



# Improvements, modifications, and alternative approaches in the processing of GPS RO data

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UCAR COSMIC Program

ECMWF/ EUMETSAT ROM SAF Workshop  
on Application of GPS Radio Occultation Measurements

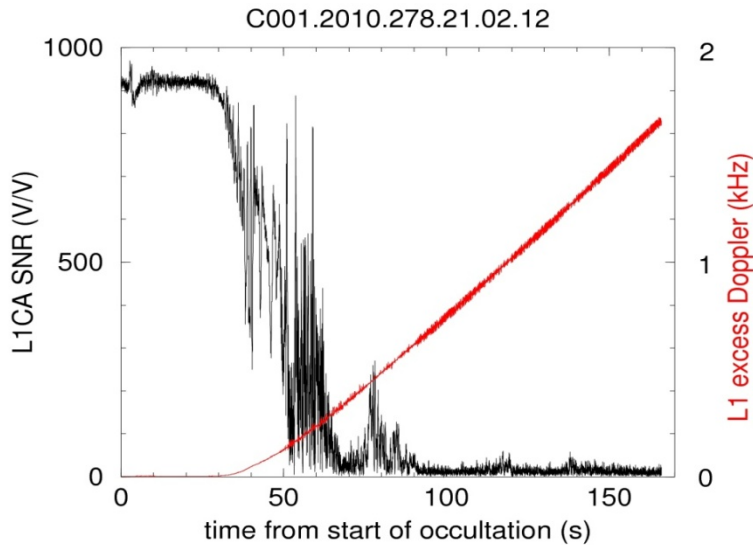
Reading, UK, 16-18 June 2014



# Outline

- Phase matching (analysis of phase function; stationary point)
- Calculation of Lat Lon from BA climatology (CIRA+Q)
- Radio holographic filtering
- Vertical resolution
- Quality control of L2P
- Extrapolation of the ionospheric correction
- Static optimization and direct fit of 1st guess
- Error characterization (RMS BA, confidence)
  
- 2<sup>nd</sup> order ionospheric correction
- Detection of SR (for high-SNR COSMIC-2 data)

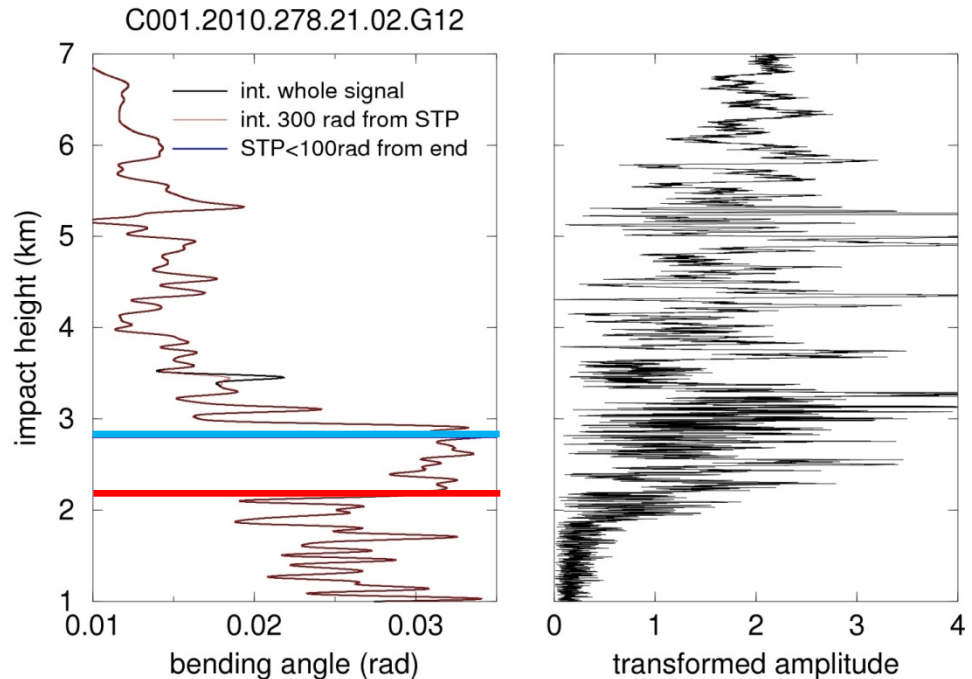
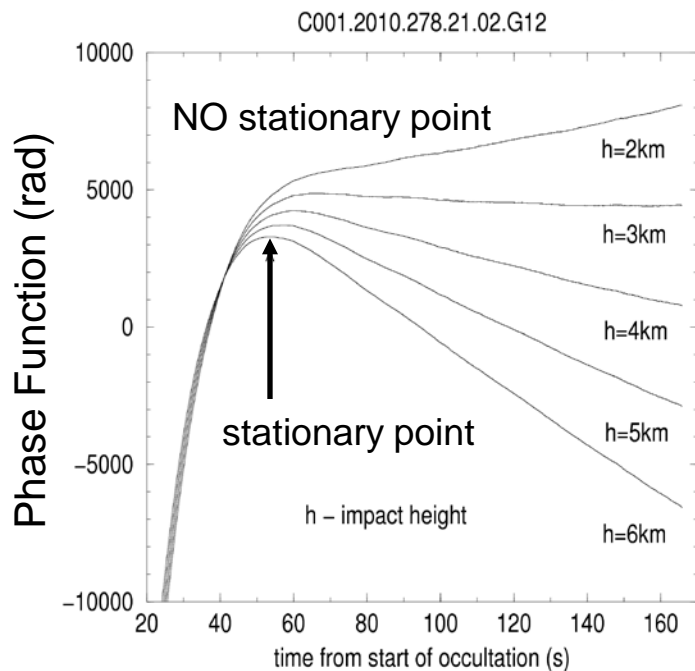
# Phase matching (Jensen et al., 2004): analysis of the structure of phase function



Key assumption for WO transform of a RO signal:  
 only one ray exists for a given impact parameter =  
 = only one stationary point.  
 In reality (tropical LT): multiple stationary points or  
 no pronounced stationary point.

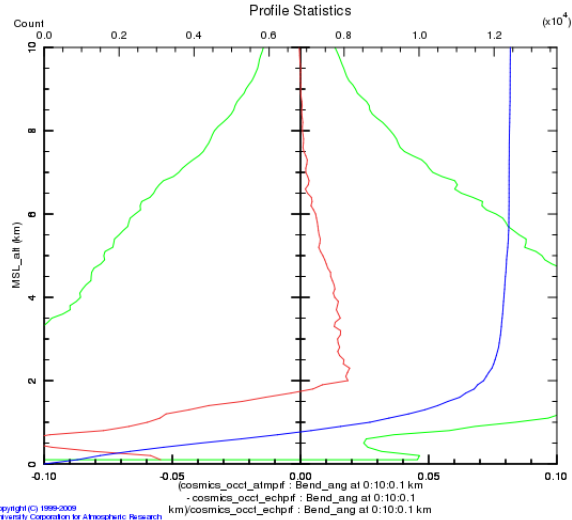
**Old approach:** FFT-based WO transform,  
 truncated based on fading of the amplitude.

**New approach:** direct calculation of WO  
 transform down to impact height where a single  
 pronounced stationary point disappears



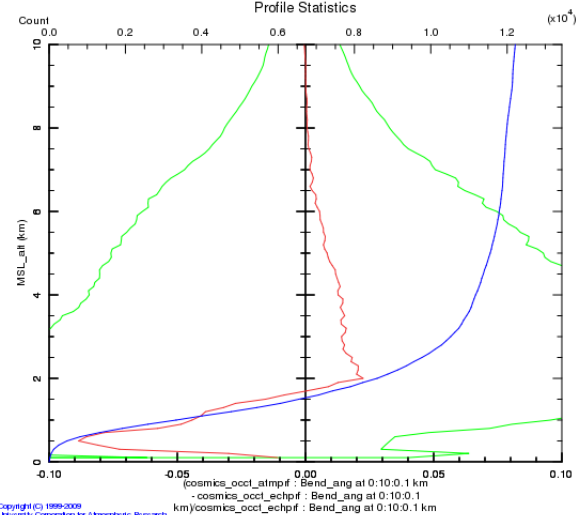
# Statistical comparison of COSMIC BA to ECMWF with old and new processings

## new, relaxed truncation



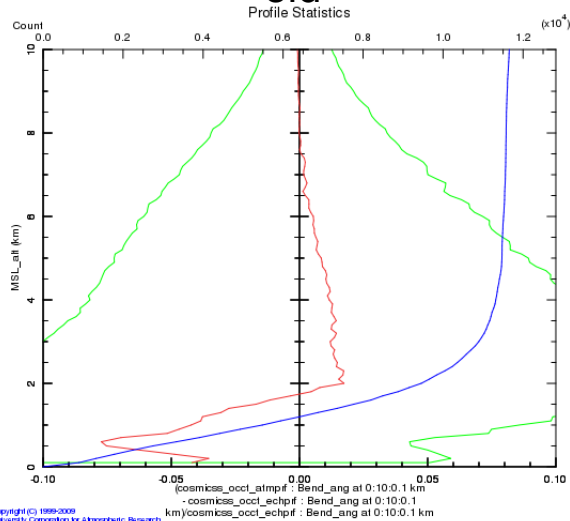
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## new, conservative truncation



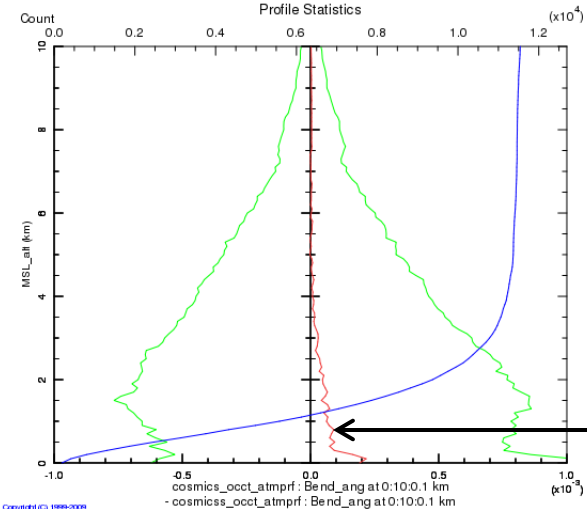
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## old



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## difference new - old



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0.1 mrad

New processing results in slightly larger BA below 2 km, but increased negative bias wrt ECMWF

