
Assimilation with a 2D bending angle operator at ECMWF

Sean Healy

The EUMETSAT
Network of
Satellite
Application
Facilities



ROM SAF

Radio Occultation Meteorology

Mats Hamrud, Chris Burrows.

Outline

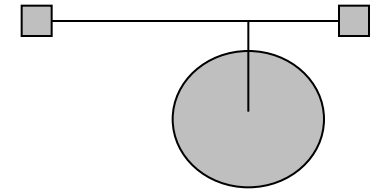
- 1D assimilation. review
- 2D bending angle operator implementation.
 - **Timings of the 2D operator in the 4D-Var. Problem noted at OPAC/IROWG**
- Initial results.
- Improving the 2D operator . **Where I need some help.**
- Summary.

1D assimilation at ECMWF (since 2006)

ROM SAF ROPP code, Met Office, MF, NRL, JMA

- 1D operator: ignore the real 2D nature of the measurement and integrate

$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\sqrt{x^2 - a^2}} dx$$



Convenient variable ($x=nr$)
(refractive index * radius)

- Forward model:
 - evaluate geopotential heights of model levels
 - convert geopotential height to geometric height and radius values
 - evaluate the refractivity, N , on model levels from P, T and Q .
 - Integrate, assuming refractivity varies exponentially or **(exponential*quadratic)** between model levels.
 - **We do not force continuity of refractivity gradients.**
 - Solution in terms of the **Gaussian error function.**

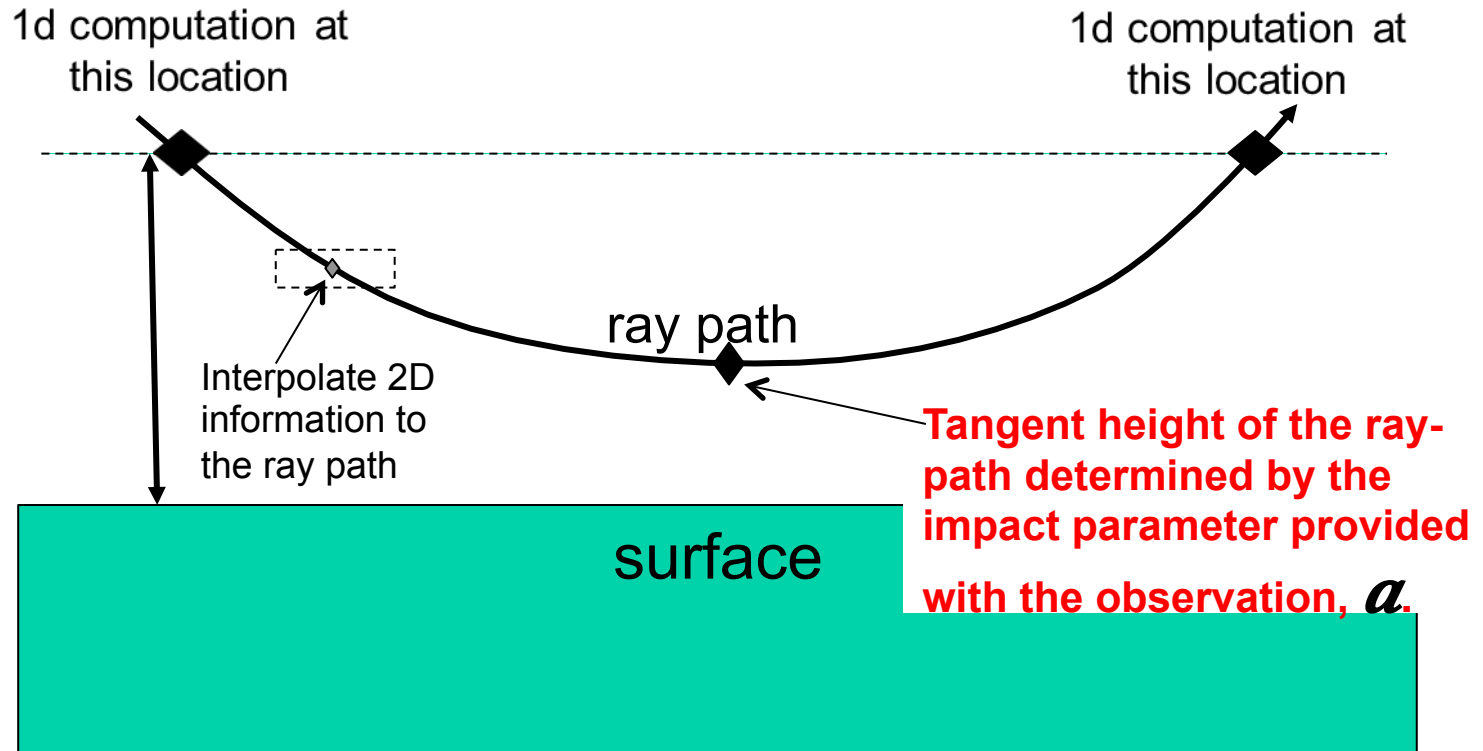
Changes since 2006

- Introduction on non-ideal gas affects in the operator (Josep Aparicio, presented at the workshop in 2008).
- Introduction of tangent point drift (Lidia Cucurull and Paul Poli): **Good change (2011)**.
- **Maximum refractivity gradient in bending angle computation:** Half the ducting gradient. Important change: 4D-Var minimization issues, because of linearity assumption in inner loop.
- Change refractivity interpolation between the model levels do reduce stratospheric forward model biases noted at the Met Office (Chris Burrows). Handle +ve refractivity gradients better.

2D operator

- **2D should mean we are less likely to misinterpret the observation information.**
- Look at the 2D operator impact when the **NWP forecast model** has higher horizontal resolution (~16 km) in **outer loop**.
- **Still assume exponential refractivity variation between the model levels, unlike new 1D operator but not important with 137 vertical levels.**
- **Refractivity gradients are NOT continuous across model level.**

2D approach



The outer loop uses 31 profiles to describe the 1200 km “occultation plane”. 7 profiles used for inner loop.

