Use of two-dimensional operators when assimilating GPS-RO measurements

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Outline

- Background on the potential benefits/limitations of 2d operators. (**Some old issues that I've expressed previously.**)
- **Work in progress – not complete**. Current experiments at ECMWF:
  - Dynamical estimates of observation errors.
  - Some promising results with 2d operators but the sample numbers are small when considering forecast scores.
- Summary.

Background

- **GPS-RO measurements have an impressive impact on temperatures in the upper troposphere to lower/mid stratosphere.**

- Impact on tropospheric temperature/humidity has been smaller, but the observation errors have been conservative and the operational centers have used 1D operators.

- ECMWF has been running a 1D bending angle operator since December 2006. Recent improvements include non-ideal gas effects (Aparicio) and tangent point drift (NCEP, MF).

- Benefits of 2D operator should be more obvious as the NWP model resolution increases. ECMWF is investigating 2D operators currently.

2D operators

- The 2D operators take account of the real limb nature of the measurement, and this should reduce the forward model errors defined as

$$H(\mathbf{x}_\mathbf{t}) - \mathbf{y}_\mathbf{t} = \boldsymbol{\varepsilon}_\mathbf{f}$$

Forward model error

Noise free observation

Discrete representation of true state from model

- Reducing the forward model errors should improve our ability to retrieve information from the observation, but this must be balanced:

Extra Information versus Additional Computing Costs.

Eyre (1994) ECMWF Tech memo 199

- Horizontal gradients mean that the GPS-RO information may be "**misinterpreted**" when assimilated with a 1D operator.
  - **2D operators mean we can make use of accurate, prior information about the gradients provided by the NWP forecast**
  - **But GPS-RO has intrinsically low horizontal resolution, so it cannot and should not change the detailed horizontal structure of the NWP forecast state.**
  - **Analogy with radiance assimilation: Broad vertical weighting functions mean that radiances cannot introduce detailed vertical structure. (This is one of the reasons why GPS-RO has a big impact on the UTLS temperatures.)**

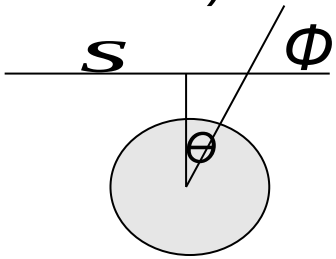
2D operators

- The GPS-RO measurement provides information on a broad (~400 km) horizontal average.
- The role of the 2D operator is essentially to compute a suitable average - or **horizontal weighting function** - on this kind of scale.
- A neat approach is the "non-local" refractivity (Syndergaard et al, 2005) or phase operator (Sokolovskiy et al 2005).
- I have looked at 2D bending angle operators (see also Zou, Poli papers).
- But **most (all?)** of these operators have some common limitations in their current form.

Interpretation of the derived impact parameter

- Bending angles are derived assuming the impact param. is a constant along the ray path (*or just same value at satellites?*):

