Inversion of neutral atmospheric COSMIC signals at COSMIC Data Analysis and archive Center (CDAAC)

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UCAR, NCAR

1st International COSMIC Workshop, Boulder, CO, 16-18 Oct. 2006

1) Summary of the principles of open-loop tracking and inverting RO signals

2) Examples of COSMIC RO signals, removal of navigation data modulation, statistical comparisons of inverted N-profiles to ECMWF global analysis

3) Monitoring atmospheric boundaries (ABL, cloud top) by COSMIC RO signals

Closed-loop (PLL)

The signal down-converted to low mean frequency in receiver for:
(i) noise filtering, (ii) removal of nav. data modulation and
(iii) connection of the phase.

The frequency model uses feedback (is based on extrapolation of the previously extracted phase)

C/A code modulation is removed by using feedback (shifting replica on the base of difference of the power in two shifted correlators)

Open-loop

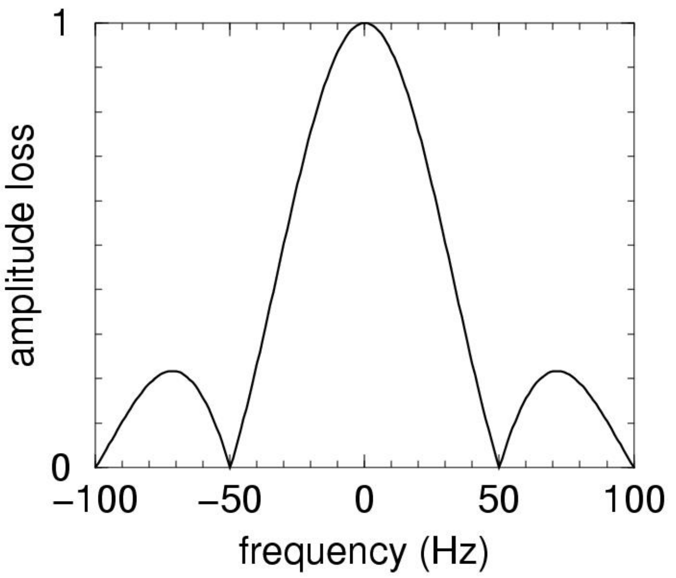
The signal down-converted to low mean frequency in receiver for only the noise filtering.

The frequency model is based on atmospheric model and orbit data (without feedback)

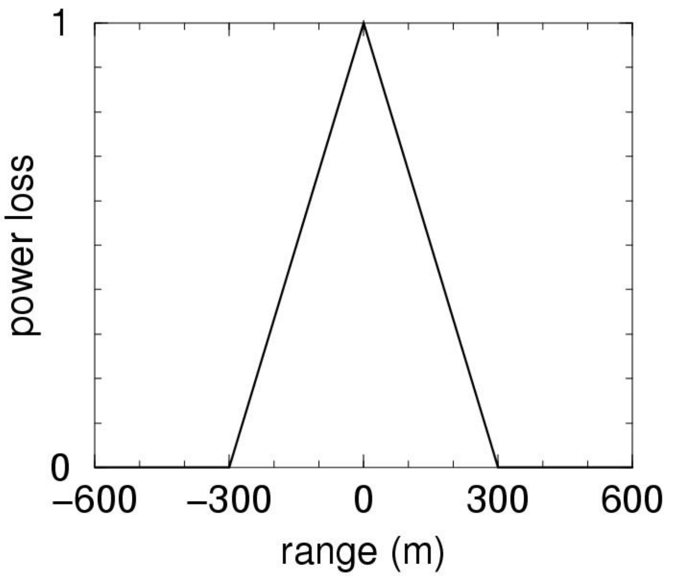
C/A code modulation is removed by using range model based on atmospheric model and orbit data (no feedback)

Removal of the navigation data modulation and connection of the phase is done in post-processing after down-conversion with more accurate model than in receiver.

20 ms integration response function



C/A code auto-correlation function



Comparison of receiver Doppler and range models with the "post-processing" models (based on orbits and climatology)

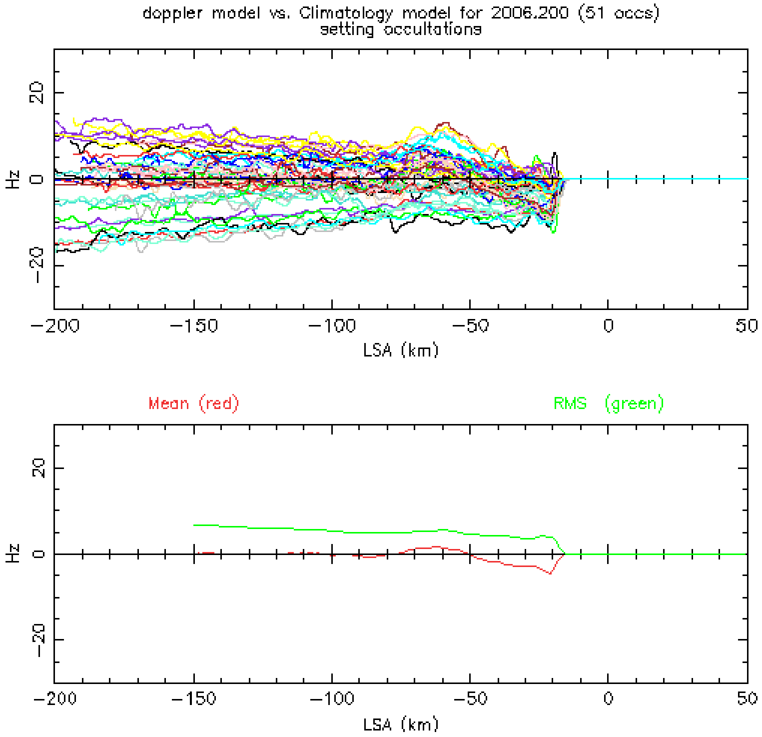
Doppler max. difference
setting ~15 Hz
rising max.~15-20 Hz

Range max. difference
setting max.~100 m
rising max.~200 m

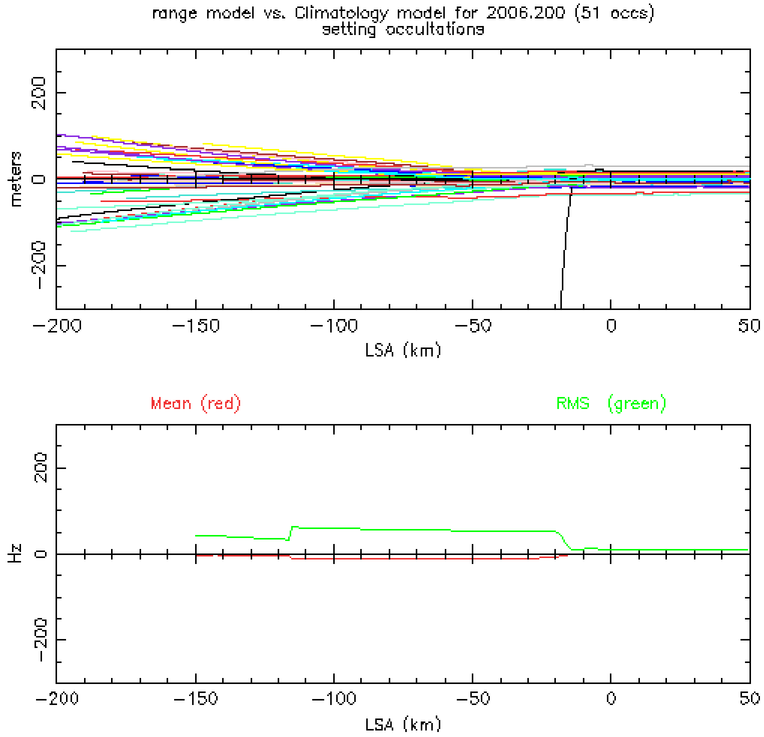
outliers

Comparison of receiver Doppler and range models to the "post-processing" model (based on bending angle climatology) doy 200

Doppler (setting)

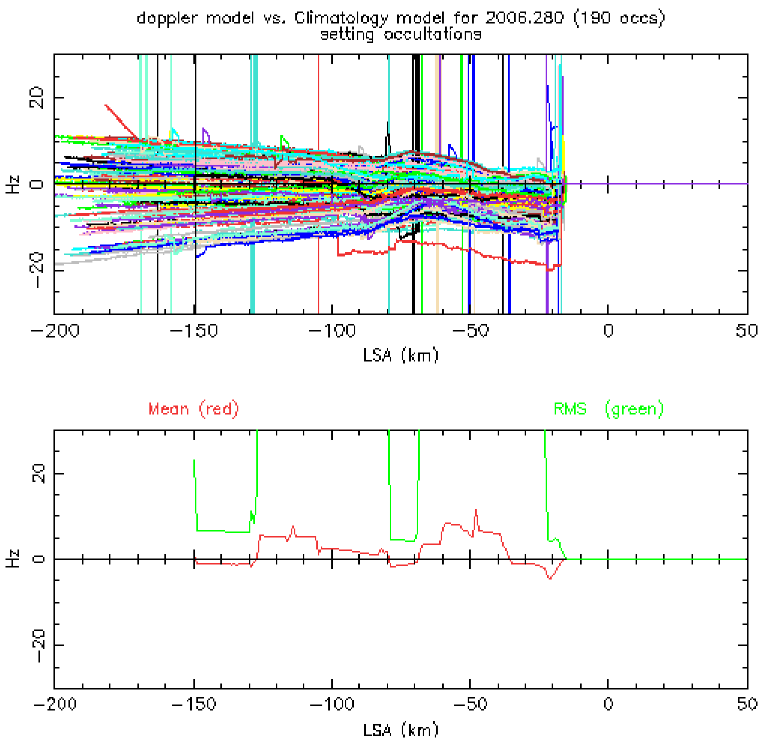


range (setting)

