Initial Assessment of COSMIC-2 Data in the Lower Troposphere (LT)

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COSMIC-2 has the highest SNR (with BF) across all azimuth angles out of current RO missions

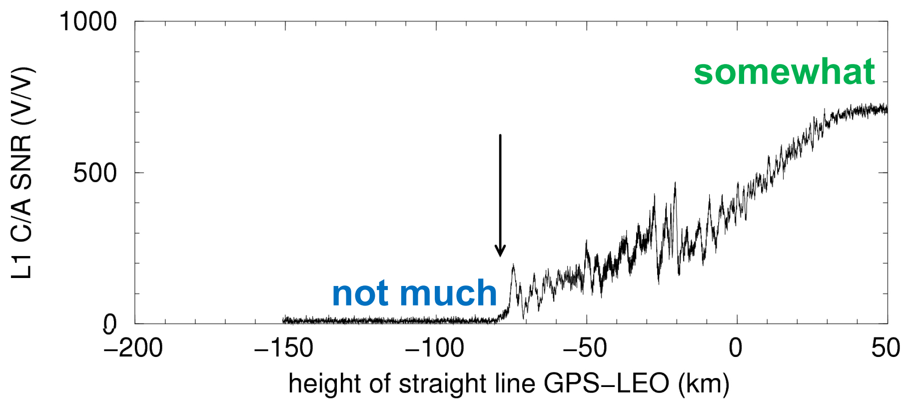
Question: Why / Where high SNR is important?

In the stratosphere – somewhat:
high SNR reduces phase noise

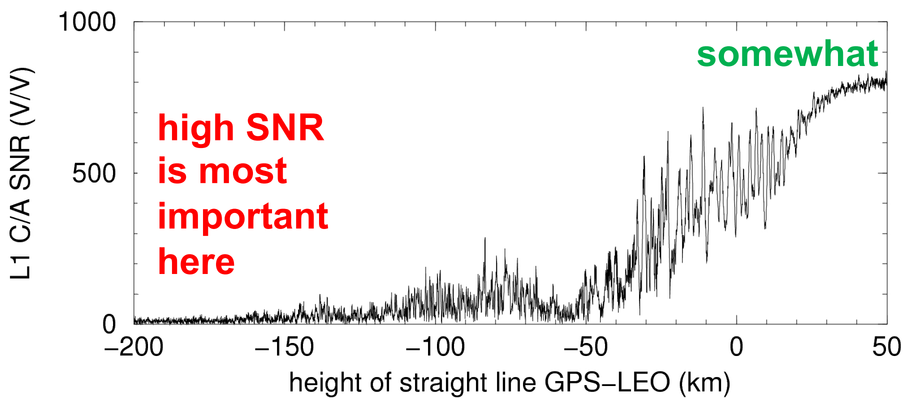
In the polar lower troposphere – not much:
RO signal reduces below noise level abruptly

In the tropical troposphere – most important:
RO signal reduces below noise level gradually; it is important to distinguish signal from noise to include in retrieval process down to lower height

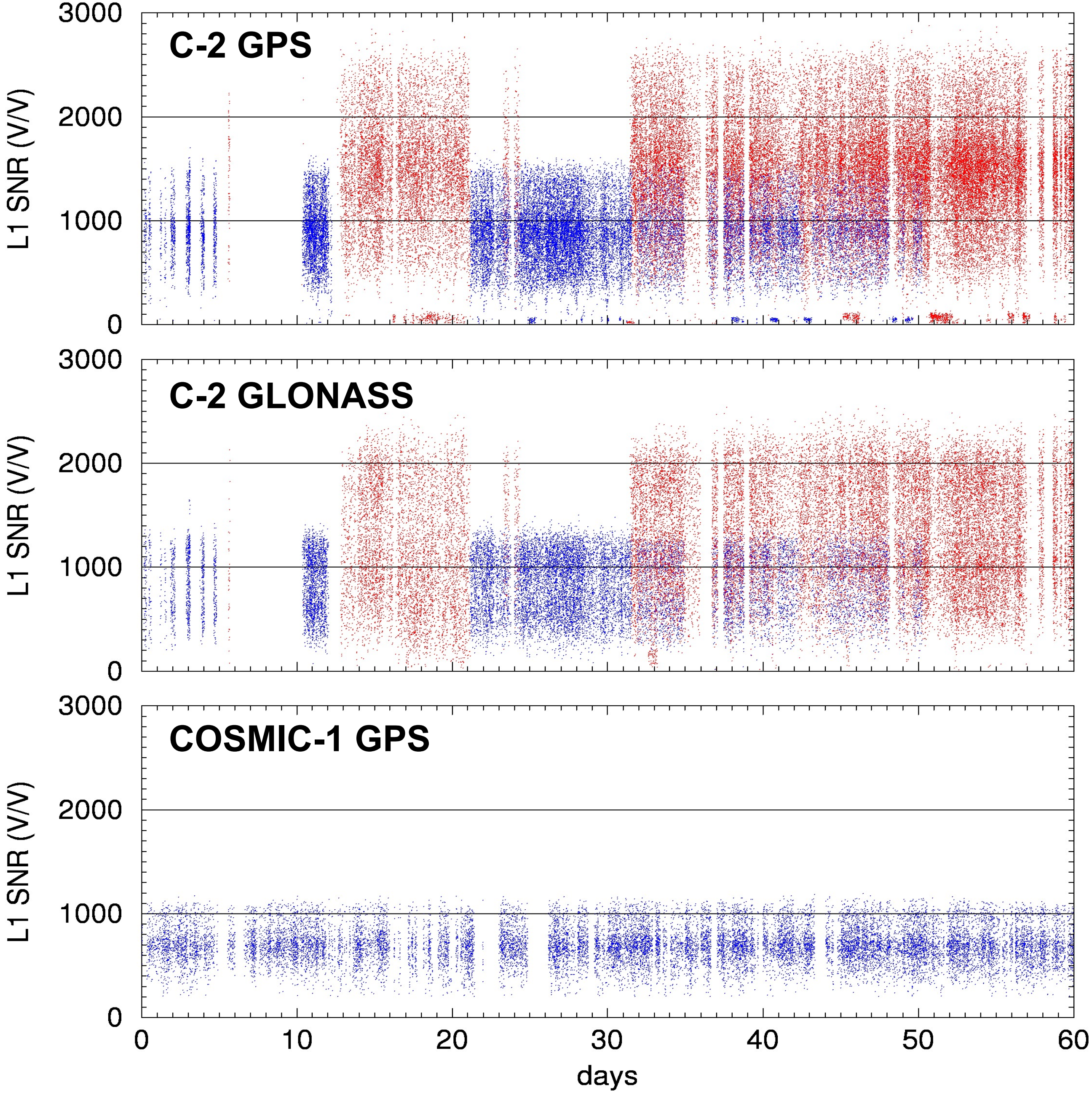
polar occultation



tropical occultation



L1 signal to noise ratio (SNR) from OCC antenna. Effect of beam forming (BF)



COSMIC-2 GPS
60 days

No BF: <SNR> = 889 V/V
BF: <SNR> = 1476 V/V
BF / NoBF = 1.66

COSMIC-2 GLONASS
60 days

No BF: <SNR> = 838 V/V
BF: <SNR> = 1307 V/V
BF / NoBF = 1.56

COSMIC-1 GPS
60 days (2018.001-060)

<SNR> = 704 V/V

What was expected from COSMIC-2 in the lower troposphere:

Reduction of some (but not all) of the tropospheric biases

Examples of some biases:

1) Super-refraction: negative N-bias, assimilation of BA is an ill-posed problem (Sokolovskiy, 2003; Xie et al., 2006; Ao, 2007)
Does not depend on the SNR

2) Fermat principle: in random N, the mean phase is always smaller than the phase in the mean N (Gorbunov et al., 2015)
Does not depend on the SNR

3) Impossibility to distinguish signal from noise (Sokolovskiy et al., 2010):