$$nr\sin\phi = a$$



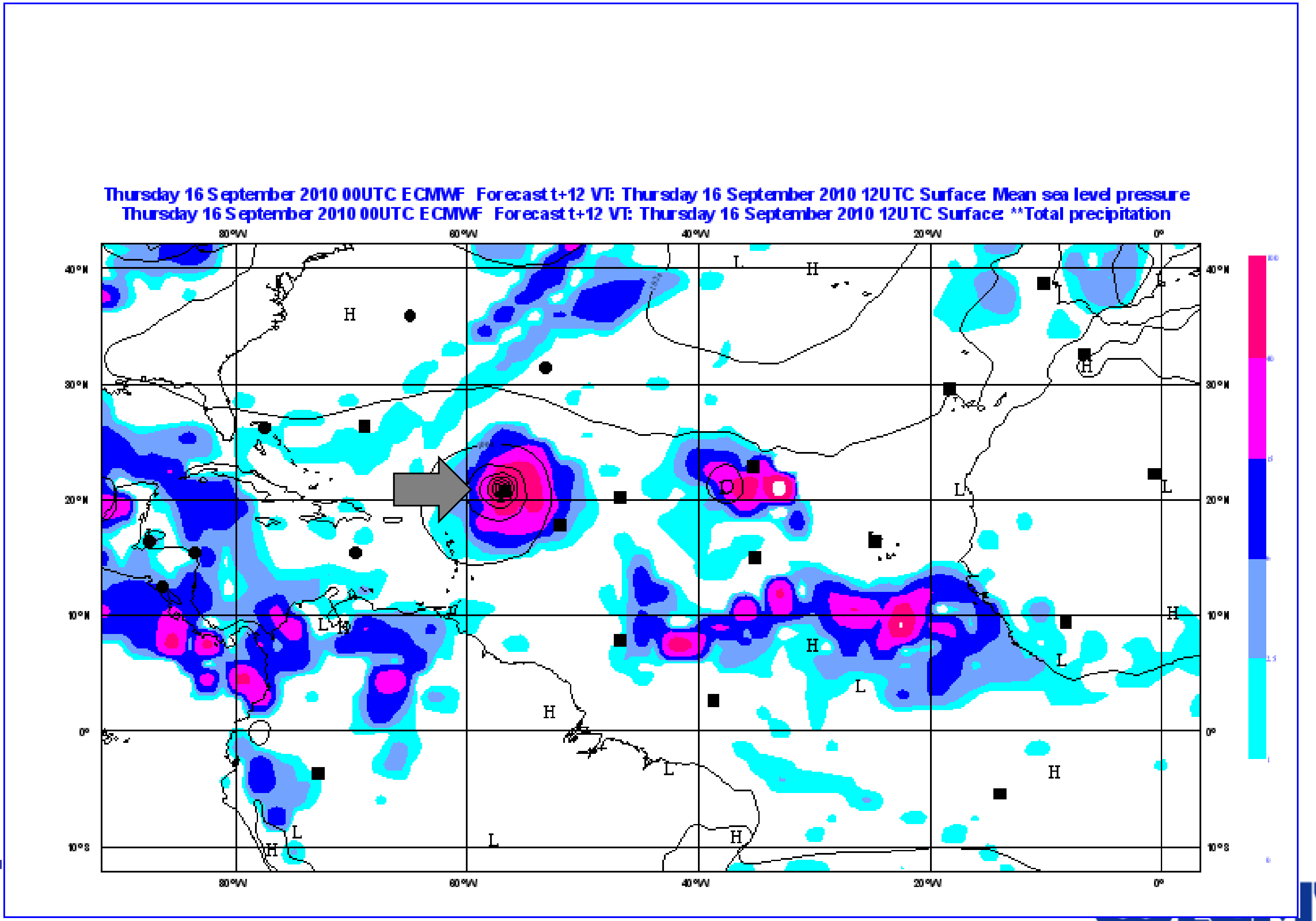
- But this quantity varies according to

$$\frac{da}{ds} = \left(\frac{\partial n}{\partial \theta}\right)_r$$

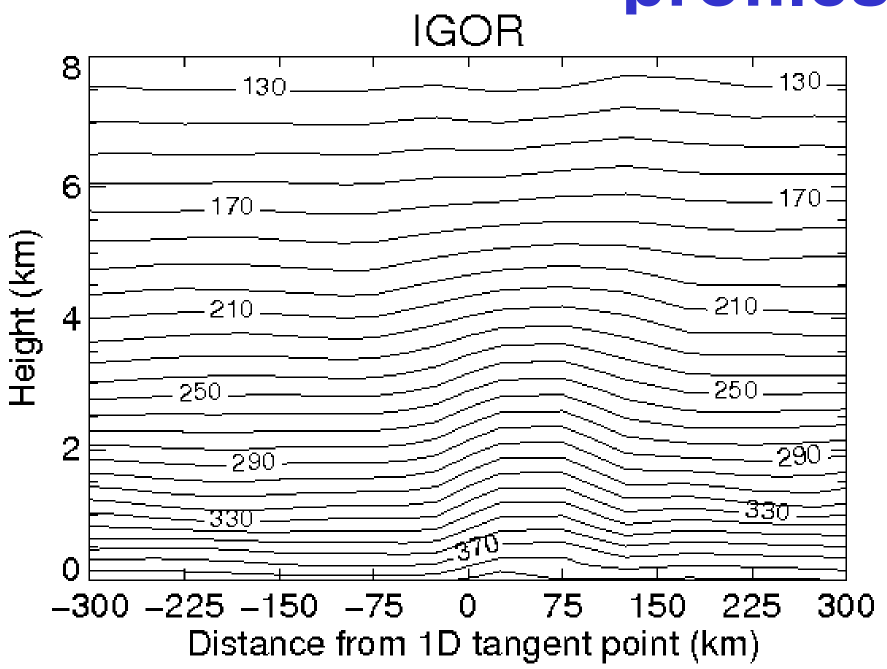
- The value provided with the observation is more closely related to the (*nr*sin*Φ)* at the receiver, **but we use it to derive the tangent height in the forward models**

$$z_t = {a}/{n_t}$$

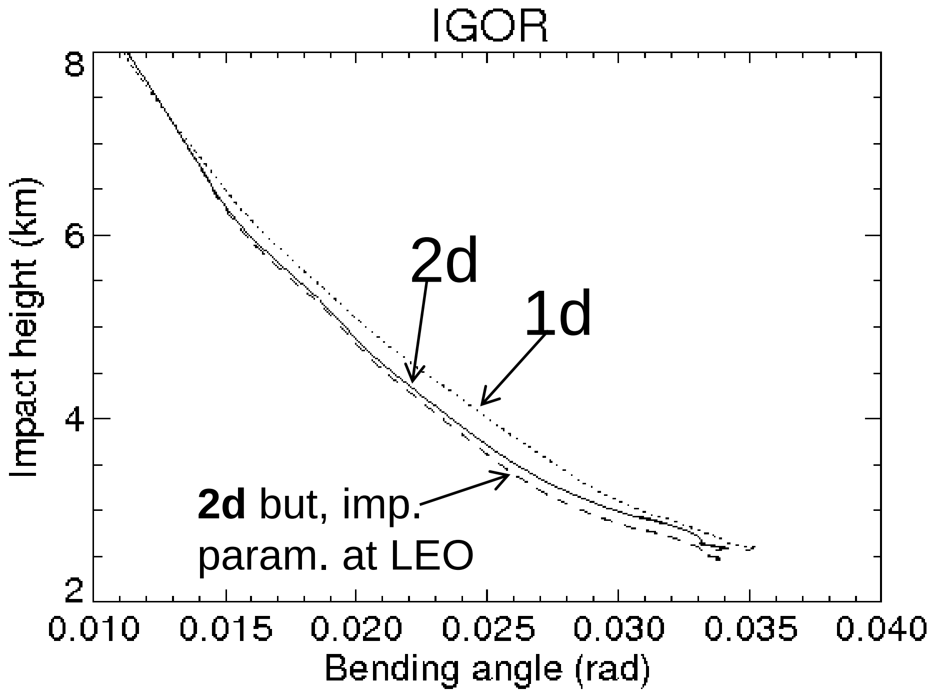
EXAMPLE: GRAS measurement at the centre of Hurricane IGOR (Sept 16, 2010)



Refractivity cross section and bending angle profiles for IGOR



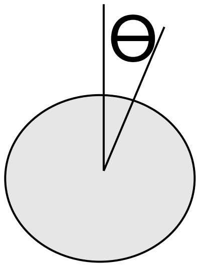
The difference between the two 2D curves is an illustration of the remaining forward model error.



The 2D operators are "blind" to some horizontal gradients

- The 2D refractivity can field be decomposed into a spherically symmetric part plus a perturbation (**tangent point: *Θ*=0)**

$$N(r,\theta) = N(r,0) + \Delta N(r,\theta)$$



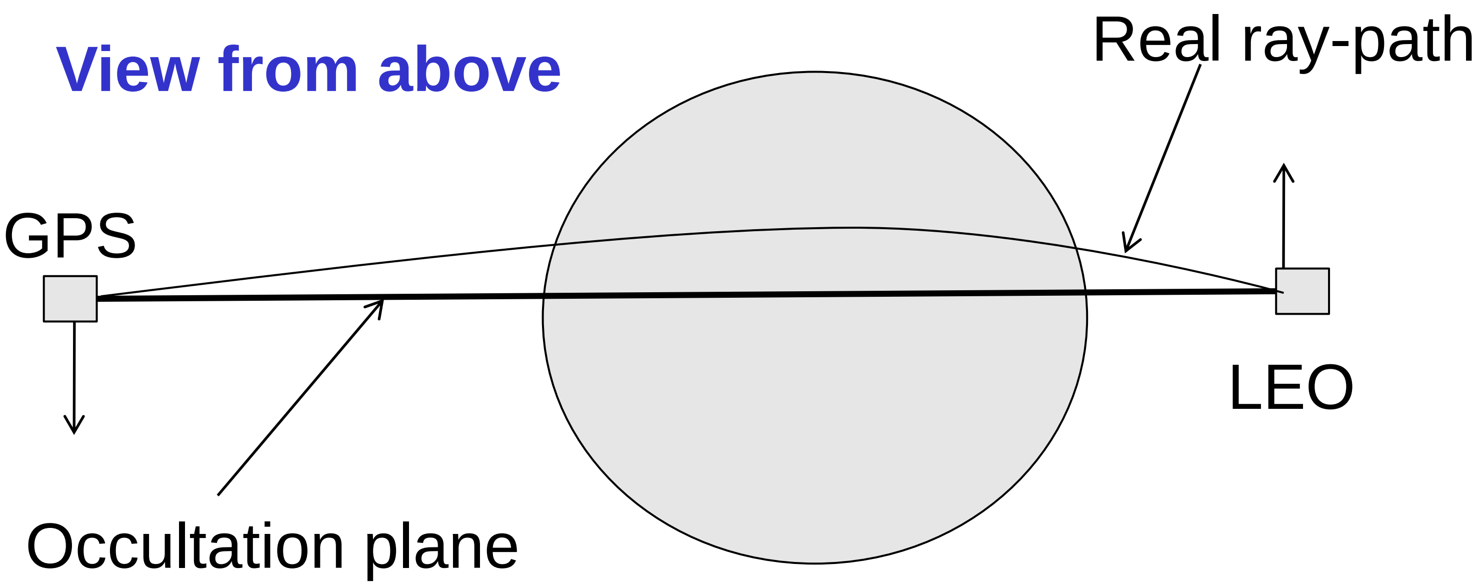
- If the perturbation is odd

$$\Delta N(r,\theta) = -\Delta N(r,-\theta)$$

- Then the local and non-local (2D) operators give the same result. **But does the observation?**

- **I don't think so because of** $$\frac{da}{ds} = \left(\frac{\partial n}{\partial \theta}\right)_r$$

GPS-RO is a 3D measurement



In the processing we assume the ray path stays in the 2D occultation plane but the "out of plane" bending means that some of the Doppler is related to the gradients perpendicular to the occultation plane.

The Doppler shift is misinterpreted.