2D operator in 40R3

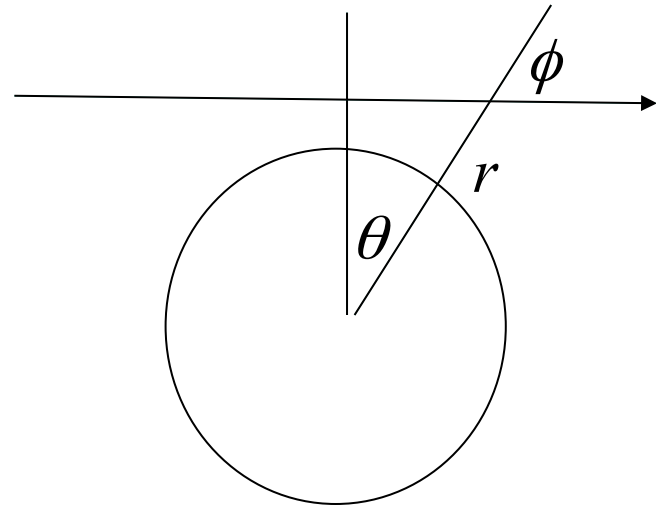
1D

$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\sqrt{x^2 - a^2}} dx$$

$$\frac{dr}{ds} = \cos \phi \quad \text{Rodgers} \\ \text{Page 149}$$

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

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



Tangent point height derived from impact parameter provided with ob.

We solve these ray equations for the path **up to 50 km** and then revert to the 1D approach to estimate the bending above **50 km**. *Zou et al suggested similar mixed bending angle/refractivity approach.*

Some timings with 2D operator for the 4D-Var “inner loop” minimization (TL and AD code.)

“Wall-clock time” (s)	2D operator	1D operator	Percentage increase
Only GPS-RO	275	214	29 %
All observations	550	435	26 %

The increases are “very significant”, in an operational context and need to be reduced before operational implementation.

Some revisions that have been tested

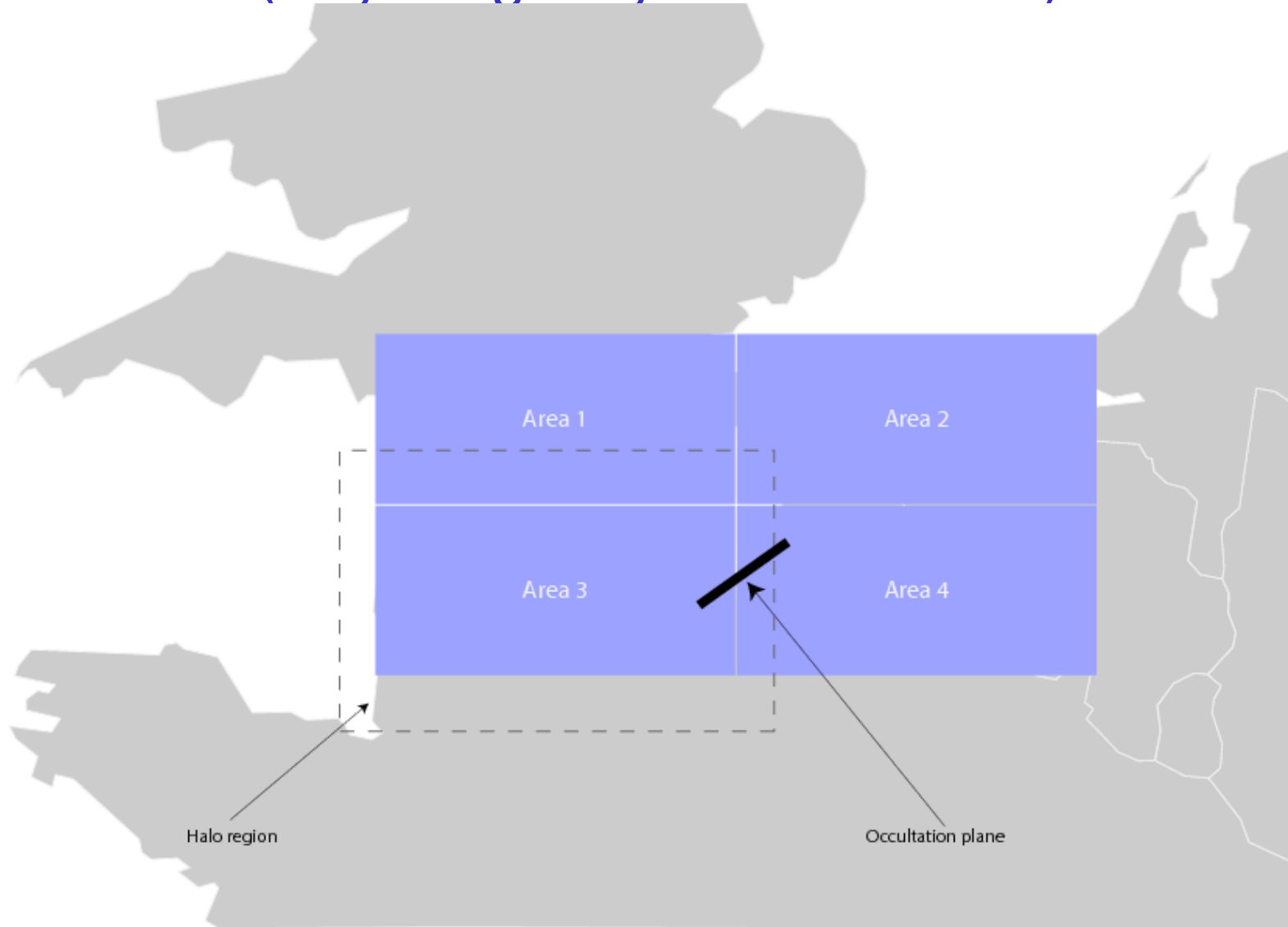
- **7 profiles in inner-loop with 200 km spacing. (KEY CHANGE*)**
- Tangent point drift: batch data in groups of 11 bending angles (~2 km in vertical).
- Simpler differential equation solver.

	1D	2D	2D (new)	2D(new)-1D (%)
wallclock time (s)	435	550	447 (464*)	+2.7 (+6.6%*)

- No clear degradation in GPS-RO (o-b)s as a result of these revisions.

2D operator implementation work

(Key insight by Mats Hamrud)



