Use of GPS-RO data in NWP at ECMWF

2D operators

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ROM SAF
Radio Occultation Meteorology

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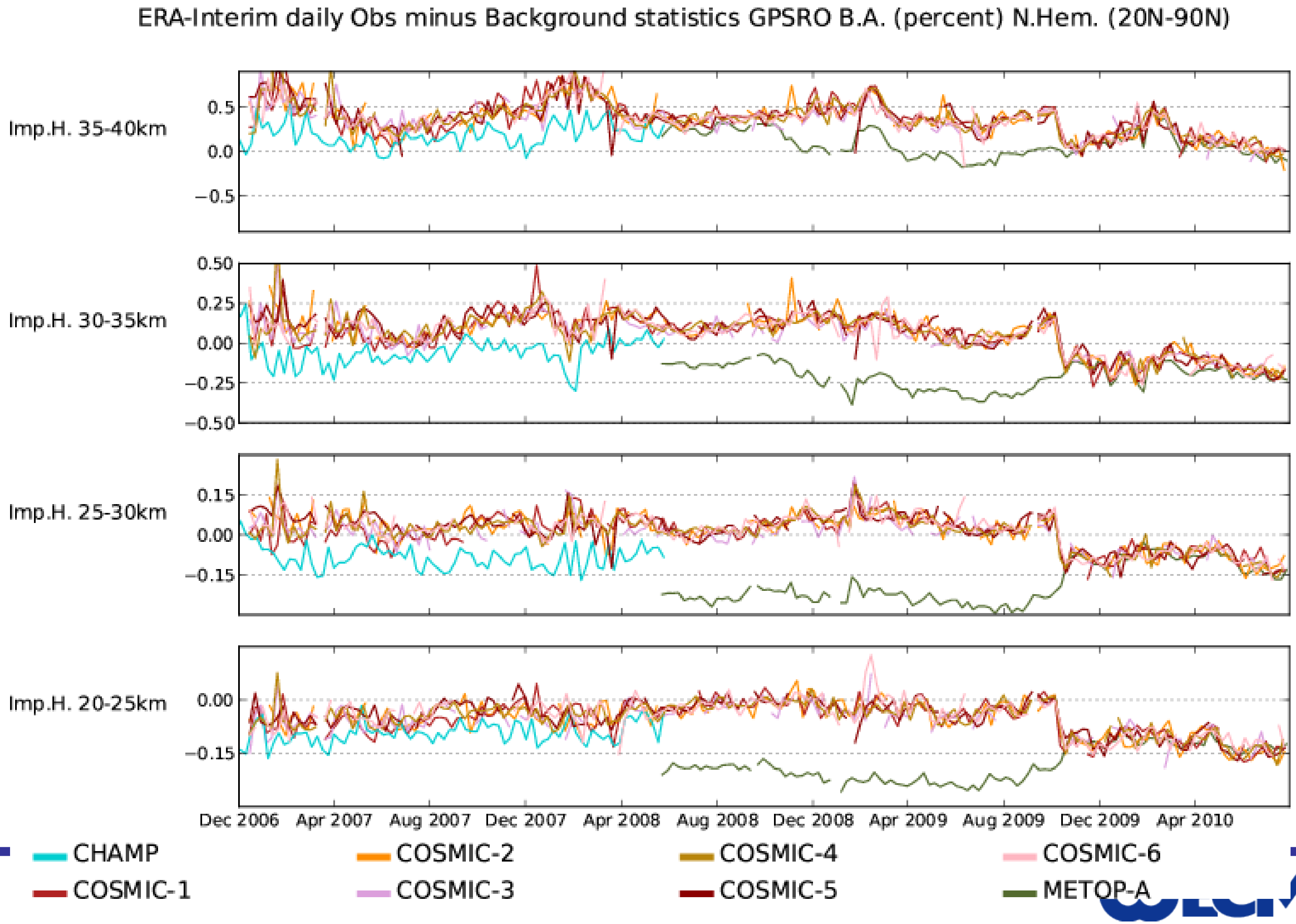
Outline

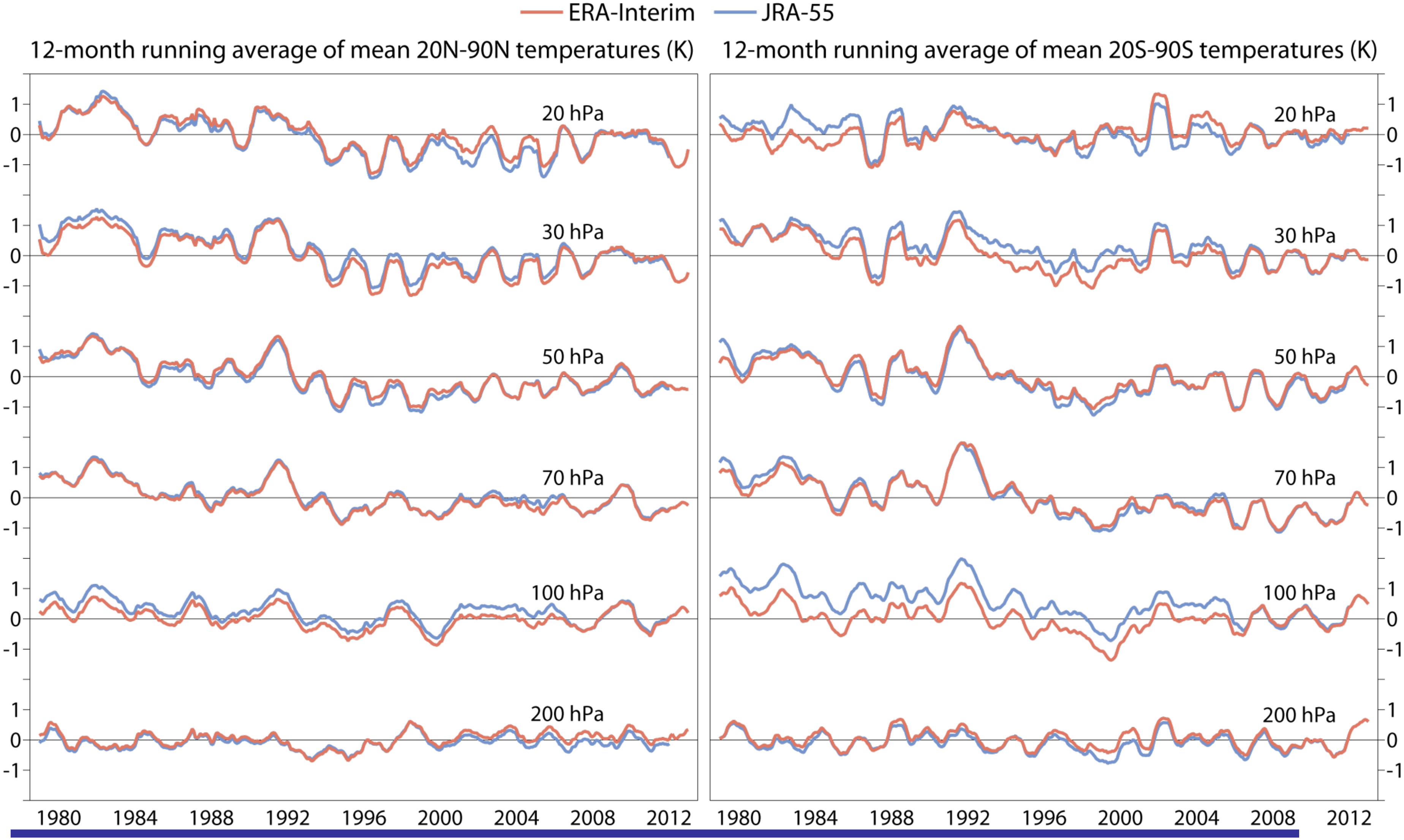
- Outline some current work at ECMWF: Reanalysis. Error statistics.
- Review improvements of the 1D operator since first implementation in 2006.
- 2D bending angle operator implementation;
  - Technical aspects, associated with 2D plane crossing a "PE boundary". **Why this is not a problem at ECMWF.**
  - Review IROWG-3 talk. **"Timings of the 2D operator in the 4D-Var."**
- Some approaches to speed up 2D operator.
- Summary.

Consistency of GPS-RO bending angles (ERA-Interim Reanalysis, Paul Poli)



Adrian Simmons

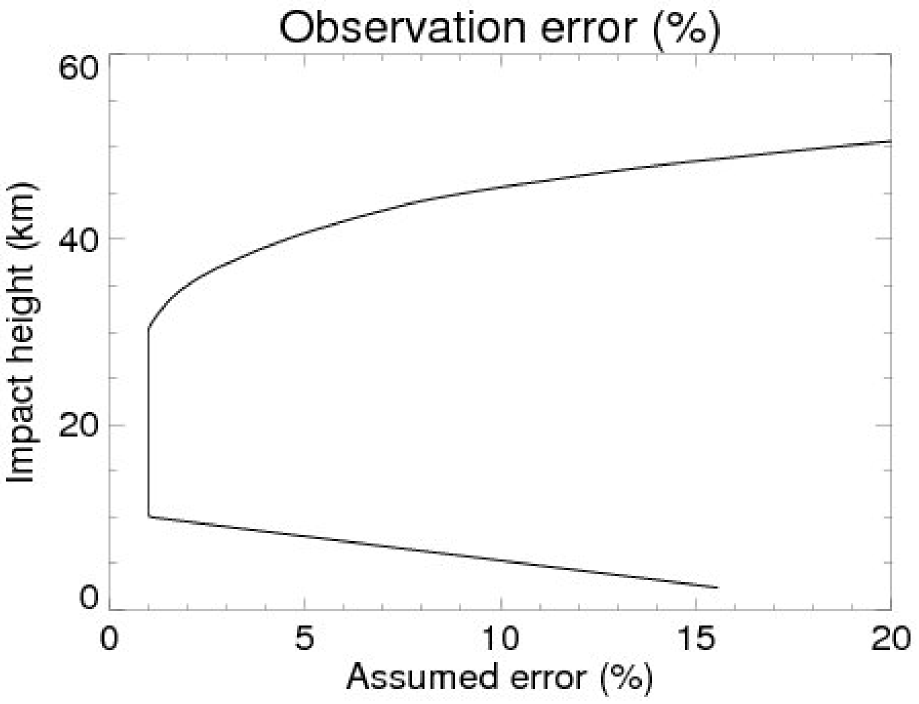
GPS-RO and extratropical-mean temperatures from ERA-Interim and JRA-55

