An introduction to GPS radio occultation and its use in NWP

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GRAS SAF Workshop on "Applications of GPS radio occultation measurements";
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An introduction to GPS radio occultation and its use in NWP

- Radio occultation (RO) – introduction
- Variational data assimilation – introduction
- Assimilation options for RO data
- Some issues for this Workshop

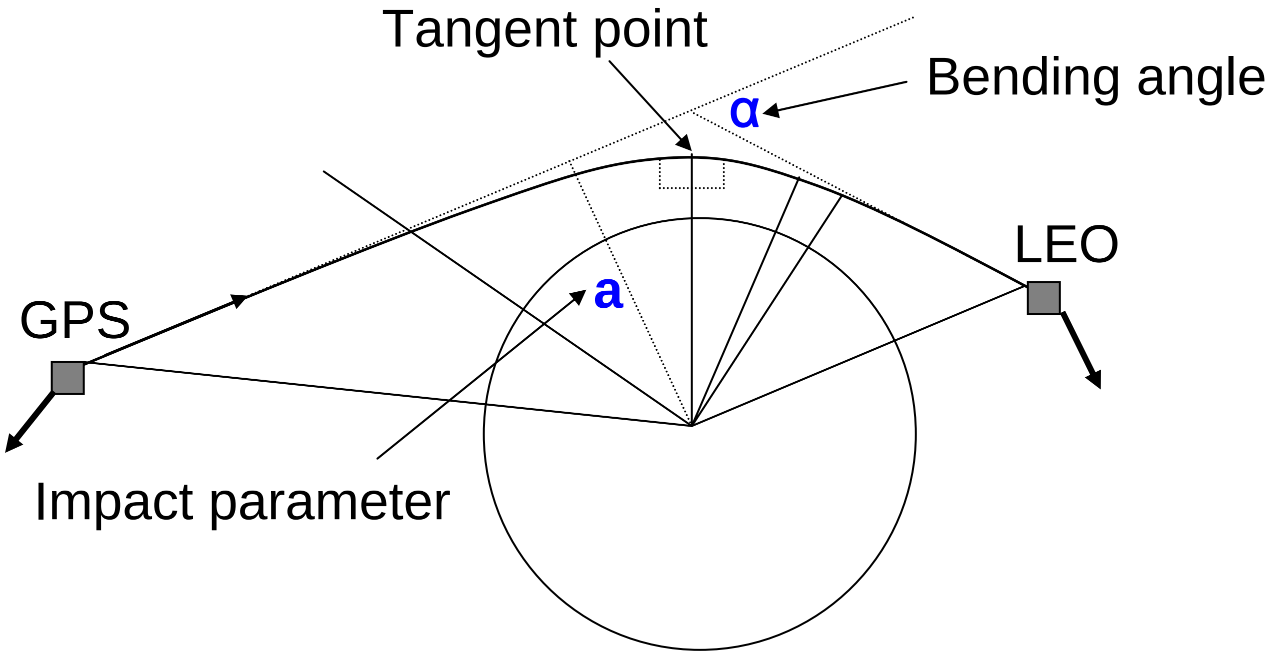
Met Office

GPS – the source data

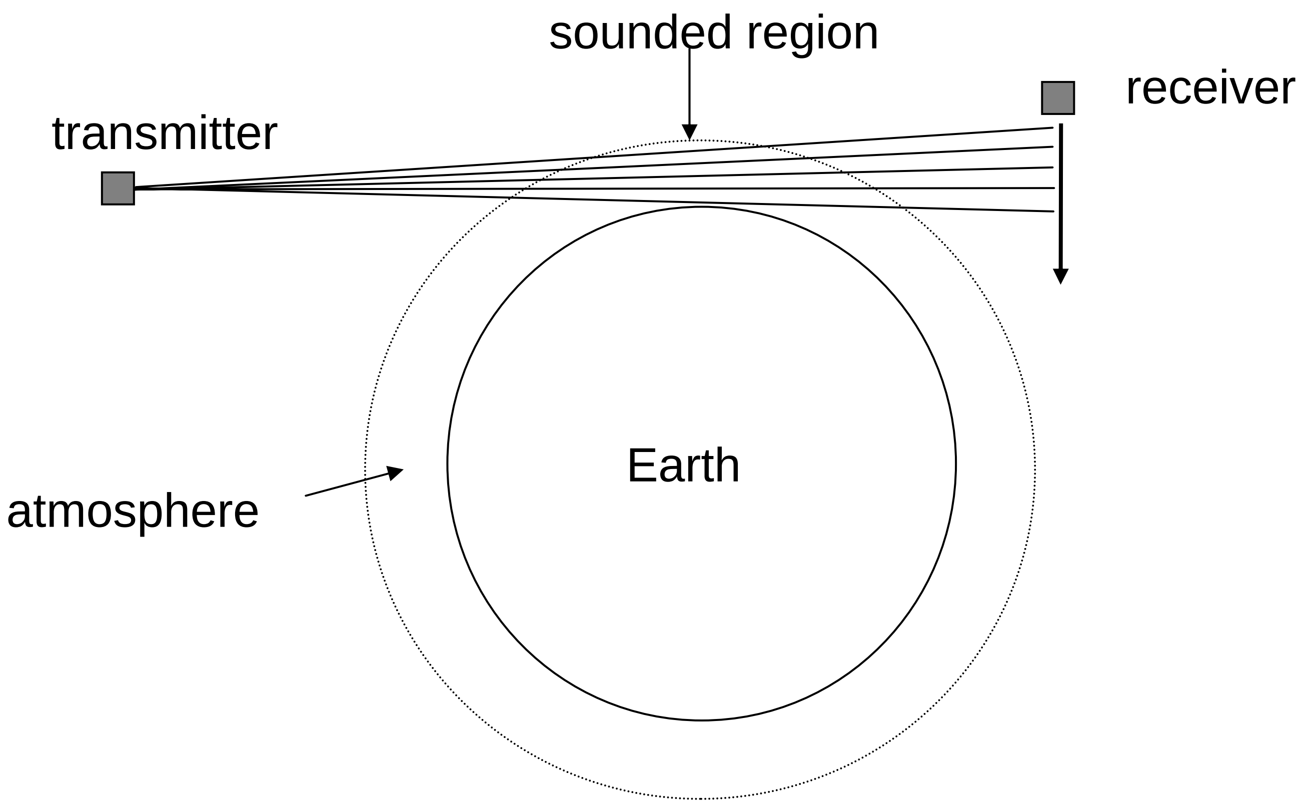
The Global Positioning System (GPS)

- multi-purpose - applications in positioning, navigation, surveying, …
- nominal GPS network = 24 satellites
- near polar orbit - height ~20000 km
- allows high-accuracy positioning of low Earth orbiters (LEOs)
- source of refracted radio signals for radio occultation