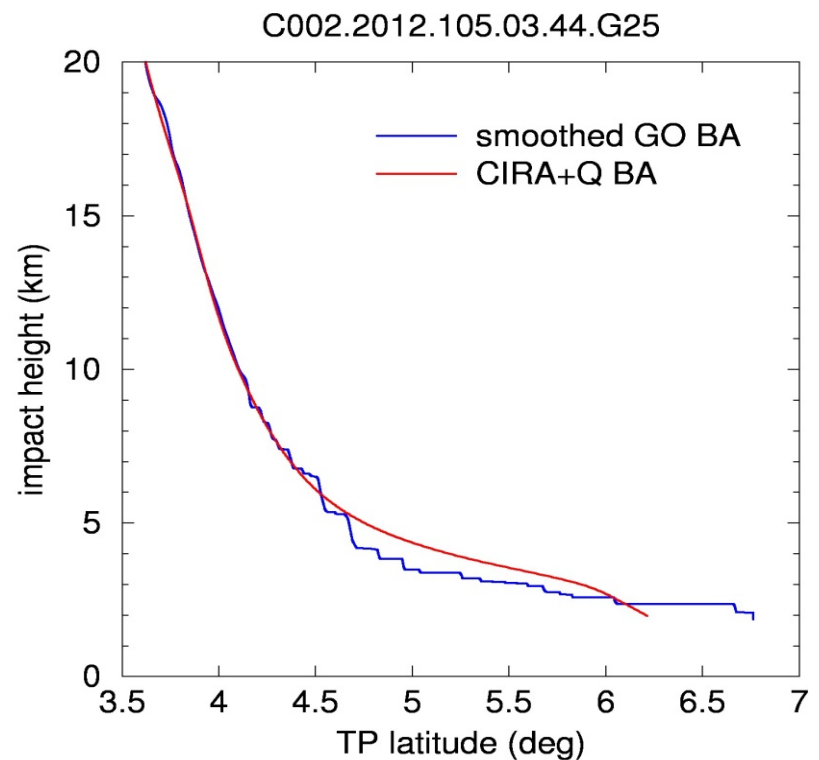
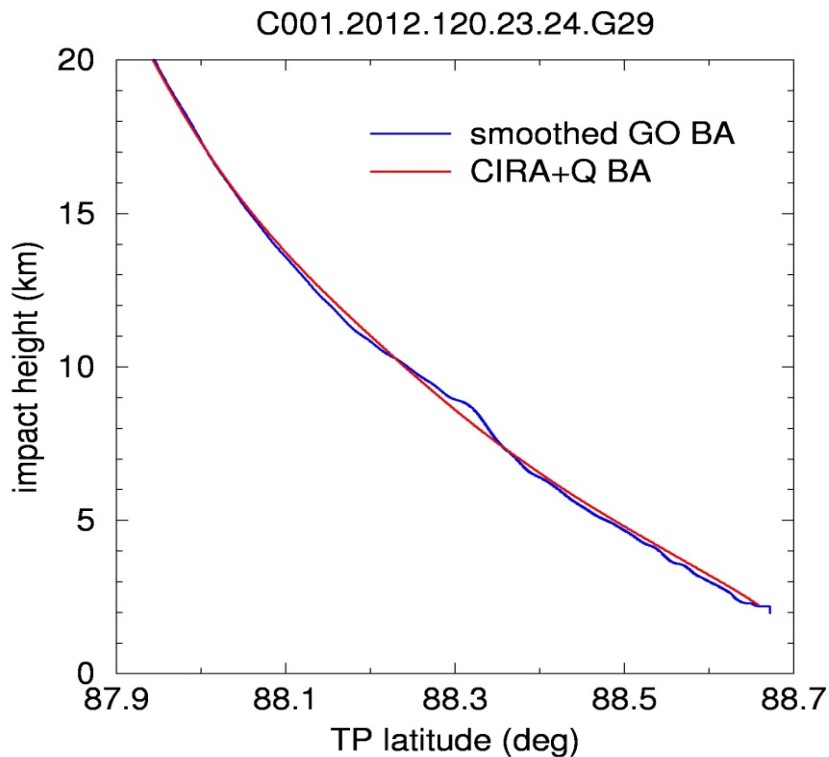
## The differences between RO and ECMWF are affected by specification of lat. & lon. of tangent point.

**Old processing:** GPS & LEO positions + GO BA from smoothed obs. Doppler (requires ad hoc correction of ambiguities; produces noisy function)

**New processing:** GPS & LEO positions + BA from CIRA + Q (produces smooth function, agrees with old in high lat.; may be quite different in tropics)

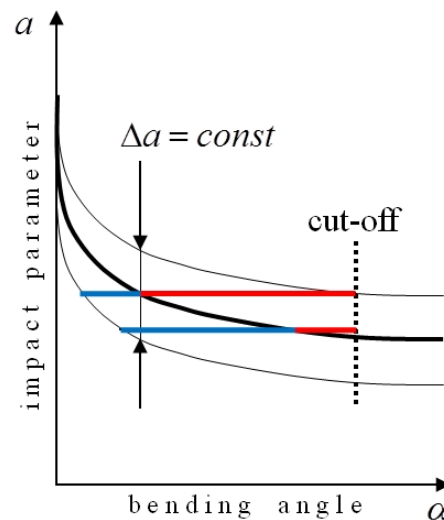
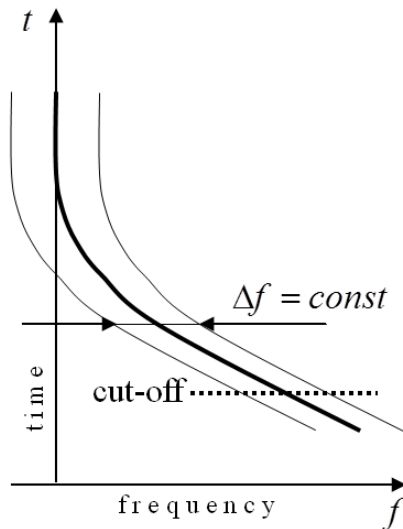
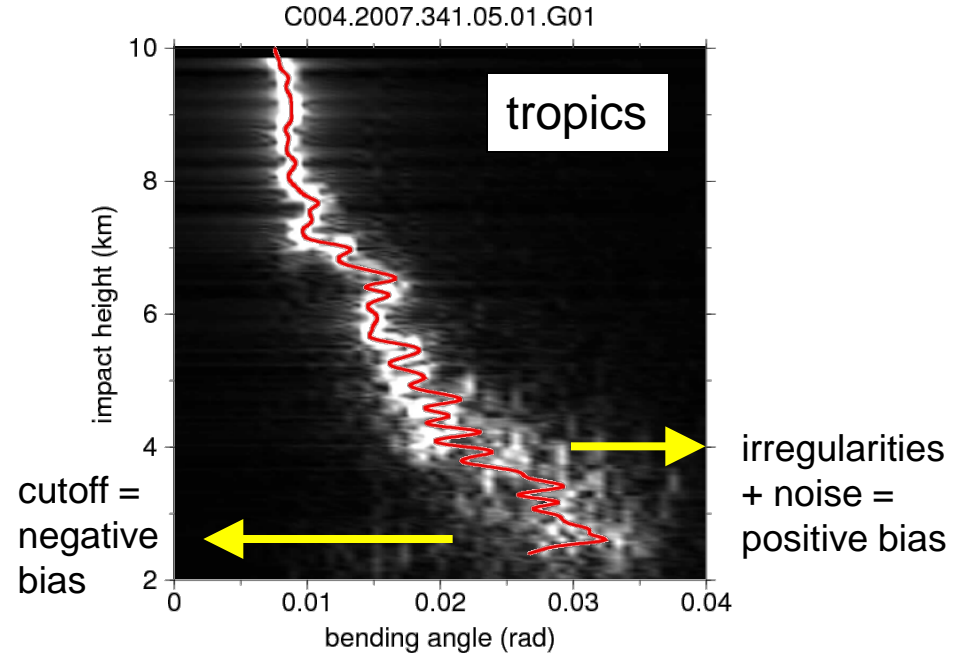
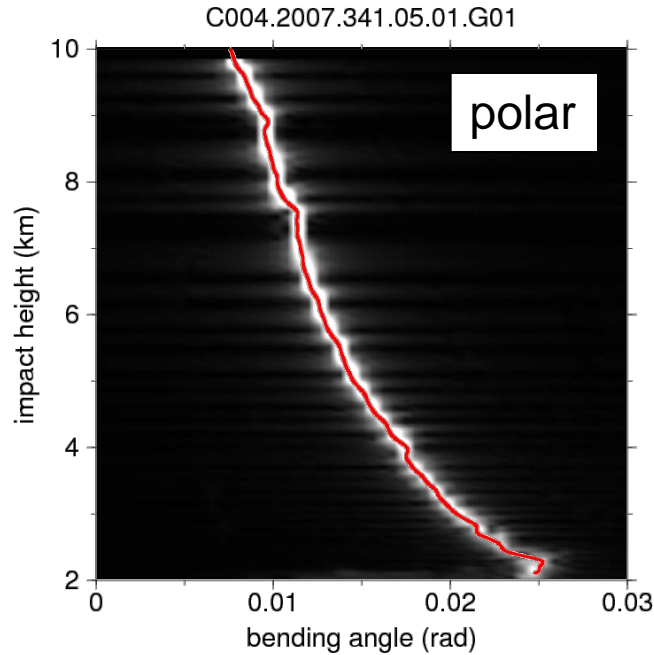
A more correct way: use GPS & LEO positions and WO BA. May result in subst. non-monotone function (especially for sharp inversion layers, such as ABL top).

**Is this acceptable?**





# Transforming RO signals from time - frequency to bending angle - impact parameter representation



Non-spherically symmetric  $N$  irregularities in tropics broaden the spectra of RO signals

Symmetric local spectrum (LS) at a given time transforms into symmetric LS at a given bending angle and asymmetric LS at a given impact parameter

truncation at a given time = truncation at a given BA

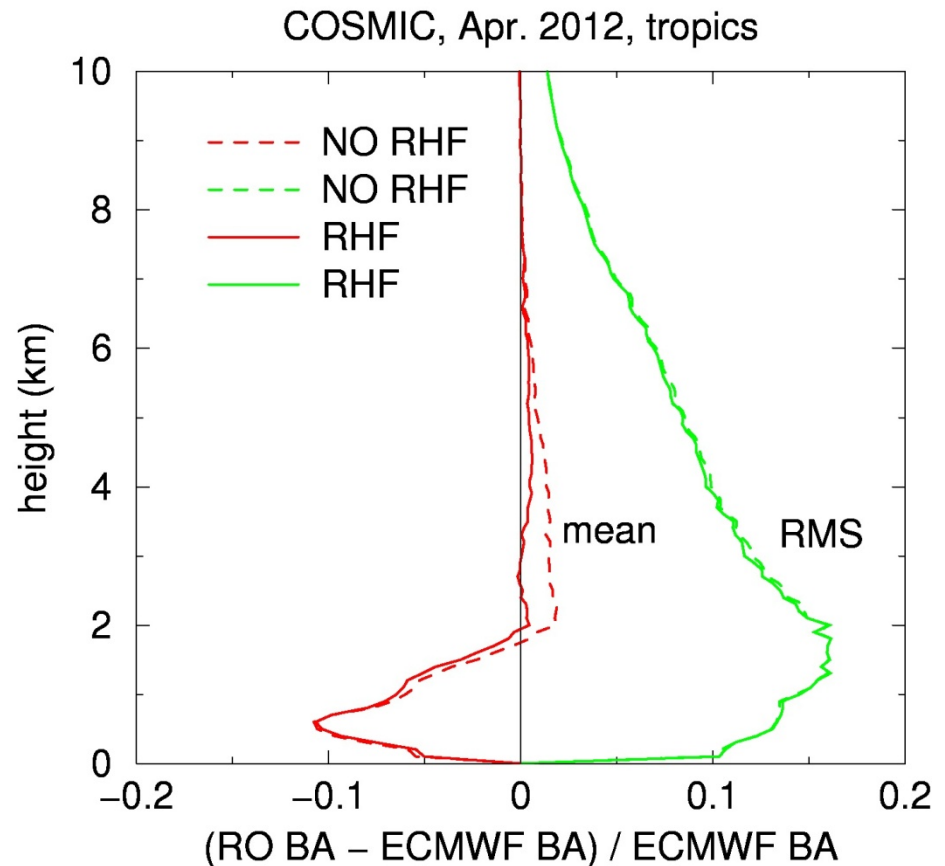
Result: negative BA bias close to truncation point; positive bias above

## "Radio Holographic Filtering" (RHF) Gorbunov, et al., JGR, 2006.

RHF consists in:

- down-conversion of complex WO-transformed RO signal close to zero frequency (BA);
- frequency model for the down-conversion is obtained from smoothed BA;
- low-pass filtering of the down-converted signal;
- up-conversion using same model.

