OPAC-1 International Workshop
Graz, Austria, September 16 – 20, 2002

Advancement of GNSS Radio Occultation Retrieval in the Upper Stratosphere

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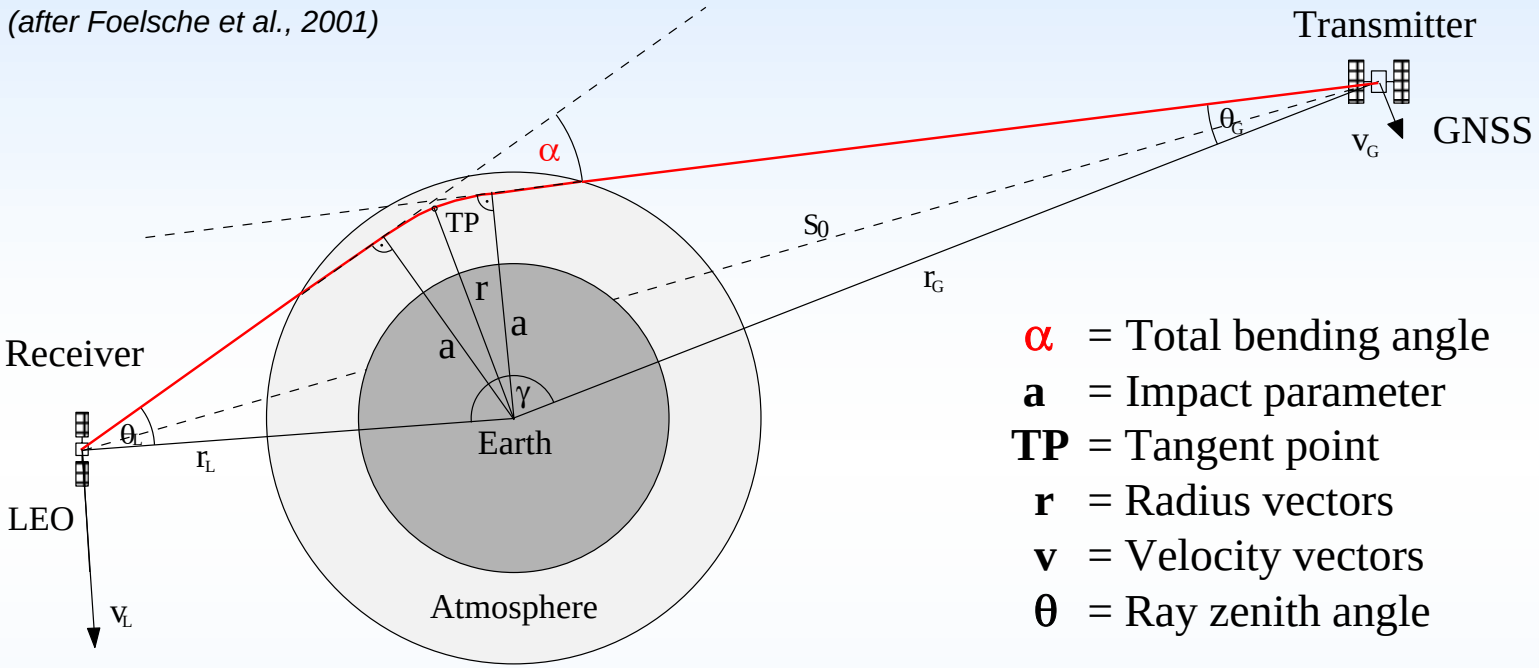
Outline

- Radio Occultation (RO) – overview
- RO-based climatologies
- Stratospheric RO retrieval
- Stratospheric retrieval validation study
- Advancing upper stratospheric retrieval / background bias correction
- Results
- Summary, conclusions, and outlook

Radio Occultation Overview



α = Total bending angle
a = Impact parameter
TP = Tangent point
r = Radius vectors
v = Velocity vectors
θ = Ray zenith angle

- **Transmitter:** Global Navigation Satellite System (GNSS); GPS, GLONASS, GALILEO
- **Signal:** L – Band (GPS: L1, f_1=1575.4 MHz; L2, f_2=1227.6 MHz)
- **Receiver** on Low Earth Orbit (LEO)
- **Primary observable:** Phase delay *L*

$$L = \int_{GNSS}^{LEO} n \, ds - S_0$$

Utility for Climate Monitoring

- **Global coverage**
  - Equal observation density above oceans and land
  - Equal observation density in northern and southern hemisphere
- **All weather capability**
  - Virtual insensitive to clouds and aerosols due to long wavelengths
- **High accuracy and vertical resolution**
  - Temperature error < 1 K at ~1 km resolution
- **Long-term stability (intrinsic self-calibration)**
  - Expected temperature drift < 0.1 K/decade

Realization of RO Climatologies

First opportunity for real RO climatology: CHAMP (and SAC-C)

- Continuously >150 occultation events per day
- First retrieval results encouraging (error <1 K in ~12 – 25 km interval), but bias above ~25 km
- Sampling error allows large-scale climatologies (>1000 km horizontal scale)
- Data may be complemented by SAC-C and GRACE in near future → up to 1000 occultation events per day
- Further future perspectives: METOP/GRAS, COSMIC, ACE+, . . .