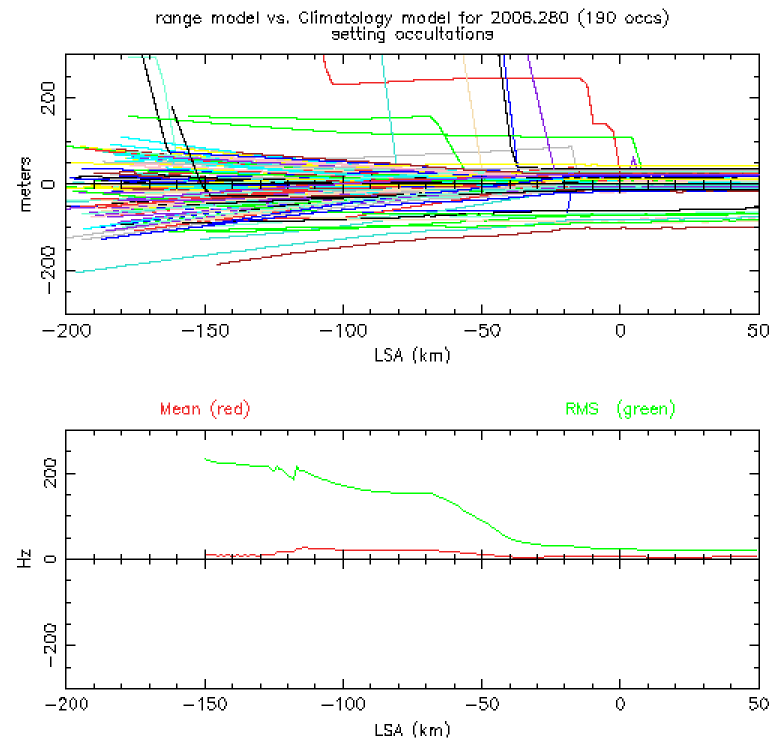


Comparison of receiver Doppler and range models to the "post-processing" model (based on bending angle climatology) doy 280

Doppler (setting)

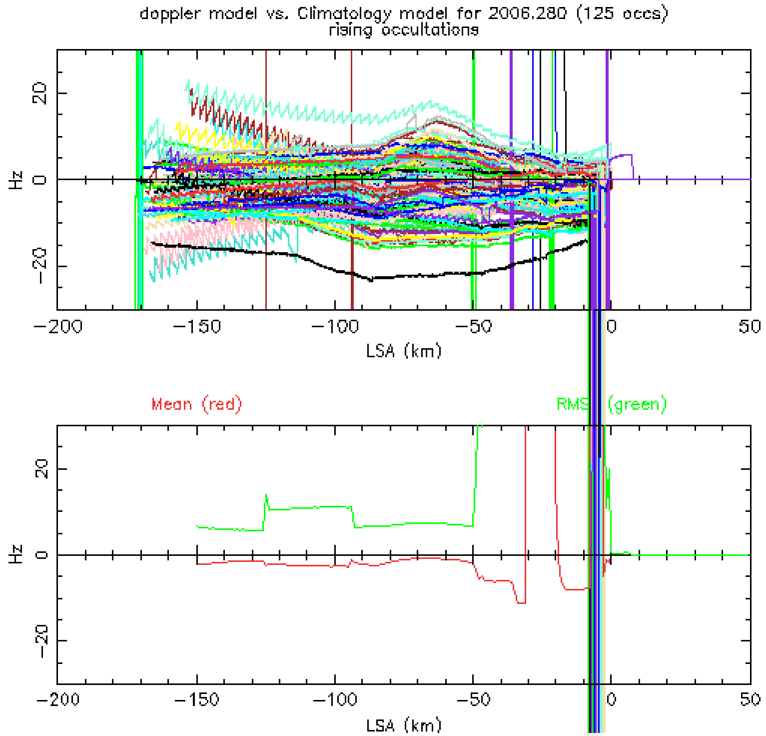


range (setting)

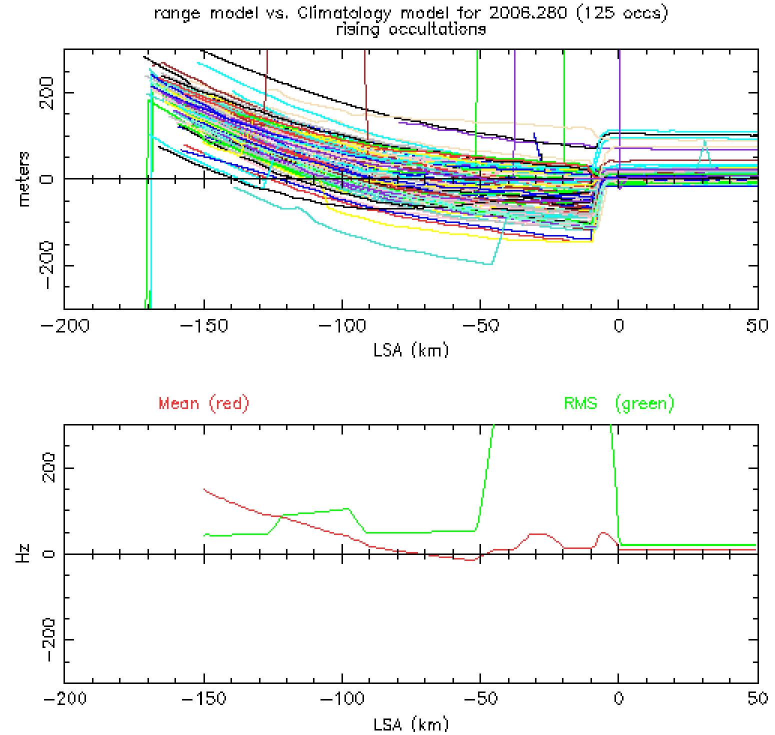


Comparison of receiver Doppler and range models to the "post-processing" model (based on bending angle climatology) doy 280

Doppler (rising)



range (rising)



Tracking firmware for **COSMIC** receivers implemented by JPL.

L1 and L2 signals are recorded in PLL mode above ~10 km.

Below ~10 km L1 is recorded in OL mode. L2 is not recorded.

CDAAC inversion SW removes navigation data modulation internally by connecting the phase, after down-conversion of L1 signal with the Doppler model (based on orbits and bending angle climatology) which statistically results in smaller residual frequency than the receiver model.

Alternatively, navigation data modulation is removed by applying externally recorded navigation data bit sequence when available.

COSMIC deployed global ground network of 6 GPS receivers (“data bit grabbers” that collect the GPS navigation data messages for demodulation of occultation signals.

In receiver:

(1) modeling of the atmospheric
Doppler and down-conversion
(2) low-pass filtering (integration)
I and Q
output signal is a sequence of complex samples with un-connected phase and un-removed NDM

$$u_{down} = A\exp(i\Phi - i\Phi_{rec\_mod})$$
$$< I > = < \mathrm{Re}(u_{down}) >$$
$$< Q > = < \mathrm{Im}(u_{down}) >$$
$$u_{out} = A_{out}\exp(i\Phi_{out})$$
$$A_{out} = \sqrt{< I >^2 + < Q >^2}$$
$$\Phi_{out} = ATAN_2(< Q >, < I >)$$

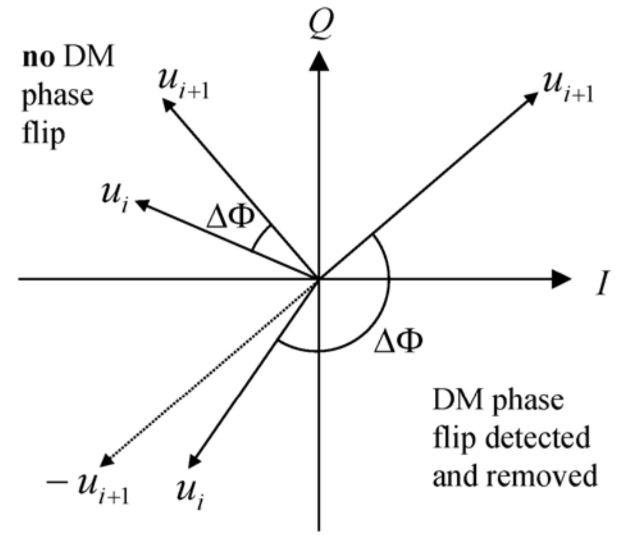
In post-processing:

(1) up-conversion
(2) down-conversion with
more accurate Doppler model*)
(3) removal of NDM
(4) connection of the phase
(resolving cycle ambiguities)

$$u_{up} = A_{out}\exp(i\Phi_{out} + i\Phi_{rec\_mod})$$
$$= A_{out}\exp(i\Phi_{up})$$
$$u_{down} = A\exp(i\Phi_{up} - i\Phi_{post\_mod})$$
$$\Phi_{i+1} = \Phi_i + 0 \text{ or } \pm 2\pi$$
$$|\Phi_{i+1} - \Phi_i| = \min$$

*) the Doppler model is based on $\alpha(h)$ climatology and orbits [Radio Sci., 2001]

Internal removal of NDM:



The signal (rotating phasor) shall be down-converted to as low mean frequency as possible.
Assumption: $\Delta\Phi = |\Phi_{i+1} - \Phi_i| < \pi / 2$

Then:
If $I_i I_{i-1} + Q_i Q_{i-1} < 0$ then $u_i = -u_i$ else $u_i = u_i$

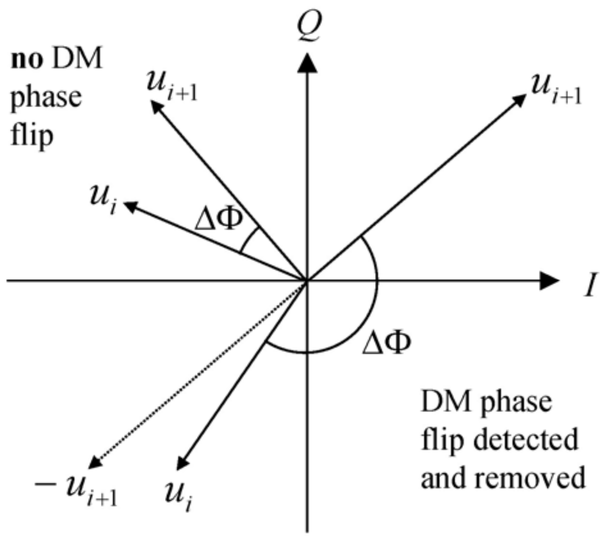
External removal of NDM:

NDM can be removed by applying of an externally-supplied bit sequence (recorded by space-based or ground-based receiver). No restriction on $\Delta\Phi$ for the removal of NDM. But $|\Phi_{i+1} - \Phi_i| < \pi$ for connection of the phase.

