Environment Canada Environnement Canada

Canada

The Use of GPSRO data at Environment Canada

ROM SAF Workshop
ECMWF, Reading, UK
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Overview

- History & current status at Environment Canada (EC)
  - Assimilated data, assimilation details
- Philosophical & engineering choices
  - Rationale
  - Trade-offs
  - Performance
- Overview of items under development
  - Low atmosphere
  - Boundary layer
  - Surface reflections
  - Horizontal gradients

History

- 2003: Begins development.
- 2004-06: Tests for different architectures
- 2007: Final structure, philosophy, settled (Refr & BA)
- 2008: Op readiness, 1st delivered implementation (Refr).
- 2009: Op production (Refr, model lid 10 hPa, 30 km)
- 2010: Vertical extension (Refr, model lid 0.1 hPa, 65 km)
- 2011: Reevaluation of physical constitutive relations
- 2013: Reimplementation with updated physics
- 2014: New BA, reflection-aware
  - Still assimilating Refr
- 2015: Activate BA & reflections? Partial activation?

Perspective: Cost function

- Variational assimilation (Bayesian optimization)
  - At EC we also have Ensemble assimilation

- Variational: Minimize departure from knowledge (x_B and O)
  - $J = J_B + J_O = \frac{1}{2}(x - x_B)^T B(x - x_B) + \frac{1}{2}\left(\frac{O-H(x)}{\sigma}\right)^2$
  - Find max probability = min cost function
  - 3DVar / 4DVar / EnKF / EnVar versions of the concept

- Variational or ensemble we need — defined by
  - List of data (N or Bend, rejection criteria) — *user, on provider spec*
  - **H(x)** function — *user, on provider spec*
  - **σ** for each datum — *now **is** user* / ***should** be provider*

Who should provide what:

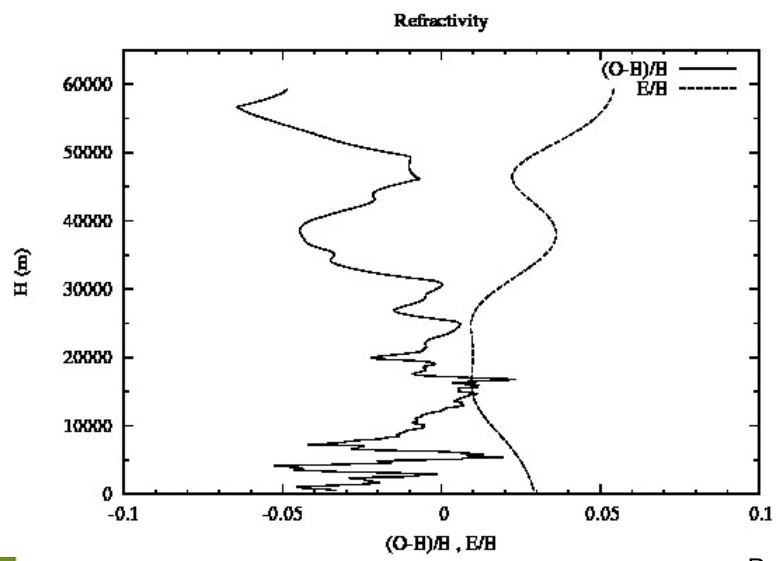
• B (estimated background covariance)		NWP system
• H(x)	obs operator	user optimal choice: H conceptually based on instrument & processing (provider-side), but x is a NWP-dependent **imperfect** representation of atmosphere (incomplete, discretized,…)
• Data choice		user optimal: (NWP **sensitivity** to obs errors/bias)
• σ Obs error, or also covariance:		**provider** (now is user)

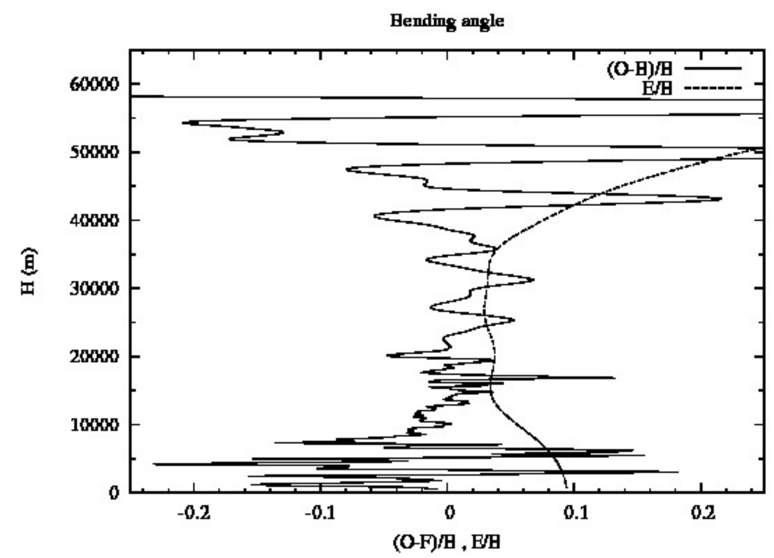
Early choices at EC

- From **datum**-oriented cost function:
- $J_O = \sum_1^{nObs} \left(\frac{O-H(x)}{\sigma}\right)^2$
- To **profile**-oriented
- $J_O = \sum_1^{nProf} \sum_1^{nData} \left(\frac{O-H(x)}{\sigma}\right)^2 = \sum_1^{nProf} f(x; \vec{O})$
- We assume that data naturally show collective properties by **profile** (not by datum / satellite / …)
- Rationale: data have been collected & processed as profiles, any anomaly will emerge collectively (orbit error, ionosphere…)

The profile cost function

- How much is the observation error σ ?
  - Very variable by instrument, inversion, circumstances, atmosphere state.
  - Some hint by providers, but still very uneven, not always offered.
- We determine our own:
- Window (5 km Gaussian) vertical rms avg of $\frac{O-H(x)}{H(x)}$ is taken as $\frac{\sigma}{H(x)}$





Profile-oriented obs error

- Valid when actual error too unknown
- Maybe not optimal, but **not too small, not too big**
- Will **dynamically** respond to transient orbit / iono error