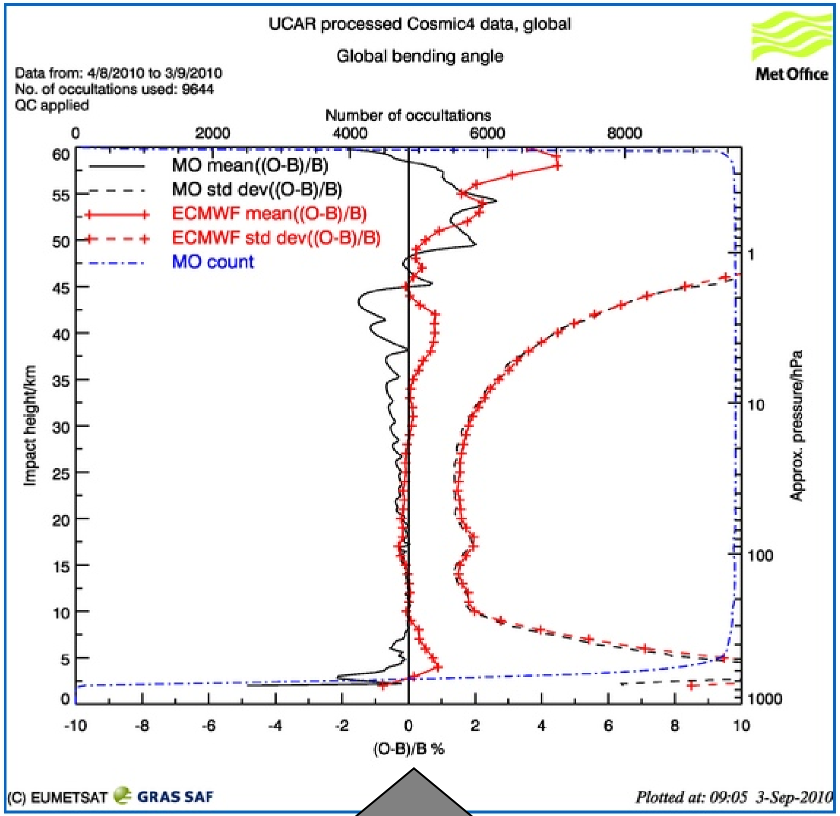


Values are relative to ERA-Interim means for 1981-2010

ECMWF

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





Consistent with o-b stats.

GLOBAL MODEL GOOD ENOUGH?

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

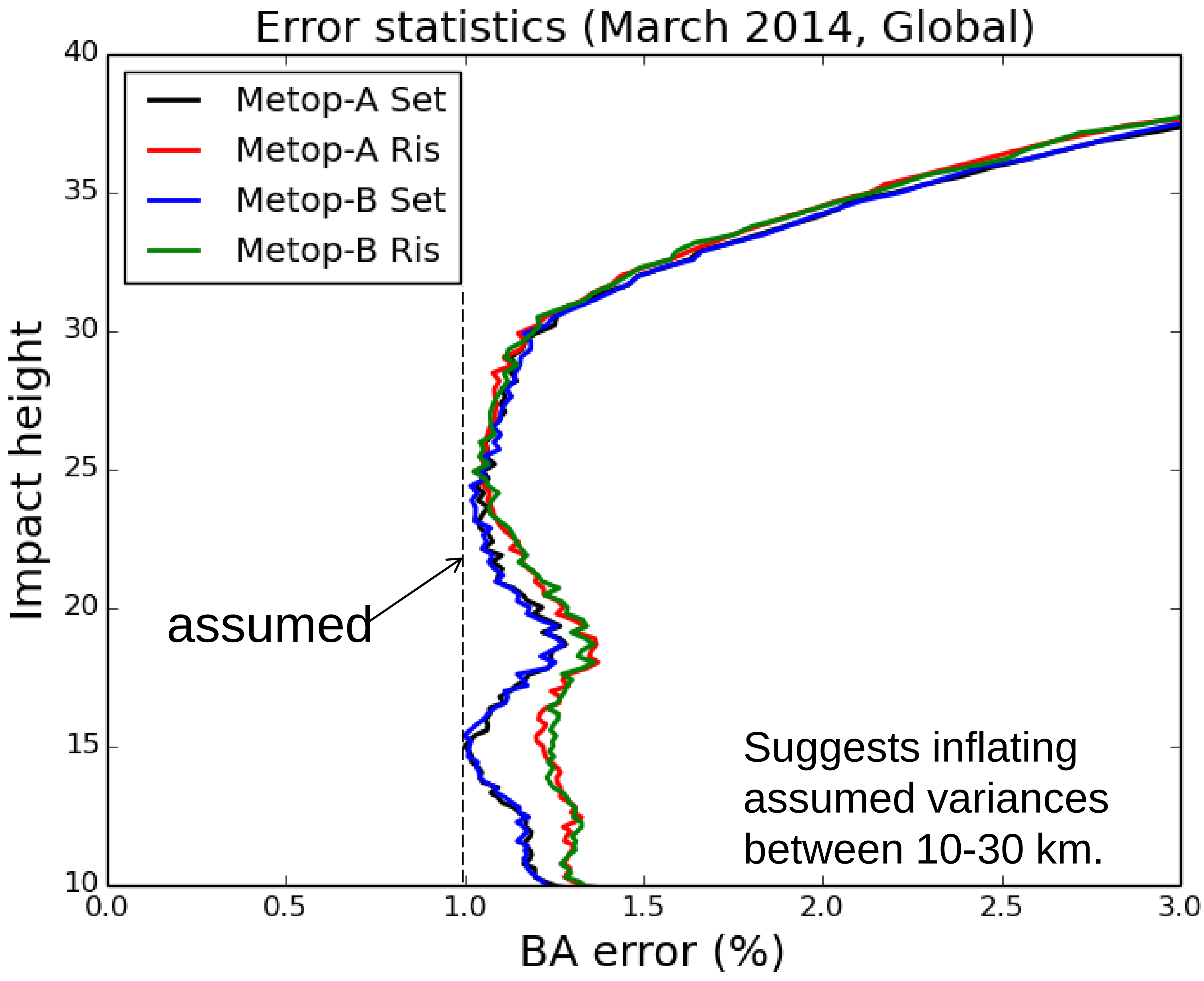
"Desrosier" diagnostics (MF, NCEP have looked at this)

- You can estimate the observation error covariance matrix from

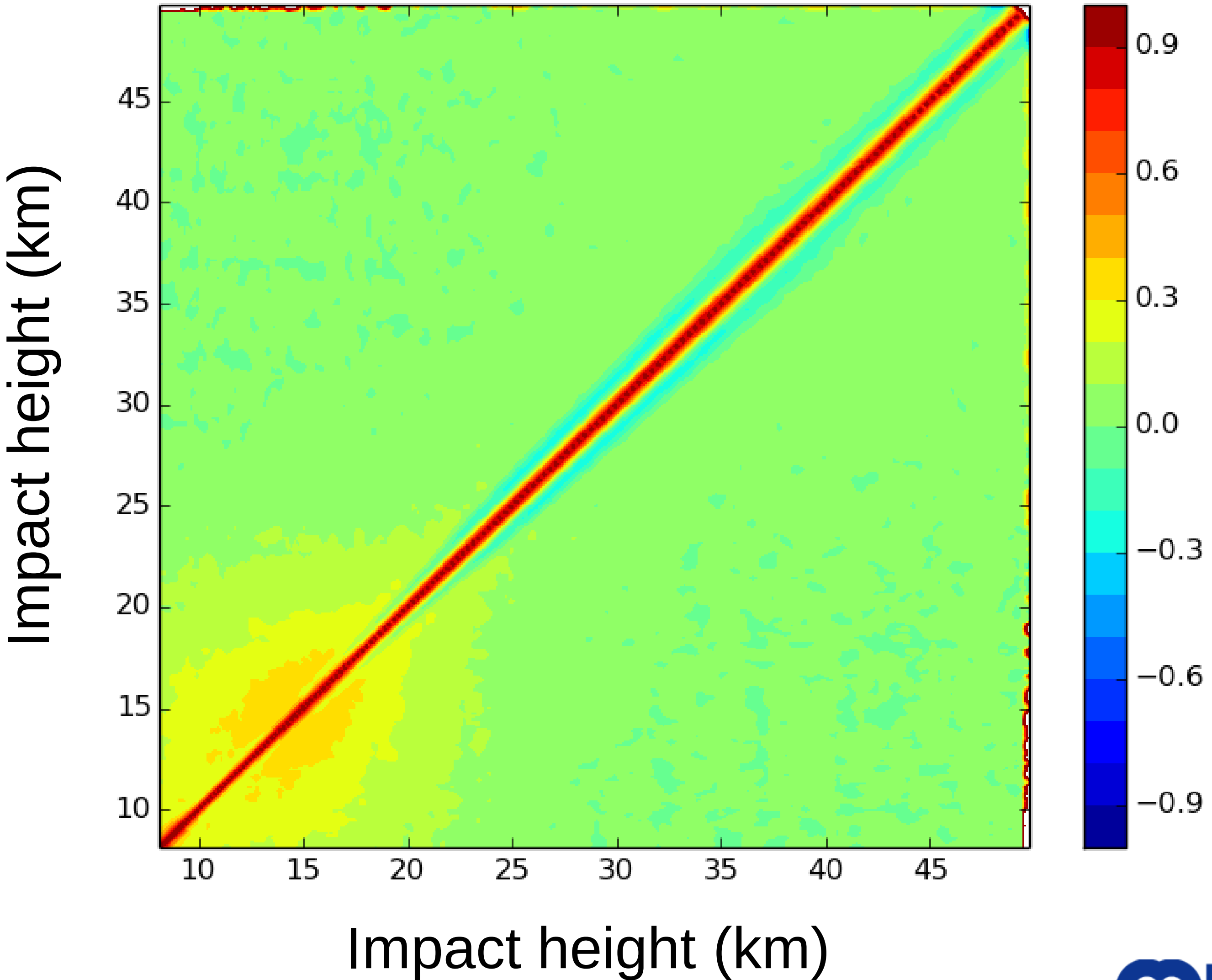
$$\mathbf{R} \approx \overline{\left(\mathbf{y} - H(\mathbf{x_a})\right)\left(\mathbf{y} - H(\mathbf{x_b})\right)^{\mathbf{T}}}$$

- This is used widely now, but strictly it will only produce the correct matrix **if the correct R and B matrices are used to compute the analysis!** It doesn't guarantee a symmetric estimate.

- Should iterate to account for incorrect matrices.


Error statistics (March 2014, Global)
Metop-A Set
Metop-A Ris
Metop-B Set
Metop-B Ris
Impact height
BA error (%)
40
35
30
25
20
15
10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
assumed
Suggests inflating
assumed variances
between 10-30 km.

