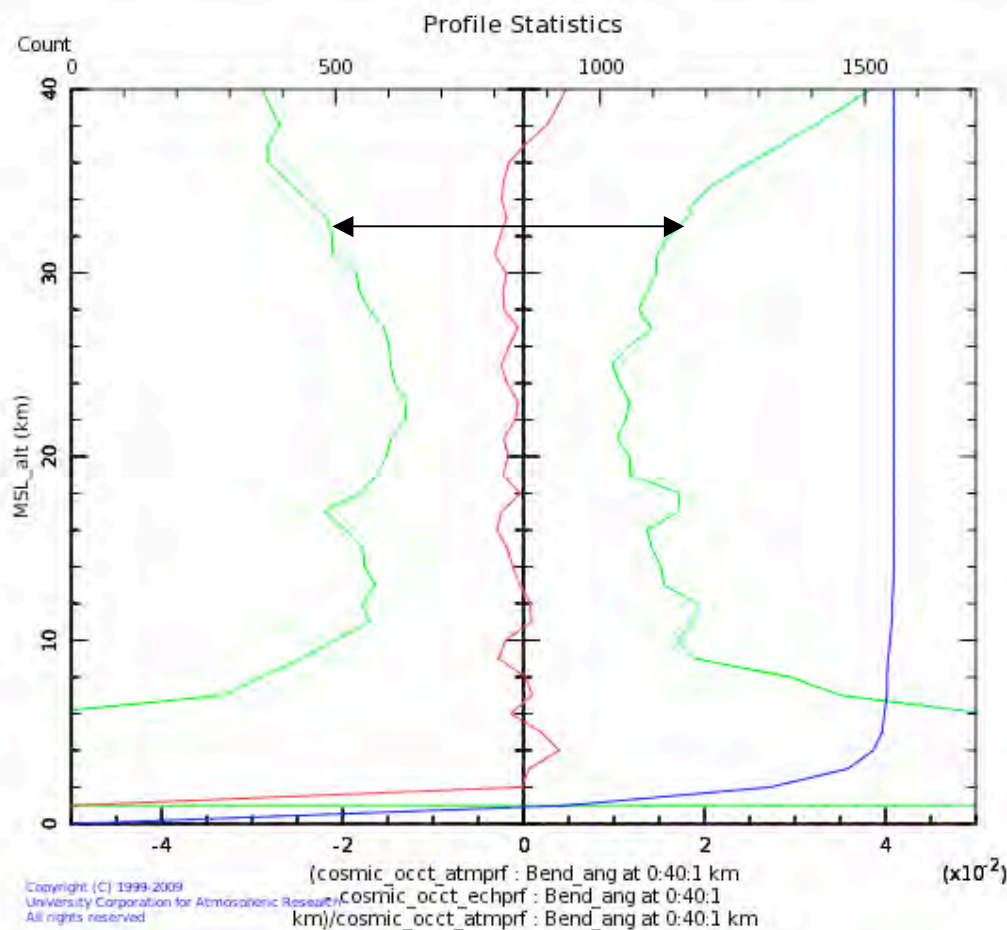


zero difference

+/- 2% stdev at ~40 km

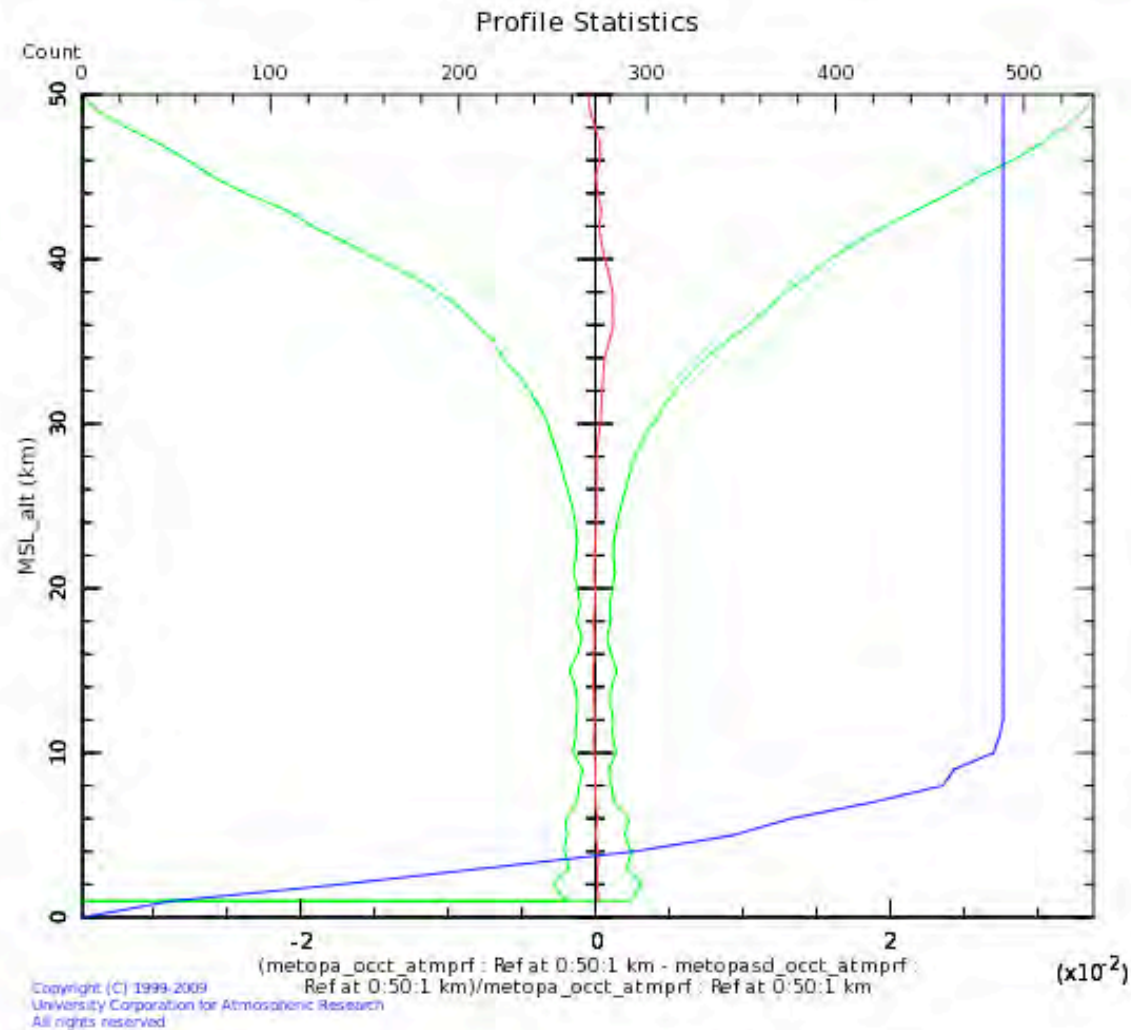


# Single Difference Results for COSMIC



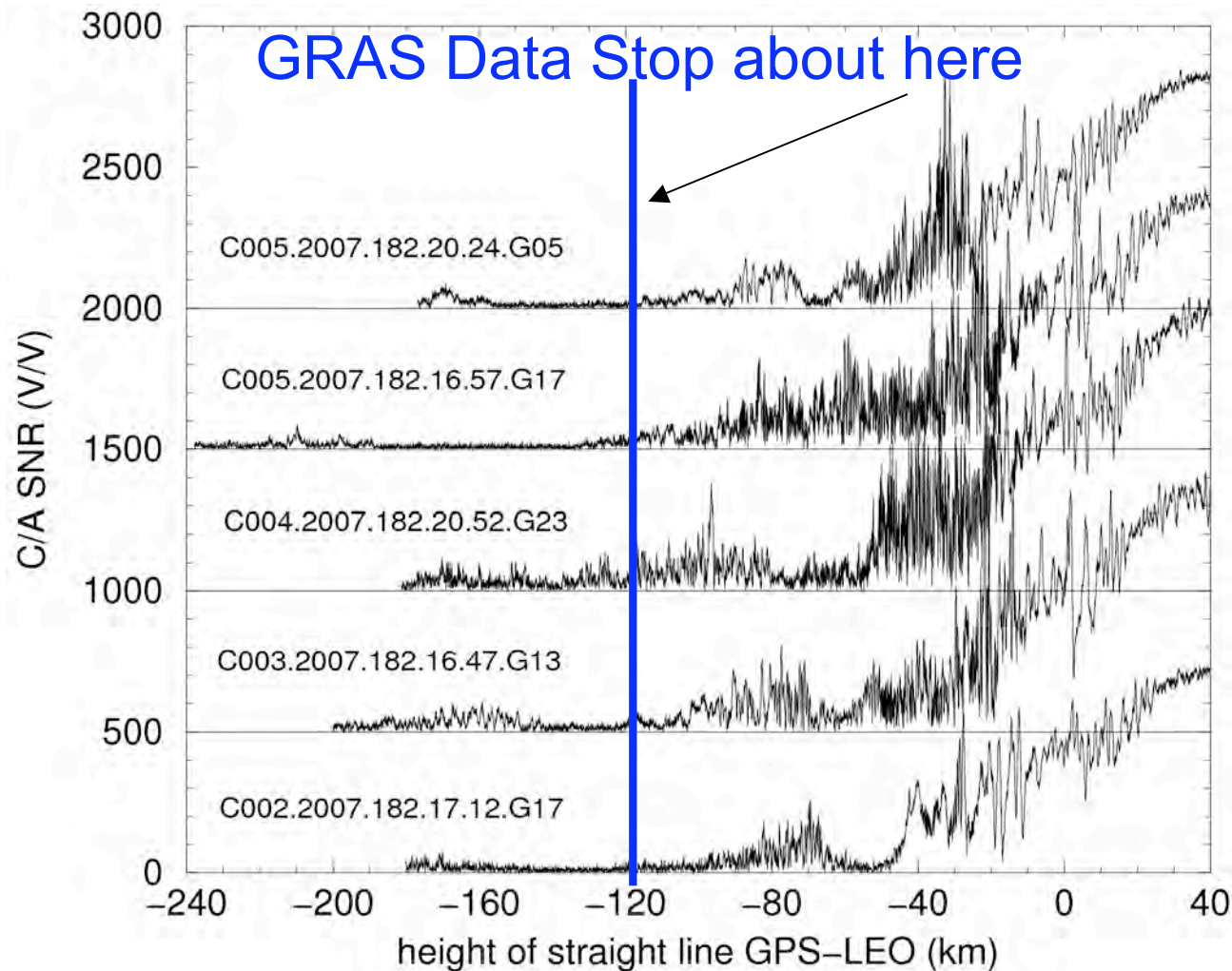