Internal/external removal of NDM result in **2/4-**quadrant phase extraction

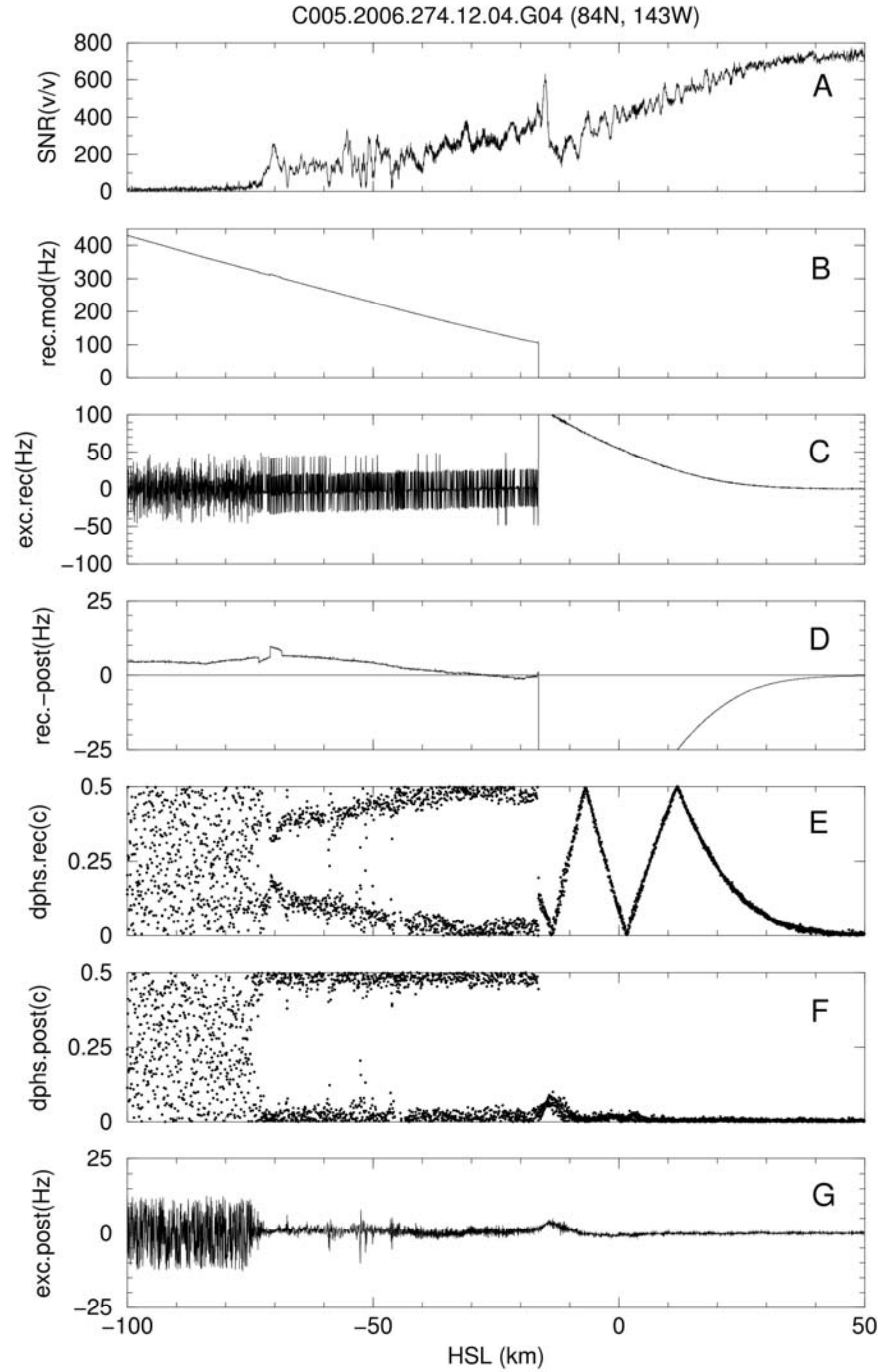
COSMIC deployed a global ground network of 6 GPS receivers providing collection of the GPS navigation data messages (“data bit grabbers”) sufficient for demodulation of all occultations.