Metop-A rising correlation matrix



Modification to account for the using the incorrect R matrix to produce the analysis

- Denote the Desrosier approximation by:

$$\mathbf{R}_{\mathrm{d}} = \overline{\left(\mathbf{y} - H(\mathbf{x}_{\mathrm{a}})\right)\left(\mathbf{y} - H(\mathbf{x}_{\mathrm{b}})\right)^{\mathrm{T}}}$$

- The **true error covariance** matrices are related to the assumed error covariance matrices used to produce the analysis:

$$\mathbf{R}_{\mathrm{t}} = \mathbf{R}_{\mathrm{a}} + \delta\mathbf{R}$$

$$\mathbf{B}_{\mathrm{t}} = \mathbf{B}_{\mathrm{a}} + \delta\mathbf{B}$$

Modified form to account for incorrect R

$$\mathbf{R}_* = \mathbf{R_a} + \left(\mathbf{R_a} + \mathbf{HB_aH^T}\right)\mathbf{R_a^{-1}}\left(\mathbf{R_d} - \mathbf{R_a}\right)$$
$$= \mathbf{R_t} + \mathbf{H}(\delta\mathbf{B})\mathbf{H^T}$$

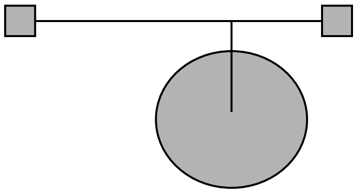
We (+ Chris Burrows) will investigate this in a 1D-Var context. Neat but does it tell us anymore than:

$$\mathbf{R} \approx \overline{\left(\mathbf{y} - H(\mathbf{x_b})\right)\left(\mathbf{y} - H(\mathbf{x_b})\right)^{\mathrm{T}}} - \mathbf{HB_aH^T}$$

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**. **These are not <u>expensive</u> – it's a (cubic*exponential) computation! Look at ROPP implementation.**

Changes since 2006

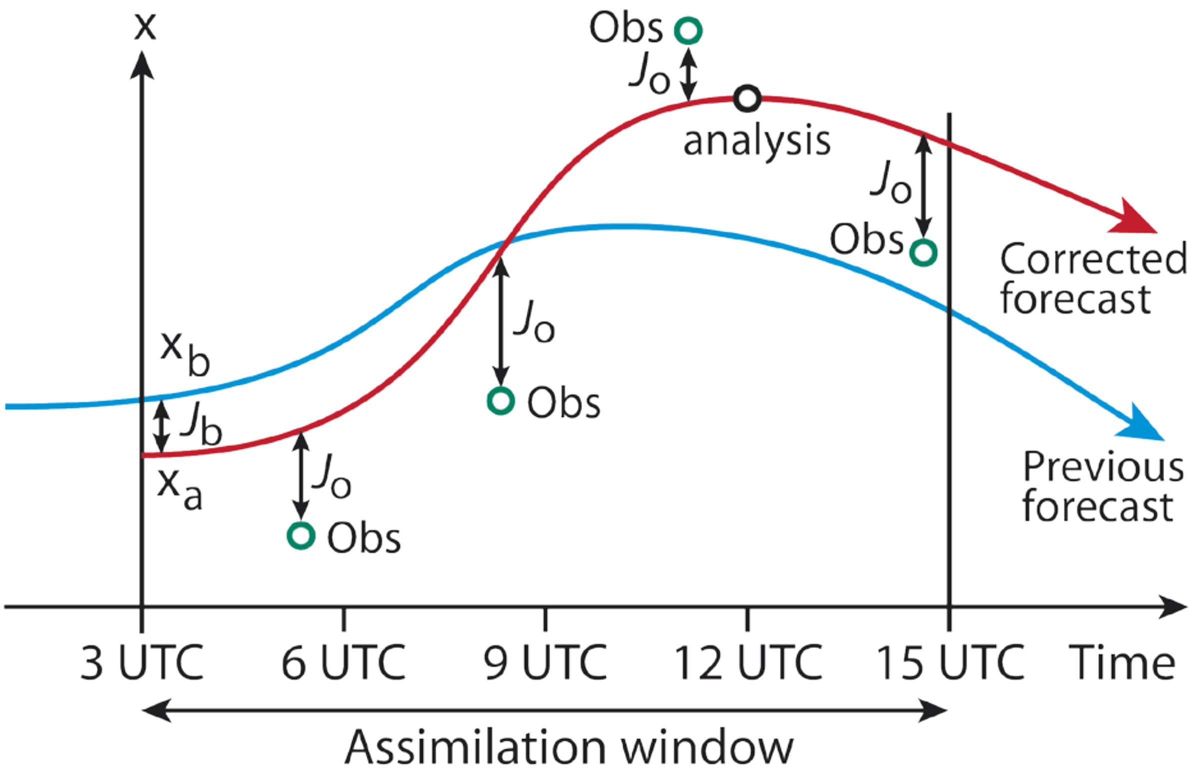
- Introduction on non-ideal gas affects in the operator (Josep Aparicio, presented at the workshop in 2008).

- Introduction of tangent point drift (Lidia Cucurull and Paul Poli): **Good change (2011)**.

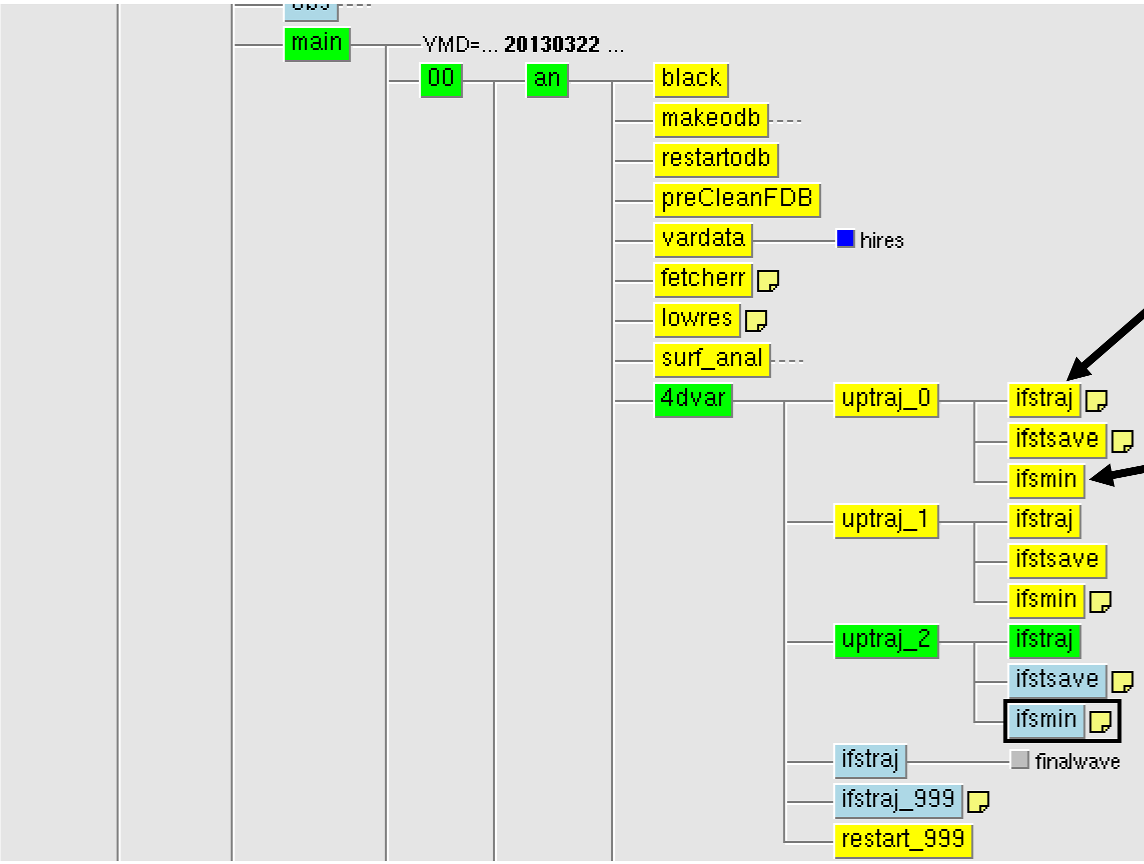
- **Maximum refractivity gradient in bending angle computation**: Half the ducting gradient. Important change: 4D-Var minimization issues, because of linearity assumption in inner loop.

- 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.

4D-Var assimilation



“Incremental” 4D-Var system



We use the full non-linear operators here in the “trajectory runs”.
This is the “**Outer loop**”.

We use the tangent-linear (TL) and adjoint (AD) codes when minimizing the linearized 4D-Var problem.

Called the “**inner loop**”.

$$\mathrm{TL} = \frac{\partial y}{\partial x}$$

$$\mathrm{AD} = \left(\frac{\partial y}{\partial x}\right)^T$$

2D operator

- **2D should mean we are less likely to misinterpret the observation information.**