Geometry of a radio occultation measurement



An occultation



A sounding from 60 km to the surface takes ~60s

Atmospheric refraction: the physics

Refractivity gradients caused by gradients in:

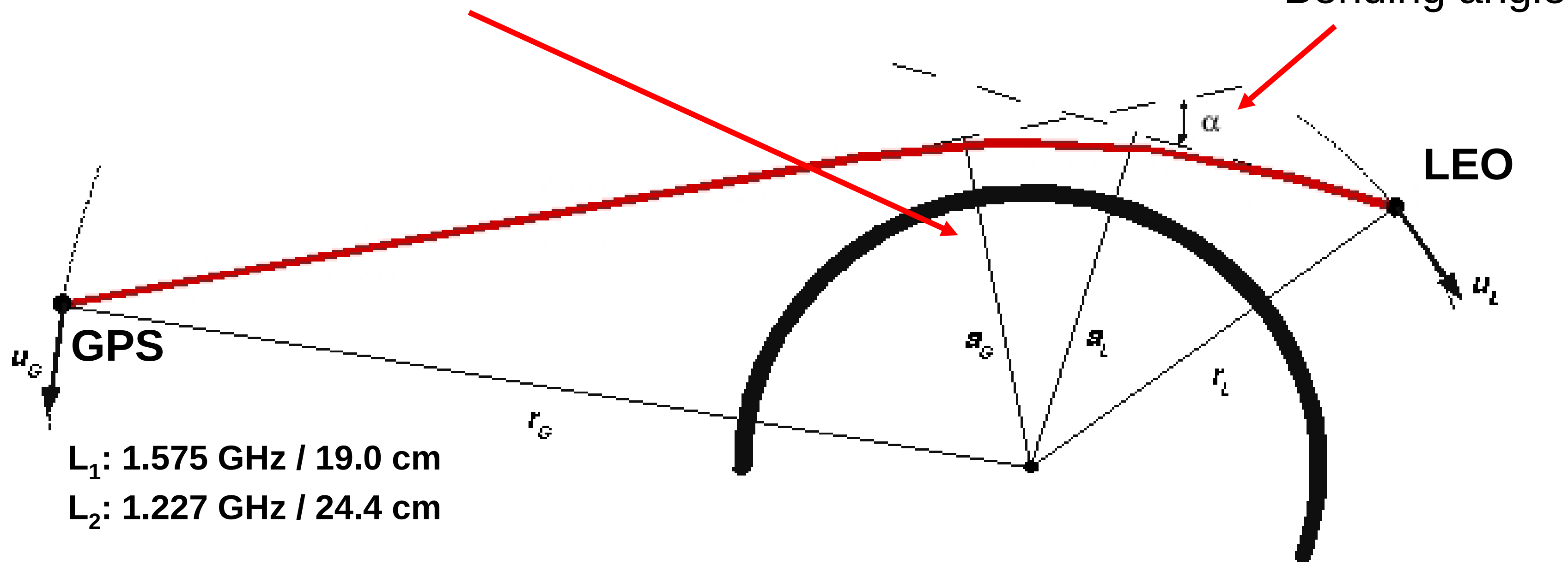
- density (pressure and temperature)
- water vapour
- electron density
- (liquid water)

$$N = \kappa_1 \, p / T + \kappa_2 \, e / T^2 + \kappa_3 \, n_e / f^2 + \kappa_4 \, W$$

"dry" "moist" ionosphere "scattering"

N = refractivity = $(n - 1) \times 10^6$
p = pressure
e = water vapour pressure
f = frequency
n = refractive index
T = temperature
n_e = electron density
W = liquid water density

From bending angle to density



$$\ln(n(a)) = \frac{1}{\pi}\int_a^{\infty} \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} da'$$

Refractive index

$$N = (n-1)\times 10^6 = \kappa_1 \frac{p}{T} + \kappa_2 \frac{e}{T^2}$$

Refractivity

Features of RO measurements

- globally distributed

- temperature in stratosphere and upper troposphere, and ...
- humidity in lower troposphere

- high vertical resolution: 0.5 - 1 km
- low horizontal resolution: ~ 200 km

- high accuracy:
  - random errors <1K
  - systematic errors <0.2K   - to be demonstrated in practice

- “all-weather”

- relatively inexpensive
- receivers x transmitters → space/time sampling

Radio occultation missions

Past:

• GPS/MET:	1995-7	1	selected periods only

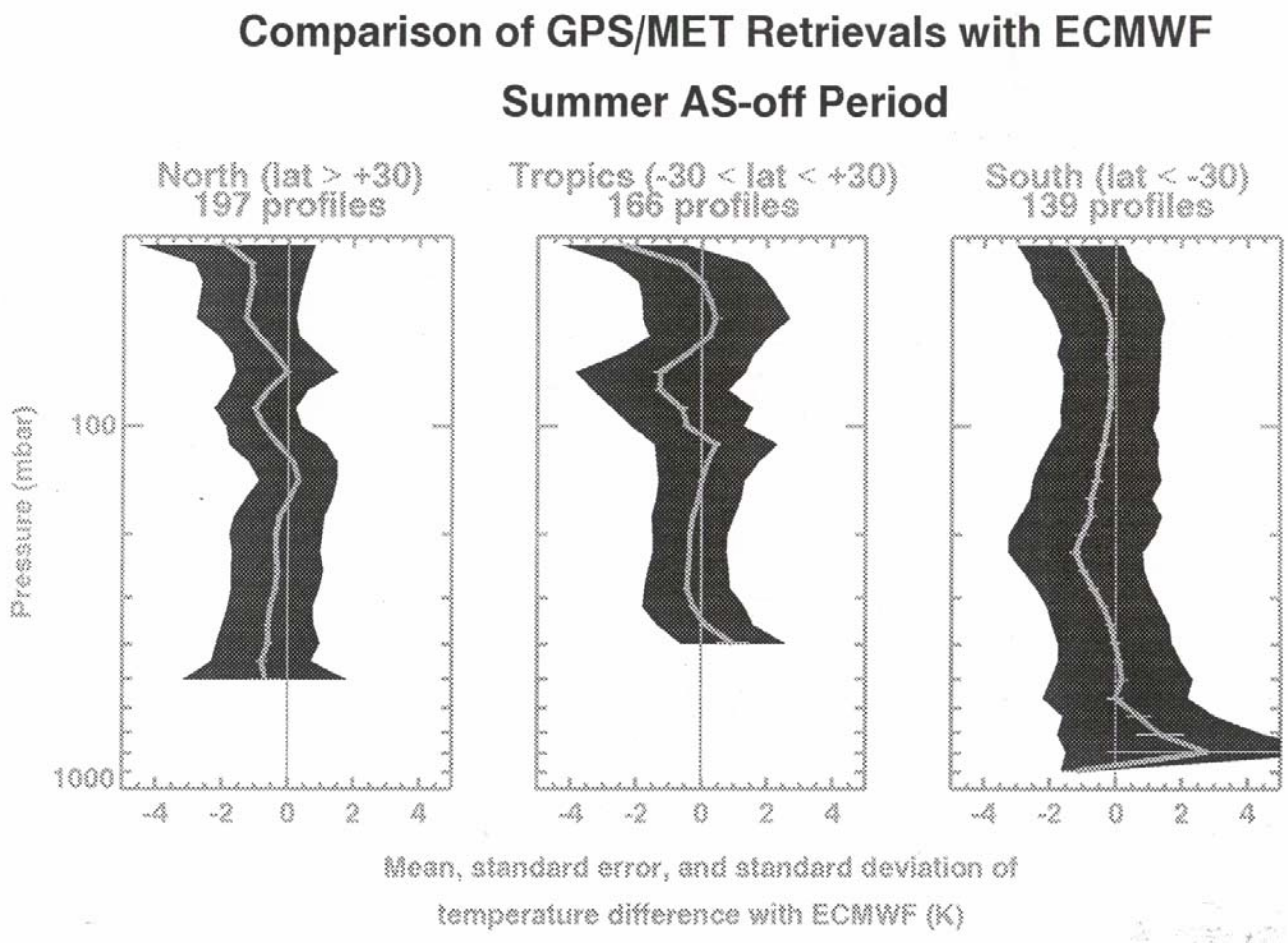
Present:

• CHAMP:	2000-	1	continuous since 2001, nrt since 2006
• GRACE-A:	2002-	1	continuous since 2003, nrt since 2006
• COSMIC:	2006-	6	quasi-operational demonstration
• GRAS:	2006-	1	operational 2008

Future:

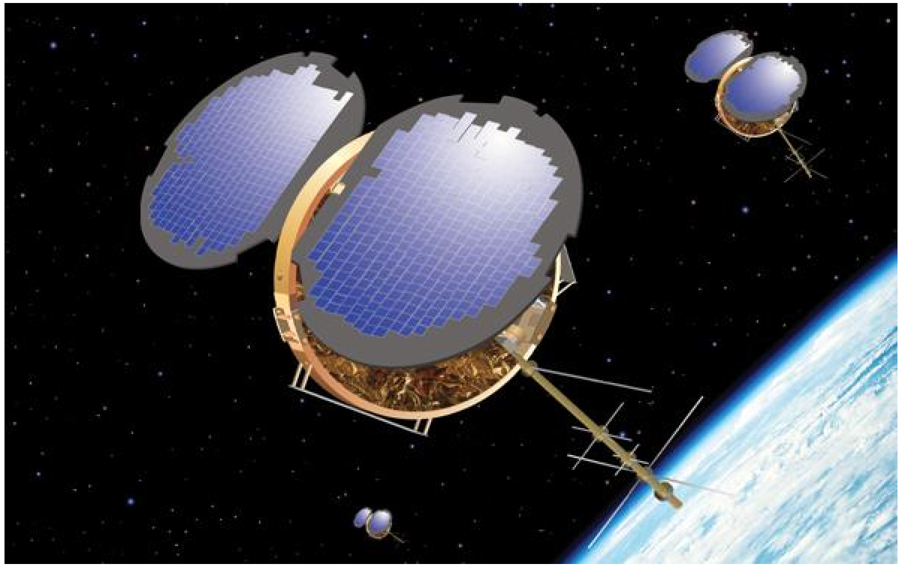
- ???

GPS/MET – early results

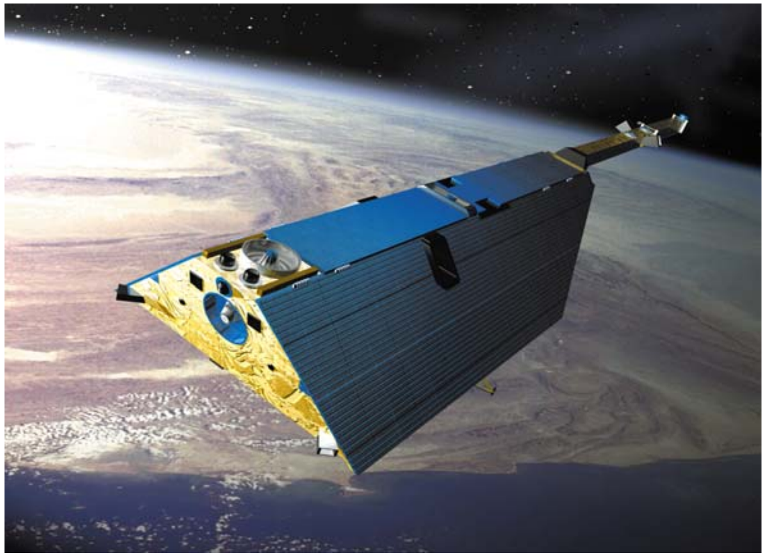


JPL: Kursinski, Hajj, Bertiger, Leroy, Romans, Schofield, et al. (6 December 1995)

