Introduction to GPS radio occultation

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Outline

1) Basic physics.

2) GPS (should really be “GNSS”) measurement geometry.

3) GPS radio occultation and “**Classical GPS RO retrieval**”.

4) Information content and resolution from 1D-Var.

5) 4D-Var assimilation of GPS RO measurements **(GPS RO null space)**.

6) Novel applications: Planetary boundary layer information from GPS RO, surface pressure.

7) Ground-based GPS measurements (**very briefly**).

8) Summary and conclusions.

The basic physics – Snel's Law

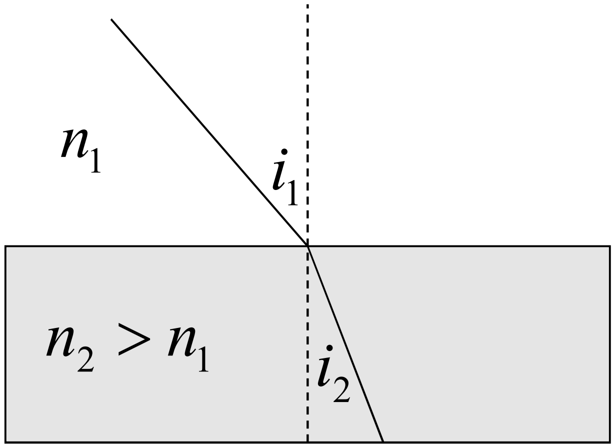
(Not "*Snell*", Peter Janssen)

- **Refractive index**: Speed of an electromagnetic wave in a vacuum divided by the speed through a medium.

$$\boxed{n = \frac{c}{v}}$$

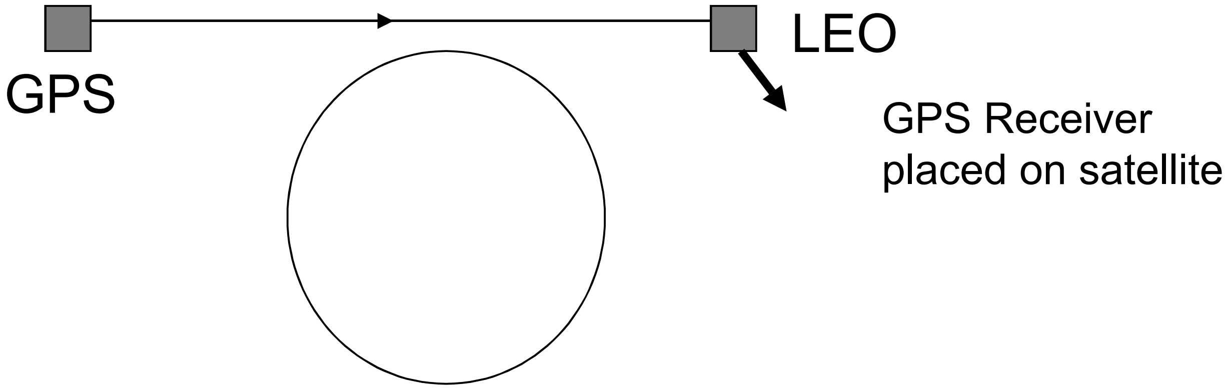
- Snel's Law of refraction

$$\boxed{n_1 \sin i_1 = n_2 \sin i_2}$$

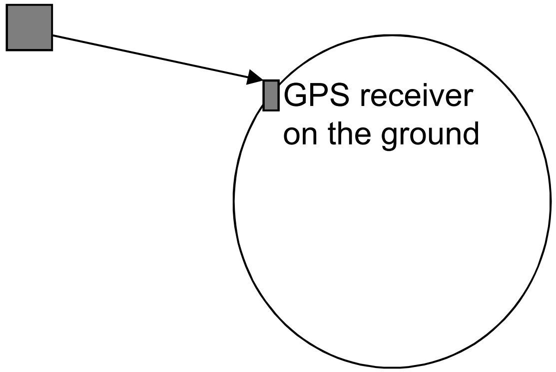


Measurements made using GPS signals

GPS Radio Occultation (Profile information)



Ground-based GPS (Column integrated water vapour)



Radio Occultation: Some Background

- Radio occultation (RO) measurements have been used by to study planetary atmospheres (**Mars, Venus**) since the 1960's. Its an **<u>active technique</u>**. We simply look at how the paths of radio signals are bent by refractive index gradients in the atmosphere.

- The use of RO measurements in the Earth's atmosphere was originally proposed in **1965**, but required the advent of the GPS constellation of satellites to provide a suitable source of radio signals.

- Use of GPS signals discussed at the Jet Propulsion Laboratory (JPL) in late 1980's. In **1996** the proof of concept "GPS/MET" experiment demonstrated useful temperature information could be derived from the GPS RO measurements.

GPS RO: Basic idea

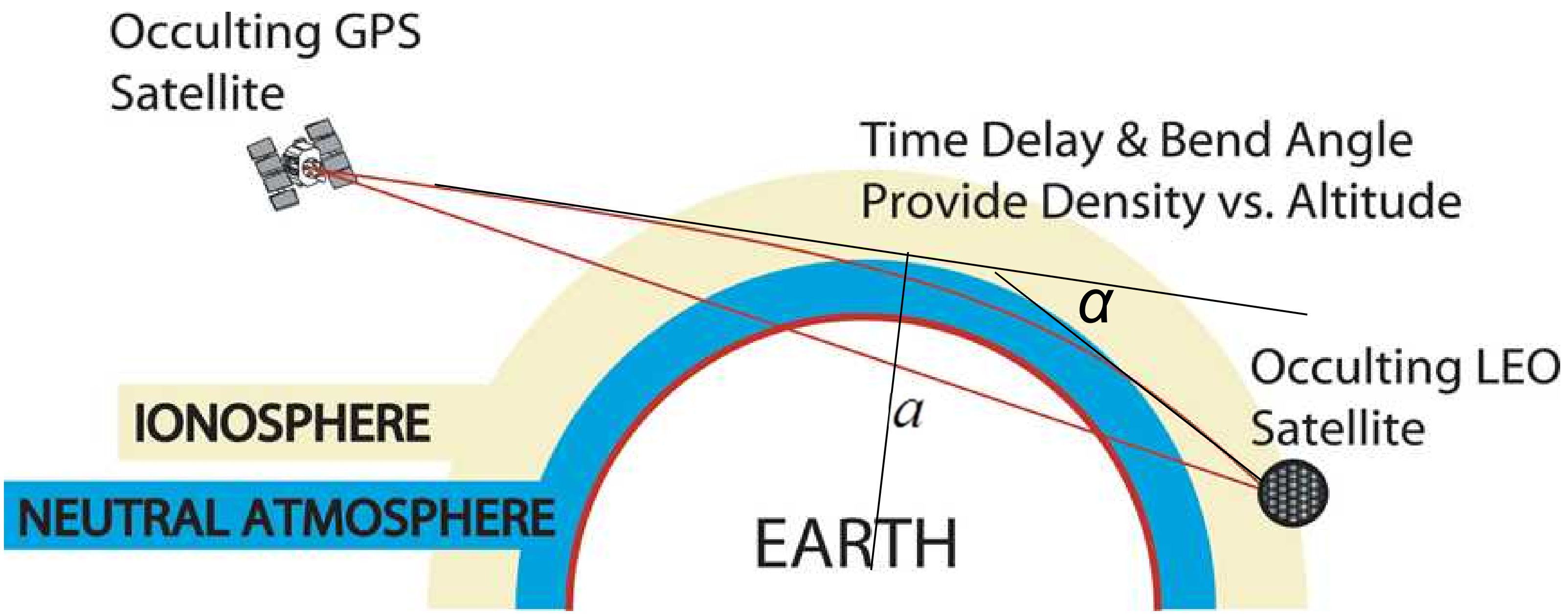
The GPS satellites are primarily a tool for positioning and navigation These satellites emit radio signals at L1= 1.57542 GHz and L2=1.2276GHz *(~20 cm wavelength*).

The GPS signal velocity is modified in the ionosphere and neutral atmosphere because the refractive index is not unity, **and the path is bent because of gradients in the refractive index**.

GPS RO is based on analysing the bending caused by the neutral atmosphere along ray paths between a GPS satellite and a receiver placed on a low-earth-orbiting (LEO) satellite.

GPS RO geometry

(Classical mechanics: Compare this picture with the deflection of a charged particle by a spherical potential!)



<u>Setting occultation</u>: as the LEO moves behind the earth we obtain a profile of bending angles, <u>α</u>, as a function of impact parameter, <u>a</u>. *The impact parameter is the distance of closest approach for the straight line path. <u>It is directly analogous to angular momentum of a particle</u>.*

GPS RO characteristics

- Good vertical resolution. Around 70% of the bending occurs over a **~450km** section of ray-path, centred on the tangent point *(point closest to surface)* – **it has a broad horizontal weighting function, with a ~Gaussian shape to first order!**

- All weather capability: not affected by cloud(?) or rain.

- The bending is ~1-2 degree at the surface, falling exponentially with height. The scale-height of the decay is approximately the density scale-height.

- A profile of bending angles from ~60km tangent height to the surface takes about 2 minutes. Tangent point drifts in the horizontal by ~200 km during the measurement.

Ray Optics Processing of the GPS RO Observations

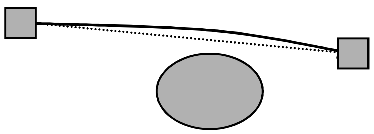
GPS receivers do not measure bending angle directly!

The GPS receiver on the LEO satellite measures a time series of phase-delays $\phi(i-1)$, $\phi(i)$, $\phi(i+1)$,… at the two GPS frequencies:

L1 = 1.57542 GHz
L2 = 1.22760 GHz

The phase delays are "**calibrated**" to remove special and general relativistic effects and to remove the GPS and LEO clock errors ("**Differencing**", see Hajj et al. (2002), JASTP, **64**, 451 – 469).

Calculate **Excess phase delays**: remove straight line path delay, $\Delta\phi(i)$.

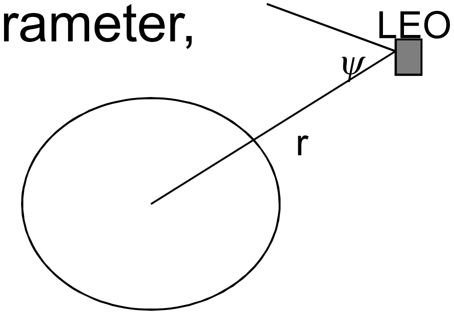


A time series of Doppler shifts at L1 and L2 are calculated by differentiating the **excess phase delays** with respect to time.

Processing of the GPS RO observations (2)

The ray bending caused by gradients in the atmosphere and **ionosphere** modify the L1 and L2 Doppler values, but **deriving the bending angles, α, from the Doppler values is an <u>ill-posed</u> <u>problem</u> (*an infinite set of bending angles could produce the Doppler*)**.

The problem made well posed by assuming the impact parameter, given by **(Spherical symmetry)**



$$\boxed{a = nr\sin\psi}$$

has the same value at both the satellites.

Given accurate position and velocity estimates for the satellites, and making the impact parameter assumption, the bending angle, α, and impact parameter value can be derived simultaneously from the Doppler.

The ionospheric correction

We have to isolate the atmospheric component of the bending angle. **The ionosphere is dispersive** and so we can take 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*.

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

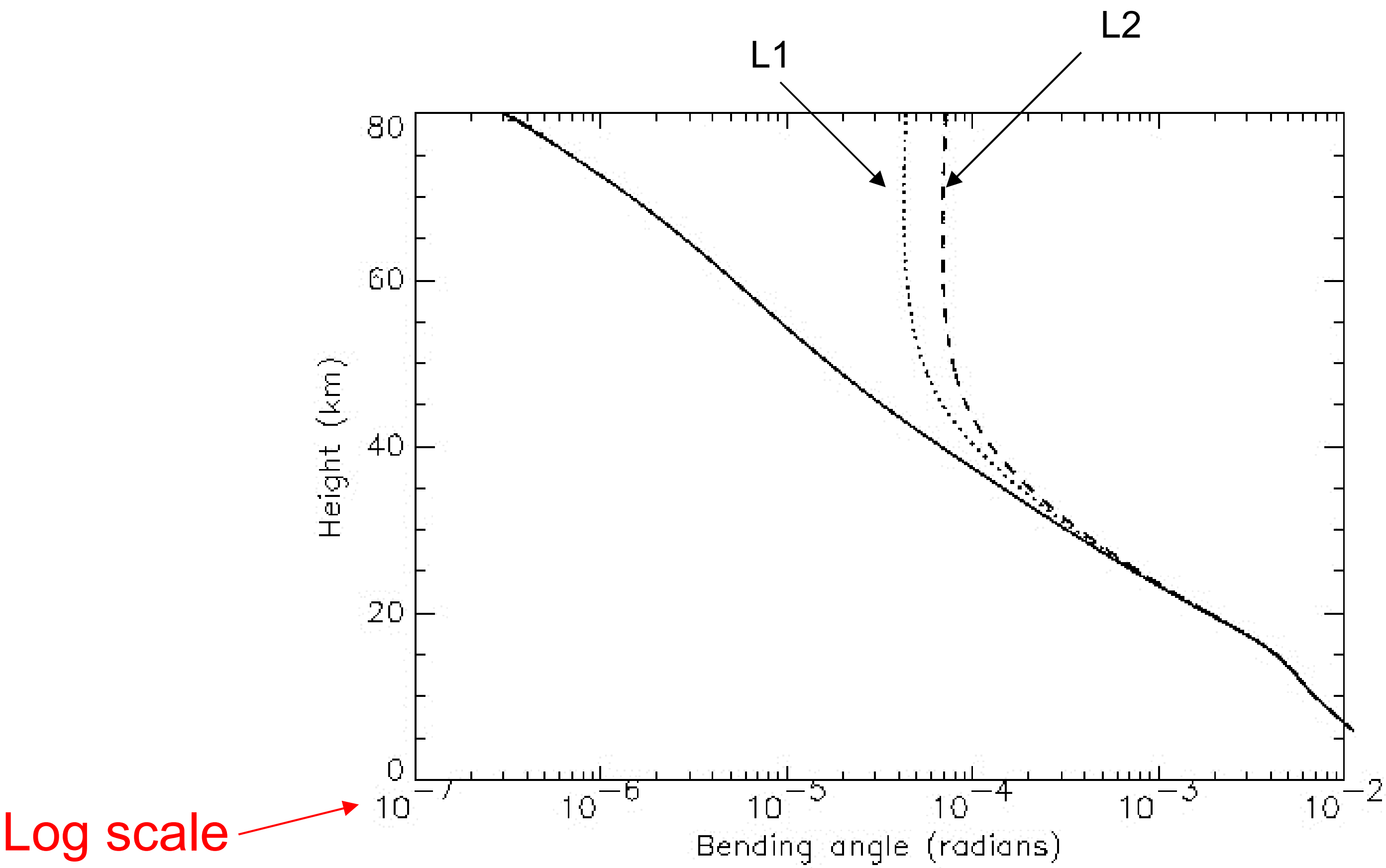
"Corrected" bending angles

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? People are starting to think about this in the context of climate signal detection. I don't think it's a major problem in regions where the GPS-RO information content is largest.