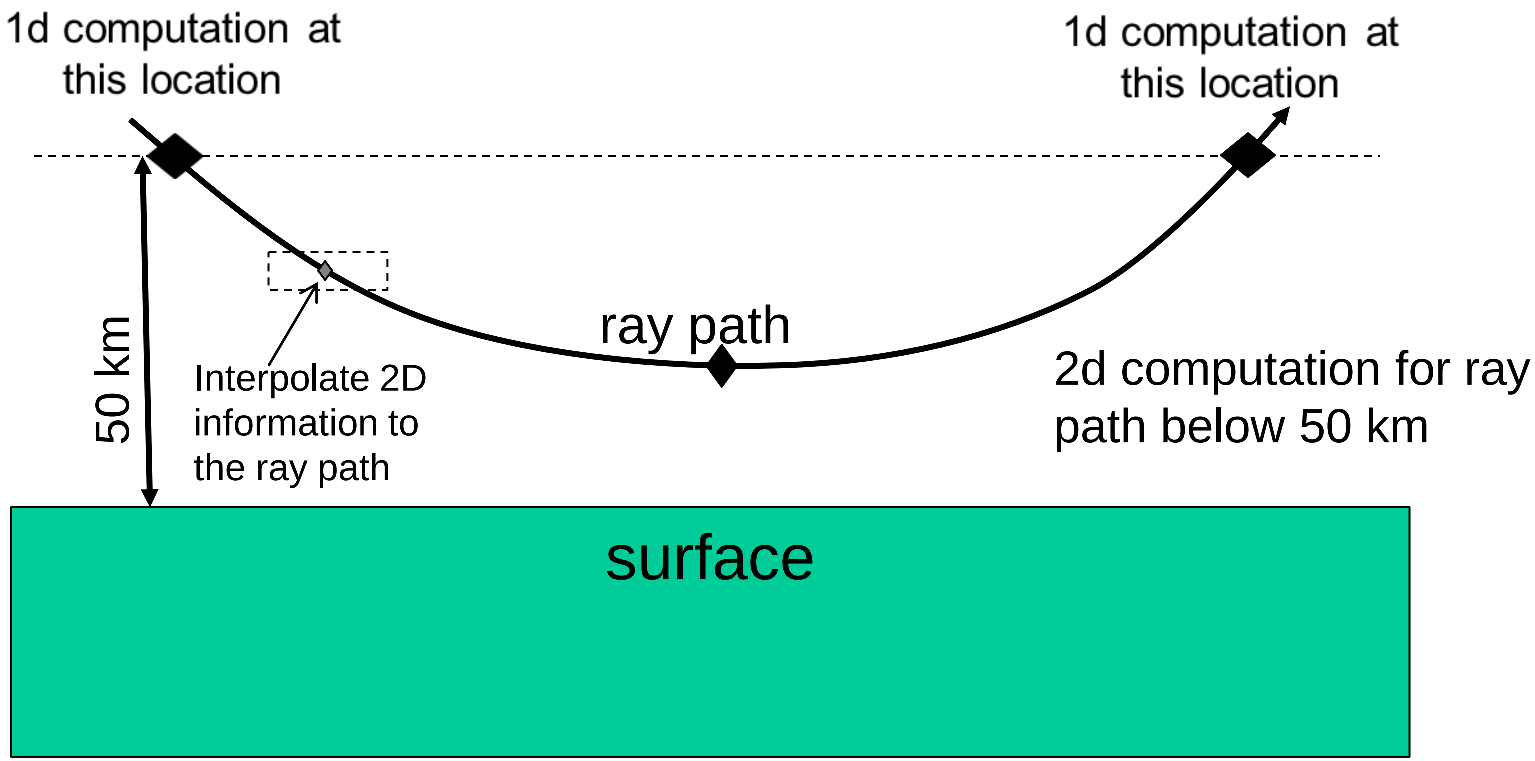
- Look at the 2D operator impact when the **NWP forecast model** has higher horizontal resolution (~16 km) in **outer loop**. (Previously 40 km).

- Perform 2D calculation up to 50 km. (Previously 20 km).

- **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



Solve the differential equations for the path below <u>50 km</u>. Revert to 1D integrals above 50 km. ***(50 km is a variable.)***

2D operator in 40R3

1D

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

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

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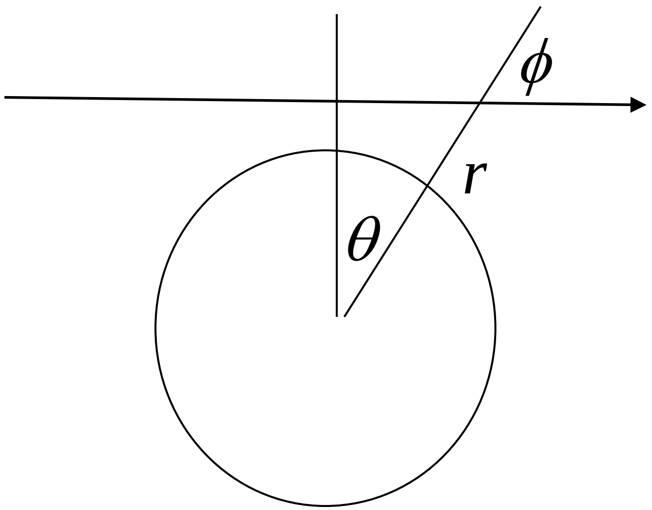
$$\frac{d\theta}{ds} = \frac{\sin\phi}{r}$$

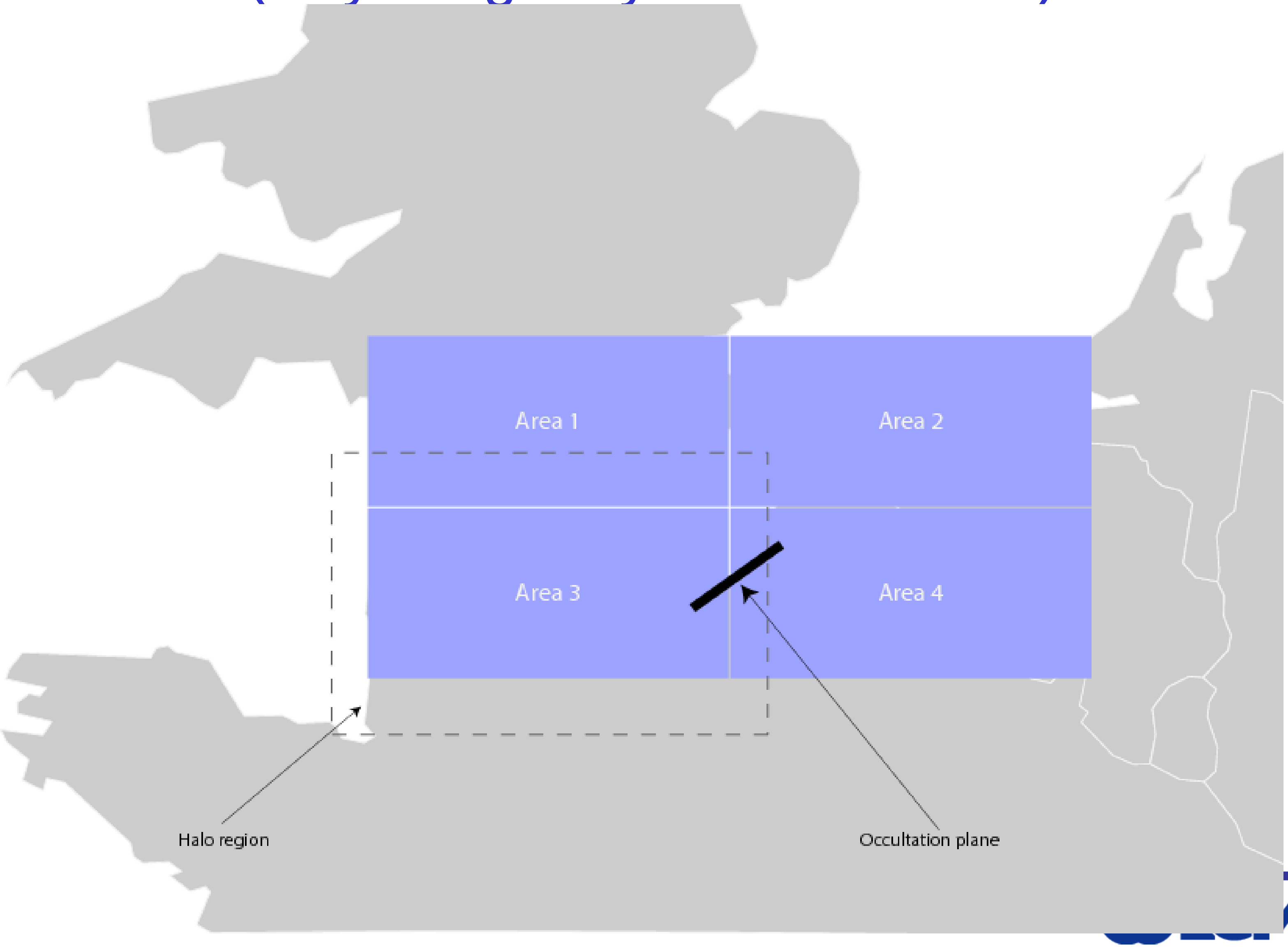
$$\frac{d\phi}{ds} \approx -\sin\phi\left[\frac{1}{r} + \left(\frac{\partial n}{\partial r}\right)_{\theta}\right]$$



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.*

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".