High-latitude occultation

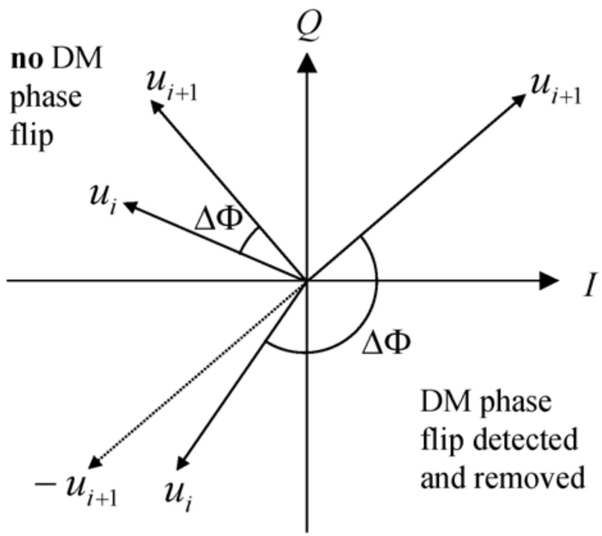


$|\Phi_{i+1} - \Phi_i|$ down-conversion with receiver model

$|\Phi_{i+1} - \Phi_i|$ down-conversion with "post-processing" model

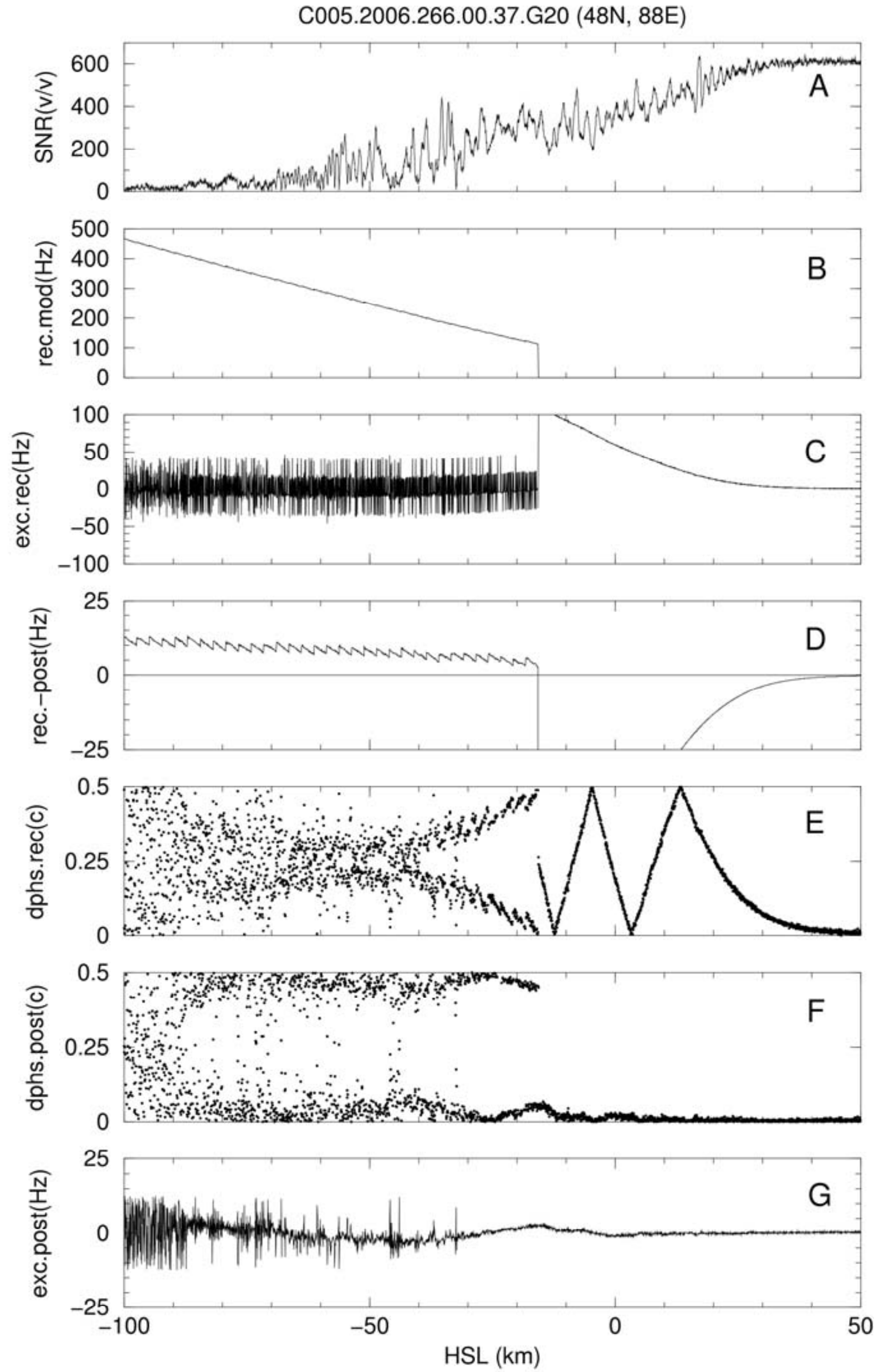


Mid-latitude occultation

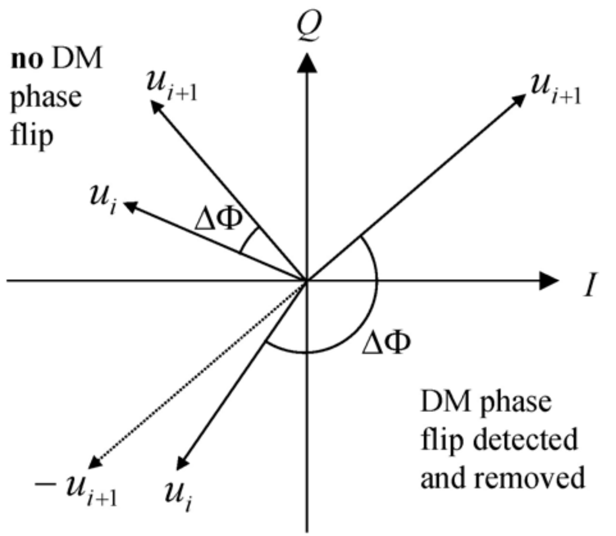


$|\Phi_{i+1} - \Phi_i|$ down-conversion with receiver model

$|\Phi_{i+1} - \Phi_i|$ down-conversion with "post-processing" model

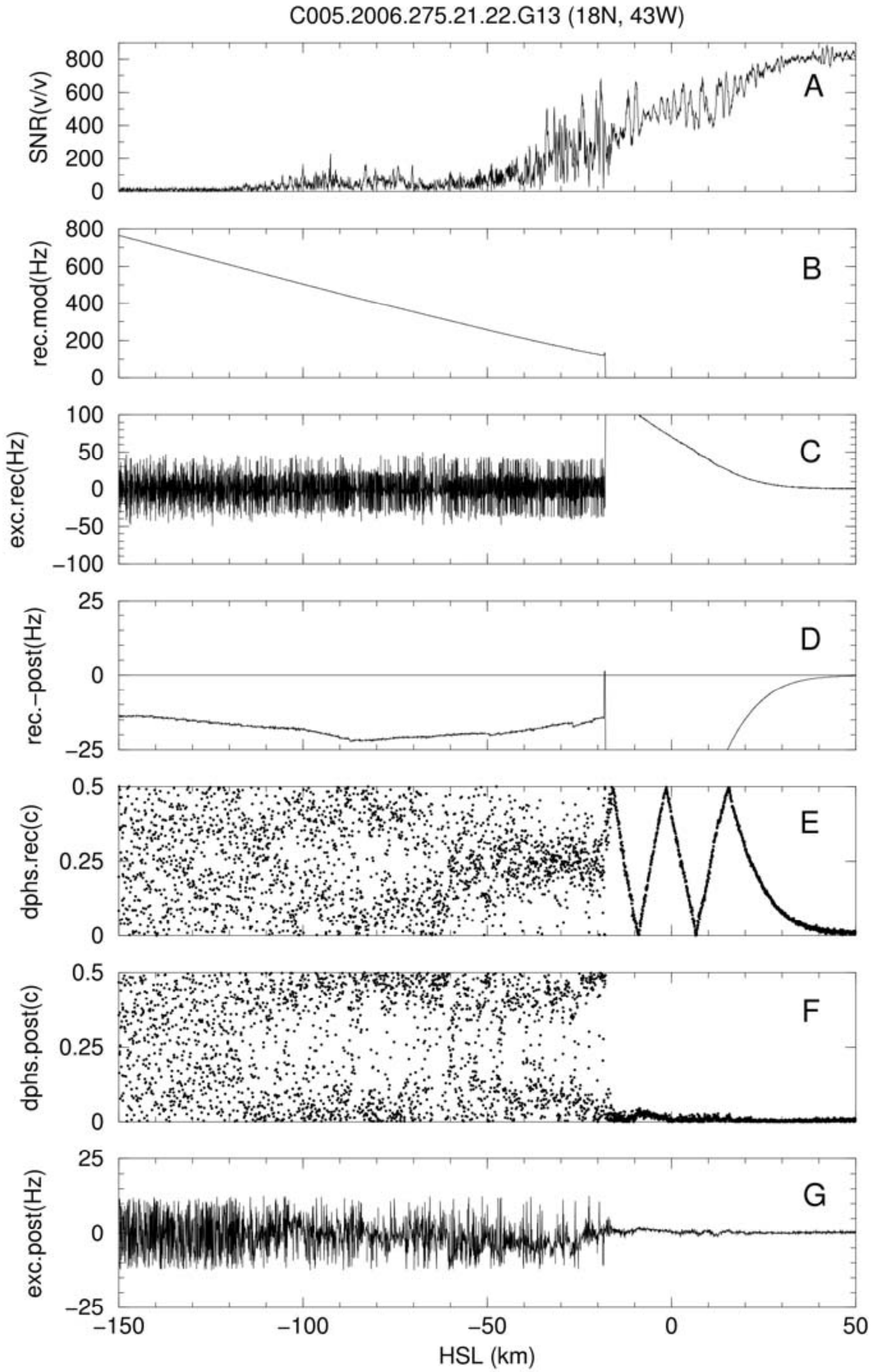


Tropical occultation

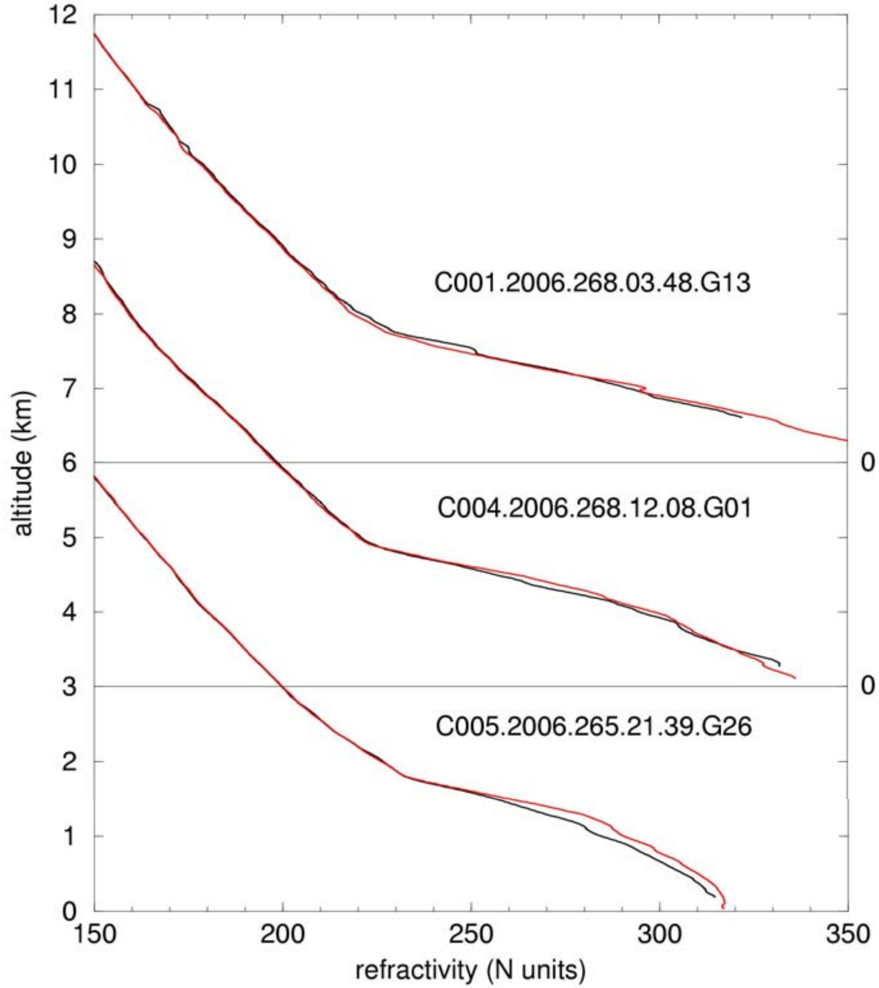


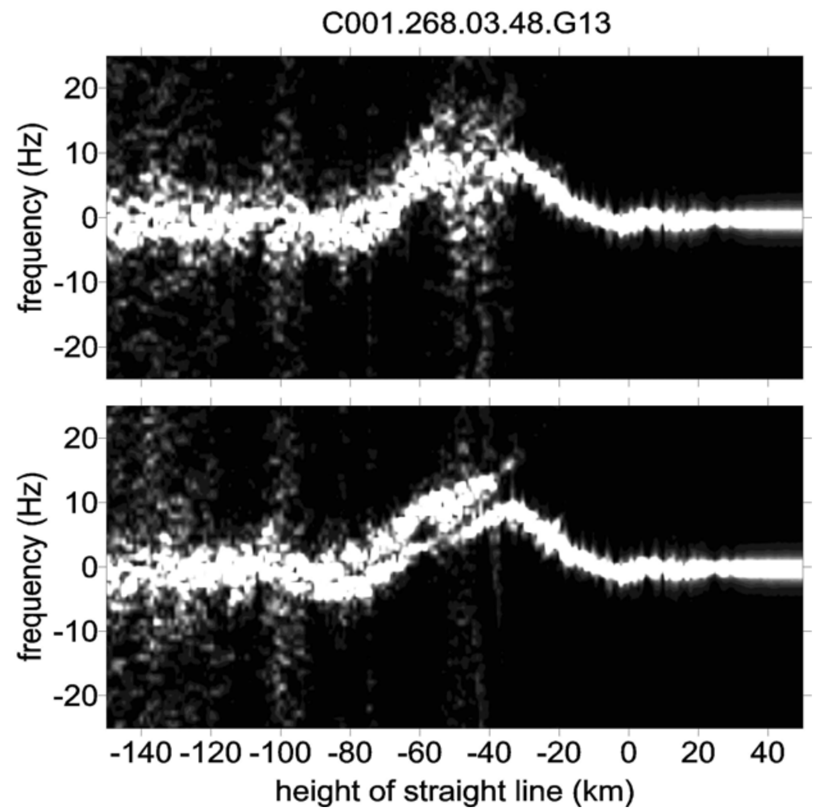
$| \Phi_{i+1} - \Phi_i |$ down-conversion with receiver model

