Carrier Phase and Bending Angle Noise in CHAMP, GRACE, COSMIC and GRAS data

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Outline

- Bending angle noise
- Upper level noise statistics for CHAMP, GRACE, COSMIC, and GRAS
- Noise < 1 μrad – what’s it good for?
- A CHAMP mystery
- Summary and outlook
- constant noise floor at high altitudes (receiver noise and residual ionospheric noise)
- varies considerably between occultations
...typically dealt with in RO refractivity retrievals by a “Statistical Optimisation”:

- estimate of upper level bending noise
- “optimized” bending angle profile as a result of a statistical optimal combination of (noisy) measurements and (smooth) “climatological values”
- Smoothed profile depends on noise characteristics of the observations

Originally proposed by Sergey (1996); there’s also a paper by Hocke et al. (1997), and some additional refinements by Healy (2000)

Work has been done to improve selection of “climatological values”, e.g. search for best matching profiles or n-parameter scalings / fits

There are other methods as well (like fitting an exponential to observations and extrapolating high up)
Upper Level Bending Angle Noise (cont’d)

Results on noise will strongly depend on details of processing (smoothing etc.) - thus:

- apply identical processing to different unsmoothed excess phase data sets to compare actual measurements (instead of processing software)

Simple, but robust method to estimate upper level noise floor of bending angles:

- calculate stddev (and bias) of \((\alpha - \alpha_{\text{Clim}})\) in a sliding window
  - 7.5 km width
  - between 60 and 80 km impact altitude
  - minimum value as noise / bias estimate for individual profile
- basically Sergey’s old QC criterion
- works well as heuristic method for simple NWP / 1DVar error estimates
In this study:

- 4 weeks (30 Sep – 27 Oct 2007) of excess phase data (atmPhs) as provided by UCAR for
  - CHAMP (4155)
  - GRACE (3868)
  - COSMIC (52576)
  - GRAS (16763, but pre-processed by ourselves)
- GO retrieval from excess phases with identical processing options (w/ GRAS prototype)
- Note that there are different pre-processing options applied:
  - CHAMP, COSMIC: single differencing
  - GRACE(?), GRAS: zero differencing
Upper Level Bending Angle Noise (cont’d)

- GRAS within its requirements (max absolute error < 1 μrad, or \( \sigma < 0.67 \) μrad)
- GRACE and COSMIC are comparable (really zero-differencing?)
- GRAS/COSMIC difference also due to high gain antenna and USO
- CHAMP is a bit odd – more on that later...
SNR Distribution

CHAMP SNR

GRACE SNR

COSMIC SNR

GRAS SNR
In a variational retrieval (1DVar), we minimise

\[ J(x) = \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}(y_0 - H[x])^T (E + F)^{-1}(y_0 - H[x]) \]

The solution can be written as

\[ \hat{x} = \left( H'^T (E + F)^{-1} H' + B^{-1} \right)^{-1} \left( H'^T (E + F)^{-1} y_0 + B^{-1} x_b \right) \]

\[ \text{analysis} = \text{weighted sum of} \quad \text{measurement} \quad \& \quad \text{a priori} \]

and it’s (inverse) error covariance as

\[ P^{-1} = B^{-1} + H'^T \left( E + F \right)^{-1} H' \]

\[ \text{analysis} \quad \text{a priori} \quad \text{measurement} \]

\[ \text{accuracy} \quad \text{accuracy} \quad \text{accuracy} \]
Information is always relative - relative to what we already know, i.e. the *a priori*.

The error covariance of the retrieval can also be written as

\[
P = B - BH^T \left( HBH^T + E + F \right)^{-1} HB
\]

i.e. the retrieval’s error is at least as small as (or smaller than) the *a priori’s* error (if all error covariances are correct, unbiased, etc.)

- A simple measure of how much information is contained in a remote sensing measurement is the amount of error reduction obtained in the retrieval.
Information Content (cont’d)

- ECMWF operational first guess errors & vertical correlations + error growth model + inflation (x 3) above 5 hPa
- Bending angle errors simplified, modelled after Kursinski (and similar to those used at ECMWF)
1DVar (cont’d)

Observations:
- Thinned bending angle profile (same levels as thinned operational product)
- Error covariance
  - No vertical error correlations
  - Simple error model (Healy, based on Kursinsky, 1997)

QC:
- Level 1a ok
- Occultation > 15 sec
- BGQC (10 sigma)
- Reduced upper level noise
  - extends the vertical range where radio occultation data are useful (e.g. in NWP)
  - allows bias correction anchoring even higher up
  - less climatology in mid stratospheric altitudes (good for temperature trend estimation)
  - better vertical resolution (GWs!)
Vertical bars denote Post-EPS breakthrough temperature requirements for
- global NWP (red, dashed)
- climate monitoring (orange, solid; same as NWP below 32 km / 10 hPa)

Within Post-EPS, the following performance level definitions are often used:

- **Threshold:**
  - minimum performance level useful for a particular application

- **Breakthrough:**
  - would give a significant delta impact on the targeted user service
  - would justify new instrument developments

- **Objective:**
  - level beyond which any improvement does not bring a clear advantage in a cost effective way
- Vertical bars denote Post-EPS breakthrough temperature requirements for
  - global NWP (red, dashed)
  - climate monitoring (orange, solid; same as NWP below 32 km / 10 hPa)

Upper Level Bending Angle Noise (again)

- That's large.
- In the early days of CHAMP, we were thinking of ~ 3 μrad
- What has happened?
CHAMP Noise Over the Years

- CHAMP sank deeper into the atmosphere; more ionospheric perturbations?
- Firmware changes?
A thought experiment:

- We do a traditional refractivity (& dry temperature) retrieval in the stratosphere.
- As measurement noise increases, the role / contribution of the a priori in the statistical optimisation increases.
- We use a simple climatology (MSIS, CIRA) – which is known to be biased warm against the present climate (SPARC, 2001).
- So as noise increases, we’ll introduce a height dependent positive trend.

- I do not claim that this actually happens. I do claim that we need to demonstrate that this is not a problem.
- This is not a problem of the measurement itself. It is problem of the processing towards higher data levels.
Thanks!
Relevance for non-variational retrievals

Dry scenario:
- extrapolate ECMWF refractivity exponentially to calculate bending angle for statistical optimisation (Sokolovsky & Hunt, 1996)
- initialise hydrostatic equation with ECMWF @ 64 km

1DVar scenario (with a few more levels, still using q):
- forward model ECMWF to bending angle, extrapolating background exponentially above model top
- errors: \( \Delta \alpha = 0.01 \, \mu\text{rad} \)
  \( \Delta T(z_{\text{top}}) = 0.01 \, \text{K} \)
  \( \Delta T(\text{elsewhere}) = 20 \, \text{K} \)
Bending angle based 1DVar:

- **obs errors:**
  \[ \Delta \alpha = 0.1 \ \mu \text{rad} \]

- **bg error:**
  \[ \Delta T(z_{\text{top}}) = 0.01 \ \text{K} \]
  \[ \Delta T(\text{elsewhere}) = 20 \ \text{K} \]
Result suggests:

- dry temperature retrieval is equivalent to a 1DVar with certain error specifications, in particular
  - bg errors too large (apart from uppermost level, where it’s too small)
  - obs errors too small

Information content results transferrable, with:

- dry temperature errors likely to be larger than 1DVar errors with (more or less) realistic error assumptions, i.e. 1K altitudes lower.