$$\mathbf{Hx} = \mathbf{H}_{\mathbf{v}}\mathbf{H}_{\mathbf{h}}\mathbf{x}$$

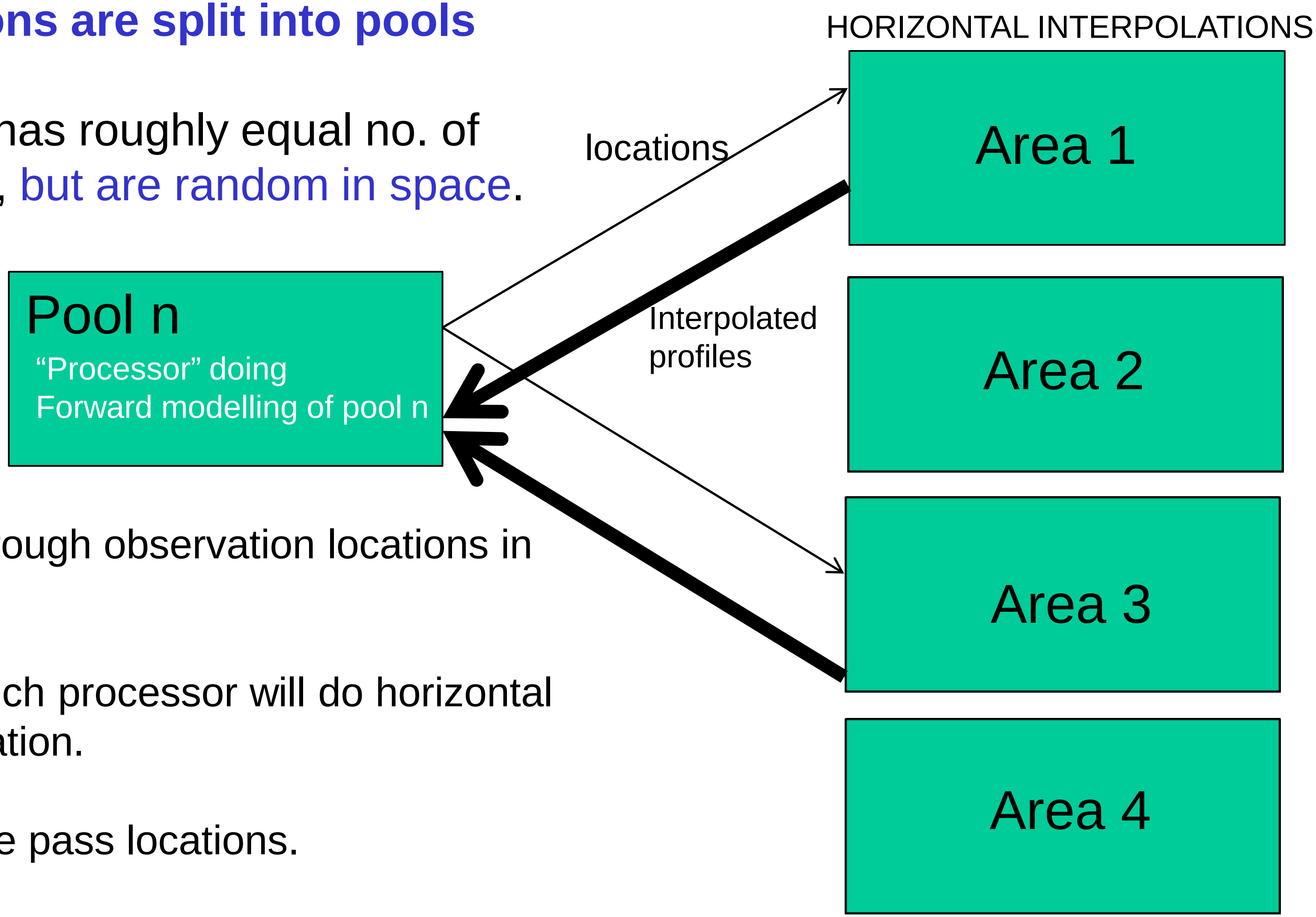
Forward model

Horizontal interpolation

Bending angle computation

Observations are split into pools

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



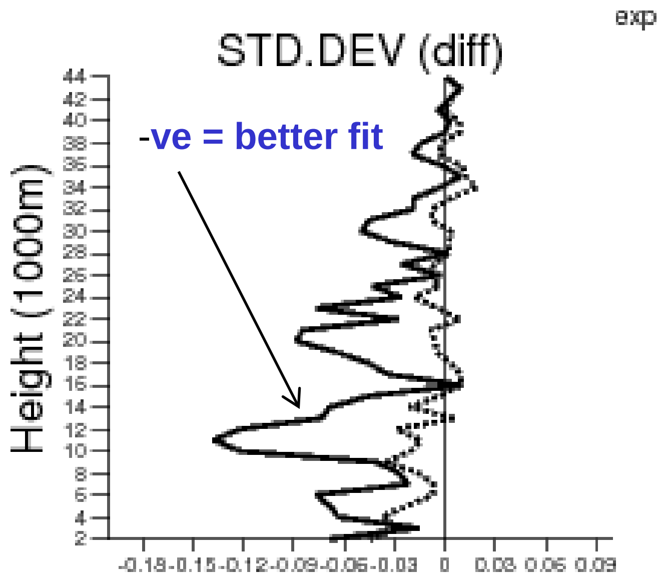
- Loop through observation locations in pool.
- Find which processor will do horizontal interpolation.
- Message pass locations.
- Message pass back interpolated profiles

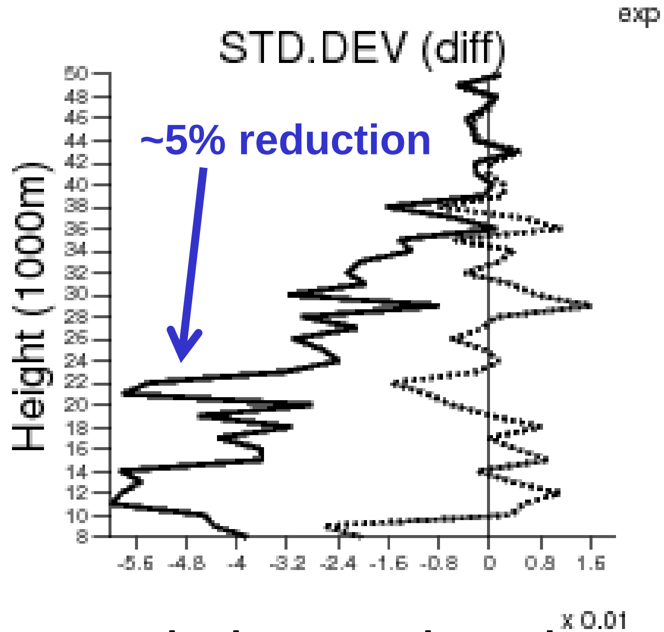
2D operator information

- 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

Improvement in standard deviation of bending angle departure statistics: Δ[(o-b)/σ]



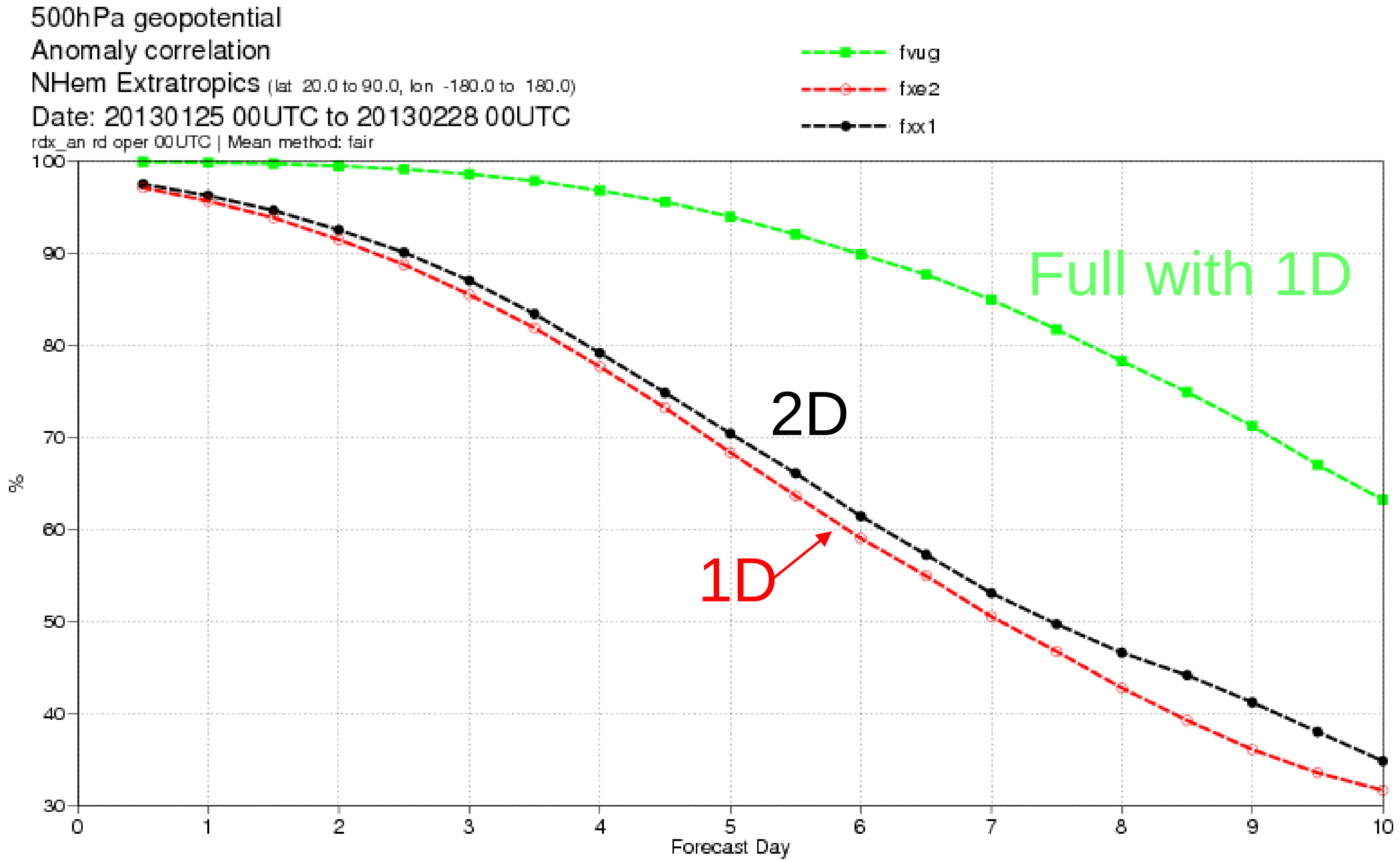


NH, RO-only: The 2D operator is improving the departure statistics even in stratosphere.

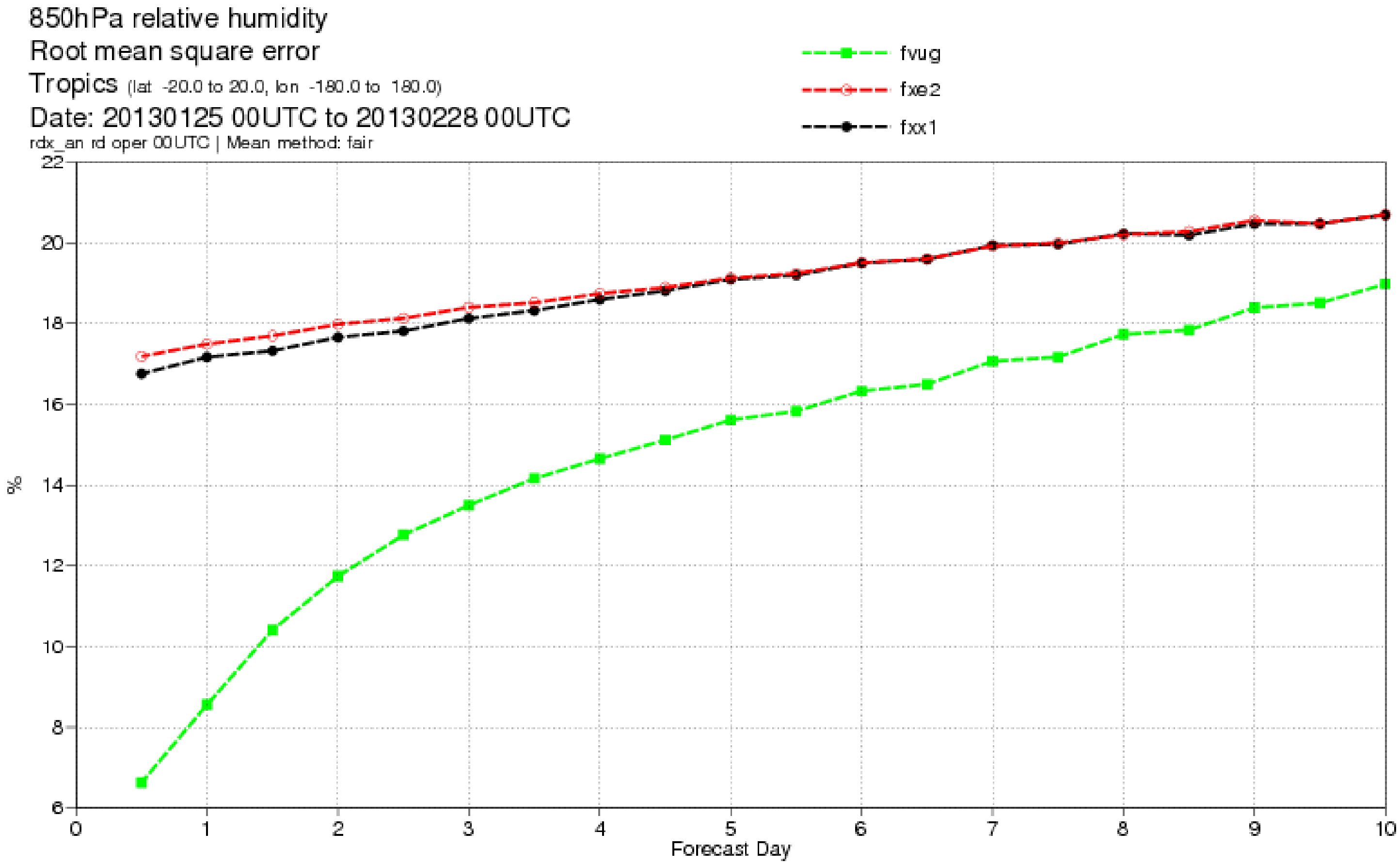
Similar size improvements in the full system.