2D operator work

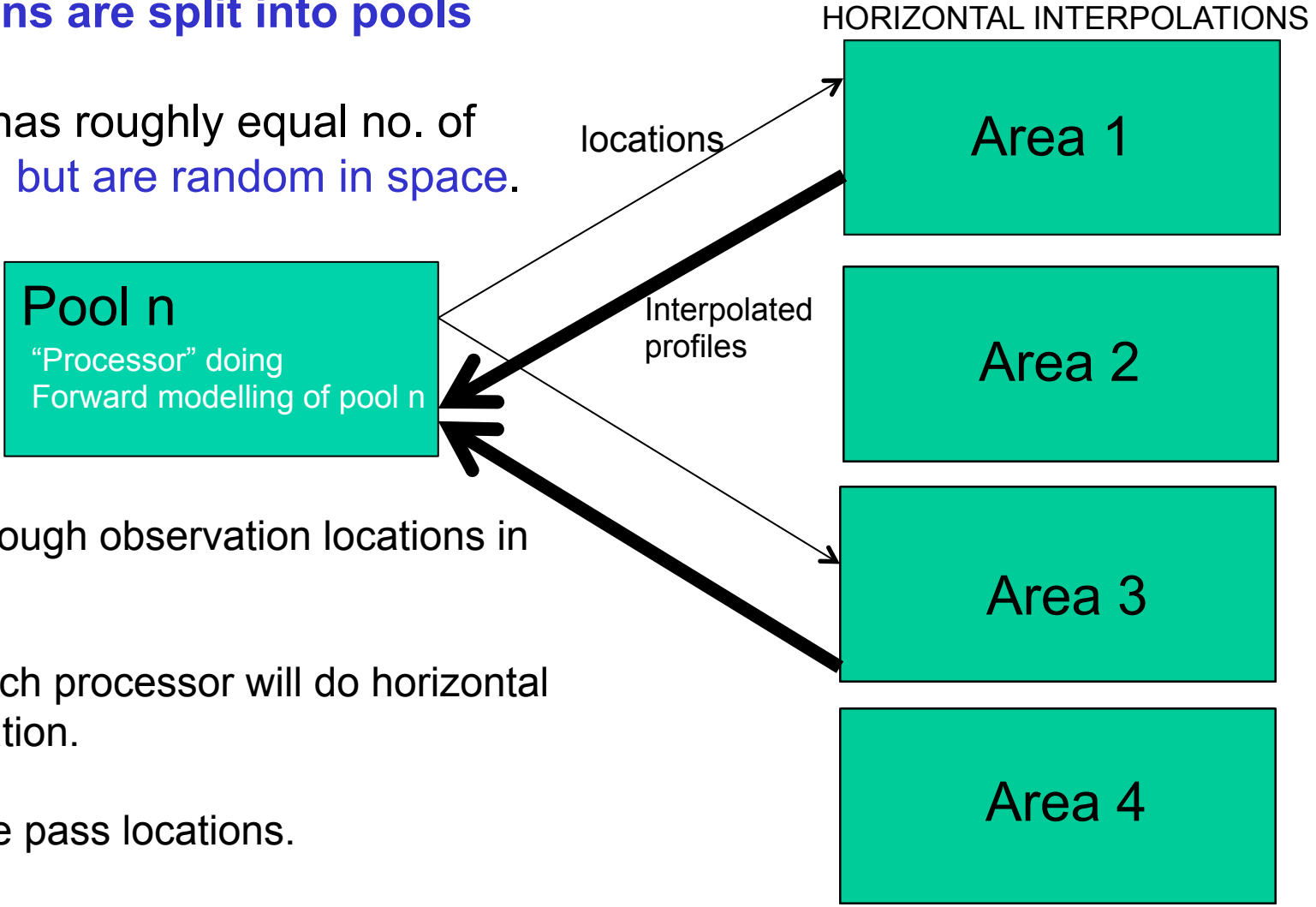
- The 2D occultation plane crosses a boundary. **Problematic?**
- **We probably assume observations** in area 3 are forward modelled using **processor 3**, but observations in area 4 use **processor 4**.
- What happens when the occultation plane goes over the boundary?
- **This situation doesn't arise at ECMWF. The basic assumption is wrong.** The horizontal and vertical “interpolations” are performed on different processors and information is “message passed”.

$$\mathbf{H}\mathbf{x} = \mathbf{H}_v \mathbf{H}_h \mathbf{x}$$

Forward model Bending angle computation Horizontal interpolation

Observations are split into pools

Each **pool** has roughly equal no. of each "type", but are random in space.



- Loop through observation locations in pool.
- Find which processor will do horizontal interpolation.
- Message pass locations.
- Message pass back interpolated profiles

