Ionosphere – impact on NWP/retrievals/climatologies

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The EUMETSAT Network of Satellite Application Facilities

ROM SAF
Radio Occultation Meteorology

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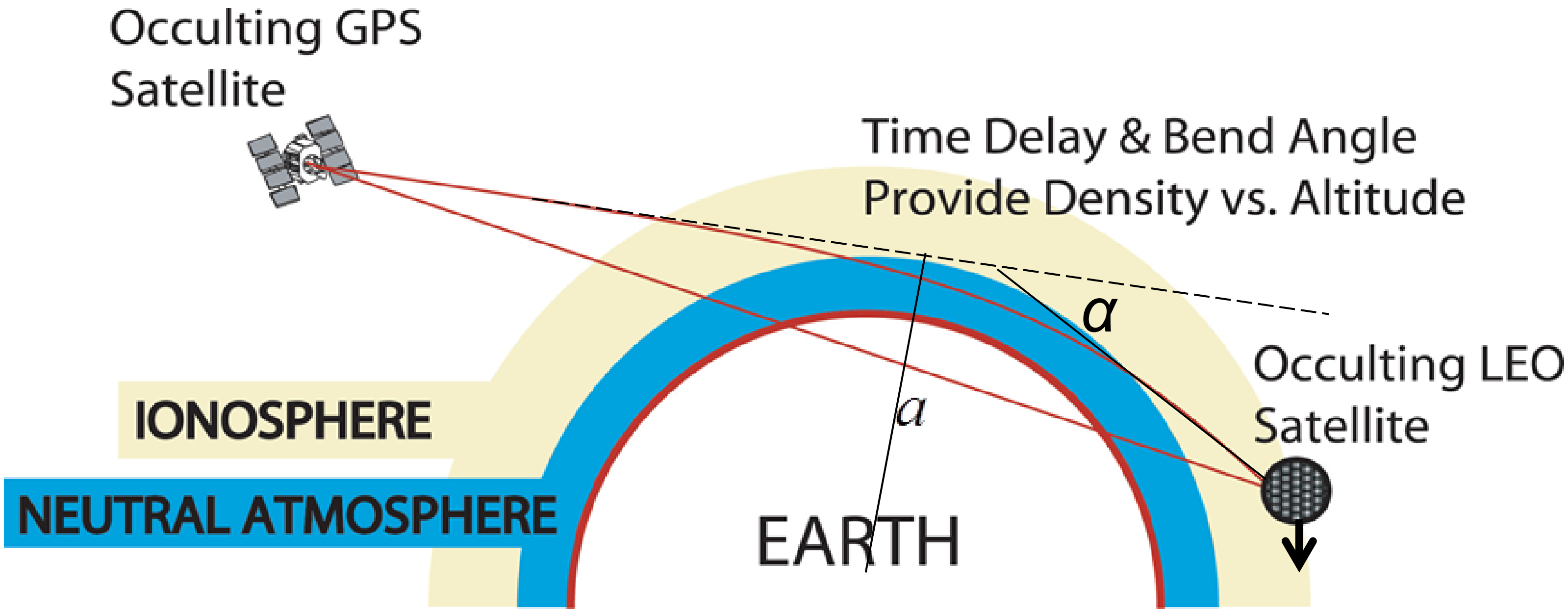
Outline

- NWP data assimilation.
- Standard bending angle ionospheric correction
  - Residual ionospheric errors. *Refer back to the original paper.*
  - New model to reduce the impact in monthly mean climatologies.
- Ideas about direct modelling of L1,L2 . 1D-Var with L1/L2 which will be released in the ROM SAF’s ROPP-8 software.
- The L1/L2 modelling will highlight some “odd” occultations.
- Summary.

GPS-RO geometry

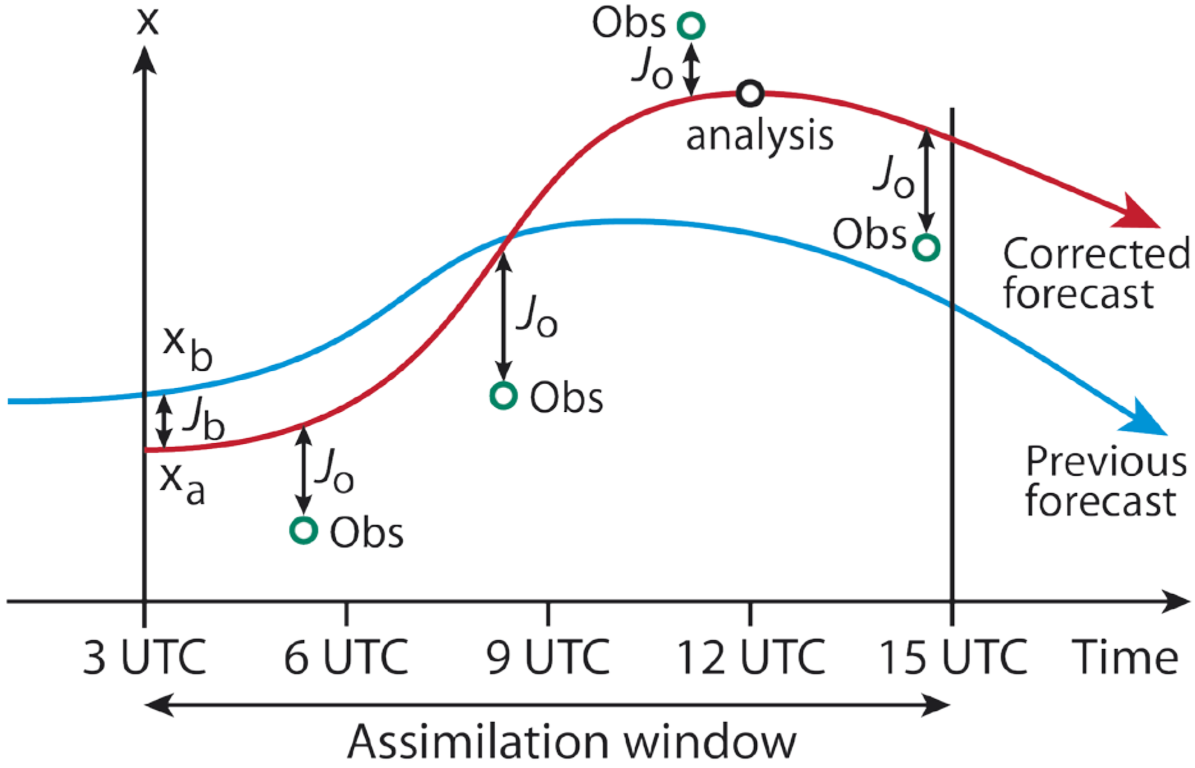
(***Classical mechanics***: **deflection in a gravitational field/charged particle by a spherical potential!)**



Setting occultation: LEO moves behind the earth.
We obtain a profile of bending angles, **α**, as a function of impact parameter, a.

*The **impact parameter** is the distance of closest approach for the straight line path. **Determines tangent height, analogous to angular momentum**.*

4D-Var assimilation



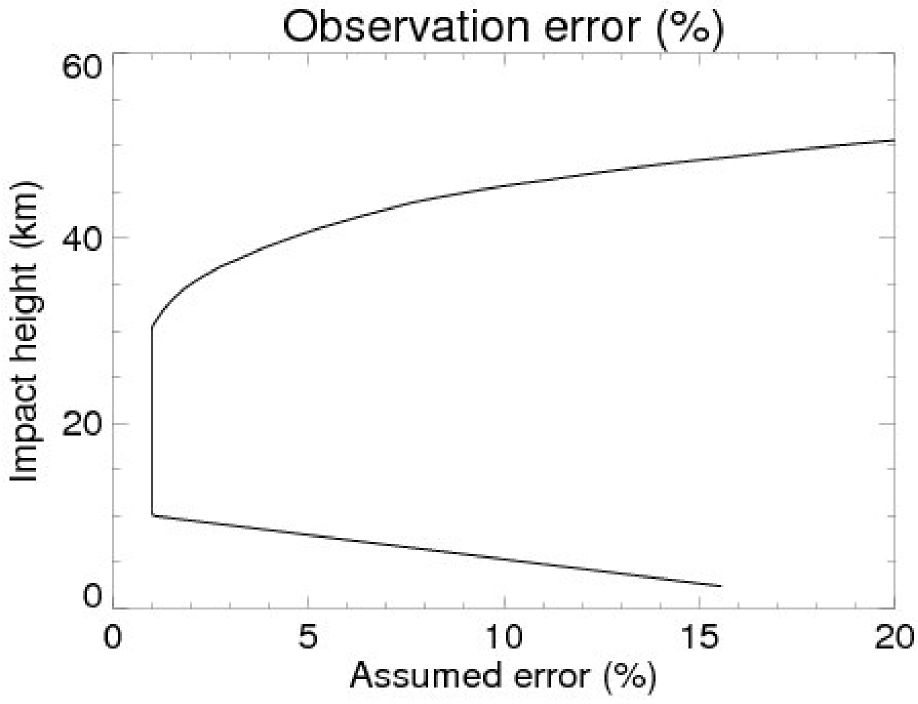
Key issues for data assimilation

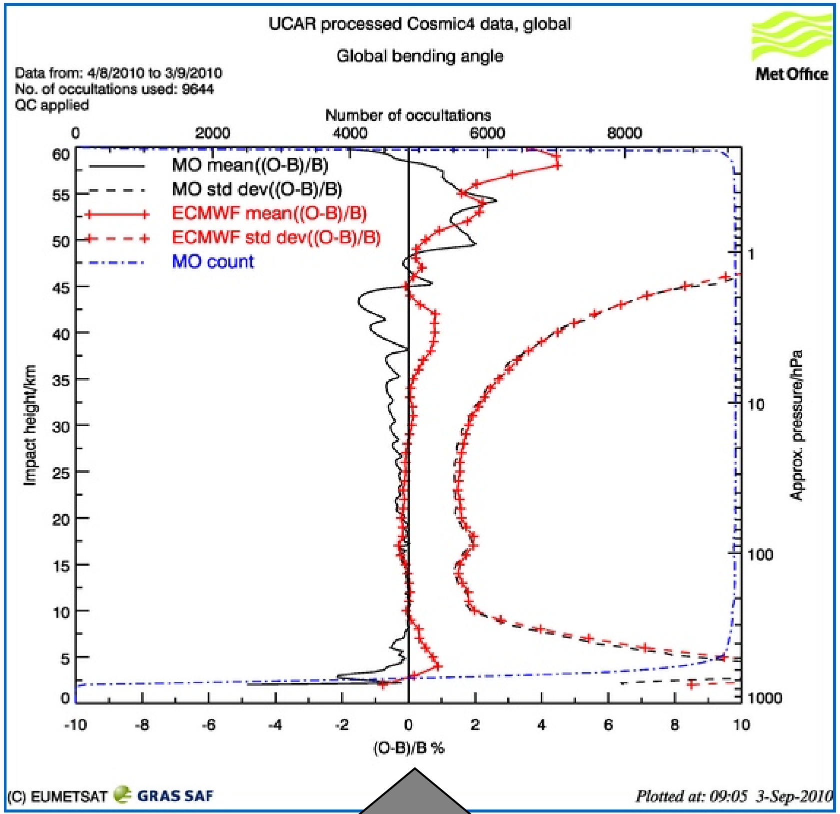
- Can you model the observations?
- Do you have a good understanding of the error statistics ?
- Then we can solve the assimilation cost function

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x_b})^{\mathrm{T}} \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x_b}) + (\mathbf{y} - H(\mathbf{x}))^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{y} - H(\mathbf{x}))$$

- We know/accept all observations have errors, but we need to have a good estimate of the error statistics.