Z500 scores, NH

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

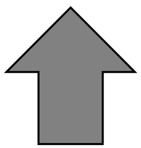


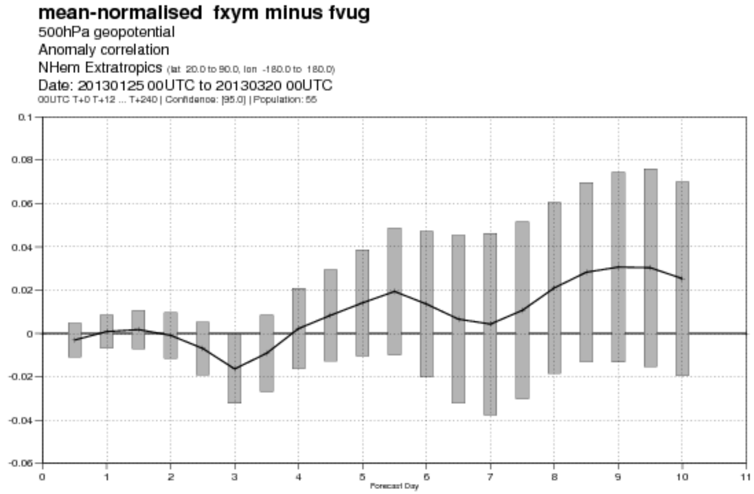
Tropics 850hPa humidity (RMS errors)

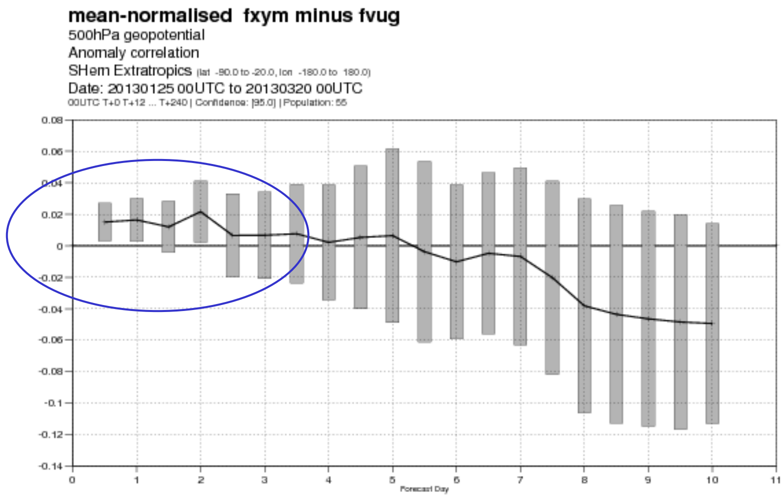


2D vs 1D in **full system**, Z500 anomaly correlation

Above 0 = good







Further science improvements of 2D operator

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

$$nr\sin\varphi = a$$ (impact parameter)

- **Its not a constant!** We should integrate along ray-path

$$\frac{d(nr\sin\varphi)}{ds} = \frac{\partial n}{\partial\theta}_r$$

- Use an "adjusted" impact parameter ($a \rightarrow (a + \Delta a)$) value will be used in the 2D operator to determine tangent height.

- Aim to present results with this change at the COSMIC workshop!

ECMWF

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.

Possible solutions to speed up 2D operator (ROM SAF Report 19: www.romsaf.org/rsr.php)

- **Do we need a Runge-Kutta 4**. (Mid-point method).

- **Tangent Point Drift**. Perhaps batch the bending angles rather than new profile/plane for each bending angle. **Do other centres including TPD actually batch the data? How many in a batch?**

- **Need 31 profiles (40 km spacing) for the inner loop?** 2D operator in outer-loop, 1D inner loop. It fits into the incremental 4D-Var approach, where models in inner loop are simpler and coarser (125 km, 80 km) than outer loop.

- **REMARK**: *Number of profiles: ~1250 occs per 12 hours. 200 bending angles per occ. Each require 31 profiles (7.75 million profiles in total)*

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.

ECMWF

Summary

- **Some interesting results from reanalysis**: Consistency of ERA-Interim and JRA-55 after the assimilation of GPS-RO.
- Started to look at assumed observation error models.
- We plan to go operational with the 2D operator in 2014 (40r3).
- Had to address some computational cost issues for the 2D operator.
- Will test variation of impact parameter later this year.

Some discussion points

- Plans for 2D assimilation at other centres?
- Assumed interpolation between model levels in BA integration.
- Assimilation at/below sharp gradients: 4D-Var linearity issues?
- Observation error statistics models
  - Use of Desrosier approach. Plans to use correlations? Should the ROM SAF produce these matrices for other users?
  - Provision of an error estimate with each observation. How do I interpret this number? Does the error variance really change every observation.

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

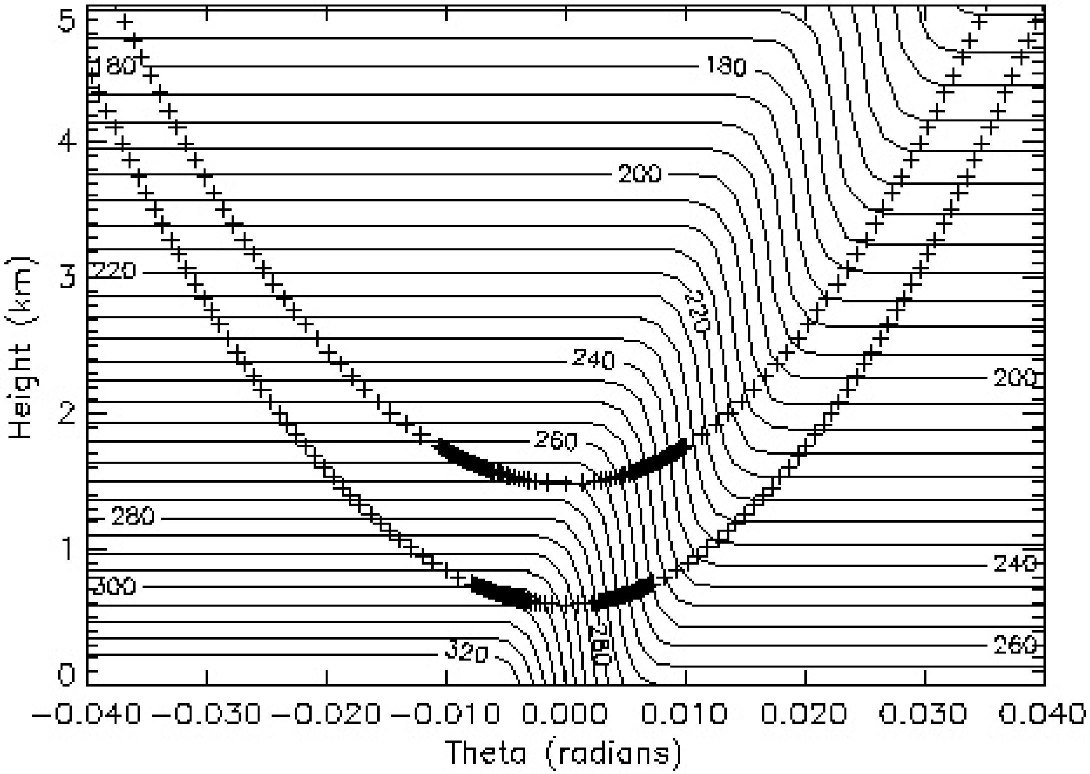
$$N(r,\theta) = N(r,0) + N'(r,\theta)$$

If the perturbation is "odd"

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

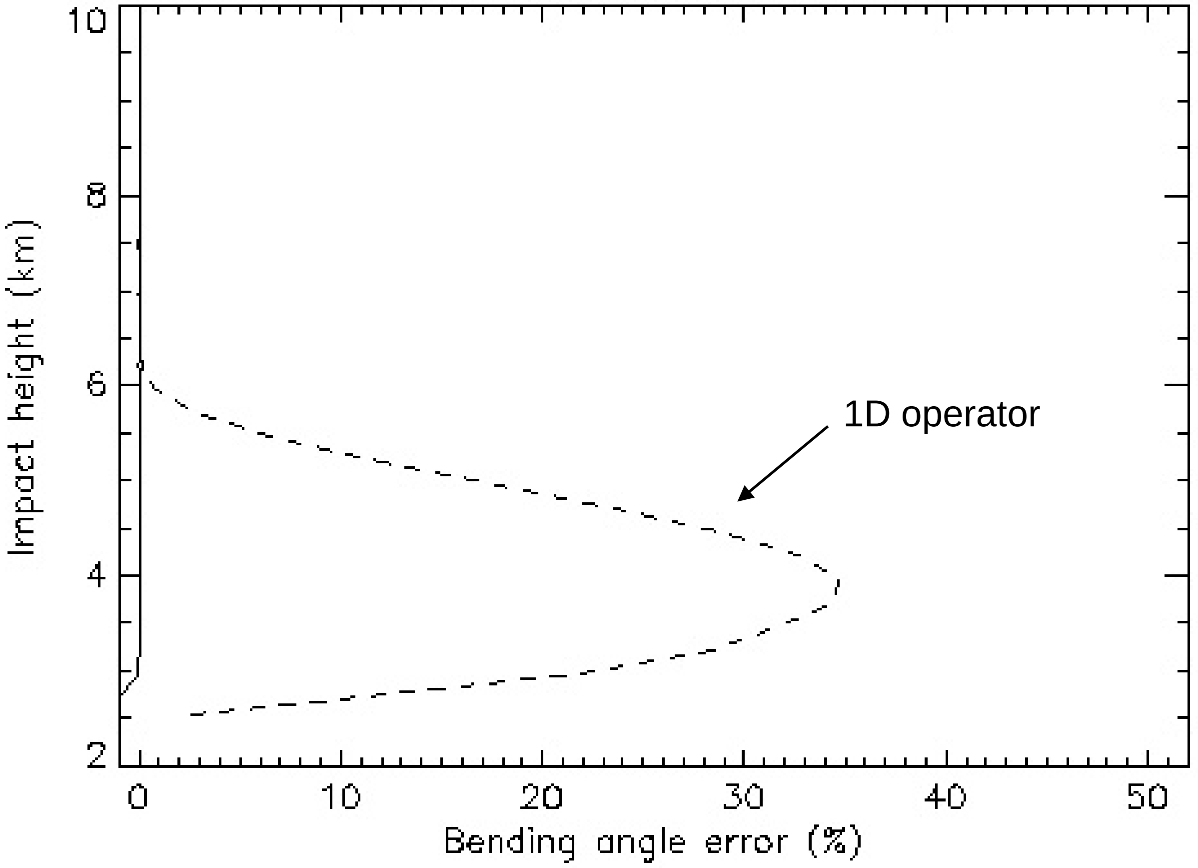
then the 1D and 2D refractivity operators give the same results because the average of the perturbation is 0.

