Progress (…) on forward modelling L1 and L2 bending angles

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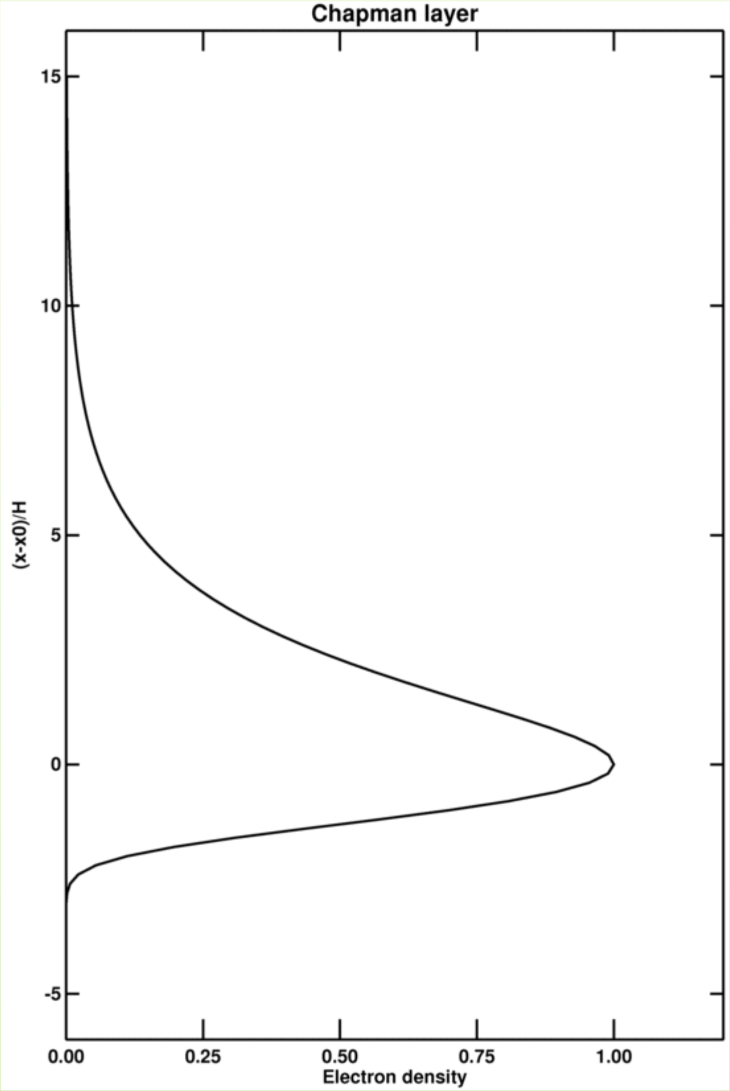
Motivation

- How to do ionospheric correction when L2 signal drops out?
- Different (better?) tropospheric retrievals if L1 and L2 both used?
- Some information on ionospheric parameters?
- Residual ionospheric error?

Model ionosphere: electron density



Single Chapman Layer (Chapman 1931)

$n_e(r) = n_e^{max} \exp[½(1 - u - e^{-u})]$,

where $u = (r - r_0) / H$.

3 parameters:

$n_e^{max} = TEC / \sqrt{(2\pi e)}\, H$

r_0 = peak height

H = *ionospheric* scale height

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Model ionosphere: bending angle

$$\alpha_{Li}(a) = -\,2a \int_a^\infty \mathrm{dlog}n/dx\; dx \,/\, \sqrt{(x^2 - a^2)}, \qquad x = nr$$

$$\approx (k_4 / f_{Li}^2)\; 2a \int_a^\infty dn_e/dx\; dx \,/\, \sqrt{(x^2 - a^2)}, \quad k_4 = 40.3\ \mathrm{m^3 s^{-2}}$$

$$\approx (k_4 / f_{Li}^2)\; 2a\, [2r_0 / (r_0 + a)^{3/2}] \int_a^\infty dn_e/dr\; dr \,/\, \sqrt{(r - a)}$$

$$= (k_4 / f_{Li}^2)\; n_e^{max}\, [4er_0^2 a^2 / H(r_0 + a)^3]^{1/2} \cdot Z(\ell)$$

where

$$\mathbf{Z(\ell) = \int_{-\ell}^\infty (e^{-u} - 1)\, \exp[\tfrac{1}{2}(1 - u - e^{-u})] \,/\, \sqrt{(u + \ell)}\;\; du}$$

is just a dimensionless, O(1) function of

$$\boldsymbol{\ell = (r_0 - a) / H}$$

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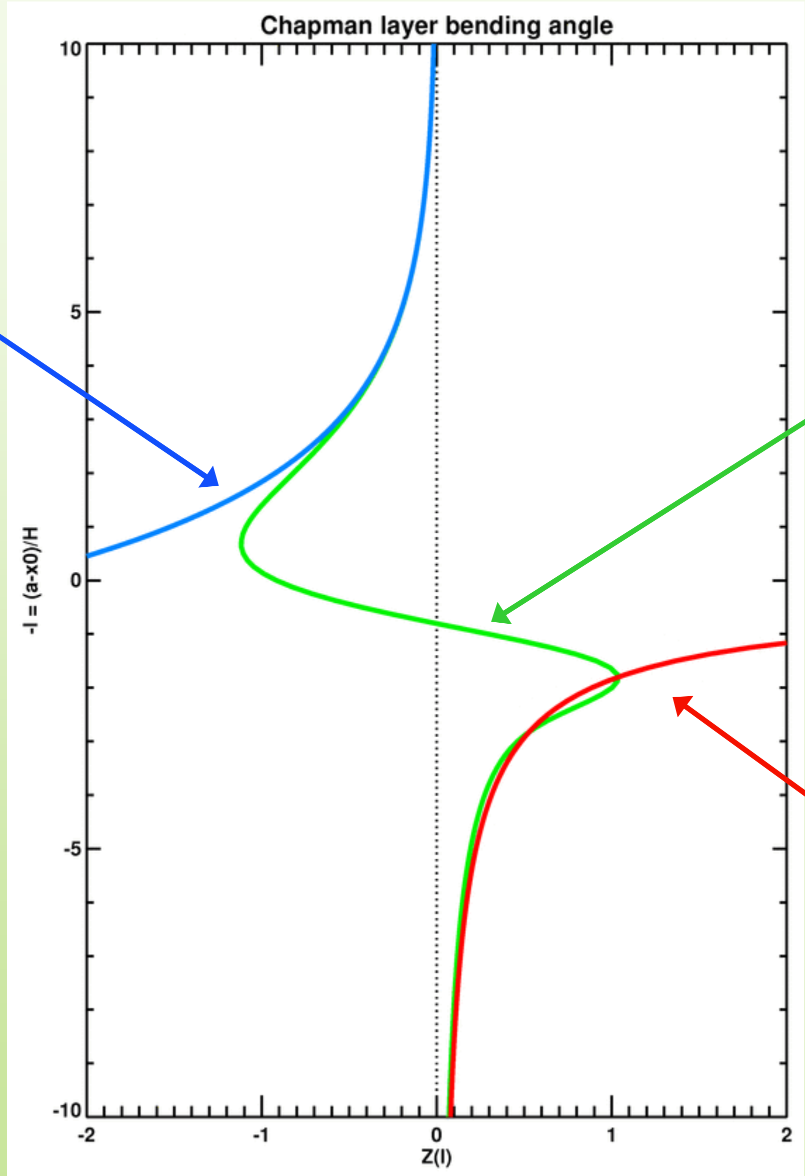
Model ionosphere: bending angle $Z(\ell)$

$-\sqrt{(2\pi)}\, e^{\ell/2}$



Actual ≈

$\sqrt{(2\pi\theta)}\sum_{i=0}^{3} p_i\theta^i / \sum_{i=0}^{5} q_i\theta^i$

$\sqrt{(2\pi/\ell^3)}$

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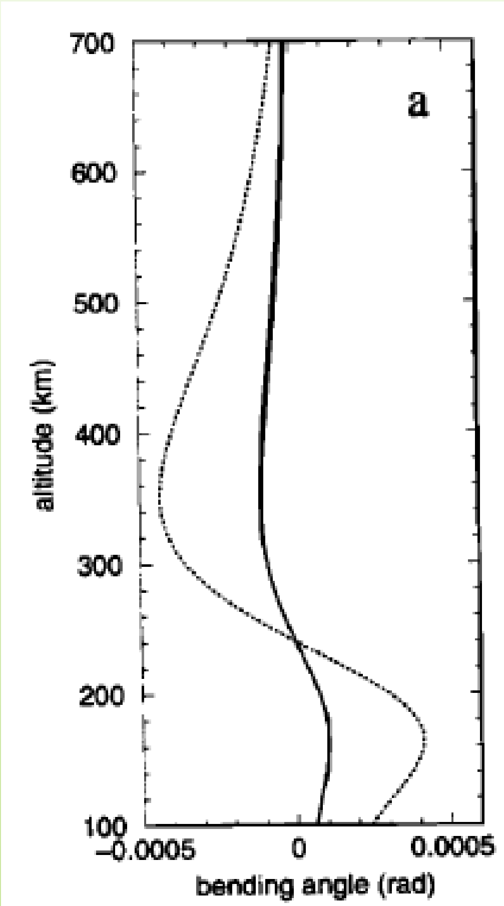
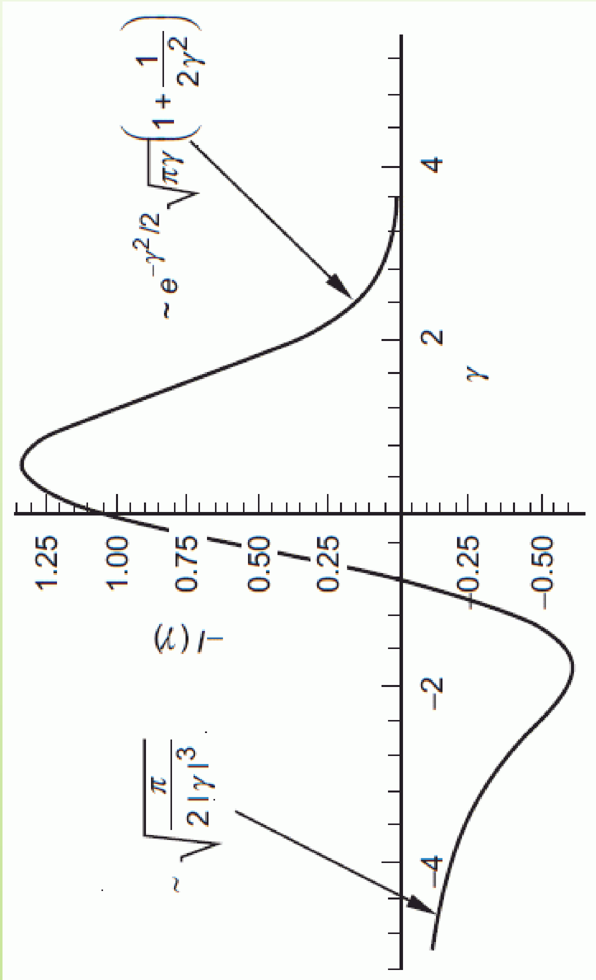
Model ionosphere: bending angle Z(ℓ)

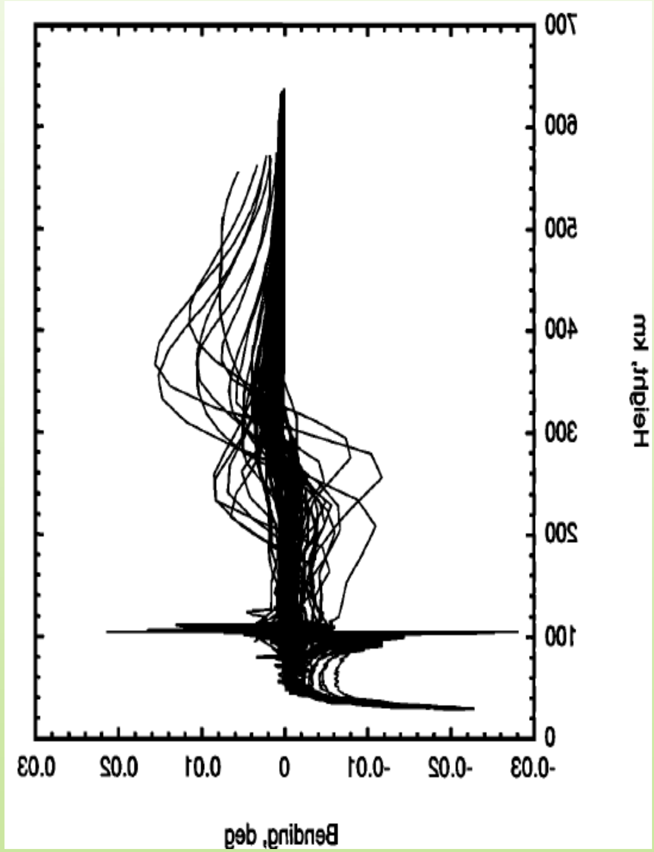
Schreiner et al, 1999, Chapman layer



Melbourne, 2004, Gaussian n_e



Hajj & Romans, 1998, GPS/MET



Direct modelling of L1 and L2 in ROPP

- The Radio Occultation Processing Package:
  - A collection of Fortran 95 code, build and test scripts, data files and documentation designed to aid users wishing to process, quality-control and assimilate radio occultation data into their NWP models.
  - Provided by ROM SAF (EUMETSAT).
  - The following features will be available in ROPP8.0 (Dec 2014).