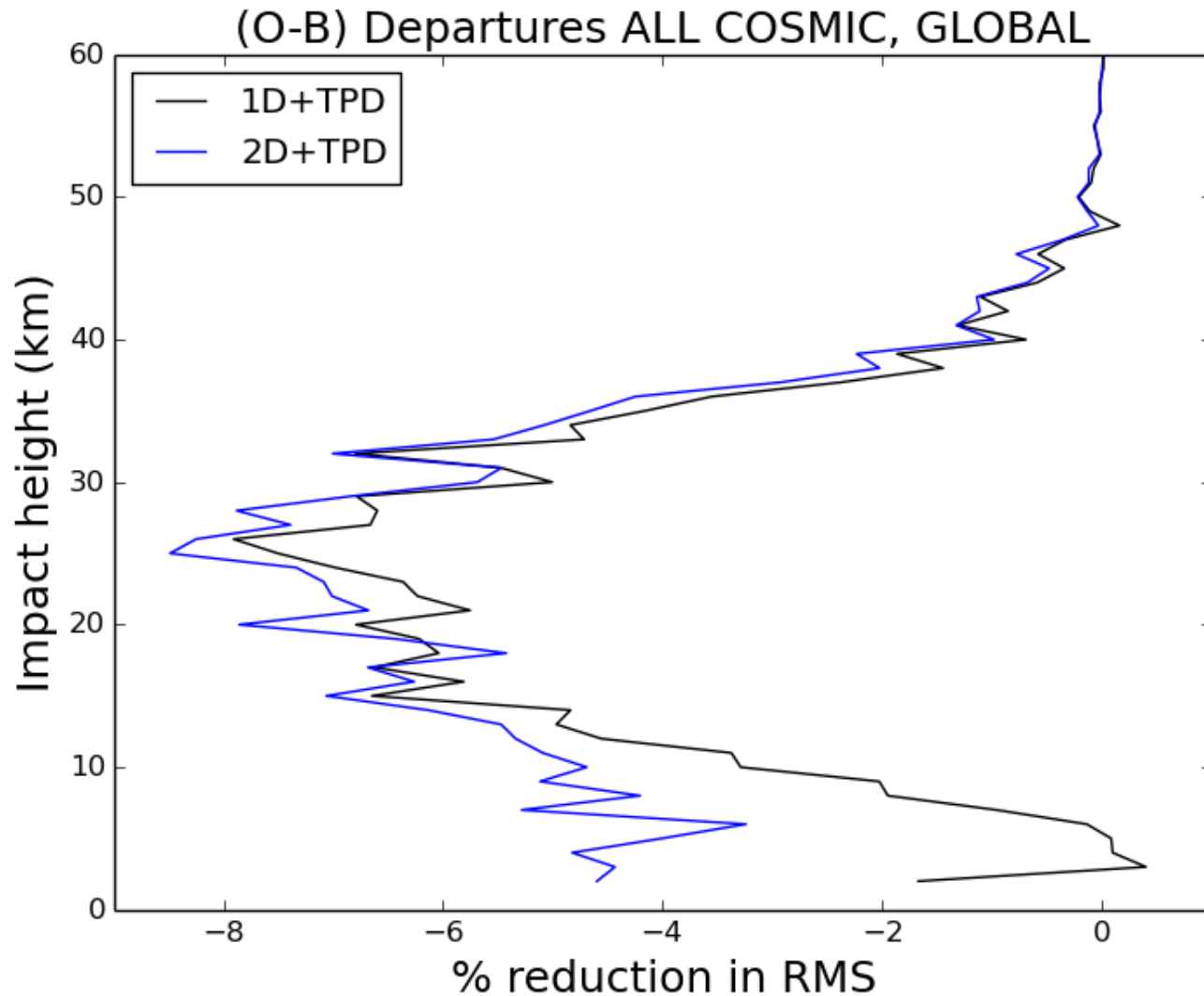
2D operator information

- 2D plane determined by the satellite locations in BUFR file and azimuthal angle.
- 31 NWP profiles in the “occultation plane” separated by 40 km. Tangent point drift.
- NWP model: 91 vertical levels to ~80 km, T1279 (~16 km) in horizontal (outer loop).
- Experiments:
 - Just RO, 1D operator
 - Just RO, 2D operator
 - Full system, 1D operator
 - Full system, 2D operator

*“Necessary but not sufficient”
for operational implementation*

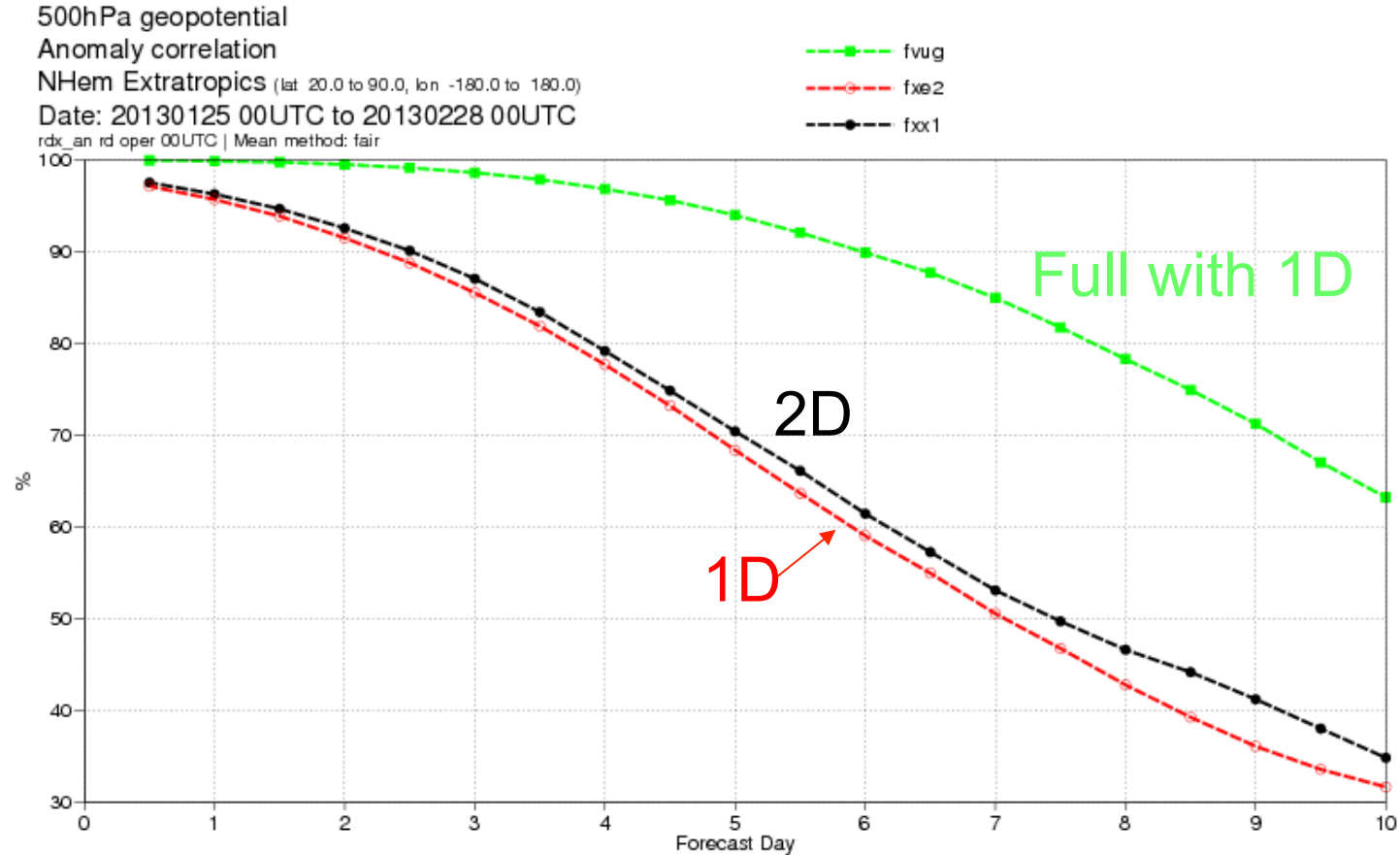


Impact of tangent point drift and the 2D operator



Z500 scores, NH

Remark: ECMWF's aim is to improve forecast skill by ~1 day per decade.