2D refractivity field Sokolovskiy's idealised front

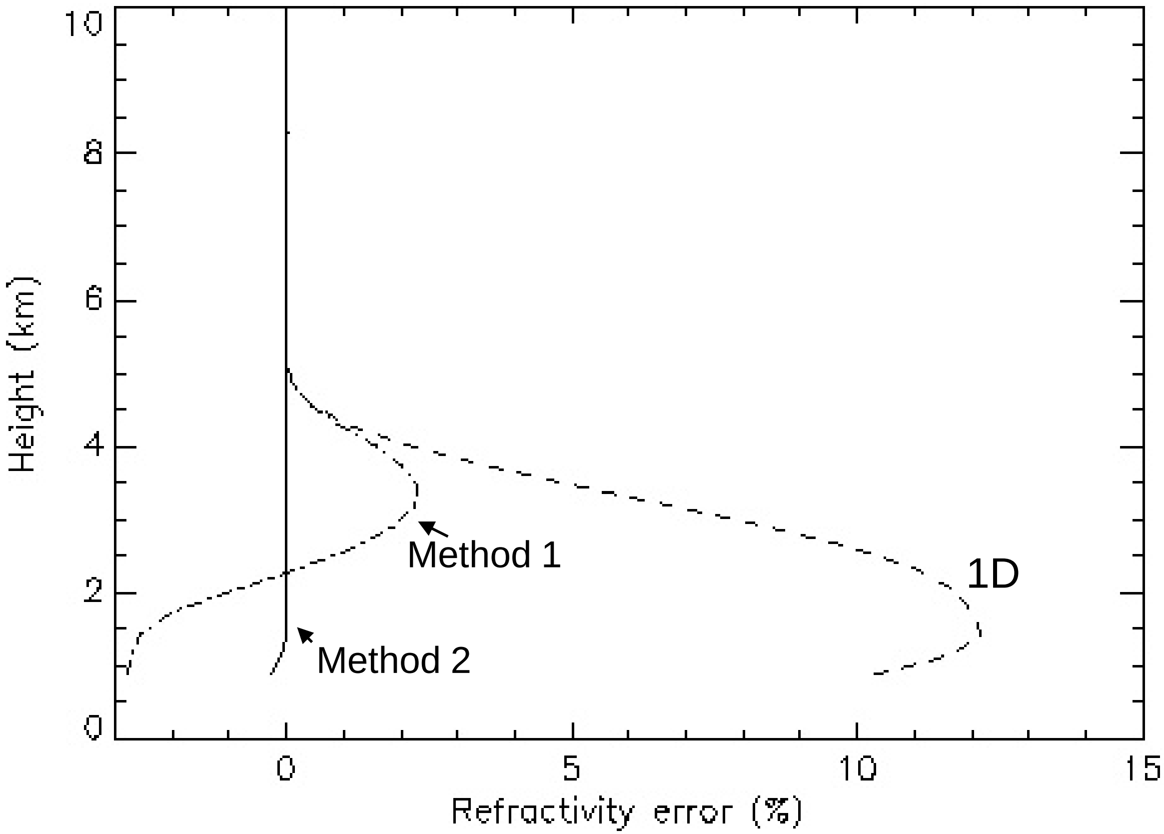


Sokolovskiy assumes the impact param. provided with the ob. is the value at the LEO. Assume ray comes from the right side. Neglect tangent drift.

1D/2D bending angle errors

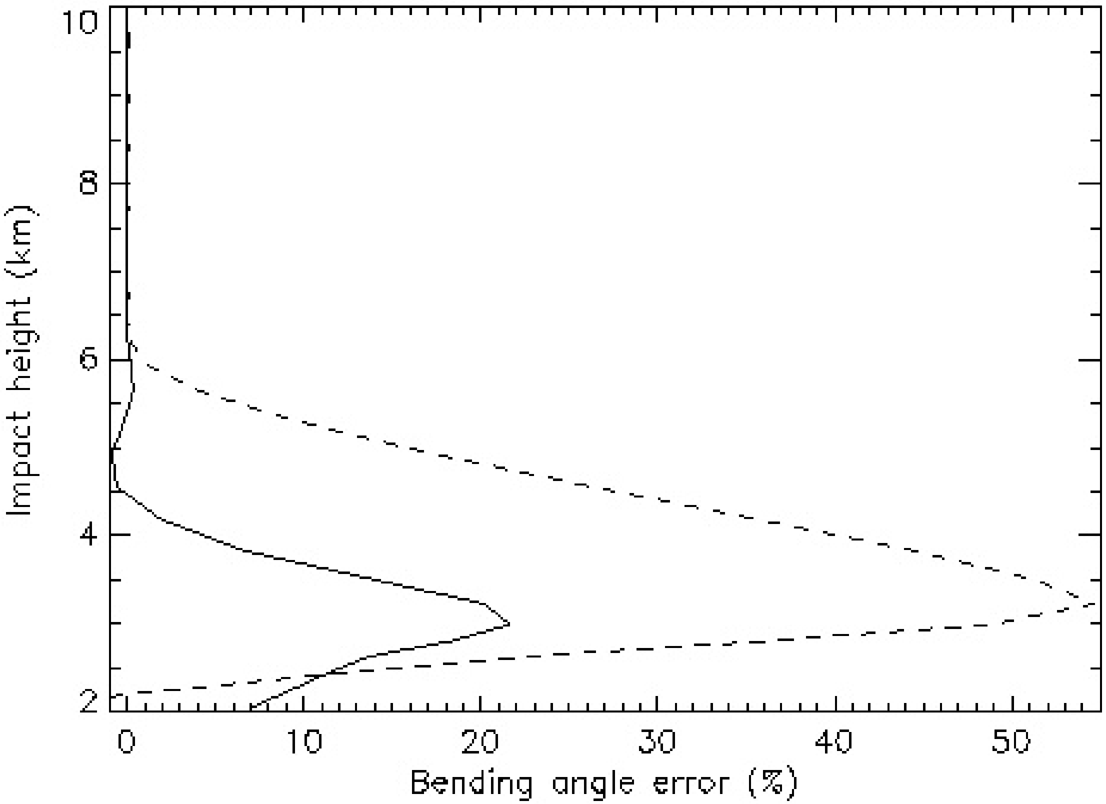


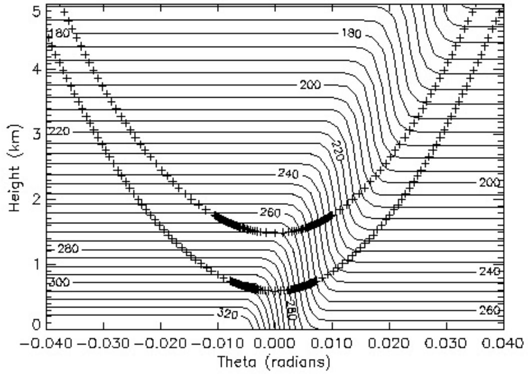
Refractivity errors



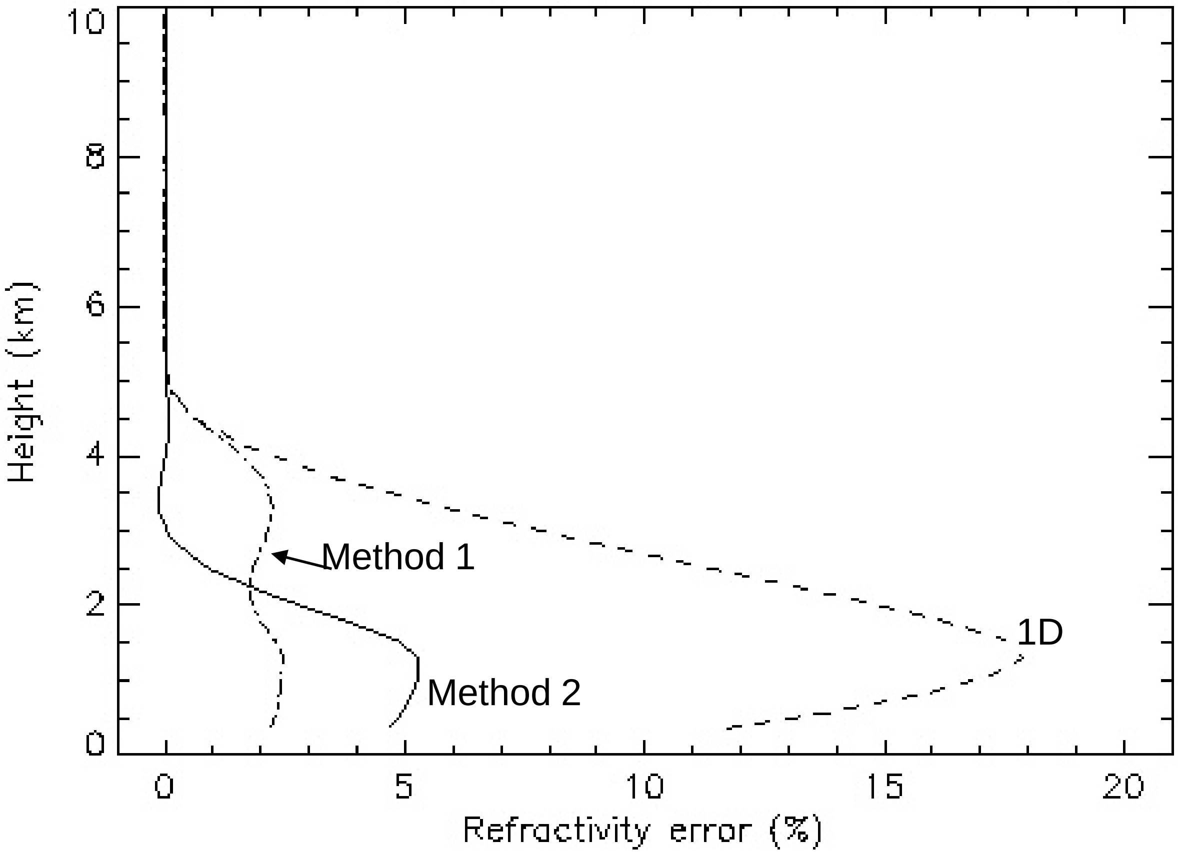
Assume ray comes from left to right. Same ray-path, but assume opposite direction