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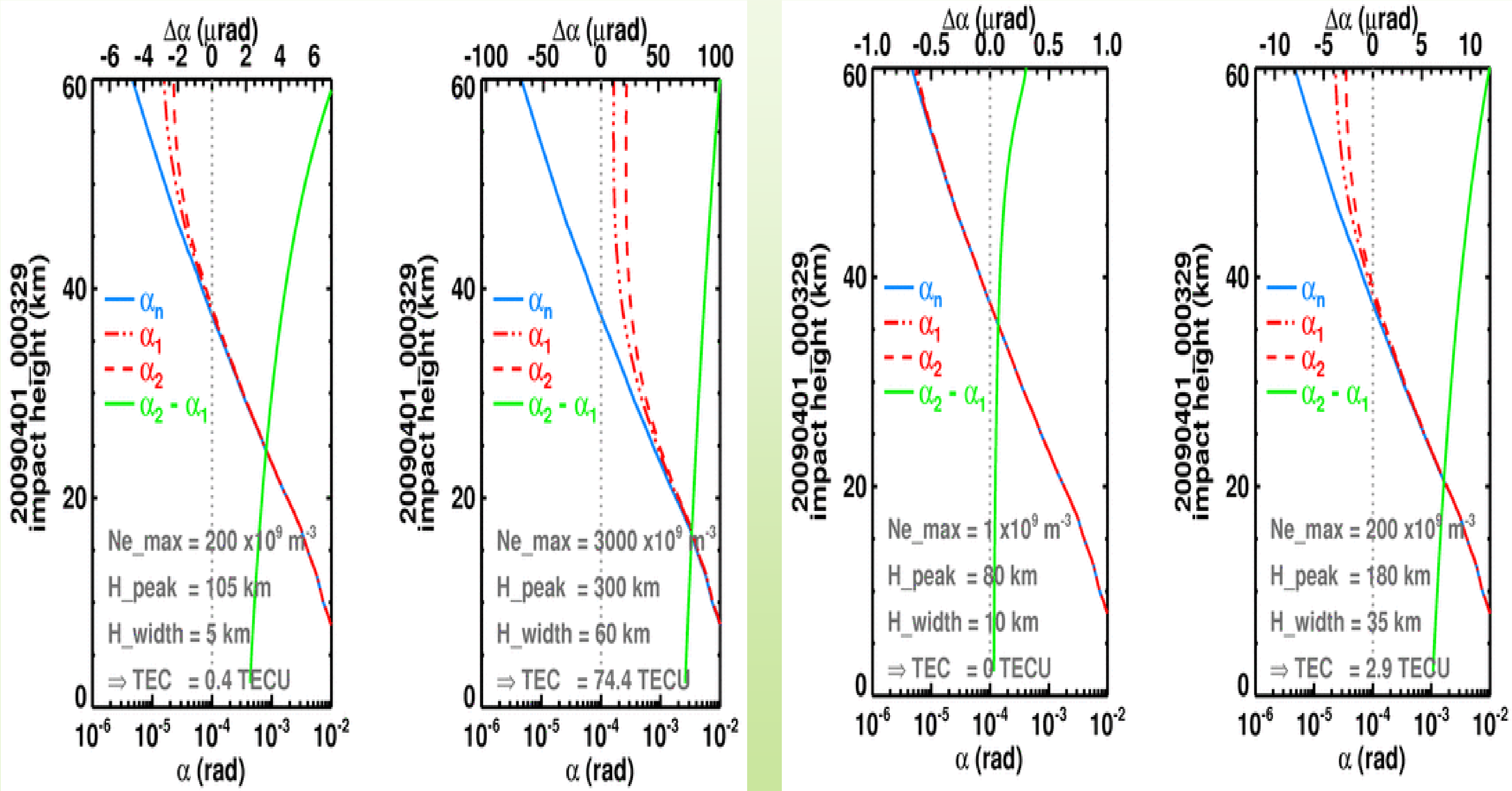
Examples of forward modelled L1 and L2 using ropp_fm

E-layer F-layer D-layer F1-layer



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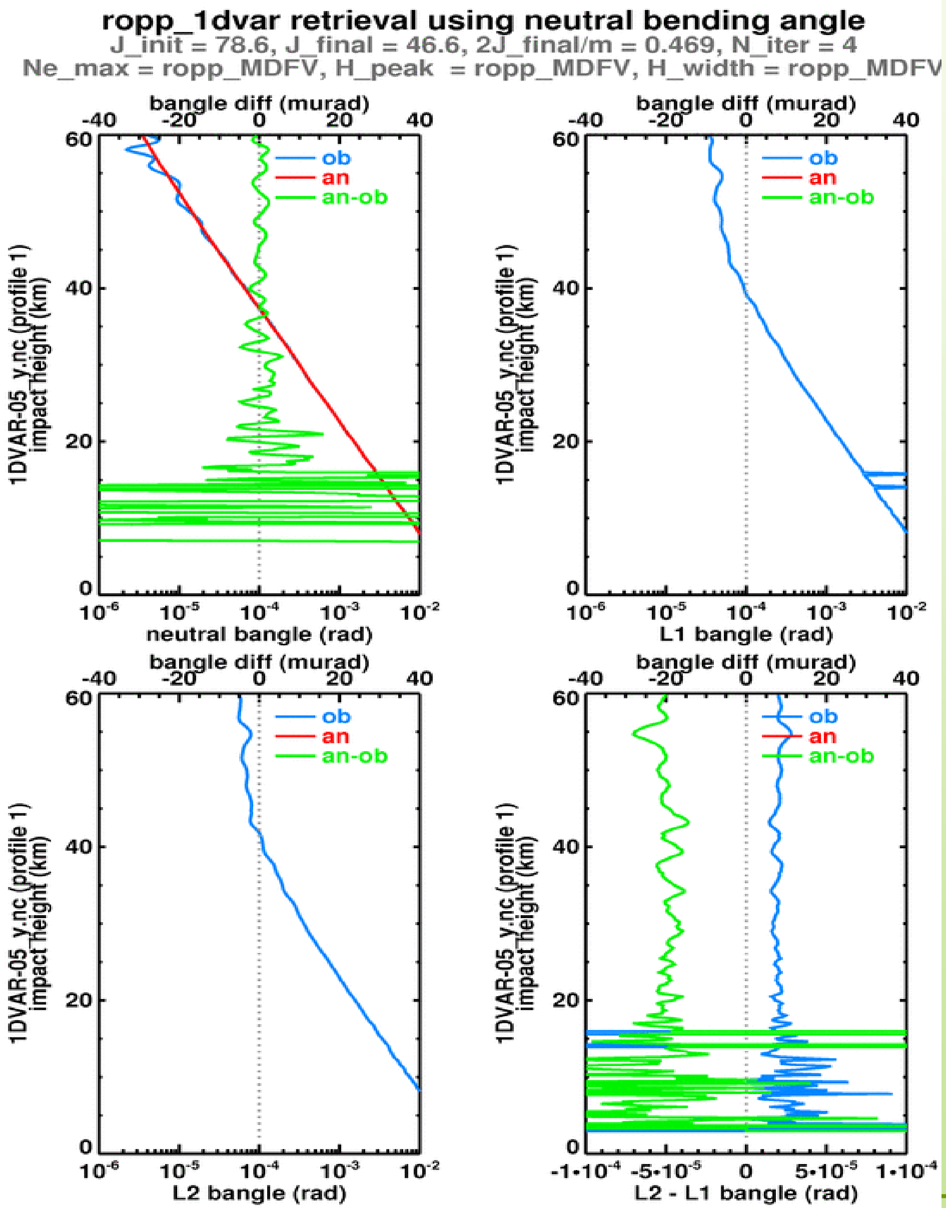
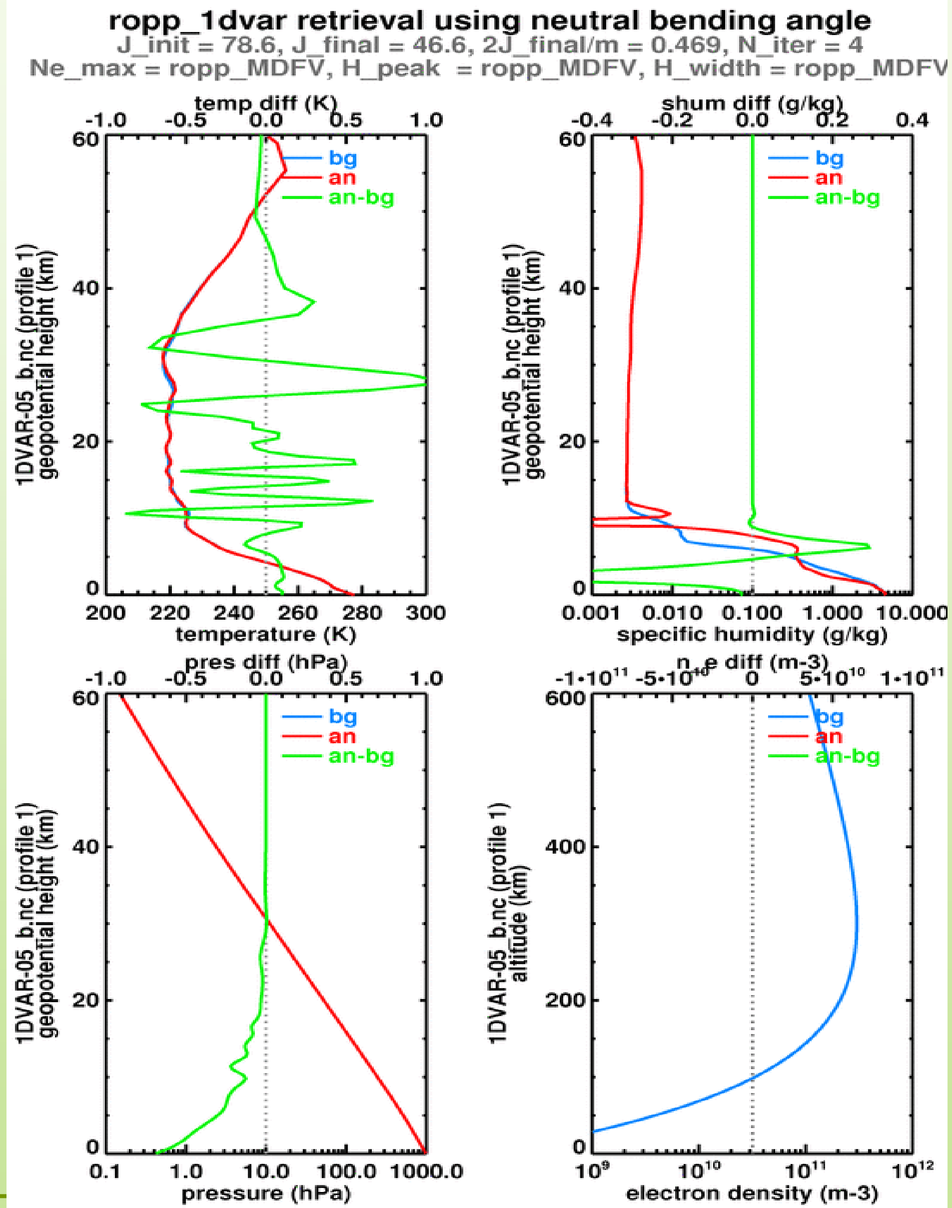
Direct modelling of L1 and L2 in ropp_1dvar

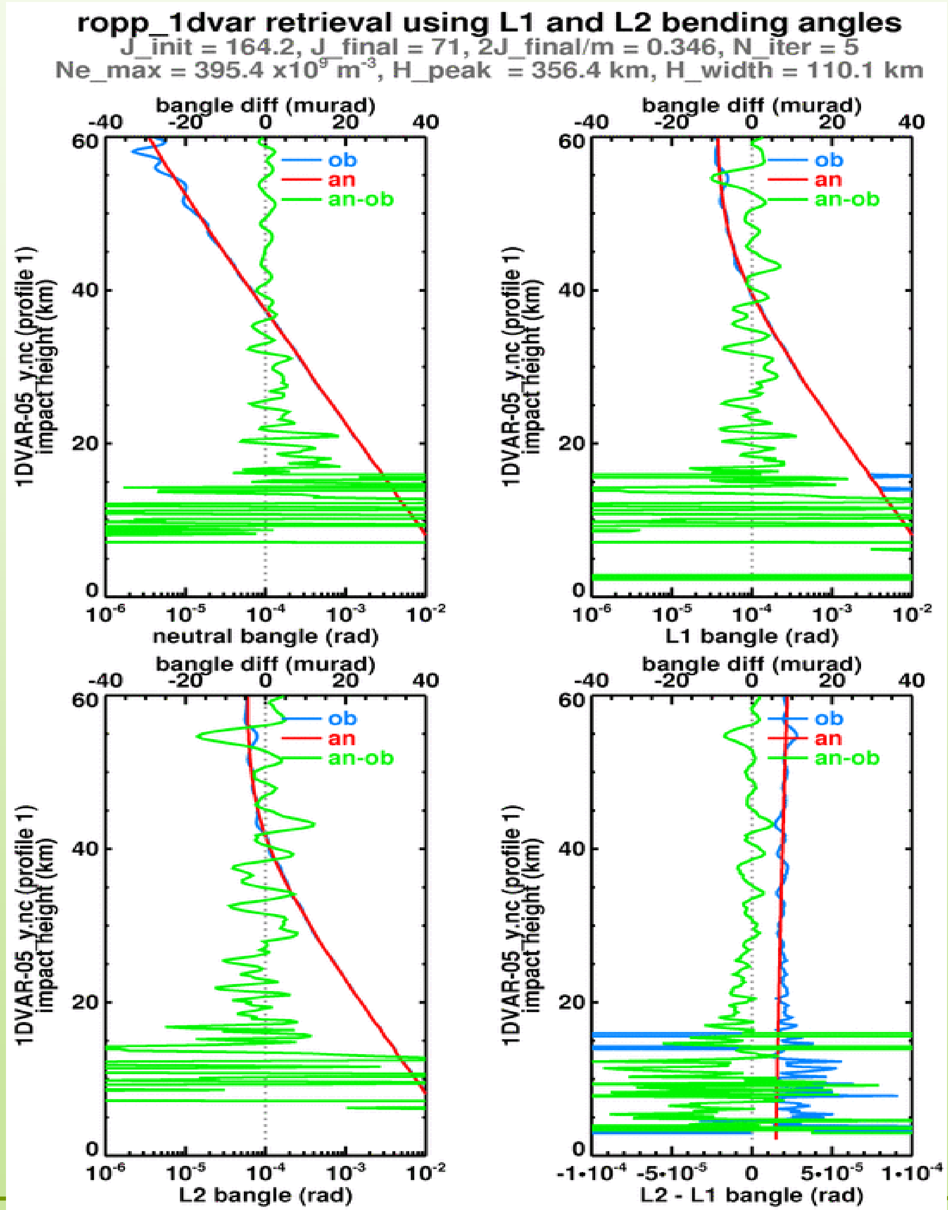
- Minimise $2J(\mathbf{x}) = (\mathbf{x} - \mathbf{b})^T \mathcal{B}^{-1} (\mathbf{x} - \mathbf{b}) + (\mathcal{H}(\mathbf{x}) - \mathbf{o})^T \mathcal{R}^{-1} (\mathcal{H}(\mathbf{x}) - \mathbf{o})$
- $\mathbf{x} = \{T, q, p^*, n_e^{max}, r_0, H\}$; $\mathbf{o} = \{\alpha_{L1}, \alpha_{L2}\}$
- $\mathcal{R}$
  - $\sigma(\alpha_{L1}) = \max(\alpha_n, 10\ \mu\text{rad})$; $\sigma(\alpha_{L2}) = \max(\alpha_n, 30\ \mu\text{rad})$
  - Assume α_{L1} and α_{L2} errors to be uncorrelated
  - Needs some experimentation
- $\mathcal{B}$
  - $\sigma(n_e^{max}) = 2e11\ m^{-3}$; $\sigma(r_0) = 150$ km; $\sigma(H) = 25$ km
  - Assume $\{n_e^{max}, r_0, H\}$ errors to be uncorrelated from each other and from those of $\{T, q, p^*\}$
  - Needs some experimentation