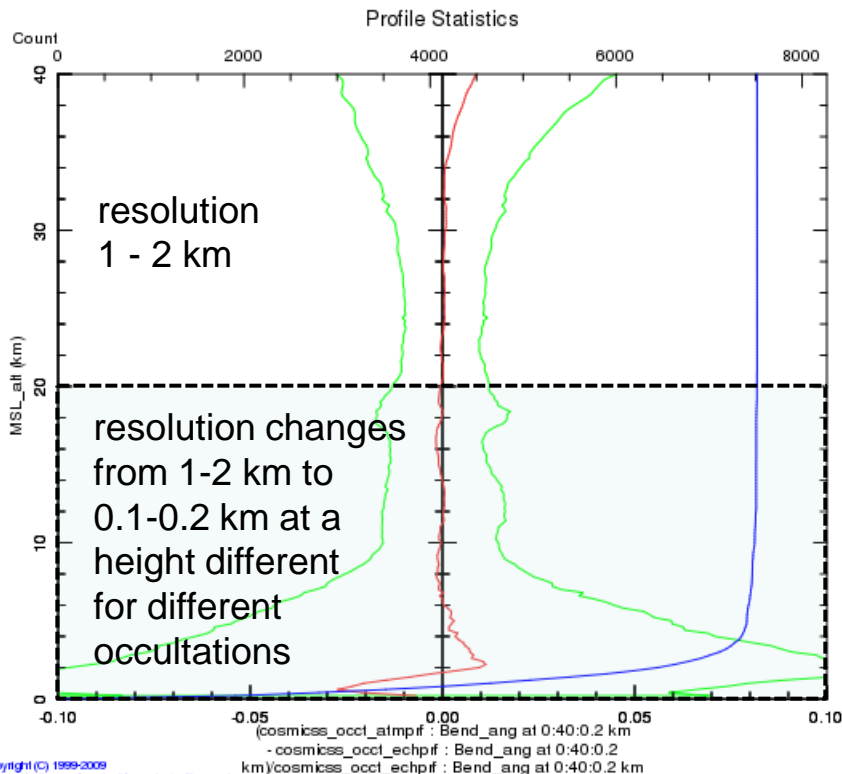
- RHF was tested at CDAAC in 2010;
  - was found to reduce positive BA bias; due to asymmetry of the spectrum of WO-transformed RO signal;
  - was found to smooth BA maxima, affecting specification of ABL depth;
  - was re-considered in 2014 by setting substantially different smoothing windows for the frequency model (0.1 km) and low-pass filter (1 km);
- this preserves sharp BA maxima, but still reduces the BA bias.



## Old processing:

The height to replace GO (resolution 1-2 km) by WO (resolution 0.1-0.2 km) and replace ionospheric correction by extrapolation is determined dynamically (individually for each occultation); can be any height below 20 km.

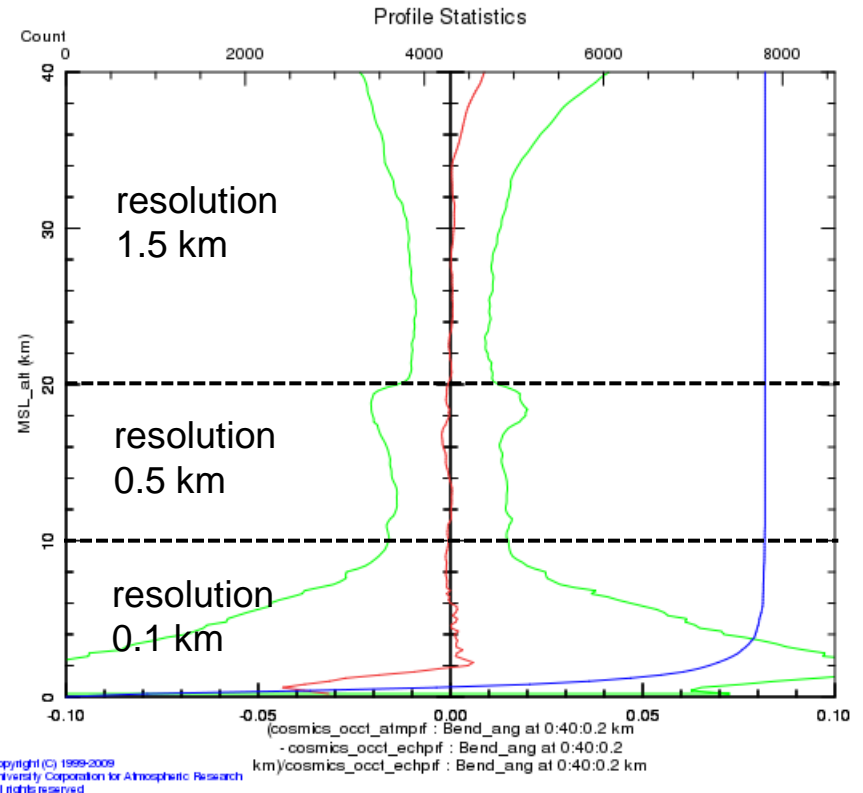
Vertical resolution below 20 km is different for different occultations.



## New processing:

GO is replaced by WO at fixed height (20 km). Ionospheric correction is replaced by extrapolation at fixed height (20 km). Resolution of GO is fixed to 1.5 km (Fresnel) Resolution of WO is fixed to 0.1 km and 0.5 km.

Vertical resolution is the same for all occultations.

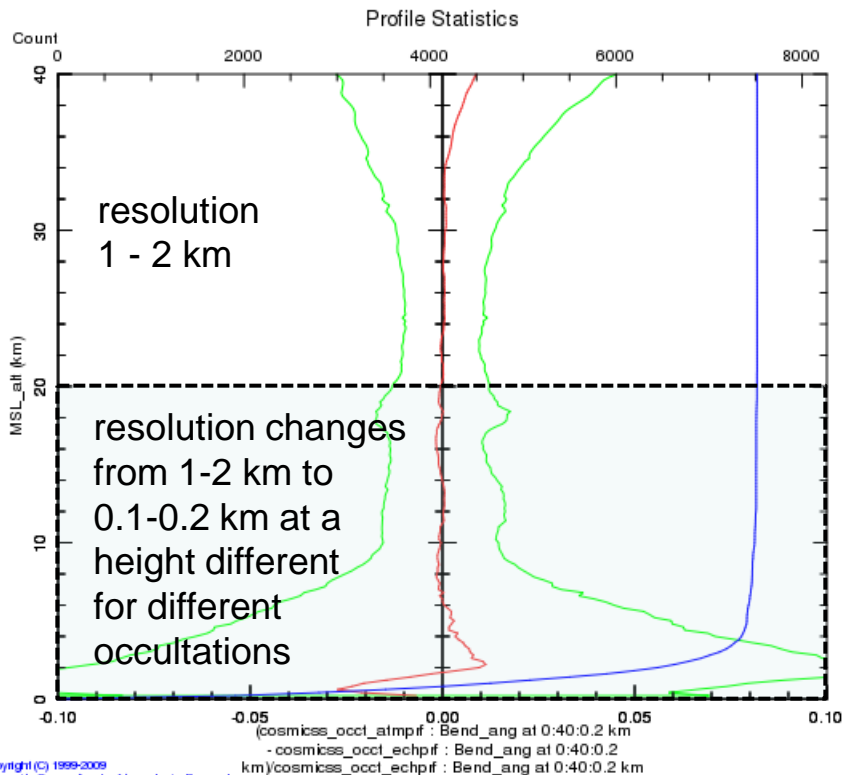




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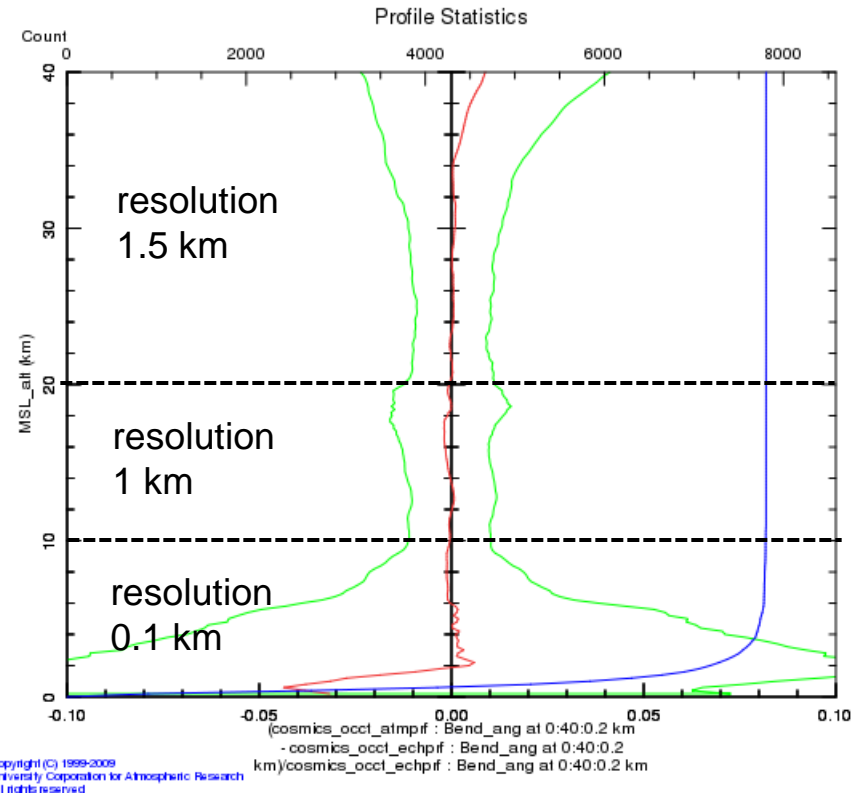
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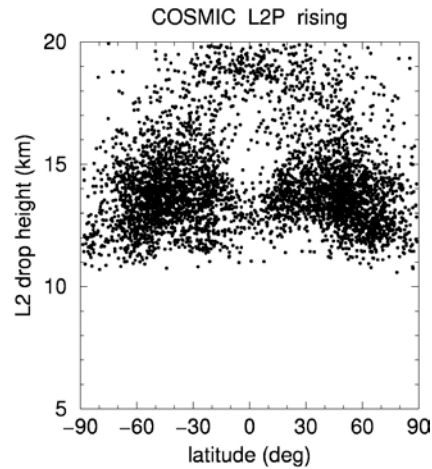
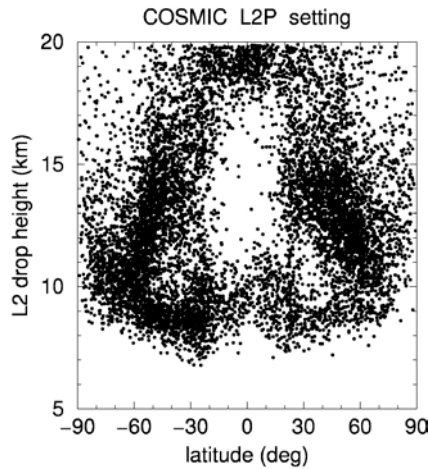
## Old processing: not all occultations are processed.