Assumed (global) observation errors and actual (o-b) departure statistics

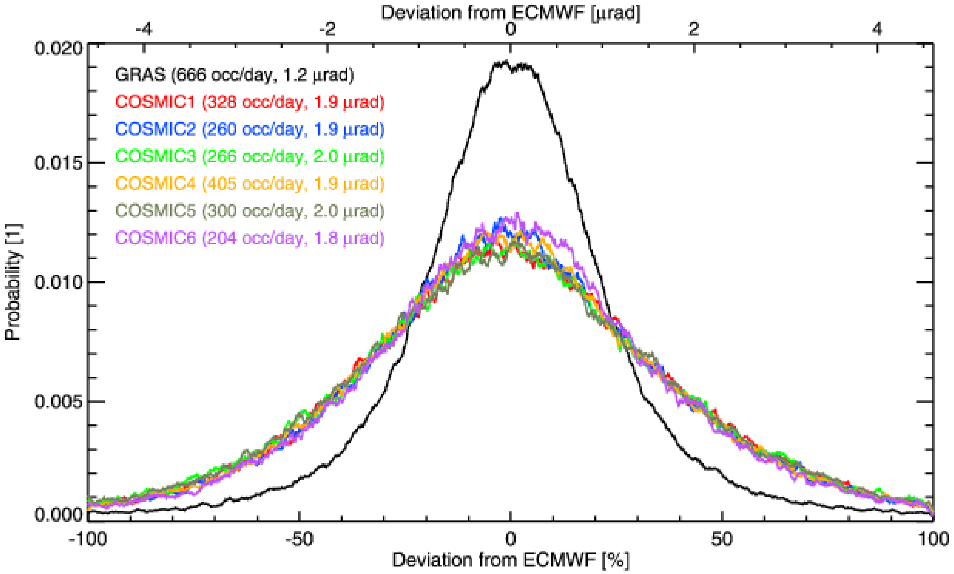




Consistent with o-b stats.

See http://www.romsaf.org/monitoring/

We can use NWP departure statistics to estimate the noise and inform our error model



(von Engeln *et al* GRL 2009)

The ionospheric correction (ECMWF training course lecture)

We have to isolate the atmospheric component of the bending angle. **The ionosphere is dispersive.** Compute a linear combination of the L1 and L2 bending angles to obtain the "corrected" bending angle. See *Vorob'ev + Krasil'nikov, (1994), Phys. Atmos. Ocean,* ***29****, 602-609*.

$$\alpha(a) = c\alpha_{L1}(a) - (c-1)\alpha_{L2}(a)$$

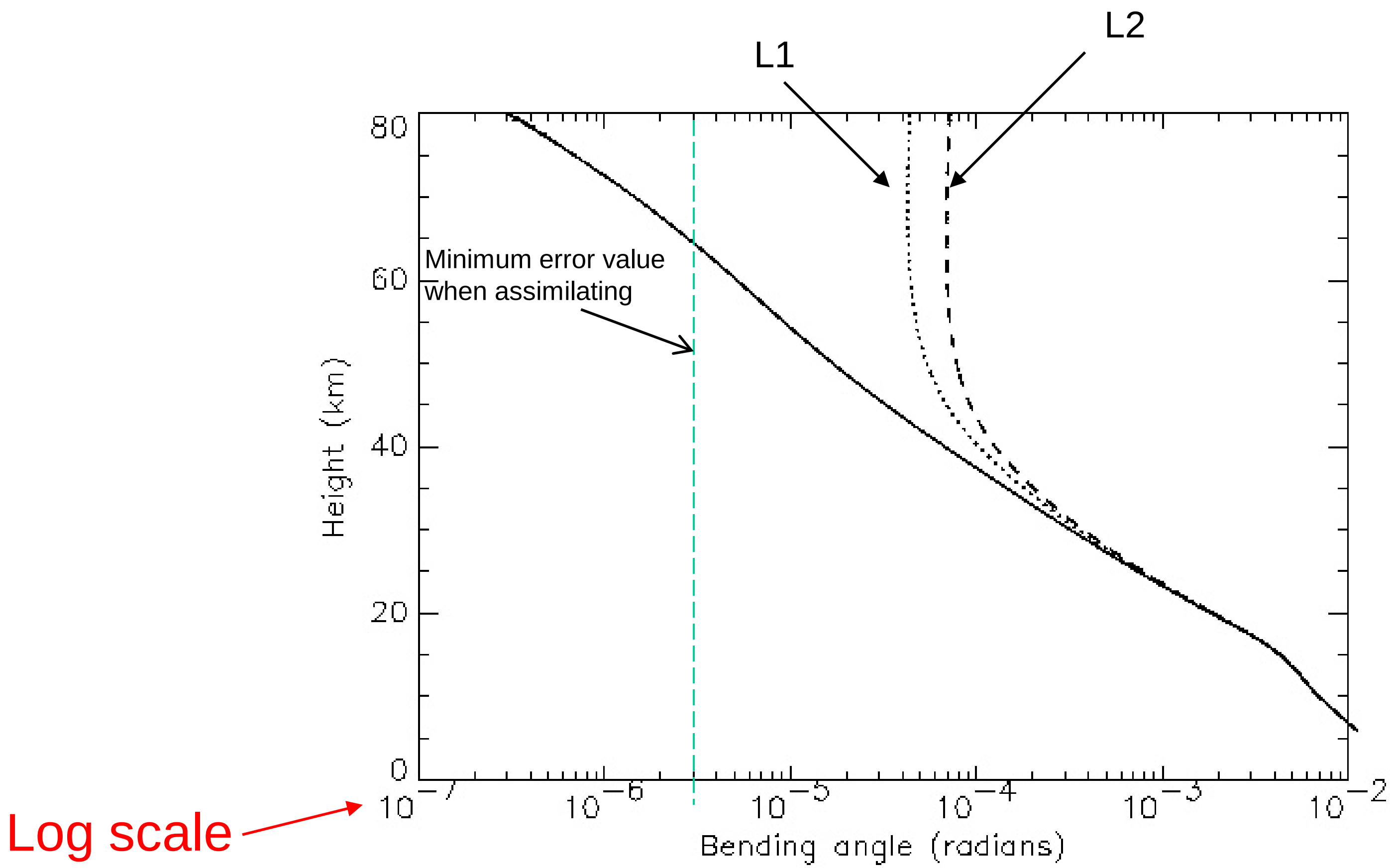
"Corrected" bending angles

Constant given in terms of the L1 and L2 frequencies.

$$\boxed{c = \frac{f_{l1}^{2}}{(f_{l1}^{2} - f_{l2}^{2})}}$$

How good is the correction? Does it introduce time varying biases? Impact on climate signal detection? ***I don't think it's a major problem in regions where the GPS-RO information content is largest.***

Ionospheric correction: A simulated example



The "correction" is significant.

Accepted fact

- If you are going to improve upon the standard correction some *a priori* ionospheric information/model is required.

Sources of residual iono error (some discussion points)

- **Horizontal gradients**. Vorob'ev + Krasil'nikova (1994) claim these only "weakly affect" the accuracy of their approach. The provide simulations to back this up.

- **Higher order terms in the refractivity expression.**

$$n = 1 - c\frac{n_e}{f^2} - K\frac{B\cos\theta}{f^3} + \ldots$$

- The "B" term is less 0.1% of the 2nd term. Syndergaard (2000) and Lui et al (2013) claim the B term can be neglected when estimating the residual iono error.

- Vergados + Pagiatakis (2013). Error ~ 1e-8 rads.

Standard bending angle correction

- This will produce a **bias** even if the atmosphere is spherically symmetric and the earth's magnetic field is B=0.
- Assumption is that bending is linear in n_e. (Forget about neutral contribution to refractive index *n*)

$$\int \frac{dn/dr}{n\sqrt{(nr)^2 - a^2}}\,dr \approx \int \frac{dn/dr}{\sqrt{r^2 - a^2}}\,dr$$

- Vorob'ev and Krasil'nikova (1994) (**VK94**) produce and integral expression that quantifies the error in this approximation.