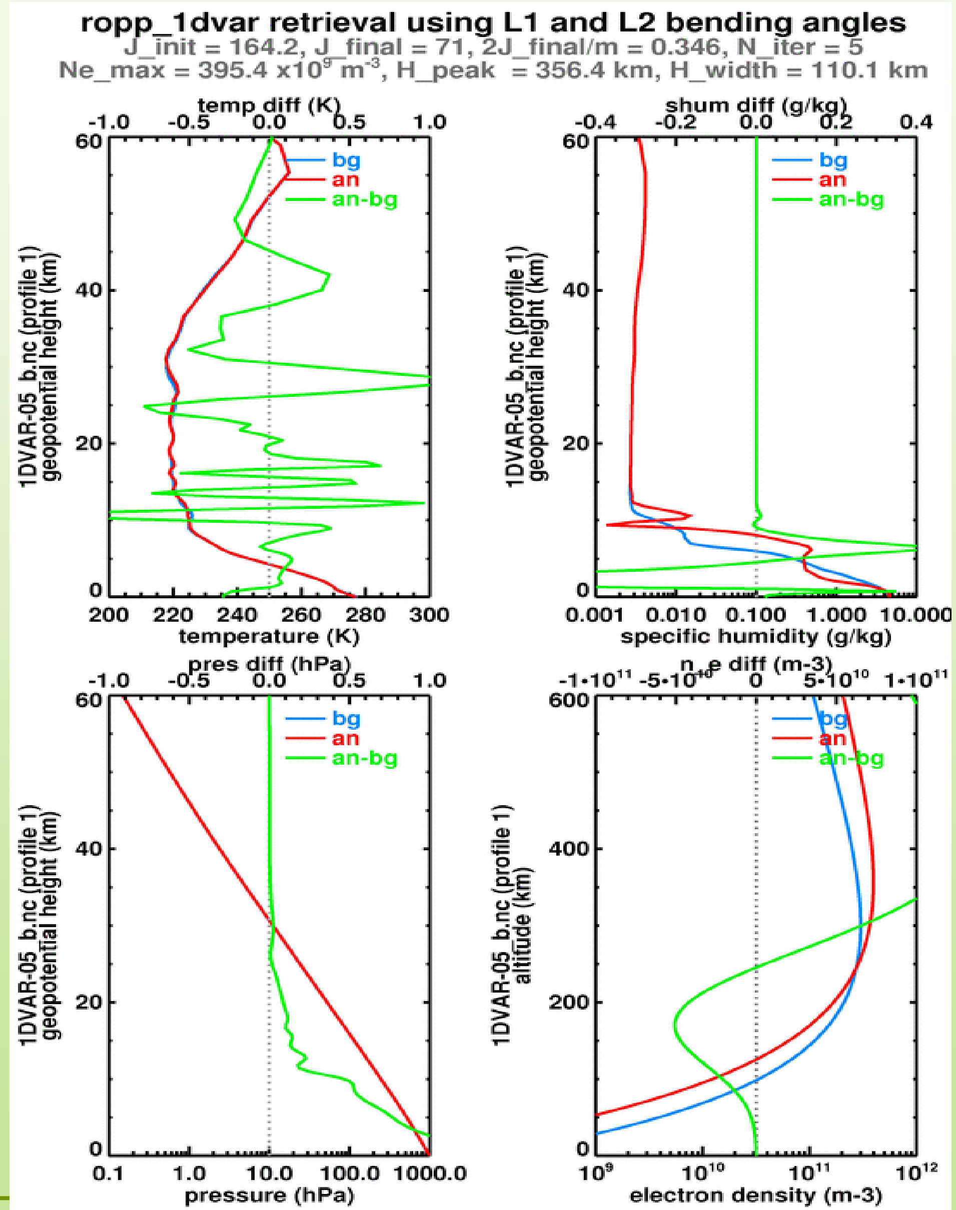
Example 1: ropp_1dvar retrieval based on neutral bending angle



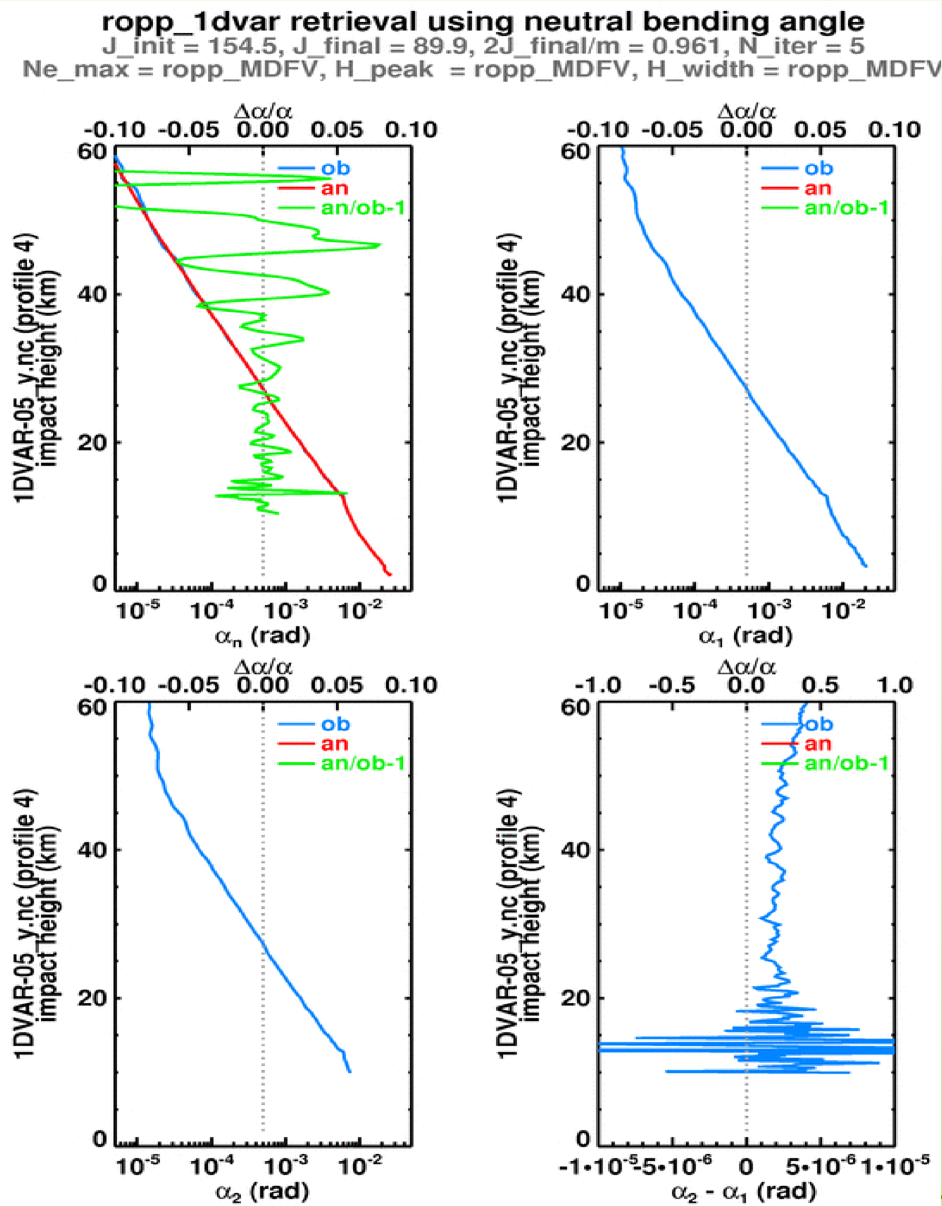


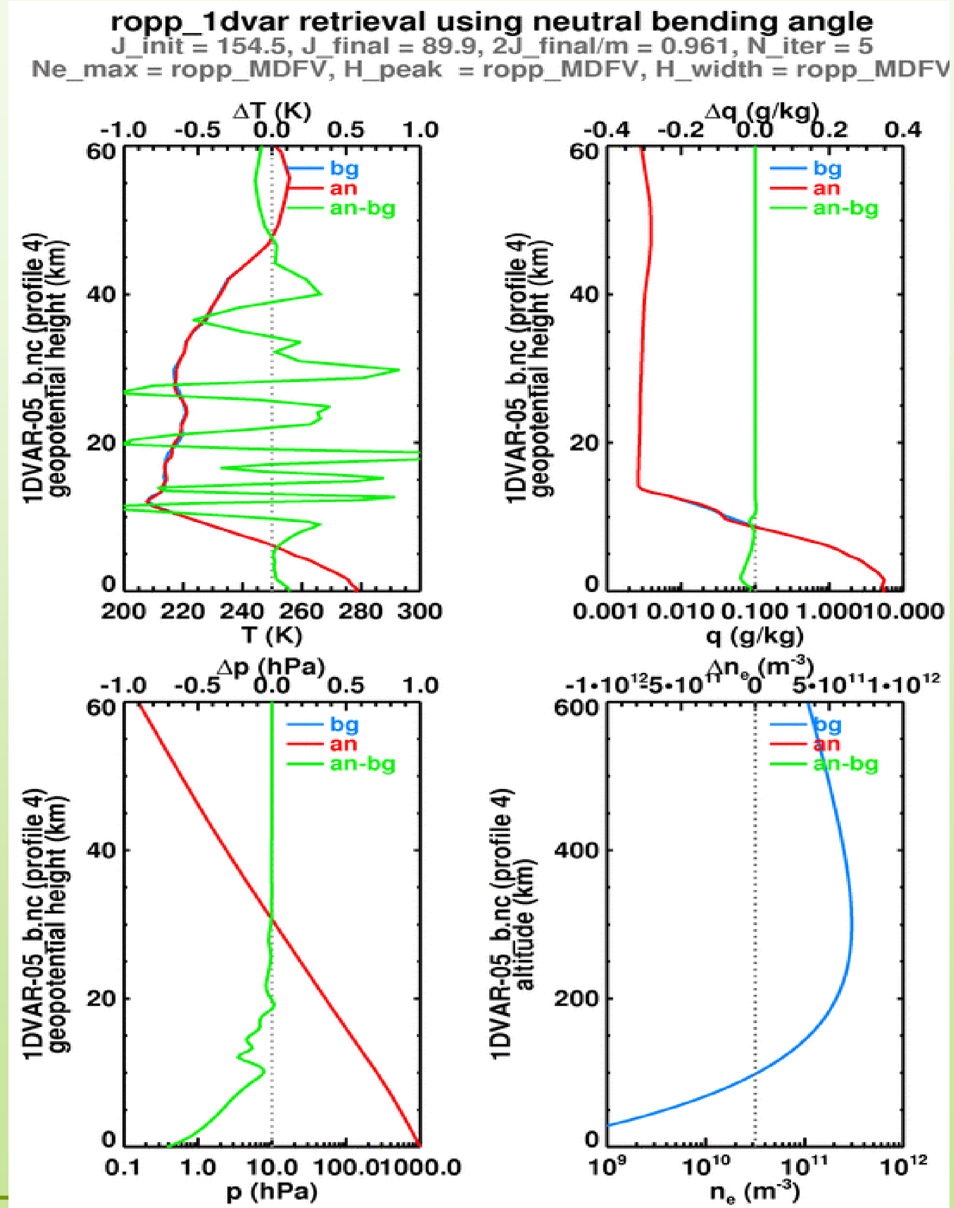
Example 1: ropp_1dvar retrieval based on L1 & L2 bending angles