3A) truncation: negative BA and N bias
Reduces with increase of SNR

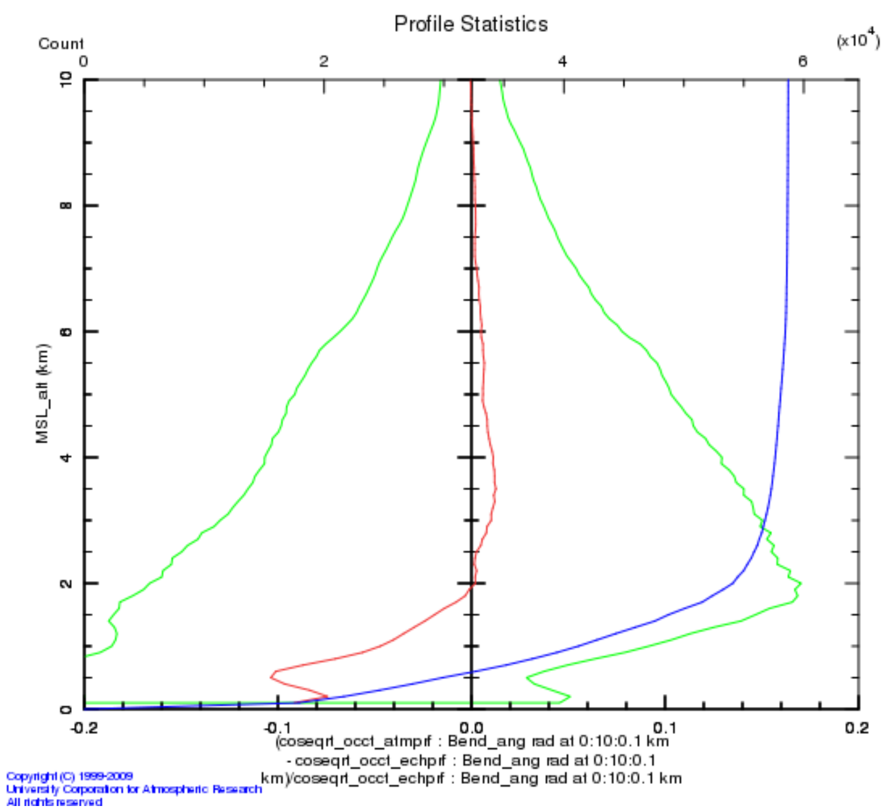
3B) using noisy signal down to lower height: positive BA and N bias
Reduces with increase of SNR
Can also be reduced by filtering in IP domain (Gorbunov et al., 2006); however, at the expense of smoothing large bending angles

It was expected that standard deviation will not reduce, on opposite, it may increase. Reason: retrieval of small-scale structures which may be reproduced differently by RO and by models.

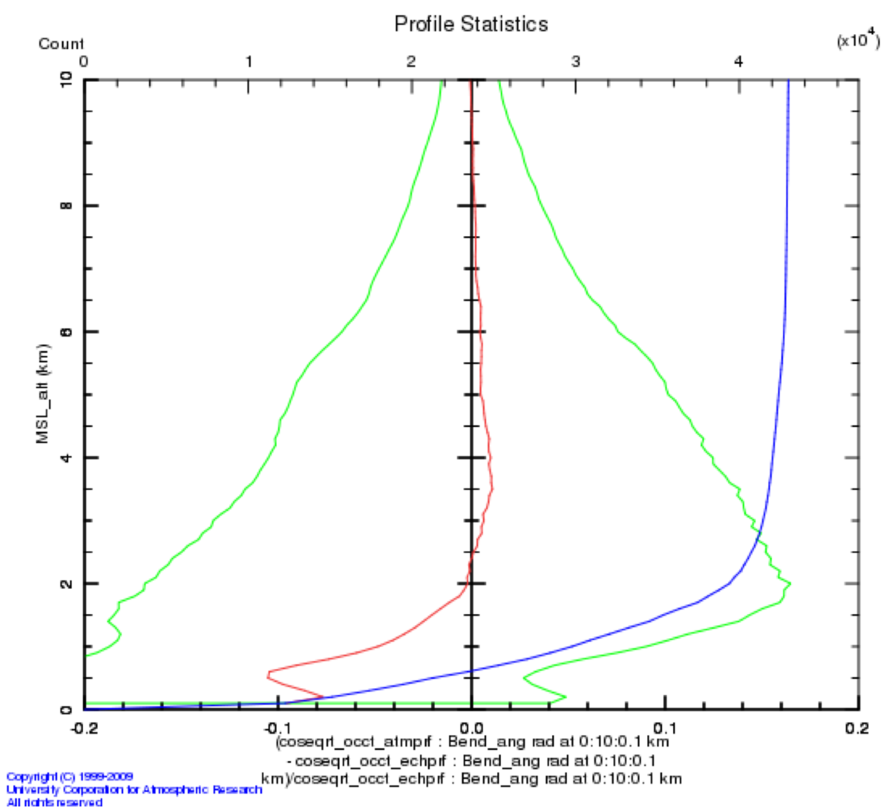
COSMIC-2 – ECMWF BA Statistics for GPS and GLONASS

Not a significant difference between C2 - ECMWF BA stats for GPS and GLONASS. GPS has higher SNR, but GLONASS has twice larger C/A code chip length. This potentially may result in lower SNR loss due to OL range miss-modeling. But this assumption has not been verified yet.

GPS



GLONASS

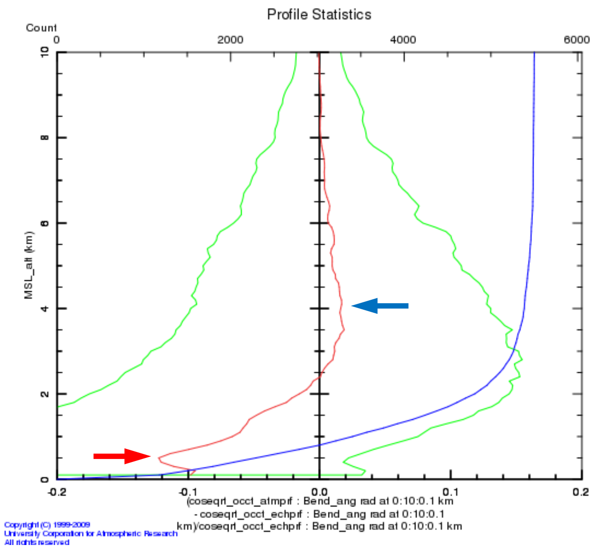


Small difference allows combined GPS and GLONASS statistical analysis in the LT for C2

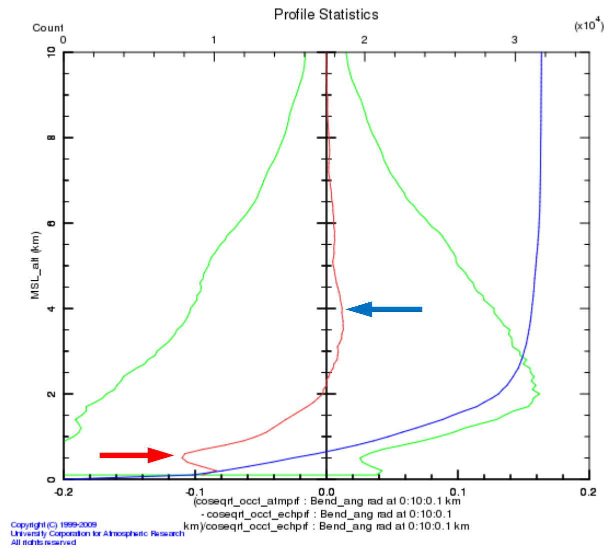
Inversion biases in the moist LT may substantially depend on processing methods
(Sokolovskiy et al., 2010)

Below: mean and stand. dev. from ECMWF of BA from standard CDAAC processing
Both negative and positive biases reduce while stand. dev. increase with increasing SNR