The ionospheric correction: A simulated example



The "correction" is very big!

Deriving the refractive index profiles

Assuming spherical symmetry the **ionospheric corrected** bending angle can be written as:

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

Corrected Bending angle
as a function of impact parameter

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

We can use an **Abel transform** to derive a refractive index profile

Note the upper-limit of the integral! *A priori* information needed to extrapolate to infinity.

$$n(x) = \exp\left(\frac{1}{\pi}\int_a^\infty \frac{\alpha(a)}{\sqrt{a^2 - x^2}}\,da\right)$$

Refractivity and Pressure/temperature profiles: **"Classical retrieval"**

The refractive index (or refractivity) is related to the pressure, temperature and vapour pressure using two experimentally determined constants (from the 1950's and 1960's!)

refractivity

$$N = 10^6 (n-1)$$

$$= \frac{c_1 P}{T} + \frac{c_2 P_w}{T^2}$$

This two term expression is probably the simplest formulation for refractivity, but it is widely used in GPSRO.

We now use an alternative three term formulation, including non-ideal gas effects

If the water vapour is negligible, the 2nd term = 0, and the refractivity is proportional to the density

$$N \approx \frac{c_1 P}{T} = c_1 R \rho$$

So we have retrieved a vertical profile of density!

"Classical" retrieval

We can derive the pressure by integrating the **hydrostatic equation**

a priori

$$P(z) = P(z_u) - \frac{1}{c_1 R} \int_{Z}^{z_u} N(z) g(z) dz$$

The temperature profile can then be derived with the ideal gas law:

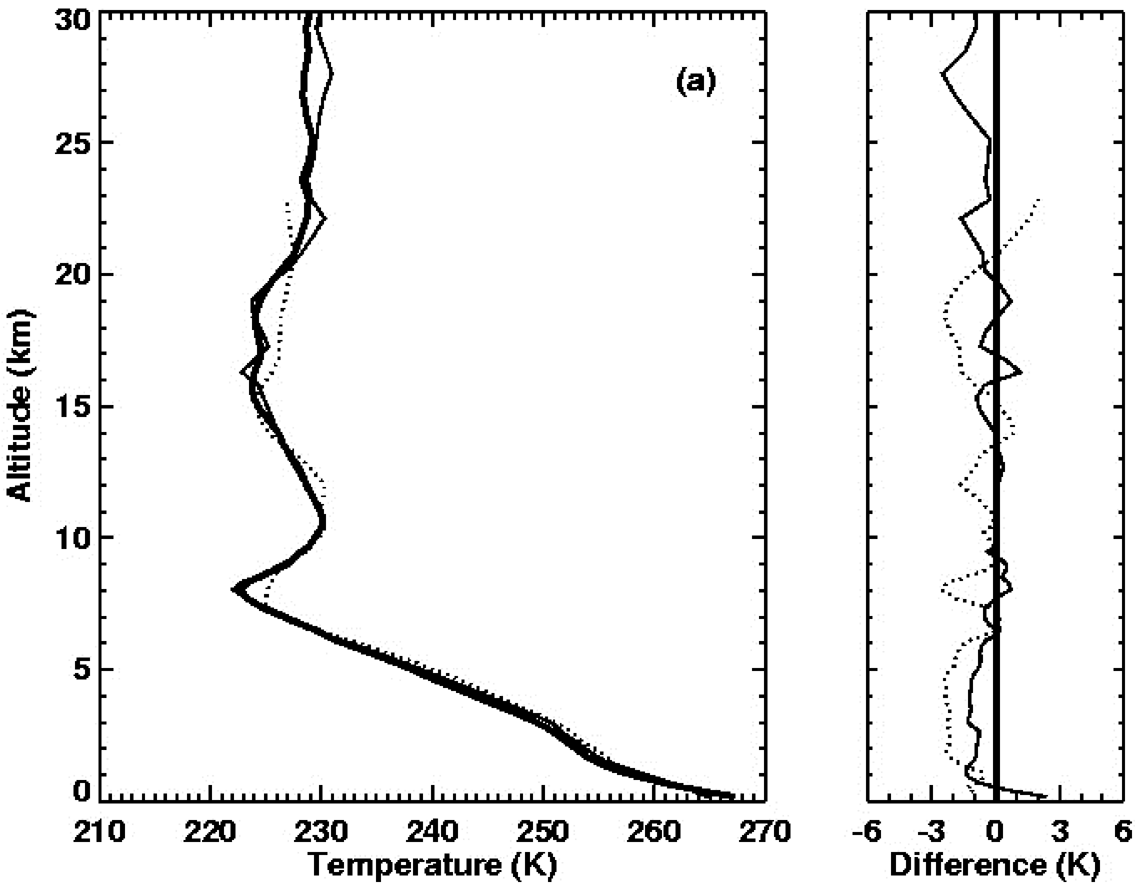
$$T(z) = c_1 \frac{P(z)}{N(z)}$$

GPSMET experiment (1996): Groups from JPL and UCAR demonstrated that the retrievals agreed with co-located analyses and radiosondes to within 1K between ~5-25km.

EG, See Rocken et al, 1997, JGR, 102, D25, 29849-29866.

GPS/MET Temperature Sounding

(Kursinski et al, 1996, Science, 271, 1107-1110, Fig2a)

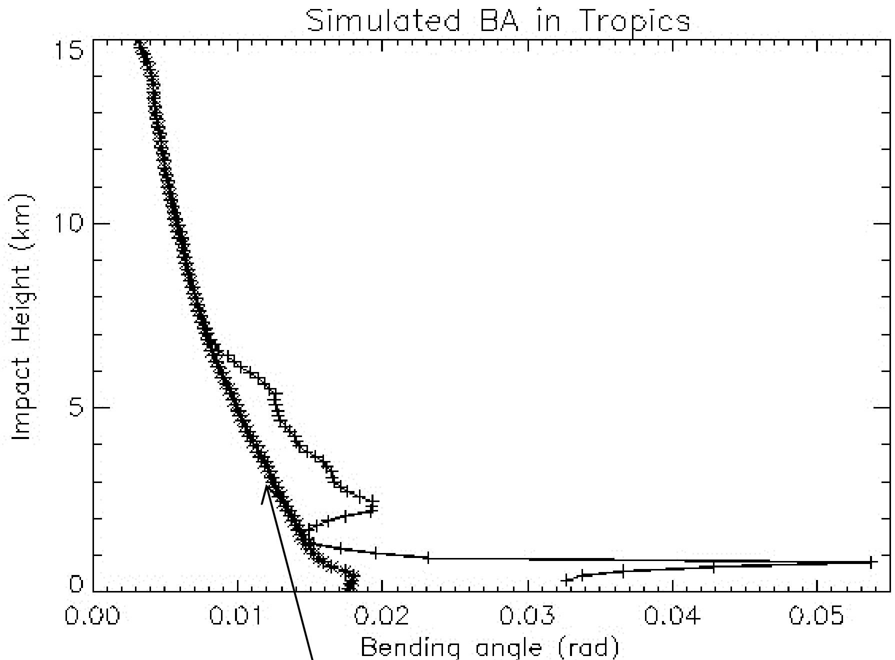


*GPS/MET - **thick solid.***
Radiosonde – thin solid.
Dotted - ECMWF anal.

Results like this by JPL and UCAR in mid 1990's got the subject moving.

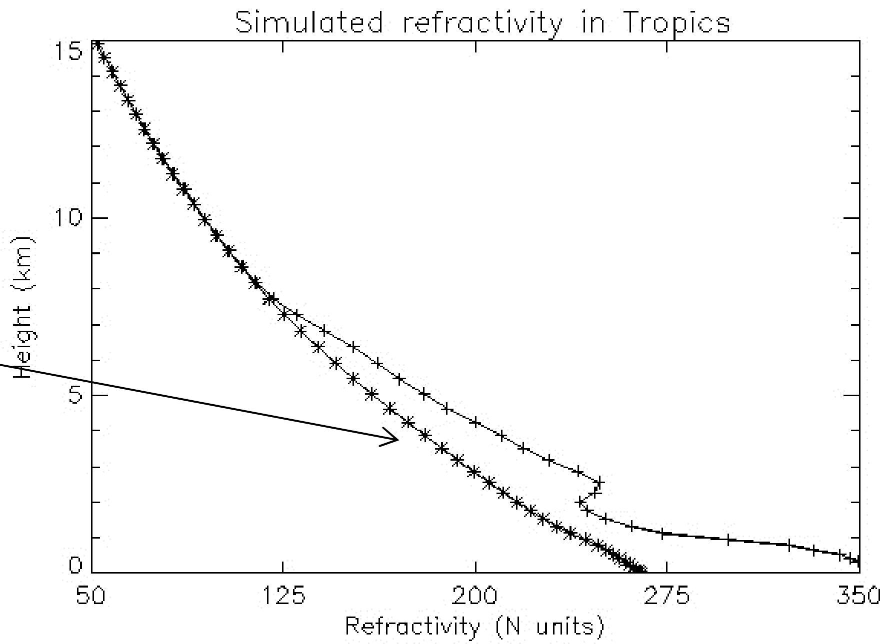
(Location 69N, 83W. 01.33 UT, 5th May, 1995)

Limitations of classical retrieval: we can't neglect water vapour in the troposphere!



Difference between the lines show the impact of water vapour.

Simulated ignoring water vapour



GPSRO limitations – upper stratosphere

In order to derive refractivity the **(noisy – e.g. residual ionospheric noise)** bending angle profiles must be extrapolated to infinity – **i.e., we have to introduce *a-priori***. This blending of the observed and simulated bending angles is called "**statistical optimisation**". The refractivity profiles above ~35 km are sensitive to the choice of *a priori*.

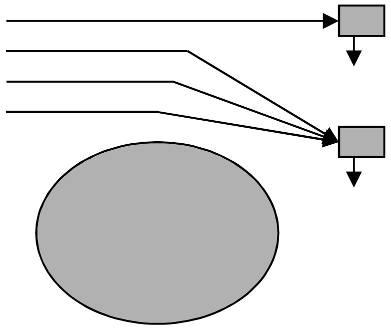
The temperature profiles require *a-priori* information to initialise the hydrostatic integration. Sometimes ECMWF temperature at 45km!

I would be sceptical about any GPSRO temperature profile above ~35-40 km, derived with the classical approach. It will be very sensitive to the *a-priori*!

Limitations – lower troposphere

The refractivity profiles in the lower troposphere are biased low when compared to NWP models, particularly in the tropics. See **Ao et al JGR, (2003), 108, doi10.1029/2002JD003216**.

•**Atmospheric Multipath** processing – more than one ray is measured by the receiver at a given time:



Single ray region – ray optics approach ok!

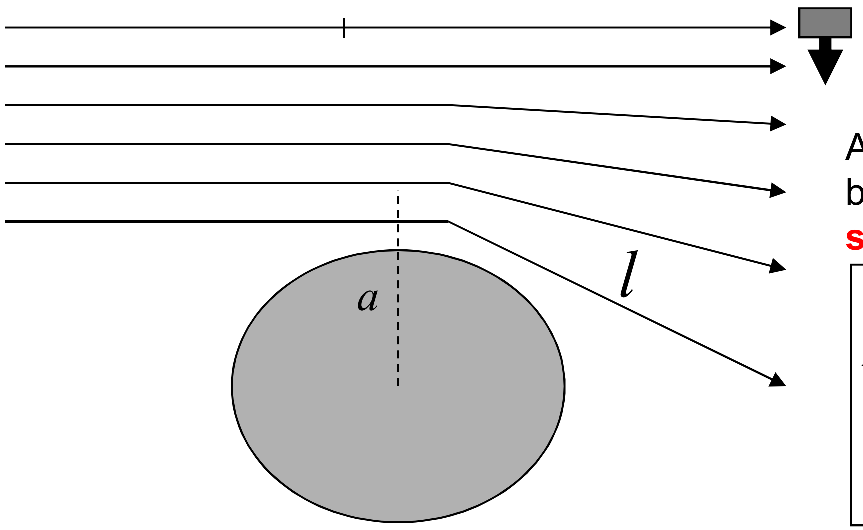
Multipath: More than one ray arrives at the receiver. They interfere.

•**Wave optics retrievals**: *Full Spectral Inversion*. Jensen et al *2003, Radio Science*, **38**, *10.1029/2002RS002763. (Also improve vertical. res.)*

•**Improved GPS receiver software:** Open-loop processing.