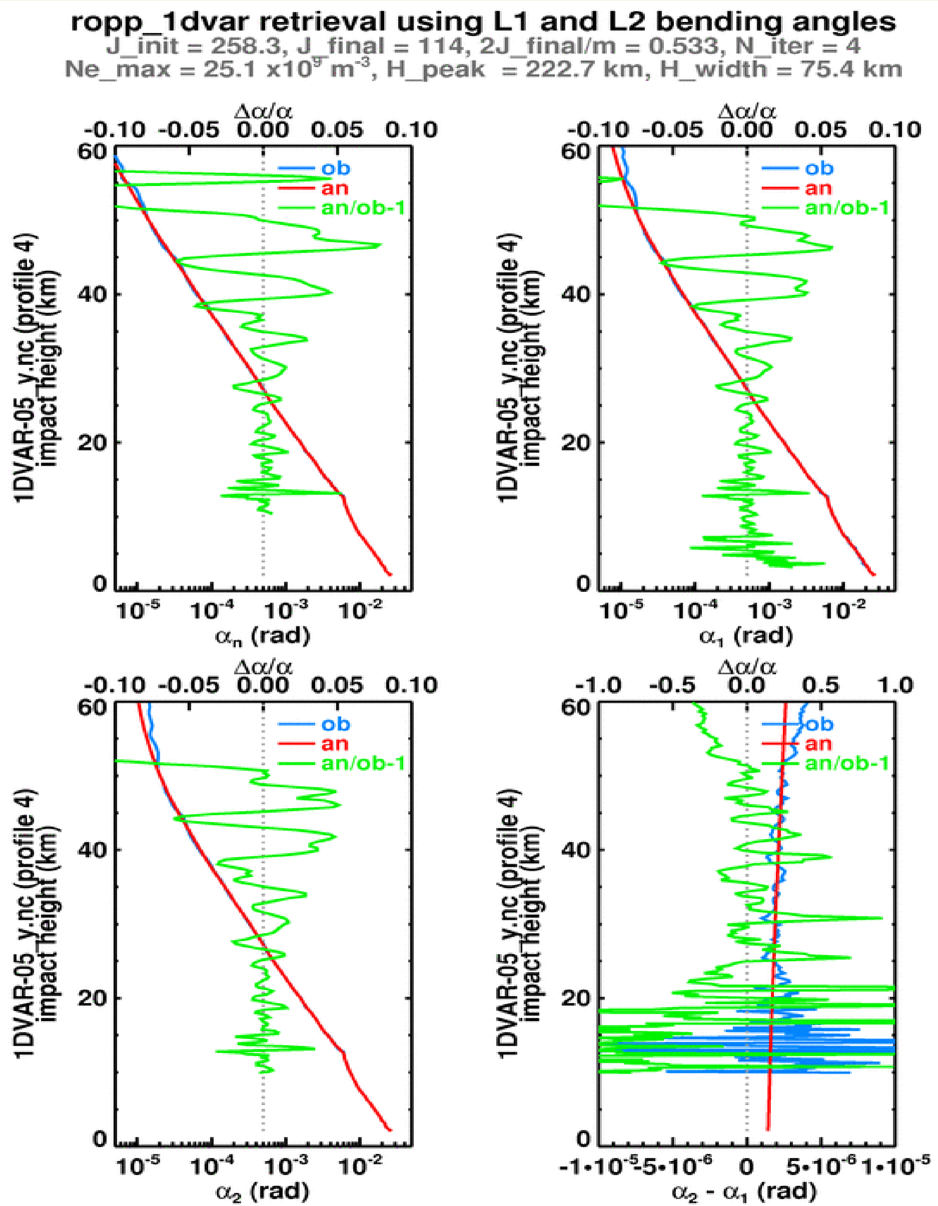


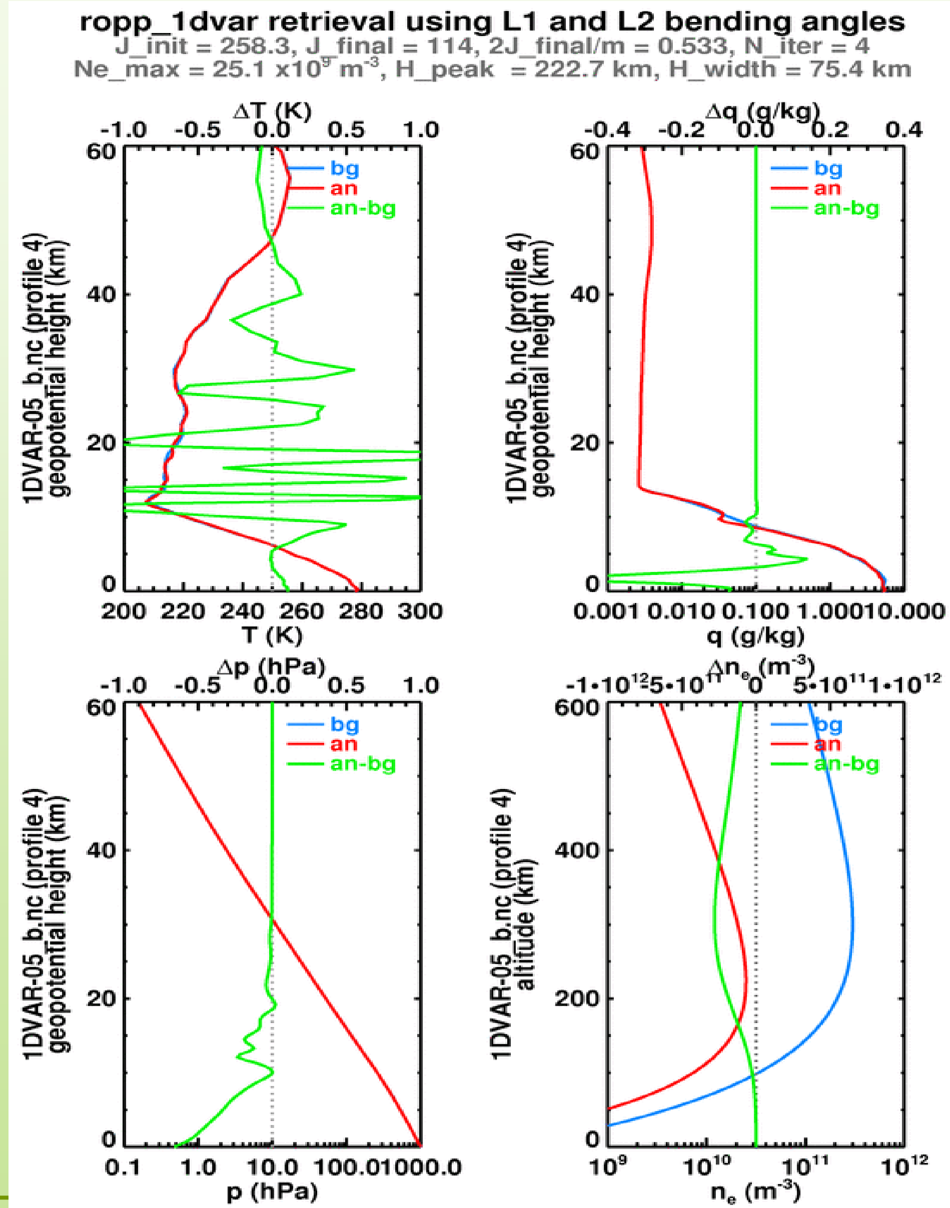
Example 2: ropp_1dvar retrieval based on neutral bending angle



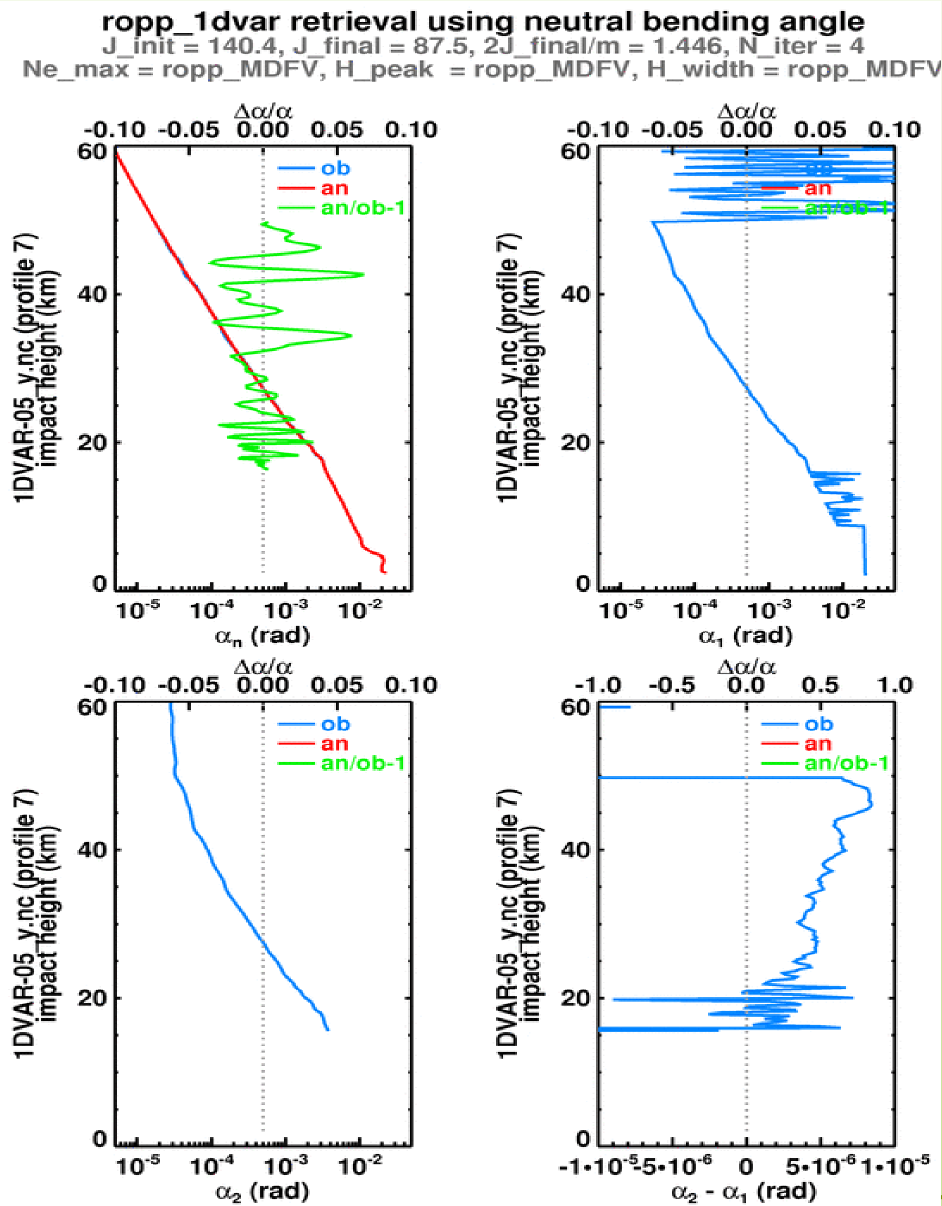


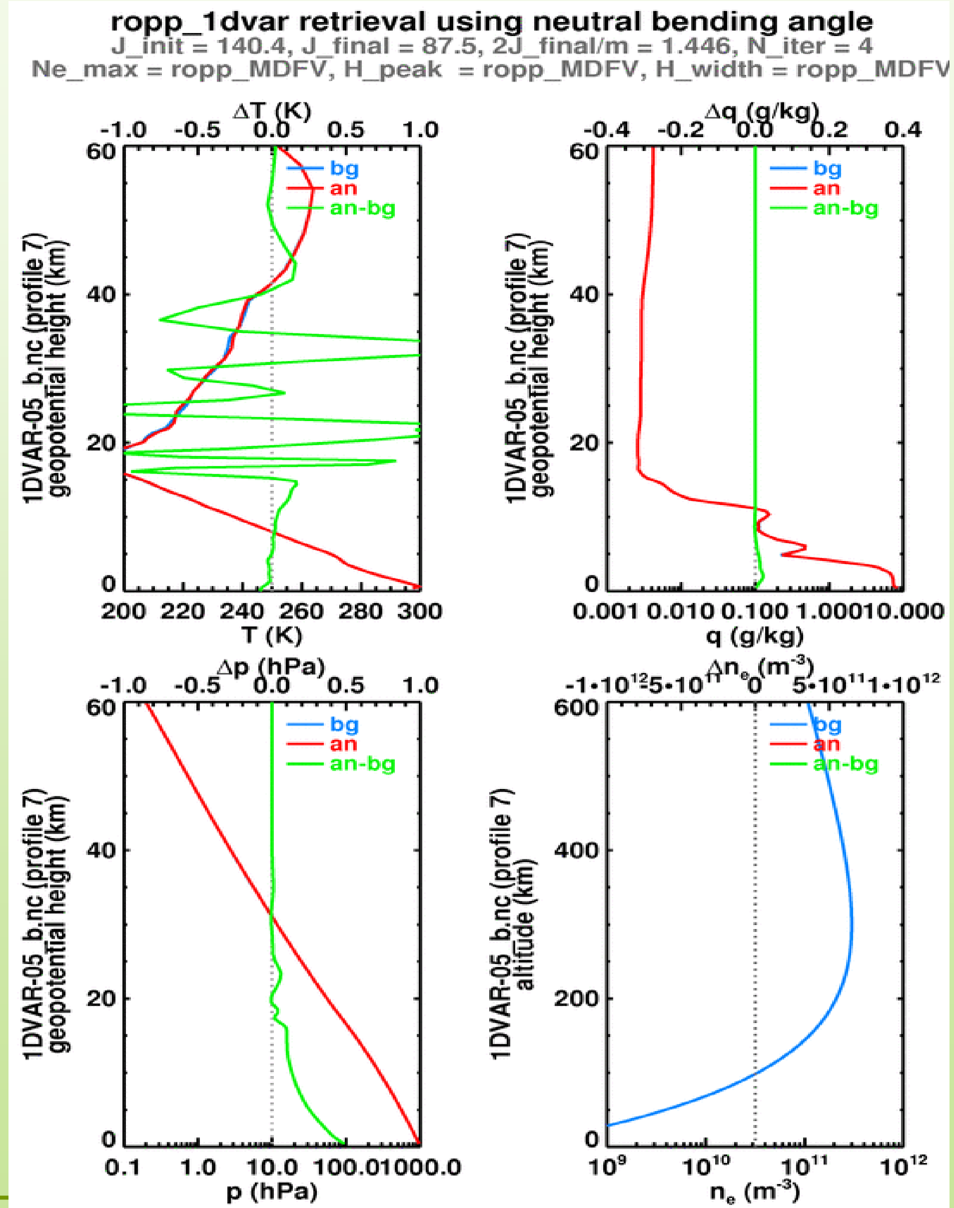
Example 2: ropp_1dvar retrieval based on L1 & L2 bending angles