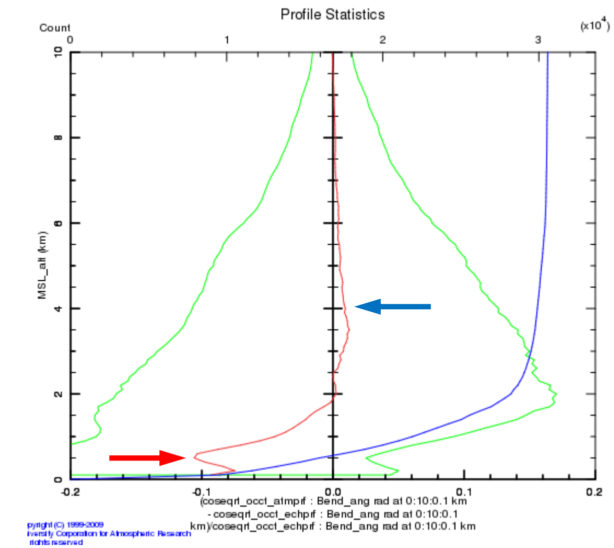
< 500 V/V



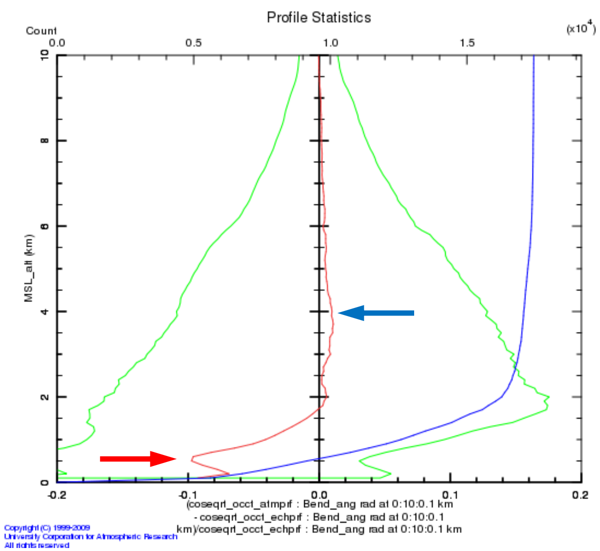
500-1000 V/V



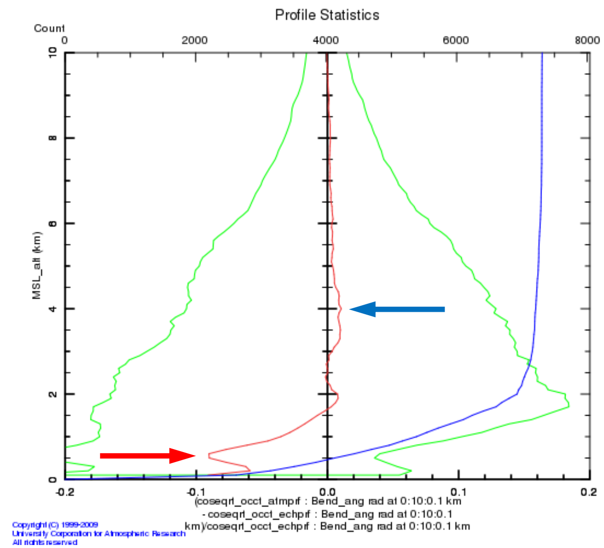
1000-1500 V/V



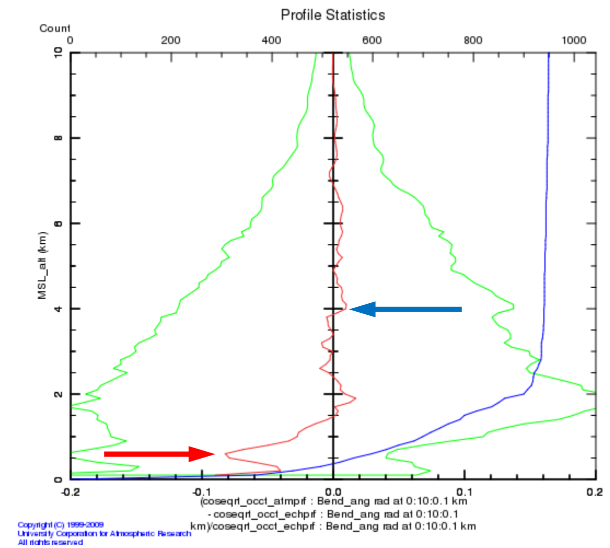
1500-2000 V/V



2000-2500 V/V



> 2500 V/V



Currently C-2 data are processed by CDAAC using standard inversion software

Modifications to make optimal use of high SNR and 100 Hz sampling
are under development

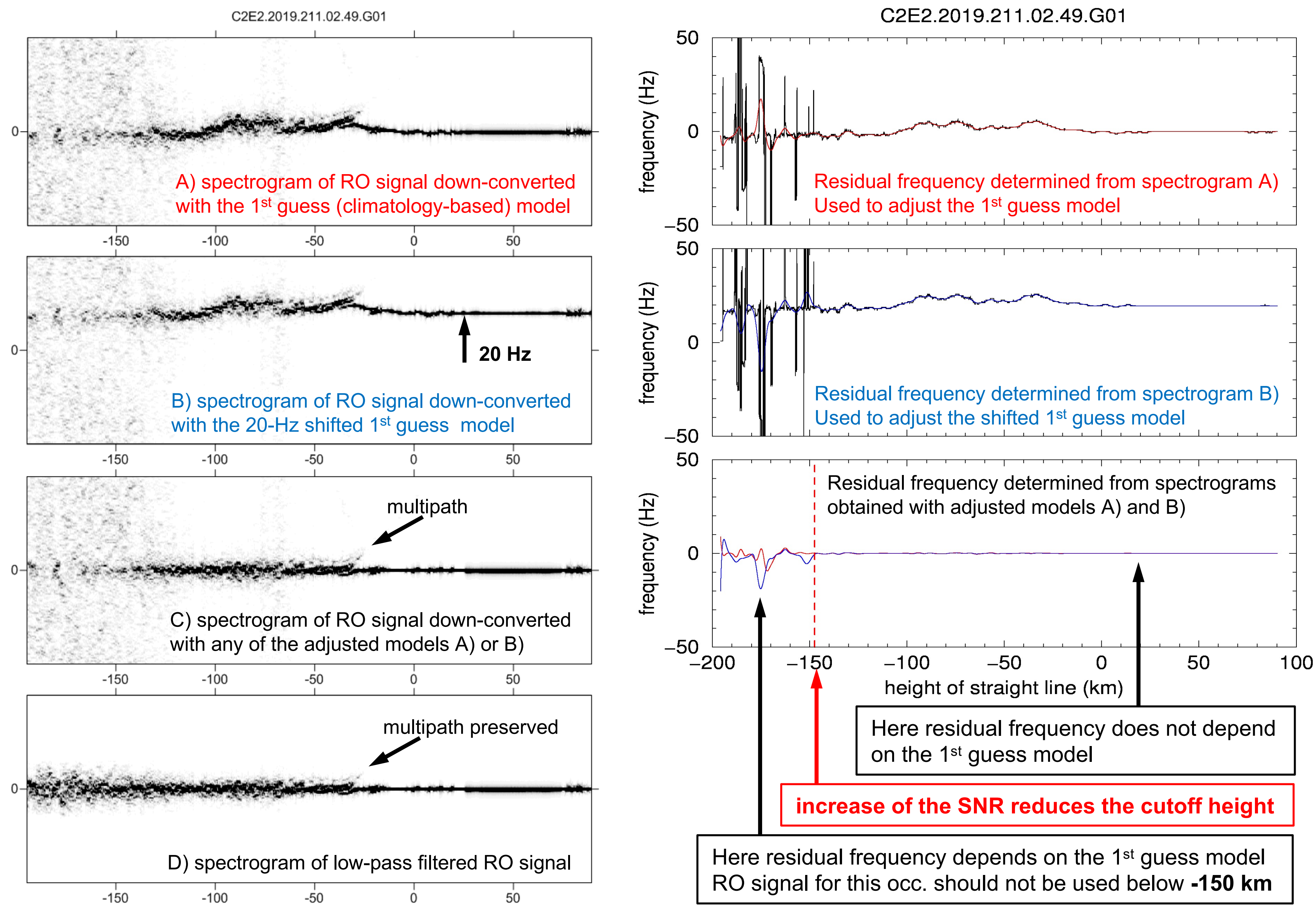
Goals:

1) To make inversion results independent on the frequency model used to connect the phase from OL data
2) To apply additional noise filtering prior to application of WO transform

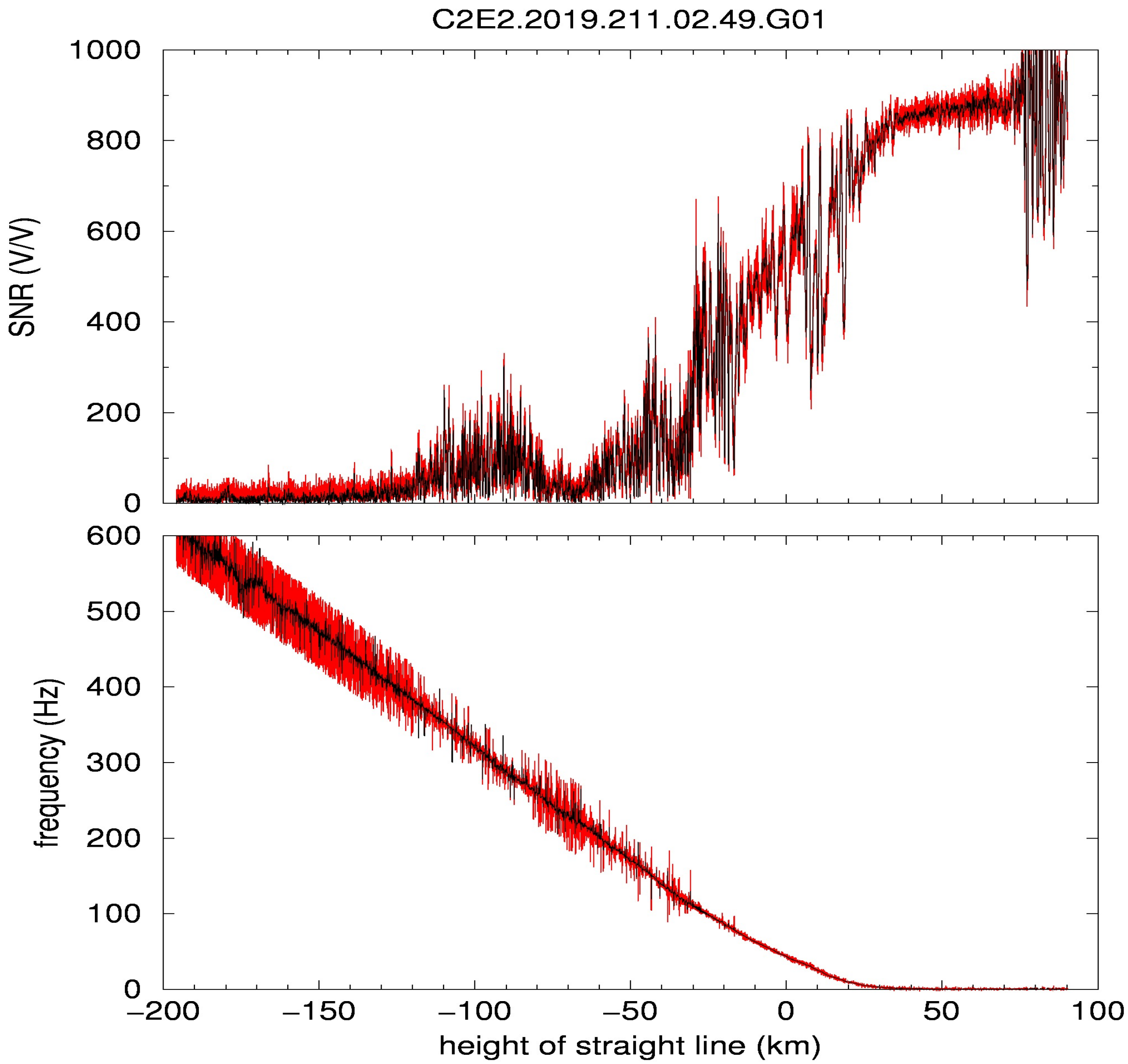
Pre-processor:

1) Estimation of the 1st guess Doppler miss-modeling from the spectrogram
2) Adjustment of the model to shift mean RO signal frequency to zero
3) Low-pass filtering with bandwidth that preserves RO signal spectrum (multipath)
4) Extraction and connection of the phase
5) Altering the 1st guess model; repeating steps (1) and (2)
6) Estimation of the minimal height where the estimated Doppler does not depend on the model; stop using RO signal below that height

Application of the pre-processor for one occultation



RO L1 signal (SNR and Doppler) from previous slide: original – red; after pre-processing - black



Detection of the tropospheric ducts on top of ABL for assimilation of BA

<u>Question</u>: is it needed?

Models like ECMWF can predict ducting on top of ABL.

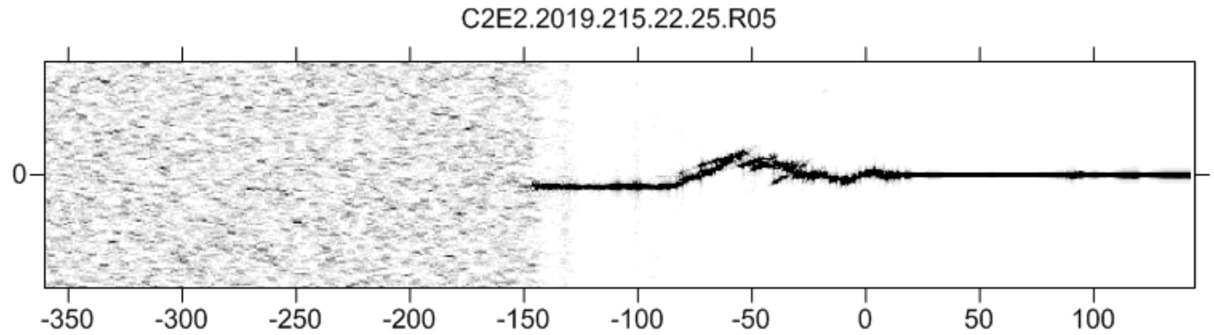
<u>Answer</u>: model is prediction; RO is direct measurement; sometimes RO shows duct, but model does not (see next slides).

Duct detection is based on existence of "deep" RO signals observed at high SNR down to -300 -400 km HSL when $dN/dz < -157\ km^{-1}$ (Sokolovskiy et al., 2014)

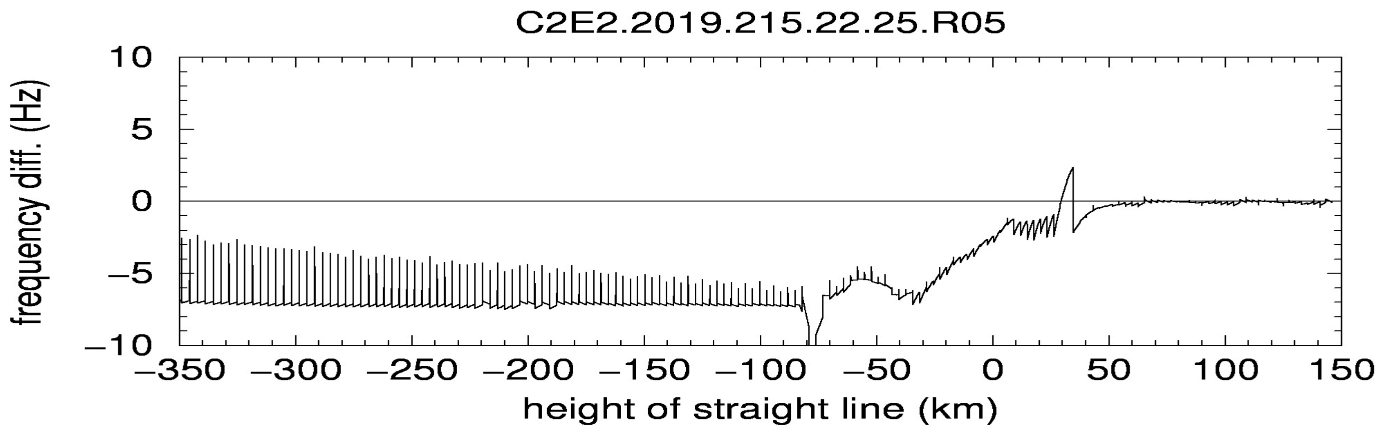
Currently, duct detection has been tested for setting C-2 occultations with SNR > 2000 V/V. For rising occultations, lower SNR and detection in automated mode are under testing.