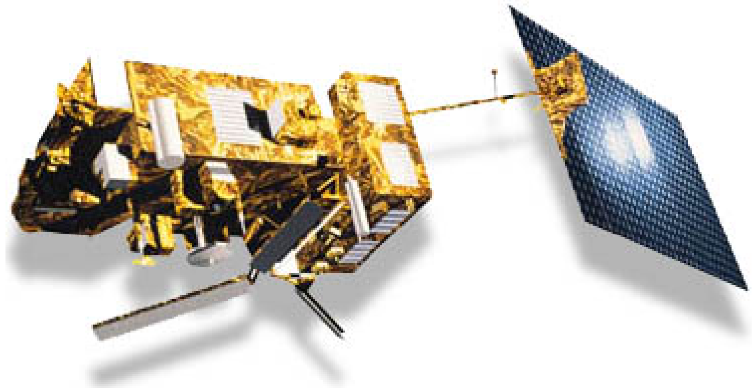
COSMIC



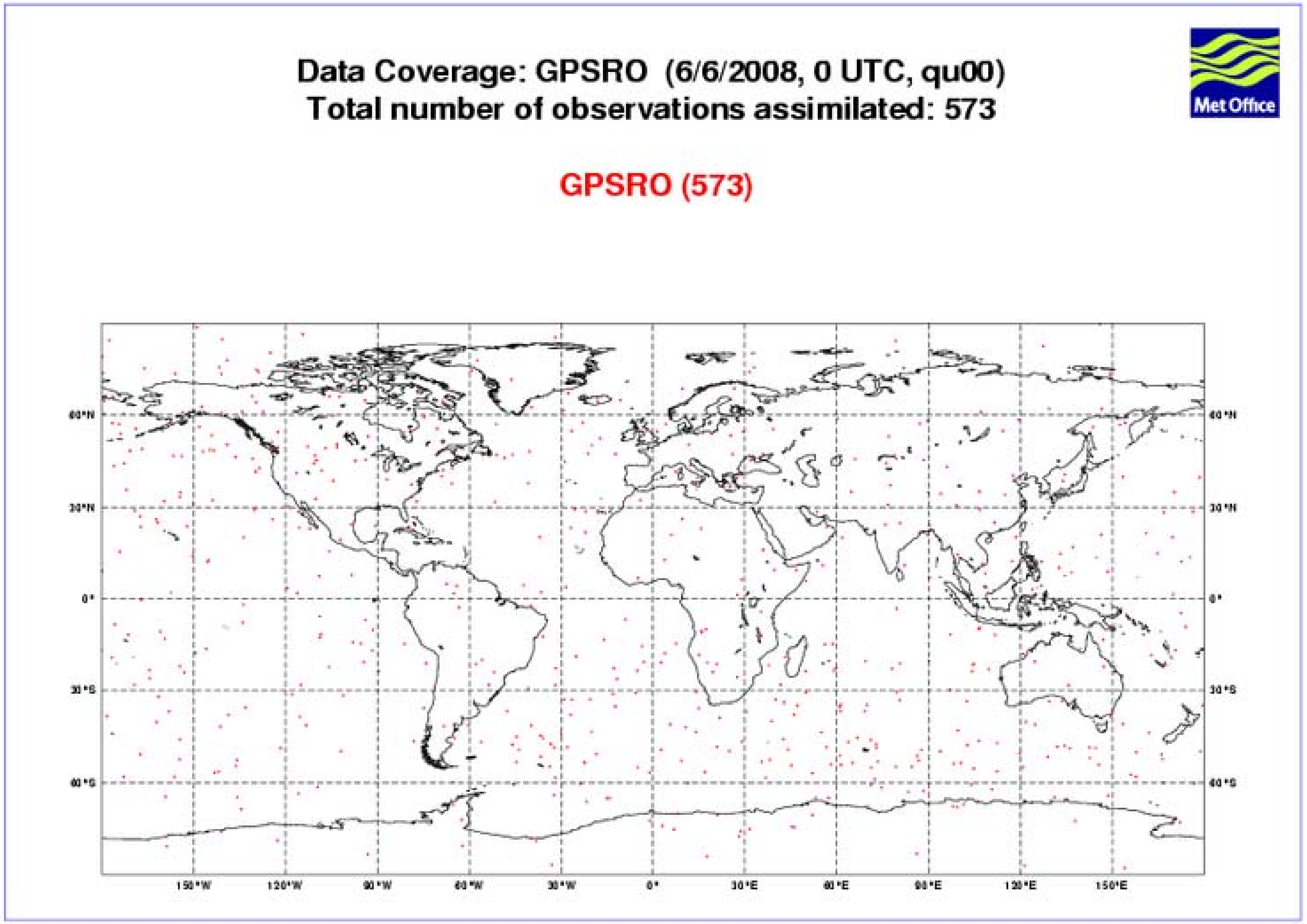
CHAMP



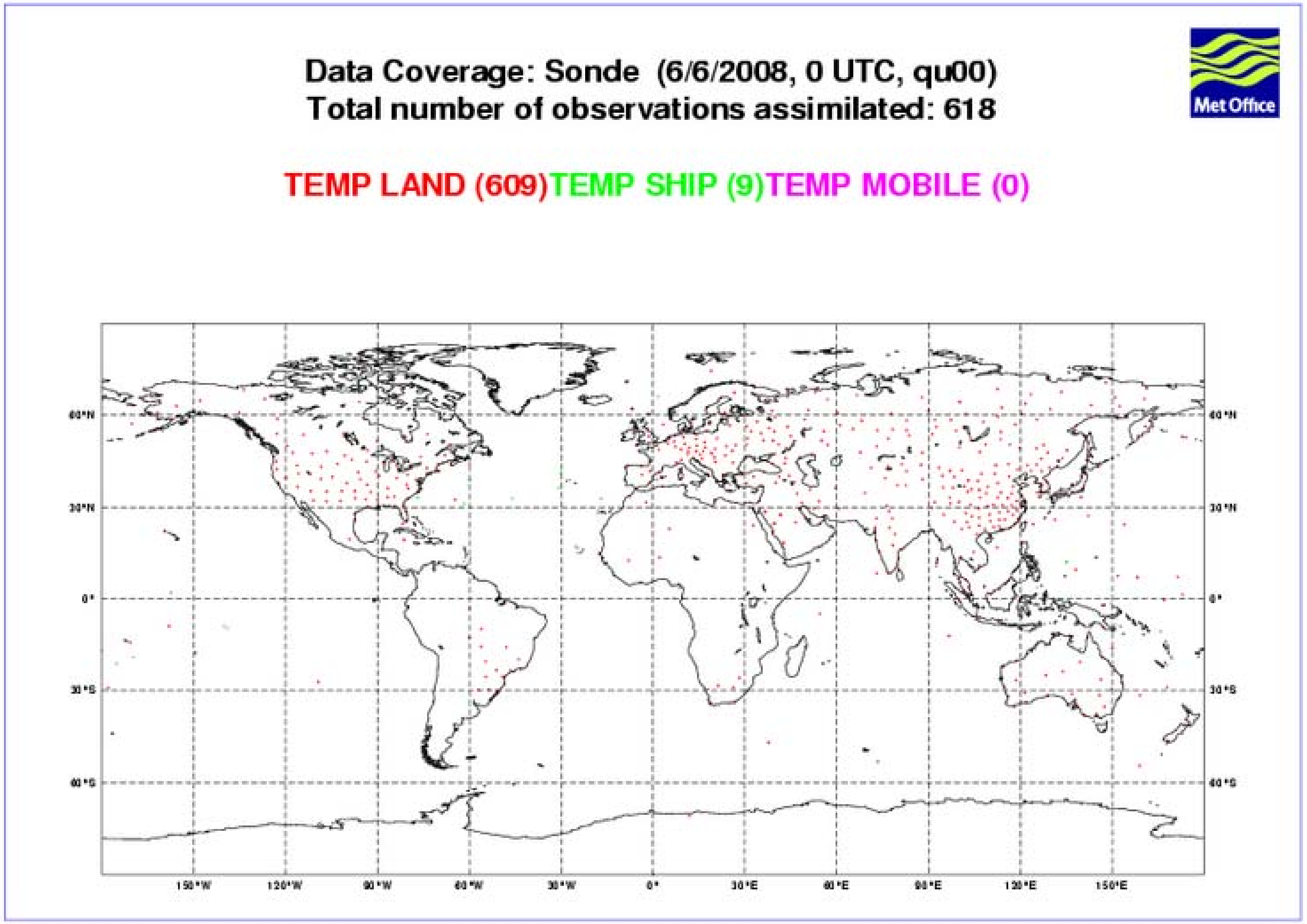
Metop/GRAS



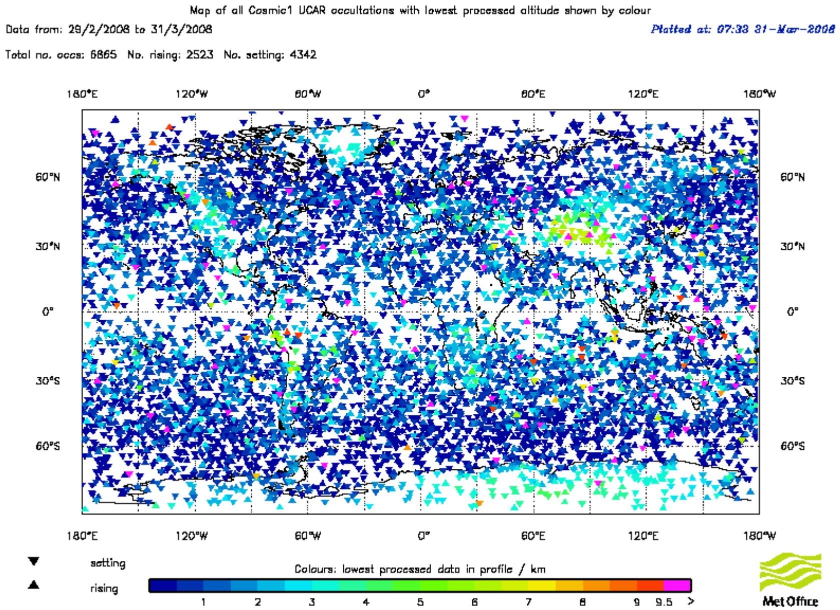
COSMIC data coverage in 6 hours

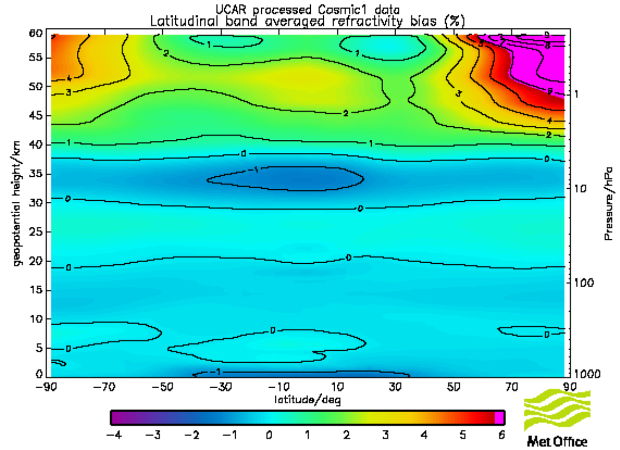


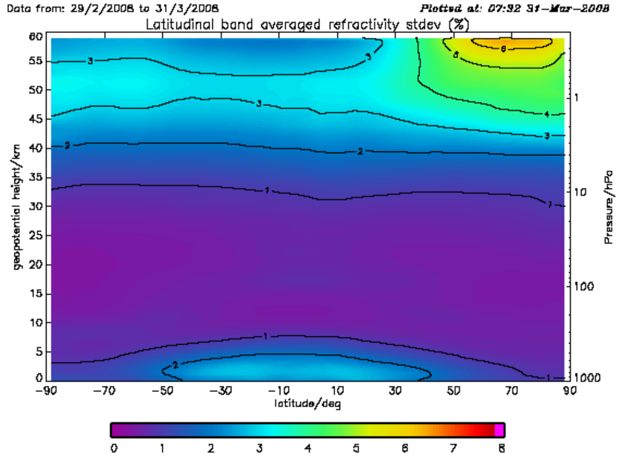
… compared with sondes

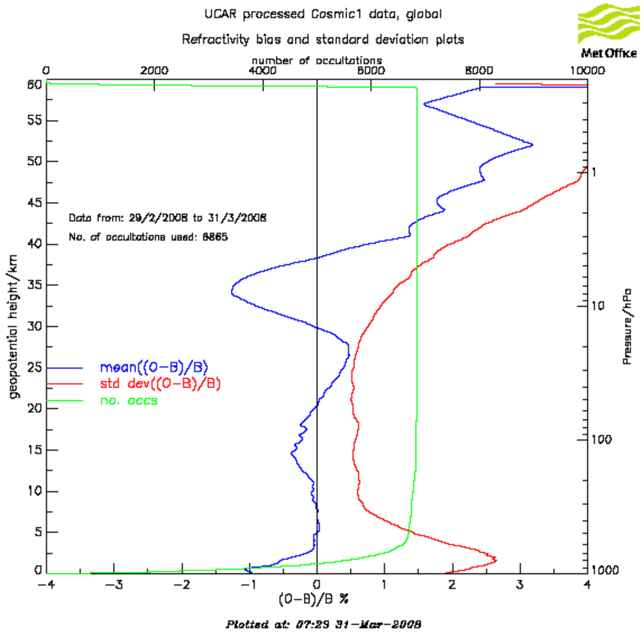


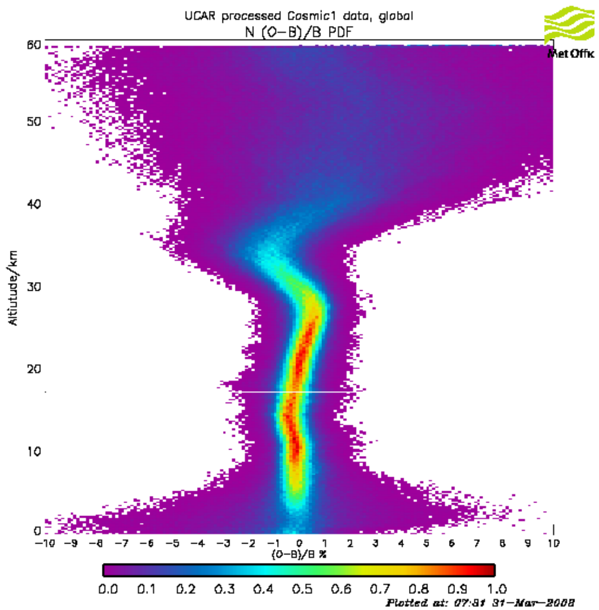
GRAS SAF Monitoring