Realization of CHAMPCLIM

- Background-independent via statistical interpolation and averaging
- Weakly background-dependent but higher resolved via data assimilation
  - 3DVAR assimilation
  - Background: ECMWF analysis
  - Result: global climate analyses, high-vertical/low-horiz. resolution (T21L60)

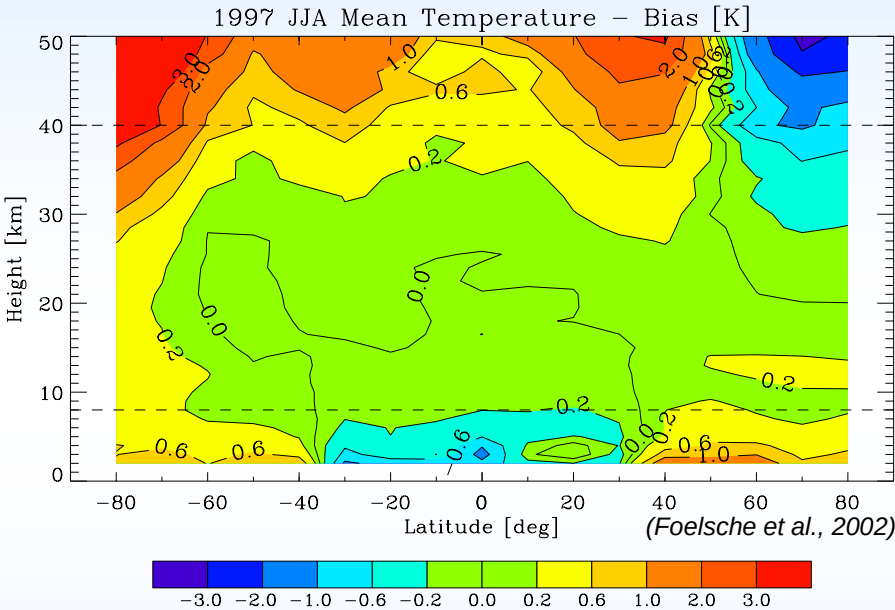
Advancement of GNSS RO Retrieval in the Upper Stratosphere

GNSS-CLIMATCH – First Results

"Testbed" Performance Analysis (JJA 1997)

GNSS-CLIMATCH Objective:
Investigation of climate change detection capability of RO-based climate monitoring systems

Method:
25 year end-to-end simulation study



Dry temperature bias [K]

Testbed setup:

- ~1000 occ. events/season (from >20000)
- Separation into 17 latitude bins (50-60 events each)
- Calculation of bias, standard deviation, sampling error, total climatological error

Results:

- Encouraging performance in the core region (bias < 0.2 K in most parts)
- high-latitude winter areas most challenging
- Error increases rapidly above ~35 km

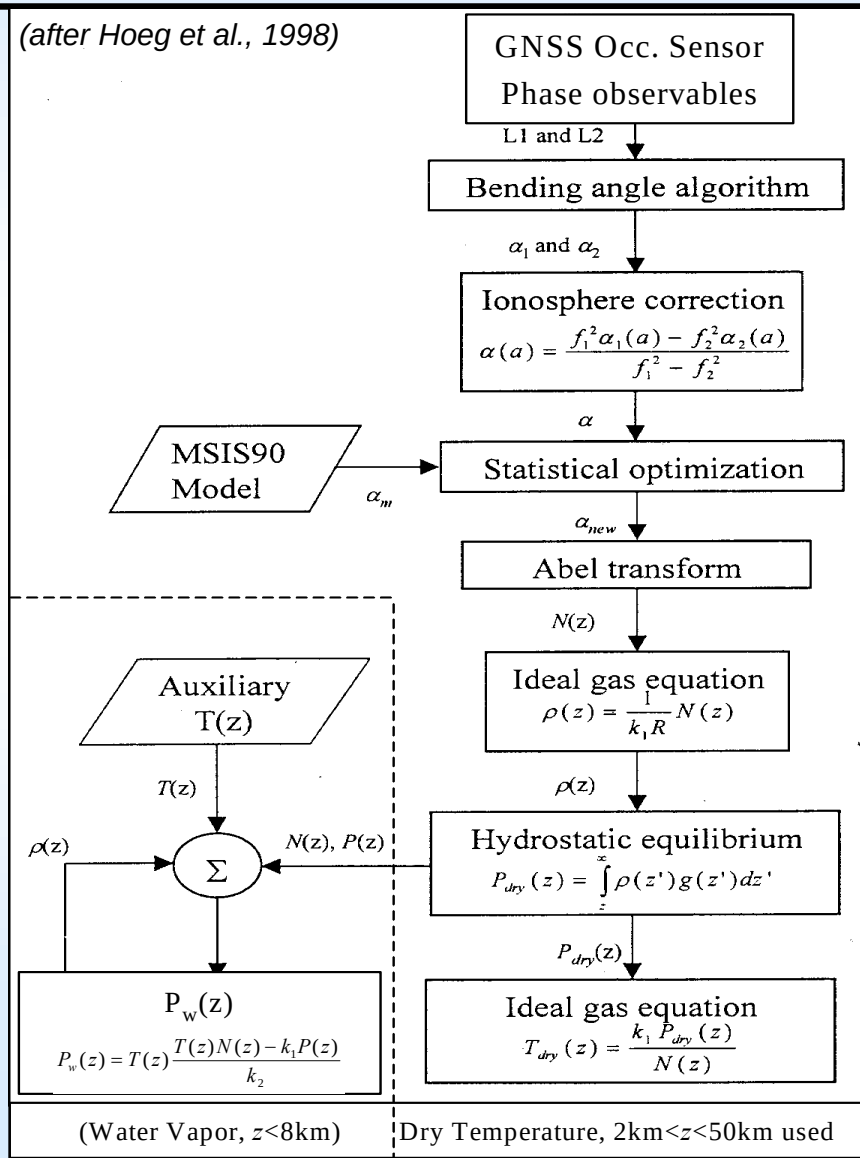
RO Retrieval Overview

- Primary observable: L1, L2 phase delay
- Bending angle via Doppler shift
- Ionospheric correction & statistical optimization
- Refractivity via inverse Abel transform
- Density, pressure, temperature, geopotential height via ideal gas equation and hydrostatic equilibrium
- Troposphere: Temperature & humidity via a priori information.