$| \Phi_{i+1} - \Phi_i |$ down-conversion with "post-processing" model



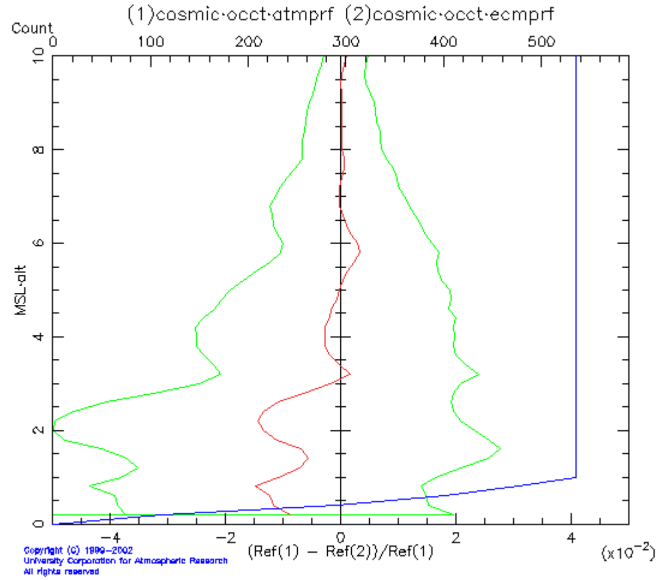
Comparison of N-profiles retrieved with internal and external removal of navigation data modulation



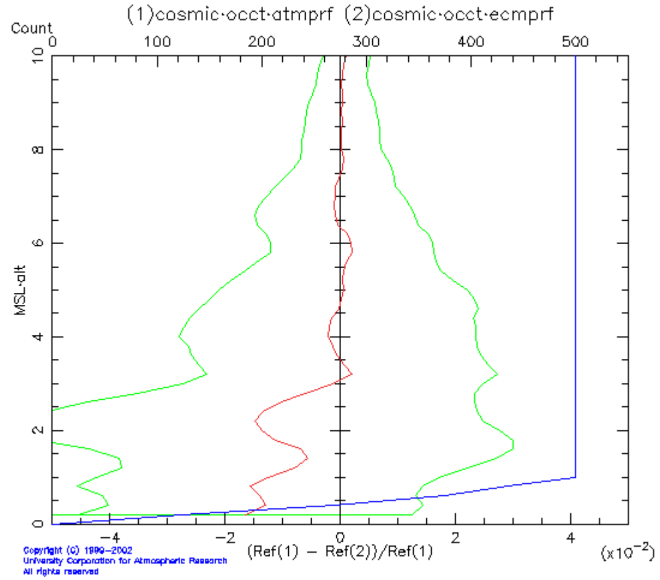


Statistical comparison of N-profiles, retrieved by internal and external removal of navigation data modulation, with ECMWF analysis

internal NDM removal



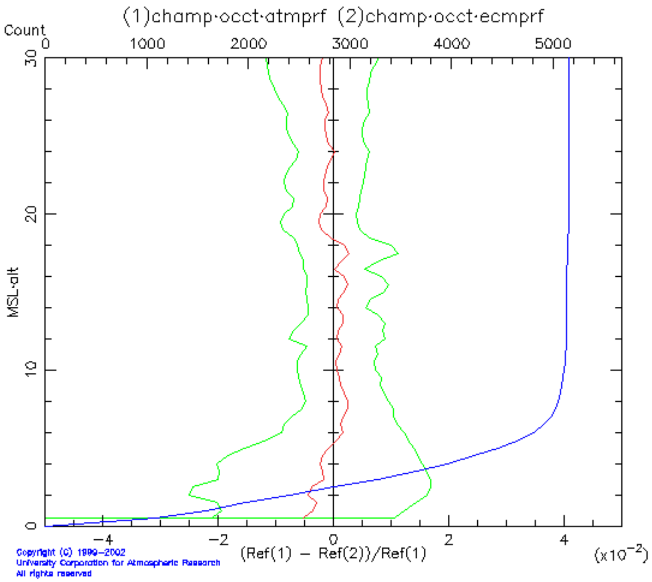
external NDM removal



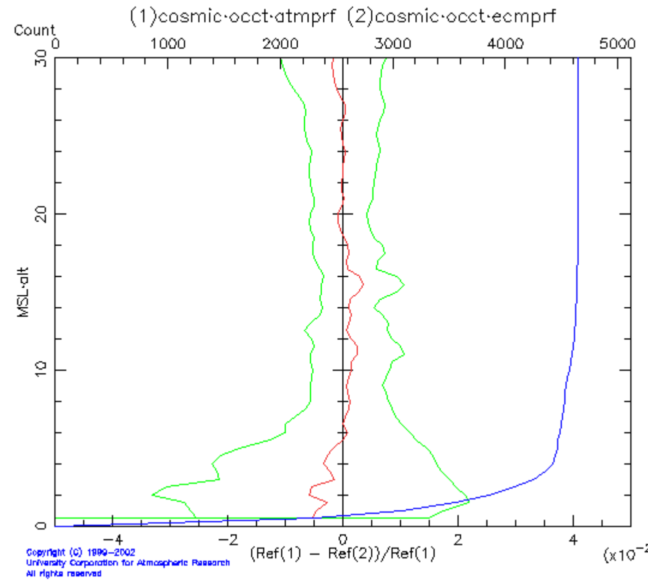
Statistical comparison with ECMWF analyses

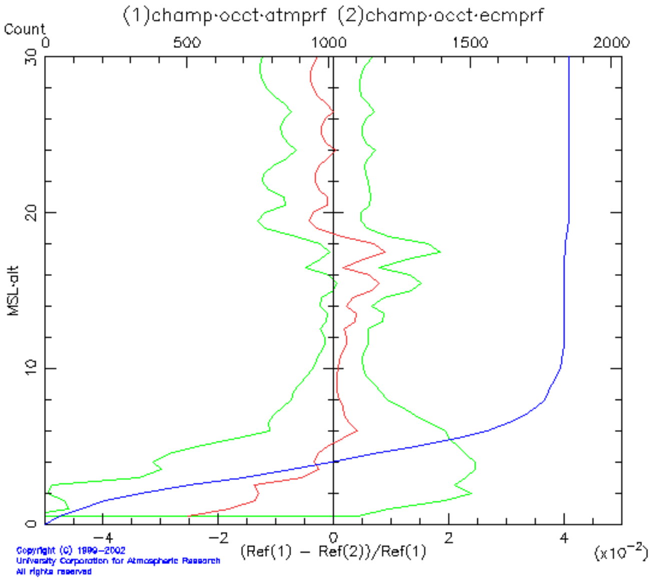
CHAMP

COSMIC

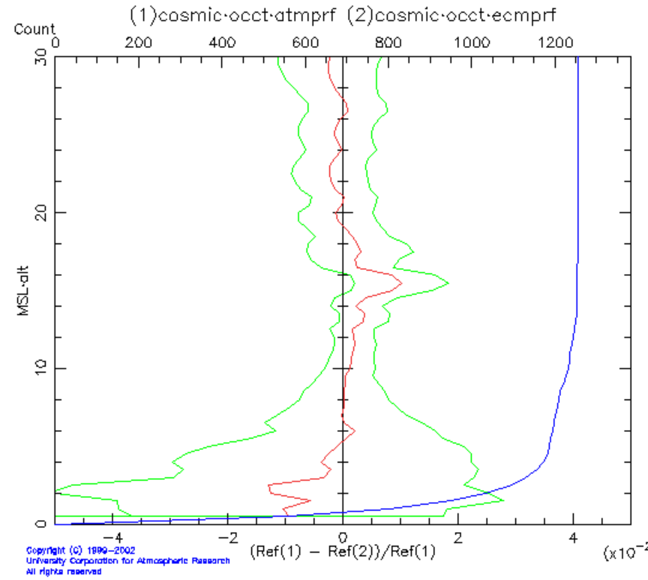


Global

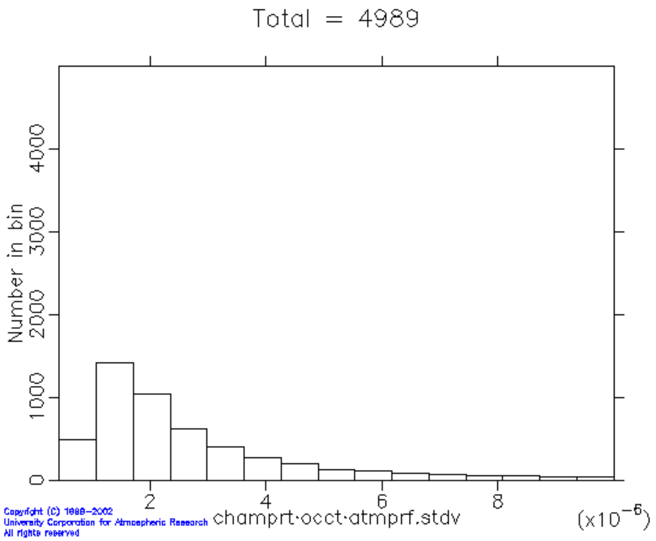




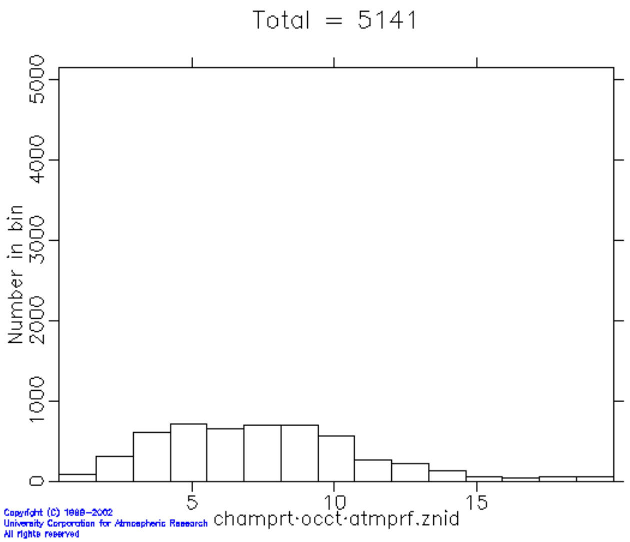
Tropics



CHAMP

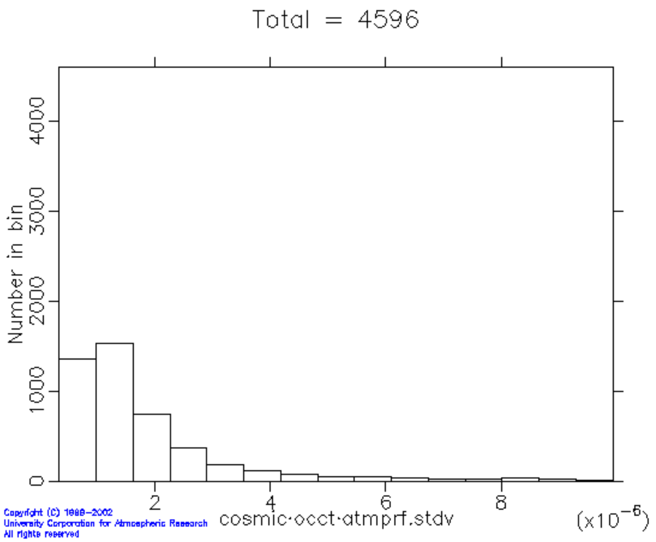


BA RMS 60-80 km (rad)