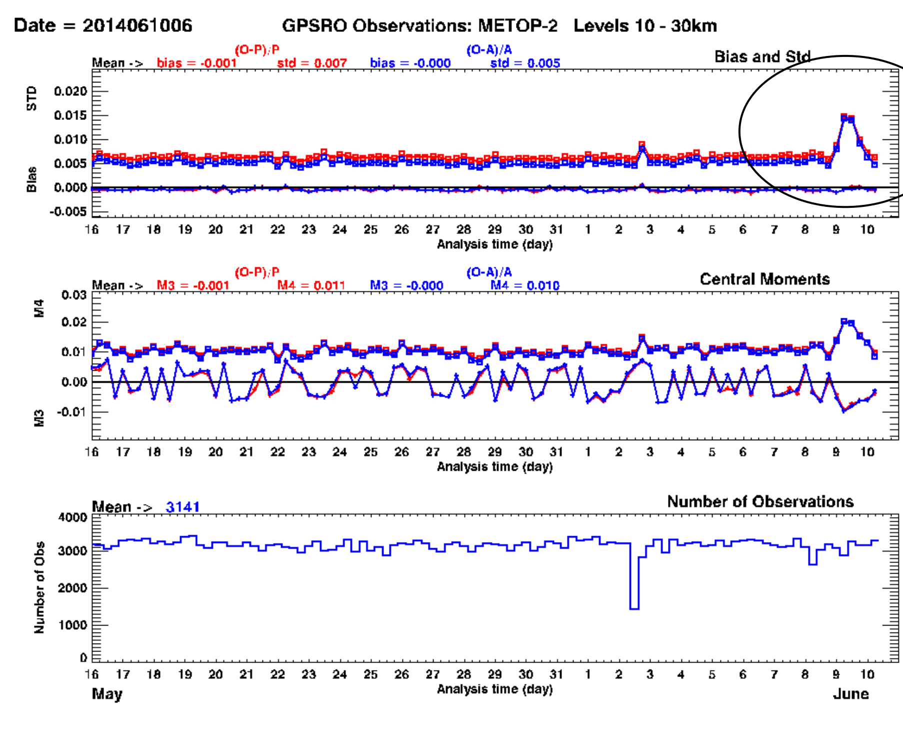
- If obs was genuinely of bad quality
  - Err will be big (bad data ignored, ok!)
- If background was of bad quality
  - Err will be big (good data ignored, but can we expect good assimilation behavior of complex vertical info over bad bg?)
- Has naturally evolved with the providers' retrieval and NWP system (**2006-2014**) without recalibration
  - UTLS err evolved from 2% to 0.6%.

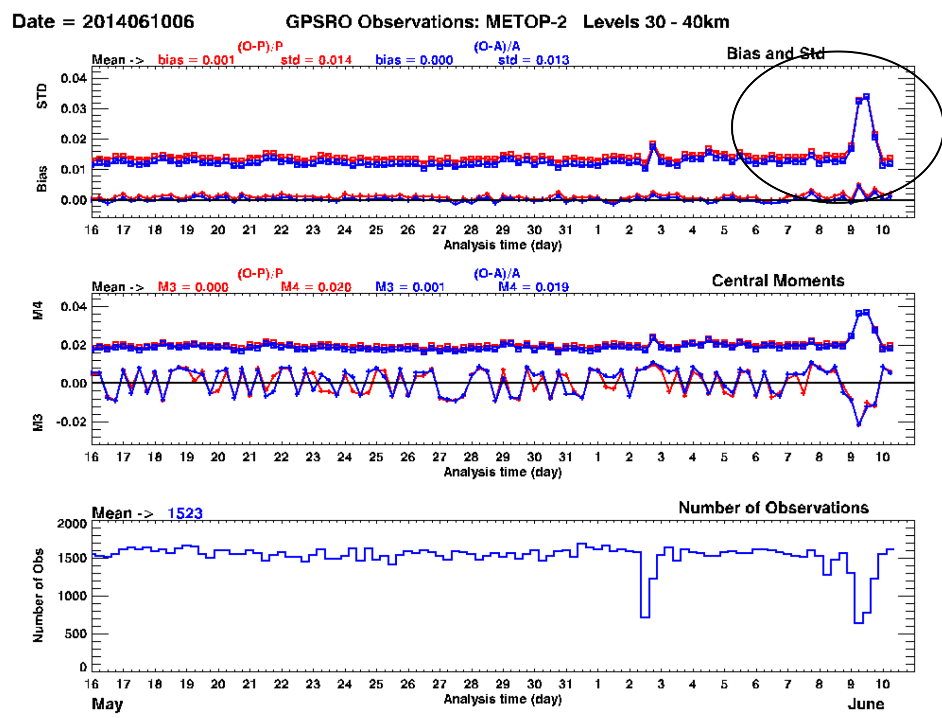
Dynamic error adjustment

June 9 2014

Error was dynamically raised, and analysis mostly ignored unflagged biased data

O-A stats = O-P stats





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Choice of data at EC

- 1st test (2006+): Refractivity
  - Model lid was 10 hPa (~30 km)
  - Became operational Mar 2009 with 10 hPa lid
  - Operational lid raised in Jun 2009 (0.1 hPa, ~65 km)
    - Only deterministic NWP was 0.1 hPa
    - Ensemble system has low lid (now 2 hPa, ~45 km)
      - Both share data, checks, bias correction, thinning.
  - **Lid limited choice of BA**
- 2nd test (2012): Bending recoding
  - Nice results from deterministic system
    - Good short term, lower bias, can consider reflections
  - **(bend+error) does NOT beat our (refrac+err) at mid & long range**
- **Research** line: Mixed
  - Unquestionable benefits from BA
  - Some benefits from Refr too

Is Refractivity so bad?

- **Providers**:
- Phase → Doppler → Bending → Refractivity
- Deprojection integral (Abel) discretized in ~**5000** points
- Numerical interpolation **not critical**

$$\frac{n(r)}{n(r_{max})} = exp\left(\frac{1}{\pi}\int_x^{x_{max}} \frac{\alpha(a)}{\sqrt{a^2 - x^2}} da\right)$$

Notice integral does not need to be extended to infinity, if we accept a ratio of n (~diff of N) rather than n itself

- **Users**:
- P, T, q fields → Refractivity → Bending
- Projection integral (Abel) discretized in ~**50-100** points (81 at EC)
  - Or equivalent integral in 2d/3d operator
- Numerical interpolation **critical** (not always accurate)

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

Pro & con

- Providers better positioned than users to perform "Abel-like" integrals
  - small scale information representable in bending obs but at the edge of model resolution (**nontrivial to assimilate**)
  - Refractivity, as a cumulative, can inject info at the required resolution
- About upper initialization (i.e. climate): We should NOT assume that we obtain

$$N(h) \qquad \int f(x)dx + C$$

but instead

$$N(h_1) - N(h_2) \qquad \int_x^{top} f(x)dx$$

where $h_2 < \infty$

- We **should** in general understand "refractivity info" as **refractivity increments**, not **absolute refractivity**.
- Superrefraction, low level structure
- Abel retrieval does **not** represent reflection