Inverse Abel transform:

$$N(a) = \exp\left[\frac{1}{\pi}\int_a^\infty \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} da'\right]$$

→ **high altitude errors propagate downwards**



Ionospheric Correction

FACTS

- RO signal is dominated by ionosphere above ~45 km
- Ionosphere is dispersive → First order correction by linear combination of L1 and L2 phase delays or bending angles possible
- Linear combination of bending angles accounts for different L1 and L2 ray-paths → Better results.

$$\alpha_{LC}(a) = \frac{f_1^2 \alpha_1(a) - f_2^2 \alpha_2(a)}{f_1^2 - f_2^2}$$

"linear correction of bending angles"

(Vorob'ev and Krasil'nikova, 1994)

PROBLEMS

- Higher order terms cause residual ionospheric errors
- Linear correction of bending angles relies on the assumption of spherical symmetry

→ QUESTIONS

- How good is the performance of the linear correction of bending angles under violation of the spherical symmetry assumption?
- How to deal with higher order residuals?

Statistical Optimization (1)

FACTS

- Ionospheric residuals and observation system errors can significantly degrade the retrieval results at heights above ~25 km
- Inverse Abel transform needs high-altitude initialization

"NO OPTIMISATION"

- select initialisation height at ~60km
- exponentially extrapolate

Drawback:

- extrapolation quality depends on noise in the data and on initial height selection
- isothermal atmosphere assumed above initialization height

STATISTICAL OPTIMISATION

- Use background data (climatology, analyses)
- Combine background and observation in an statistical optimal way

$$\alpha_{opt} = \alpha_b + (\mathbf{B}^{-1} + \mathbf{O}^{-1})^{-1}\mathbf{B}^{-1}(\alpha_o - \alpha_b)$$

$$\alpha_{opt}(a) = \alpha_b(a) + \frac{\sigma_b^2(a)}{\sigma_b^2(a) + \sigma_o^2(a)}\left(\alpha_o(a) - \alpha_b(a)\right)$$

(*Sokolovskiy and Hunt,* 1996)

Drawback:

- Stat. opt. approach assumes unbiased errors; background data are likely to be biased

Statistical Optimization (2)

Basic DMI/IGAM statistical optimization scheme

- **Background**

  Climatology: MSIS90, no NWP analyses (bias and “incest” problems)

  Global search in MSIS90 (45 - 65 km).

- **Definition of errors:**

  $\sigma_b(z) = 0.2\alpha_b(z)$

  σ_o estimated from observation at z > 70km

- **Vertically correlated errors:**

$$\mathbf{B}_{ij} = \sigma_i \sigma_j \exp\left(-\frac{(a_i - a_j)^2}{l^2}\right), \quad l = 6 \text{ km (correlation length)}$$ (*Healy, 2001*)

  Same for $\mathbf{O}_{ij}$, $l = 1$ km

Retrieval Validation – Study Setup (1)

Forward modeling

- **Ionosphere** (NeUoG):
  - 4 ionization levels (no ionosphere, $F_{10.7}$=70, $F_{10.7}$=140, $F_{10.7}$=210)
  - 3 ionospheric a/symmetry types (NICE, NASTY1, NASTY2)
- **Same neutral atmosphere for all occultation events**
- **Receiving system:**
  - idealized (no errors)
  - realistic (GRAS-type errors)