<u>On next slides:</u>

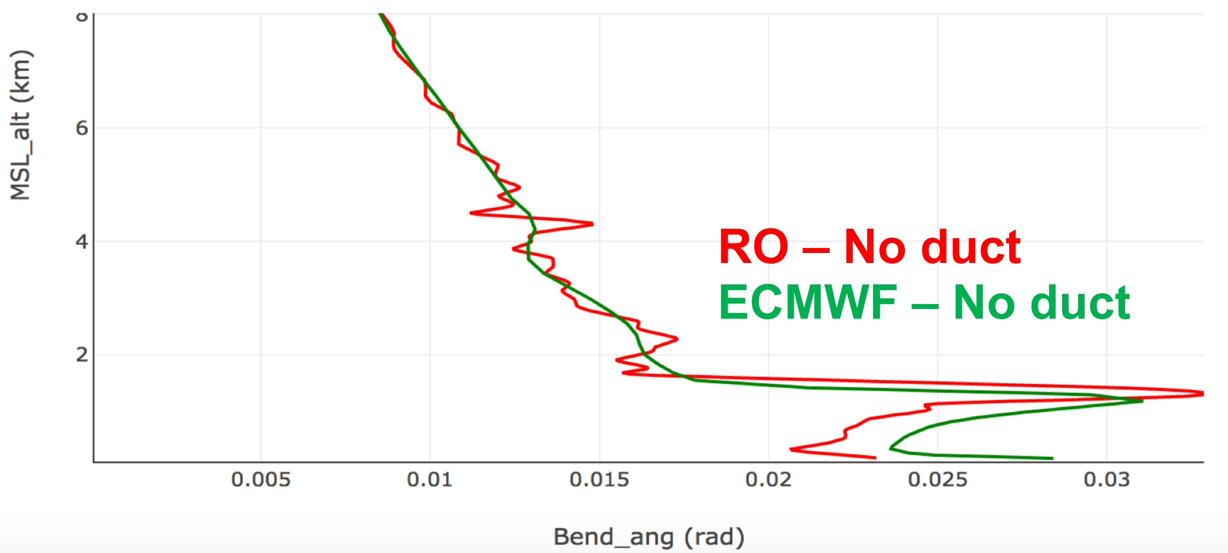
1) **spectrogram of RO signal down-converted with the 1st guess model**
2) **difference between the 1st guess and receiver models**
3) **BA profiles from C-2 RO and ECMWF**



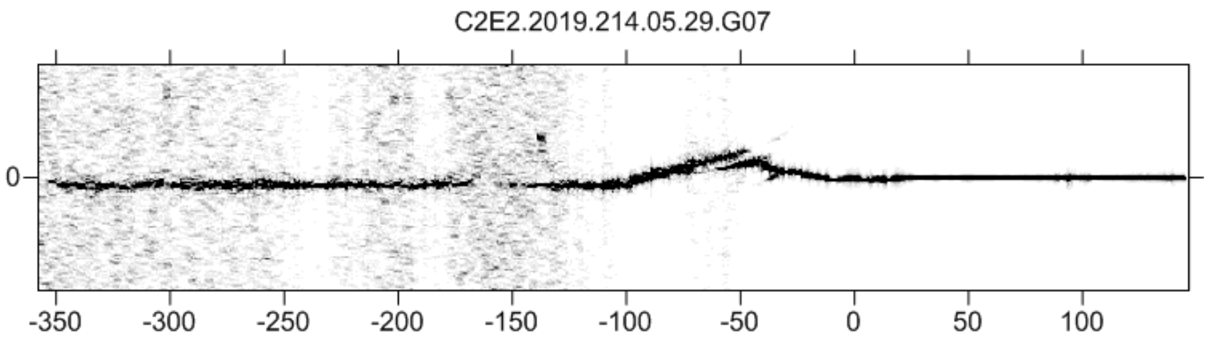
C2E2.2019.215.22.25.R05
0
-350 -300 -250 -200 -150 -100 -50 0 50 100

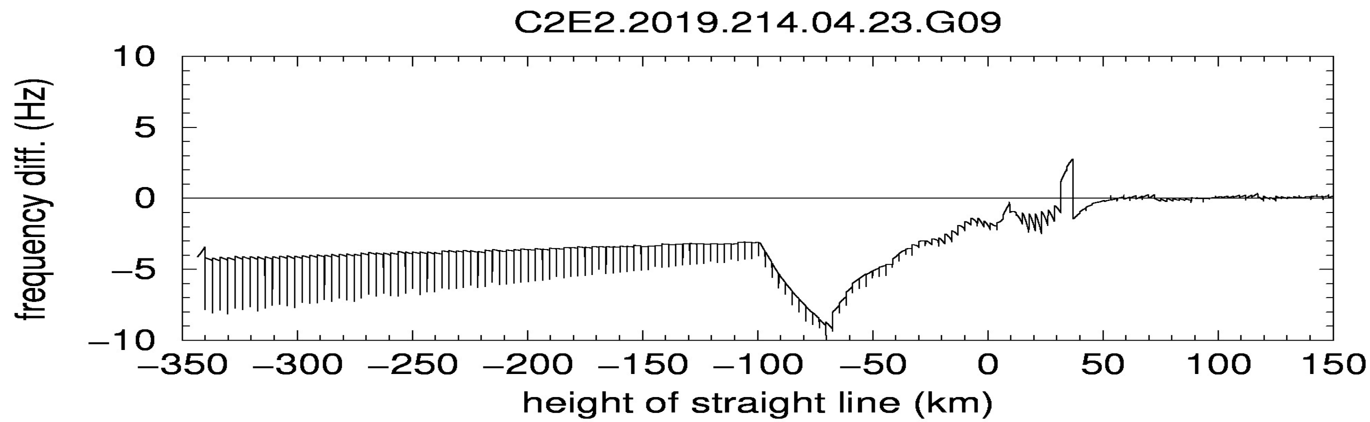


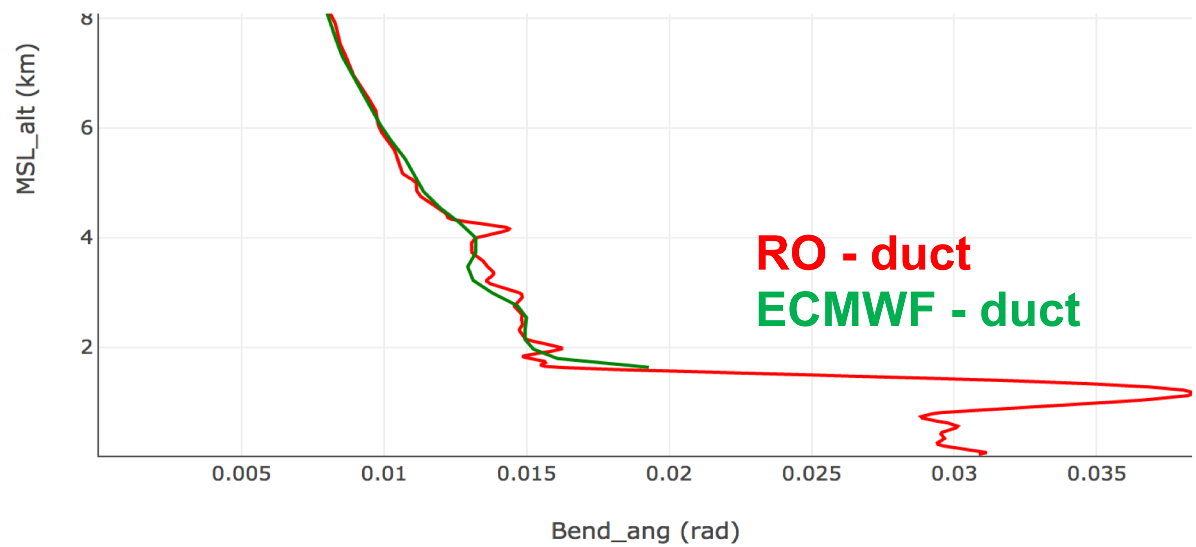
C2E2.2019.215.22.25.R05
frequency diff. (Hz)
10 5 0 −5 −10
−350 −300 −250 −200 −150 −100 −50 0 50 100 150
height of straight line (km)