Physical basis of the operators

- Equation of state
- Thermodynamic expression of refractivity
- Earth's geometry
- Interpolation in the discretized grid
- Refraction & reflection

Locality of operators

- Measurement is $N(h)$ or $\alpha(a)$
  - h or a are expressions of location $\vec{x}$
- Must be interpreted as fields of P, T, q
- Required
  - Refractivity expression $N \leftrightarrow P, T, q$

    Local relationship (thermodynamic)
  - Geometric structure of the atmosphere $\vec{x} \leftrightarrow P, T, q$

    Nonlocal (hydrostatic eqn, etc)

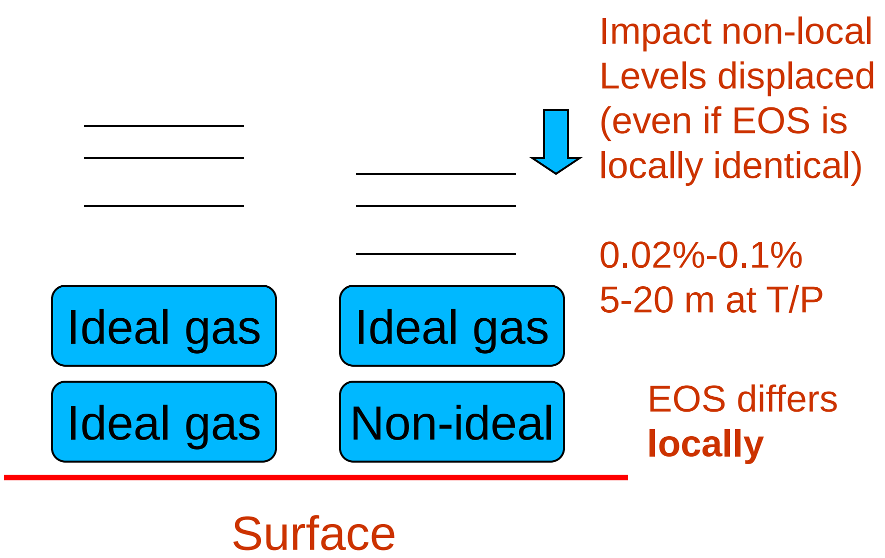
Even $\boldsymbol{N(h)}$ <u>is nonlocal</u>

Equation of state

- We assume hydrostatic equilibrium
- We need there the equation of state (EOS)
- Found that the deviation of EOS from ideal is small but non-negligible
- **<u>Non-local</u>**
- 0.05%, which **is** relevant for NWP if **<u>systematic</u>** (affects the anchor of radiances)

$$\nabla P = -\vec{g}(\vec{x})\rho$$

$$P(\rho, T, x_w)$$



Earth's geometry

- **We know the following to be relevant for RO**
  - Earth is not spherical
  - Local curvature depends on lat, azimuth
  - Mean sea level (~geoid) shape
  - Strength of gravity varies with latitude and altitude

- **We assume**
  - Shape of WGS84
    - Curvature, strength of gravity (lat, alt)
  - Height of MSL over WGS84 as main equipotential surf in EGM96

- **We neglect**
  - Gravity anomaly (geoid-dependent, lat & lon)
  - Sea surface topography (sea temperature, dynamics or salinity)
  - Variation of MSL within an occultation

Setup at Env Canada

Hydrostatic equation

$$g(\lambda, h)$$

- Should consider
- EOS should include compressibility

$$\rho(P, T, x_w)$$

Refractivity expression

- Calibration should have included compressibility
- Expressions of the form

$$N = k_1 P_d / T + k_2 P_w / T + k_3 P_w / T^2$$

cannot attain stated accuracy (for any set of coefficients)

- By theory or experiment should consider
  - Air composition
  - Molecular polarizability
  - Electric dipoles (H2O)
  - Magnetic (O2) dipoles
  - Dielectric enhancement
  - Univocal meaning

Proposal:

$$N = N_0(1 + N_0 \cdot 10^{-6} / 6)$$

$$N_0 = (222.682 + 0.069 \cdot \tau) \cdot \rho_d + (6701.605 + 6385.886 \cdot \tau) \cdot \rho_w$$

$$\tau = 273.15 / T - 1$$

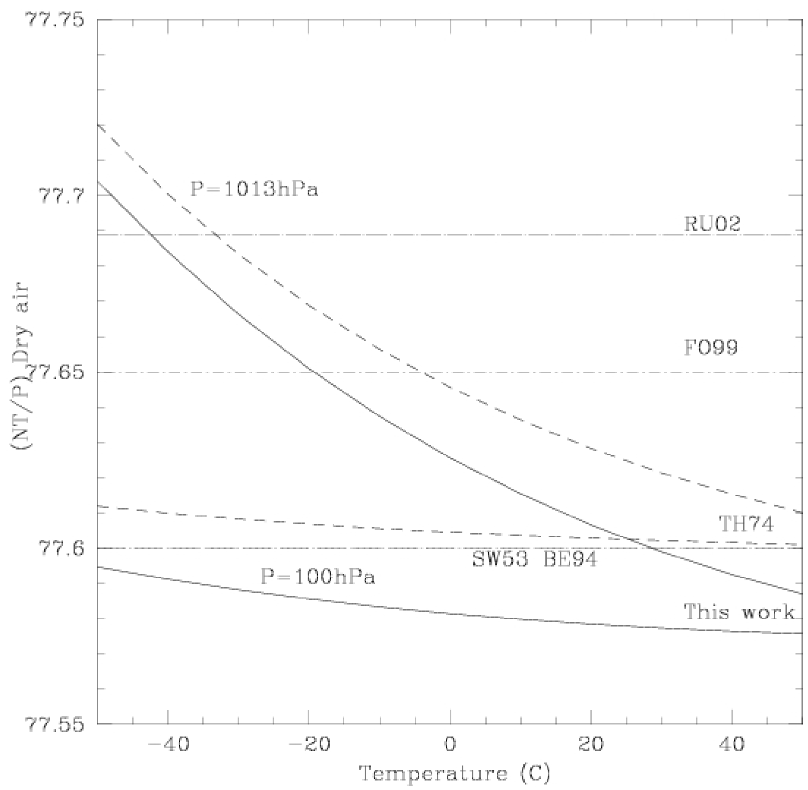
Dry air refractivity

What is normally called k1 (NT/P for dry air)