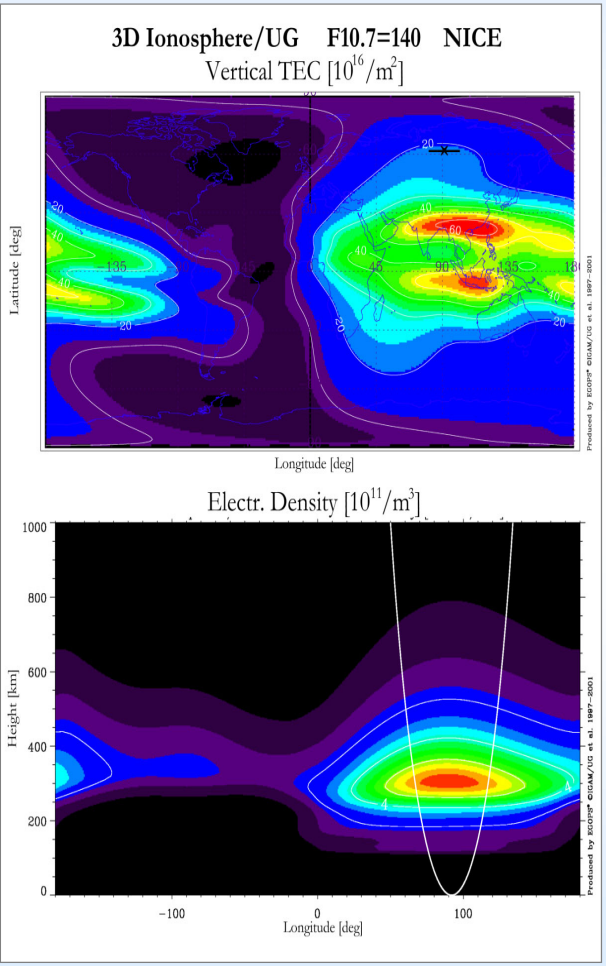
Retrieval schemes

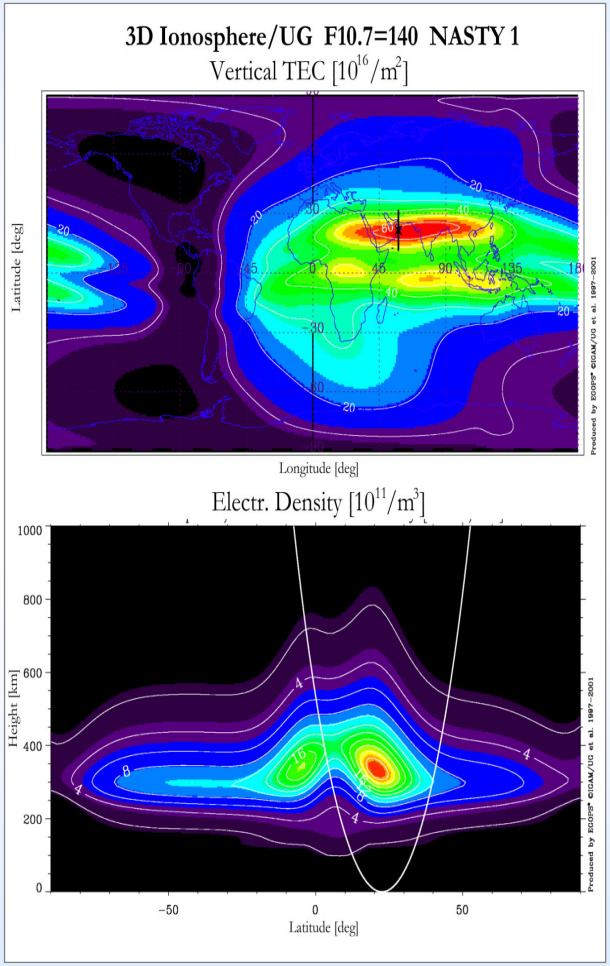
- **Ionospheric correction:**
  - linear combination of bending angles
- **Statistical optimization:**
  - no optimization (exponential extrapolation)
  - inverse covariance weighting optimization without background profile search in MSIS90)
  - inverse covariance weighting optimization with background profile search in MSIS90)

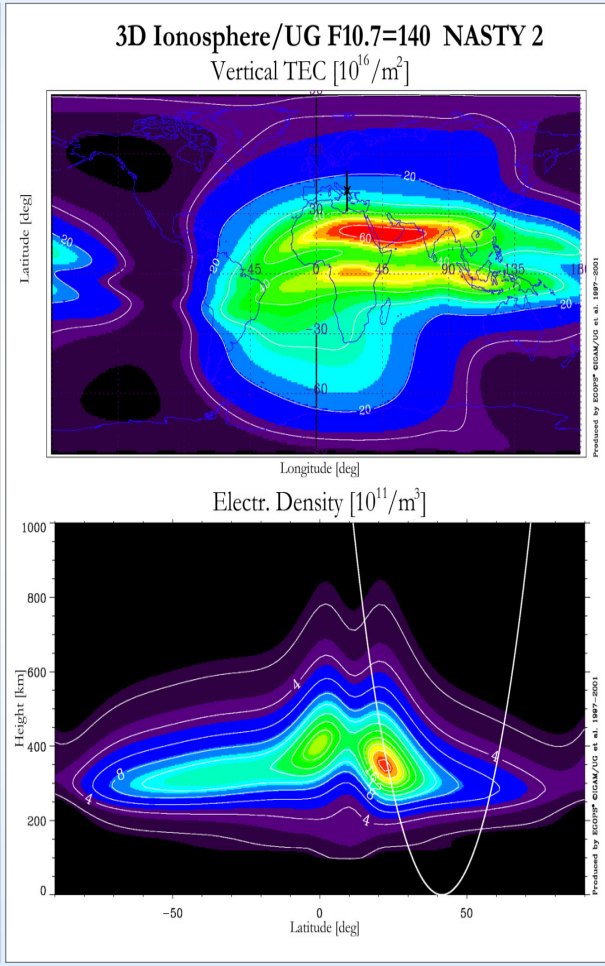
More information:

Gobiet, A., and G. Kirchengast, Sensitivity of atmospheric profiles retrieved from GNSS occultation data to ionospheric residual and high-altitude initialization errors, *Tech. Rep. ESA/ESTEC-1/2002,* 58p., IGAM/UniGraz, Austria, 2002.

Retrieval Validation – Study Setup (2)