Below the height where raw  $|L1-L2|$  Dopplers  $>$  threshold (6 cm / samp) at  $<$  40 km (after full and half cycle slip correction of L1):

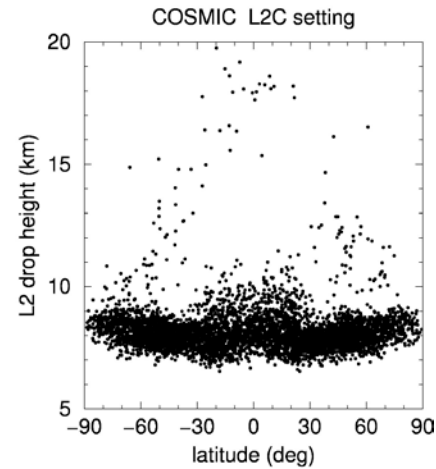
Ionospheric correction is replaced by extrapolation of L1-L2 BA, GO is replaced by WO;

If this height  $>$  20 km, the occultation is not processed.

### COSMIC L2P

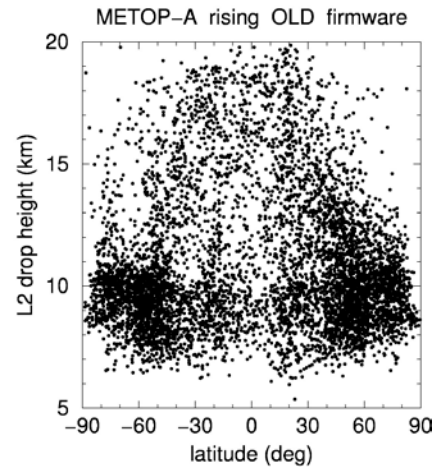
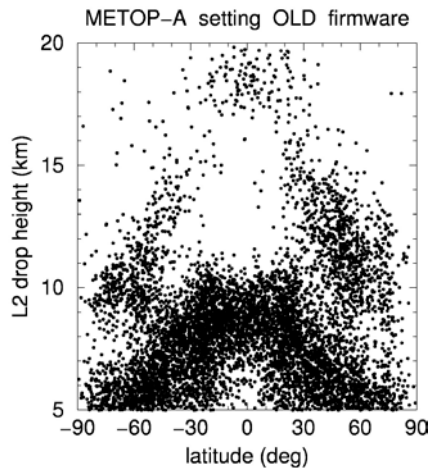


### COSMIC L2C

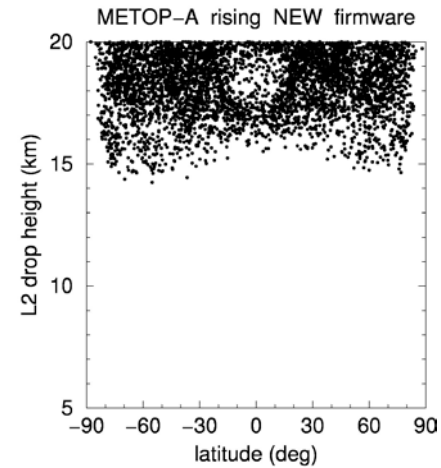
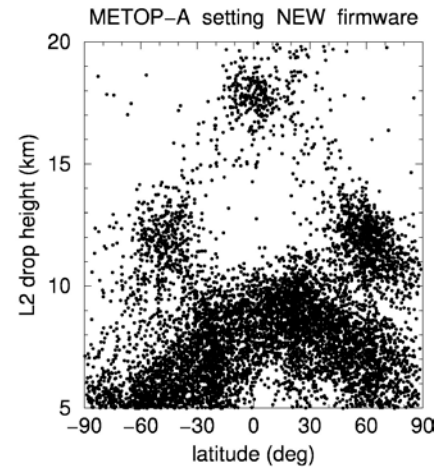


currently, L2C  
is not tracked  
in rising occs.

### METOP-A before 2013 firmware update



### METOP-A after 2013 firmware update



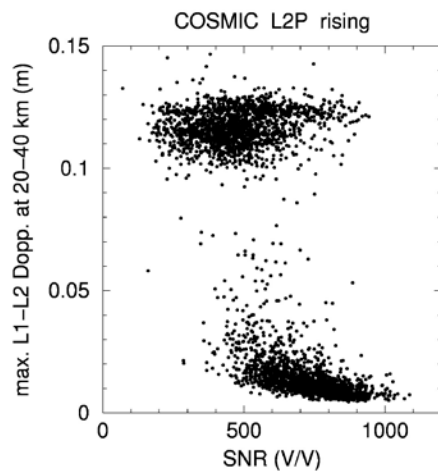
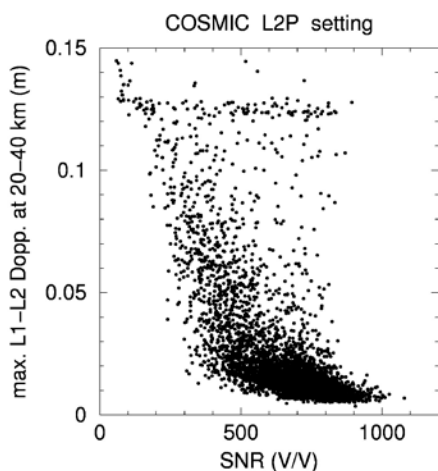
## New processing: all occultations are processed.

L2 quality control (QC) via max. difference of raw  $|L1-L2|$  Dopplers between 20 and 40 km (after correction full and half cycle slip correction of L1).

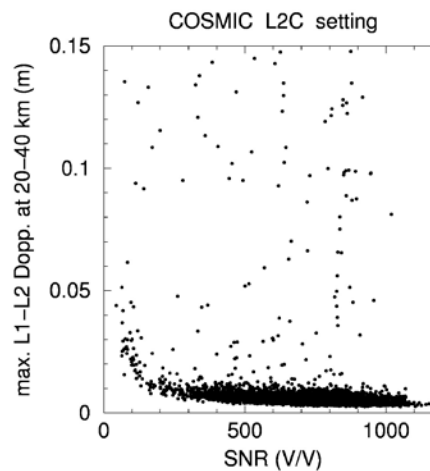
If the difference  $>$  threshold (10 cm /samp) the occultation is tagged "bad".

Testing of half cycle slip correction of L2 does not seem to improve results

### COSMIC L2P

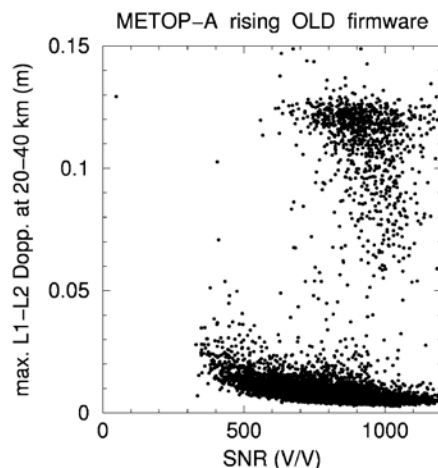
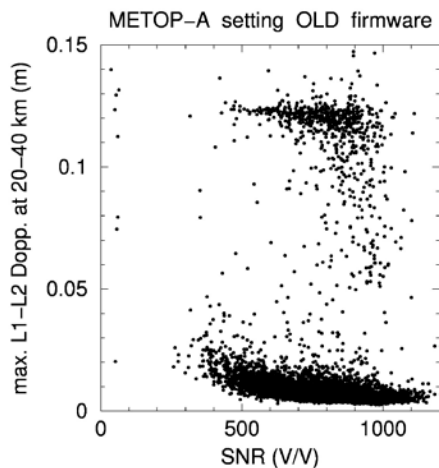


### COSMIC L2C

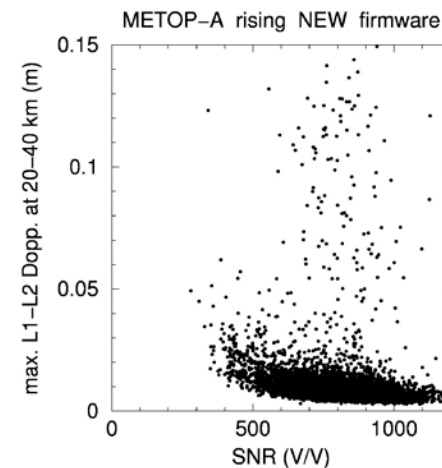
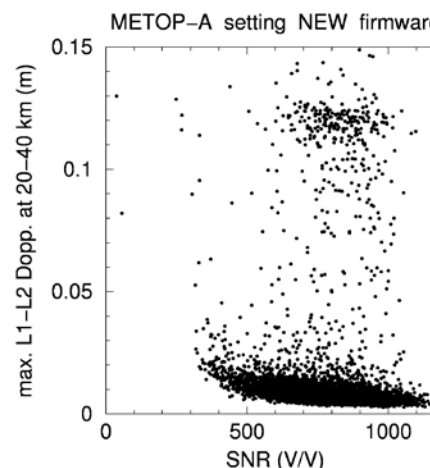


currently, L2C  
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### METOP-A before 2013 firmware update