Not a constant

<u>No constant would fit</u> to better than 0.1% rms

(max err up to 0.2%)



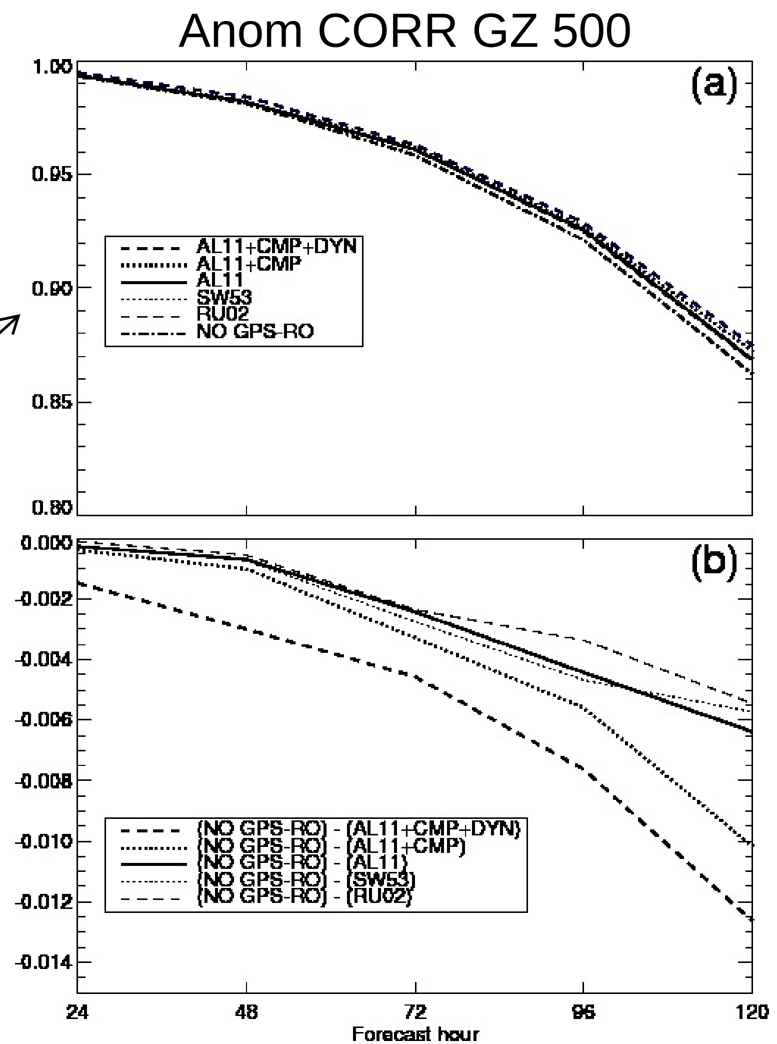
Higher at

- low T
- high P

Impact of the physical calibration

- Same other data, same NWP
- SW53, RU02, AL11 refract
- With/without RO
- Ideal gas, non-ideal
- Dynamic/static Bcor
- Above: World Anom Corr
- Below: loss of skill if we withdraw RO

- A large fraction of impact depends on constitutive relations
  - About 2x



All Jan 2009, World

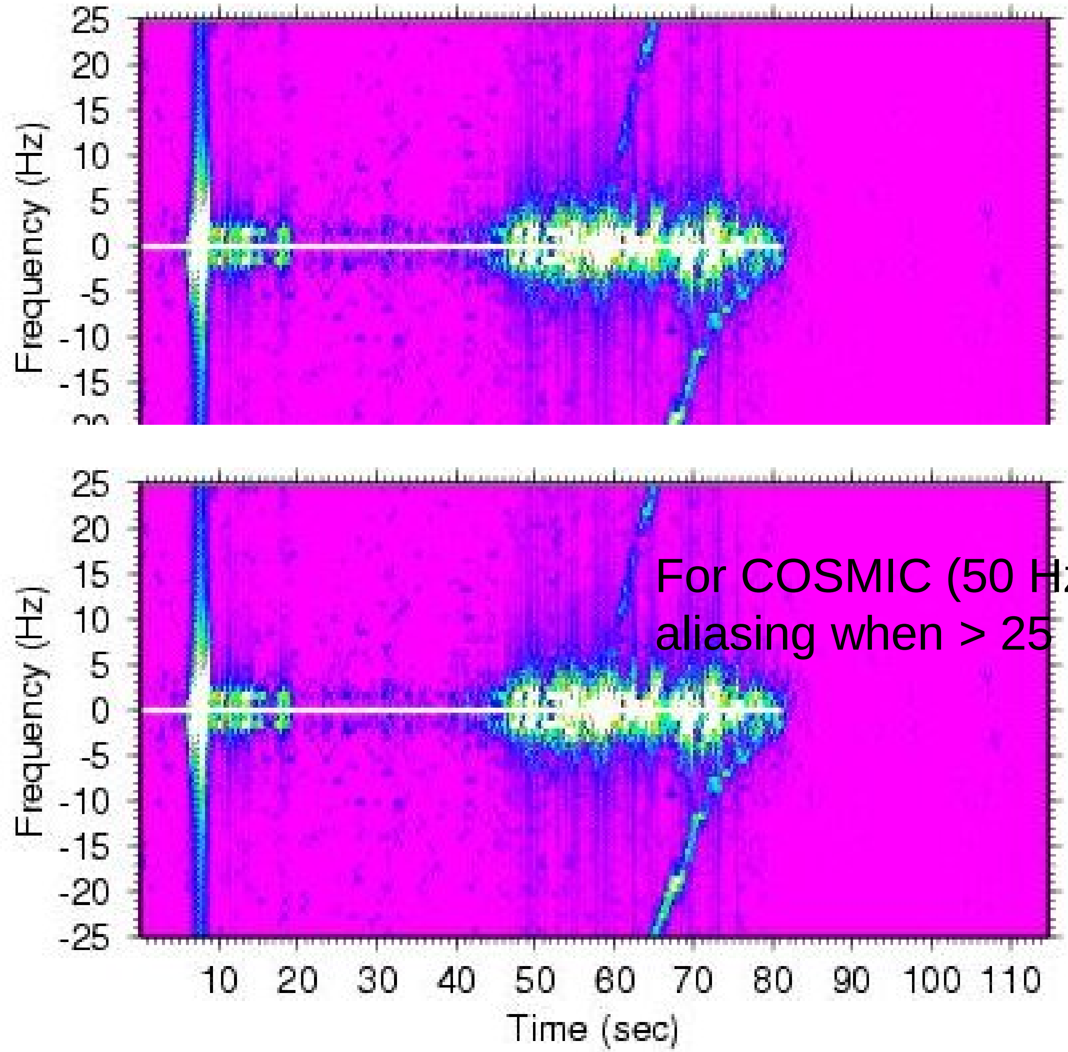
Vertical interpolation

- We have a discrete vert grid
  - Virtual T linear between grid points
    - For the hydrostatic equation
  - log N linear between grid points
    - Interpolation for refractivity operator (between grid points)
    - Derivative for the bending operator at the grid points
  - Height grid sequence assumed monotonic
  - Impact grid sequence NOT assumed monotonic
  - log α linear between grid points

What about superrefraction?