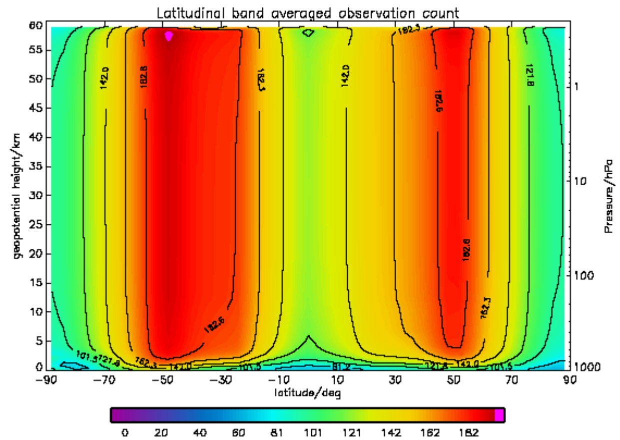












Variational data assimilation

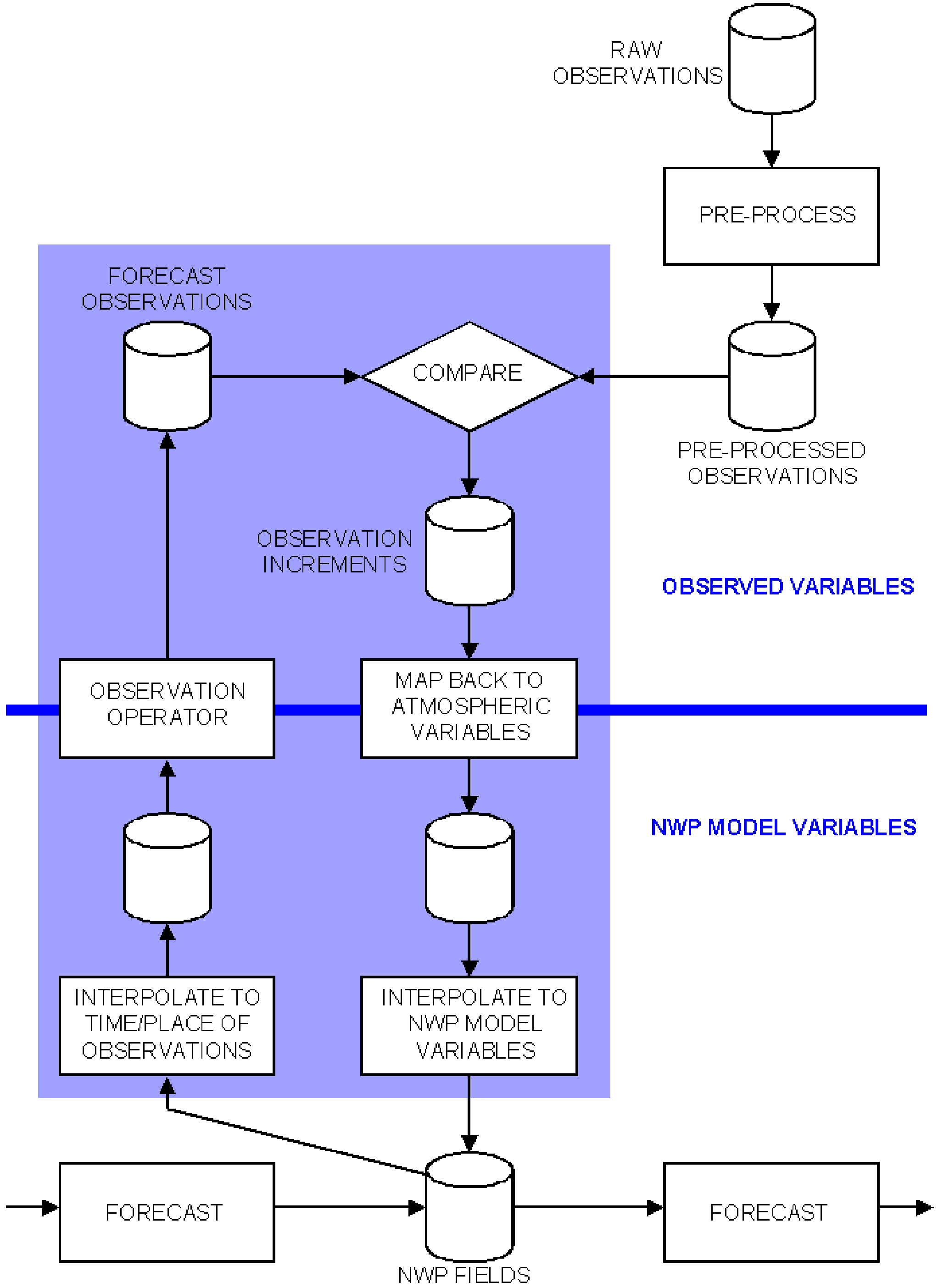
Minimize:

$$J[x] = \tfrac{1}{2}(x-x^b)^T B^{-1}(x-x^b) + \tfrac{1}{2}(y^o-H[x])^T (E+F)^{-1}(y^o-H[x])$$

x	NWP model state
x^b	background estimate of x (short-range forecast)
B	its error covariance
y^o	vector of measurements
H[...]	“observation operator ” or “forward model” mapping state x into “measurement space”
E	error covariance of measurements
F	error covariance of forward model.

$$\nabla_x J[x]^T = B^{-1}(x-x^b) - \nabla_x H[x]^T (E+F)^{-1}(y^o-H(x)) = 0$$

Assimilating observations into a NWP model



Assimilation options for RO data

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Options:

(1) assimilate retrieved profiles of temperature and humidity

(2) assimilate retrieved profile of refractivity, $N(z)$

(3) assimilate measured bending angles, $\alpha(a)$, directly

Special problems with RO data:

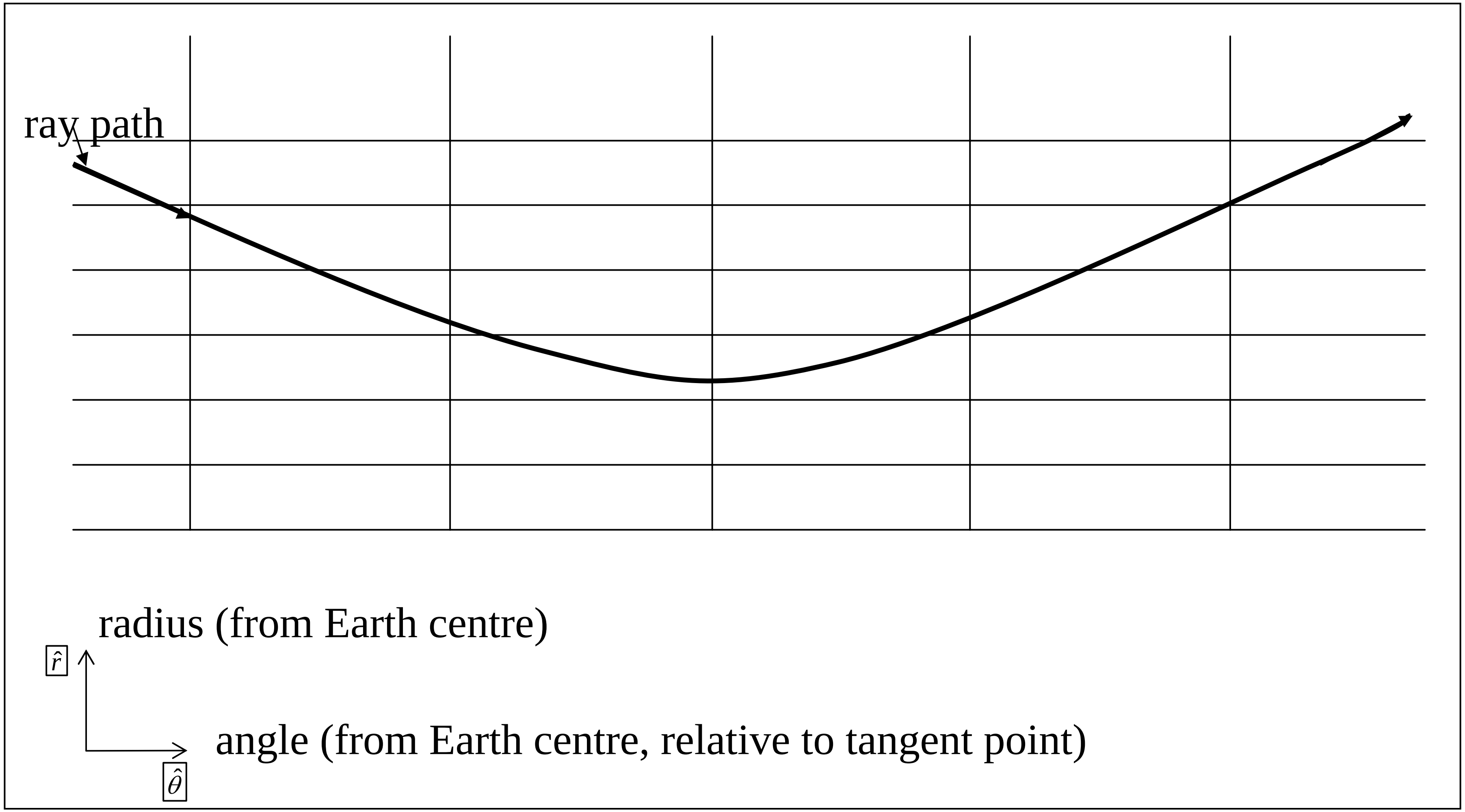
- non-separability of temperature and humidity
  - addressed by (2) and (3)
- limited horizontal resolution / problems of horizontal gradients
  - partially addressed by (3)

Forward modelling for RO data

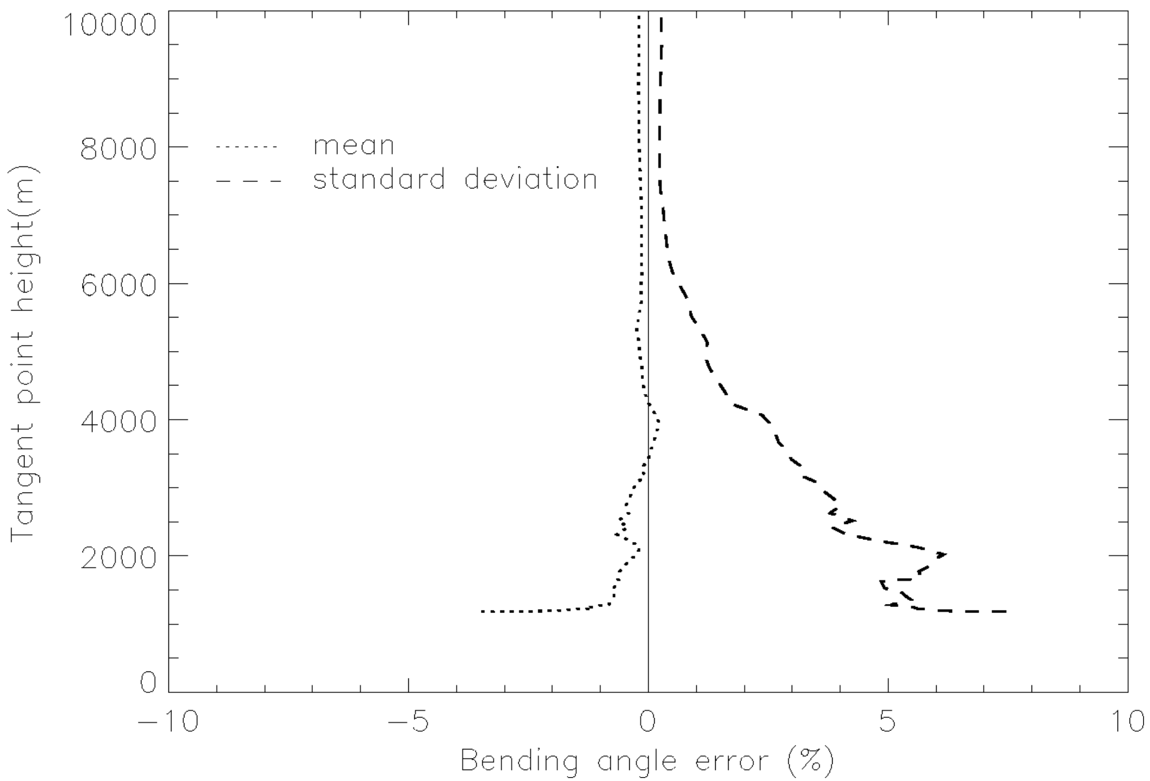
Forward problem:

3D fields of T,q ↓	temperature and humidity
3D field of N ↓	refractivity
REFRACTION MODEL ↓	
α(a)	refracted angle as a function of impact parameter