VK94 bias term (see their eq.22)

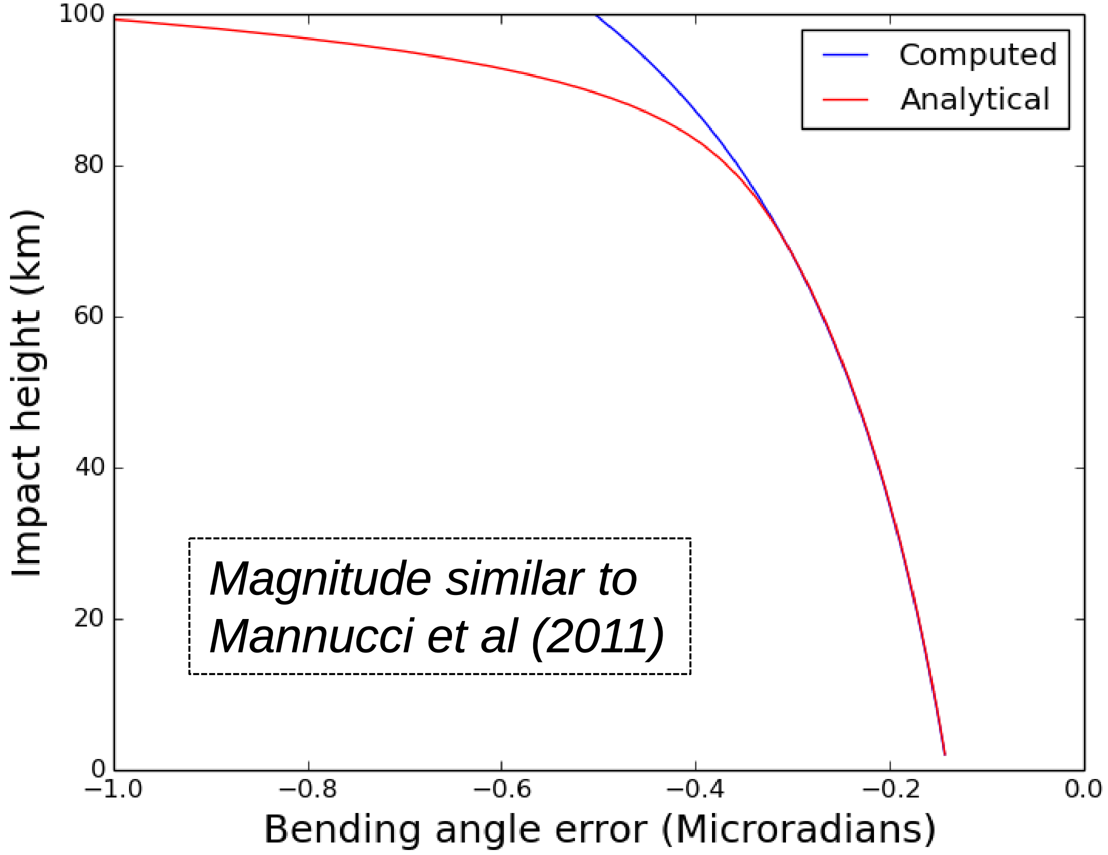
- Error in corrected bending angle (*slightly different to their eq.22 expression*)

Assumes n_e is 0 at tangent point

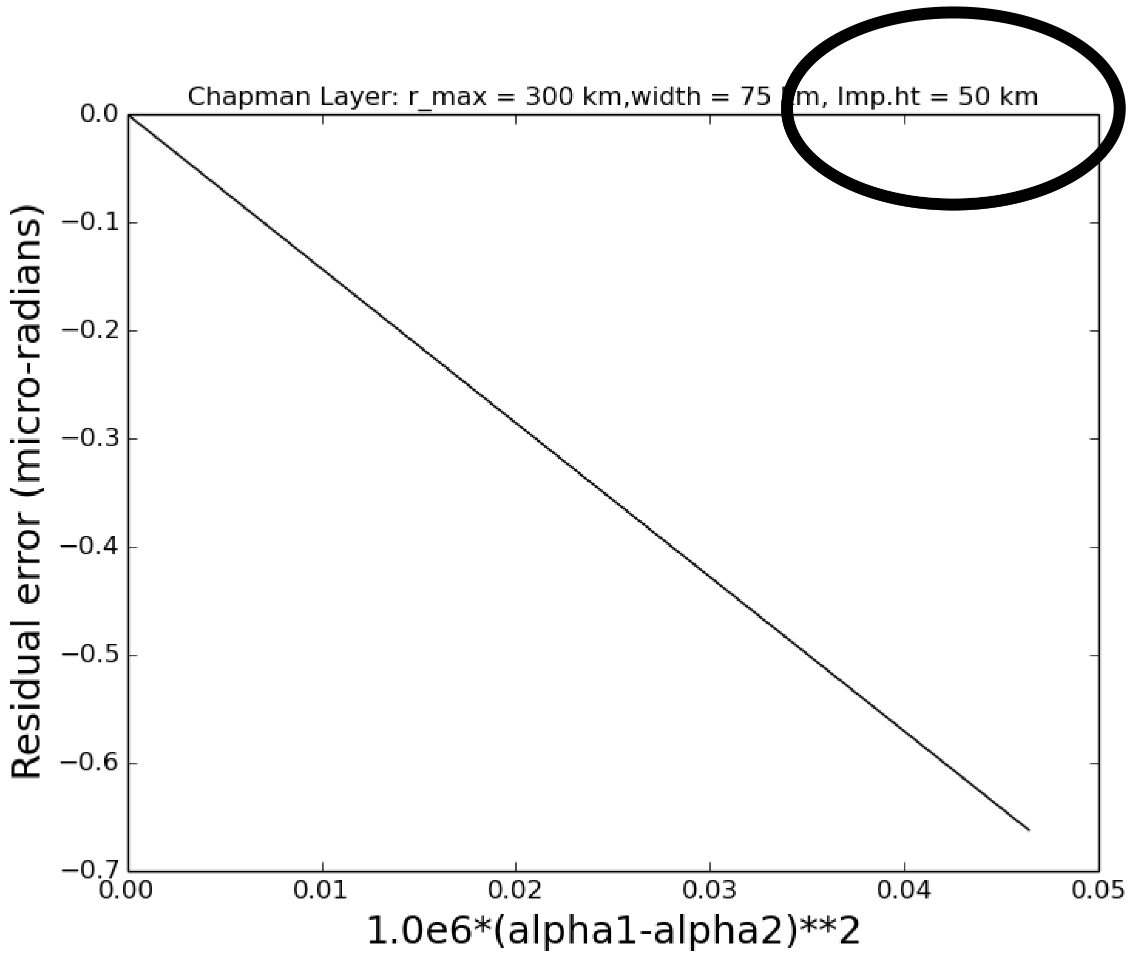
$$\Delta\alpha \propto -\int \frac{\left(2r^2 - a^2\right) d\left(n_e^2\right) / dr}{\left(r^2 - a^2\right)^{3/2}} \, dr$$

- Noted in Syndergaard (2001), Danzer et al 2013, but I can't recall many other references to this.
- Main source of residual iono bias in climatologies?
- Works very well in 1d simulations.

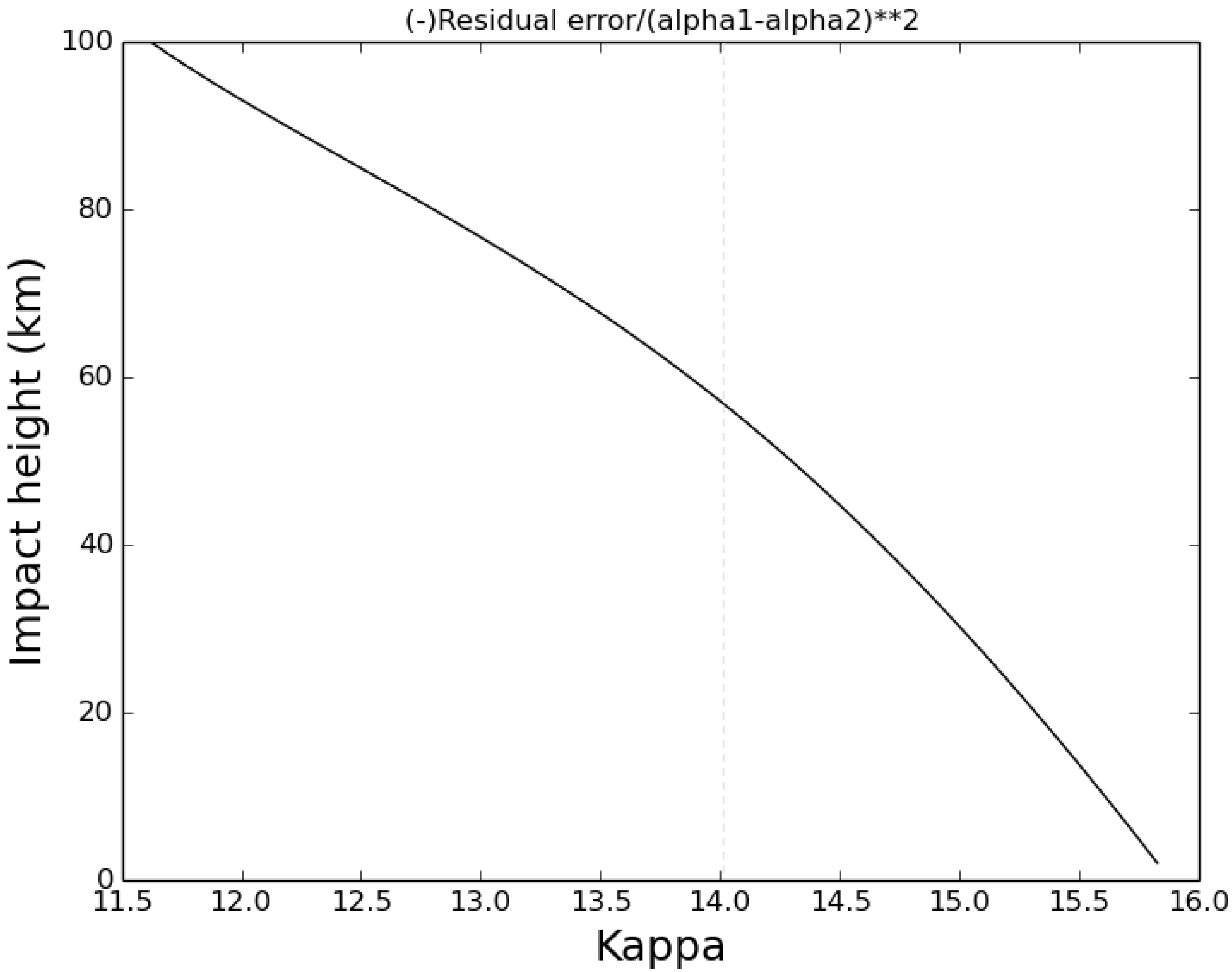
Computed and estimated residual ionospheric errors for a Chapman layer (~solar max)