    - Interpolation for bending operator (between grid points)
    - a non-monotonic: there may be jumps (superrefraction)
- Original grids P,T,q (limited by model)
  - 1^{st} derived grids N, h, a (operator applied)
  - 2^{nd} derived grids α (another operator applied)

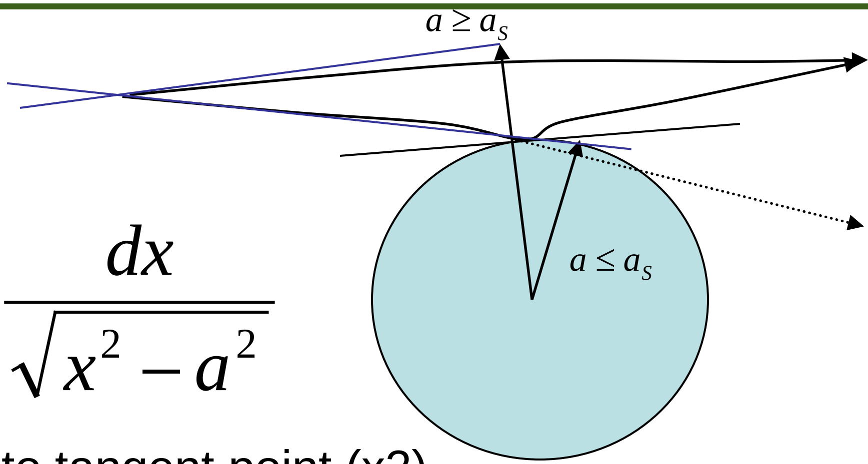
Power spectrum around direct signal



For COSMIC (50 Hz sampling), aliasing when > 25 Hz off main signal

Theoretical description

$$a_S = n_S R$$



- Direct signal:

$a \geq a_S$

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

Refraction over the curved path, up to tangent point (x2)

- Reflected signal:

Not reaching tangent point

2xElevation angle

$a \leq a_S$

$$\alpha_R(a) = -2a \int_{a_S}^{\infty} \frac{d \ln n}{dx} \frac{dx}{\sqrt{x^2 - a^2}} - 2 \arccos\left(\frac{\mathrm{a}}{\mathrm{a}_S}\right)$$

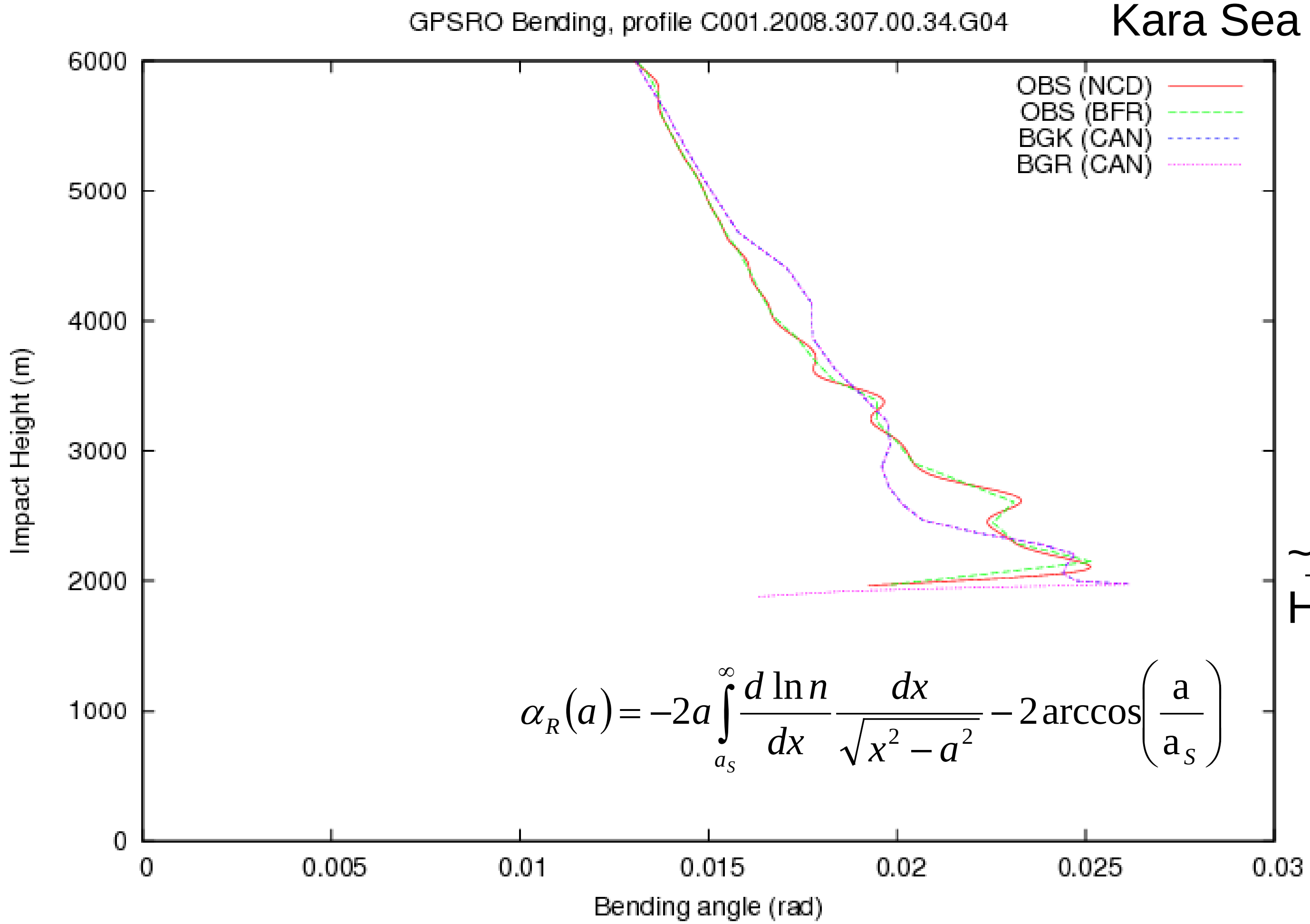
Nearly always downwards (>0)