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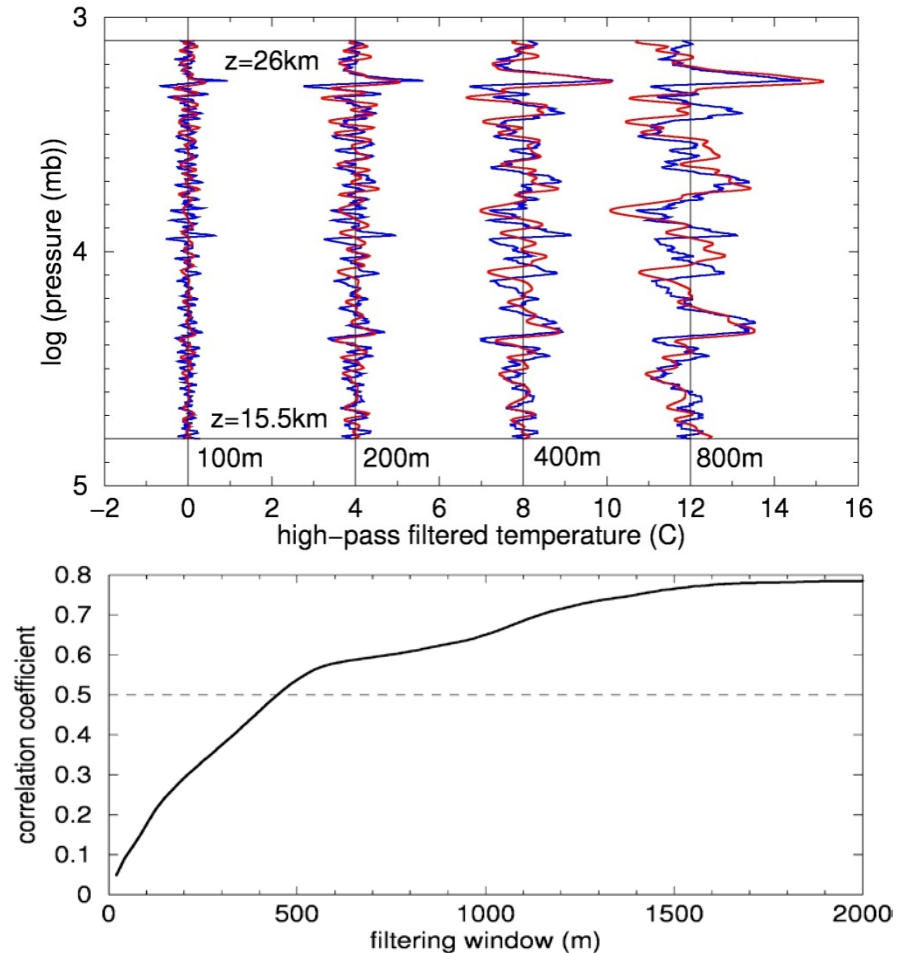
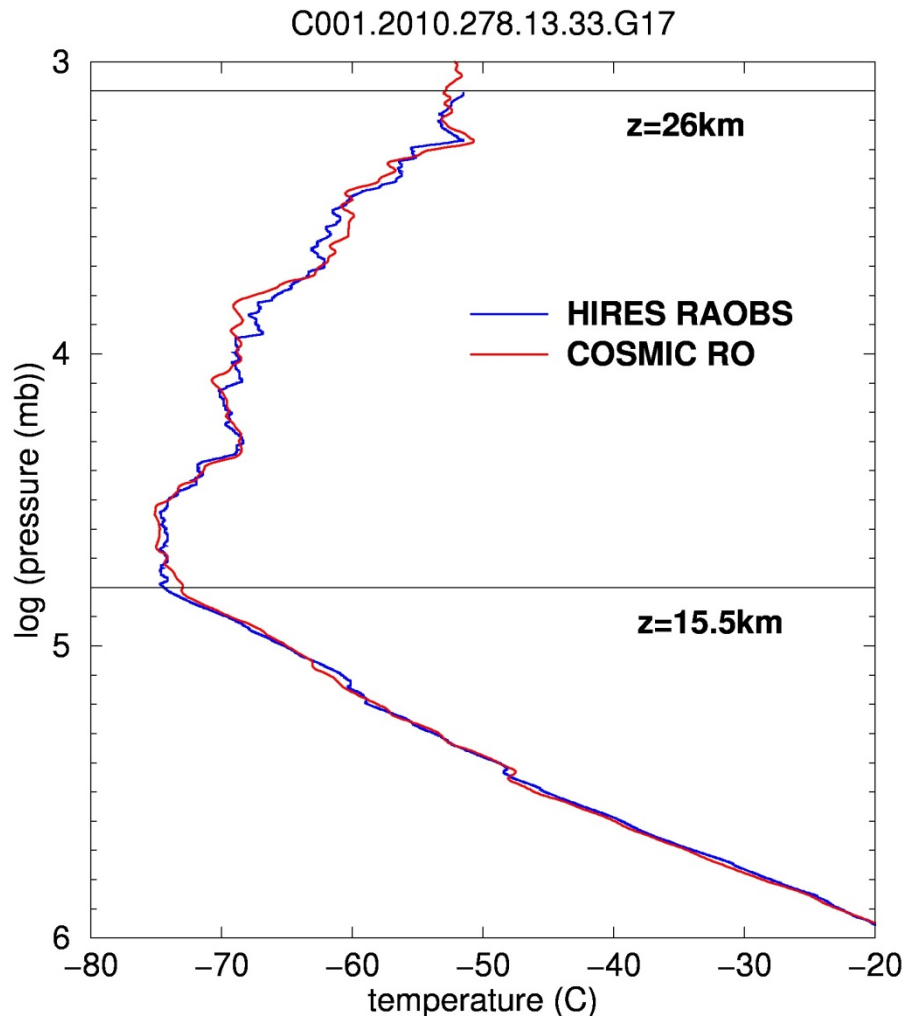
# What vertical resolution of RO is necessary around and above the tropopause?

Wave optics ~ 0.1 km; Geometric optics ~ 1.5 km (Fresnel).

1) Tsuda et al. (AMT, 2011), based on analysis of gravity waves, recommends 0.5 km.

2) Comparison of COSMIC RO to collocated SPARC HIRES RAOBS shows:

for some occultations, correlation of high-pass filtered temperatures extends down to vertical scales of 400-500 m.

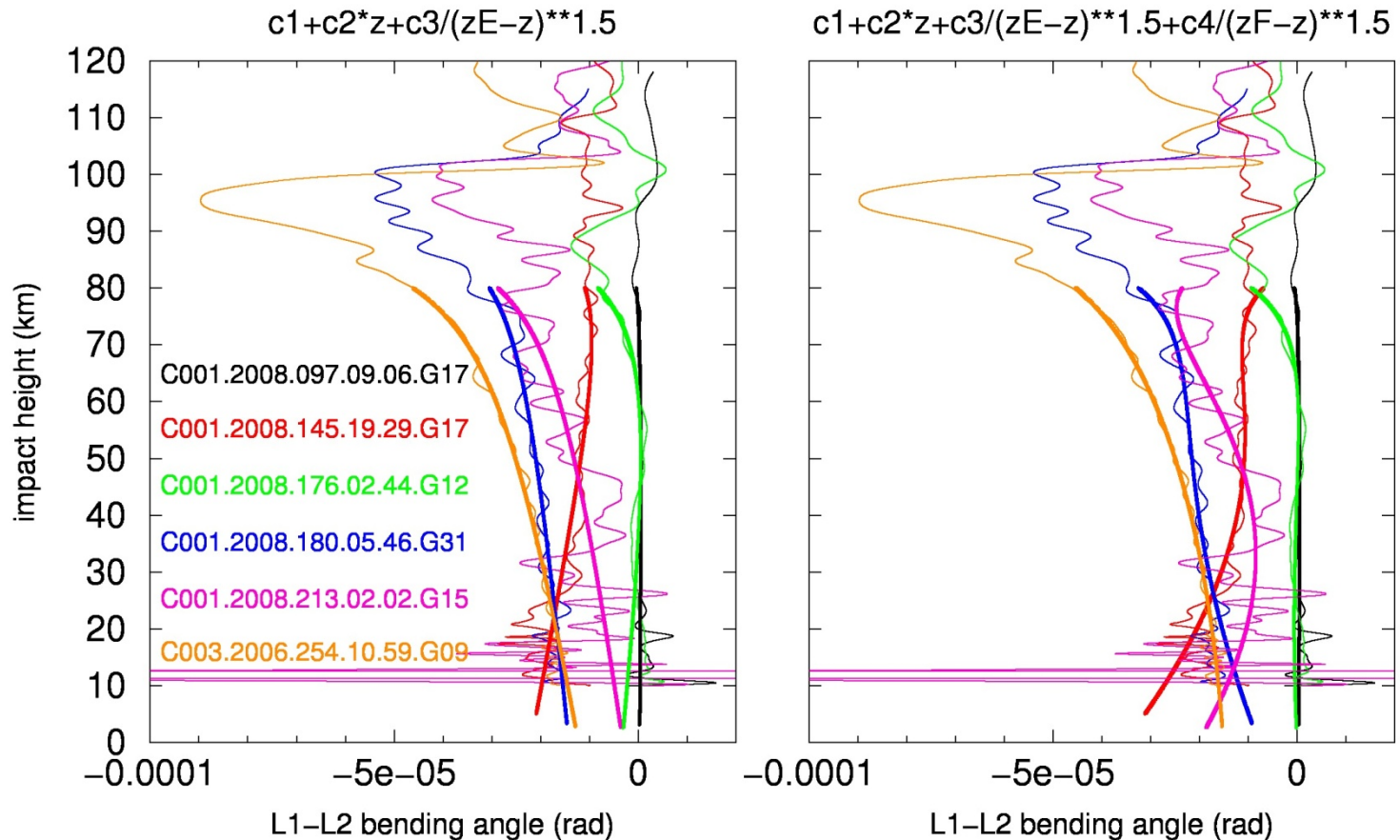


# Extrapolation of the ionospheric correction of BA into the troposphere

In the troposphere, L2 either is not available or, when available, LC is noisy.

Approximation of L1-L2 BA at 20-80 km by linear function + response from E layer or E and F layers ( $z_E=100\text{km}$ ,  $z_F=300\text{km}$ ).

Including F layer causes instability of extrapolated L1-L2.