Physical limitations in lower troposphere

Atmospheric defocusing: If the bending angle changes rapidly with height, the signal reaching the receiver has less power



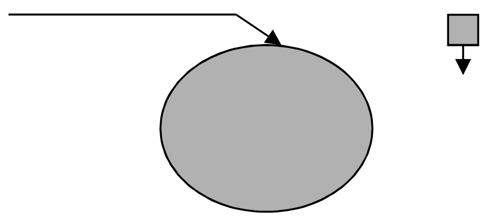
A tube of rays is spread out by the ray bending and the **signal to noise falls**.

$$DF \propto \frac{1}{1 - l\left(\frac{\partial \alpha}{\partial a}\right)}$$

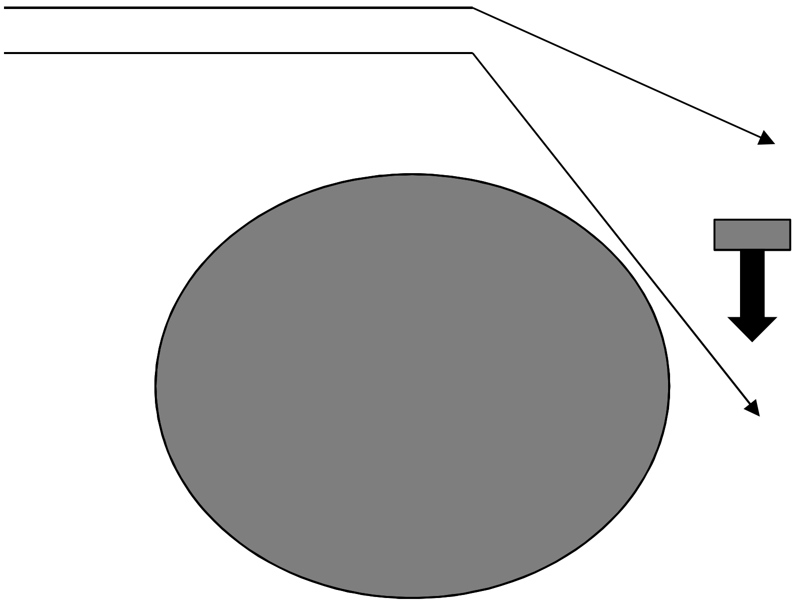
Atmospheric ducting: if the refractive index gradient exceeds a critical value the signal is lost

Not affected by clouds? ***But we often get ducting conditions near the top of stratocumulus clouds***

$$-{}^{dn}/_{dr} \geq {}^{1}/_{R_e}$$



Maximum bending angle value (related to defocusing)



Seems obvious but the receiver has to be measuring a long time to see the large bending angle values. We rarely see an observed bending above ~0.05 rads.

Data availability

- The “proof of concept” GPS/MET mission in 1996 was a major success. This led to a number of missions of opportunity, proposals for a constellation of LEO satellites and first dedicated operational instruments.

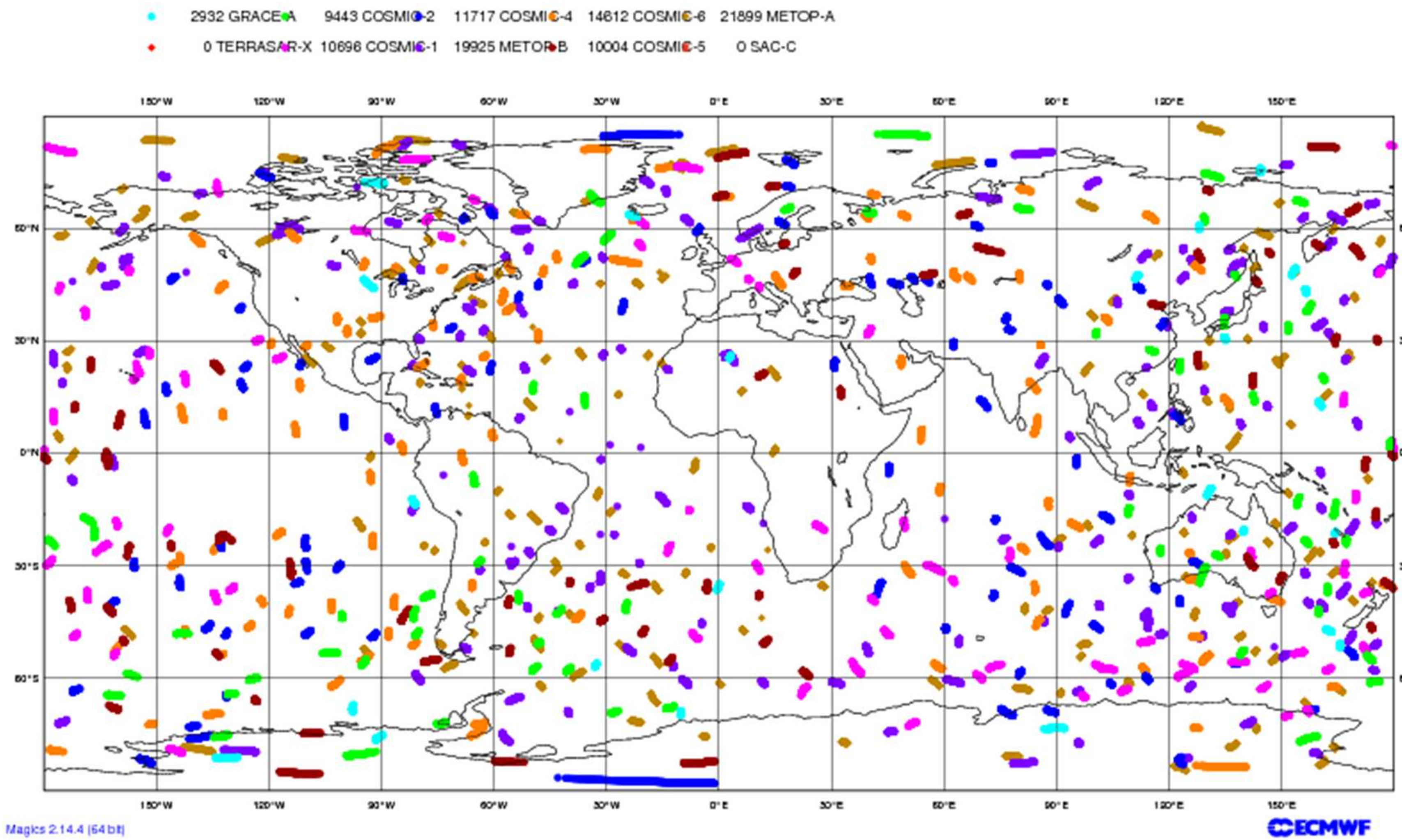
- Current status:

  - Missions of opportunity: **GRACE-A**, **TerraSAR-X and Tandem-X (not assimilated currently)**.

  - The COSMIC constellation of 5 LEO satellites was launched 2006. Currently providing ~800 - 900 occultations per day (2200 at peak).

  - The GRAS instrument on Metop-A and Metop-B provides ~1300 measurements. **GRAS is the only fully operational instrument. GRAS on METOP-B has been assimilated since May 21, 2013.**

ECMWF Data Coverage (All obs DA) - GPSRO
18/Mar/2014; 00 UTC
Total number of obs = 101228



But why are GPS RO useful for NWP given that we already have millions of radiance measurements?

1) **GPS RO can be assimilated without bias correction***. They are good for highlighting model errors/biases. Most other satellite observations require bias correction to the model. GPSRO measurements anchor the bias correction of radiance measurements. **Importance of anchor measurements in weak constraint 4D-Var.** (**Climate/reanalysis applications**).

2) GPS RO (limb sounders in general) have **sharper weighting functions** in the vertical and therefore have good vertical resolution properties. The GPSRO measurements can "see" vertical structures that are in the **"null space"** of the satellite radiances.

******The observed refractivity values are biased low near the surface. See Ao et al, JGR, 2003, D18*, 4577, *doi:10.1029/2002JD003216*.

Use of GPS RO in NWP

- NWP centres assimilate either bending angle (most now) or refractivity.

- The classical retrieval is very useful for understanding the basic physics of the measurement, but not recommended for use in NWP.

- We can test bending angle and refractivity observation operators in 1D-Var retrievals to estimate the **information content** and **vertical resolution** of the measurements.

1D-Var retrieval

The 1D-Var retrieval minimises the cost function:

$$J(\mathbf{x}) = \tfrac{1}{2}\left(\mathbf{x}-\mathbf{x}_{\mathrm{b}}\right)^{T}\mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}_{\mathrm{b}}\right)+\left(\mathbf{y}_{m}-H(\mathbf{x})\right)^{T}\mathbf{R}^{-1}\left(\mathbf{y}_{m}-H(\mathbf{x})\right)$$

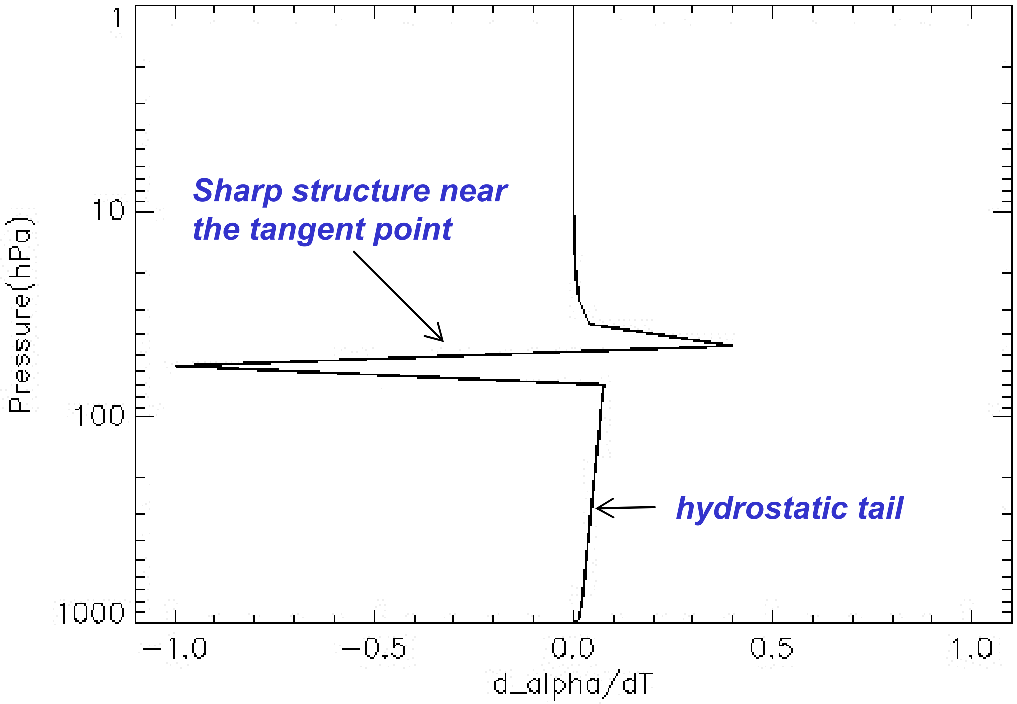
The observation operator - simulating bending angles or refractivity from the forecast state.

The 1D-Var approach provides a framework for testing observation operators that we might use in 3D/4D-Var assimilation.

We can also investigate various information content measures.

1D bending angle weighting function $\left(\frac{\partial \alpha}{\partial T}\right)$

(Normalised with the peak value)



(*See also Eyre, ECMWF Tech Memo. 199.*)

Weighting function peaks at the pressure levels above and below the ray tangent point. Bending related to vertical gradient of refractivity:

$$N = {c_1 P}/{T}$$

$$\Delta\alpha \propto (N_l - N_u)$$

Increase the T on the ***lower level*** *– reduce the N gradient – less bending!*

Increase the T on the ***upper level*** *– increase N gradient more bending!*

Very sharp weighting function in the vertical – we can resolve structures that nadir sounders cannot!

Useful 1D-Var diagnostics

- 1D-Var provides an estimate of the solution error covariance matrix.

Solution error cov. matrix

Linearised forward model

$$\mathbf{A} \approx (\mathbf{B}^{-1} + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H})^{-1}$$

Assumed background error cov. Matrix.

Assumed observation error cov. matrix

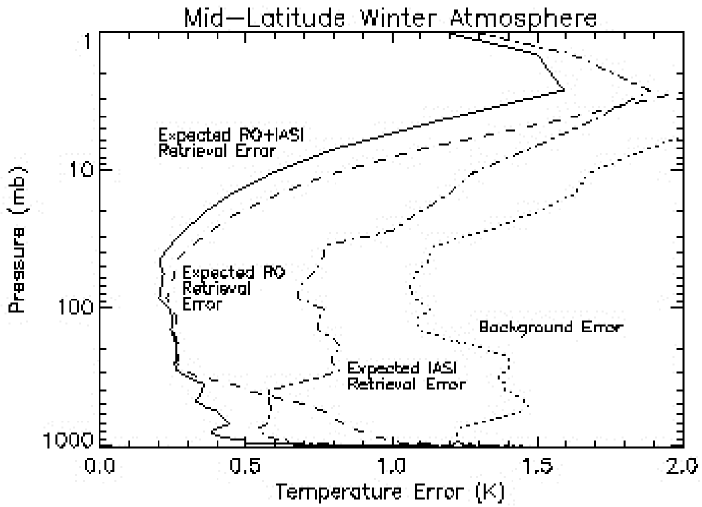
- **Information content**: related to the uncertainty before and after the measurement is made.

- It also gives **vertical resolution** diagnostics – the averaging kernel.