Upwards (<0)

Impact parameter that is tangent at surface

Bending with reflection operator

Kara Sea (Arctic)



$$\alpha_R(a) = -2a\int_{a_S}^{\infty} \frac{d\ln n}{dx}\frac{dx}{\sqrt{x^2-a^2}} - 2\arccos\left(\frac{a}{a_S}\right)$$

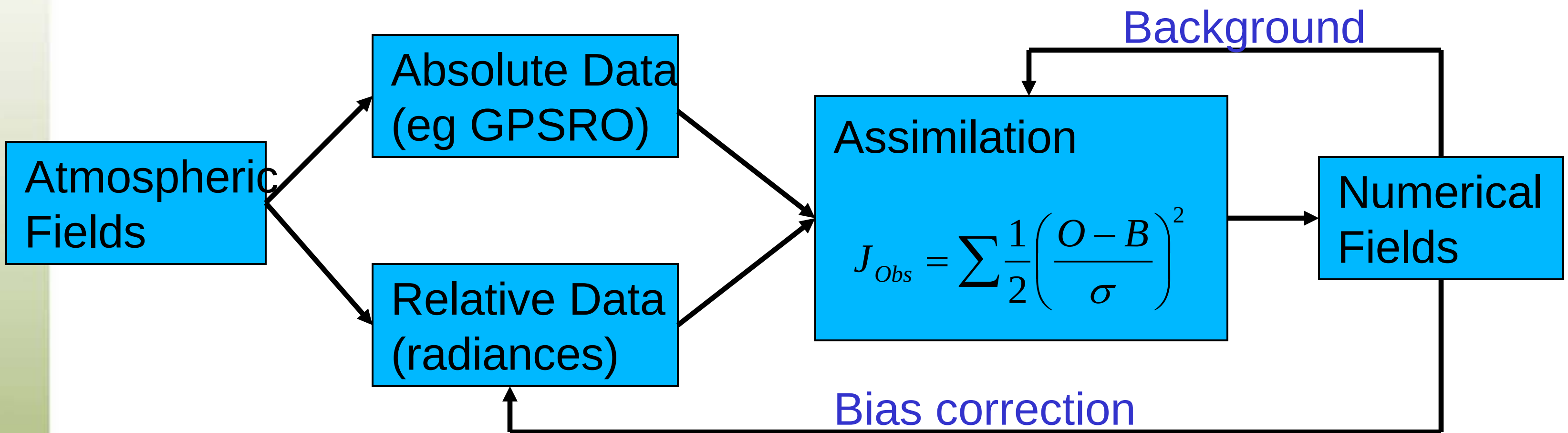
~Apparent Horizon

Bending operator can handle both refraction & surface reflection

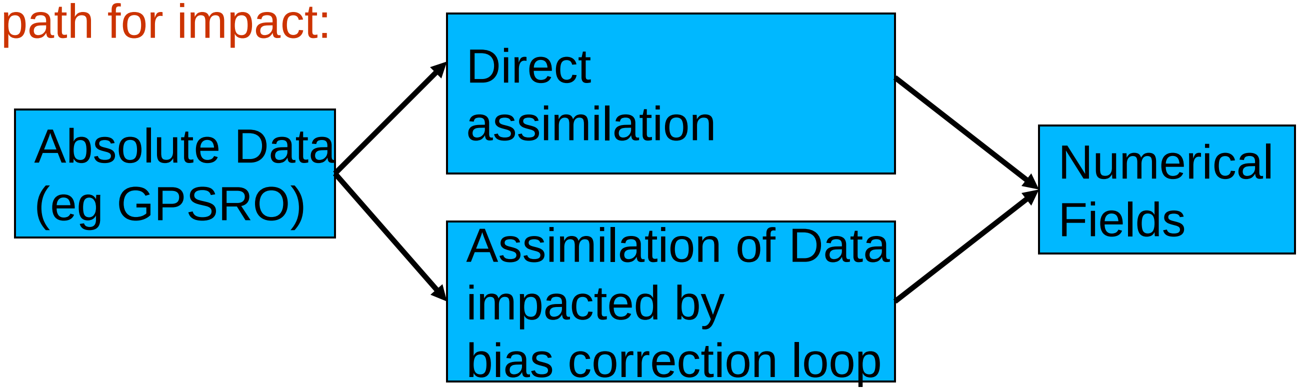
- However:
  - Standard wave optics procedures disentangle small diffraction.
    - Small multipath
  - Do they disentangle reflections?
    - Large multipath (**still entangled after backpropagation**)

- **Concern: Can upstream Doppler-to-bending processing handle true multipath?**

Information flow from data

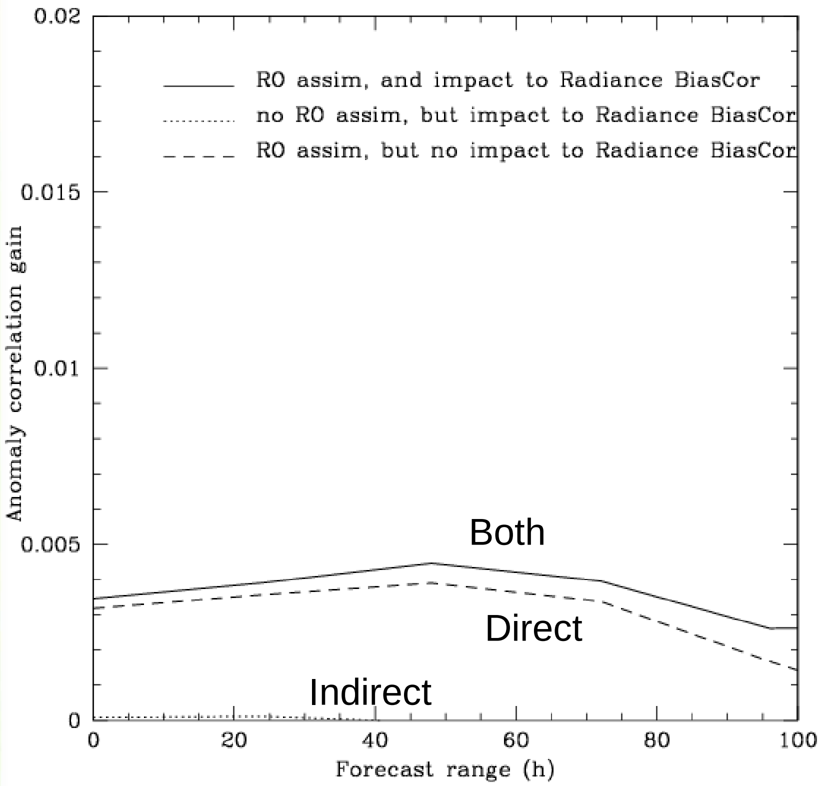


Double path for impact:

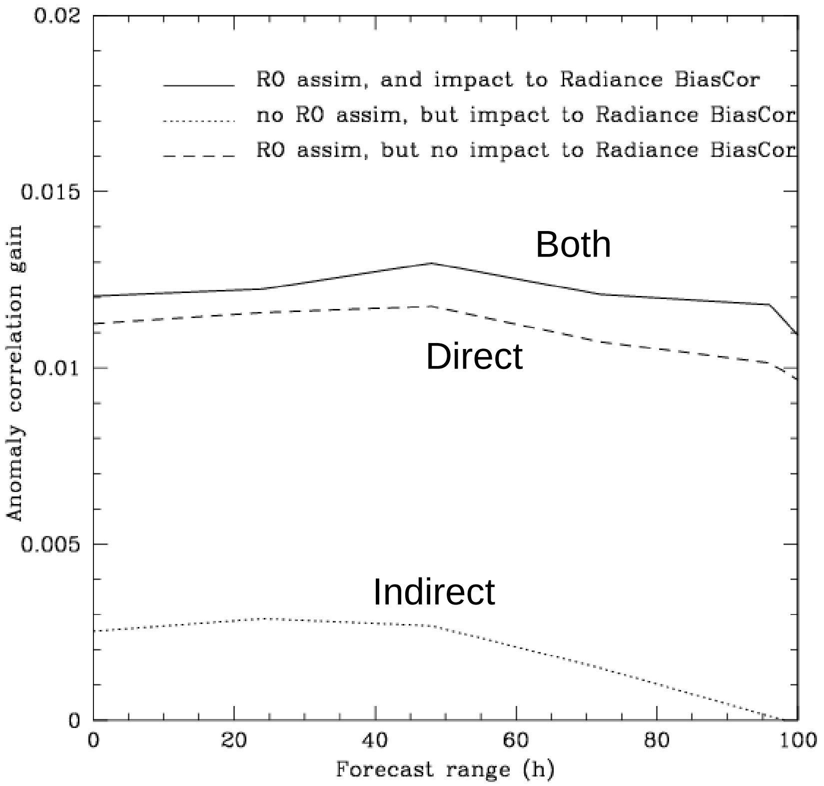


Direct and indirect impact
Temp 100hPa

AC Gain, Northern Extratropics



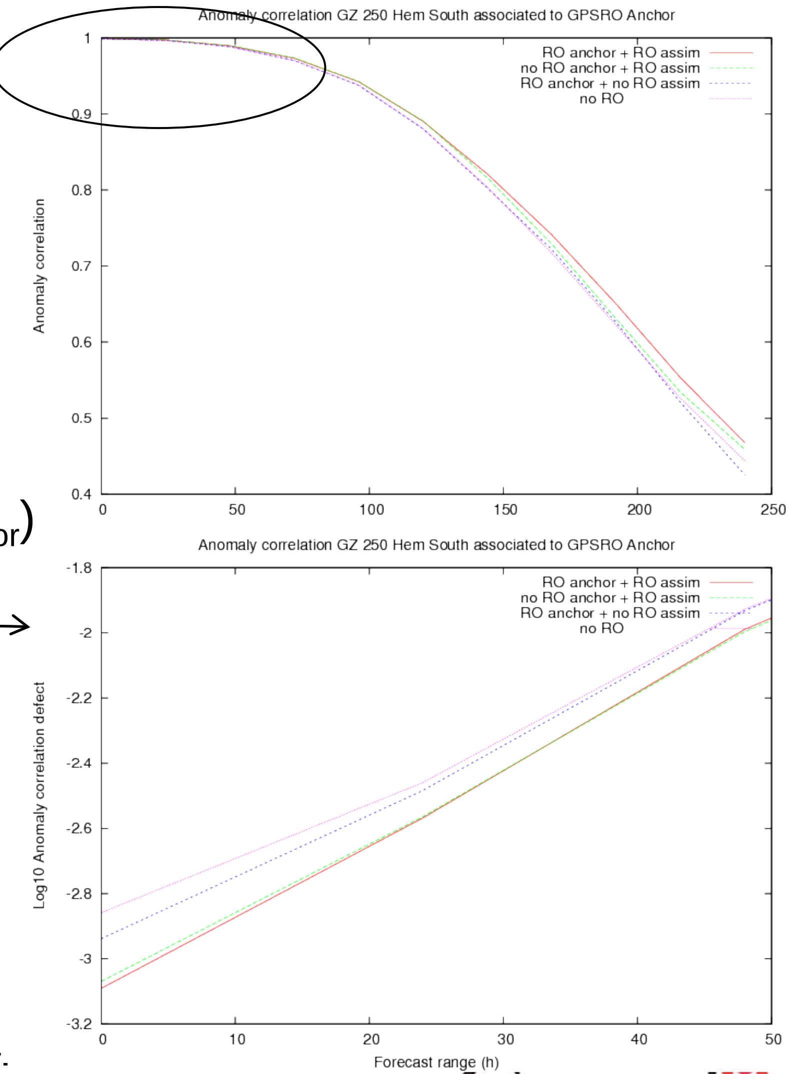
AC Gain, Southern Extratropics



GPSRO as anchor: Predictive gain

- Bias corr subsystem
  - Coefficients estimated upon "trustable" data (RS, surface, aircraft, RO)
- 4 Runs (approx what will oper this summer)
  - Full system
  - RO withdrawn from trustable subset, but kept in analysis
  - RO kept in trustable subset, withdrawn from analysis
  - RO denied