BUT 2D operators are more realistic description than 1D and we are testing them

- Running T511 (~40 km) impact experiments with two 2D operators.
  - **Approach 1**: is based on a numerical solution of the ray-path equations below 20 km, reverting to a 1D calculation above 20 km. **(Doesn't include non-ideal gas)**
  - **Approach 2**: a weighted average of 1D bending angle values in the occultation plane.
  - Tangent point drift included. **(Too many profiles at the moment – I'll have to reduce the number by batching observations)**
  - Each plane consists of 31 profiles separated by 40 km.

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Approach 1: 4th order Runge-Kutta solver (ROPP code)

$$\frac{dr}{ds} = \cos\phi$$

Rodgers
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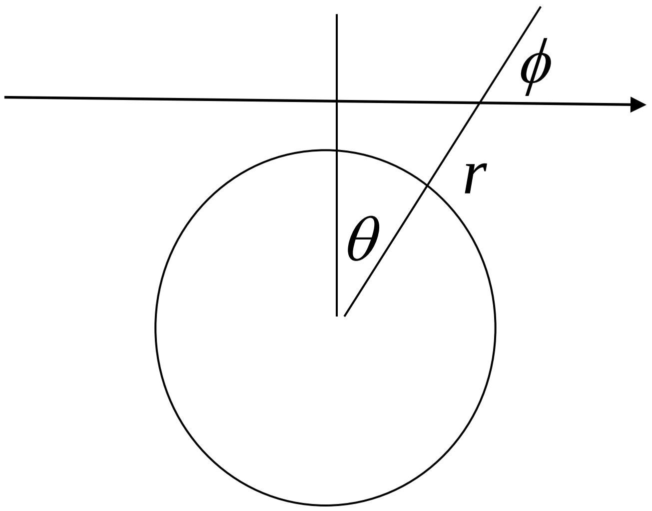
$$\frac{d\theta}{ds} = \frac{\sin\phi}{r}$$

$$\frac{d\phi}{ds} \approx -\sin\phi\left[\frac{1}{r} + \left(\frac{\partial n}{\partial r}\right)_{\theta}\right]$$



We solve these ray equations for the path **up to 20 km** and then revert to the 1D approach to estimate the bending above 20 km. *Zou et al suggested similar mixed bending angle/refractivity approach.*

Approach 2: a weighted average of 1D values in the occultation plane

- This approach is closer to the non-local refractivity/phase operators
  For an **exponentially decaying** atmosphere, scale height, *h*

$$\frac{d\alpha}{d\theta} \approx c \exp\left(-\frac{r_e}{2h}\theta^2 \right)$$

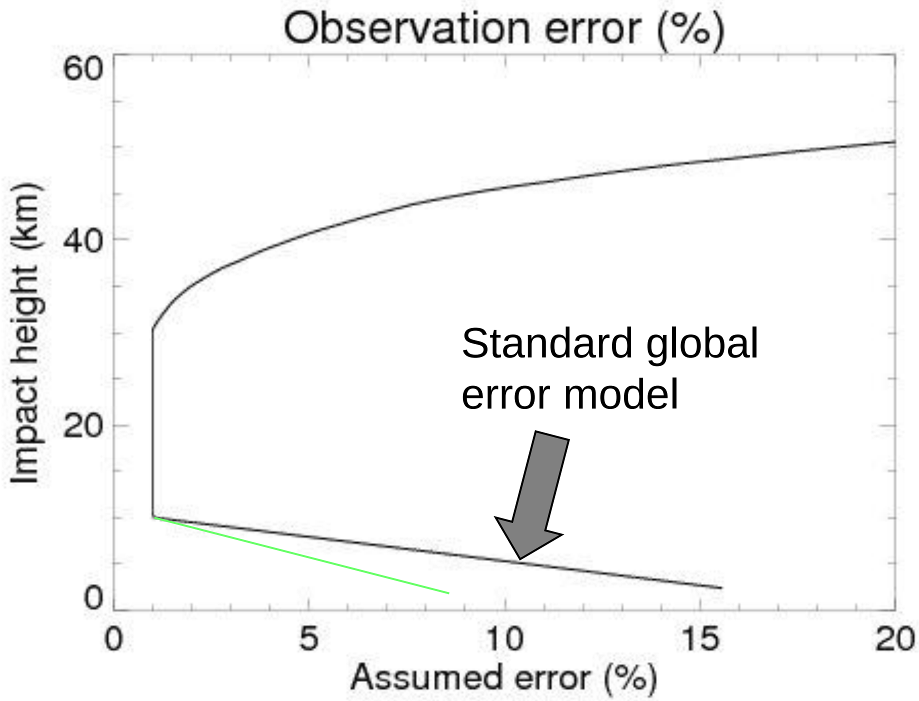
constant

- Forward model calculates

$$\langle \alpha(a) \rangle = \frac{\sum_i w(\theta_i)\alpha_{1d}(a,\theta_i)}{\sum_i w(\theta_i)}$$

$$w(\theta_i) = \exp\left(-\frac{r_e}{2h}\theta_i^2 \right)$$

Dynamical estimates of errors from variation of 1D bending angles in plane

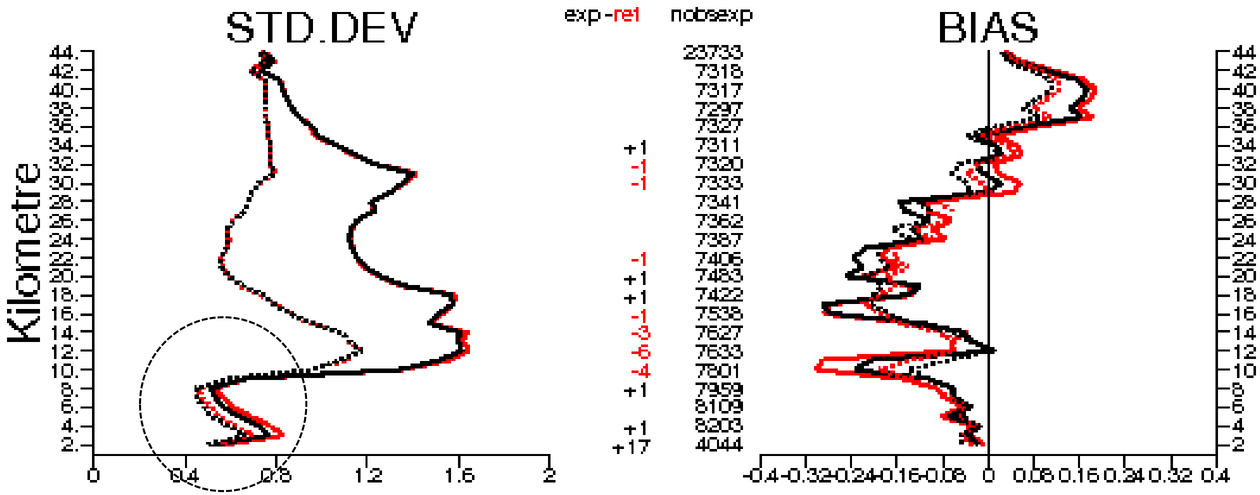


Try reducing the assumed errors to the green line in general, but use

$$\sigma_\alpha^2 = \langle \alpha^2 \rangle - \langle \alpha \rangle^2$$

when it is larger.