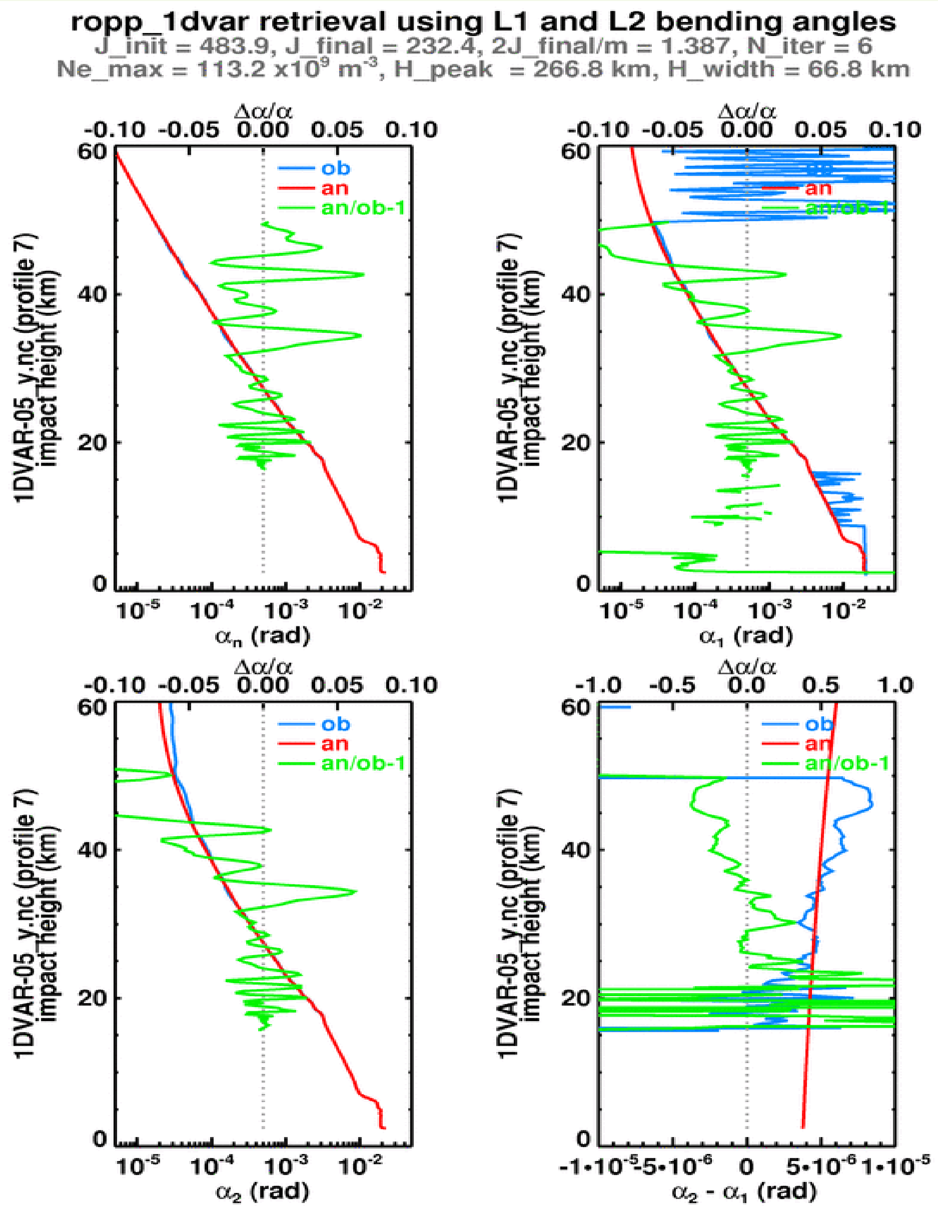


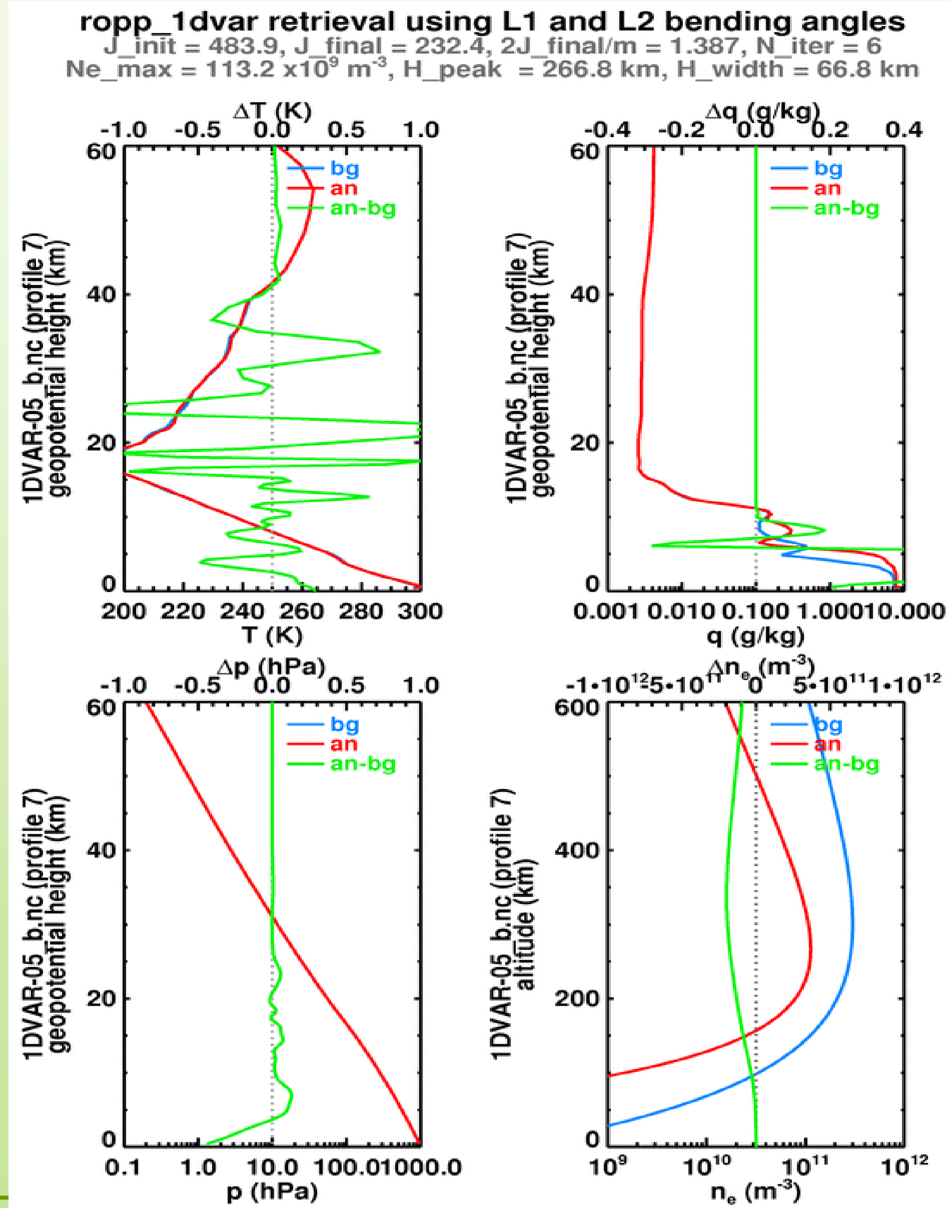
Example 3: ropp_1dvar retrieval based on neutral bending angle



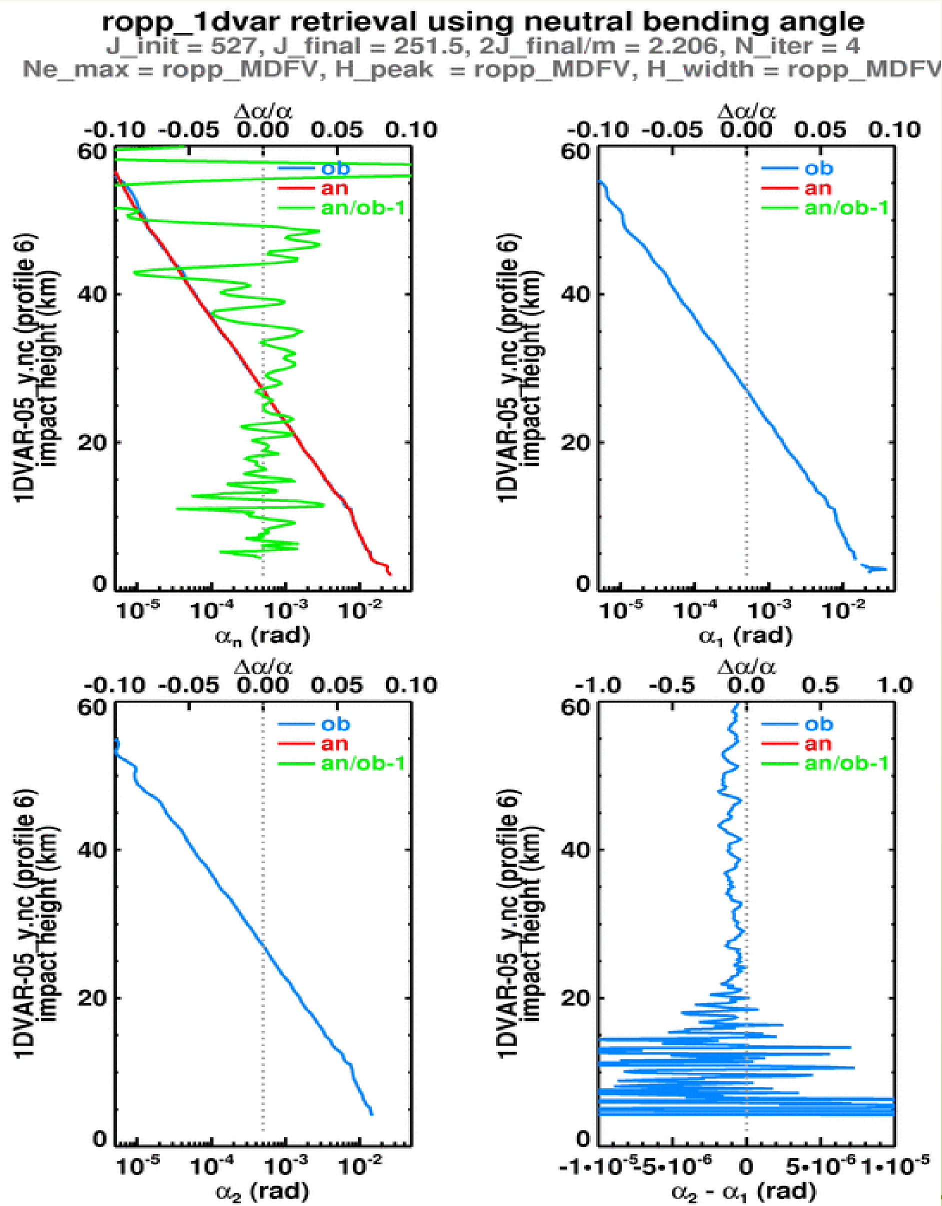


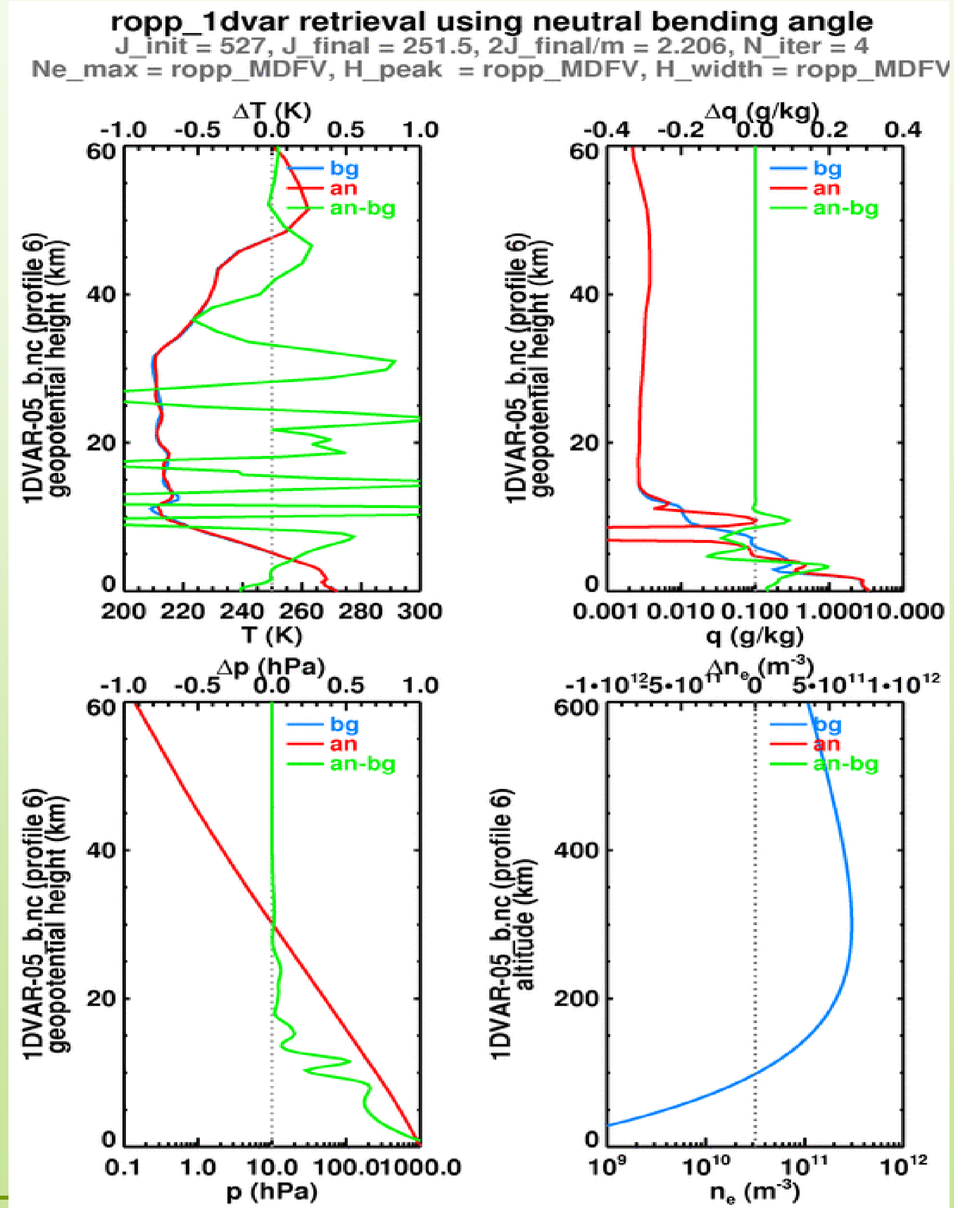
Example 3: ropp_1dvar retrieval based on L1 & L2 bending angles