2D fast forward model of refraction in plane of occultation



RO forward model: accuracy

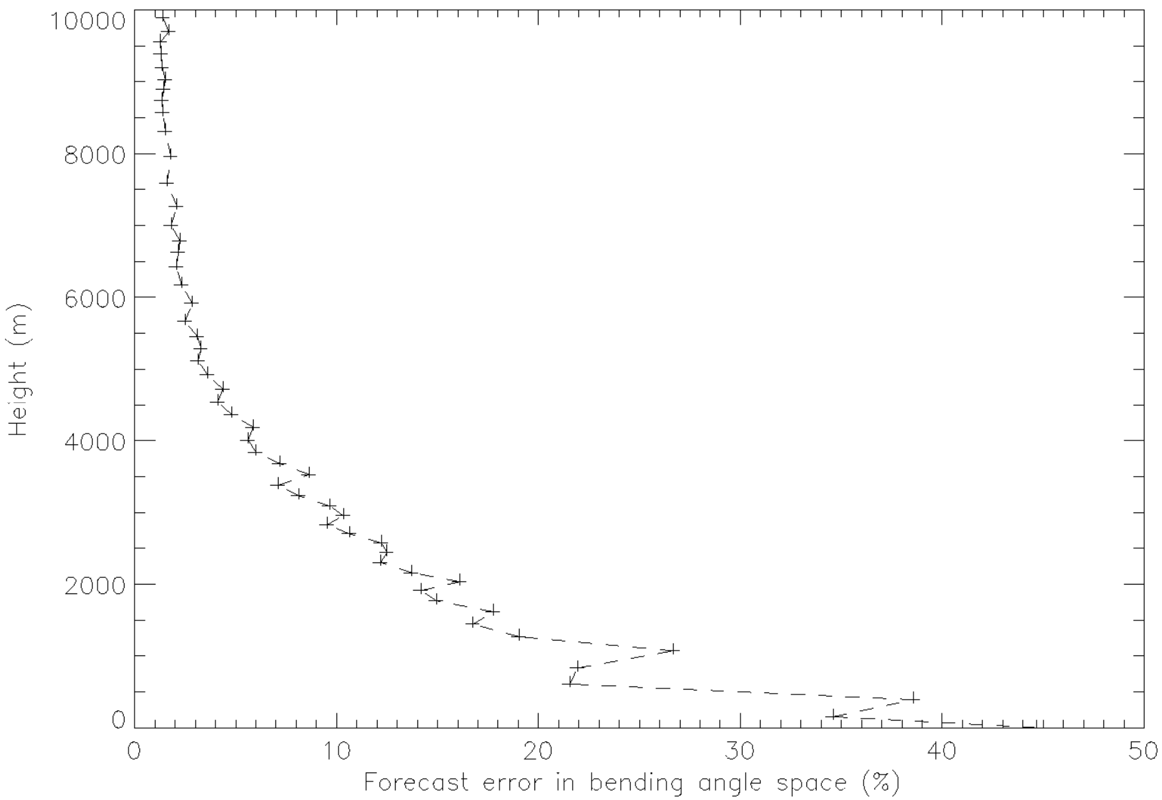


Comparisons against a 3D ray tracer for simulations in the domain of the Met Office mesoscale model. 160 cases.

Healy and Eyre, 2003.

Largest source of error - using impact parameter to derive tangent point height.

Forecast errors mapped into bending angle space



Diagonal of
$\nabla_x H[x] .B. \nabla_x H[x]^T$

Significantly larger than the forward model errors

Healy and Eyre, 2003.

Information content of RO data

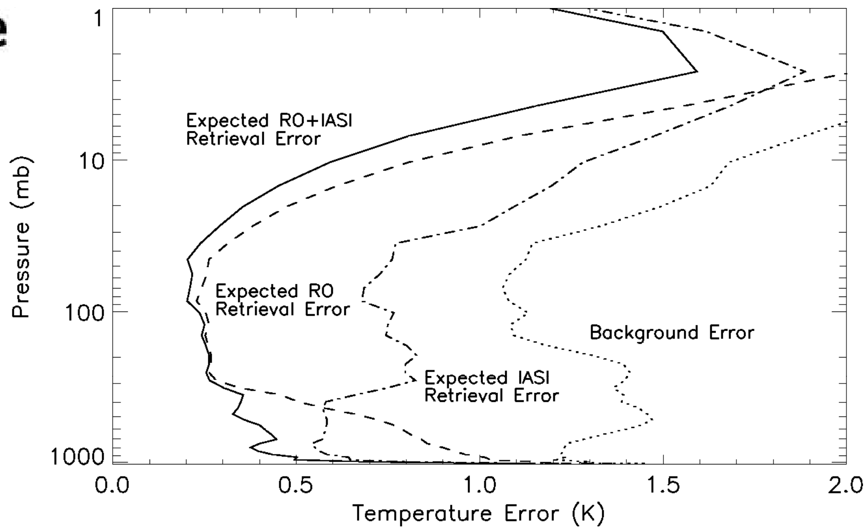
- Information is always relative - relative to what you already know, the "prior" information

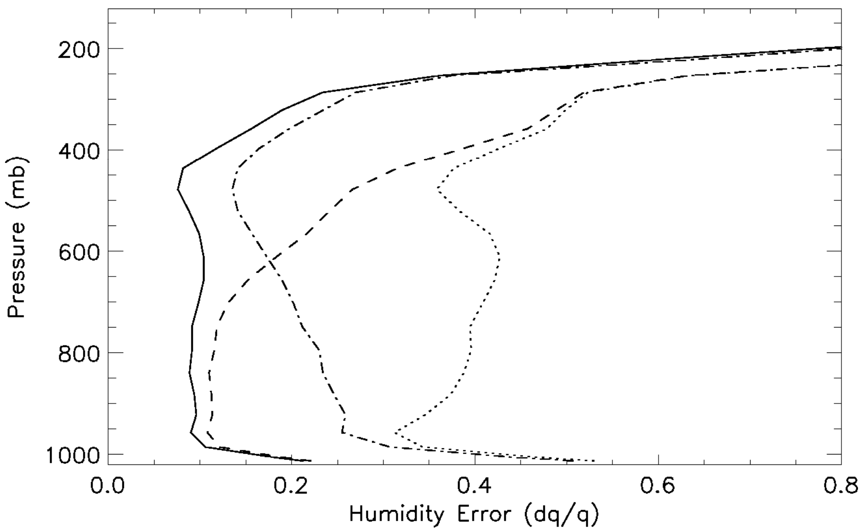
- For NWP, the information content of an observation depends on the accuracy of the "background" information from a short-range forecast:

$$A^{-1} = B^{-1} + \nabla_x H[x]^T \, . \, (E+F)^{-1} \, . \, \nabla_x H[x]$$

retrieval "accuracy" = background "accuracy" + measurement "accuracy"

Information content: RO and IASI





Collard and Healy, QJRMS 2003

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Summary

Radio occultation measurements:

- sensitive to vertical gradients of atmospheric refractivity
- → and hence to atmospheric profiles of temperature and humidity

- used to study atmospheres of other planets since mid-1960s
- powerful new technique for sounding the Earth's atmosphere with high vertical resolution and accuracy

- great potential for NWP and climate monitoring

- temperature and humidity effectscannot be separated unambiguously, but ...
- variational data assimilation allows optimal exploitation in NWP

Some issues for this Workshop

Met Office

NWP

- Early impacts very good
- What is limiting impact? – relative biases?

Climate

- Stability – truly self-calibrating?

Other applications

- PBL information – NWP and other applications
- Reflected signals

Future systems

- How many receivers x transmitters needed? - OSSEs?
- How do we ensure follow-on missions?

Thank you! Questions?