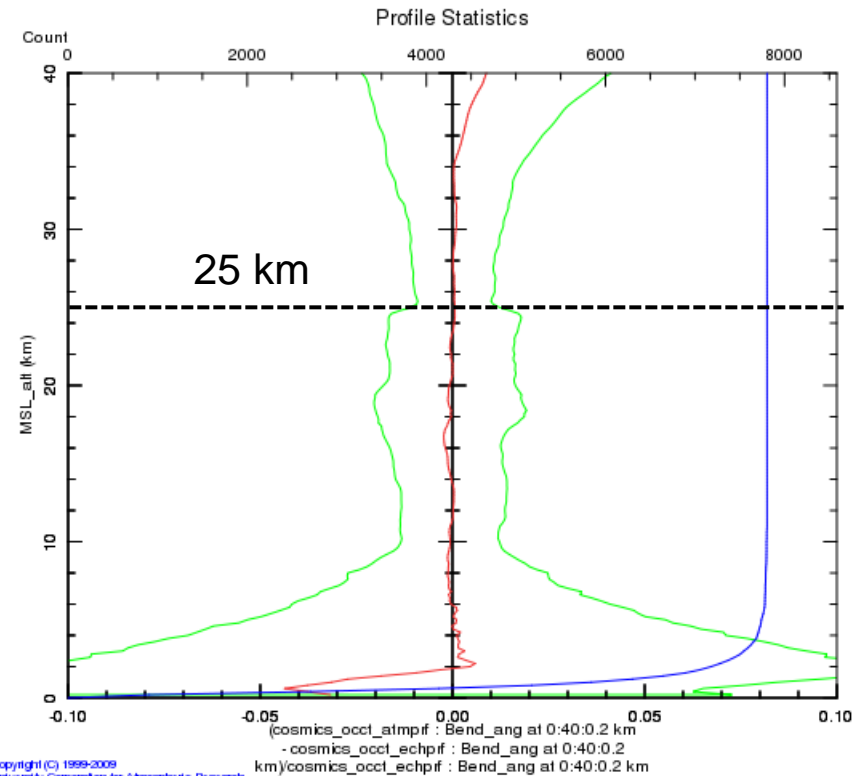
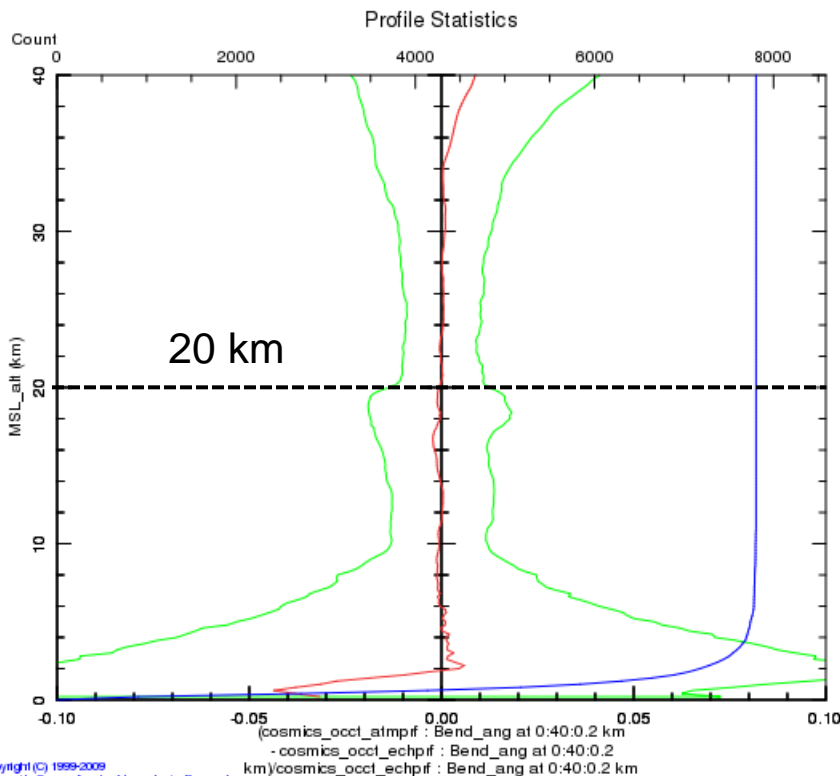




# Effect of the height for extrapolation of the ionospheric correction on BA stats.

Increase of the height for extrapolation of the ionospheric correction from 20 km to 25 km increases BA errors induced by uncorrected ionospheric effects.

These effects may be significant below 20 km as well, but not all occultations allow extension of the ionospheric correction below 20 km due to tracking errors of L2P. A dynamic extrapolation height results in different BA error characterizations for different occultations and for different missions.





# Optimization of the bending angles for Abel inversion

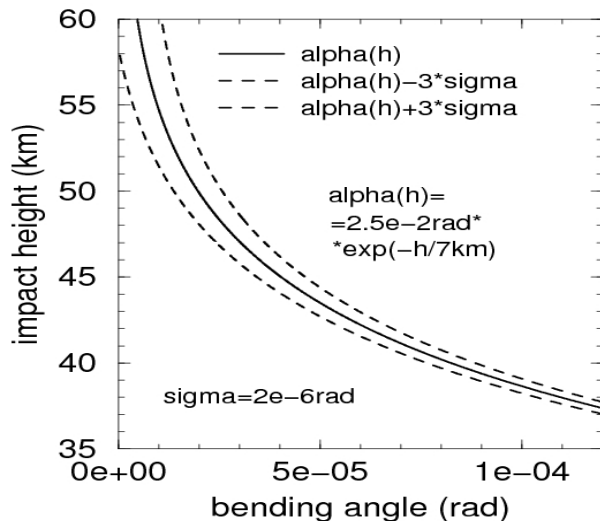
**Current approach:** Lohmann, Radio Sci., 2005 (dynamic error estimation; log-fitting of background to obs. BA; dynamic estimation of the height interval for the fitting)

**Revised approach** (eliminates dynamic estimates in favor of climate applications)

- 1) Direct fitting of background to obs. BA (eliminates bias)
- 2) Fixed height interval for the fitting: 35 - 60 km
- 3) Mixing obs. BA with fitted background in fixed interval 35 - 60 km
- 4) Mixing of mixed (3) BA with background in fixed interval 55 - 65 km

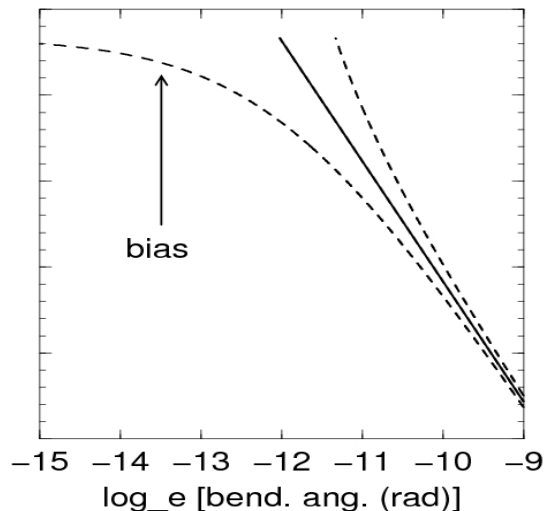
direct fitting

$$\left\| \alpha_{obs} - c \alpha_{bgr}^\beta \right\| = \min$$



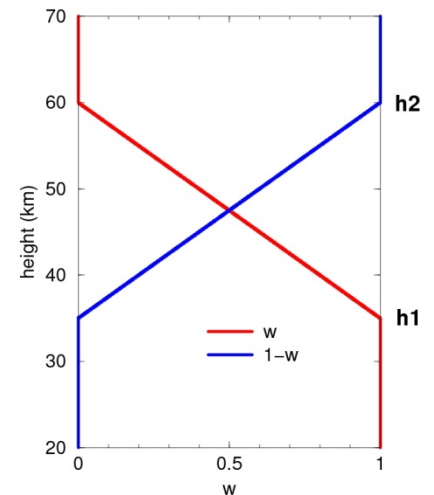
log-fitting

$$\left\| \ln \alpha_{obs} - c \ln \alpha_{bgr} - d \right\| = \min$$



mixing

$$\alpha = w \alpha_{obs} + (1 - w) \alpha_{bgrfit}$$

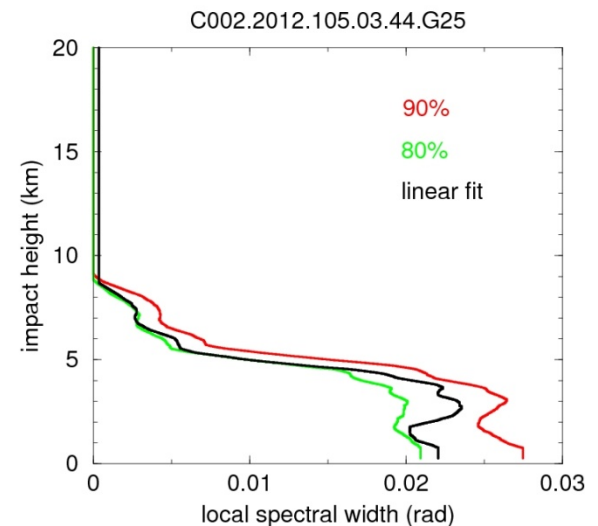
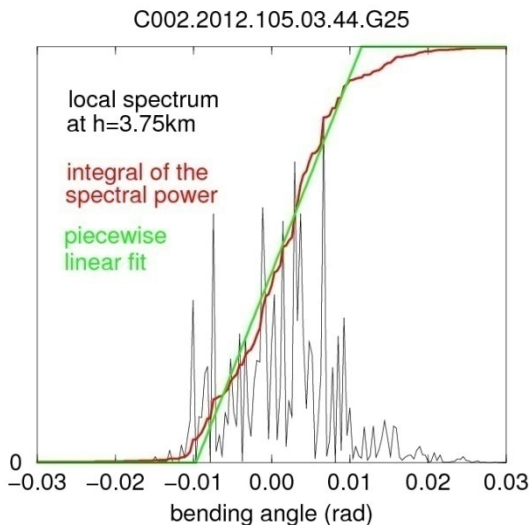
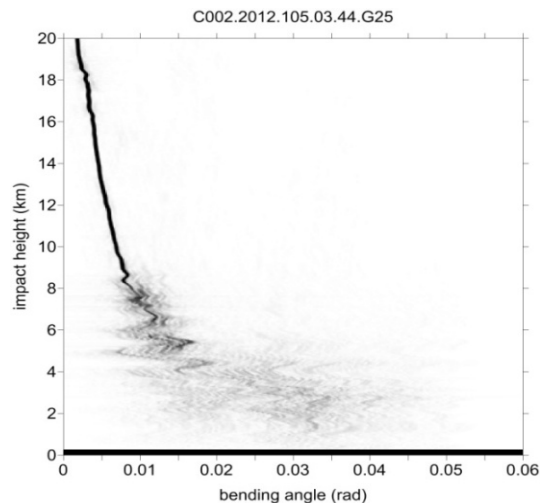
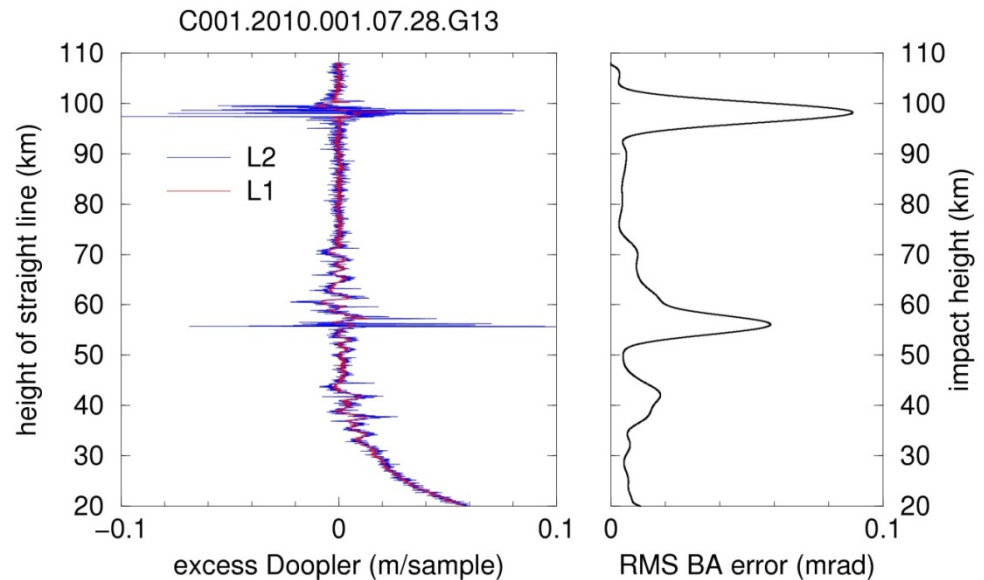


Feltz et al., 2014 (AMTD) found biases between COSMIC and METOP temperatures in the stratosphere. The biases were confirmed at CDAAC, disappeared after re-processing with the static optimization.