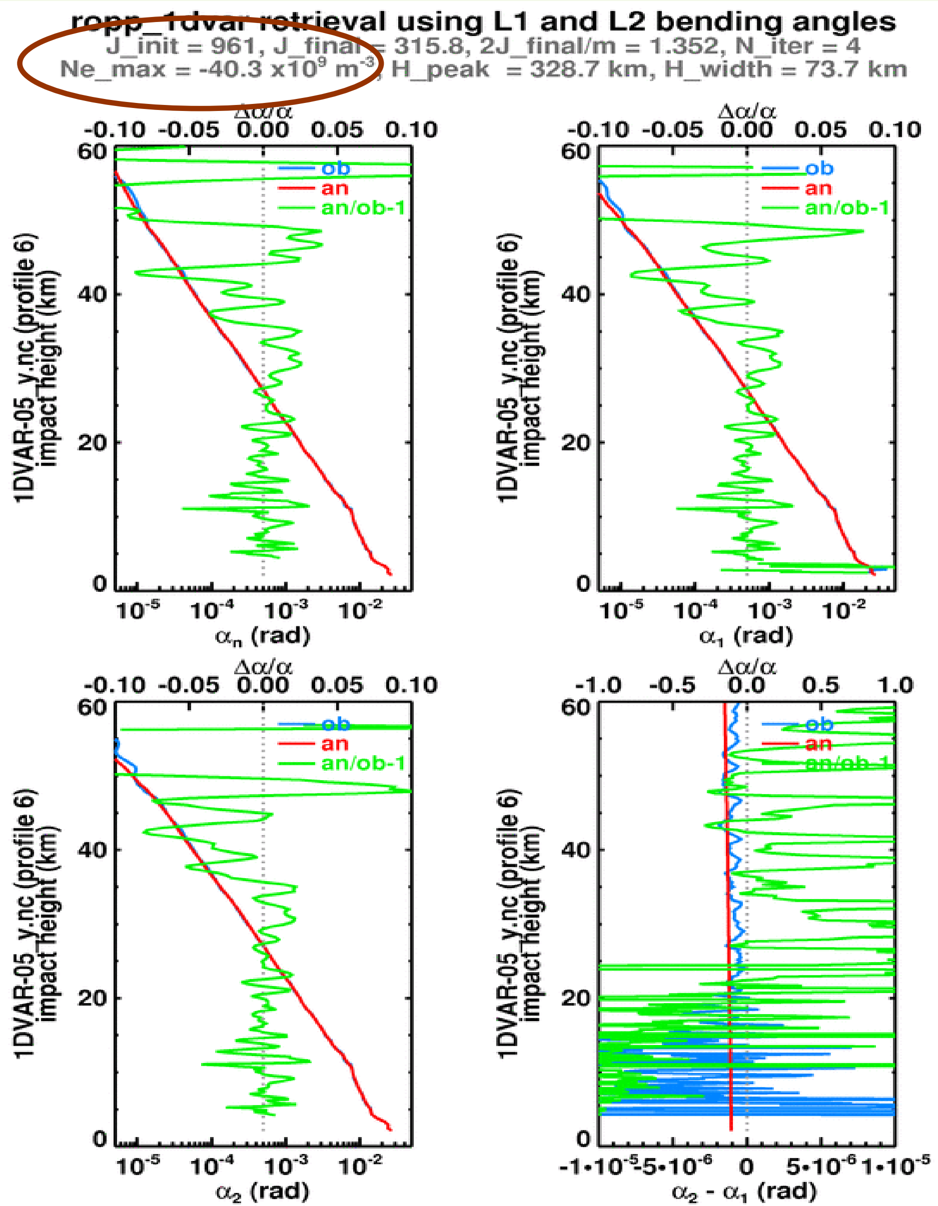


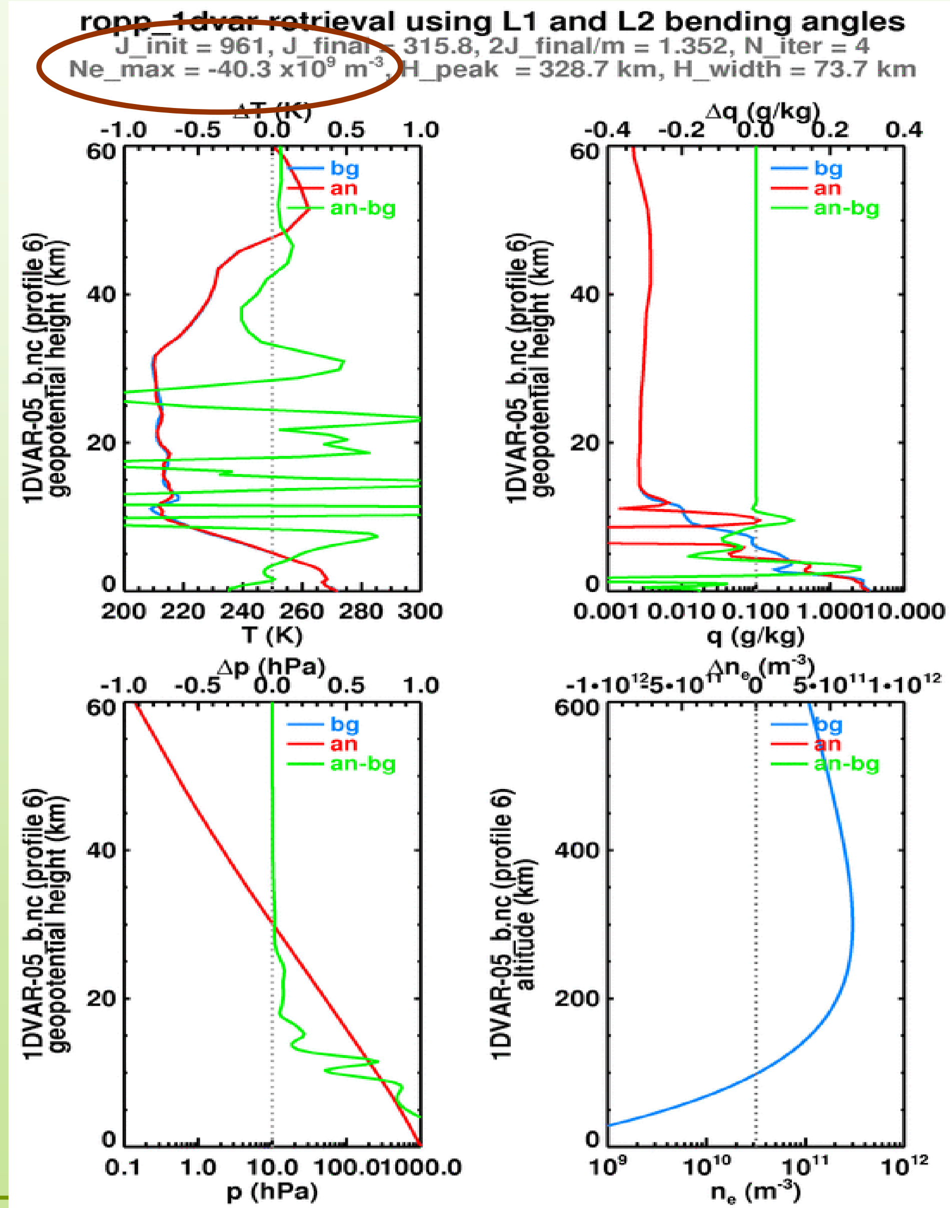
Example 4: ropp_1dvar retrieval based on neutral bending angle



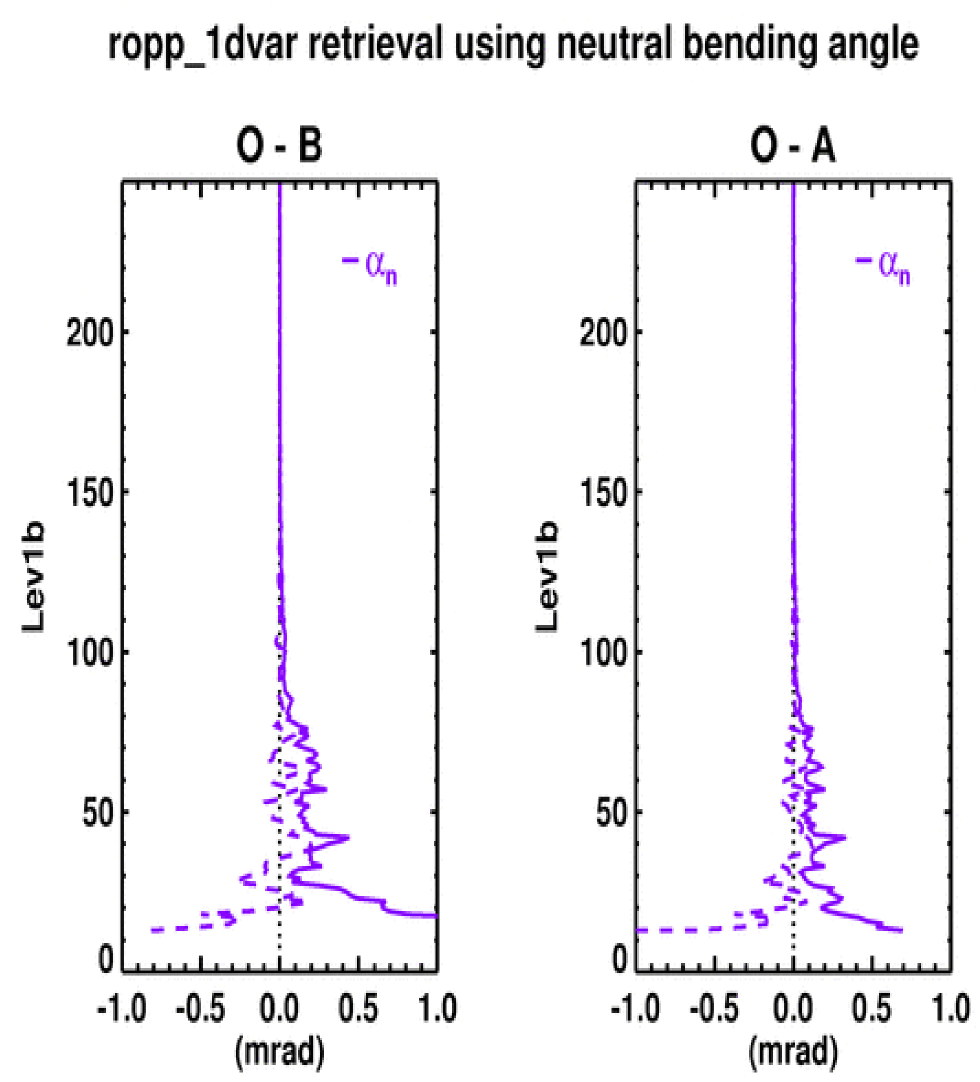


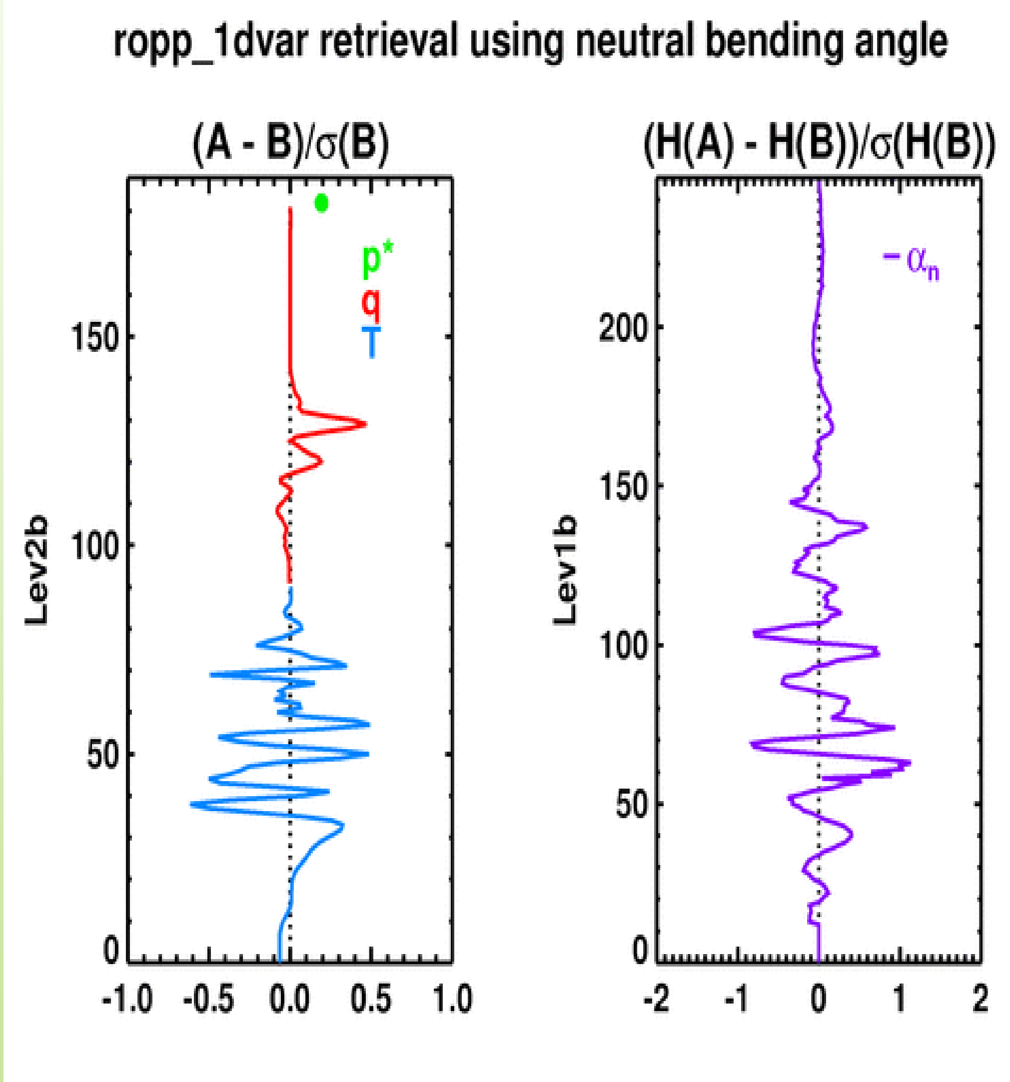
Example 4: ropp_1dvar retrieval based on L1 & L2 bending angles