+/- 2% stdev at ~33 km

# Single Difference vs. Zero Difference



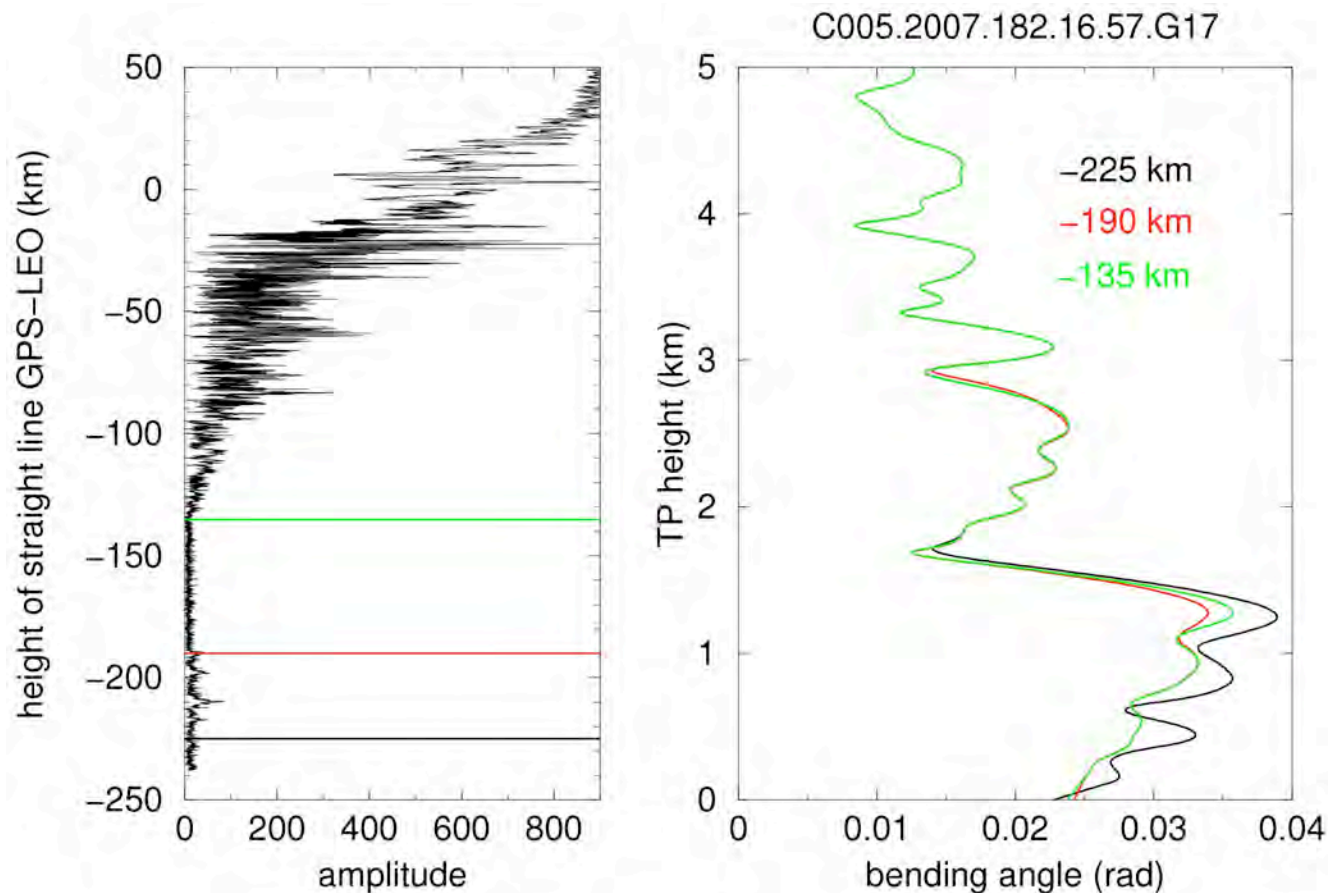
# On the importance of raw sampling to very low straight - line heights

Examples of deep RO signals in COSMIC. Minimal