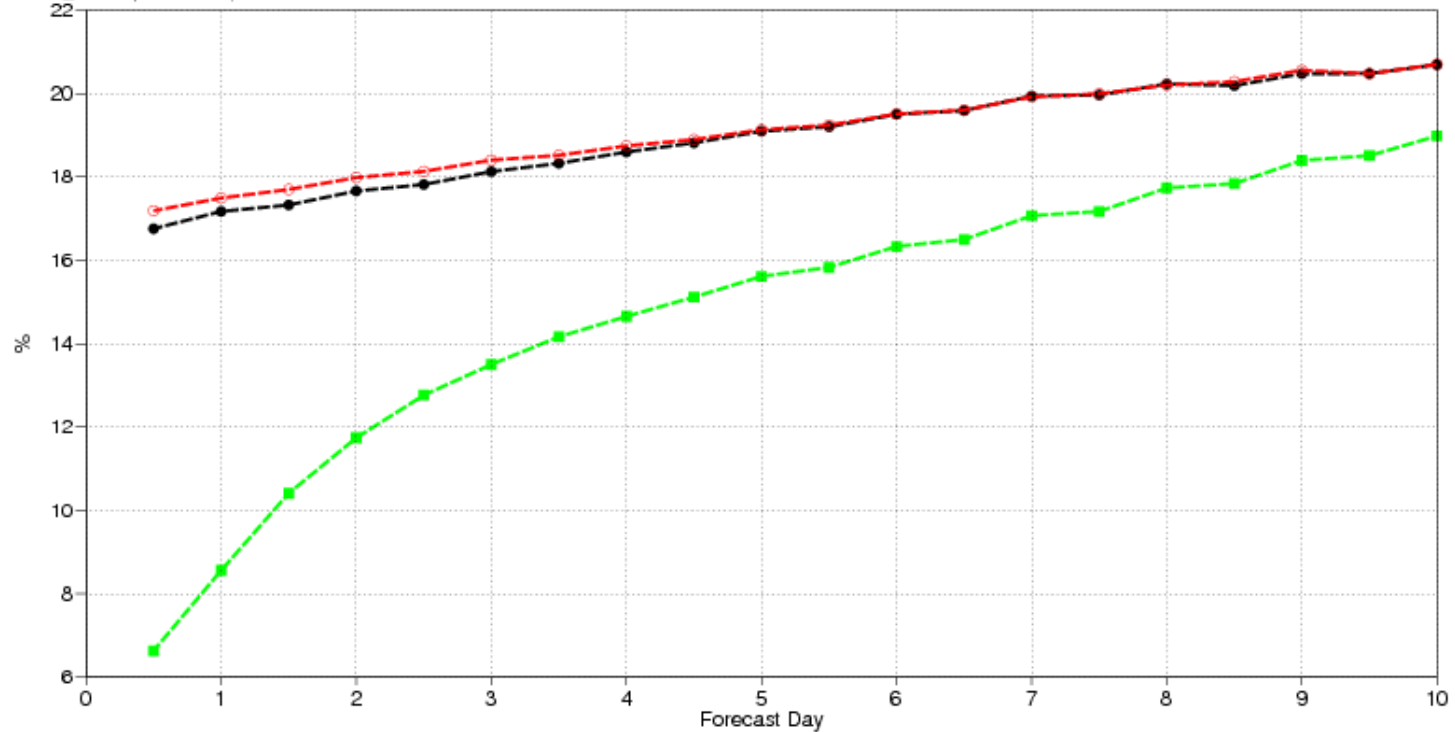
Tropics 850hPa humidity (RMS errors)

850hPa relative humidity
Root mean square error

Tropics (lat -20.0 to 20.0, lon -180.0 to 180.0)

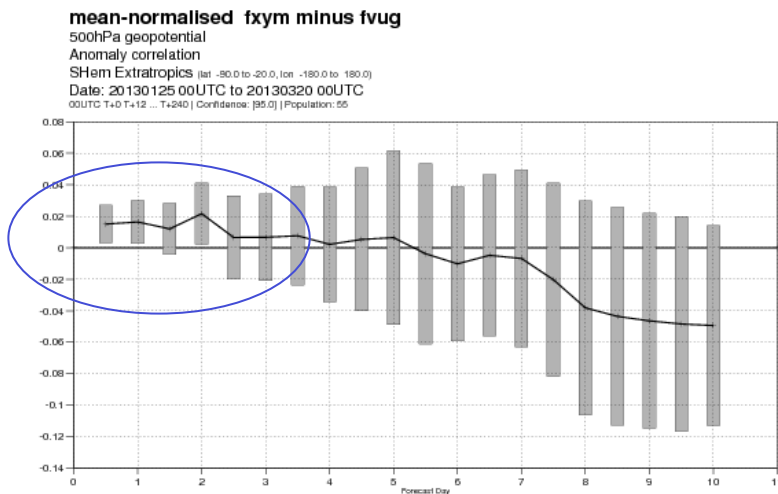
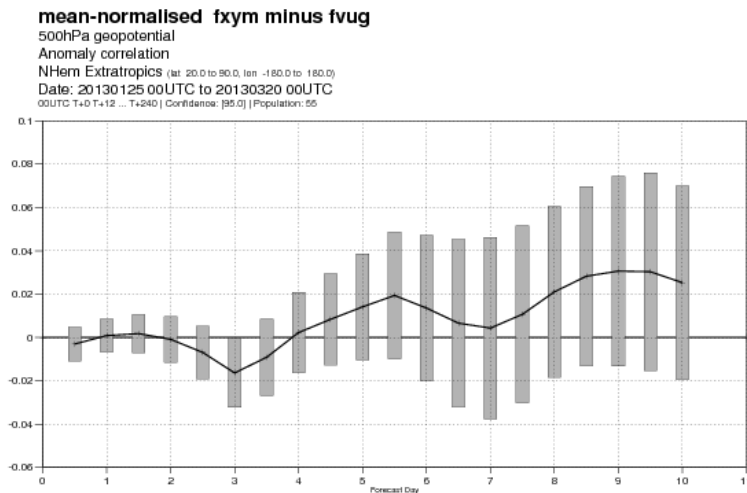
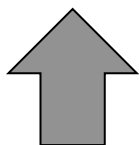
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rdx_an rd oper 00UTC | Mean method: fair



2D vs 1D in full system, Z500 anomaly correlation

Above 0 = good



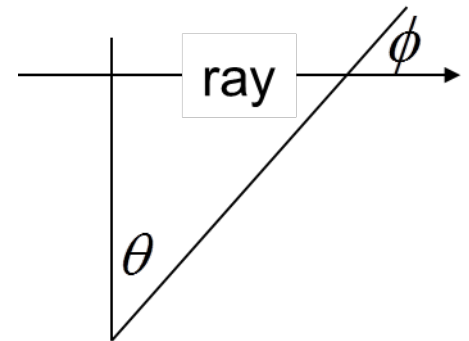
Improvement of 2D operator

- **Some physics is missing.** The ray tangent height is estimated from a “*constant of motion*” along the path.

$$nr \sin \phi = a \quad (\text{impact parameter})$$

- **Its not a constant!** It varies along ray-path

$$\frac{d(nr \sin \phi)}{ds} = \frac{\partial n}{\partial \theta_r}$$



- **The impact parameter provided with the ob. does not determine the tangent height.** I misplace the tangent point in the vertical (100s m).
- Use an “adjusted” impact parameter ($a \rightarrow (a + \Delta a)$) in the 2D operator to determine tangent height.

Aim – work in progress

- Use the NWP forecast model state to provide a relationship between the **impact parameter value at the tangent point** and the **impact parameter value provided with the observation**.
- Solve the equation

$$a = f(a_t, H(\mathbf{x}_b), \underbrace{\mathbf{r}_G, \mathbf{v}_G, \mathbf{r}_L, \mathbf{v}_L}_{\text{geometry}})$$

provided \nearrow a \nwarrow want

- This is solved in the screening run, and then the adjusted impact parameter, a_t , is used in the assimilation.
- The function f is based on geometrical optics processing.

Why is this important (JGR, 2001)

- The impact parameter we get is not what we want!