Fit to observations with 2D vs 1D operators (NH, Fixed error ob. error. Estimates)



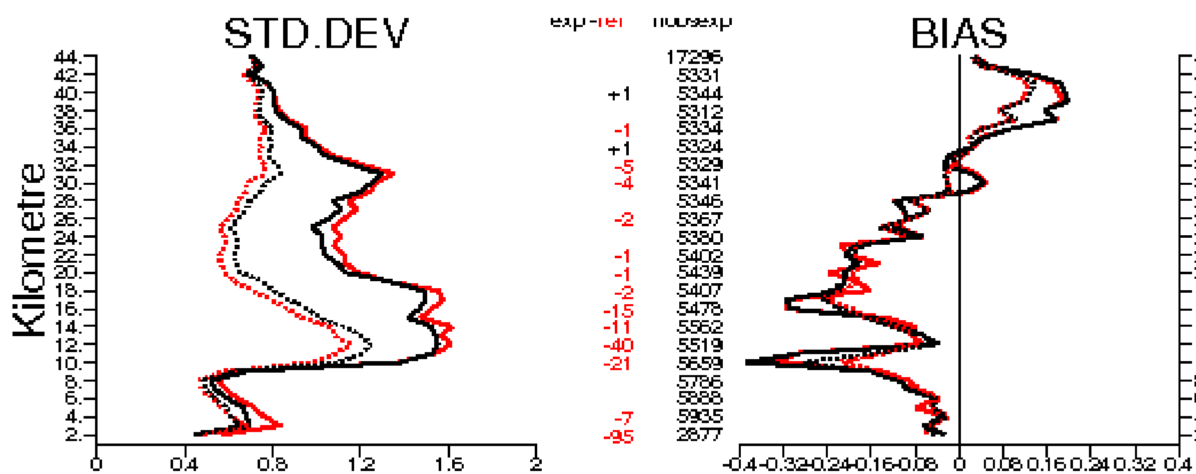
Approach 1

Ray tracer up to 20 km, then the 1d approach

Approach 2

Simpler approach seems to be doing a better job (O-B), but (O-A)'s bigger?

Encouraging result!



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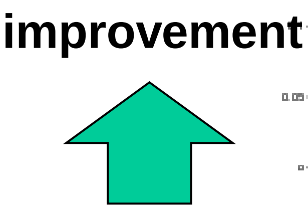
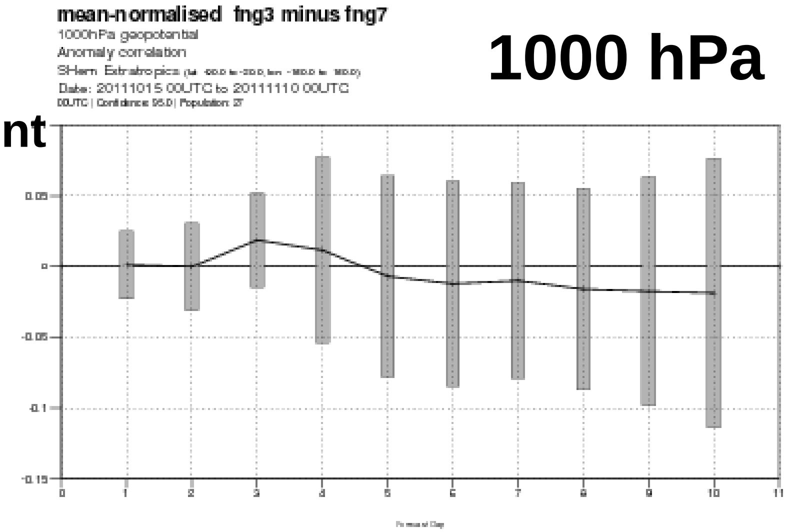
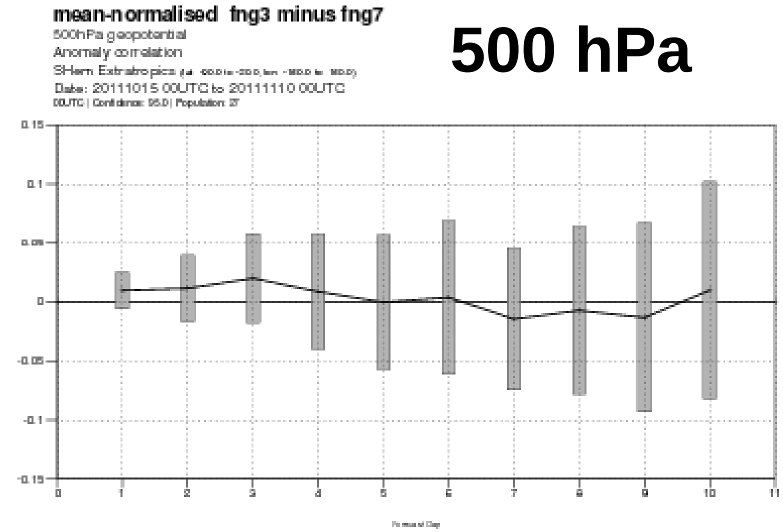
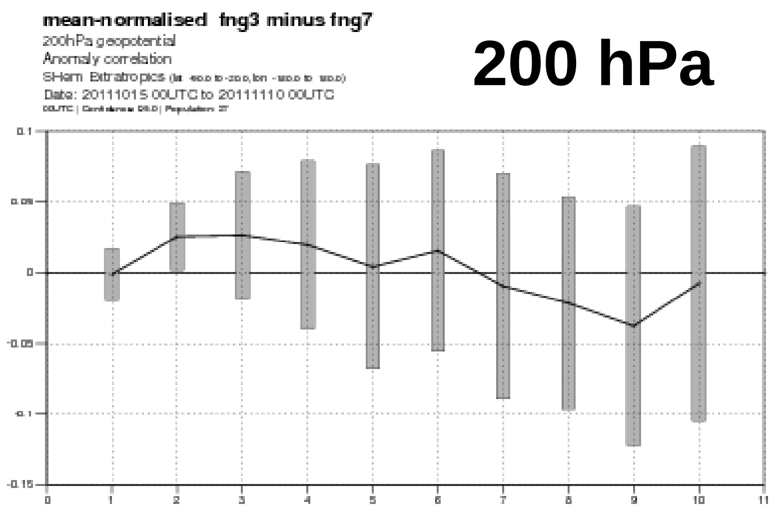
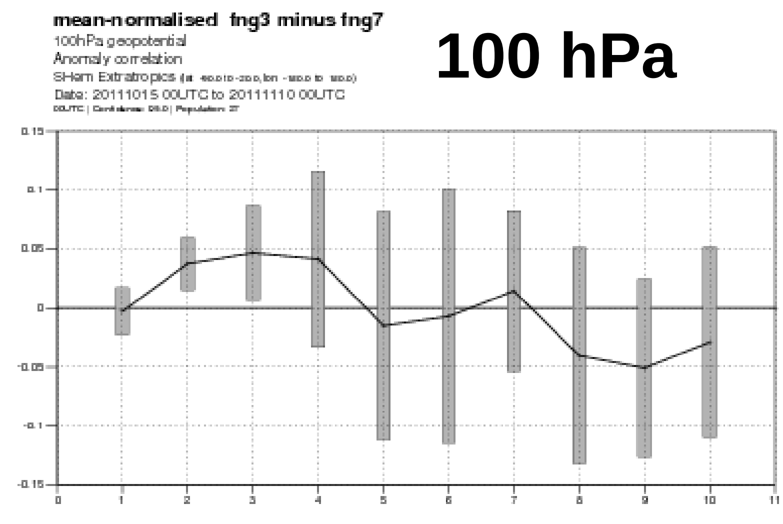
Geopotential Anomaly Correlation forecast scores (SH) Approach 1 with variable errors vs 1D approach.