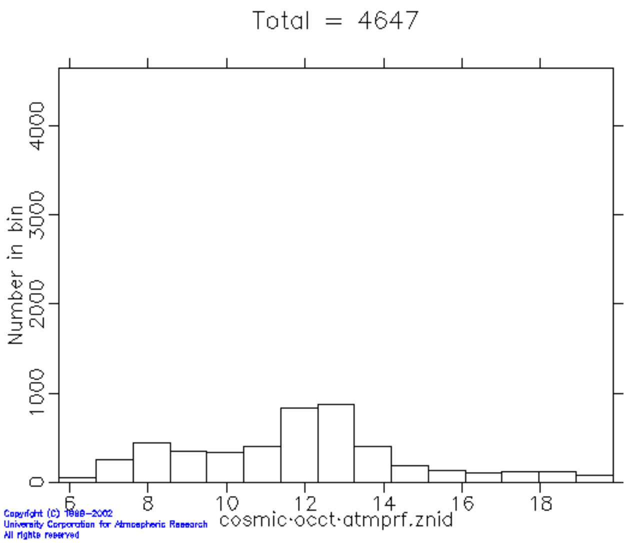


zL2drop (km)

COSMIC



BA RMS 60-80 km (rad)

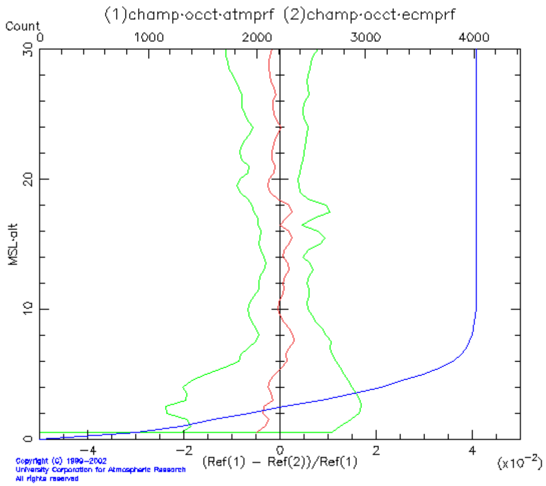


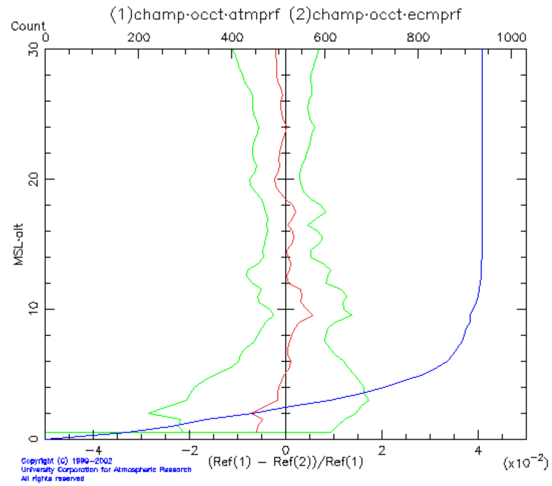
zL2drop (km)

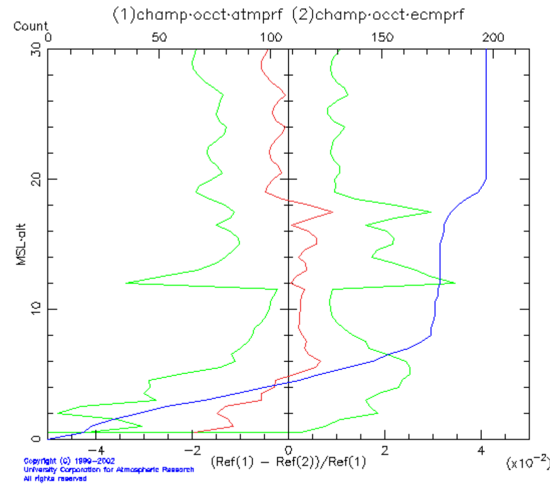
Statistical comparison of retrieved N with ECMWF when L2 was discarded at different altitudes (extrapolation of L1-L2 below zL2)

zL2drop<10km | 10km<zL2drop<15km | 15km<zL2drop<20km

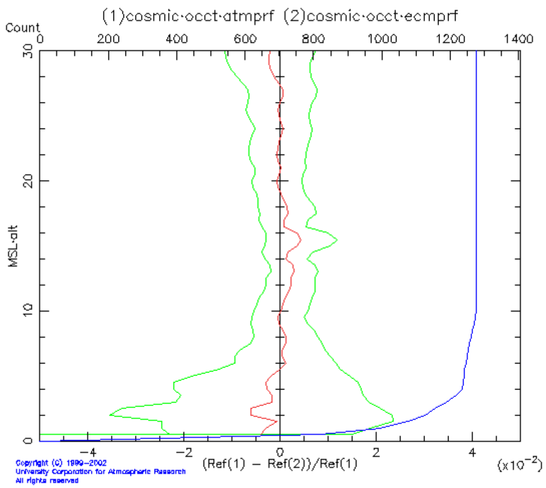
CHAMP

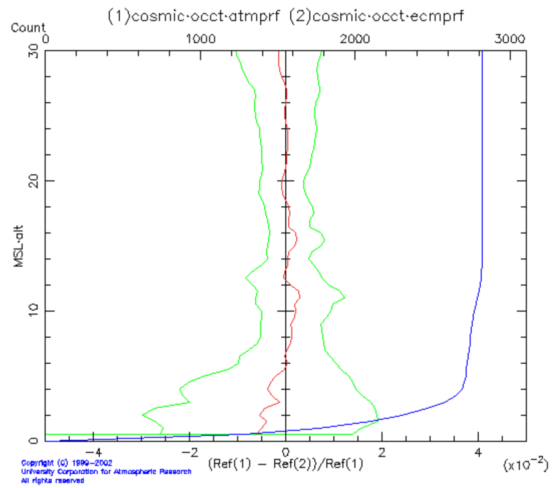


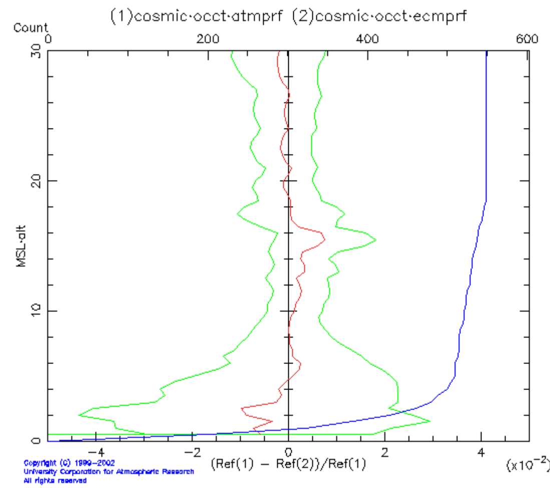




COSMIC







Monitoring tropospheric boundaries by radio occultations

Characterization:

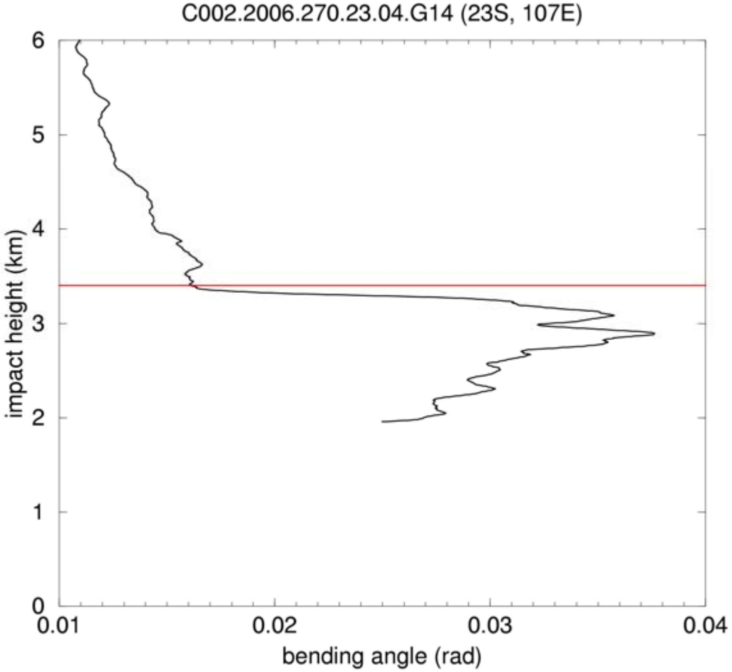
1) by sharp mean gradients of humidity traced by gradients of retrieved bending angle and refractivity profiles

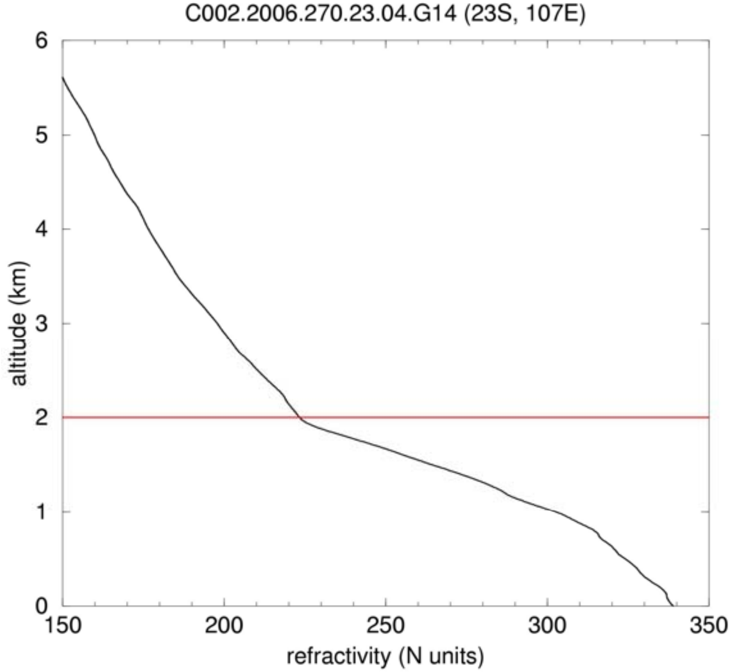
2) by turbulent and convective mixing in the presence of humidity traced by scintillation of RO signals transformed to impact parameter representation.