1D/2D bending angle errors



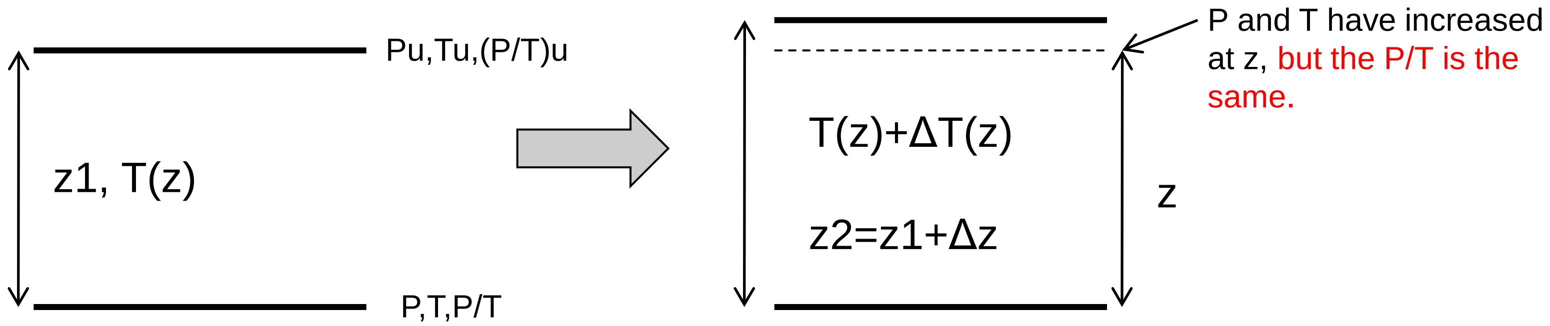


Refractivity errors



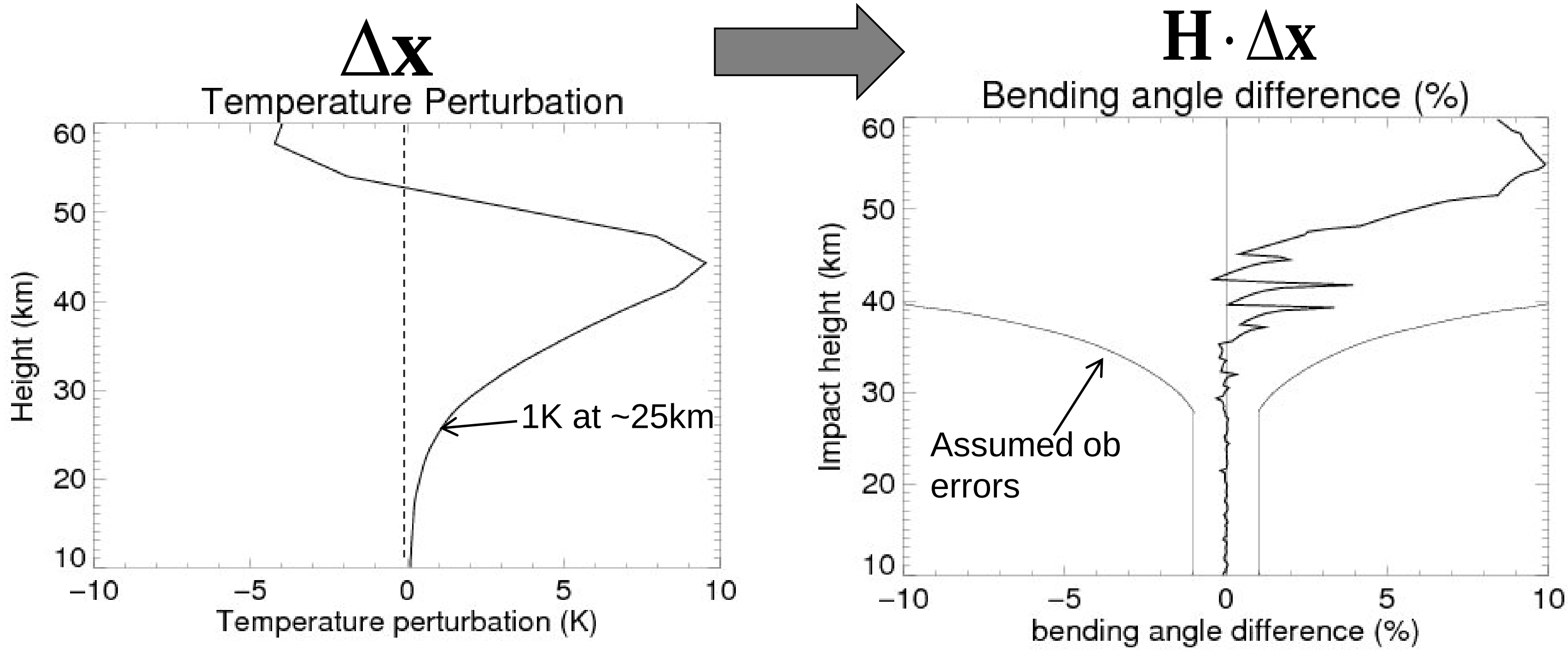
BUT GPS-RO has a "null space"

- **The measurement is related to density (~P/T) on height levels and this ambiguity means that the effect of some temperature perturbations can't be measured**. Assume two levels separated by z1, with temperature variation T(z) between them. Now add positive perturbation $\Delta T(z) \sim k^* \exp(z/H)$, where H is the density scale height



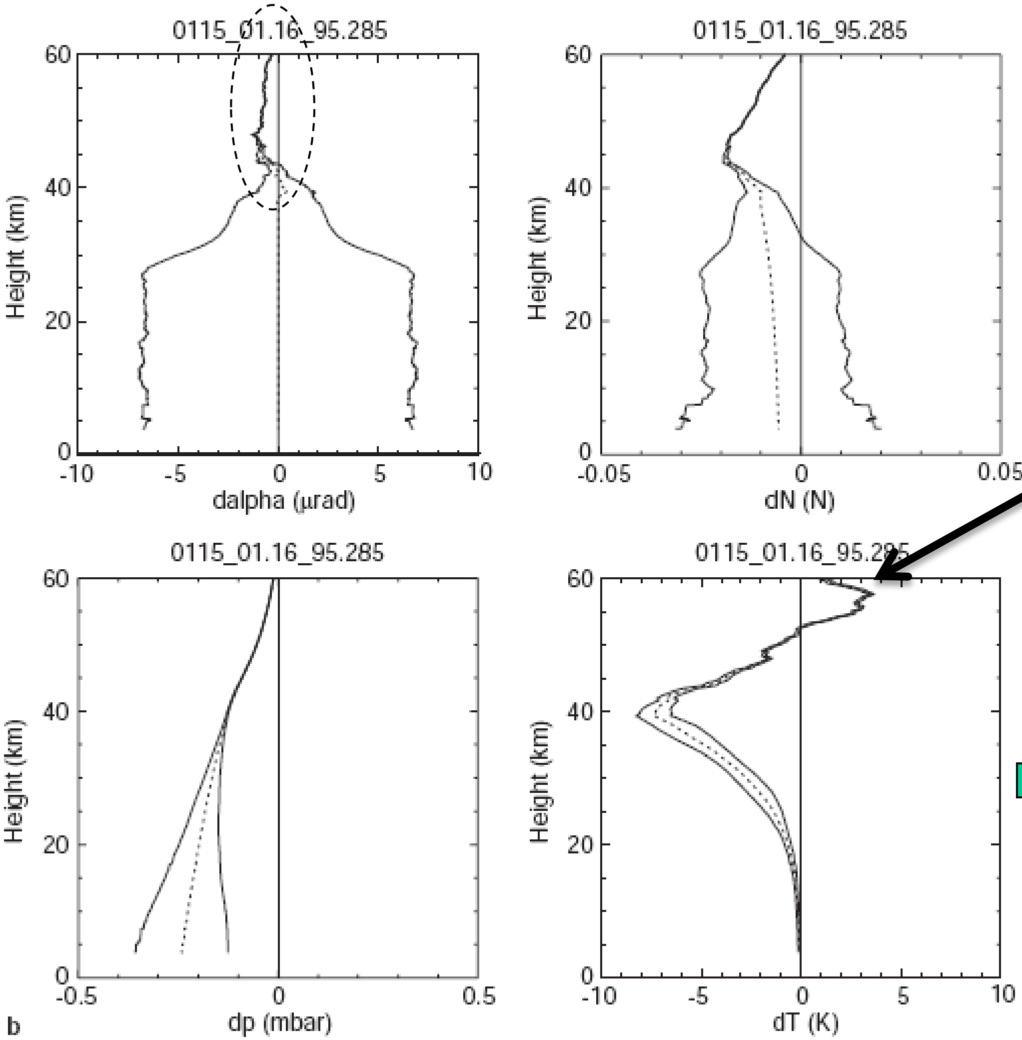
- The density as a function of height is almost unchanged. **A priori information required to distinguish between these temperature profiles. (Height of a pressure level).**

Null space – how does the temperature difference at the S.Pole propagate through the observation operator



The null space arises because the measurements are sensitive to ~P(z)/T(z). *A priori* information is required to split this into T(z) and P(z).

Compare with Steiner et al (Ann.Geophs., 1999,17, 122-138)



Temperature retrieval error caused by a 5 % bias in the background bending angle used in the statistical optimization