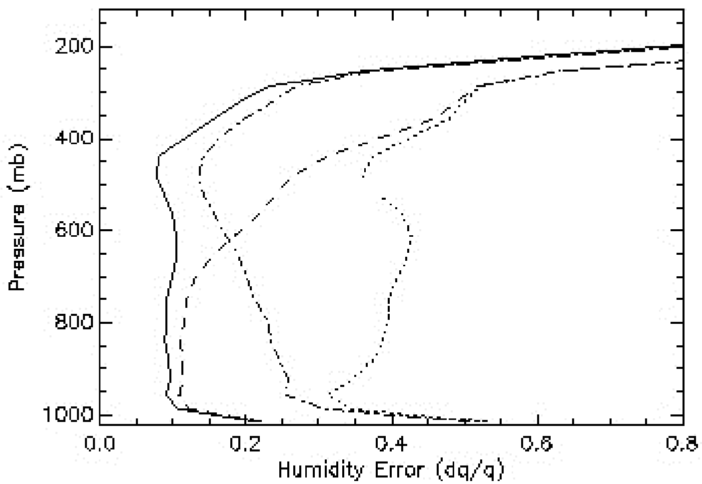
$$\mathbf{G} = (\mathbf{B}^{-1} + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H}$$

1D-Var information content (Collard+Healy, 2003)

QJRMS, 2003, v129, 2741-2760



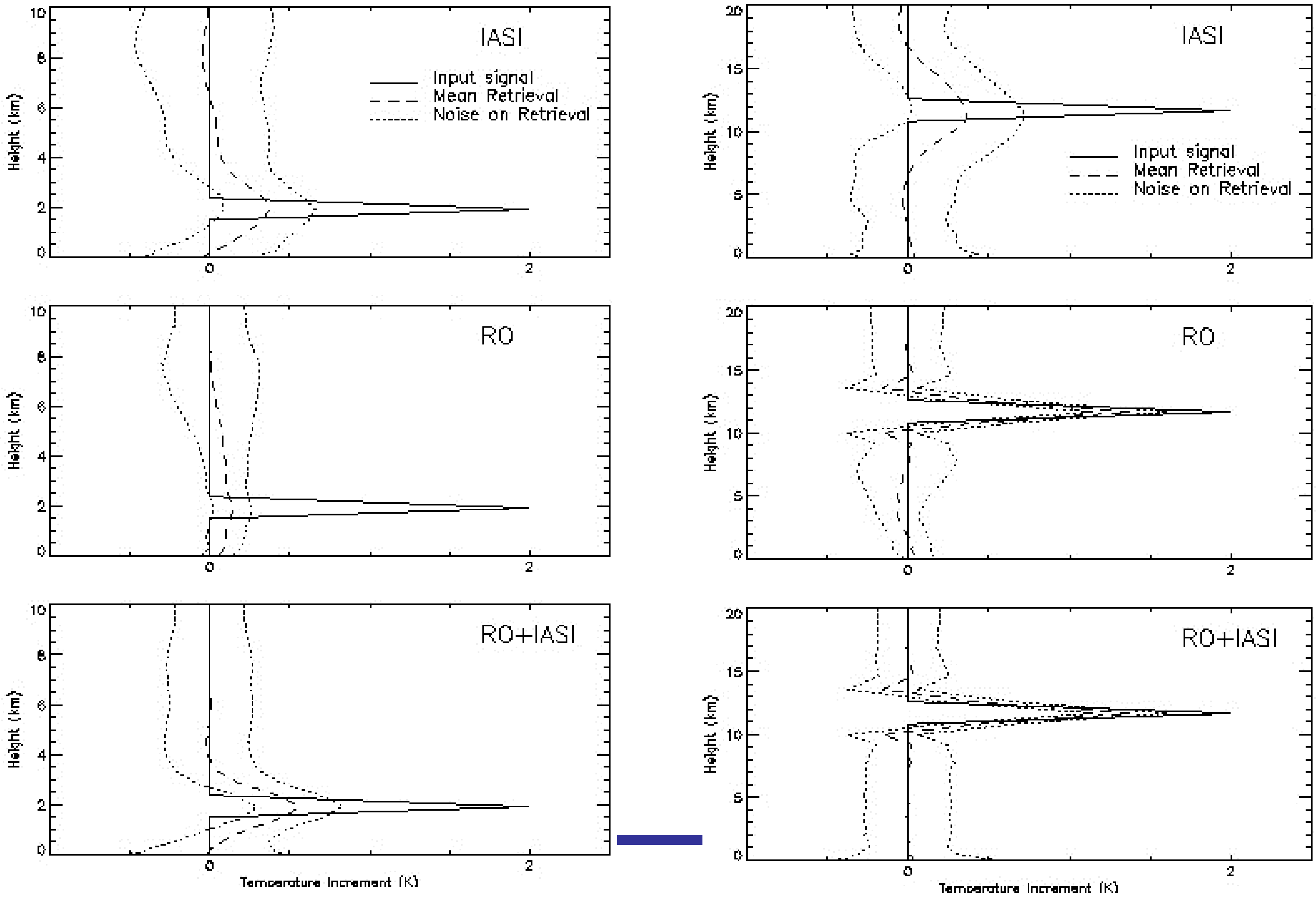
RO provides good temperature information between 300-50hPa. IASI retrieval performed with 1000 channels, RO has 120 **refractivity** values. (*Refractivity errors are vertically correlated because of the Abel transform*).



In theory RO should provide useful humidity information in the troposphere. **Further work needed to demonstrate the value of water vapour derived from GPSRO at NWP centres.**

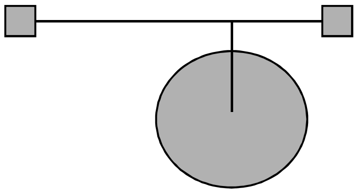
RO provides very little humidity information above 400hPa. The “wet” refractivity is small compared to the assumed observation error.

Vertical resolution (1D-Var averaging kernels – **how well a retrieval can reproduce a spike)**



Assimilation at ECMWF

- We assimilate bending angles with a 1D operator. We ignore the 2D nature of the measurement and integrate

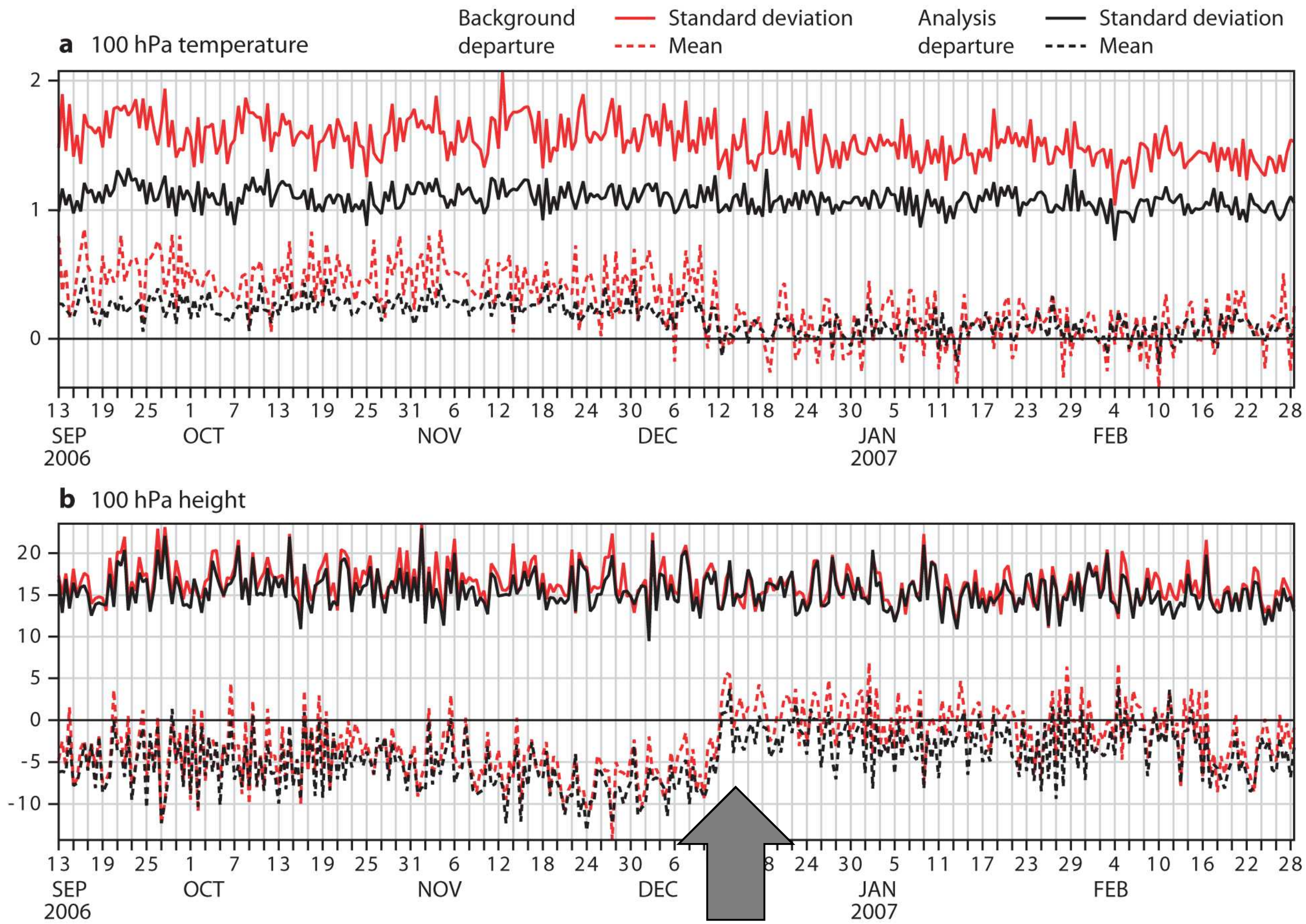


$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\sqrt{x^2 - a^2}} \, dx$$

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

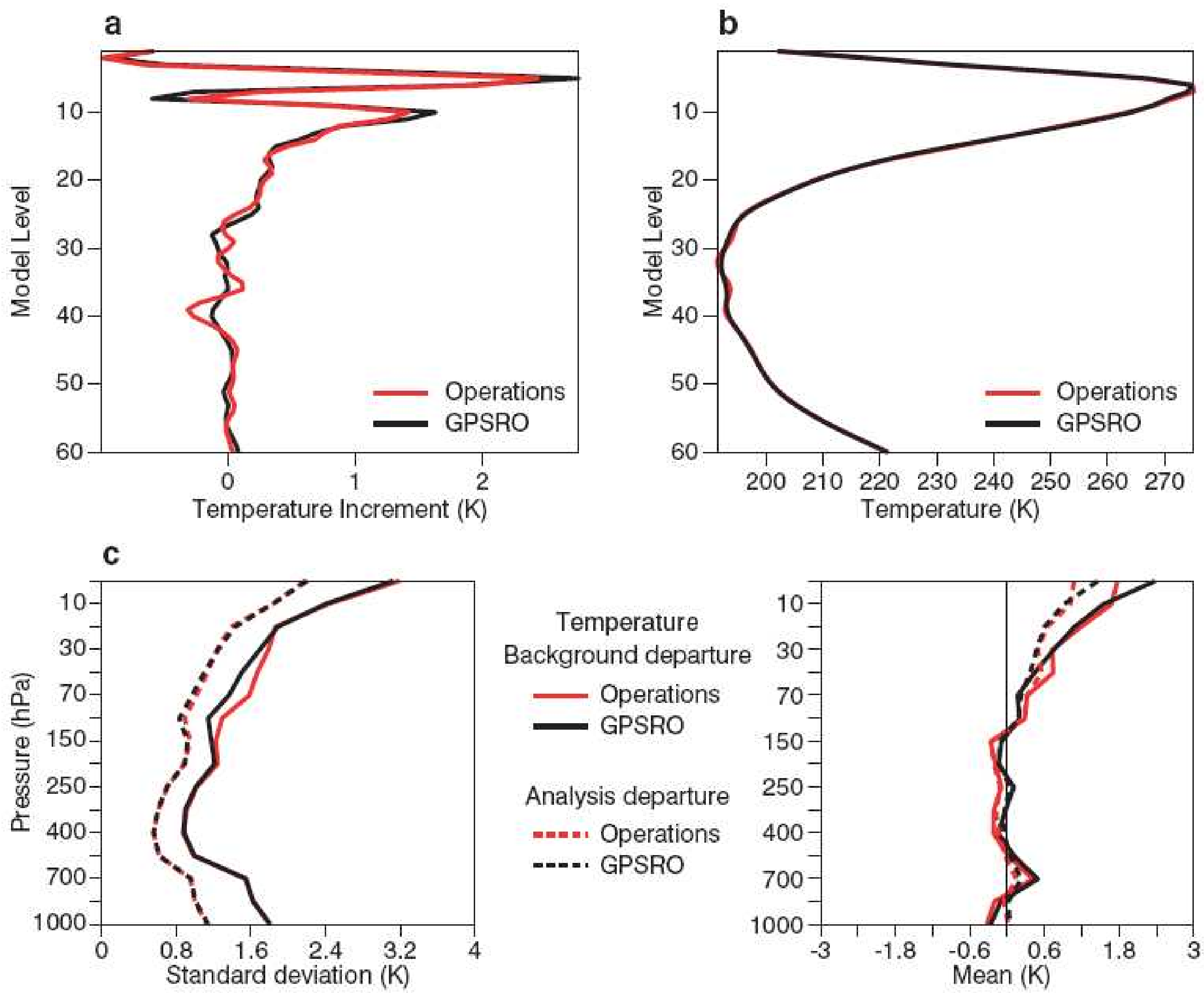
- The forward model is quite simple:
  - evaluate geopotential heights of model levels
  - convert geopotential height to geometric height and radius values
  - evaluate the refractivity, N, on model levels from P,T and Q.
  - Integrate, assuming refractivity varies ~*exponentially* between model levels. (*Solution in terms of the Gaussian error function*).
  - **We now include tangent point drift (May 2011).**
  - **2D operator being tested currently at ECMWF.**