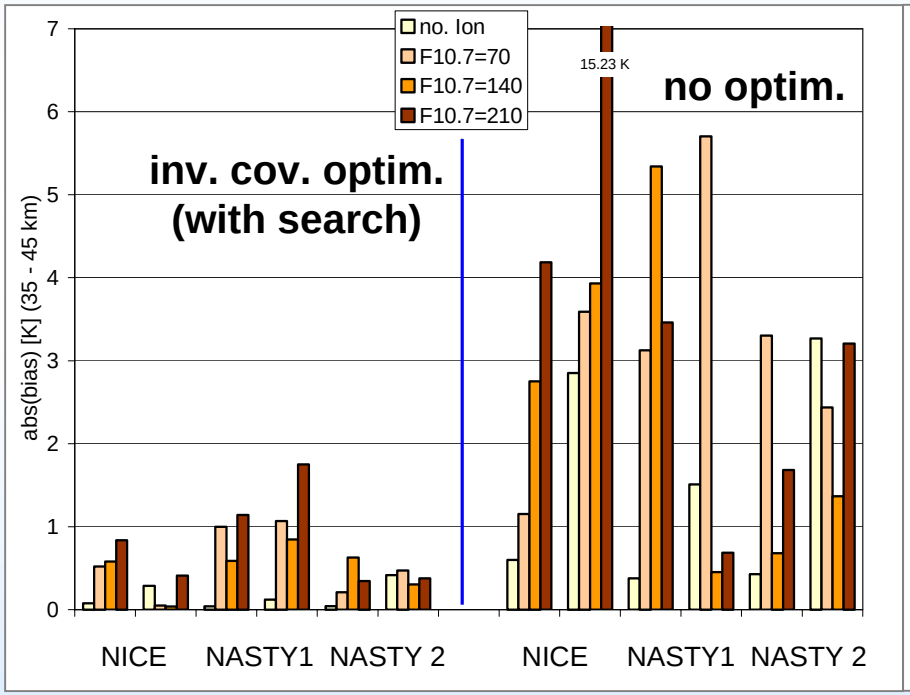
NICE: low electron dens. grad., near-spherical symmetry

NASTY1 & NASTY2: high electron density gradients, spherical symmetry assumption violated

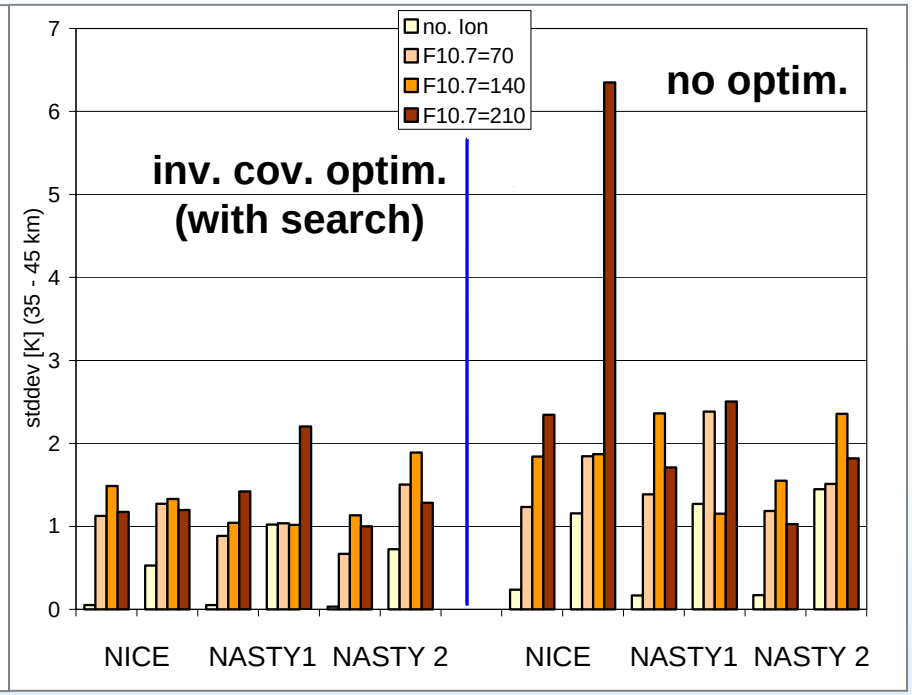
Retrieval Validation – Results (1)

Upper stratosphere temperature bias and standard deviation

(35 km – 45 km height interval)



bias (mean dev. from 'true') [K]

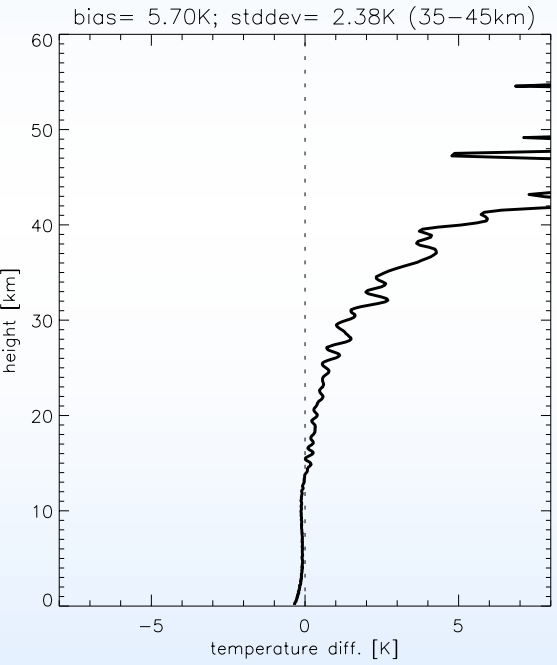


standard dev. (mean fluctuation about bias) [K]

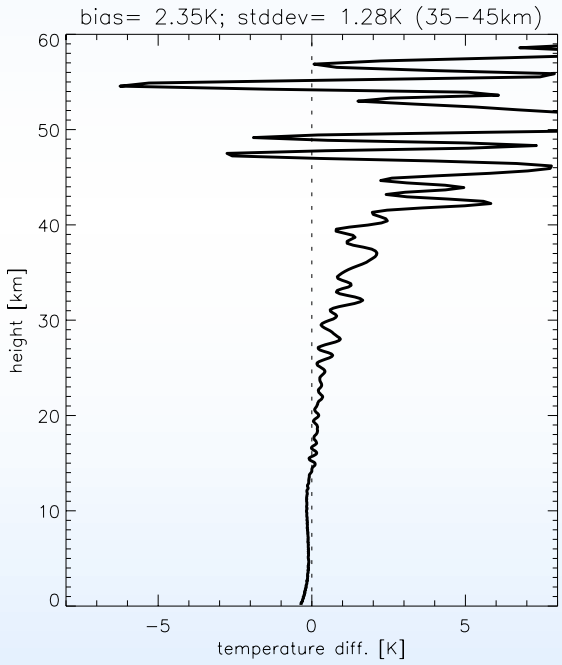
Retrieval Validation – Results (2)