Vary the peak electron density and plot error



$$\Delta\alpha = -\kappa(a) \times \left(\alpha_1 - \alpha_2\right)^2$$



We can estimate kappa analytically for some 1D ionospheres

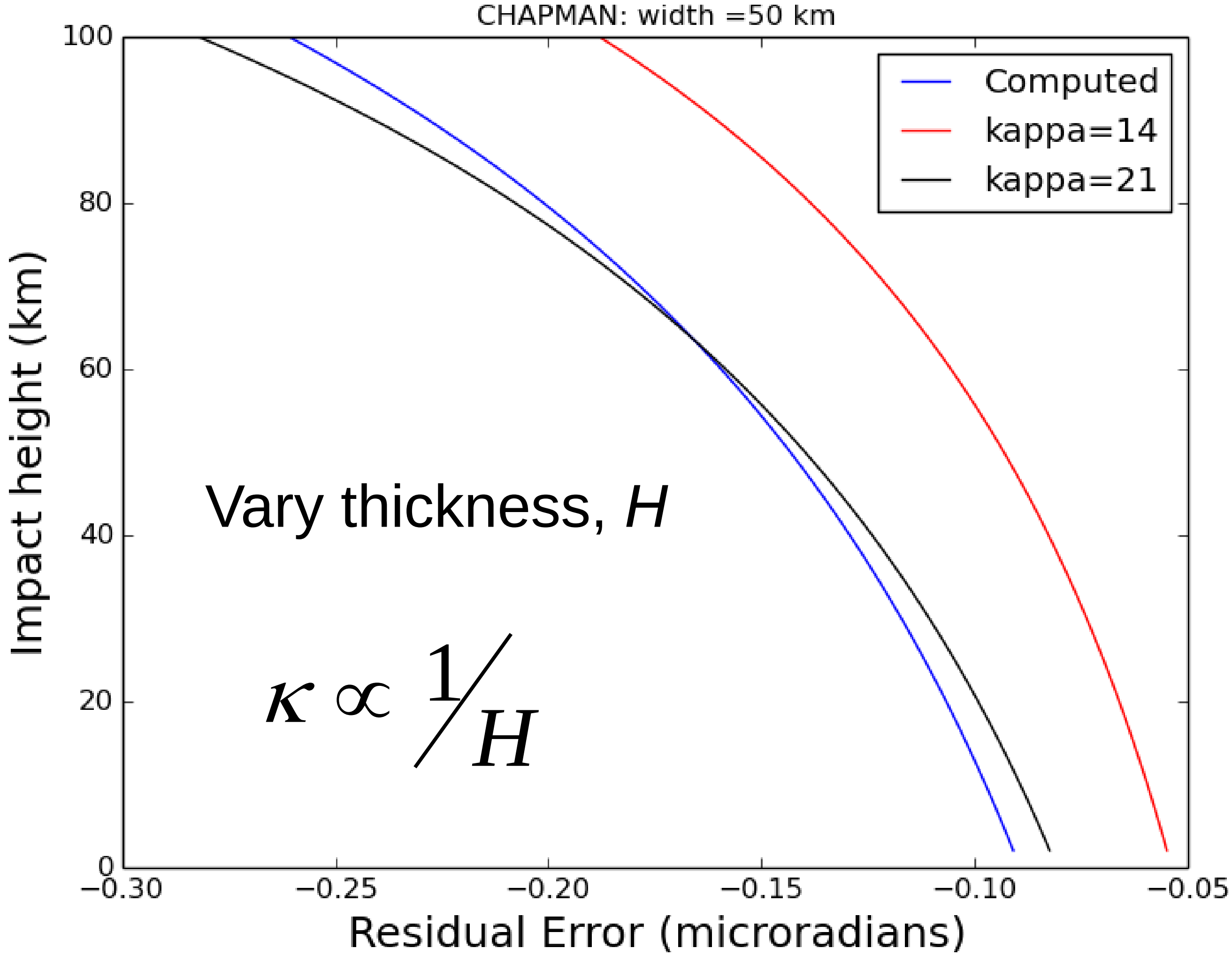
- Approach :

  1. Solve the bending angle integral analytically for simple profile.

  2. Solve VK94 error integral analytically.

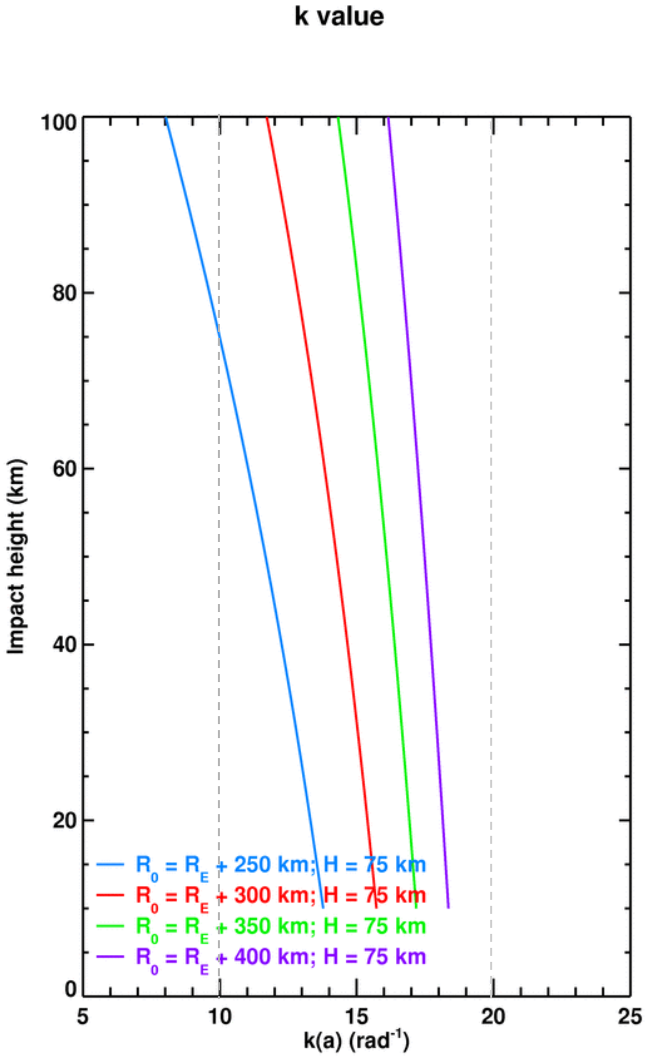
  3. Substitute answer for 1) into 2) ...

  We can produce kappa values close to computed values.



$$\kappa \propto 1/H$$

Variation with height of peak n_e



Remarks

- We still assume an *a priori* ionospheric model. **Its buried in kappa**.
- Question: is the main temporal variation of this residual bias captured by the bending angle squared term?

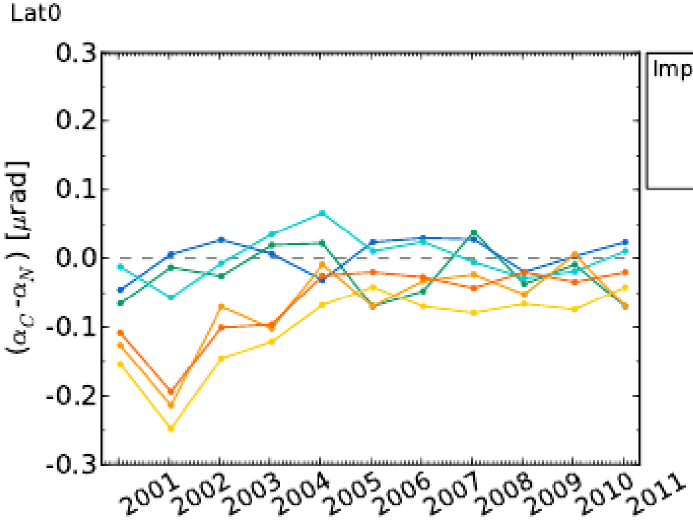
$$\Delta\alpha = -\kappa(a)\times\left(\alpha_1 - \alpha_2\right)^2$$

- Could we use a model like this to improve monthly/seasonal mean climatologies from GPS-RO.
- Perhaps link this in with the new average bending angle approach (Ao et al 2012; Gleisner and Healy 2013).

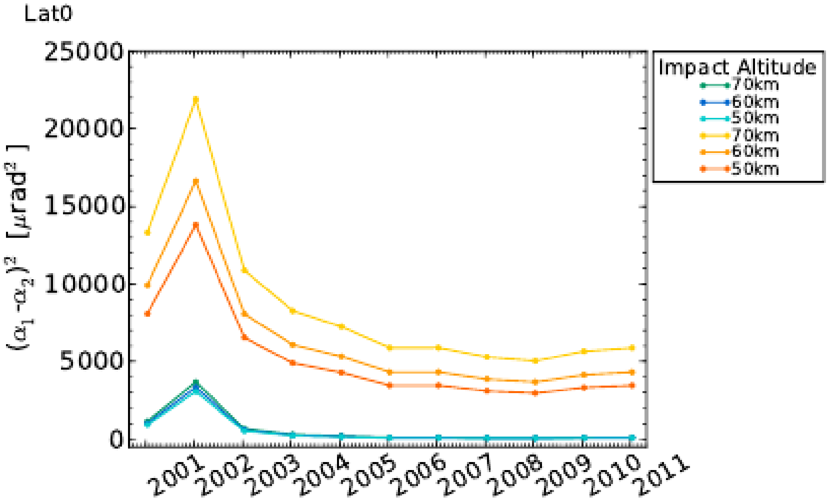
Results from a EUMETSAT ROM SAF visiting scientist activity

- Julia Danzer (Univ. Graz) Paper in prep. Report available at
  - http://www.romsaf.org/visiting_scientist.php
- **(See VS report 24)**

ROM SAF VS24



(a) Residual vs Time



(b) Temporal model term vs Time

Fig. 2: Residual night (blue) and day time (orange) bending angle error dependent on time and night and day time temporal model term dependent on time, studied on three impact altitudes and for latitude band 0°.