Impact of GPS-RO on ECMWF operational biases against radiosonde measurements



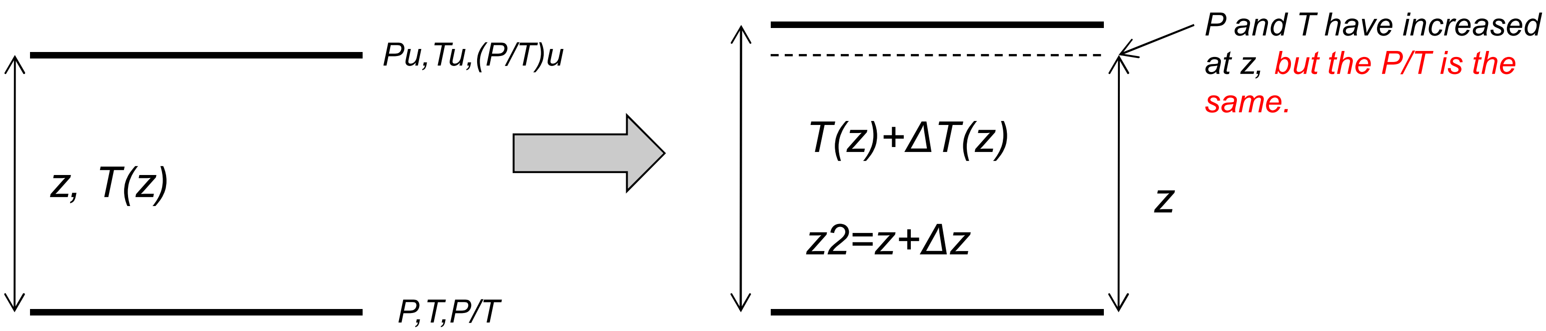
Operational implementation

<u>Stratospheric ringing</u> problem over Antarctica solved by assimilating GPS-RO



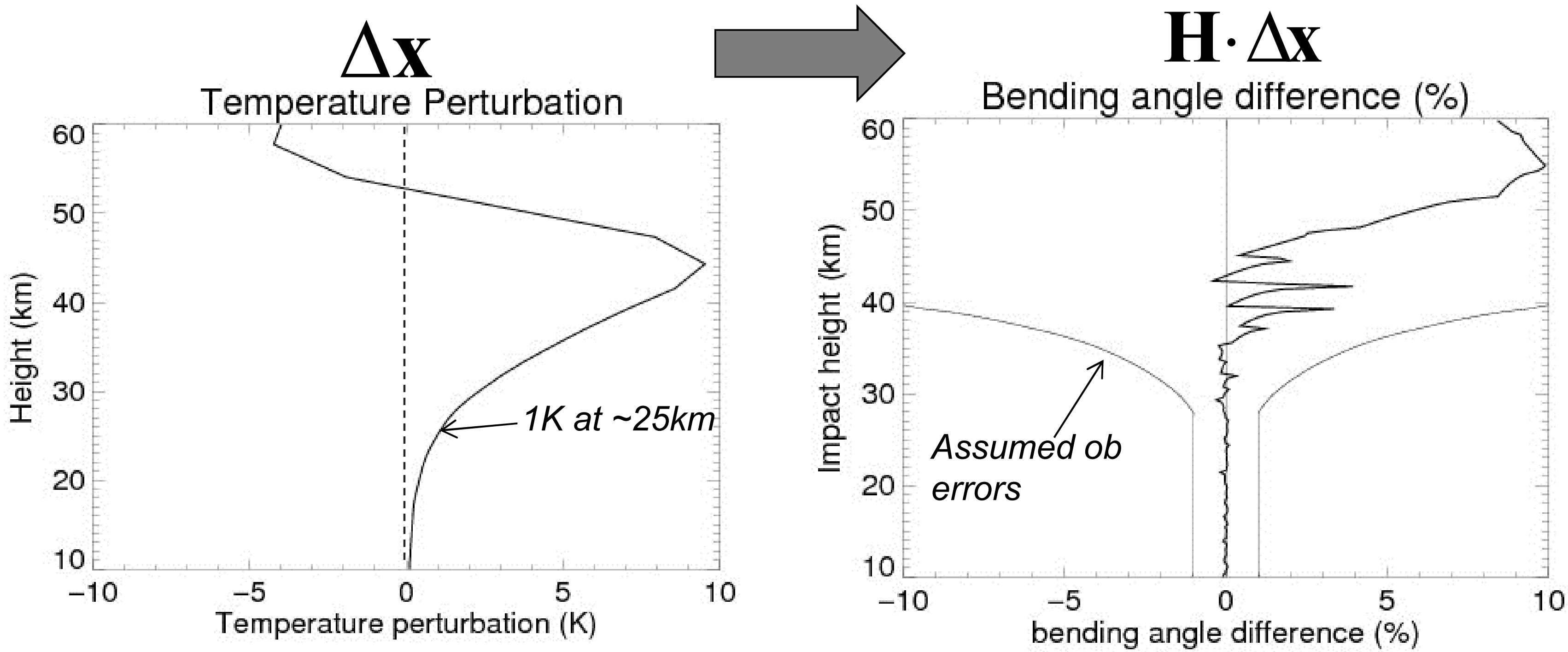
GPS RO also has a "null space"

- **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 z, with temperature variation T(z) between them. Now add positive perturbation $\Delta T(z) \sim \exp(z/H)$, 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. This is the GPS-RO null space.**

Null space – how does a temperature perturbation propagate through the bending angle observation operator



The null space arises because the measurements are sensitive to density as function of height (~P(z)/T(z)). A priori information is required to split this into T(z) and P(z). We can define a temperature perturbation ΔT(z)~exp(z/H) which is in the GPSRO null space. <u>Therefore, if the model background contains a bias of this form, the measurement can't see or correct it</u>.

Climate/re-analysis applications

- **RO is likely to become more useful for climate monitoring as the time-series lengthens (*see also work by RoTrends project*).**

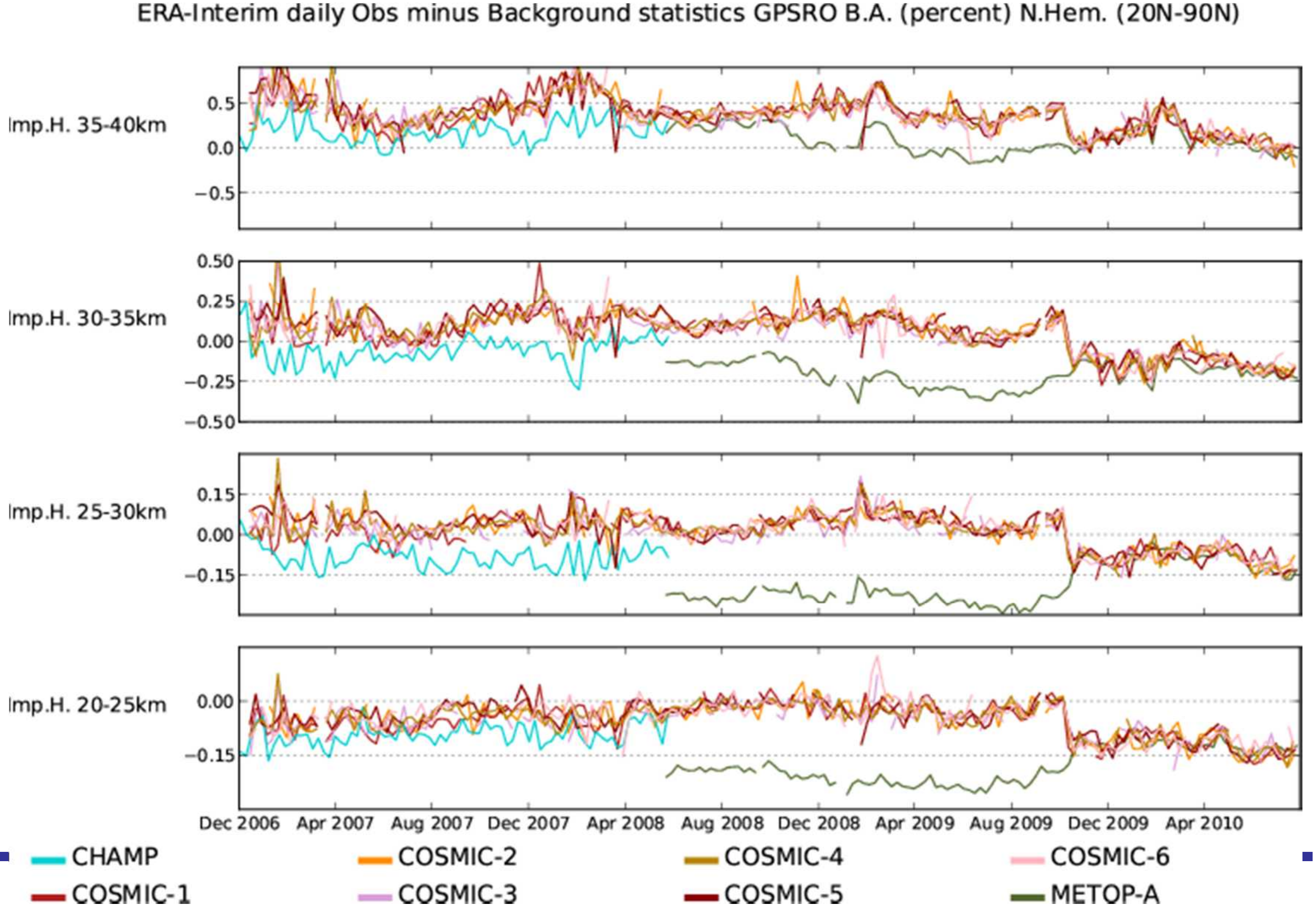
- Claim: GPS-RO measurements should not be biased.

  – It should be possible to introduce data from new instruments without overlap periods for calibration.

  – No discontinuities in time-series as a result of interchange of GPS-RO instruments.

- **Bending angle departure statistics derived from the ERA-Interim reanalysis can be used to investigate this claim.**

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



Novel applications: Deriving planetary boundary layer information from GPSRO measurement

- Some papers have suggested that we should be able to derive information on the height of the planetary boundary layer from the GPSRO bending angle and refractivity profiles.

  - Sokolovskiy et al, 2007, GRL, **34**,L18802,doi10.1029/2007GL030458
  - VonEngeln et al, 2005, GRL, **32**, L06815,doi10.1029/2004GL022168

- The central idea is that you see big changes in the bending angle and refractivity profile gradient across the top of the PBL.

Sokolovskiy et al, (2007)

L18802 SOKOLOVSKIY ET AL.: OBSERVING THE MOIST TROPOSPHERE L18802

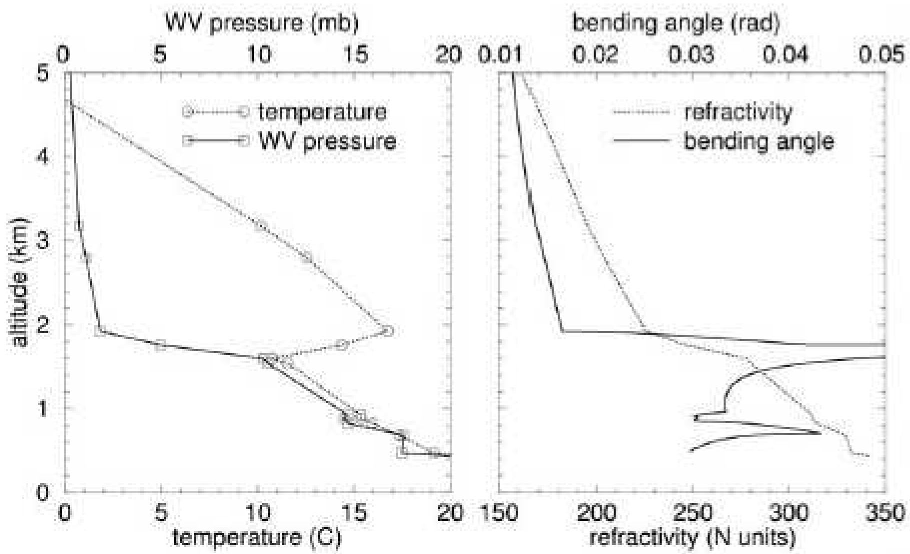
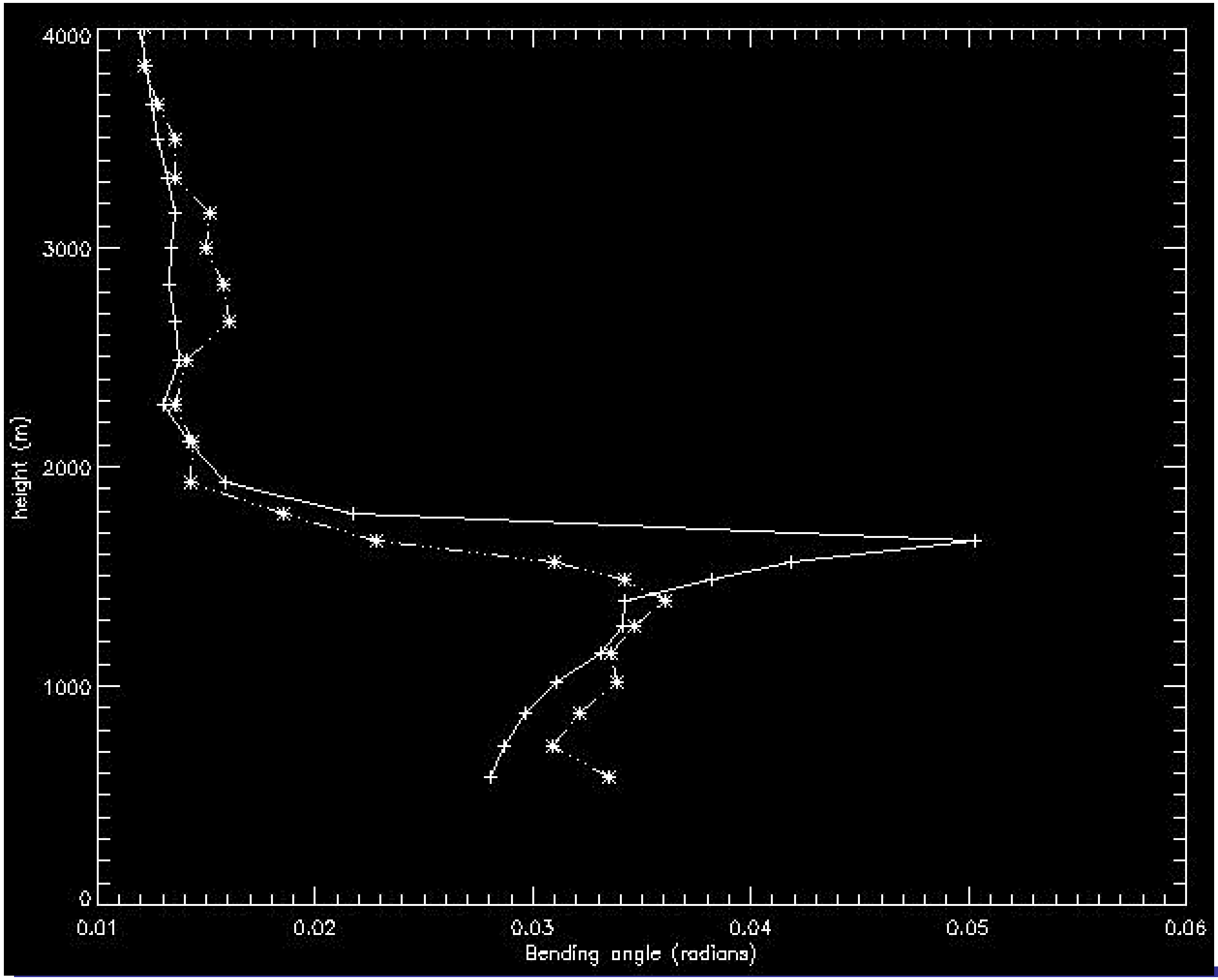


Figure 1. (left) Temperature water vapor pressure profiles observed from a radiosonde 15.97°S, 5.70°W, January 23, 2002. (right) Refractivity and bending angle calculated from the profiles on the left.