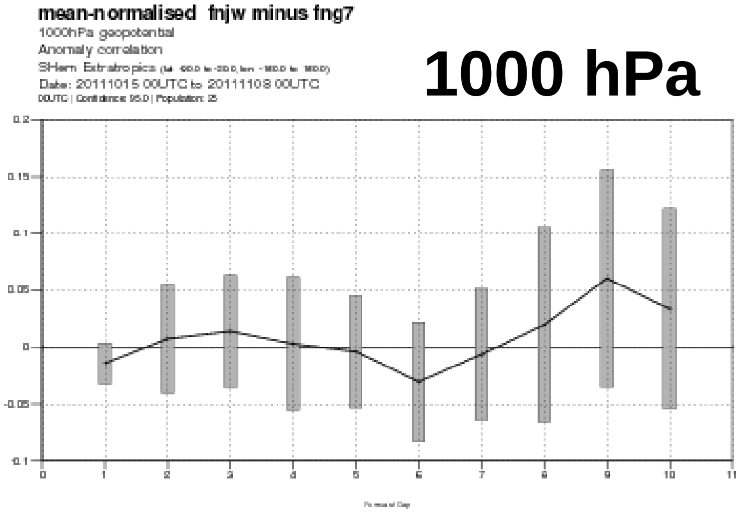


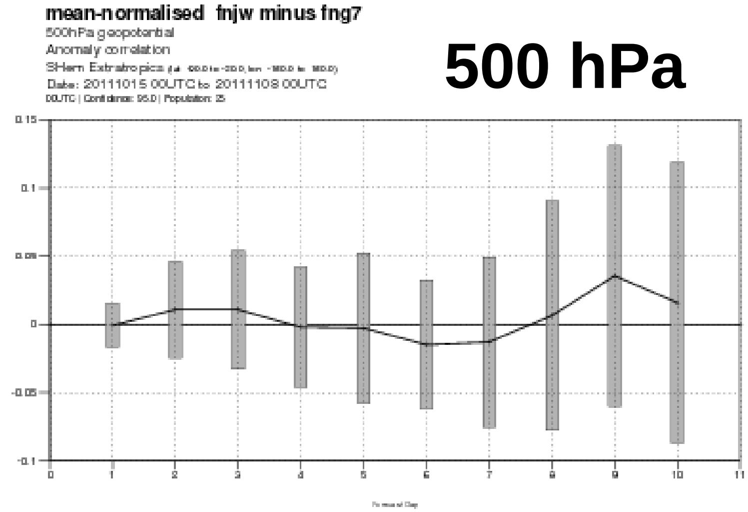


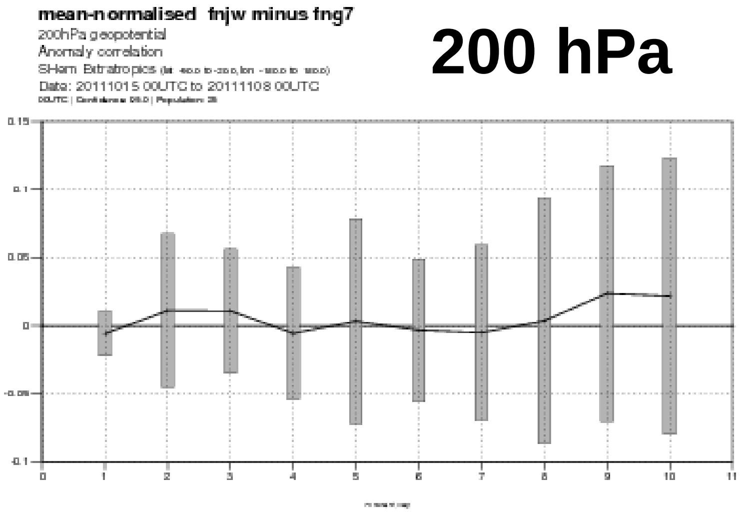


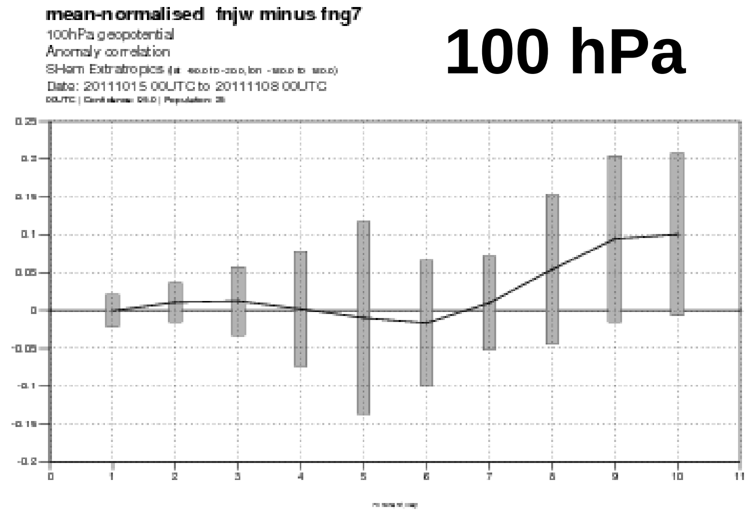


Approach 2, vs 1d

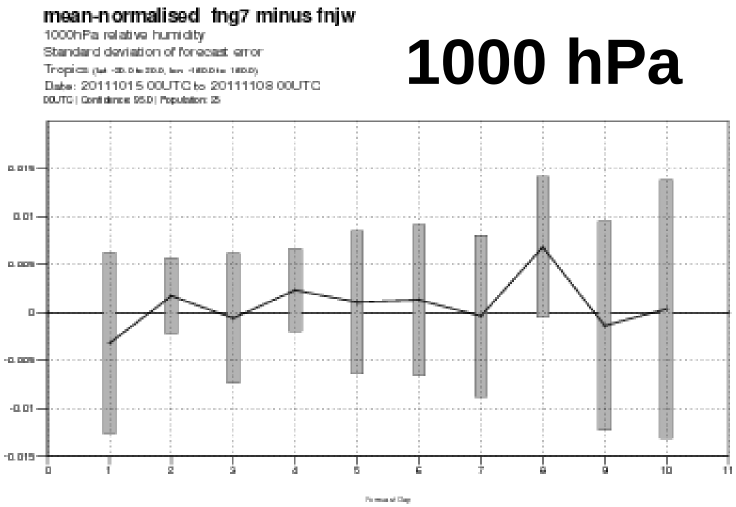


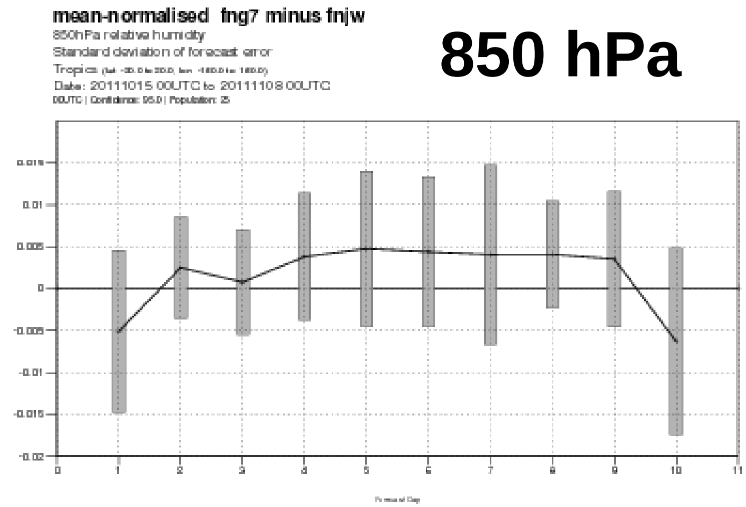


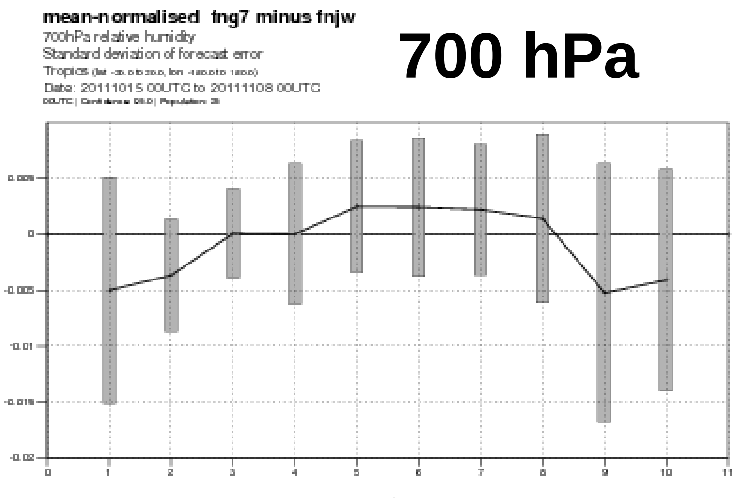


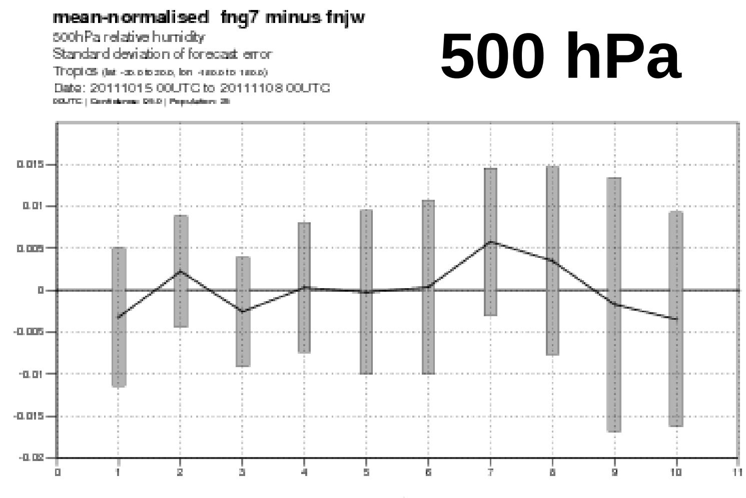


Approach 2: Fractional improvement in standard deviation of relative humidity errors in Tropics





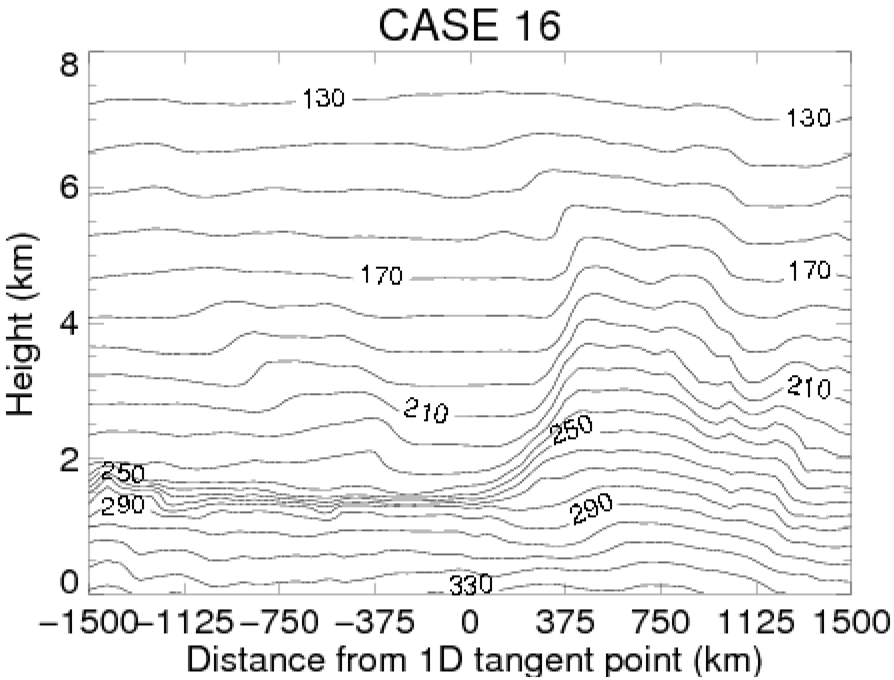


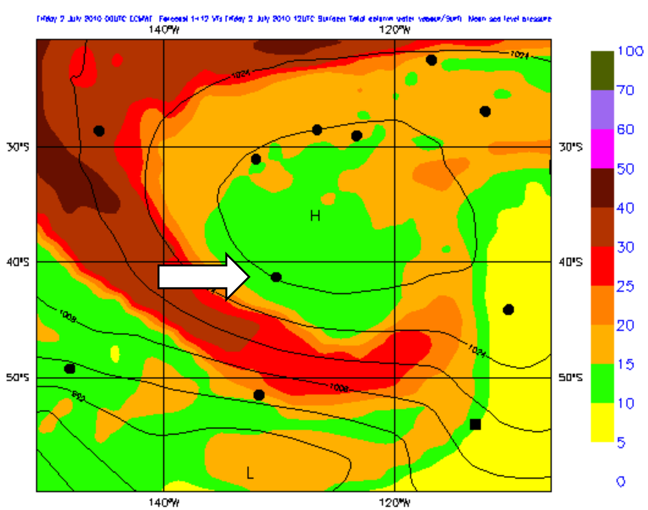