tracking height shall be lowered (this applies even more to GRAS receiver).



Excluding deep RO signals from RH inversions may result in significant negative inversion biases.

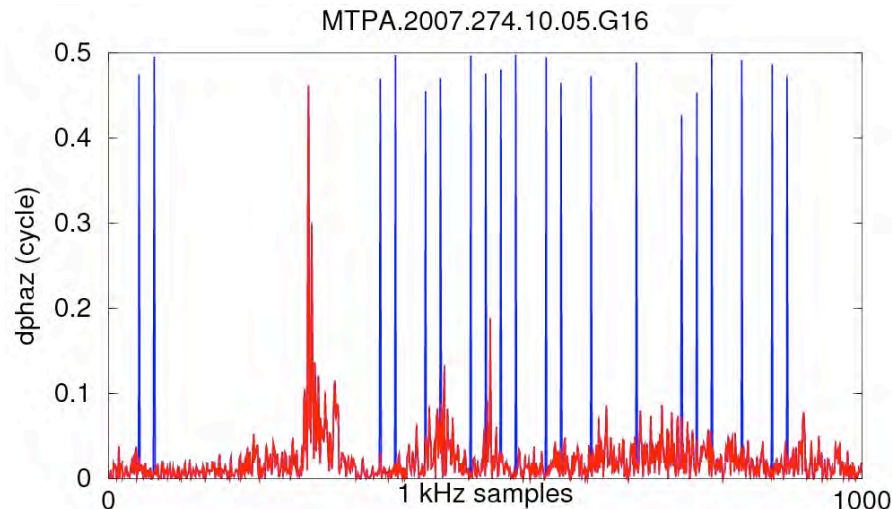
Inversions with different cutoff heights show that the  $\sim -10\%$  bias below  $\sim 1.5$  km is caused by sub-signals at  $-190$ - $220$  km (no significant positive bias caused by noise at  $-130$ - $190$  km).