It is a very interesting idea, which still needs to be investigated further. Horizontal gradient errors. Meaning of PBL height averaged over 300-400 km?

Observed and first-guess bending angle from operations (2008.08.29) 22:59, lat=-11, lon=-157



Solid line = simulated
Dot-dash = observed

We don't seem to be seeing these really sharp structures in the observations.

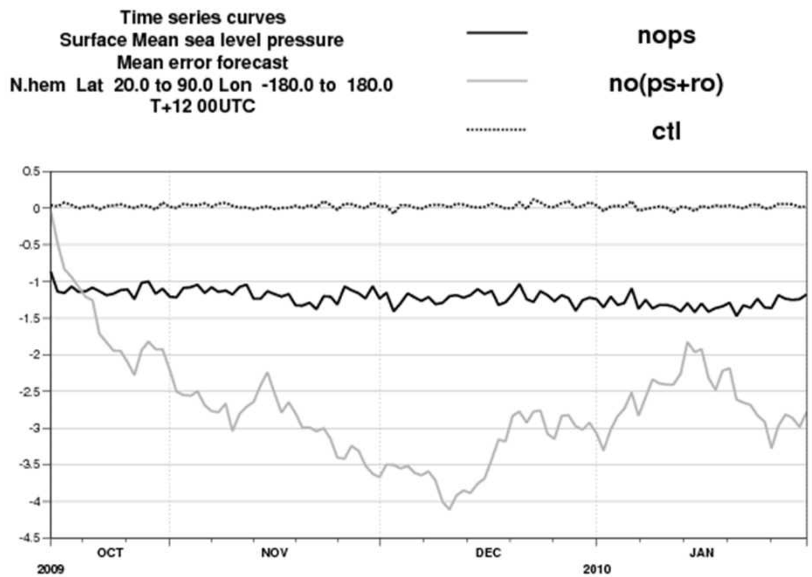
Atmospheric defocusing?
SNR drops so we can't measure the really sharp structure.

Surface pressure information from GPS-RO

- Measuring or retrieving surface pressure information from satellite radiances has been discussed for many years (Smith et al, 1972).
- The GPS-RO measurements have a sensitivity to surface pressure because they are given as a function of height.
- Hydrostatic integration is part of the GPS-RO forward model. If we increase the surface pressure the bending angle values increase.
- **Can GPS-RO constrain the surface pressure analysis when <u>all conventional surface pressure measurements</u> are removed?**

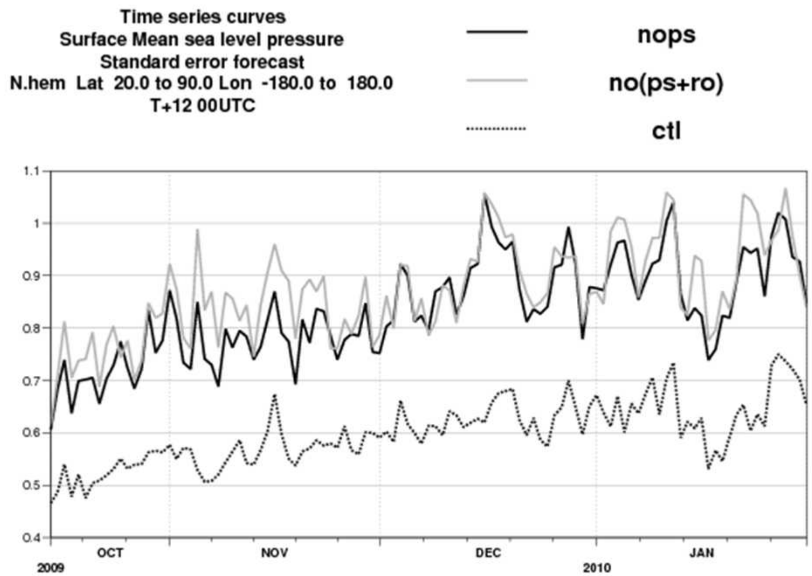
NH 12 hour PMSL forecast scores

Mean



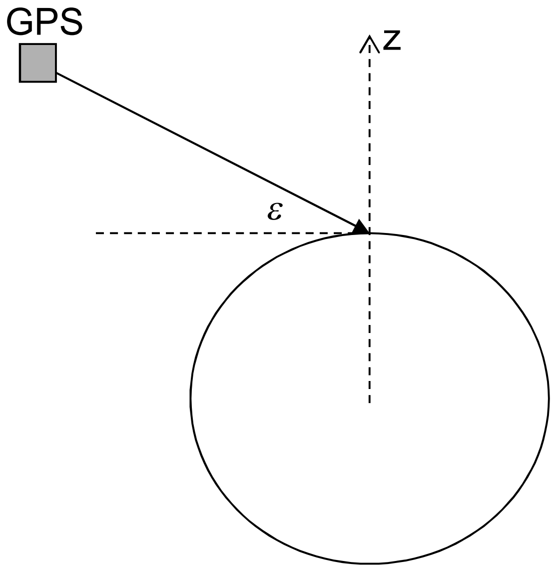
GPS-RO included.
The GPS-RO measurements manage to stabilise the bias.

Standard deviation



Ground-based GPS measurements

- **ECMWF currently monitors ground based GPS zenith delay measurements in operations. Will assimilate in 2014.**



Consider a receiver placed on the surface.

Ignoring **bending**, the **excess slant delay** caused by the atmosphere is

Straightline path

$$\Delta\phi = \int n(s)ds - S$$

$$= 10^{-6}\int N(s)ds$$

The slant delays are mapped to a zenith delays using **mapping functions**.
(eg Niell, 1996, J. Geophys. Res., 101(B2), 3227-3246)

ECMWF monitors zenith total delay

$$ZTD = \int_0^\infty \left[\frac{c_1 P}{T} + \frac{c_2' P_w}{T} + \frac{c_3 P_w}{T^2} \right] dz$$

Typically 2.3 m

"Hydrostatic delay"

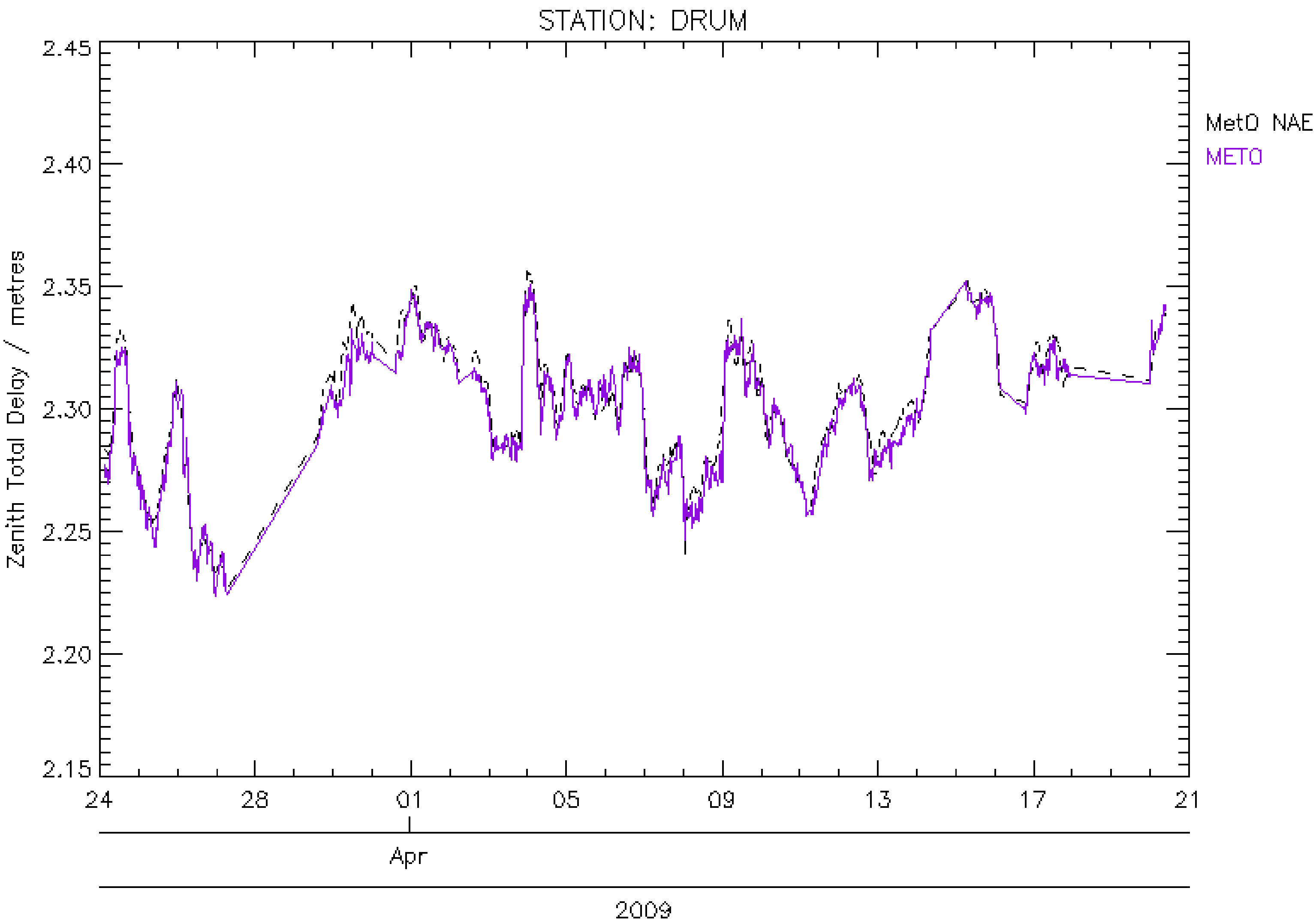
"wet delay"

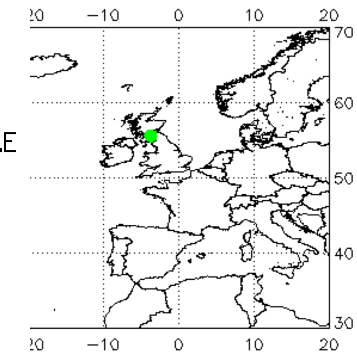
Information content

The "hydrostatic delay" is large (90% of total), but it is only really sensitive to the surface pressure value at the receiver.