Indicate top of ABL or convective (cloud) layer above;

indicate stable or convective state of the moist tropical/ subtropical troposphere.

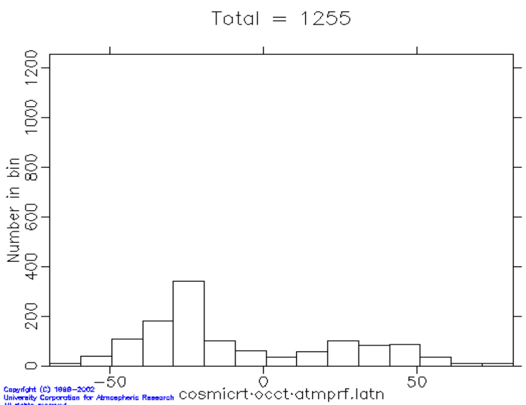
Examples of retrieved bending angle and refractivity profiles in the presence of sharp boundary (ABL top) at ~ 2 km altitude



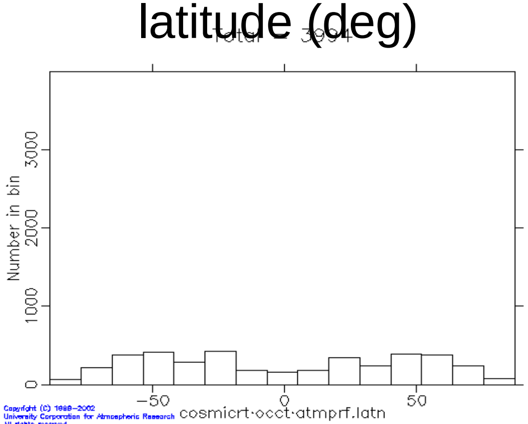


Bending angle profiles are scanned with 0.5 km window and the height of the maximum lapse (HML) is estimated for each profile. Statistical analysis is constrained by the magnitude of ML.

Zonal distribution of the heights of max. bending angle lapse (>1E-2 rad) doys 266-275, 2006 (top of ABL or cloud top).
Color scale shows the max. bending angle lapse



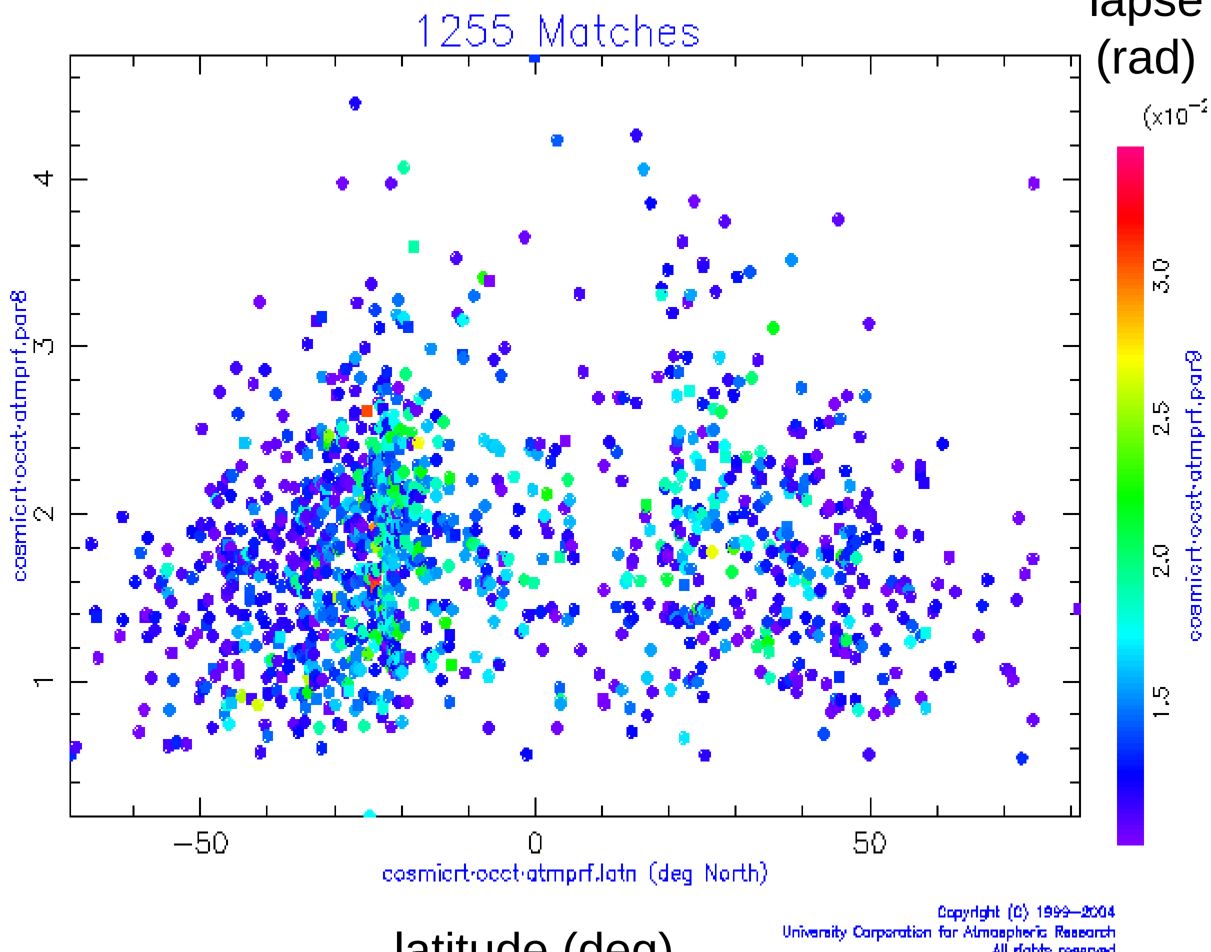
latitude (deg)



latitude (deg)

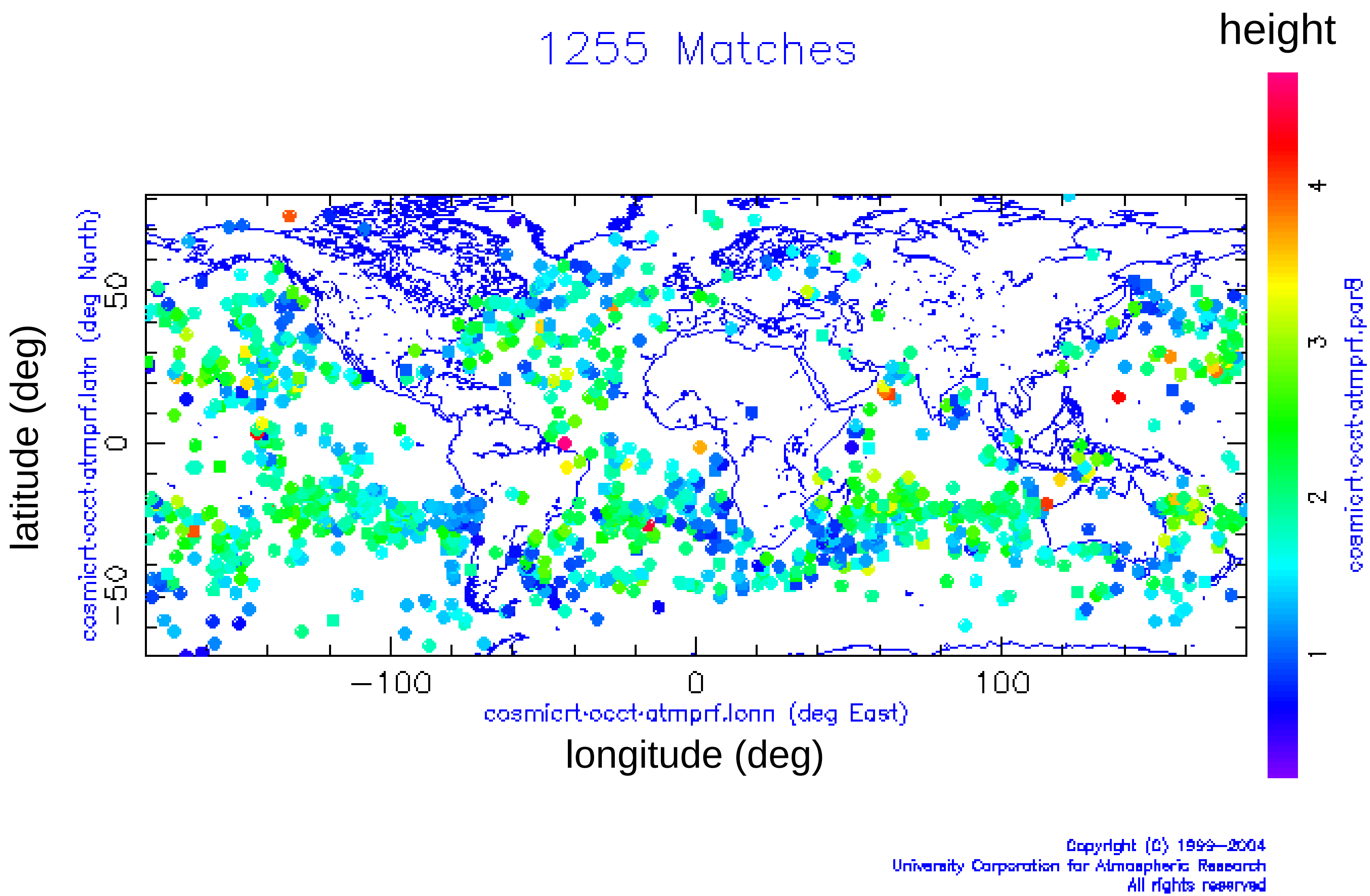
altitude (km)