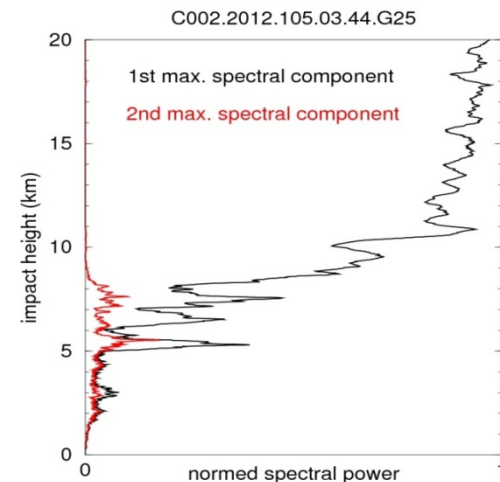
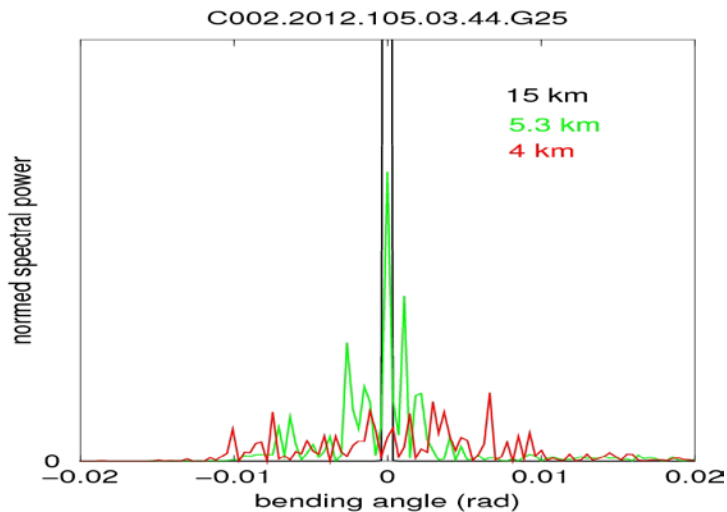
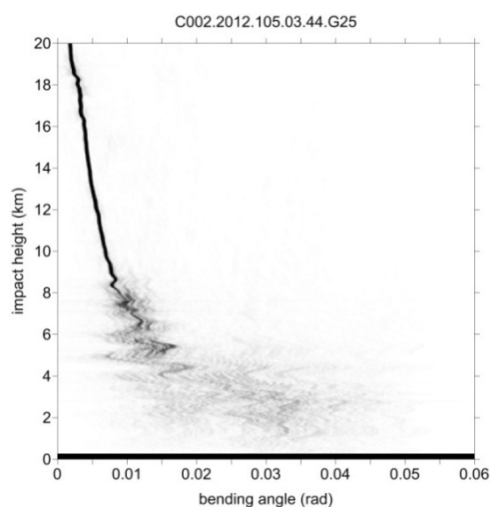
# Dynamic (individual for each occ.) BA error characterization

**In the stratosphere:** based on RMS fluctuation of the LC Doppler in 1 s sliding window.

**In the troposphere:** based on local spectra of WO-transformed RO signal (Gorbuonv et al., JGR, 2006) but with different definition of the local spectral width.

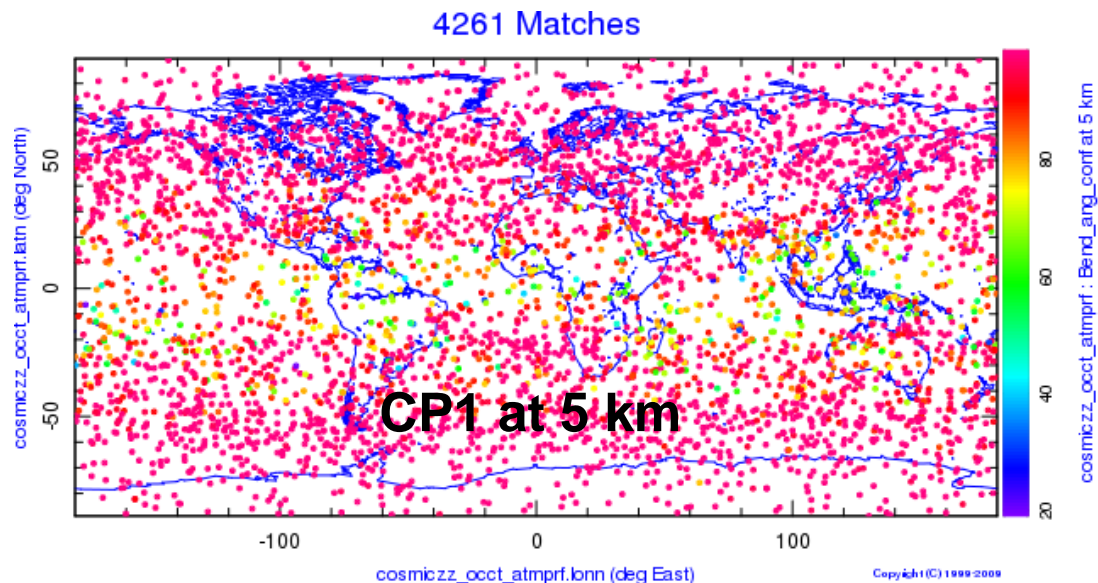
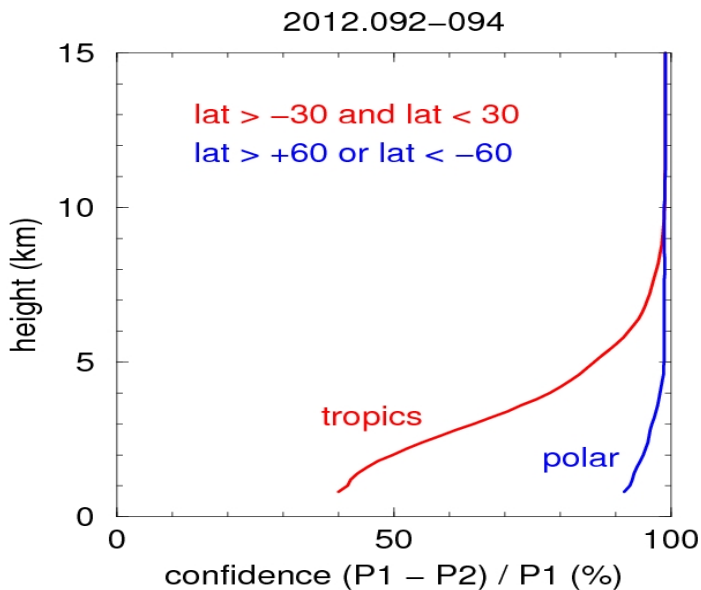


# Another quality characterization of BA in LT ("confidence parameter (CP)") based on pronounced single maximum in local spectrum of WO-transformed RO signal



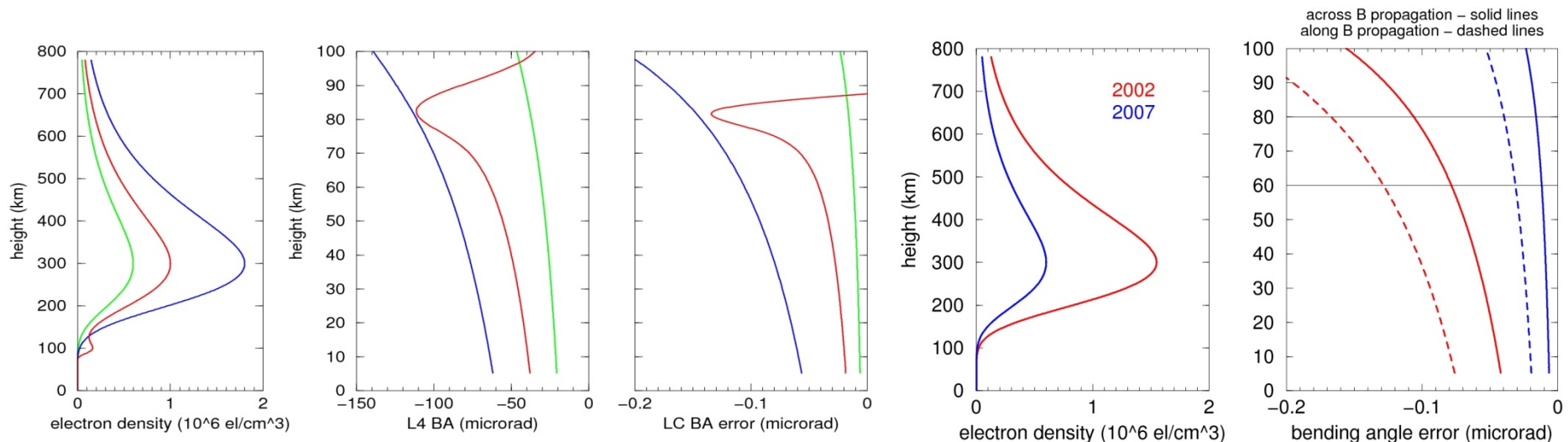
definition:  $CP1 = (P1 - P2) / P1$

an alternative definition:  $CP2 = P1 / \text{SUM}(P)$



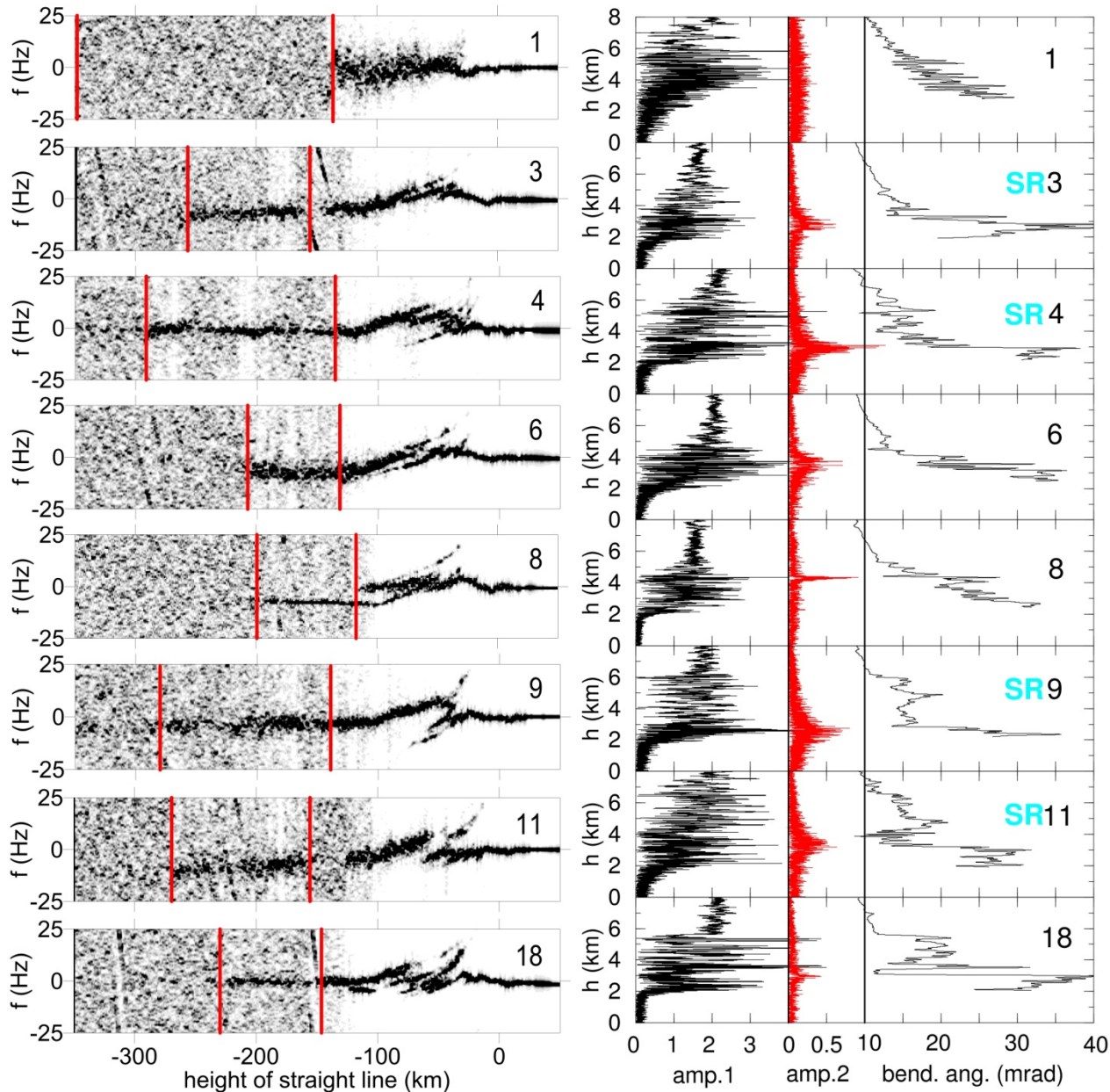
## 2nd order ionospheric correction for GPS RO climate applications in the stratosphere