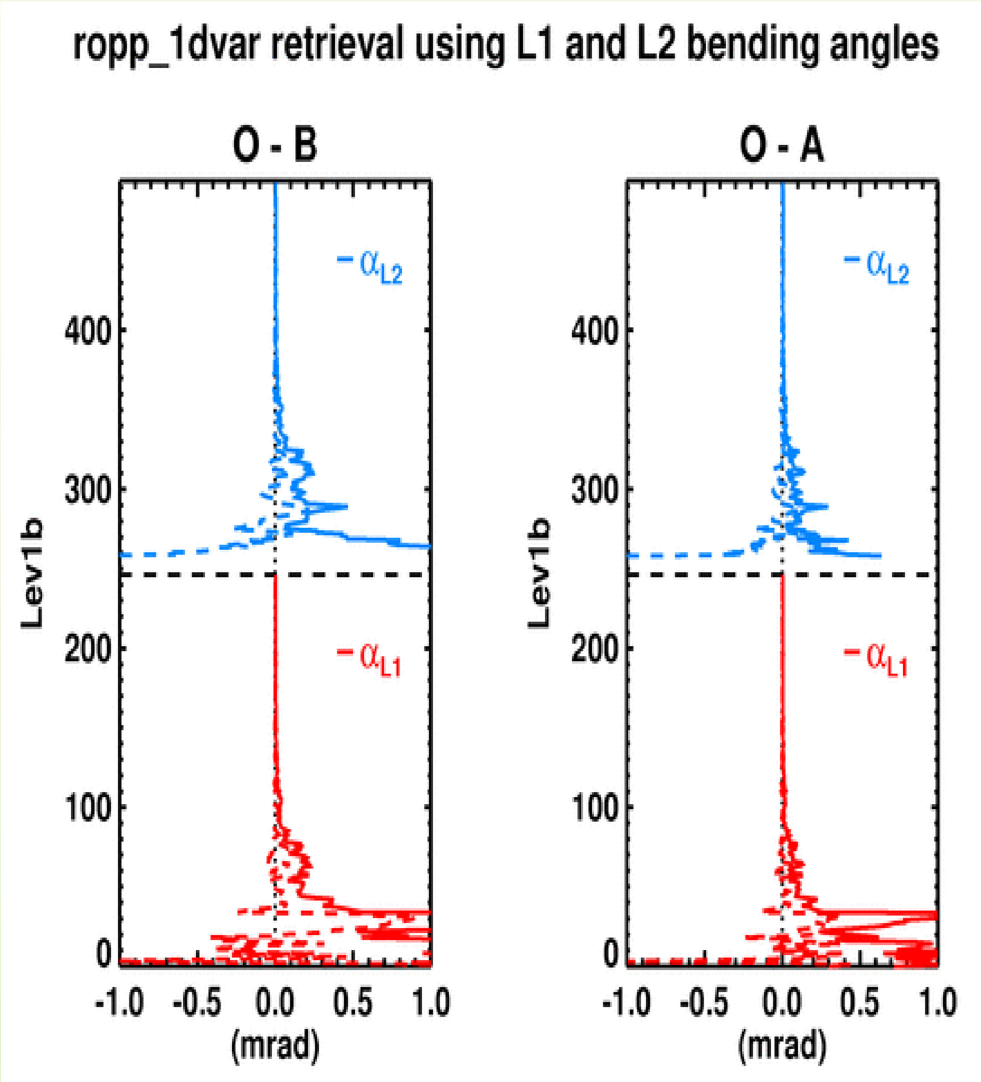


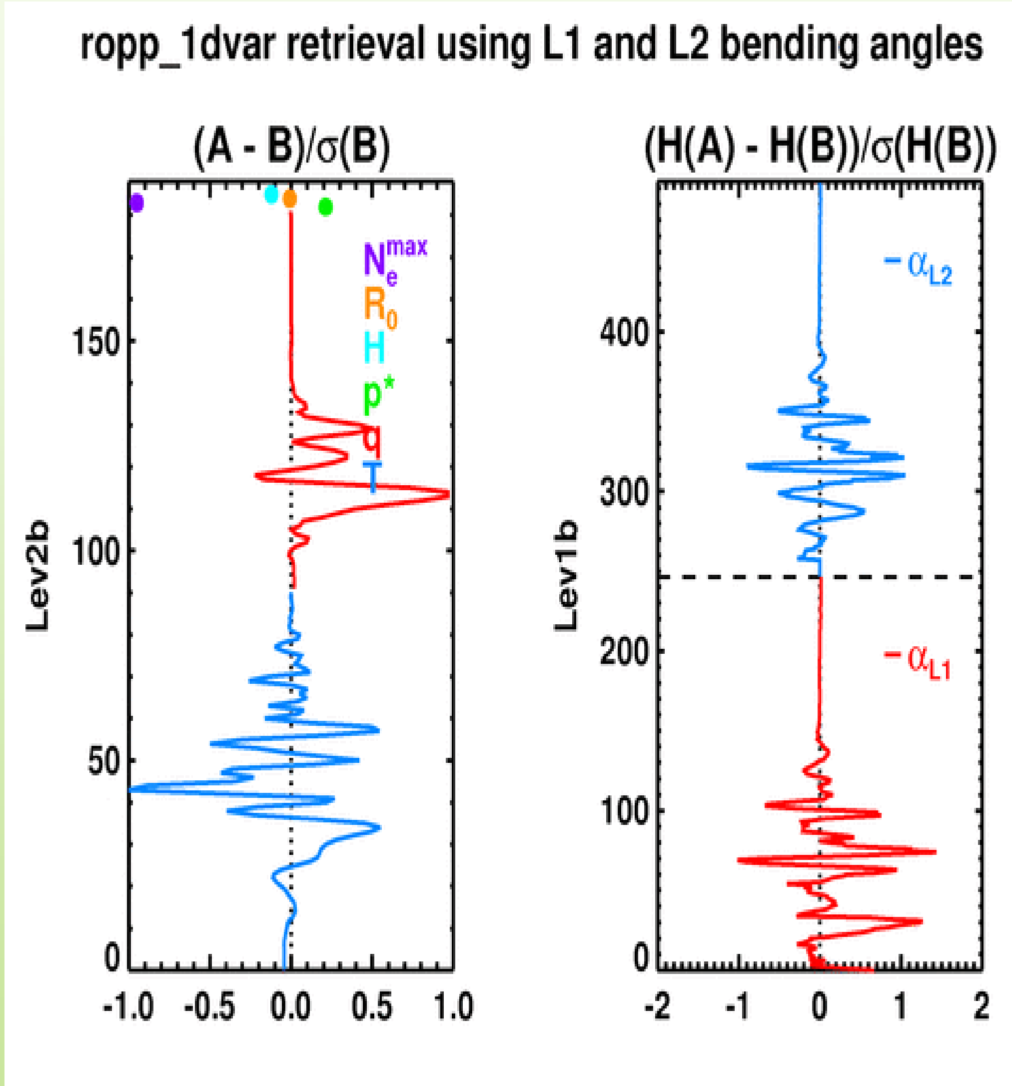
Direct modelling of L1 and L2 in ROPP: α_n stats





Direct modelling of L1 and L2 in ROPP: α_{Li} stats





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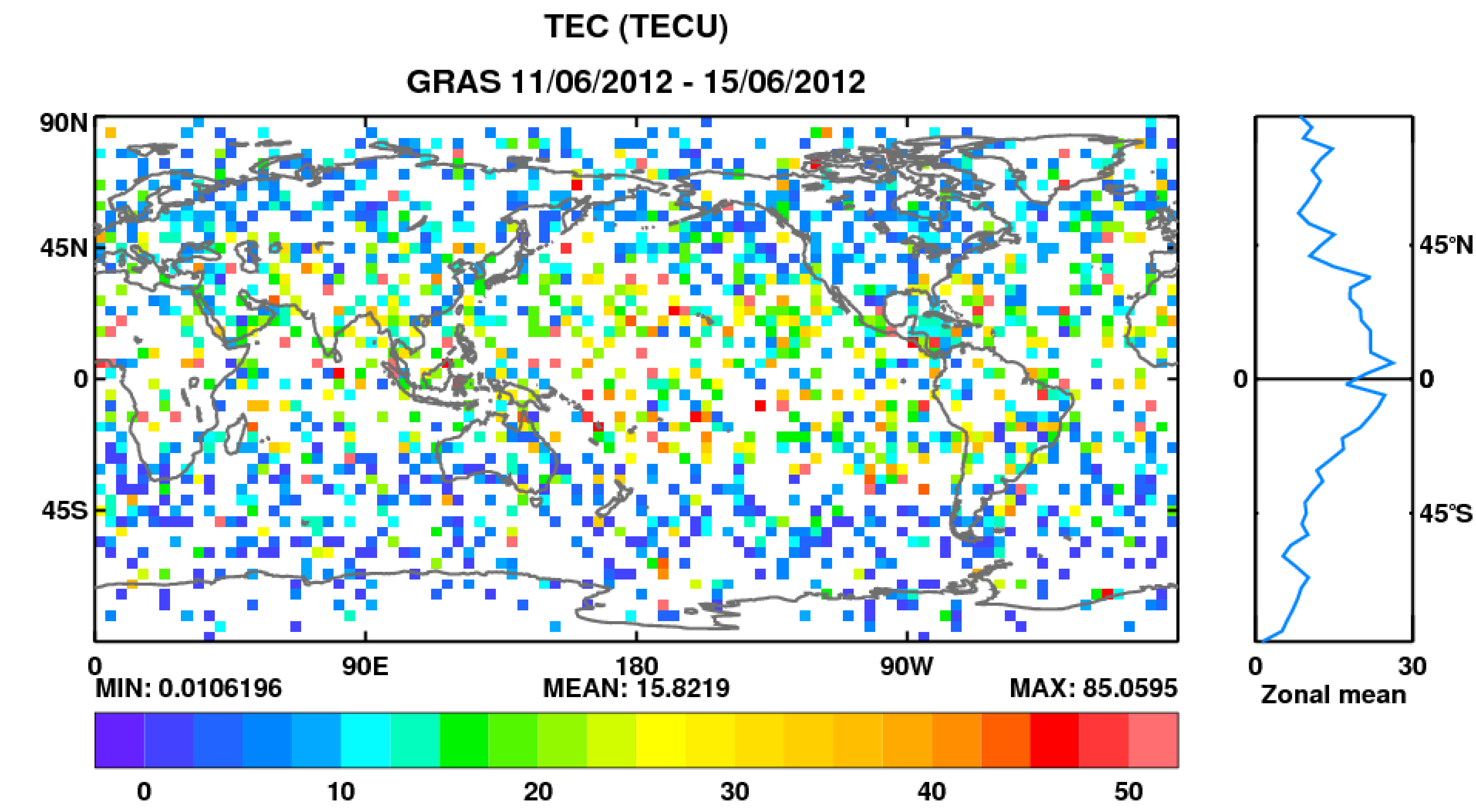
"Retrieved ionospheric parameters"

Fit "normal" L1-L2 to Z(ℓ) for every GRAS occultation for 5 days in June 2012



Direct modelling of L1 and L2 in ROPP: summary

- Can forward model α_{L1} and α_{L2} by assuming simple Chapman layer ionosphere

- Allows extrapolation of α_{L1} and α_{L2} based on whole profiles of data

- Retrievals using α_{L1} and α_{L2} are possible in principle BUT
  - Bigger impacts on q and tropospheric T?
  - Not always capturing curvature of L1 and L2 at top?
  - Require $n_e^{max} < 0$ to get decent fit in some cases!

- Backgrounds/errors/covariances of n_e^{max}, r_0 and H
  need some experimentation.

- Errors/covariances of α_{L1} and α_{L2} need some experimentation.

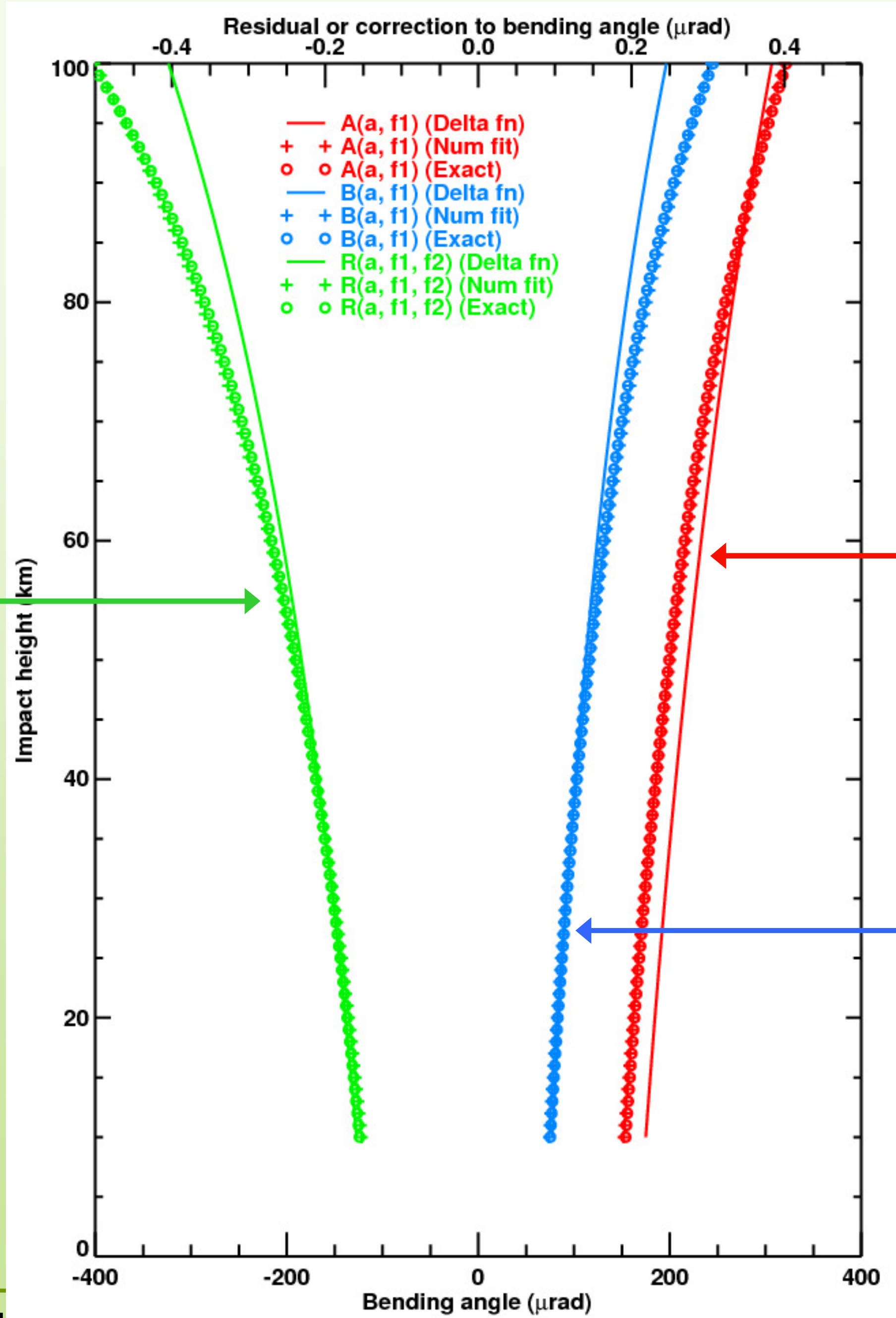
Residual ionospheric correction

- Working on a model for the residual error that remains after standard ionospheric correction (Vorob'ev and Krasil'nikova,1994)
- $\alpha(a) = -2a \int_a^\infty d\log n/dx \, dx / \sqrt{(x^2-a^2)} \approx$

  $-2a \int_a^\infty N' \, dr / \sqrt{(r^2 - a^2)}$ Basic bending angle, $\propto TEC/f^2$

  $+2a \int_a^\infty NN' \, dr \, (2r^2 - a^2)/(r^2 - a^2)^{3/2}$ 1st order correction, $\propto TEC^2/f^4$
- Implies that residual after standard ionospheric correction $\propto (\alpha_{L1} - \alpha_{L2})^2$ X some *slowly* varying function of height, which we can estimate/calculate analytically for a Chapman layer.
- We are working with Julia Danzer (GFZ/ROM SAF VS) to test this.
- Could have implications for RO-based climatological mean temperatures.

Residual



α_{L1}

(cf climate change trend ~ few μrad per decade)

α_{L1} correction

Conclusions

- Calculated bending angle produced by a spherically symmetric Chapman layer ionosphere.

- Incorporated in ROPP forward model and 1dvar system.

- Expressed residual bending angle, after standard ionospheric correction, in terms of $(\alpha_{L1} - \alpha_{L2})^2$.