ROM SAF VS24

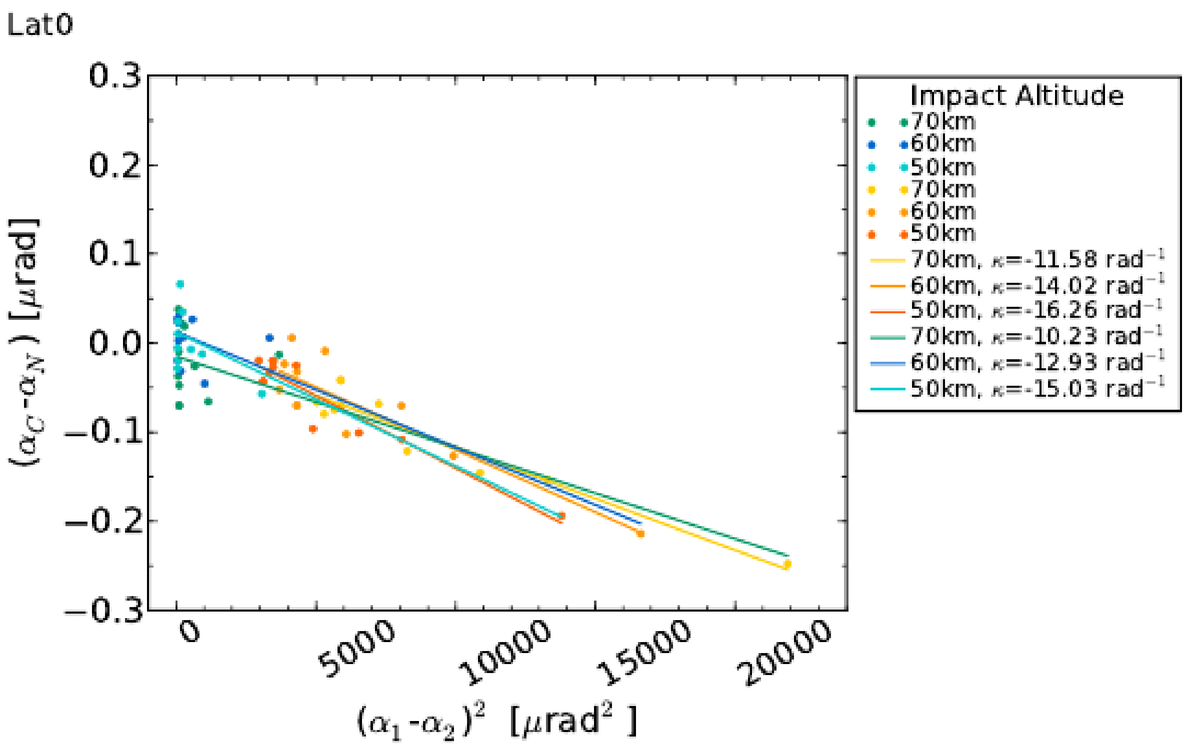


Fig. 3: Scatter plot and linear fit with fitting coefficient κ of the night (blue) and day time (orange) residual error versus the temporal model term, analyzed for three impact altitudes and for latitude band 0°.

ROM SAF VS24

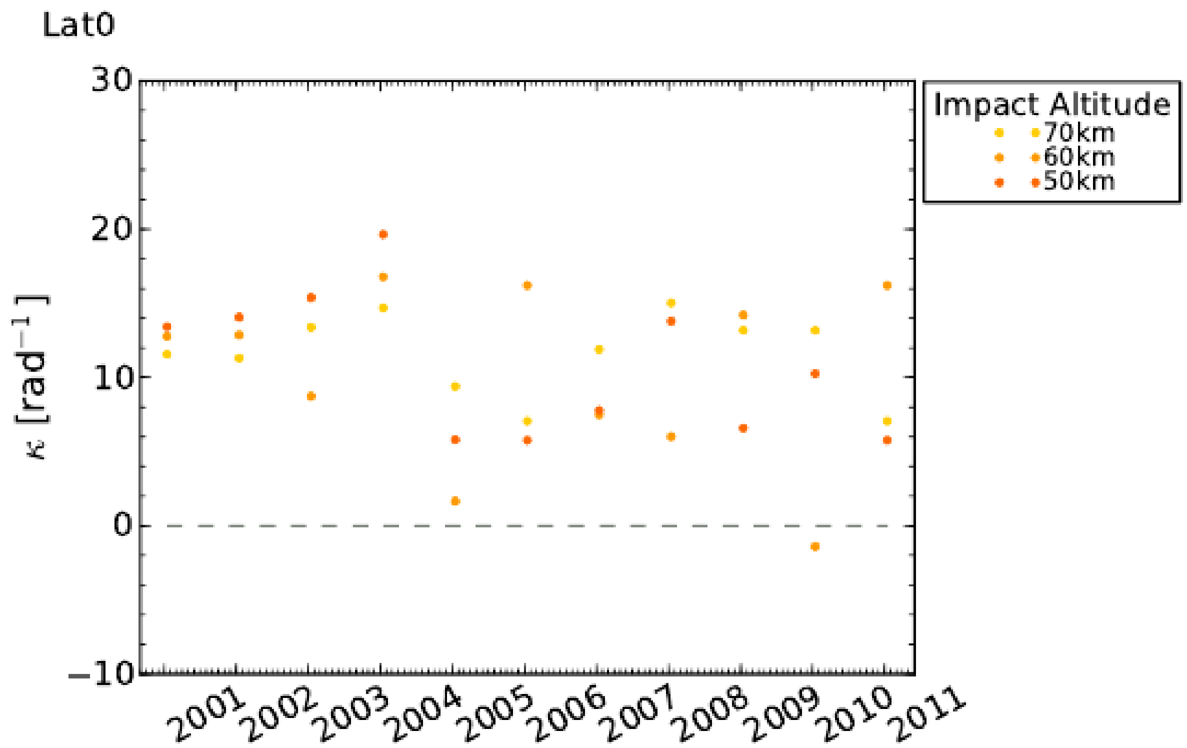


Fig. 4: The coefficient κ dependent on time for day time profiles and latitude band $0°$, studied for three impact altitudes.

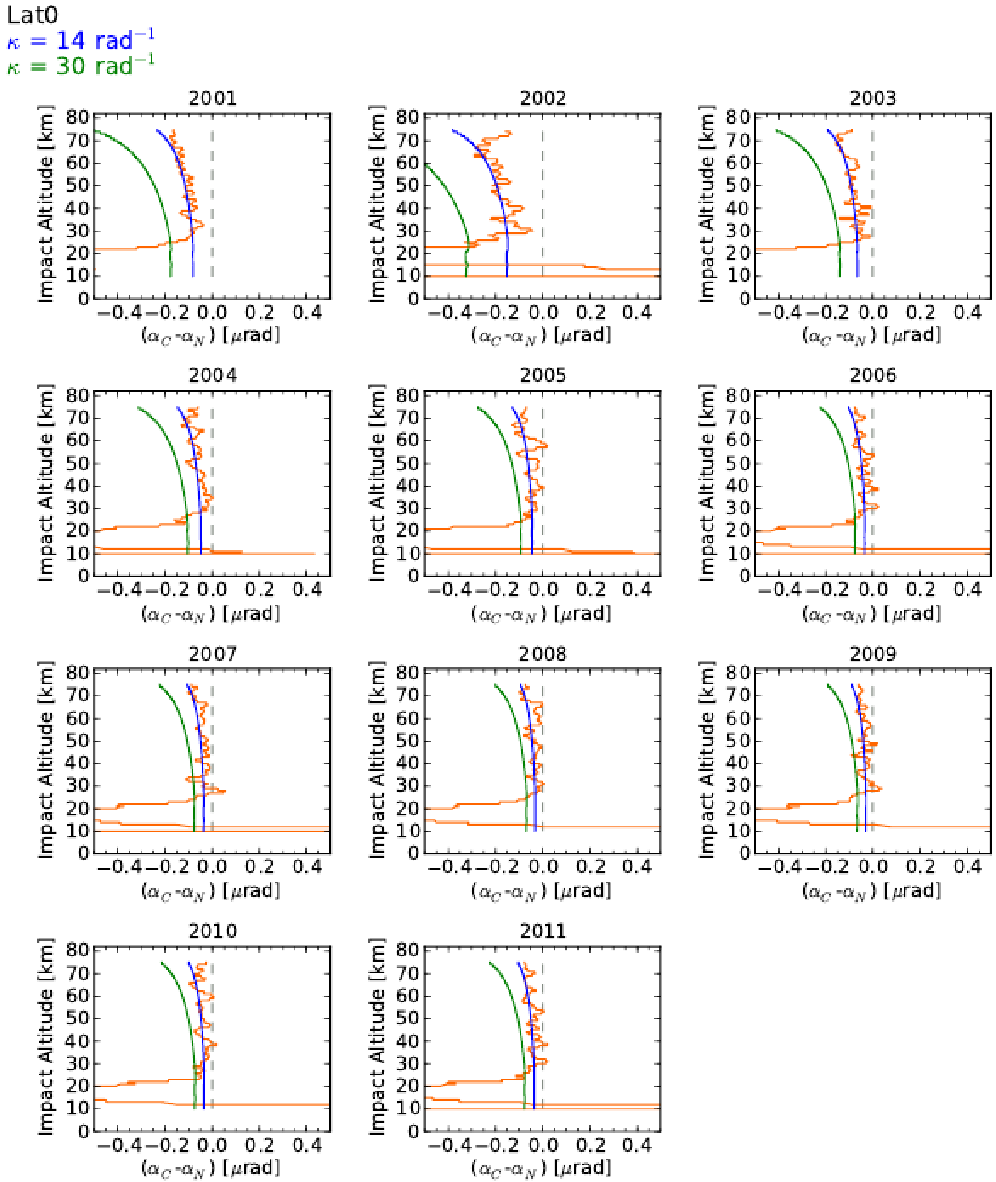


Fig. 5: Comparing the residual ionospheric correction to the monthly mean day time residual error at latitude band 0°, choosing $\kappa(a) = 14\text{rad}^{-1}$ (blue) and $\kappa(a) = 30\text{rad}^{-1}$ (green) in the correction model.