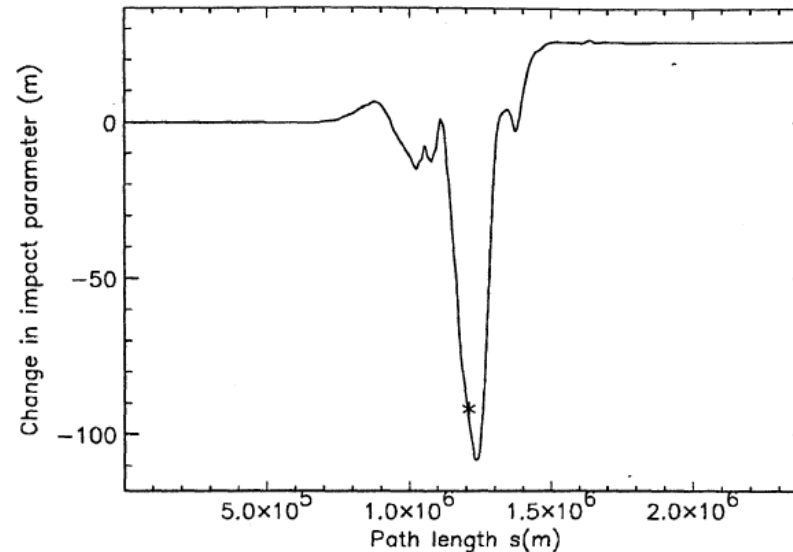
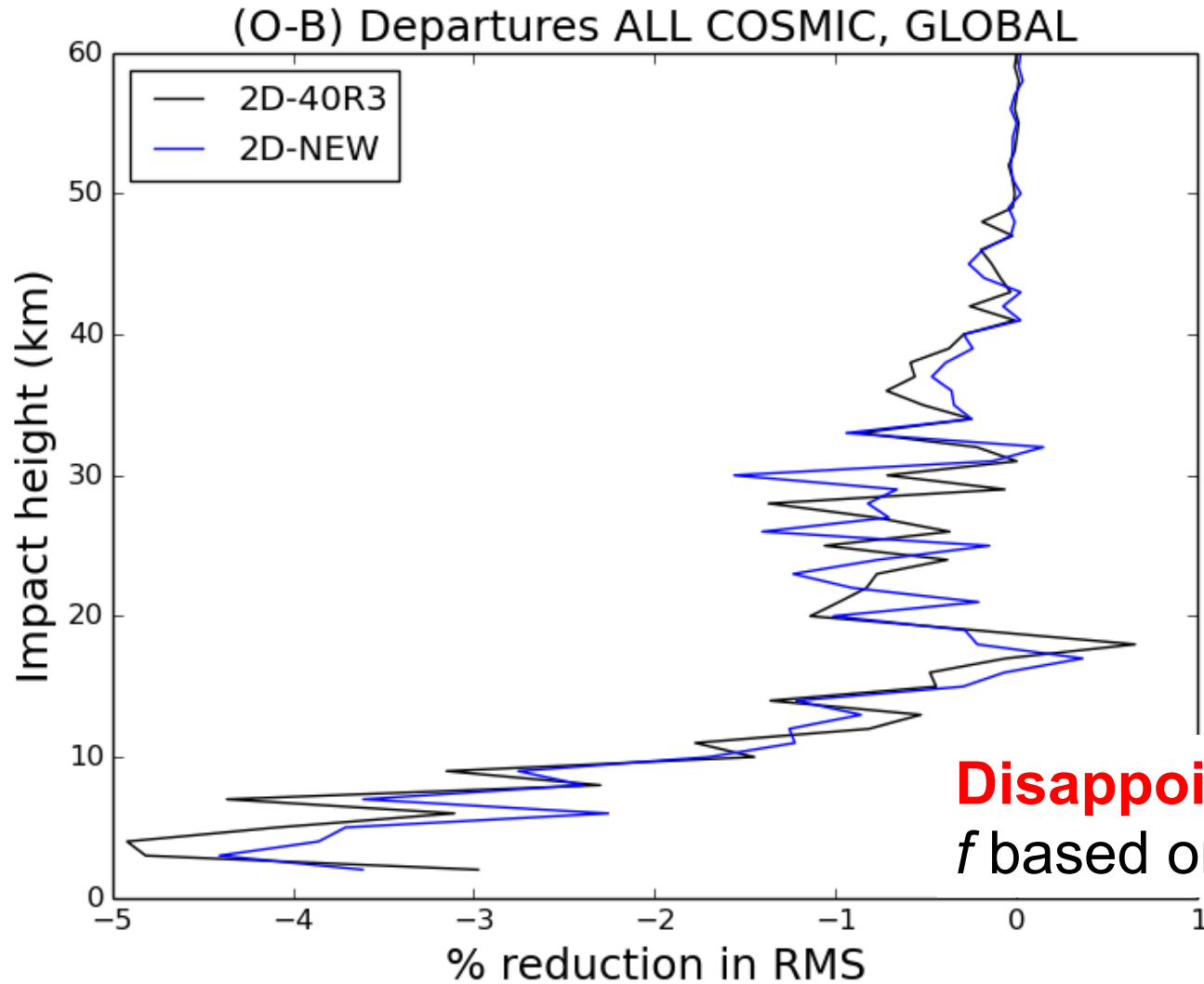


Figure 6. The variation of the impact parameter value along a ray path with a tangent point 1200m above the surface. The asterisk marks the position of the tangent point.

$$\begin{aligned}
 a_d - a_{\tan} &= \frac{r^T \cos \phi^T}{r^T \cos \phi^T - kr^R \cos \phi^R} \int_s \left(\frac{\partial n}{\partial \theta} \right)_r ds \\
 &- \int_{s_T} \left(\frac{\partial n}{\partial \theta} \right)_r ds_T,
 \end{aligned} \tag{16}$$

Initial results



Disappointing !
f based on GO picture

Summary

- ECMWF will go operational with the 2D operator in the next upgrade (40r3). Computational cost is now acceptable.
- The 2D approach clearly improves fit to observations and complements the earlier tangent point drift change.
- Forecast scores are slightly +ve in the short-range, but not a big signal.
- 2D framework will enable further development.
 - Adjusting the impact parameter value has been disappointing.

EXTRA – OLDER MATERIAL

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 $\sim 3\%$ near the surface with a 1D operator. Are we saying that we should use $\sim 0.3\%$ when assimilating RO with a non-local refractivity operator?

2D refractivity operators

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

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

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

- Method 2, Abel transform of 2D bending angles

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

Abel transform
+ conversion to
Height.