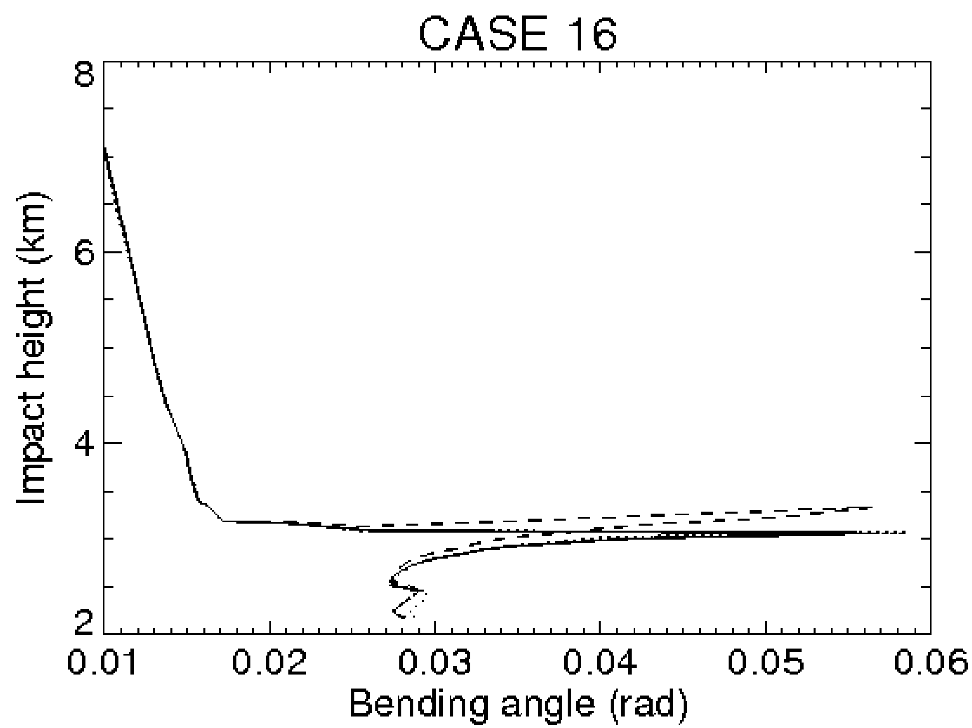
Summary

- There are good reasons to move to 2D operators, and they are being tested.
- Tried to demonstrate the limitations of the current 2D operators. Hopefully we can discuss this during the workshop.
- Described the two approaches being tested at ECMWF, and a suggested a method for dynamically estimating the assumed errors.
- 2D operators improve the fit to observations which is an important first step.
- Forecast scores versus operational analyses is neutral but more work required, and the sample size is still small.