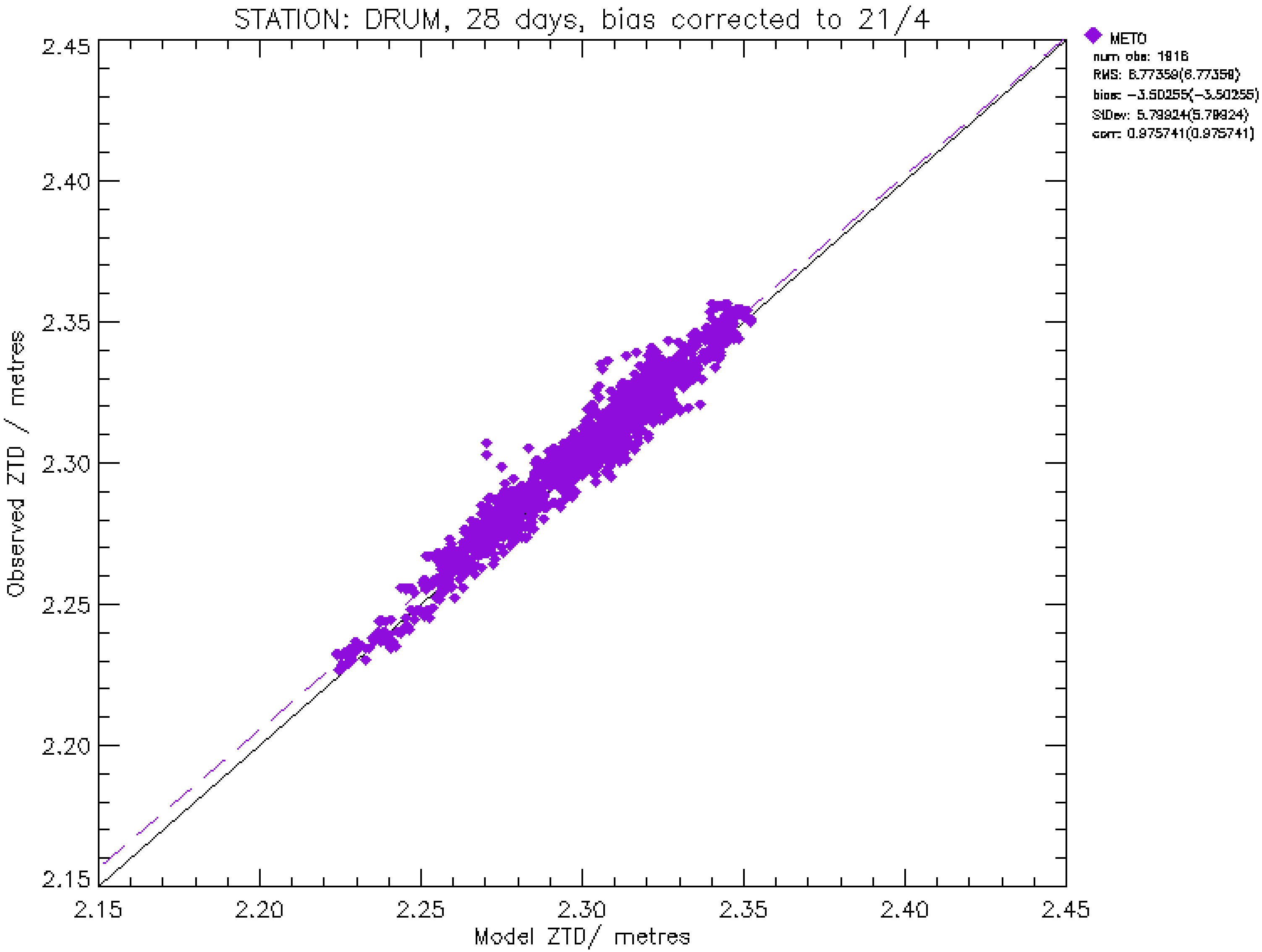
The "wet delay" is smaller, but more variable. The wet delay is related to the vertical integral of the water vapour density.

(See Bevis et al, (1992), JGR, vol. **97**, 15,787-15,801, for the ***classical retrieval*** of integrated water vapour.)





Courtesy of Adrian Jupp (Met Office)


STATION: DRUM, 28 days, bias corrected to 21/4
METO
num obs: 1816
RMS: 6.77358(6.77358)
bias: -3.50255(-3.50255)
StDev: 5.79924(5.79924)
corr: 0.975741(0.975741)
2.45
2.40
2.35
2.30
2.25
2.20
2.15
Observed ZTD / metres
2.15
2.20
2.25
2.30
2.35
2.40
2.45
Model ZTD/ metres

Summary

- GPS RO is a satellite-to-satellite limb measurement.

- Outlined the basic physics of the GPS RO technique and the classical retrieval.

- Measurements **do not require bias correction**. This may be important for climate applications. The observation operators are quite simple. Very good vertical resolution, but poor horizontal resolution (~450 km average). Also, be wary of classical temperature retrievals above 35-40 km. They mainly contain a-priori information.

- Information content studies suggest GPS RO should provide good temperature information in the upper troposphere and lower/mid stratosphere. Operational assimilation of GPSRO supports this.

- New applications: PBL work is an interesting application, but more work required. Surface pressure information from GPS-RO.

- Briefly outlined the ground-based GPS technique for estimating integrated water vapour.

Useful GPSRO web-sites

- International Radio Occultation Working Group (IROWG) www.irowg.org.
- The COSMIC homepage www.cosmic.ucar.edu. This contains latest information on the status of COSMIC and an extensive list of papers www.cosmic.ucar.edu/references.html, with some links to .pdfs of the papers, workshops.
- The Radio Occultation Meteorology (ROM) SAF homepage www.romsaf.org.
  - You can find lists of ROM SAF publications www.romsaf.org/publications.
  - Links to GPS RO monitoring pages (Data quality, data flow of COSMIC, GRACE-A, CHAMP and GRAS).
  - In addition, you can register and download for the **ROM SAF's Radio Occultation Processing Package (ROPP)**. This F90 software package containing pre-processing software modules,1D-Var minimization code, bending angle and refractivity observation operators and their tangent-linears and adjoints.
  - 2015 and 2008 ECMWF/ROM SAF Workshops papers and presentations.

    www.ecmwf.int/newsevents/meetings/workshops/2008/GPS_radio_occultation/index.html.

    www.ecmwf.int/en/fifth-eumetsat-rom-saf-user-workshop-applications-gps-radio-occultation-measurements

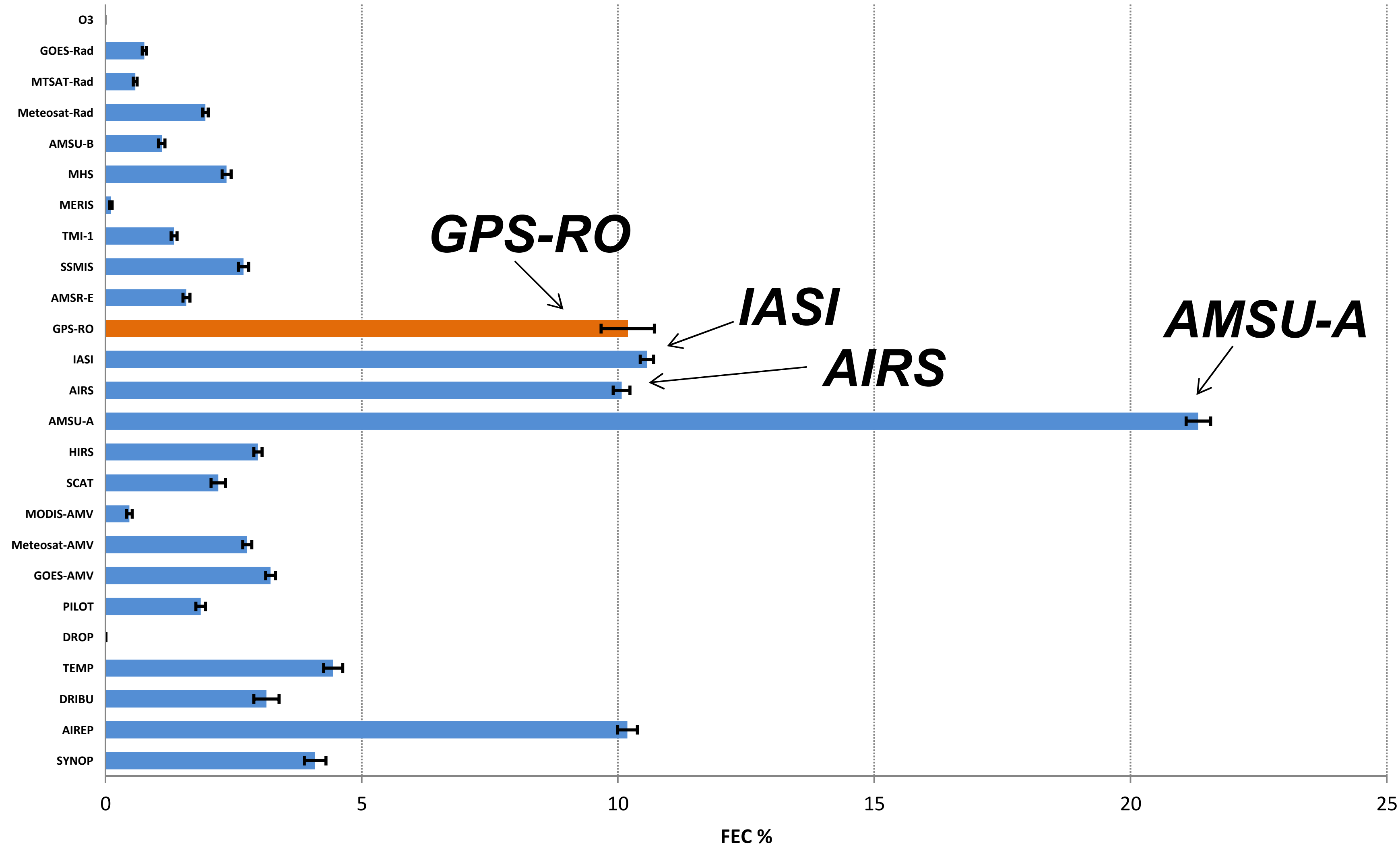
Adjoint-based data assimilation diagnostics (ECMWF work by Carla Cardinali)

- Data assimilation scientists at NWPcentres have developed sophisticated techniques to estimate which observing systems (e.g. all AMSU-A) contribute most in reducing the ***24 hour forecast errors***.
- The mathematics can be found in ECMWF Tech Memo 599 (http://www.ecmwf.int/publications/library/do/references/list/14).
- Essentially, they look at how the observing systems reduce the 24hr errrors in a **weighted average** of (*surface pressure, tropospheric and* ***stratospheric*** *temperatures and winds*).
- **Latest ECMWF results from June 2011. GPS-RO scores well because of its impact in the stratosphere.**

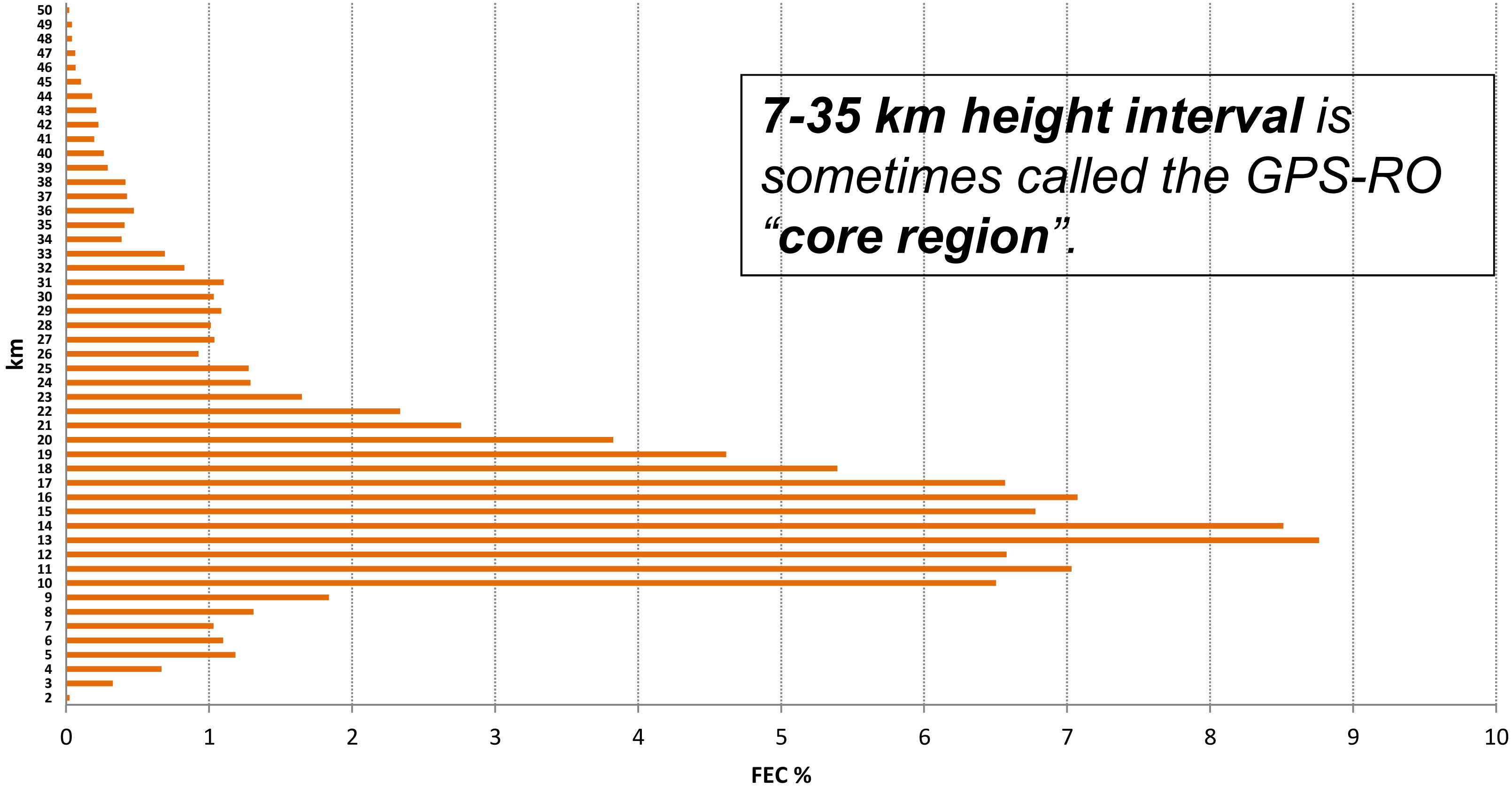
EXTRA SLIDES

Not planning to present the following.

ECMWF System (June 2011)



Heights where GPS-RO is reducing the 24hr errors



Remark: *Agrees with early 1D-Var information content studies.*

GPS-RO and the bias correction of radiances

- “**Bias correction schemes need to be grounded by a reference.**” The reference measurements are often called **“anchor”** measurements.

- “**Recommendation to NWP Centres** to identify part of global observing system (e.g. high quality Radio-sondes, GPS Radio Occultation) as reference network which is actively assimilated but NOT bias corrected against an NWP system.”