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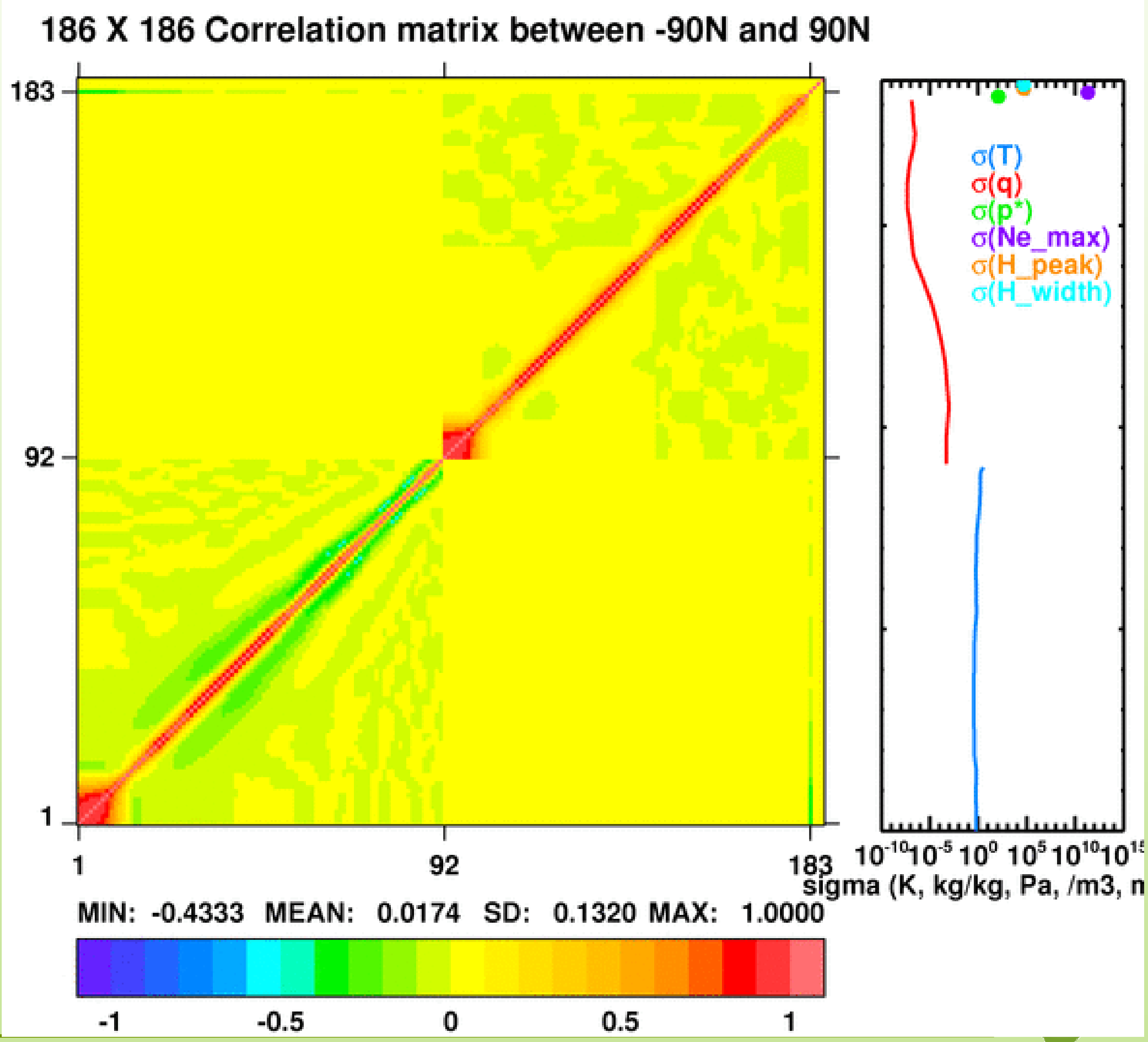
Background error covariance matrix



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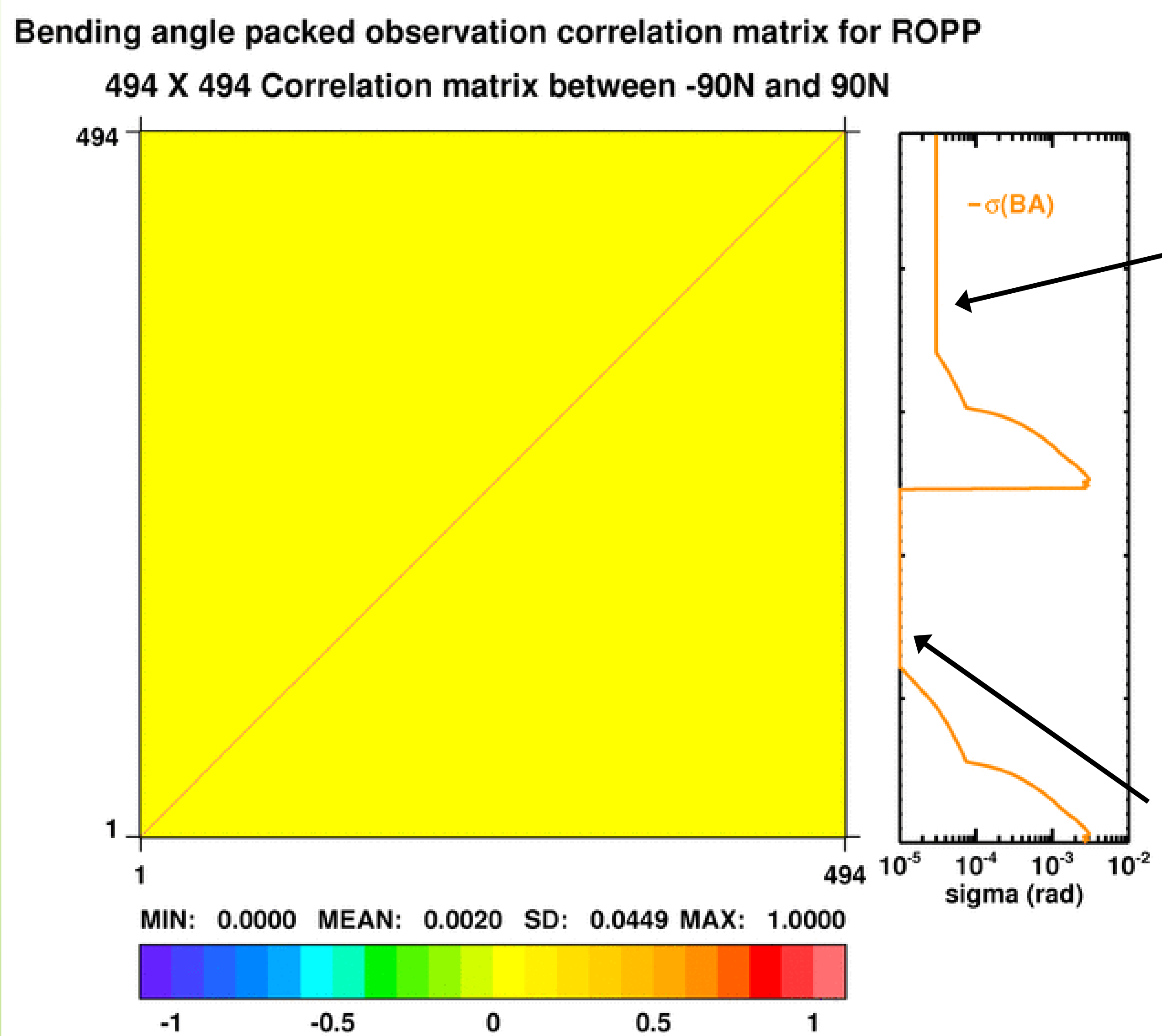
Bending angle error covariance matrix



σ_2^{min} = 30 μrad

cf σ_n^{min} = 6 μrad

σ_1^{min} = 10 μrad

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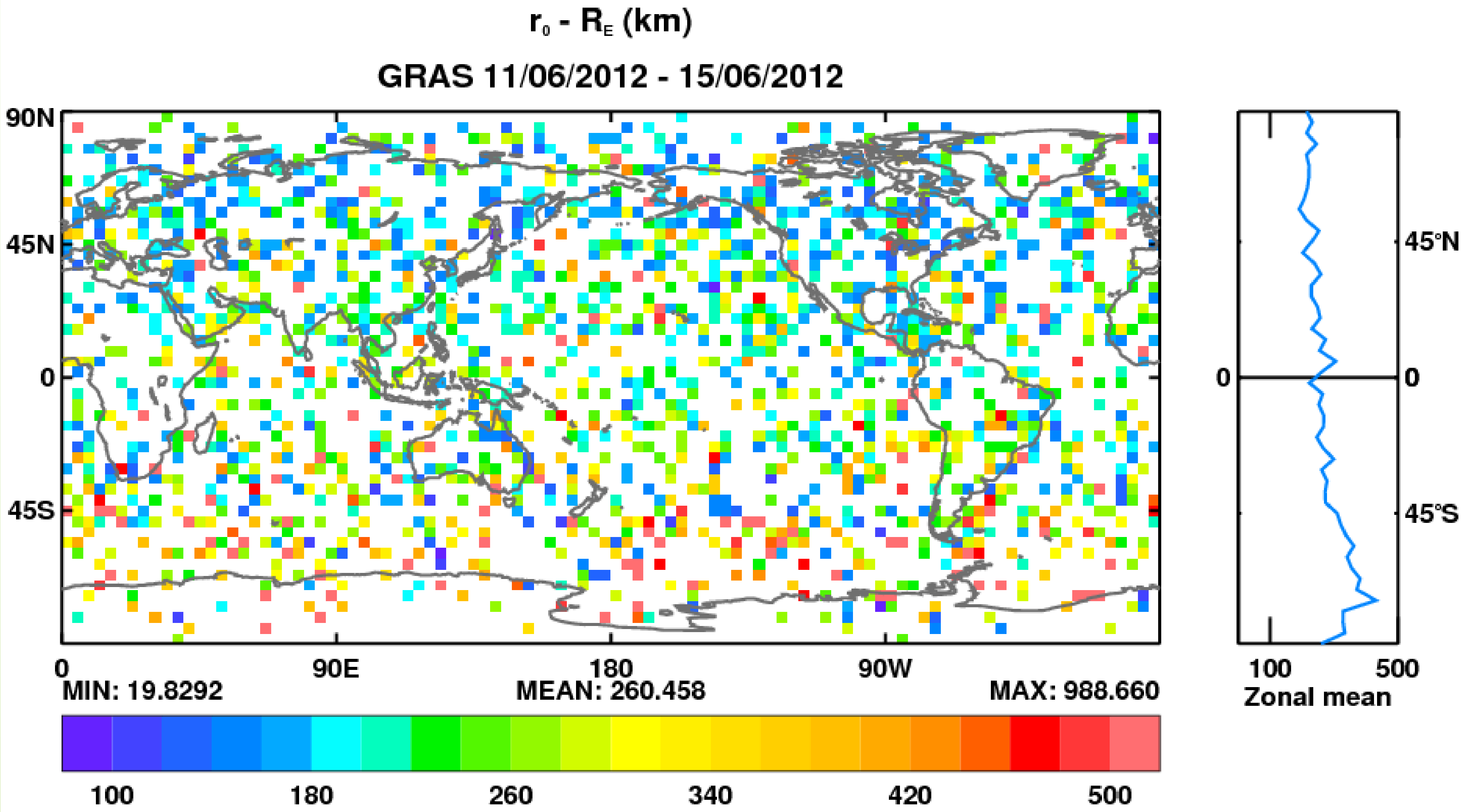
Fit “normal” L1-L2 to Z(ℓ) for every GRAS occultation for 5 days in June 2012



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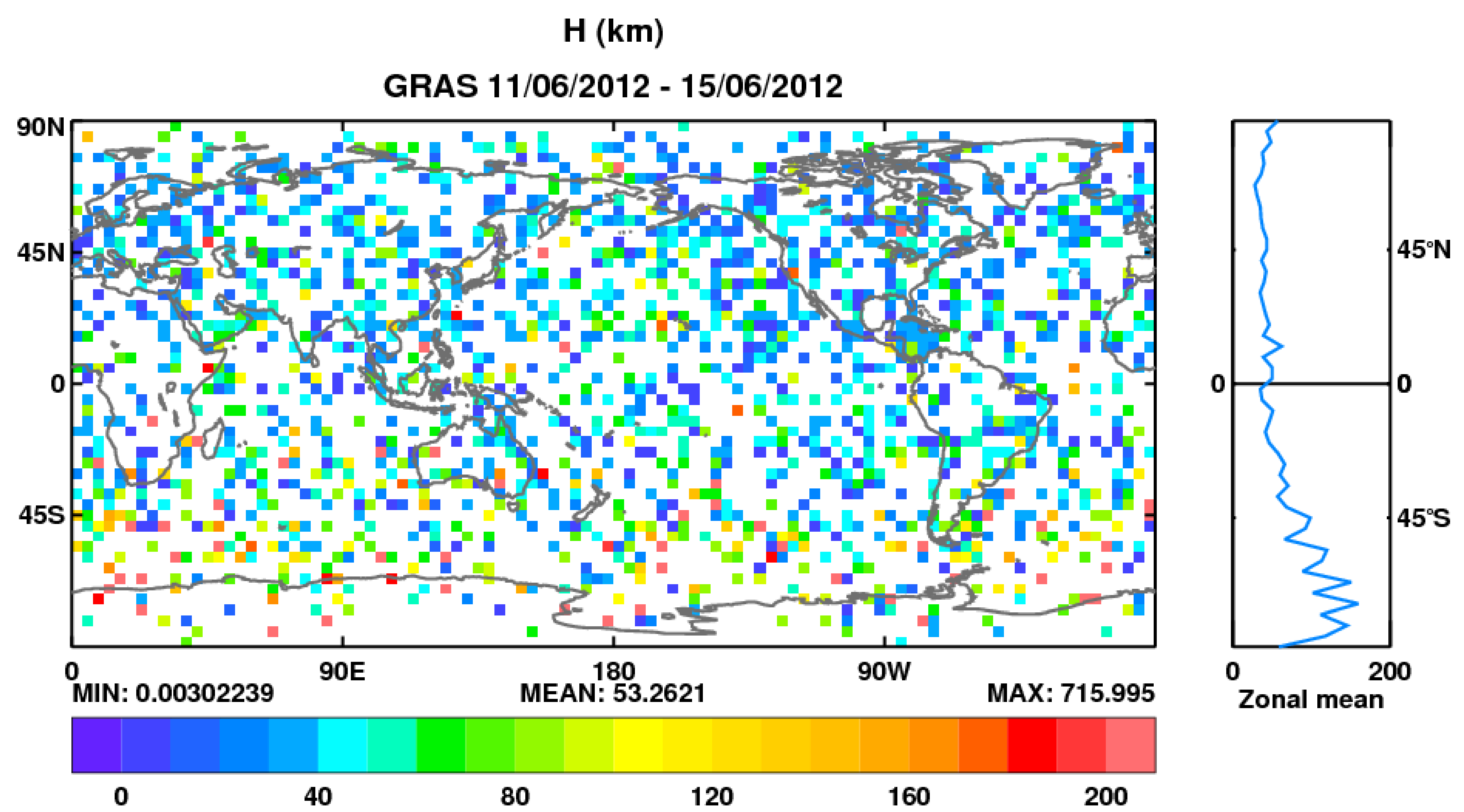

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