RK raytracer

Straightline

A limitation of method 1

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

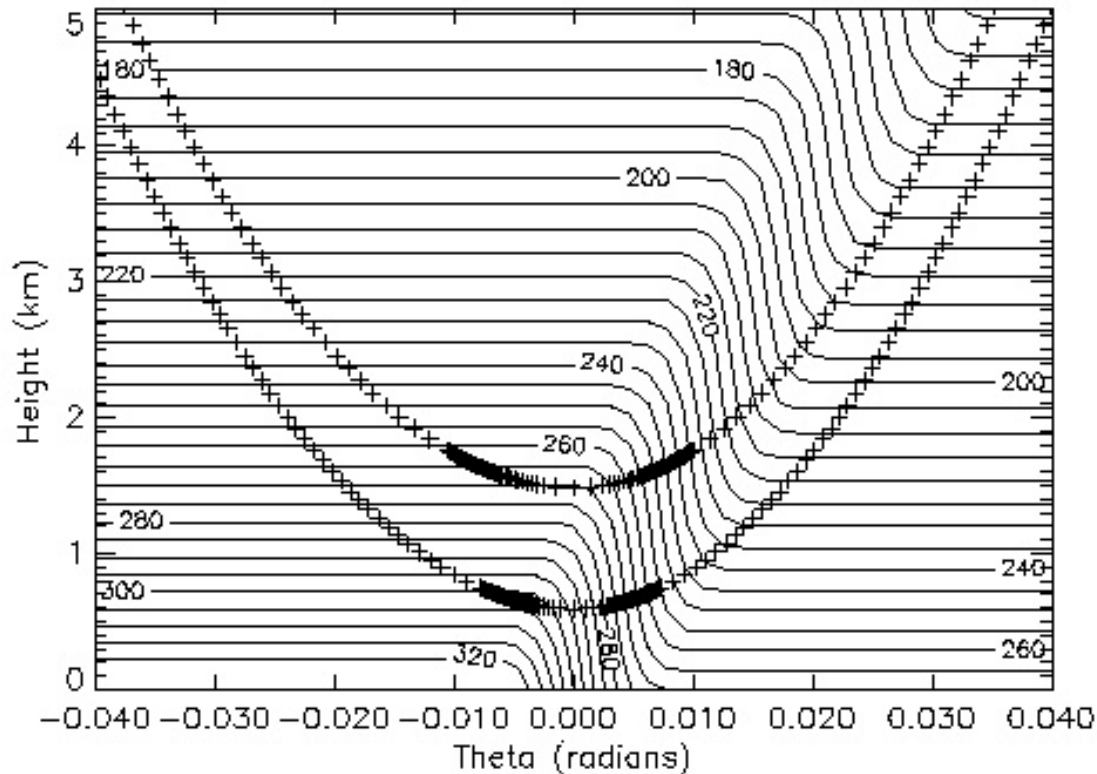
$$N(r, \theta) = N(r, 0) + N'(r, \theta)$$

If the perturbation is “odd”

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

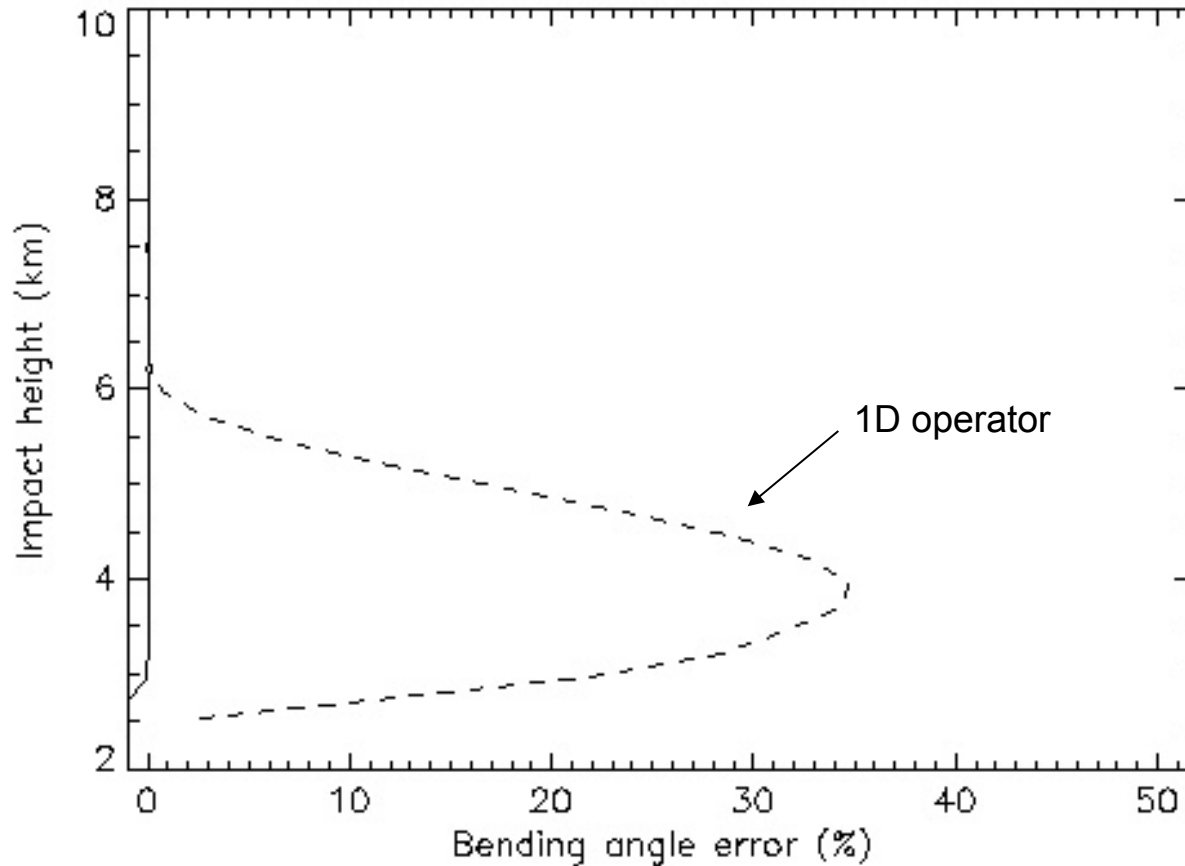
then the 1D and 2D refractivity operators give the same results because the average of the perturbation is 0.