Temperature error profiles [K]

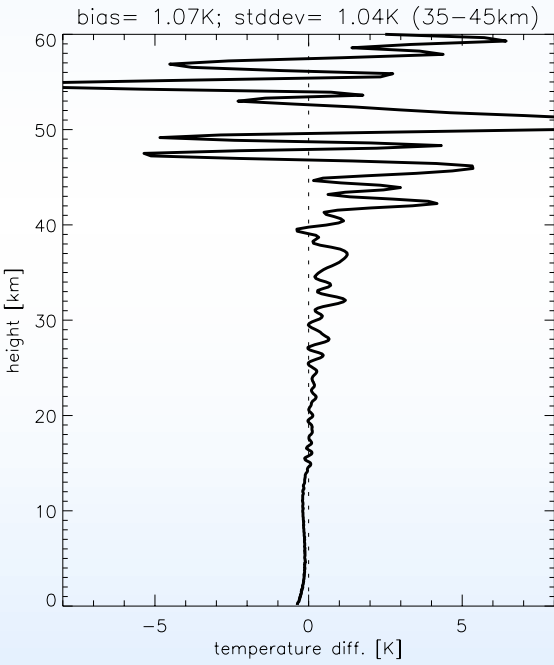
("Nasty 1" event, $F_{10.7}$ = 70, realistic receiving system)



no optimization



inverse covariance optim.
no background search



inverse covariance optim.
background search

Validation Results – Summary

- Ionospheric correction of bending angles is robust against extreme ionospheric conditions
- Statistical optimization is vital above ~25 km
- Statistical optimization is limited to bias-free observation and background errors but background errors are rather systematic than statistical
- In some regions no unbiased background profiles can be found in MSIS90 (high latitude winter)

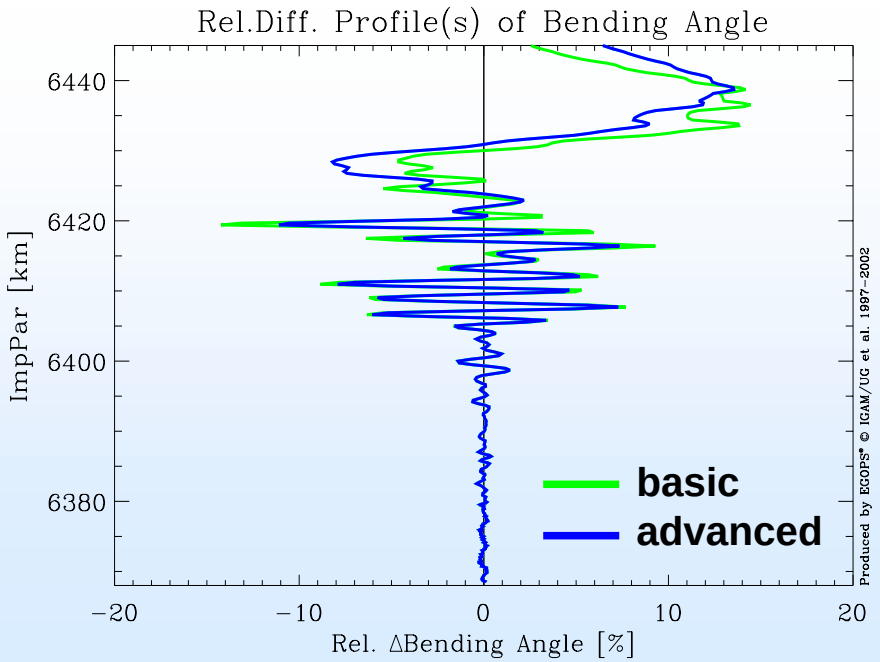
→ **advanced background bias correction**

