Updates on the neutral atmosphere inversion algorithms at CDAAC

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Outline

- Phase matching (analysis of the phase function; stationary point)
- Definition of Lat Lon of TP 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)

**Under development:**

- 2nd order ionospheric correction
- Detection of SR (for high-SNR COSMIC-2 data)
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.

**Common approach**: FFT-based WO transform; truncation based on fading of the amplitude.

**Alternative approach**: direct calculation of WO transform down to minimal impact height where a single pronounced stationary point exists.

Phase matching (Jensen et al., 2004): analysis of the structure of phase function; multiple truncation heights.
Statistical comparison of COSMIC BA to ECMWF with old and new processings

**new, less conservative truncation**

**new, more conservative truncation**

**old**

**difference new - old**

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).
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.

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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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, recommend 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.
Old processing: not all occultations are processed.

Below the height where raw $|L1-L2|$ Dopplers > threshold (6 cm / smp) 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.

Currently, L2C is not tracked in rising occs.

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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 currently, L2C is not tracked in rising occs.

METOP-A before 2013 firmware update

METOP-A after 2013 firmware update
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 (zE=100km, zF=300km). 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) Transition of mixed (3) BA to background in fixed interval 55 - 60 km

\[
\| \alpha_{obs} - c \alpha_{bgr}^\beta \| = \min \quad \| \ln \alpha_{obs} - c \ln \alpha_{bgr} - d \| = \min
\]

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

Feltz et al., 2014 (AMTD) found biases between COSMIC and METOP temperatures in the stratosphere. The biases were confirmed at CDAAC; substantially reduced after re-processing with static optimization.
Static BA initialization eliminates dependence of the weight of background on noise

stdv - standard deviation of BA from background between 60 and 80 km; mainly driven by the ionospheric residuals and receiver noise on both occulted and reference links

Old processing: dynamic BA initialization (optimization)

New processing: static BA initialization

40 - 60 N

stdv < 1 mcrad

40 - 60 N

stdv > 2 mcrad
Dynamic (individual for each occ.) BA error characterization

**In the stratosphere:** based on RMS fluctuation of raw LC Doppler in 1 s sliding window and calibration by stdv (at 60 - 80 km)

**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: \[ CP_1 = \frac{(P_1 - P_2)}{P_1} \]
an alternative definition: \[ CP_2 = \frac{P_1}{\text{SUM}(P)} \]

\[ CP_1 \text{ at } 5 \text{ km} \]

\[ \text{2012.092–094} \]
lat > $-30$ and lat < 30
lat > +60 or lat < -60

\[ \text{4261 Matches} \]

CP1 at 5 km
2nd order ionospheric correction of GPS RO for climate applications in the stratosphere

History:
- 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: found to be most sensitive to model electron density below F max

Options:
- model-dependent correction: ray-tracing through ionospheric model; bottom-side ionosphere & HmF2 must be well reproduced by the model
- model-independent correction: non-linear regression on L4=L1-L2 BA; regression coefficient does not depend on scaling factor, but depends on HmF2 and bottom-side structure; may substantially depend on horizontal gradients

Validation problems:
- direct validation: datasets for comparison do not exist
- indirect validation (by use of 11-year solar or diurnal cycle): residual ionospheric effects are mixed with the neutral atmospheric effects (climate trends or tides)

2nd order correction \( \sim C (L_{1BA} - L_{2BA})^2 \)
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

These heights correspond to the heights 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 ~ 1000 V/V
- for reliable detection should be ~ twice larger than the noise level (SNR ~ 2000 V/V)
- deep RO signals can be used as an indicator of ducting (causes N-bias in Abel inversion)
Summary

New CDAAC inversion software is completed, but certain processing steps can be further modified
- calculation of lat. & lon.
- output of multiple truncation heights

Under development: an automated analysis of spectrograms aimed at:
- detection of deep RO signals (super-refraction flag)
- detection of interfering signals (cross-PRN tracks)
- detection of reflected signals

Plan to update UCAR BUFR products on GTS
- UCAR will provide test dataset (2-months) of BUFR products to NWPCs
- update COSMIC GTS products once NWPCs approve the test dataset

UCAR plans to make full re-processed COSMIC datasets available shortly