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

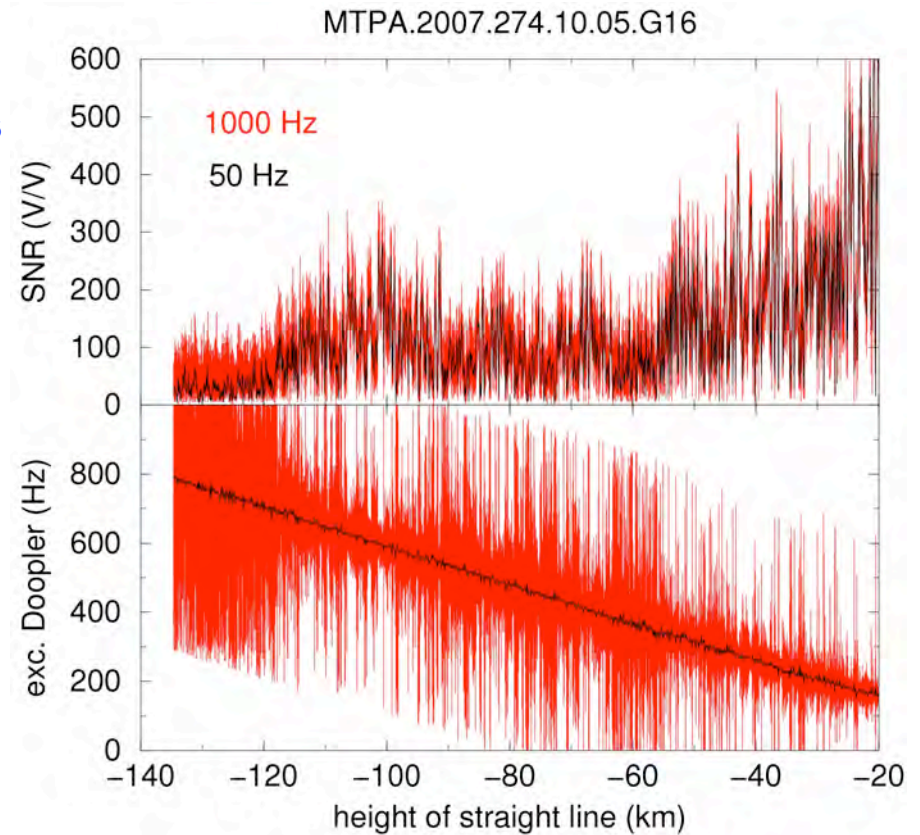
Raw signal downconverted with the reference frequency (phase) model based on orbits and N-climatology.

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:



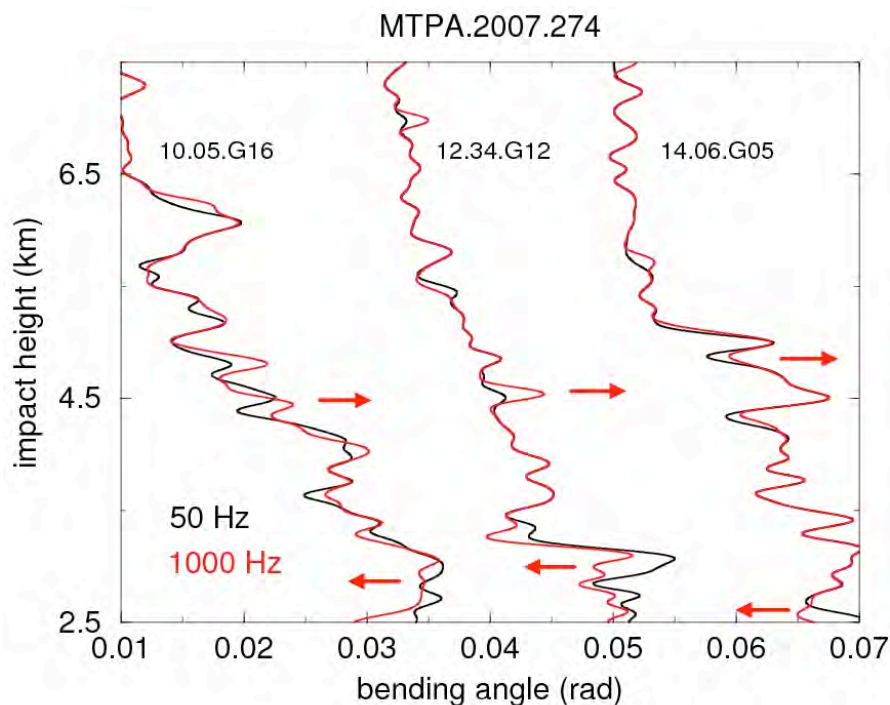
and from the signal down-sampled to 50 Hz by 20 ms integration of the I and Q and up-conversion.

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

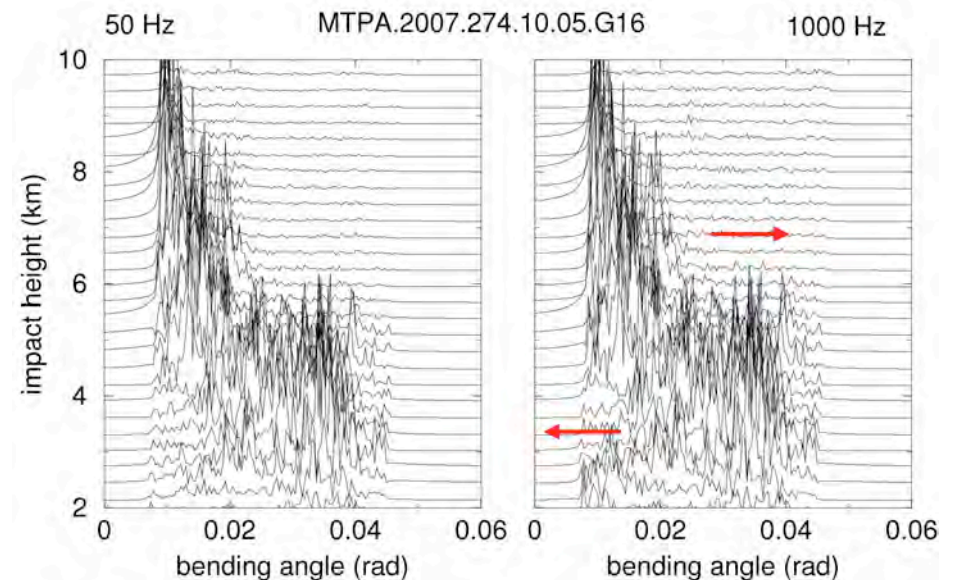


# Processing of the METOP OL data with and without downsampling

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).

# Summary

- UCAR / CDAAC developed processing string for GRAS data
  - Level 0-1 translator was based on original code from EUMETSAT
  - Used existing CDAAC software to the extent possible
  - Processed one month of data
- Orbits estimated at EUMETSAT and UCAR show no significant bias
- Bending angle profiles processed at UCAR and EUMETSAT agree in height range 8-30 km without any bias
- Bending angle “Mean MAD” setting profiles agree at a level that is consistent with multicenter comparisons based on CHAMP data
- Gaps in GRAS data contribute to structural uncertainty below 10 km
- GRAS data zero difference processing reduces noise in stratospheric BA profiles
- 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
- Metop GRAS should log open-loop data to greater SLH to avoid negative biases
- 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