Working group 3, ECMWF/EUMETSAT NWP-SAF Workshop on “Bias estimation and correction in data assimilation” (2005).

http://www.ecmwf.int/newsevents/meetings/workshops/2005/NWP_SAF/index.html

VarBC is used at ECMWF
Dee, QJRMS (2007), **131**, pp 3323-3343

- Bias corrected radiances are assimilated.

$$\tilde{\mathbf{y}} = \mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x})$$

$$\mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) = \sum_i \beta_i \mathbf{p}(\mathbf{x})$$

$$J(\mathbf{x}, \boldsymbol{\beta}) = (\mathbf{x}_\mathbf{b} - \mathbf{x})^\mathrm{T} \mathbf{B}_\mathbf{x}^{-1} (\mathbf{x}_\mathbf{b} - \mathbf{x})$$
$$+ (\boldsymbol{\beta}_\mathbf{b} - \boldsymbol{\beta})^\mathrm{T} \mathbf{B}_{\boldsymbol{\beta}}^{-1} (\boldsymbol{\beta}_\mathbf{b} - \boldsymbol{\beta}) +$$
$$(\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))^\mathrm{T} \mathbf{R}^{-1} (\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))$$

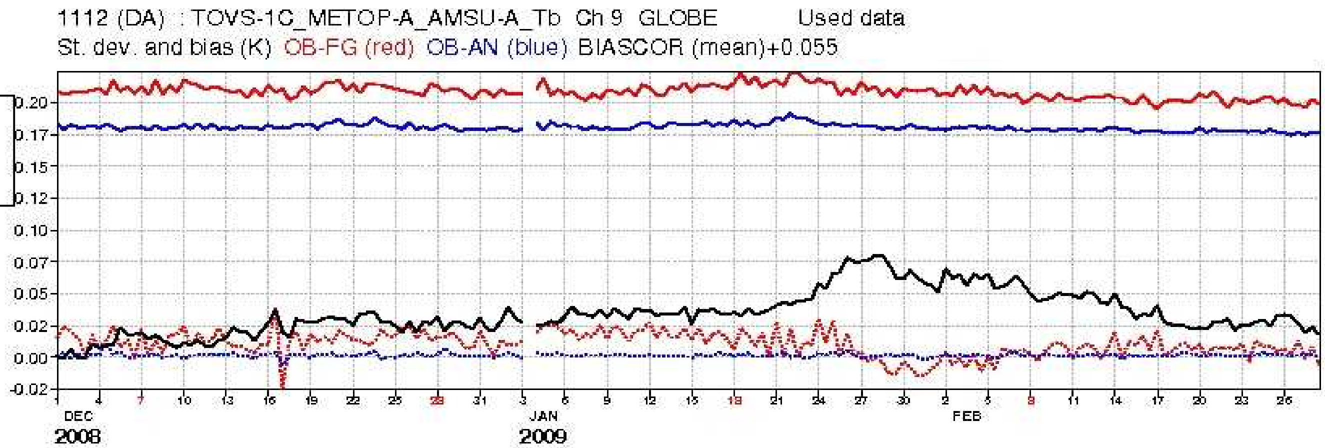
In the 4D-Var, we minimize an augmented cost function, where the bias coefficients are estimated.

- **VarBC assumes an unbiased model.**

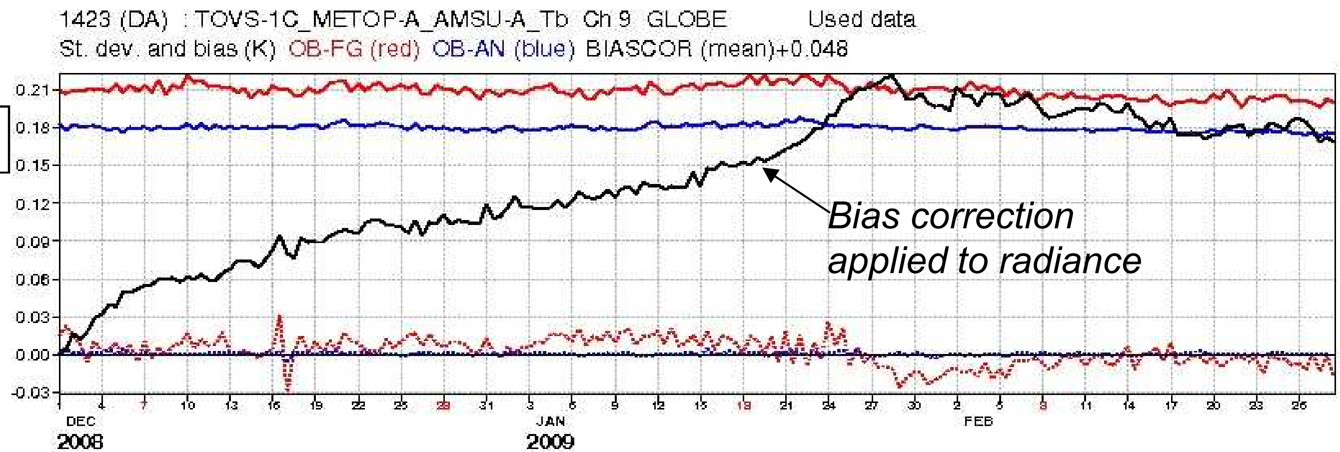
Recent experiment removing GPS-RO from ERA-Interim (Dec. 08, Jan-Feb 09)

- Impact on bias correction. E.g., globally averaged **MetOP-A**, **AMSU-A channel 9 bias correction**.

GPSRO assimilated



No GPSRO



GPS-RO for climate monitoring

Simulation study using the Hadley Centre climate model

Simulation studies to assess:

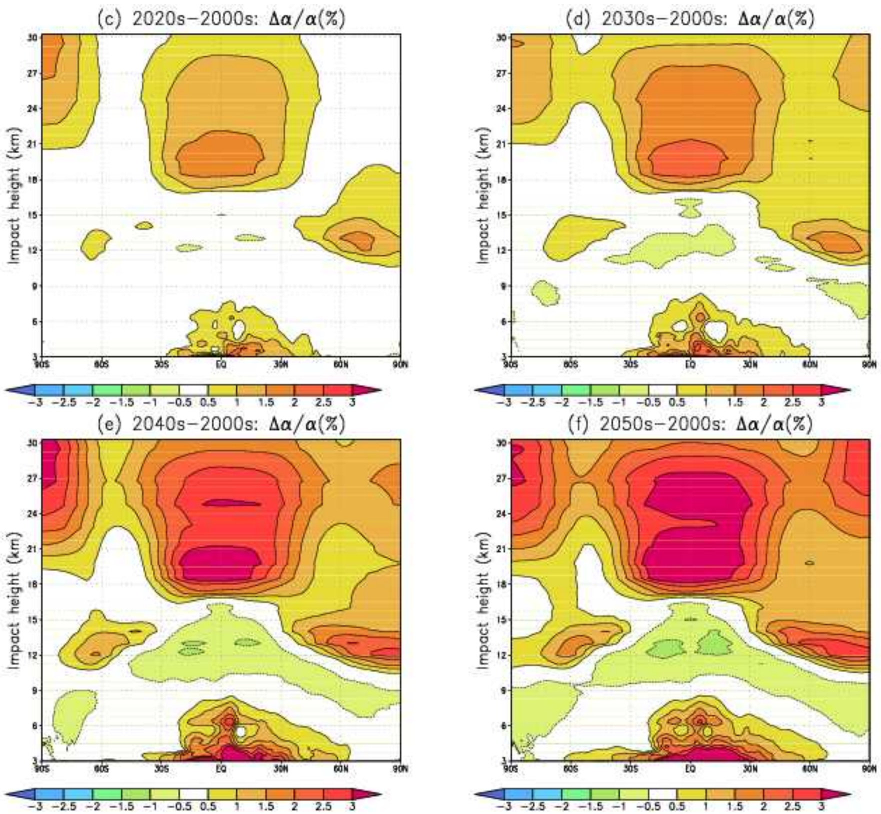
- potential of GPS-RO for detecting climate trends
- information content of GPS-RO in relation to other sensors

Simulations use:

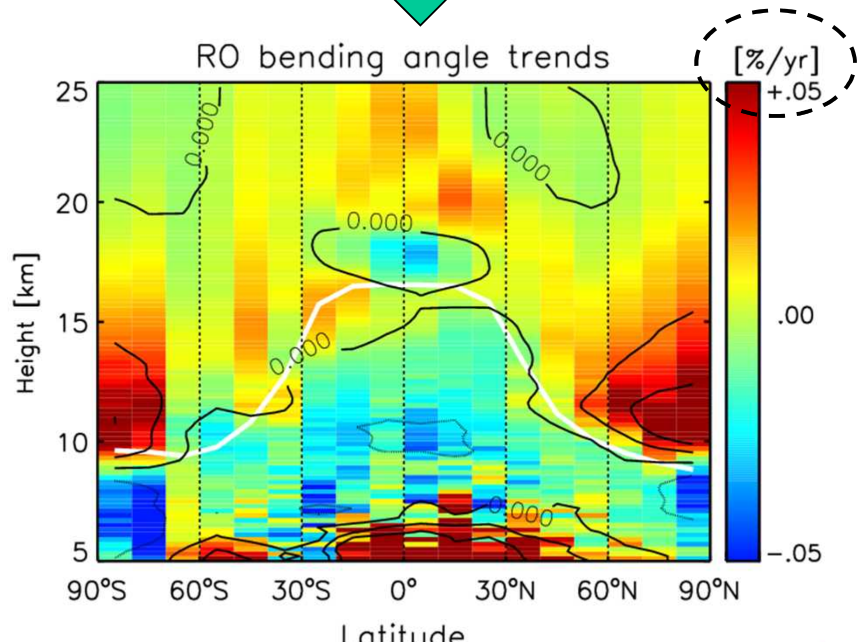
- Met Office Hadley Centre coupled climate model (HadGEM1)
- Climate change scenario (A1B) for 2000 – 2100
- Forward modelling of the GPS-RO bending angles
- Forward modelling of MSU/AMSU brightness temperatures

Provided by Mark Ringer (Hadley Centre)

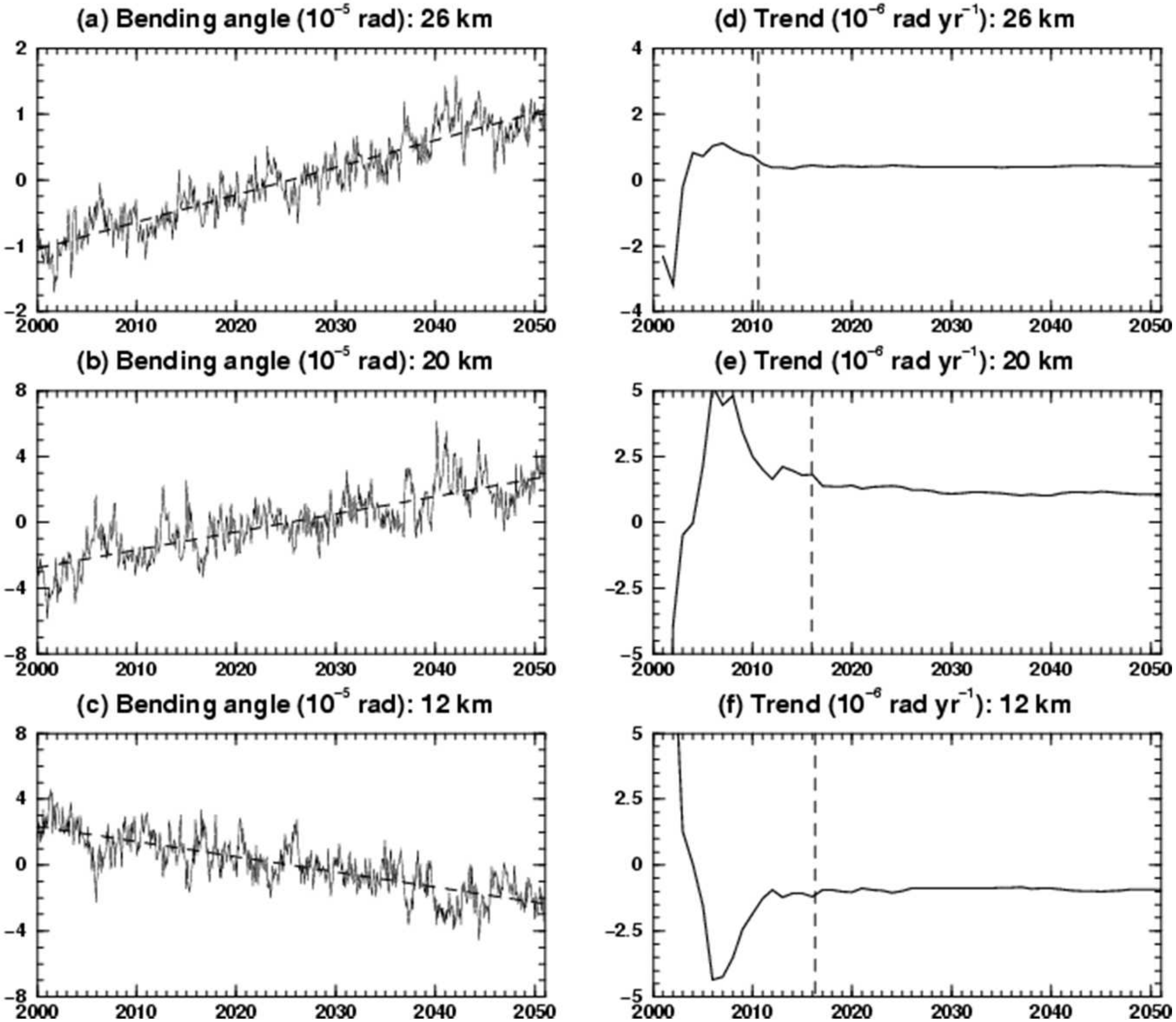
Initial comparison with observations



Bending angle trends 2001 – 2011. Courtesy of Torsten Schmidt, GFZ, Potsdam, Germany.



Trends in the tropics may be detectable in about ~15 years



Detection times

(95% confidence intervals)

26 km: *9.4 – 11.7 years*

20 km: *13.6 – 18.7 years*

12 km: *14.6 – 18.2 years*