- 2nd order ionospheric effects in GPS RO and their correction: Hardy et al., 1993
- 2nd order model-dependent ionospheric correction by ray tracing: MPI Report No.210, 1996: most sensitive to model electron density below F max
- some details of 2nd order ionospheric correction outlined by Rocken et al., 2009 (AMS)
- 2nd order ionospheric effect on BA is not a bias; it may substantially depend on height
- model-dependent correction: significant effect of E-layer; must be well reproduced by model
- model-independent correction: non-linear regression on  $L4=L1-L2$  BA; is less accurate
- validation problems:
  - direct validation: datasets for comparison do not exist
  - indirect validation (using diurnal or 11-year solar cycle): residual ionospheric effects are mixed with the neutral atmospheric effects
- different ionospheric models may better reproduce E or F layer; combined model can be used for ray-tracing
- output from ray-tracing:
  - 1st order effect for evaluation of the ionospheric model by comparison to RO L4 BA below 100 km;
  - 2nd order effect: for correction of LC BA (in case of positive evaluation of the model)





# Deep COSMIC RO signals; WO inversions of full RO signals and their fragments



Some tropical RO signals are observed down to HSL -300 km

Spectrograms of these occultations show strong geometric multipath typical for horizontally extended layers

Amplitude of WO transform of deep sections of RO signals shows approximate impact height from which the signals arrive

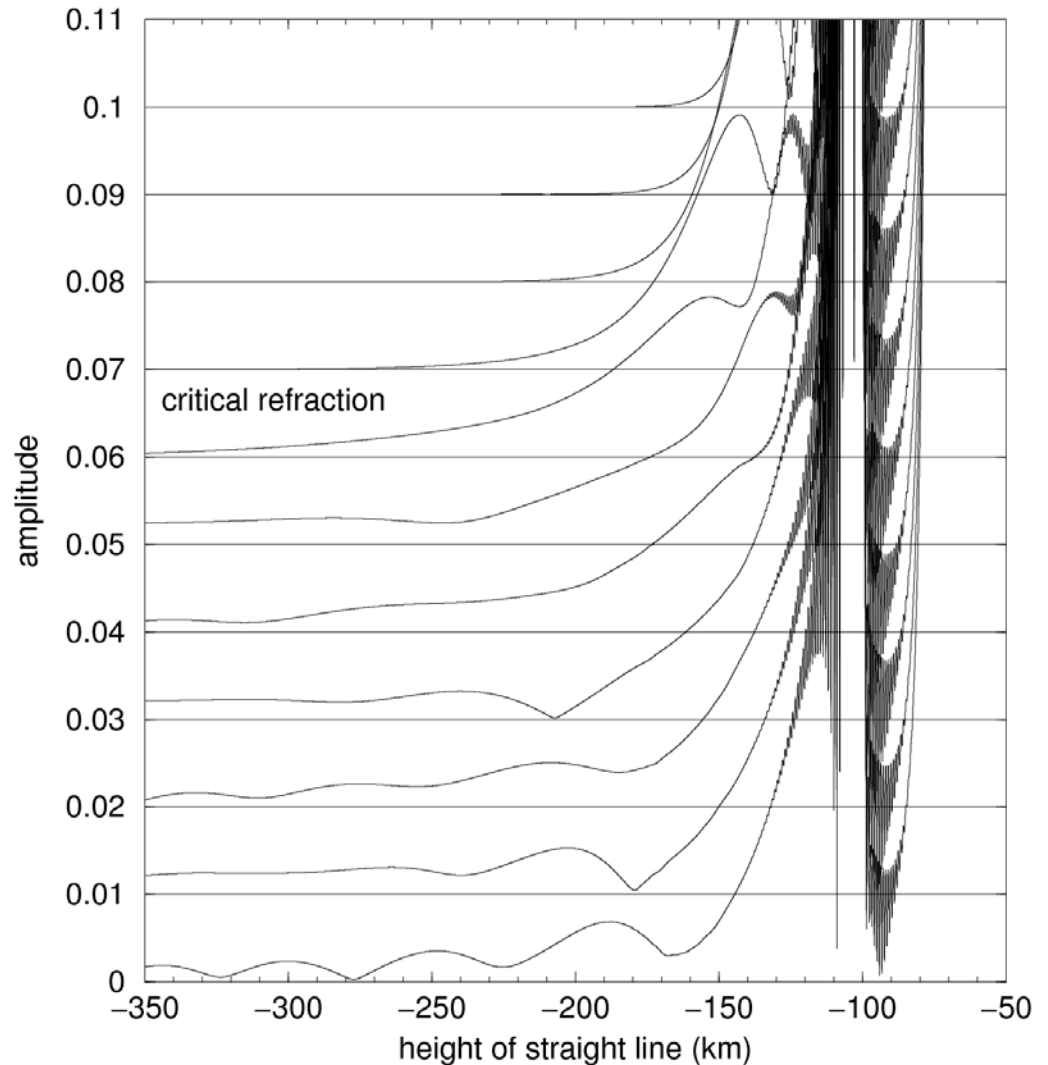
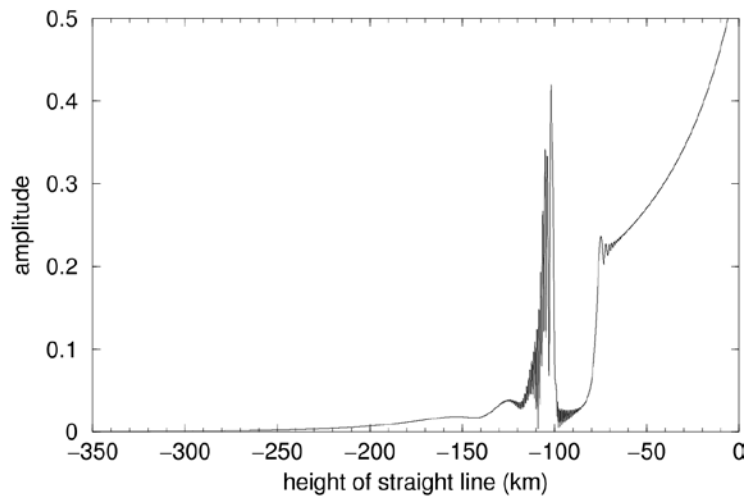
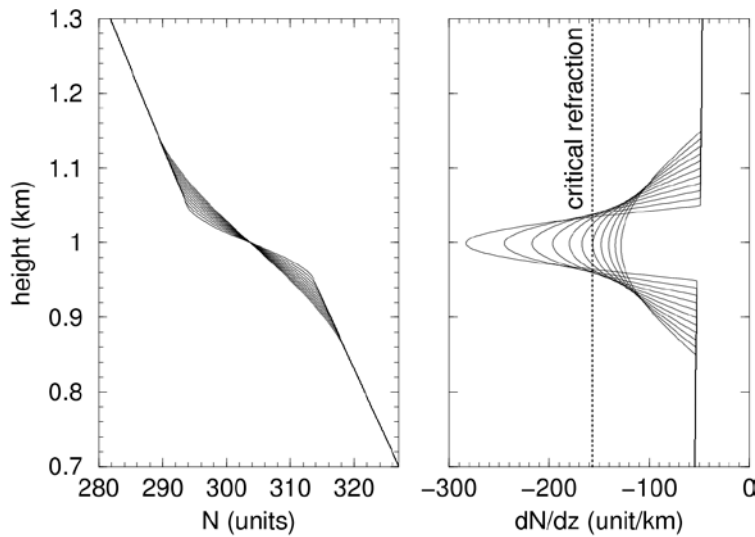
This height corresponds to the height of inversion layers from BA profiles

In some cases, ECMWF model shows N-gradient exceeding critical

Deep signals may indicate super-refraction and used as the QC flag in assimilation. This is confirmed by modeling (next slide)

# Wave optics modeling of RO signal in the presence of strong inversion layer

- when N-gradient exceeds critical, the deep weak RO signal appears
- small amplitude, of order of 0.1%; equivalent to the noise level at SNR  $\sim 1000$  V/V
- for reliable detection should be  $\sim$  twice larger than the noise level (SNR  $\sim 2000$  V/V)
- deep RO signals can be used as an indicator of ducting (causes N-bias in Abel inversion)





# Summary

- NEW CDAAC retrieval software is finalized, but certain processing steps may be further modified based on feedback from workshop attendees:
  - Calculation of Lat. & Lon. for the retrieved profiles.
    - Are non-monotone functions OK?
  - What resolution is needed below 20 km for NWP?
- Plan to update UCAR BUFR products on GTS
  - UCAR will provide test dataset (2-months) of BUFR products to NWP in Sept 2014
  - Update COSMIC GTS products once NWP give approval of test dataset
- UCAR plans to make full re-processed datasets for COSMIC and CHAMP available in Sept 2014

# Acknowledgments

- Support to attend this Workshop was provided by EUMETSAT ROM SAF
- US National Science Foundation
- Taiwan's National Space Organization
- NASA/JPL, NOAA, USAF, ONR, NRL
- Moog - Broad Reach Engineering
- Other RO Missions, CHAMP, SAC-C, GRACE, TerraSAR-X, C/NOFS, Metop-A/GRAS



UCAR



NSF



NASA



USAF



NOAA



NSPO



ONR