2D refractivity field Sokolovskiy's idealised front

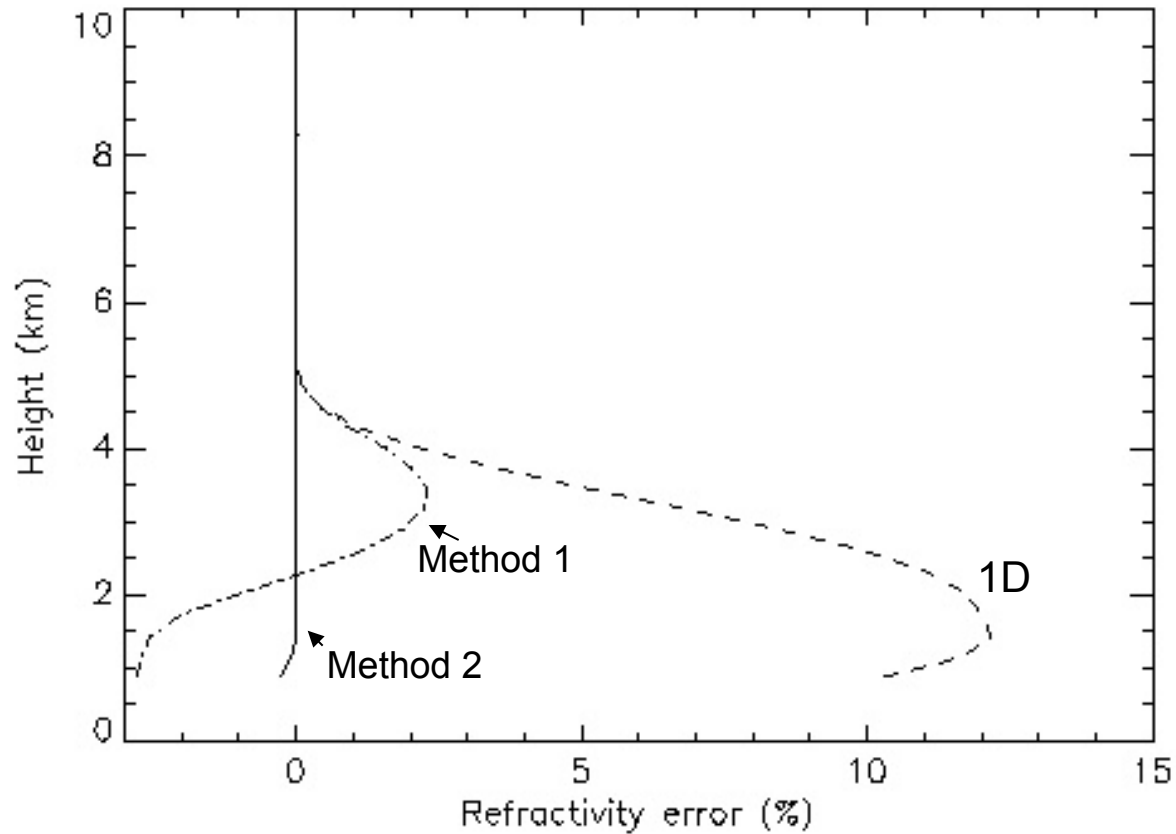


Sokolovskiy assumes the impact param. provided with the ob. is the value at the LEO. Assume ray comes from the right side. Neglect tangent drift.

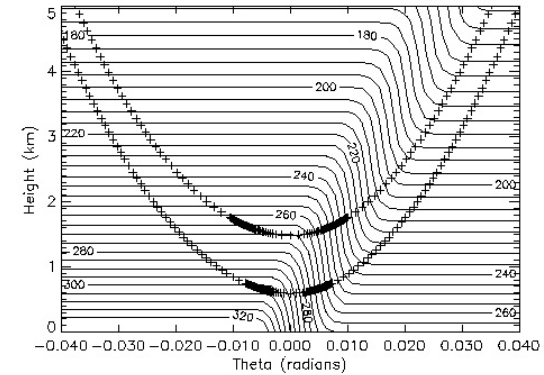
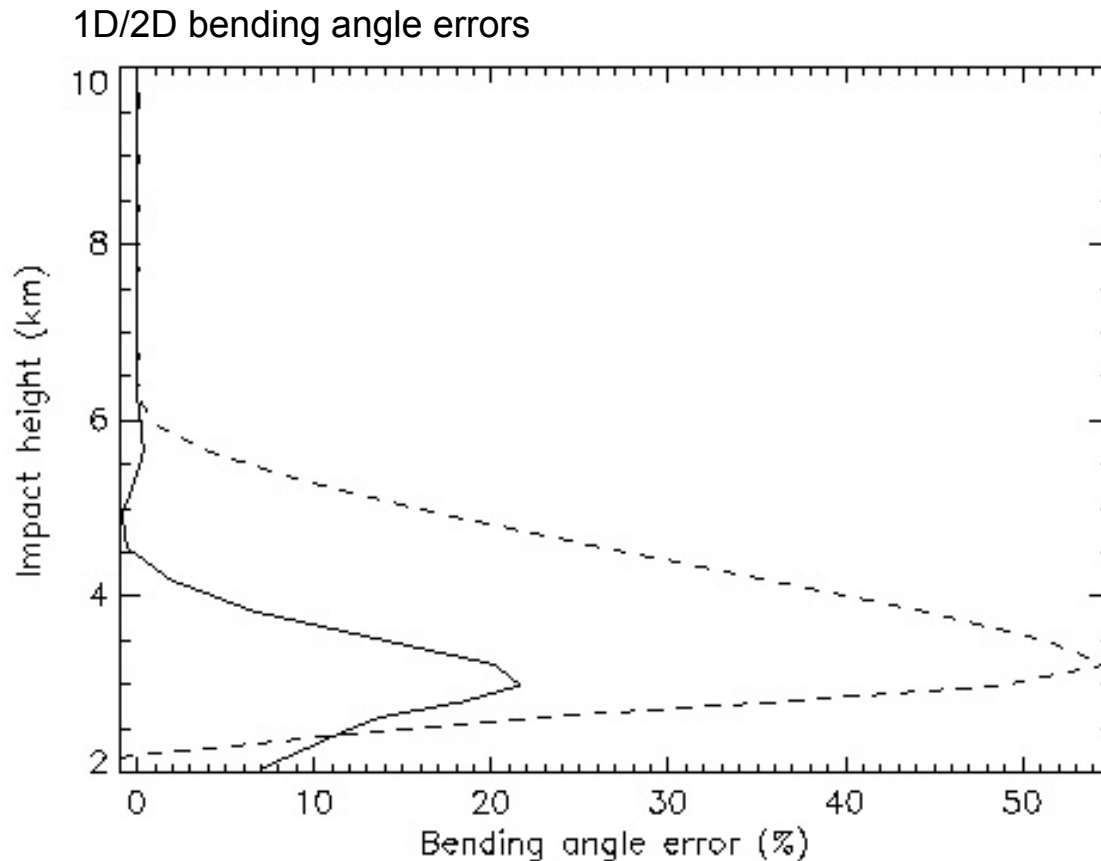
1D/2D bending angle errors



Refractivity errors



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



Refractivity errors