Background Bias Correction

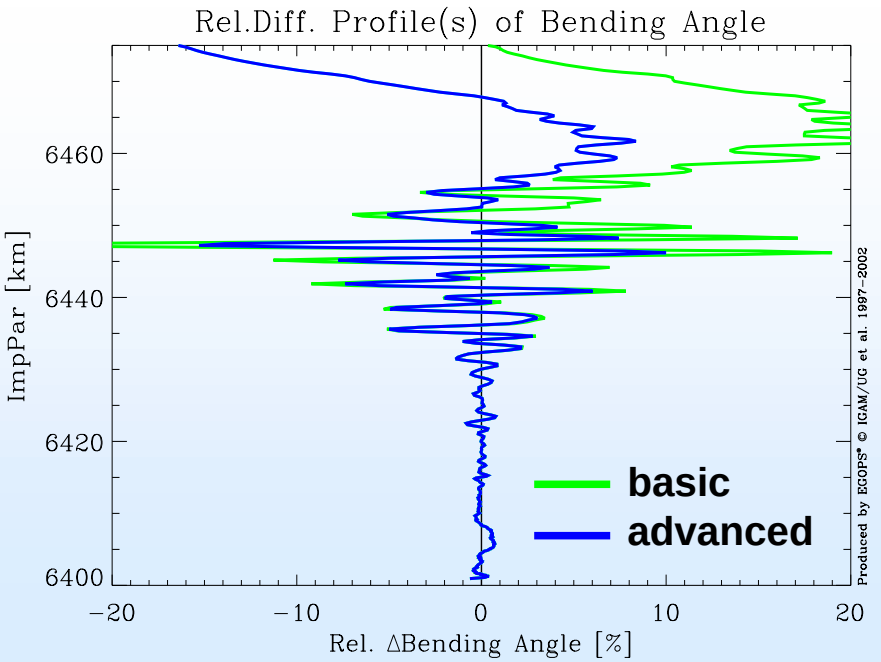
ENHANCED BACKGROUND BIAS CORRECTION SCHEME

- Optimization of the search algorithm by smoothing of observations
- Additional background bias correction by linearly fitting at high altitude
- Reduce background error to 15% (empirical evaluation preceded)
- Background: MSIS90

lat. = 13°S, bias correction: 0.2 %



lat. = 76°S, bias correction: 15.9 %



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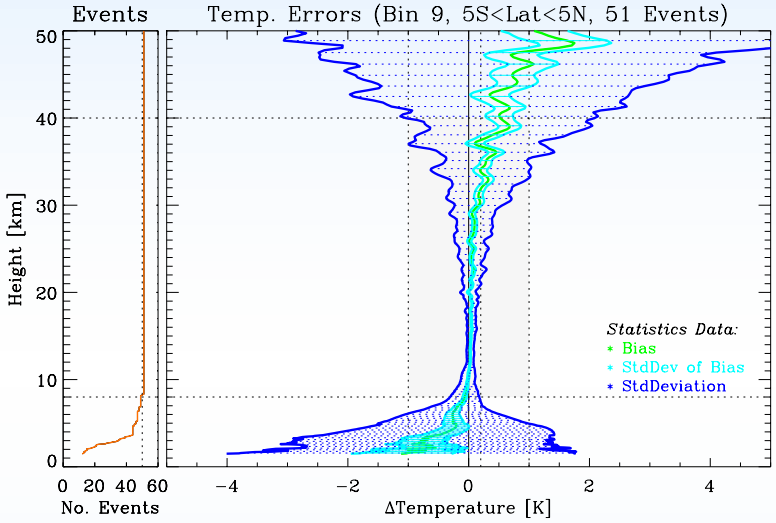
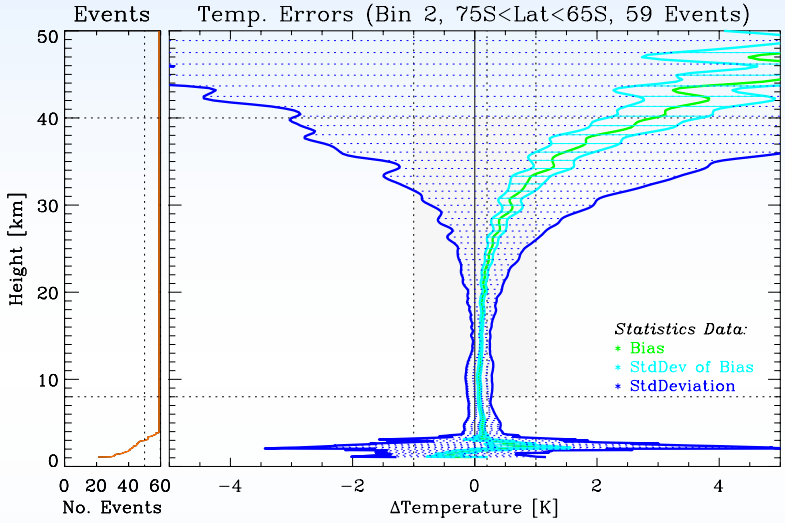
Background Bias Correction – Results (1)

Mean dry temperature error profiles [K]