BA lapse (rad)



latitude (deg)

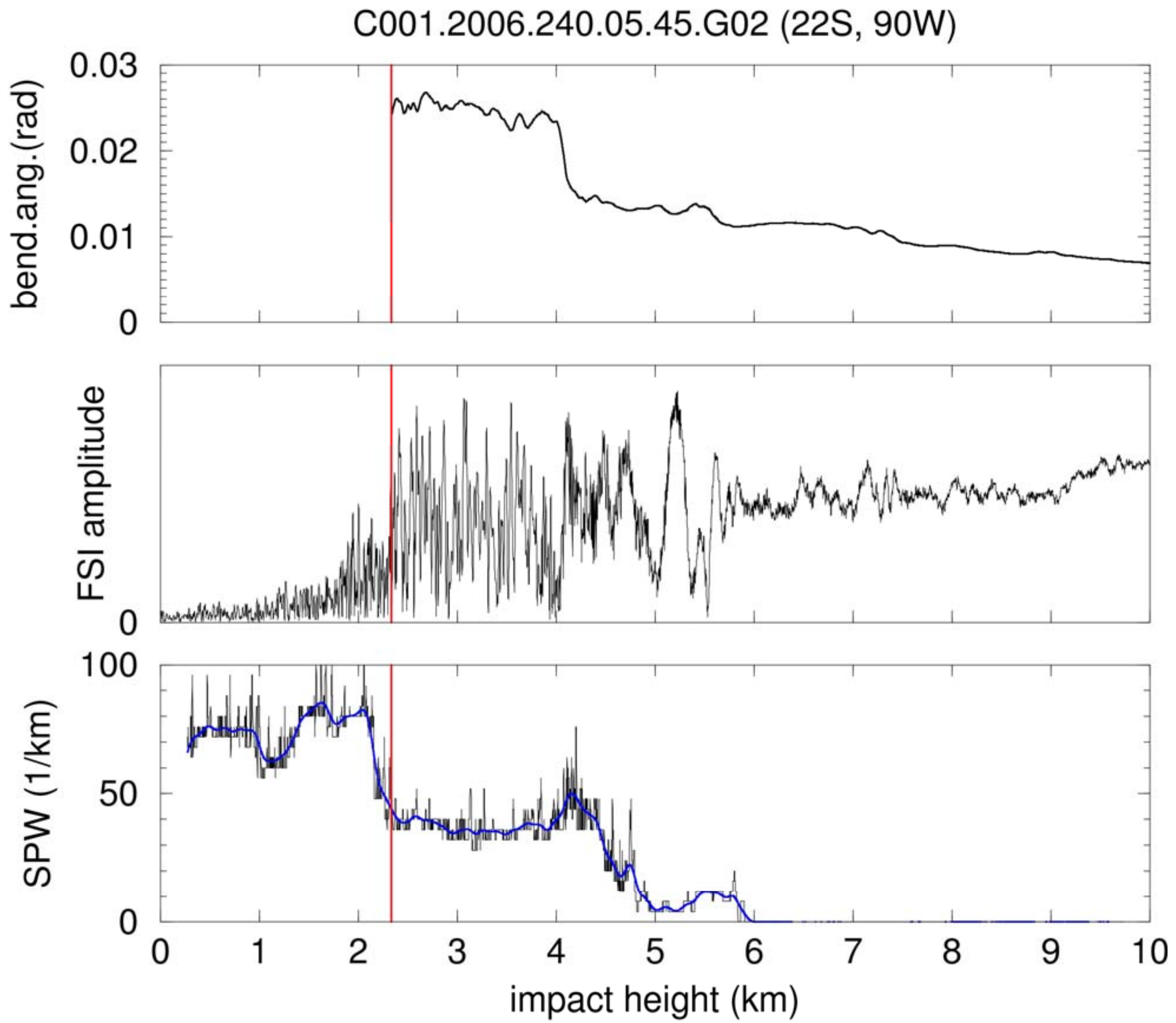
Latitude-longitude distribution of the heights of max. bending angle lapse (>1E-2 rad) doys 266-275, 2006 (top of ABL or cloud top). Color scale shows the max. bending angle lapse



Bending angle, FSI amplitude and width of the sliding spectrogram as functions of impact height. The spread of the spectrum indicates turbulence/convection in the presence of moisture. Low top.

amplitude subjected to spectral analysis in sliding window 0.5 km

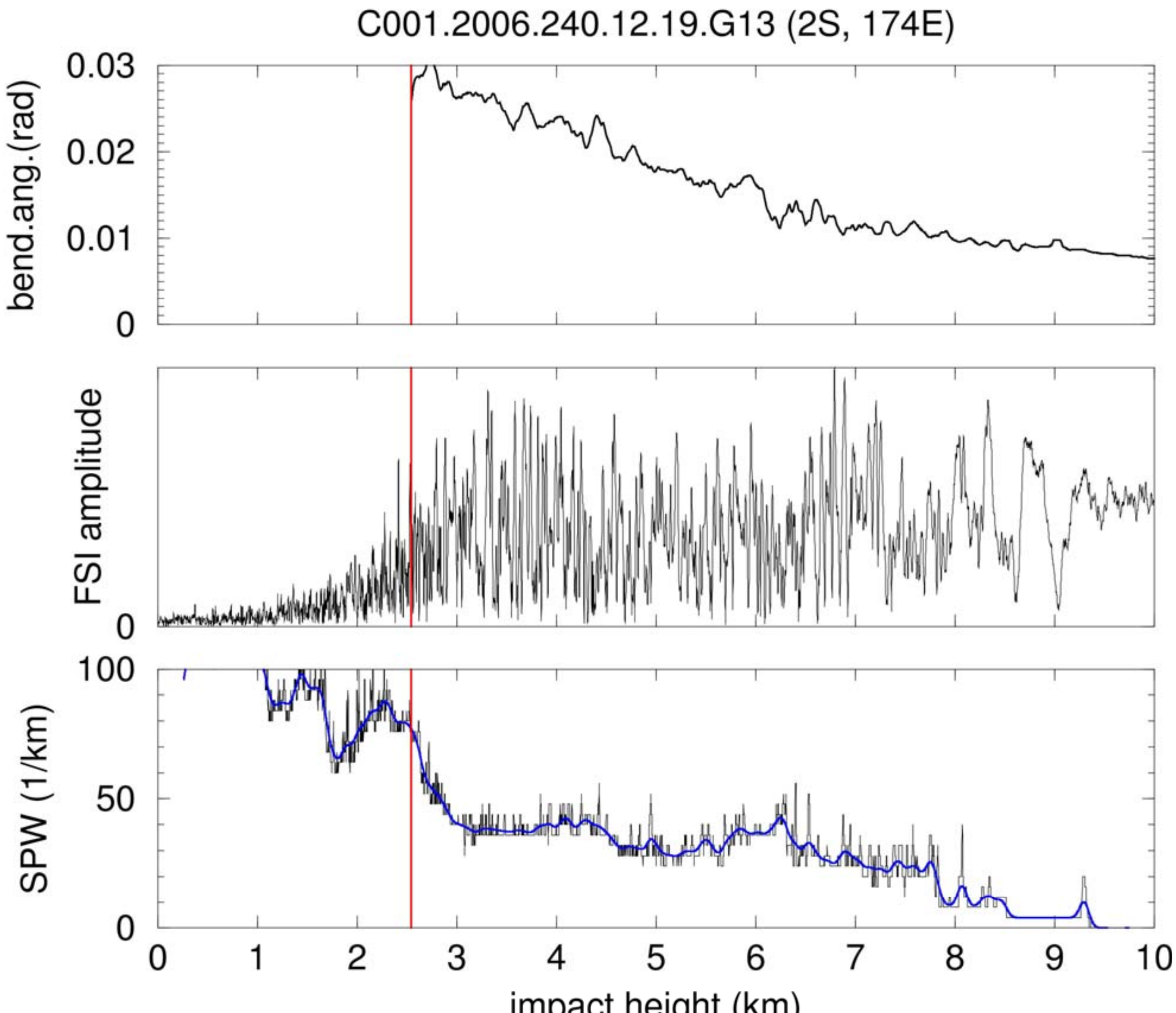
The width of the spectrum in each window estimated by integration of the spectrum and truncation at 0.25 and 0.75 levels



Bending angle, FSI amplitude and width of the sliding spectrogram as functions of impact height. The spread of the spectrum indicates turbulence/convection in the presence of moisture. High top.

amplitude subjected to spectral analysis in sliding window 0.5 km

The width of the spectrum in each window estimated by integration of the spectrum and truncation at 0.25 and 0.75 levels



Conclusions

Currently, COSMIC is providing >1000 occultations daily.

CDAAC inversion SW is processing data in real time by using internal or external navigation data demodulation based on availability of ‘bits’.

Preliminary estimates of the data quality (incl. stat. comparison of the inversion results to ECMWF), compared to CHAMP data show:
- lower noise level;
- significant improvement of penetration;
- smaller negative N-bias in the troposphere.

OL data are useful for monitoring tropospheric boundaries characterized by sharp N-gradients and convection (PBL, cloud top)

Research ongoing to understand what affects the quality and quantity of RO data in general (receiver OL models in particular) and to how improve them.