Example of refractivity cross section







Some ideas about non-local refractivity/phase operators

- Non-local refractivity operators are useful because 2D bending angle operators are 1) slow (“a few days” CPU time, OPAC 2 proceedings) and 2) extrapolation above the NWP model top is a problem. Neither of these points is correct!

- Non-local refractivity operators can reduce the forward model errors by an **order of magnitude** and therefore a lot more weight can be given to them in the assimilation process. Has anybody looked at the O-B refractivity statistics for CHAMP? What about the tangent height error – old stuff, but its completely ignored in this context!

- Kuo et al estimated the **total** refractivity observation error ~3% near the surface with a 1D operator. Are we saying that we should use ~0.3% when assimilating RO with a non-local refractivity operator?

2D refractivity operators

- Method 1, based on the "quasi" phase, straight line approx.

Straightline

$$s = \int N(r,\theta)dl$$

$$N_{2d}^{1}(r_t) = -\frac{1}{\pi}\int_{r_t}^{r_m} \frac{\left(\frac{ds}{dr}\right)}{\sqrt{r^2 - r_t^2}}\,dr$$

- Method 2, Abel transform of 2D bending angles

$$N_{2d}^{2}(r_t) = A(H_{2d}(a))$$

Abel transform + conversion to Height.

RK raytracer

A limitation of method 1

Let the 2D refractivity field be written as the refractivity at the tangent point plus a 2D perturbation

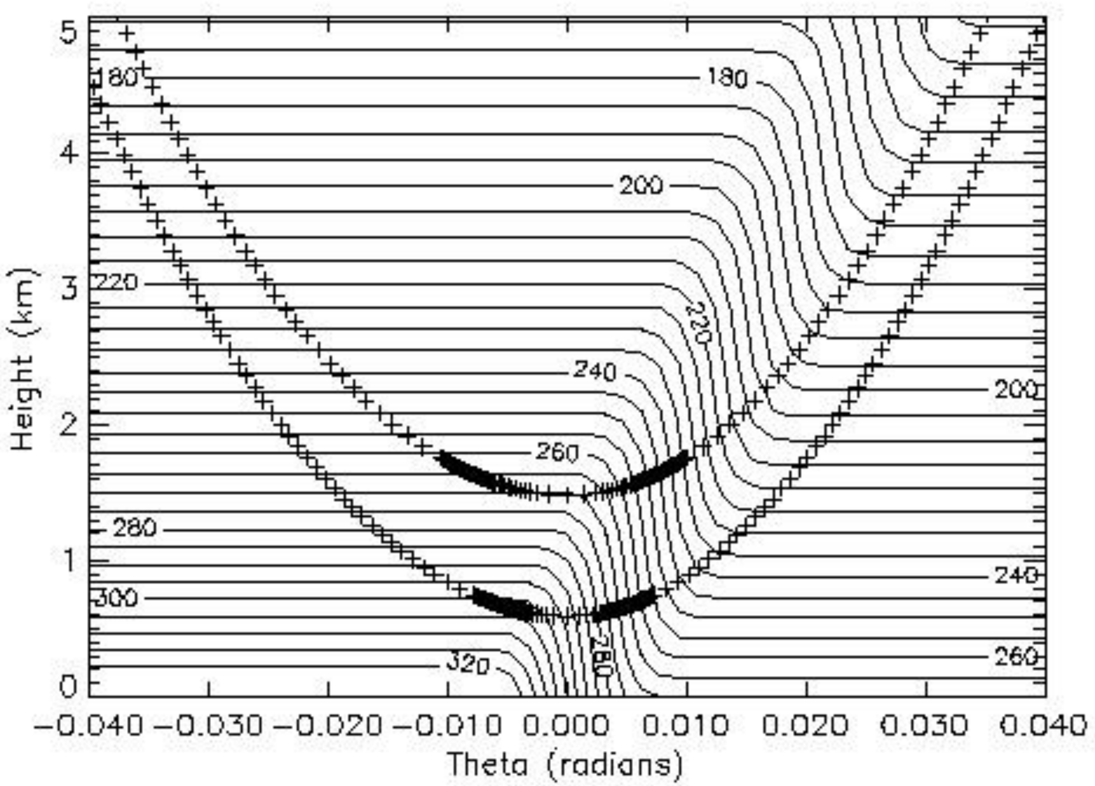
$$N(r,\theta) = N(r,0) + N'(r,\theta)$$

If the perturbation is “odd”

$$N'(r,-\theta) = -N'(r,\theta)$$

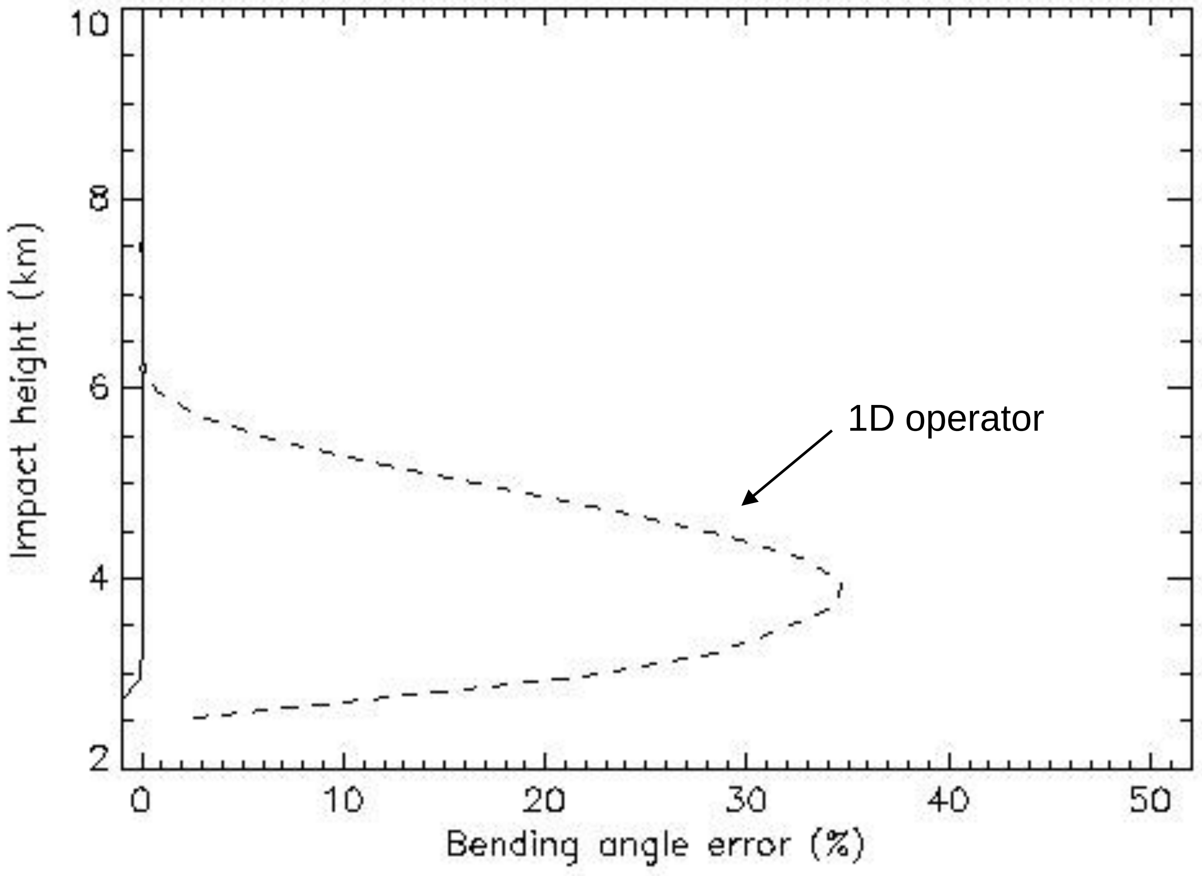
then the 1D and 2D refractivity operators give the same results because the average of the perturbation is 0.