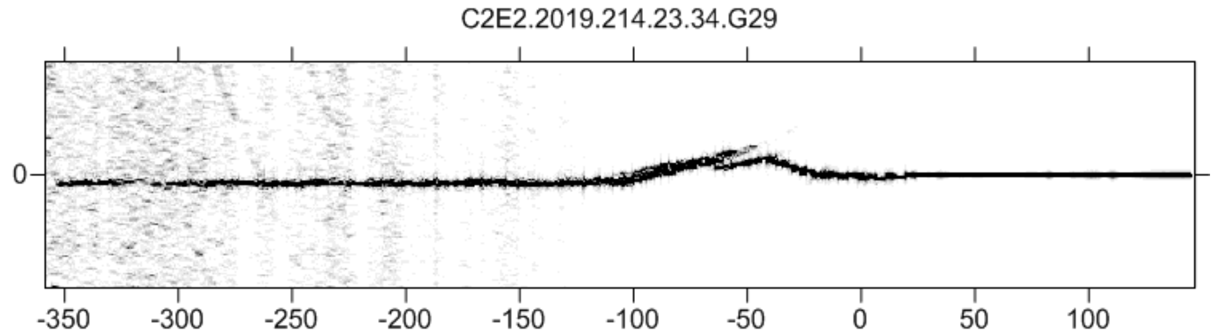


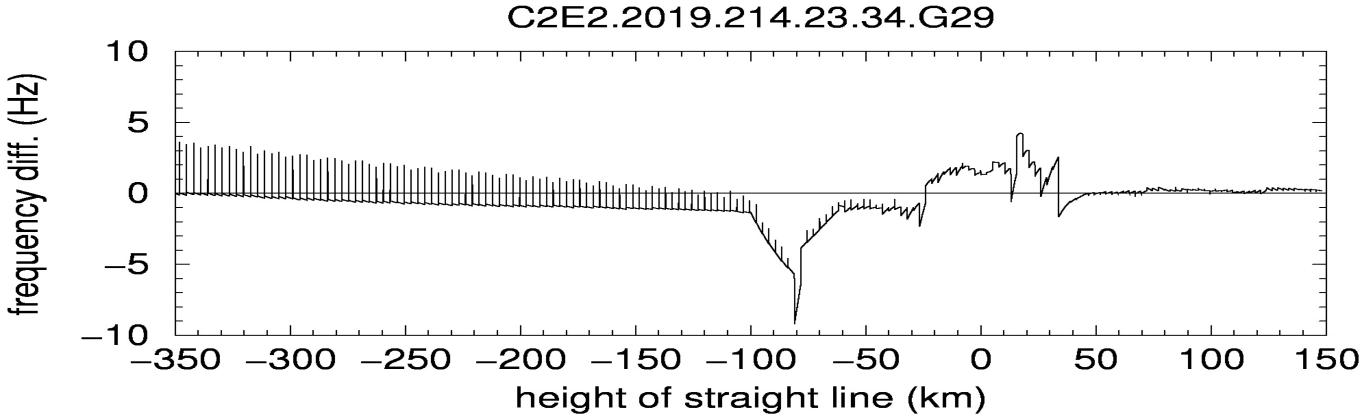
MSL_alt (km)
8 6 4 2
0.005 0.01 0.015 0.02 0.025 0.03
Bend_ang (rad)
RO – No duct
ECMWF – No duct