IMPACT on monthly mean temperatures

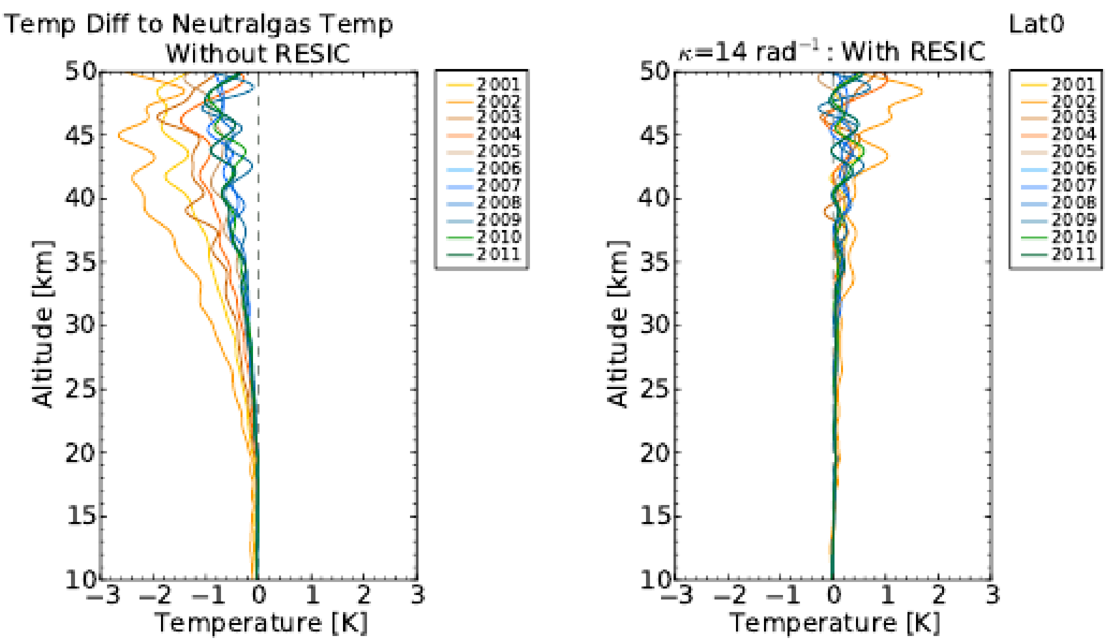


Fig. 6: Testing the effect of the residual ionospheric correction on temperature profiles, studied for latitude band $0°$ and using the coefficient $\kappa(a) = 14\text{rad}^{-1}$ from calculations.

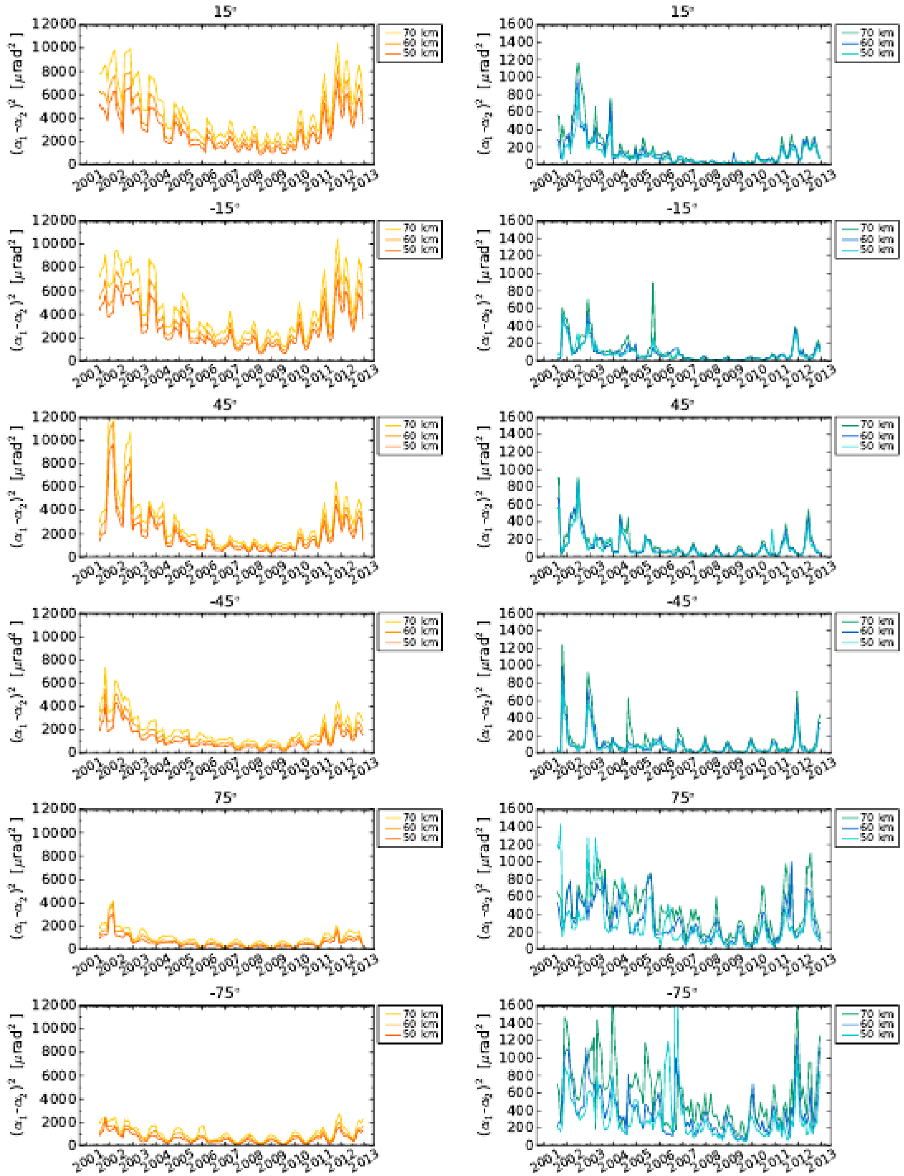


Fig. 7: Time series of $(\alpha_1 - \alpha_2)^2$, studied for day time (l.h.s.) and night time (r.h.s.) 30° zonal monthly mean satellite data on three different impact altitudes.

Looks very promising

- Kappa=14 is essentially assuming Chapman ionosphere, peaking at 300 km, with a width of 75 km. It is a model! There is uncertainty on these values. (±5 rad^-1)

- Perhaps we could do better with monthly mean peak height/thickness information.

- Information available?

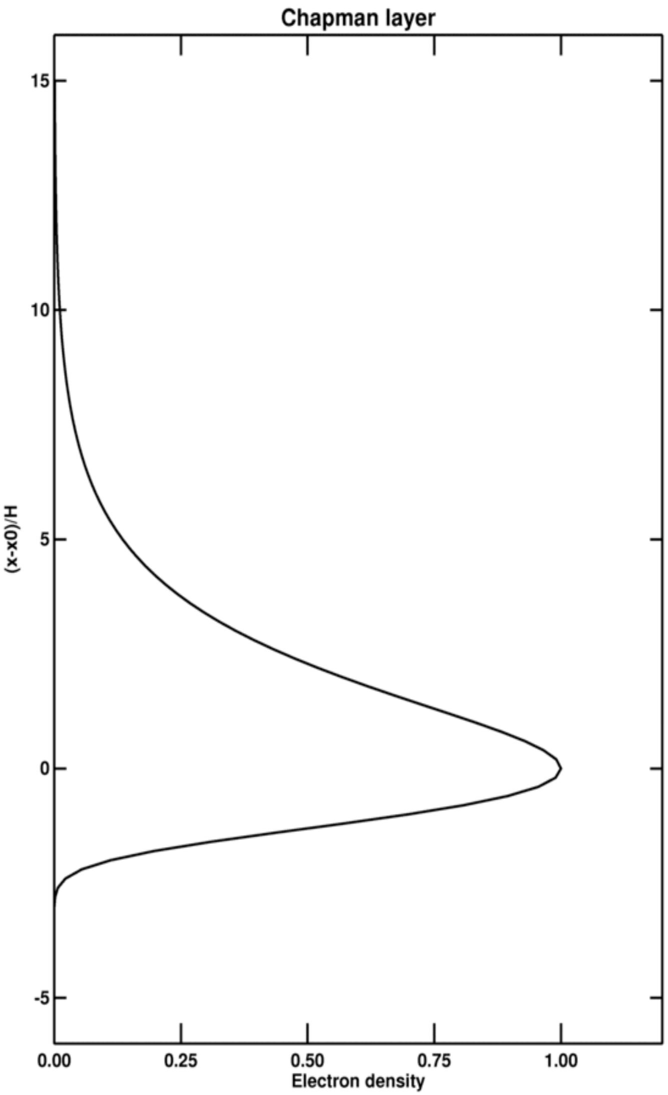
  - Derive kappa from an ionospheric model?
  - Derive from COSMIC ionospheric retrievals?

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

Ian Culverwell, Met Office

Sean Healy, ECMWF

Model ionosphere: electron density



Single Chapman Layer

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

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

Model ionosphere: bending angle

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

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

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

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

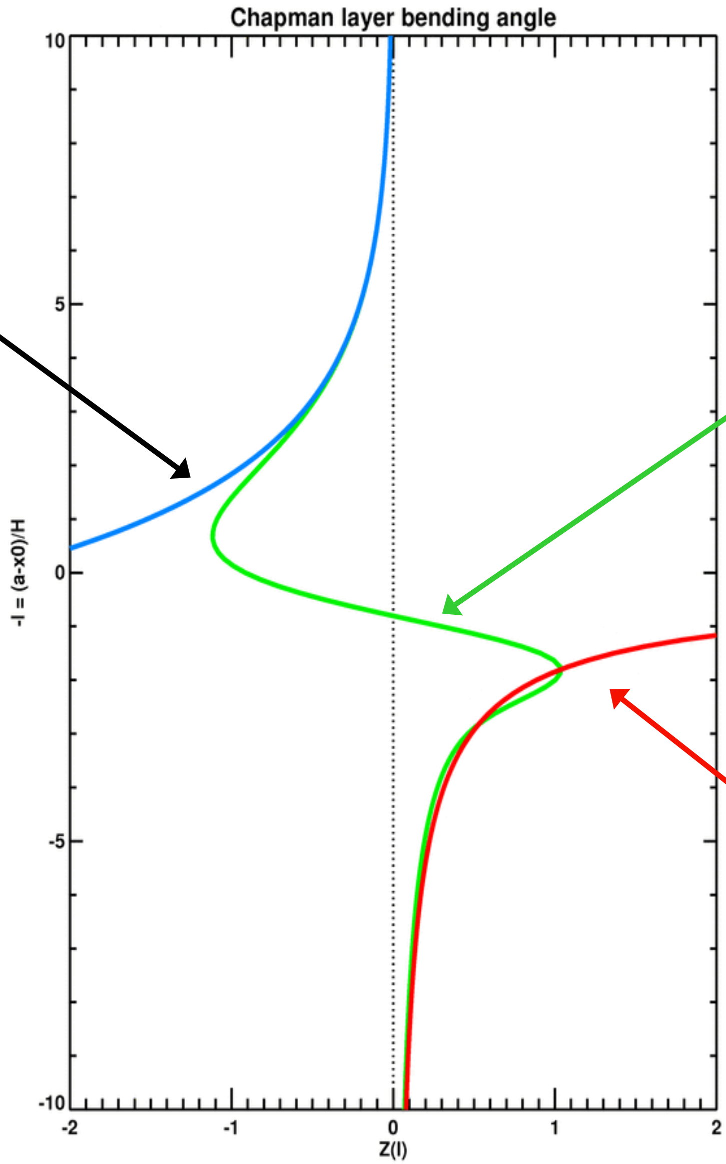
where

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

is just a dimensionless, O(1) function of

$$\mathbf{l = (r_0 - a) / H}$$

Model ionosphere: bending angle Z(l)