2D refractivity field Sokolovskiy's idealised front

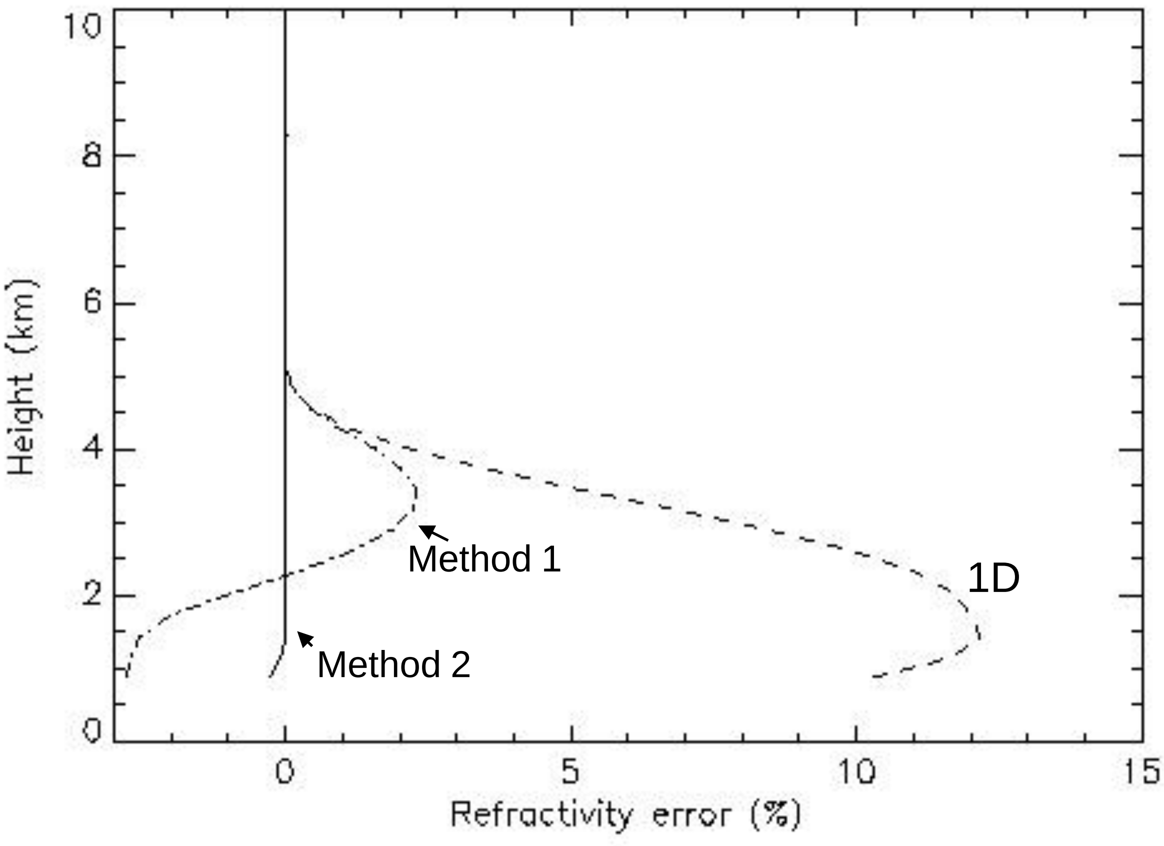


Sokolovskiy assumes the impact param. provided with the ob. is the value at the LEO. Assume ray comes from the right side. Neglect tangent drift.

1D/2D bending angle errors

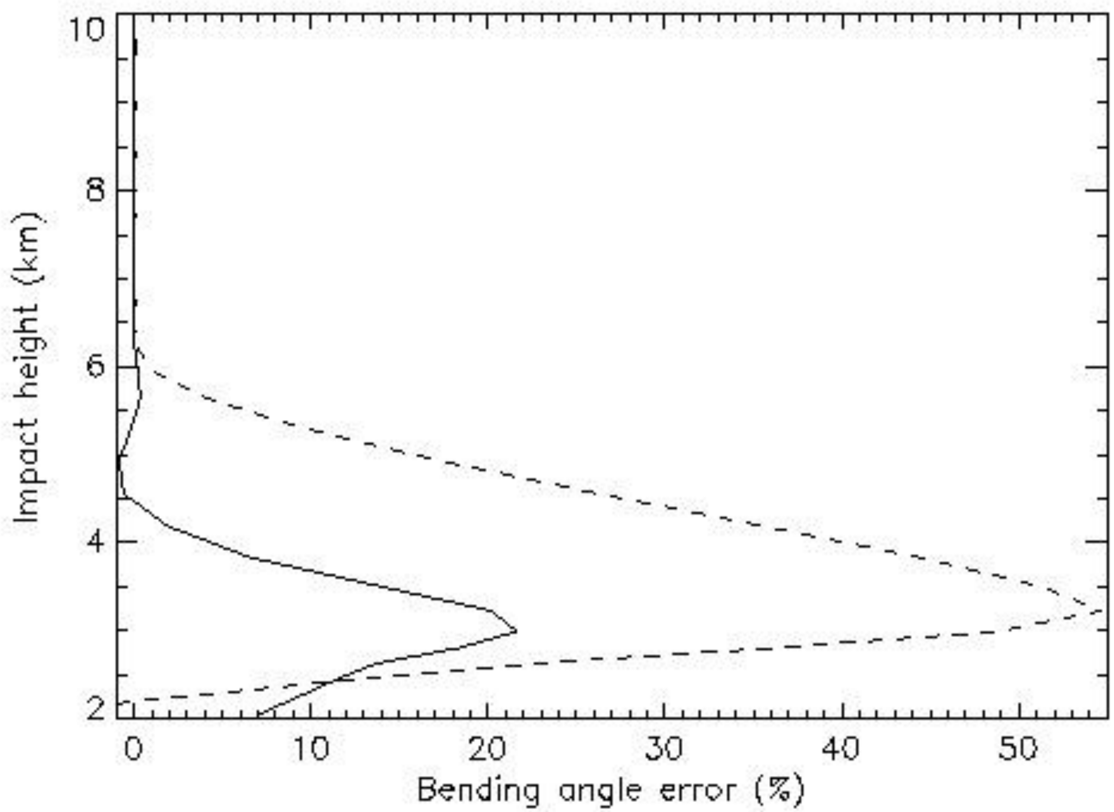


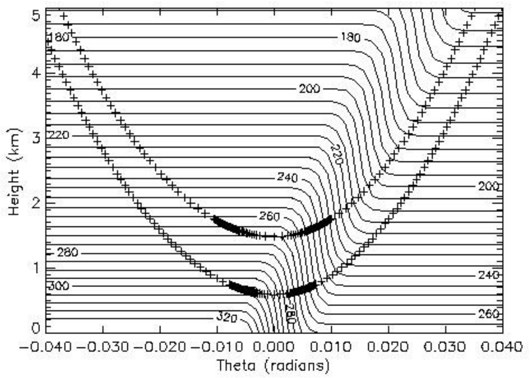
Refractivity errors



Assume ray comes from left to right. Same ray-path, but assume opposite direction

1D/2D bending angle errors





Refractivity errors