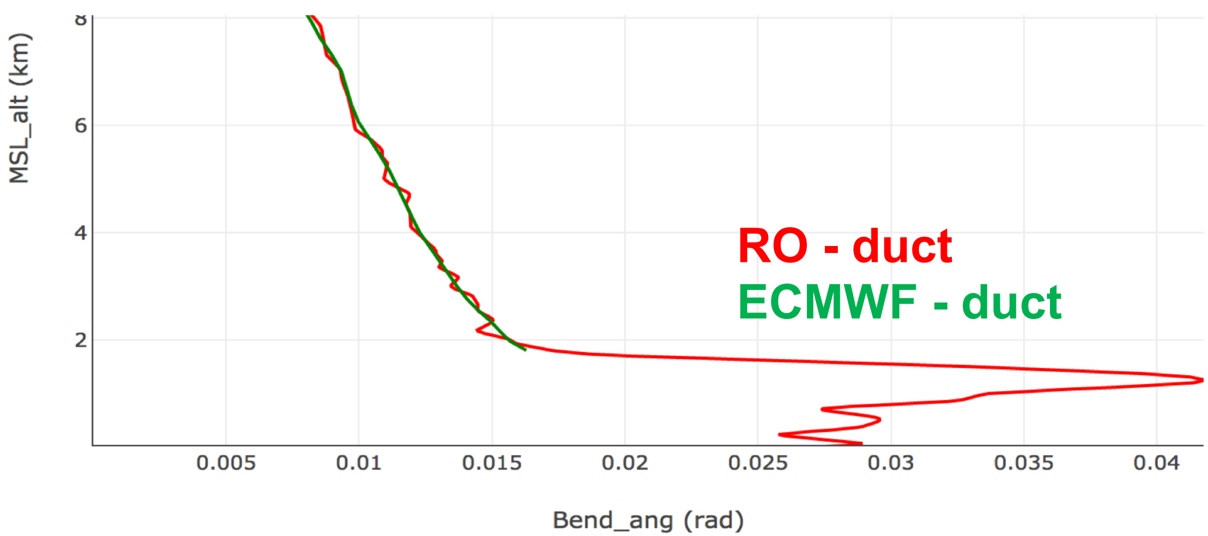

C2E2.2019.214.05.29.G07
0
-350 -300 -250 -200 -150 -100 -50 0 50 100

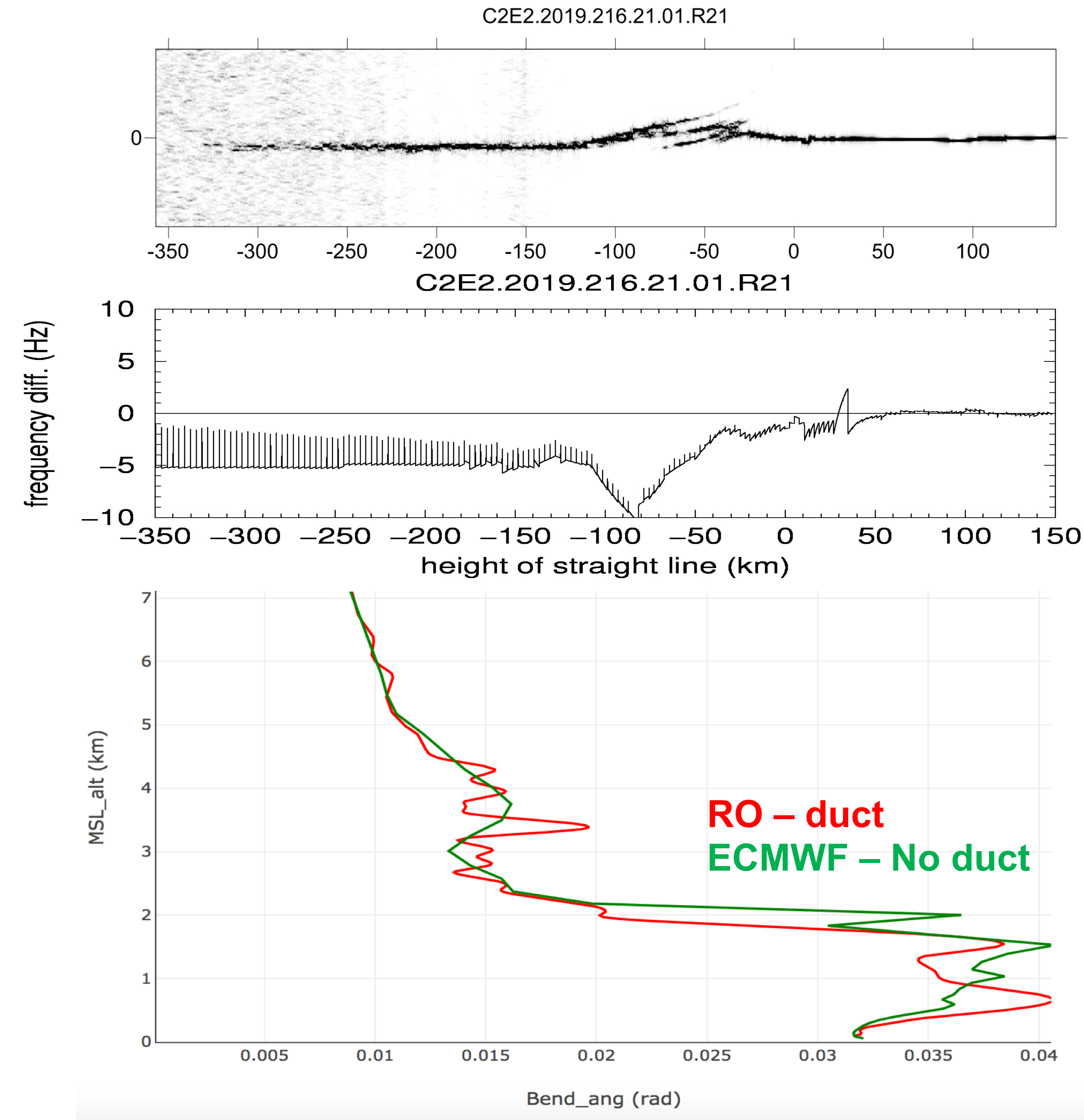

C2E2.2019.214.04.23.G09
frequency diff. (Hz)
10 5 0 −5 −10
−350 −300 −250 −200 −150 −100 −50 0 50 100 150
height of straight line (km)


MSL_alt (km)
8 6 4 2
0.005 0.01 0.015 0.02 0.025 0.03 0.035
Bend_ang (rad)
RO - duct
ECMWF - duct


C2E2.2019.214.23.34.G29
0
-350
-300
-250
-200
-150
-100
-50
0
50
100


C2E2.2019.214.23.34.G29
frequency diff. (Hz)
10
5
0
−5
−10
−350
−300
−250
−200
−150
−100
−50
0
50
100
150
height of straight line (km)

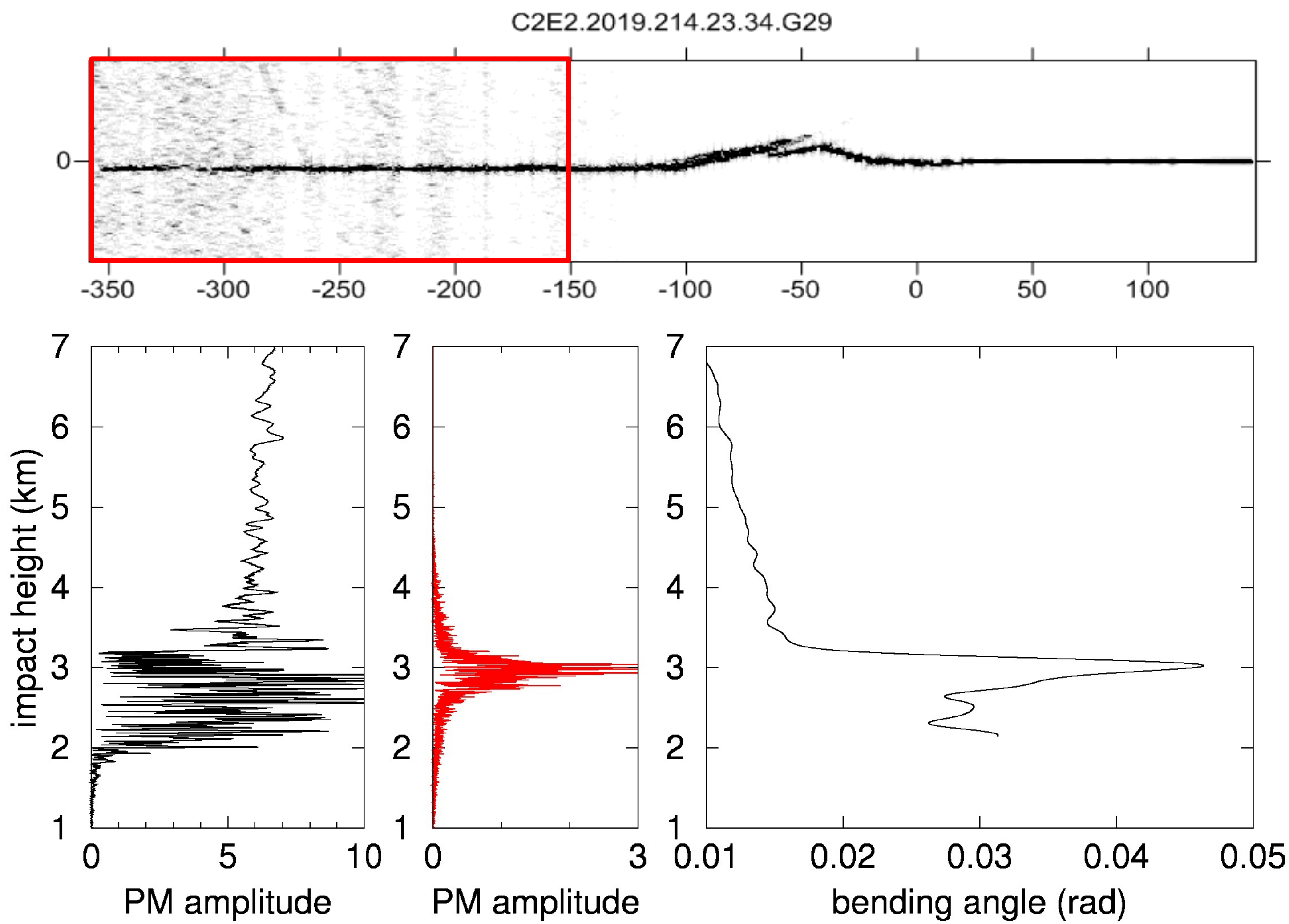

MSL_alt (km)
8
6
4
2
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
Bend_ang (rad)
RO - duct
ECMWF - duct