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

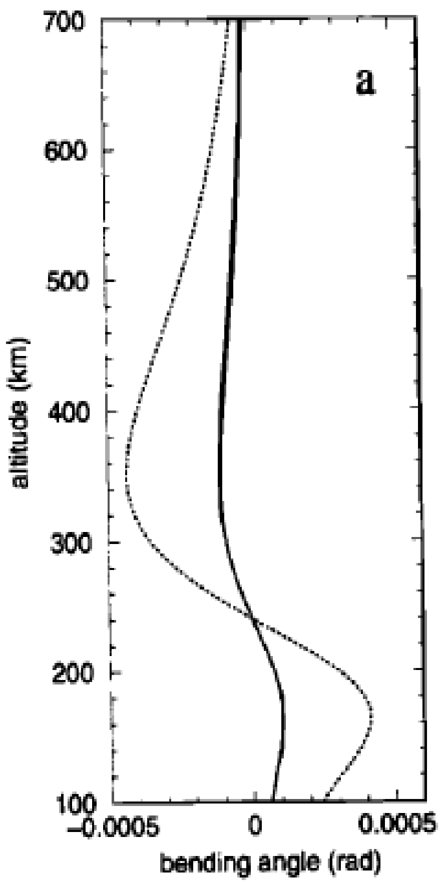
Actual ≈

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

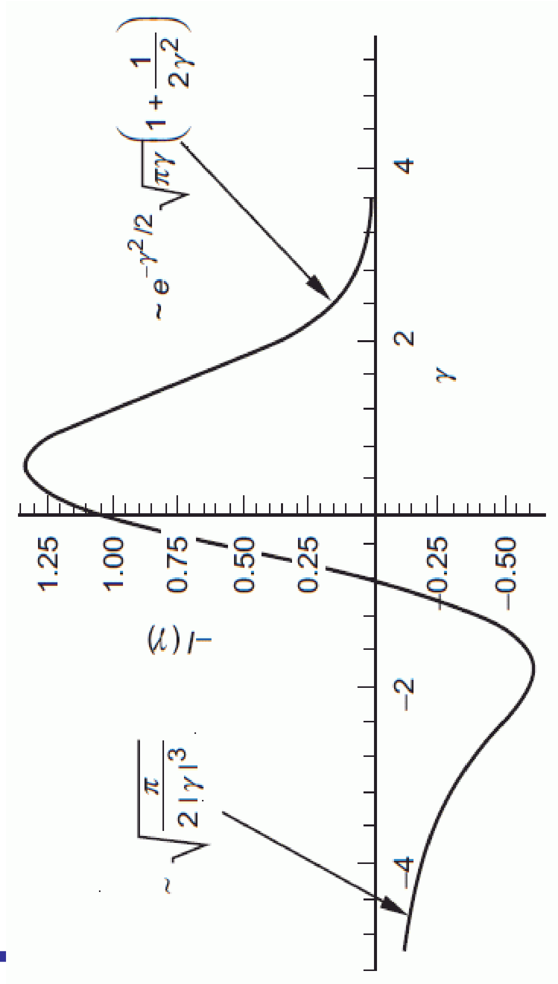
$\sqrt{(2\pi/l^3)}$

Model ionosphere: bending angle Z(I)

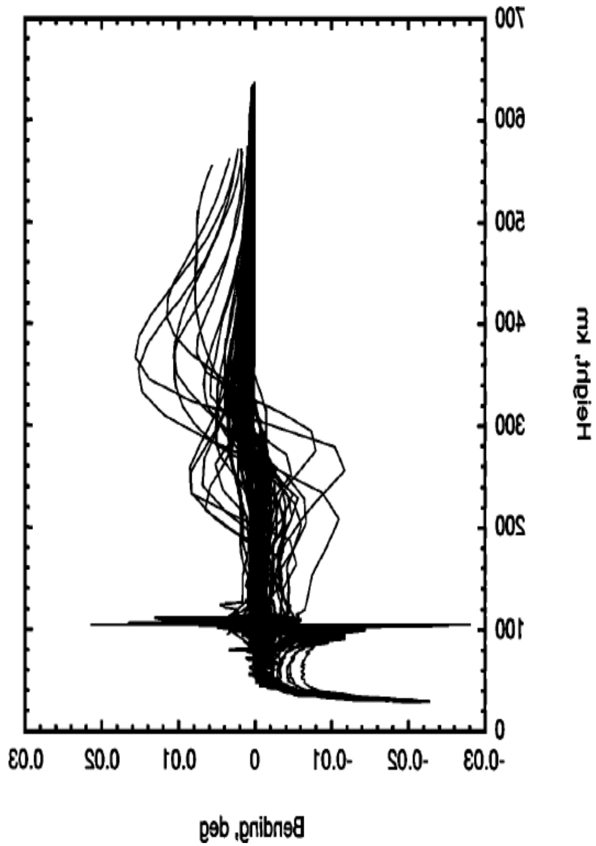
Schreiner et al, 1999, Chapman



Melbourne, 2004, Gaussian



Hajj & Romans,

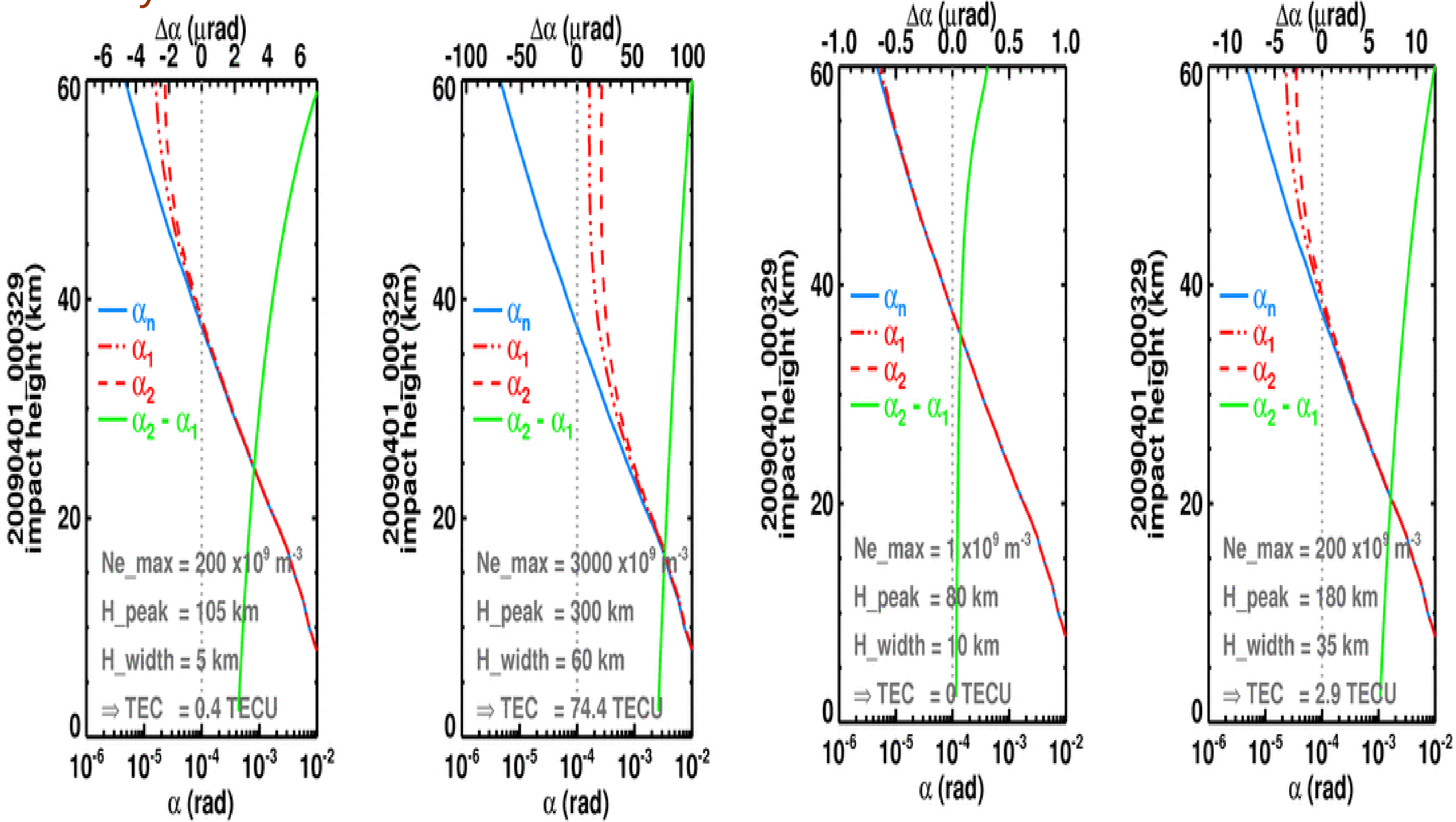


Direct modelling of L1 and L2 in ROPP

- 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).