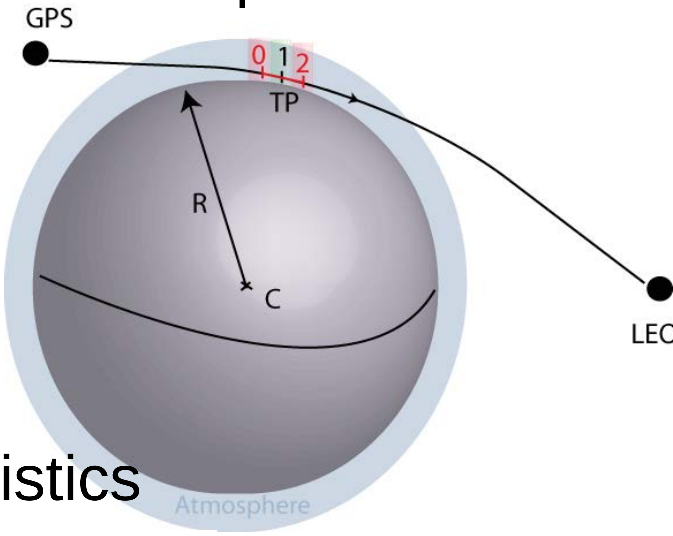
$\log_{10}(1\text{-}A_{cor})$



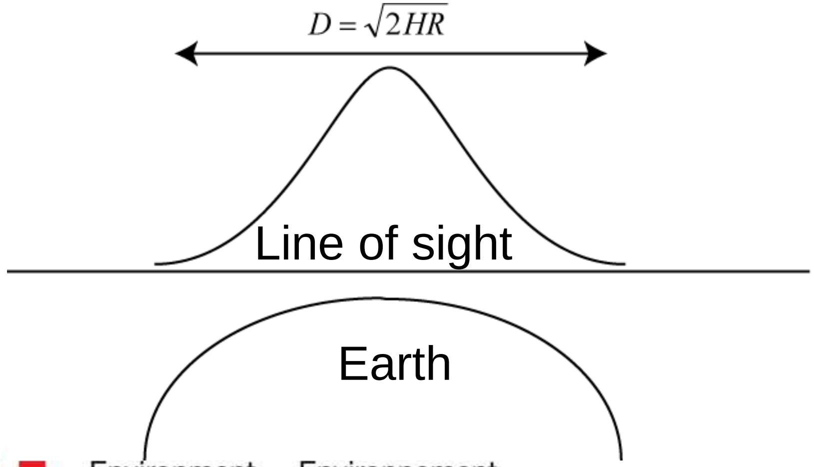
GZ 250 Hem S

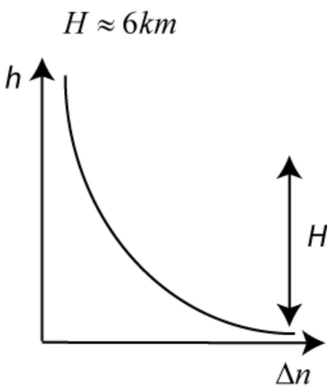
Our approach

- How atmospheric gradients have been computed ?
  - Along the ray (1D operator)
  - Location of RO profiles (1) deduced from atmprf files: *observable*
  - Atmospheric profiles location (0-2)



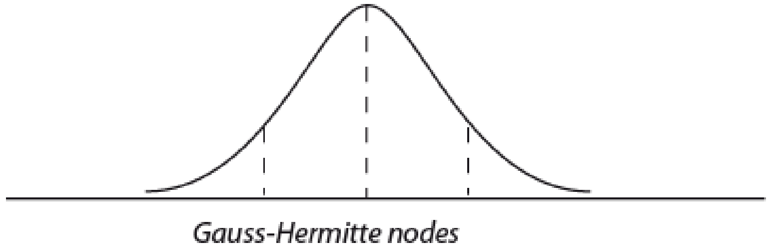
- Gradients and refractivity characteristics

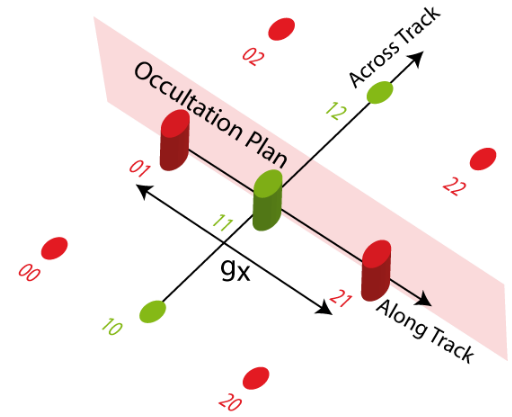




Our approach

- Characteristic size of the Gaussian region (250km)





- 3rd order Gauss-Hermitte quadrature
  - Cheapest simplification of a quasi-gaussian to 3 points

Occultation plan coordinates extracted from atmPrf files

- Along track gradients are then computed with the background refractivity field from Environment Canada model

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Approach for horizontal gradients

Provider-retrieved bending vs impact **assume** no gradient.

We **do** have a background value.

Dependence depends only on generic satellite geometry (simple)

Can be forward modeled from

– 1D operator results (a_0, α_0)

and

– background value of g=dN/dx along line of sight

- $a = a_0 + \frac{da}{dg} g$
- $\alpha = \alpha_0 + \frac{d\alpha}{dg} g$

Critical perspective I

- Physical choices are user-side recommendations
  - Equation of state
  - Refractivity
  - Gravity acceleration
  - Careful geometry
- Anchoring properties are “nice to know” and support GPSRO as a technology within the Global Earth Obs System…
- Recommendations to providers as user?
  - Do offer **provider error estimates**
  - **All of α, a, N, h** have errors (not only α, N)
  - To consider: Can hard multipath be handled? Should?

Critical perspective II

- At Env Canada we still assimilate Refractivity
  - Not fashionable, but still peaks performance for us (because of adaptive error? Limits to the representativity of vert gradient?)
  - Not assimilated as individual data, but as **profiles**
- Refractivity data should be understood as increments
  - **Not absolute refractivity** (we do not have absolute N)
  - Provider-side Abel integral more accurate than user-side's
    - **Valid** product **if** not misused
- Low atmosphere dominated by small scale structure
  - better use bending
    - Injects info at higher vertical wavenumber
    - Can handle reflection data

Critical perspective III (Our plan)

- Keep profile-oriented assimilation (not datum-oriented)
- Can we use a mixed approach?
  - Both bending and refractivity vectors used (not double assim!)
  - Info injection in upper atmosphere at low wavenumber
    - through thick layers (N increments, not N!)
  - Info injection in low troposphere at high wavenumber
    - through thin layers (Bending, reflection)
- Is hard multipath a problem?
  - Multipath that does not resolve with backpropagation/similar.
- Horiz Gradients:
  - **Large scale** (smooth) gradients tractable (Boniface et al, IROWG-2)
    - We do plan to include these
  - With small structure: technologically **impractical for ops** in near future

Thank you

- The presenter acknowledges support from EUMETSAT's Radio Occultation Meteorology Satellite Applications Facility (ROM SAF)