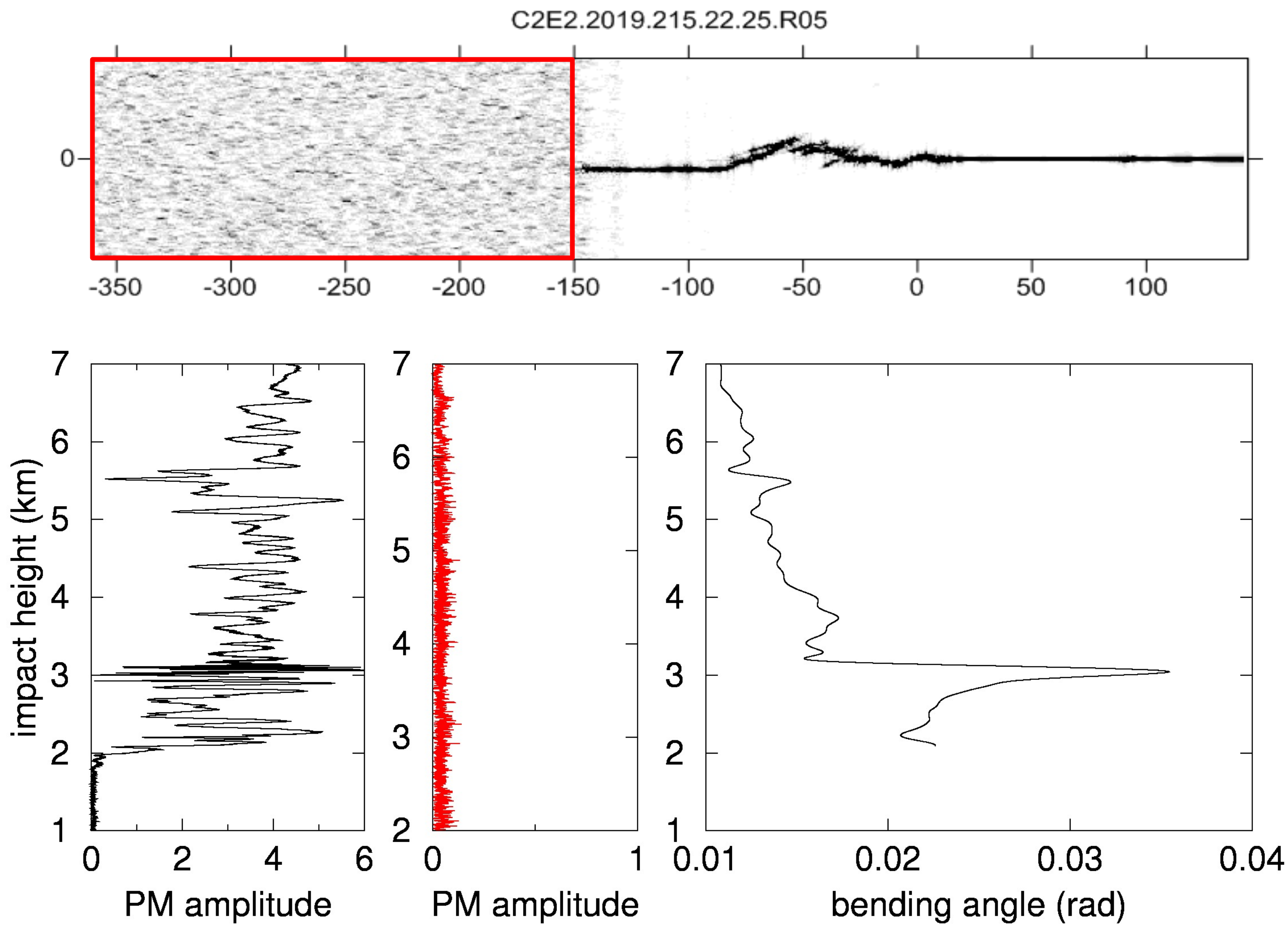
C2E2.2019.216.21.01.R21
0
-350 -300 -250 -200 -150 -100 -50 0 50 100
C2E2.2019.216.21.01.R21
frequency diff. (Hz)
10 5 0 −5 −10
−350 −300 −250 −200 −150 −100 −50 0 50 100 150
height of straight line (km)
MSL_alt (km)
0 1 2 3 4 5 6 7
0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04
Bend_ang (rad)
RO – duct
ECMWF – No duct

How do we know from what impact height the deep signal is arriving?

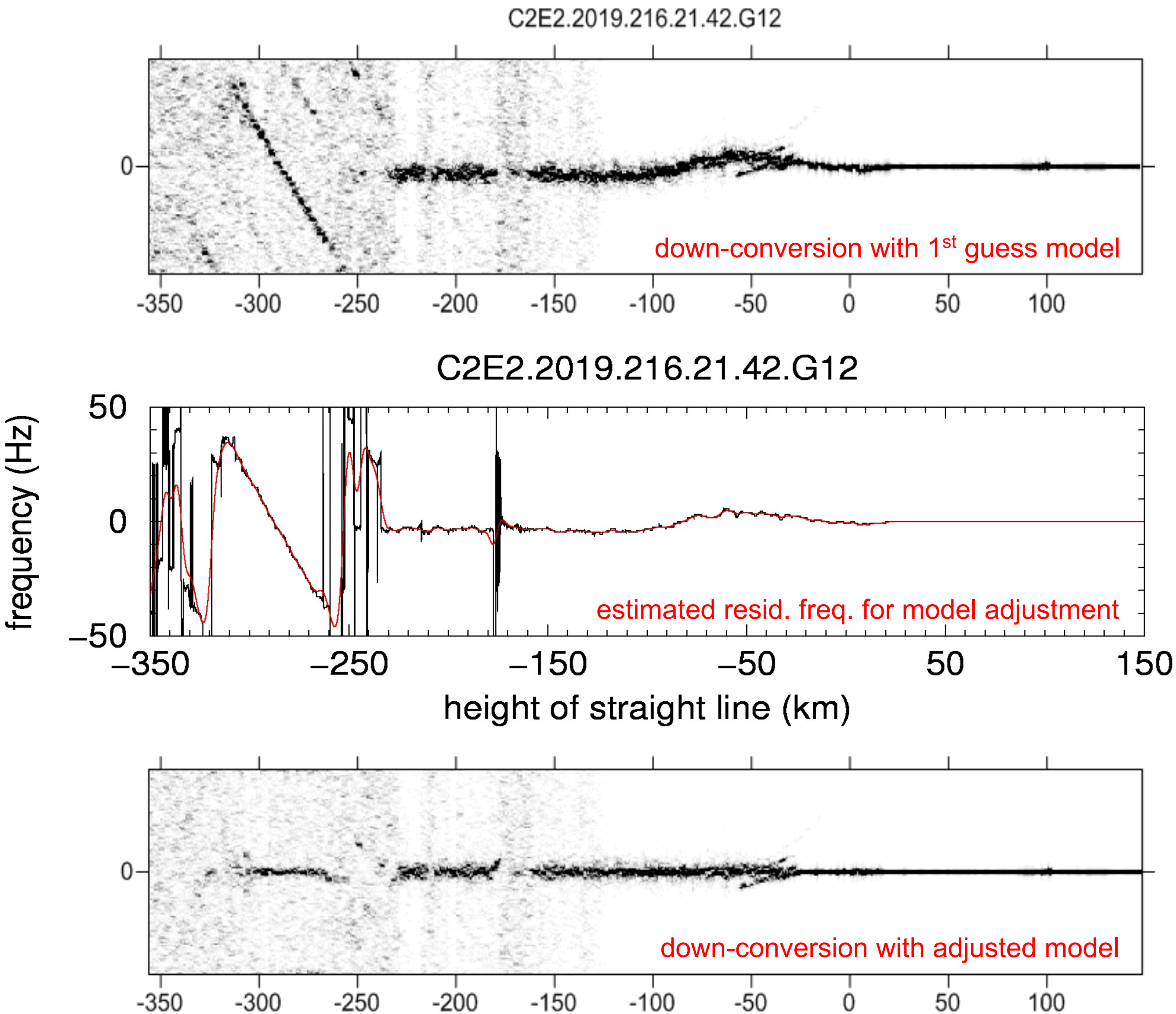
This follows from the distribution of the amplitude after applying WO transform for only part of RO signal below -150 km.
Maximum of amplitude points to strong inversion layer.



Same test for the occultation with strong inversion layer, but no deep signal



Possible cross-PRN interference of GPS signals must be taken into account in analysis of deep signals. Should not exist for GLONASS due to FDMA.



Summary

COSMIC-2 performs as expected in LT in terms of the bias, rms deviation, penetration, and their dependence on SNR

Biases in the LT are reduced (but not eliminated) with the increase of SNR

There is no noticeable difference in LT between GPS and GLONASS occultations

A pre-processor which makes retrieved BA model-independent and provides additional noise reduction has been tested

Ducts are found to be detectable for setting occultations with high SNR

In most, but not all cases ducts detected by RO are also reproduced by ECMWF.