Examples of forward modelled L1 and L2 using ropp_fm

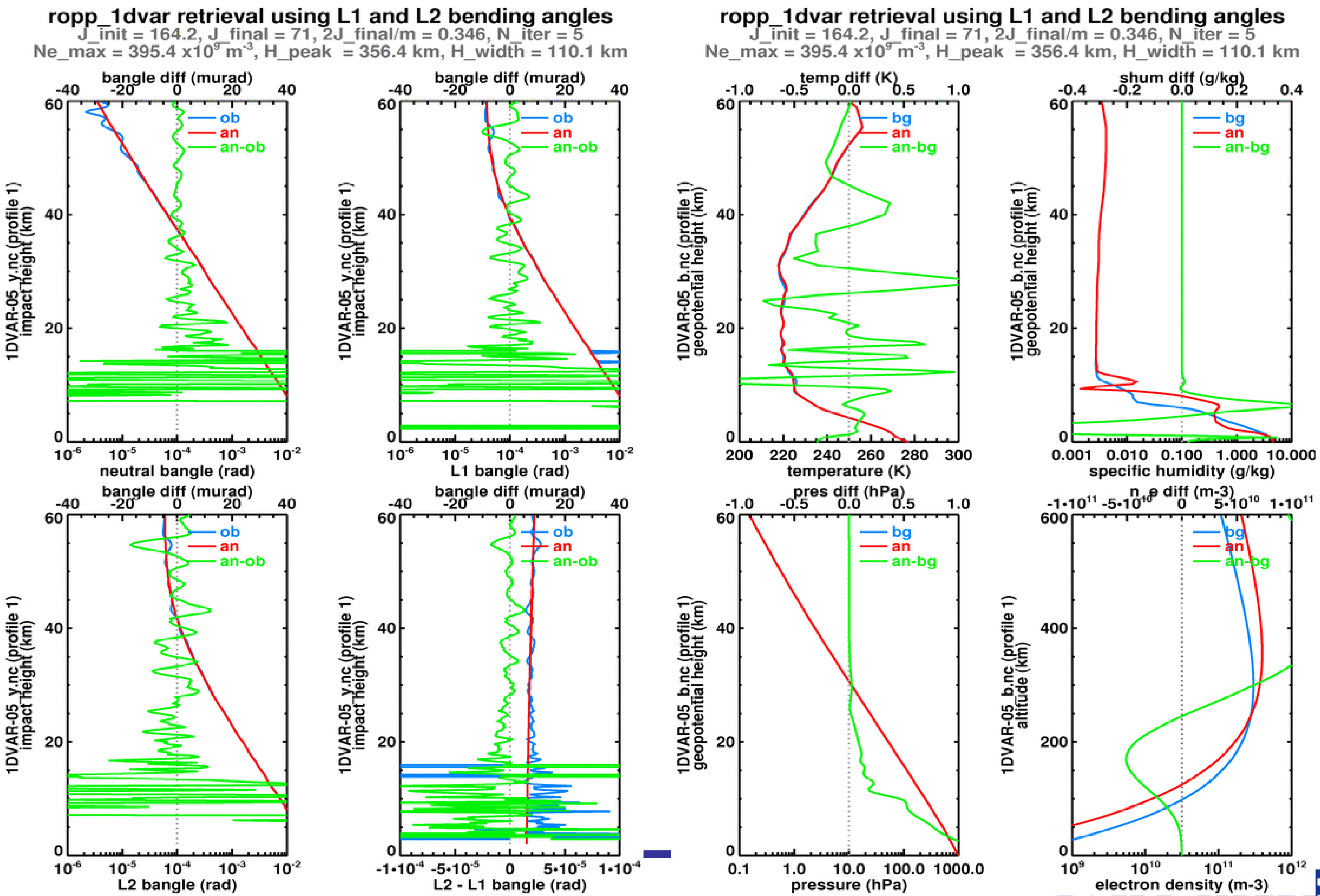
E-layer layer F-layer D-layer F1-



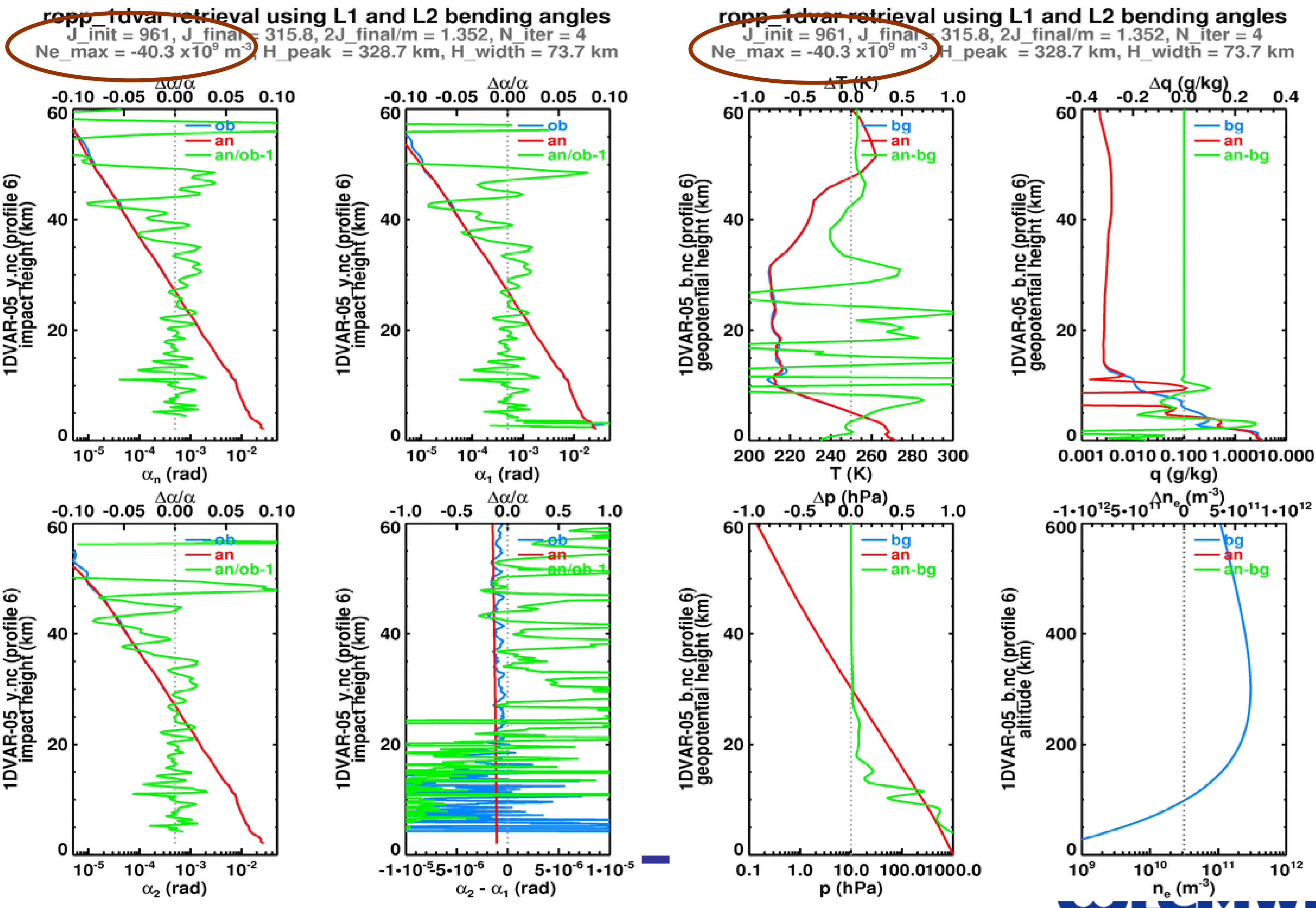
Direct modelling of L1 and L2 in ropp_1dvar

- Minimise $2J(\mathbf{x}) = (\mathbf{x} - \mathbf{b})^T \mathcal{B}^{-1} (\mathbf{x} - \mathbf{b}) + (\mathbf{H}(\mathbf{x}) - \mathbf{o})^T \mathcal{R}^{-1} (\mathbf{H}(\mathbf{x}) - \mathbf{o})$
- $\mathbf{x} = \{T, q, p^*, n_e^{max}, r_0, H\}$; $\mathbf{o} = \{\alpha_{L1}, \alpha_{L2}\}$
- $\mathcal{R}$
  - $\sigma(\alpha_{L1}) = \max(\alpha_n, 10\ \mu\text{rad})$; $\sigma(\alpha_{L2}) = \max(\alpha_n, 30\ \mu\text{rad})$
  - Assume α_{L1} and α_{L2} errors to be uncorrelated
  - Needs some experimentation
- $\mathcal{B}$
  - $\sigma(n_e^{max}) = 2\text{e}11\ \text{m}^{-3}$; $\sigma(r_0) = 150$ 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 L1 & L2 bending



Example 4: ropp_1dvar retrieval based on L1 & L2 bending



L1 > L2

- Can’t happen for a spherically symmetric ionosphere.
- Happens ~13% of GRAS profiles, more often winter/night when iono bending is small.
- Must be
  - Horizontal gradients in the ionosphere.
  - Assumption that n=1 at the LEO in processing Doppler to bending angle . (my current favourite).
  - Diurnal cycle of n_e at ~800 km in winter?

Summary

- We need a good understanding of the error statistics of the observations for NWP, and residual ionospheric errors are significant in the stratosphere.

- L1/L2 1D-Var in ROPP-8.

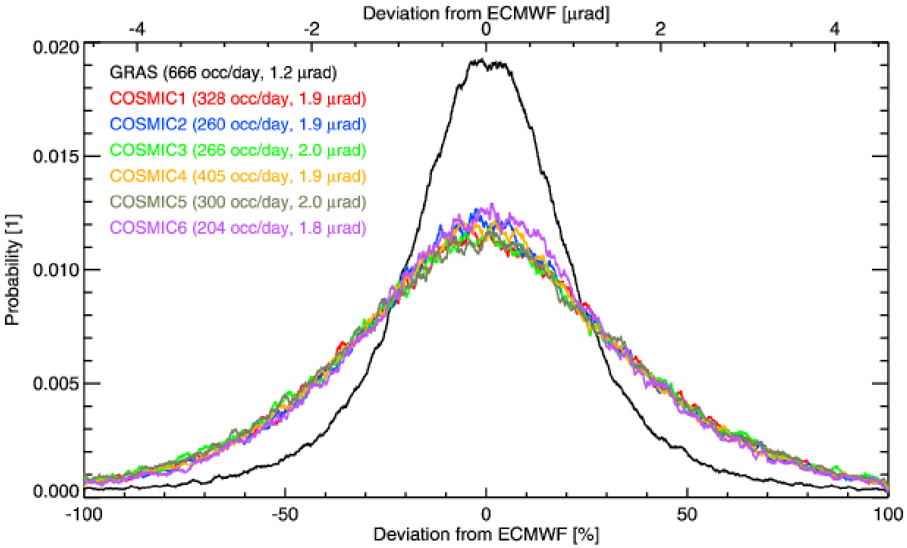
- Sources of residual ionospheric errors

  – Horizontal gradient errors?
  – Importance of the B term?

- VK94 error. Correction strategy for GPS-RO climatologies.
  – *Could we do better with monthly mean iono. Thickness and height information for kappa?*

noise

We can use NWP departure statistics to estimate the noise



(von Engeln *et al* GRL 2009)