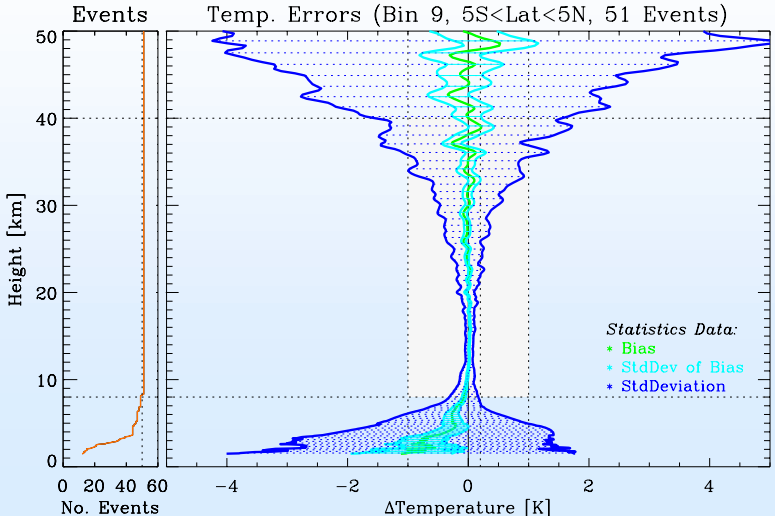
Equatorial **High lat.**

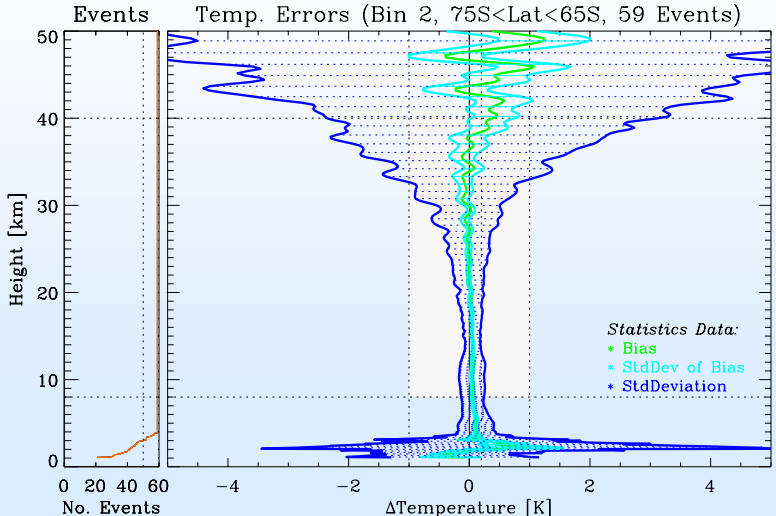
Basic retrieval





Enh. bias correction retrieval





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Background Bias Correction – Results (2)

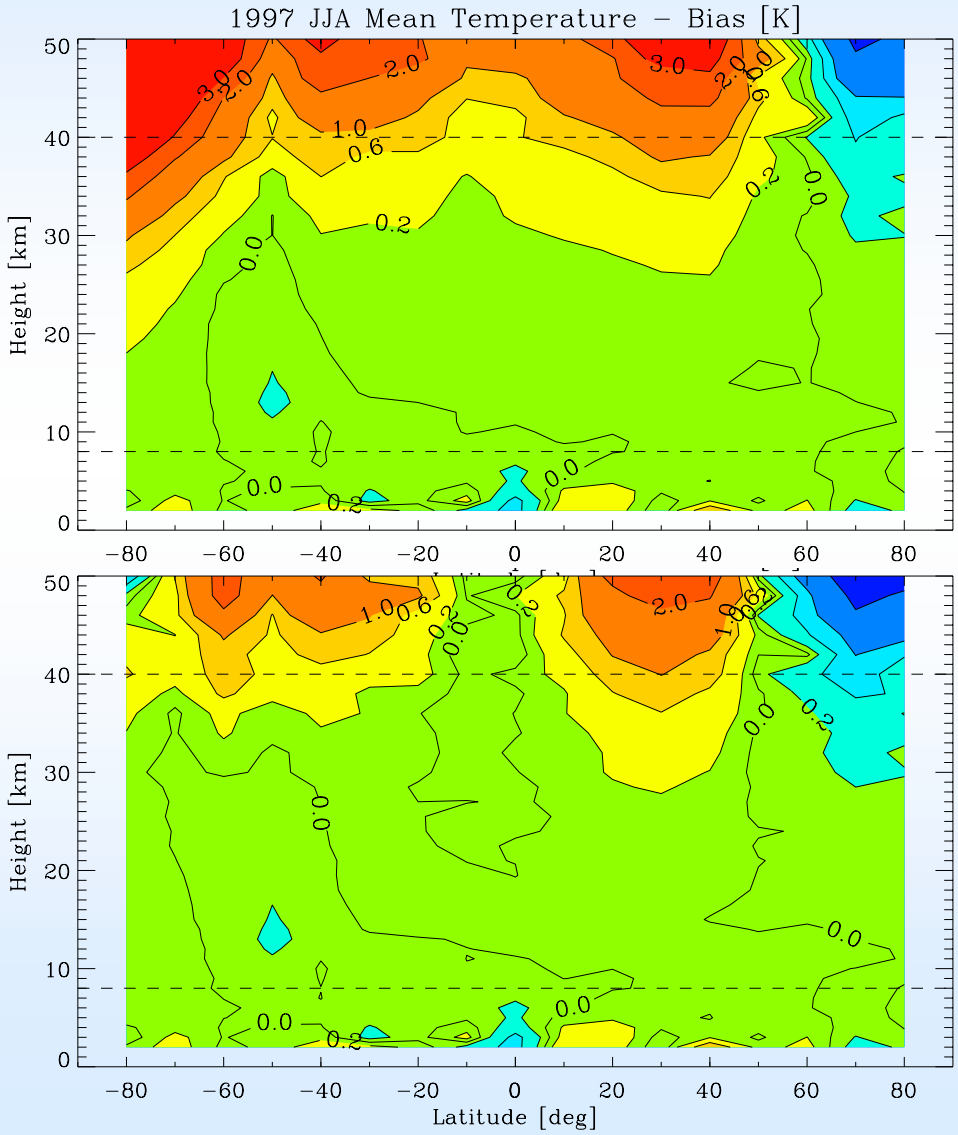
Basic retrieval →

Mean dry temperature bias

(GNSS-CLIMATCH “testbed” sample, ~1000 occultation events)

ΔT [K]

−3.0 −2.0 −1.0 −0.6 −0.2 0.0 0.2 0.6 1.0 2.0 3.0



Enhanced background → bias correction retrieval

Summary, Conclusions & Outlook

High altitude retrieval validation

- Statistical optimization is vital above ~25 km
- Ionospheric correction of bending angles is robust against extreme ionospheric conditions
- Most critical: Biases in background data

Enhanced background bias correction scheme

- Empirical background bias correction
- Very effective, especially in the so far most critical regions

Outlook

- Retrieval performance study based on CHAMP data
- Further retrieval development:
  - background & observation error definition
  - lower tropospheric retrieval
- First RO-based climatologies are on their way . . .