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The absolute calibration of GPSRO and its application in NWP

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The tolerance to bias (in NWP) : 1

Standard view within the GPSRO community:

- “GPSRO is self-calibrating, unbiased”

But outside the community, users may ask:

- 1: Is it true?
- 2: Is it verifiable?
- 3: Includes a “user manual”?
(i.e. set of procedures to realize the accuracy)

Many measurements in NWP (radiances) are much more biased (10x-100x)

- But nobody is claiming that they are unbiased
- Radiances are somehow allowed to “float” and adjust (bias correction)
- **By claiming no-bias** GPSRO has been given responsibility to
 - Guarantee that it is itself unbiased (is it true?)
 - Guarantee that radiances are unbiased (they are anchored, largely to GPSRO)

The tolerance to bias (in NWP) : 2

- From an **NWP user** perspective, the no-bias claim means:

“Sufficiently unbiased to avoid degrading forecast performance”

$\text{bias/std} \leq 1/10 \text{ or } 1/20$ ($\text{std} \sim 0.5\%$ → **bias < 0.02-0.05%**)

- **No-bias requirement stronger with increasing precision**
- Window of optimum forecast quality is very narrow
 - Verified in different ways at EC, ECMWF, NCEP.

→ The question is not simply use (or not) GPSRO

→ A careful procedure to minimize bias is required

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Treaceability of GPSRO

- Chain of measurements related through physically understood relationships, to within a given accuracy, linked to a fundamental property.

- For GPSRO:

TAI – GPS Ground segment - GPS clocks – Receivers – Refractivity - Atmosphere

1

2

3

4

5

-Links 1-2 outside GPSRO community

-Link 3 a hardware issue

-Links 4-5 fall within the retrieval/user community

-Link 5 (Refractivity-Atmosphere) is the weakest

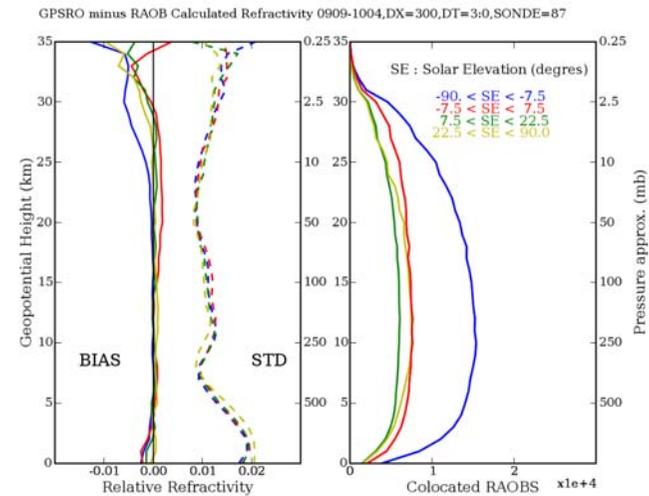
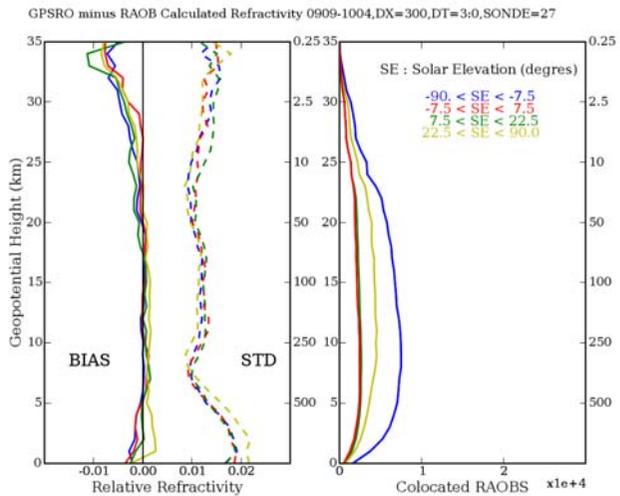
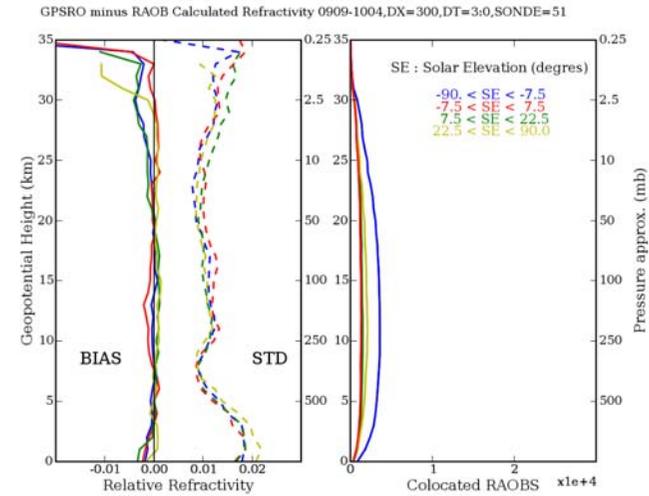
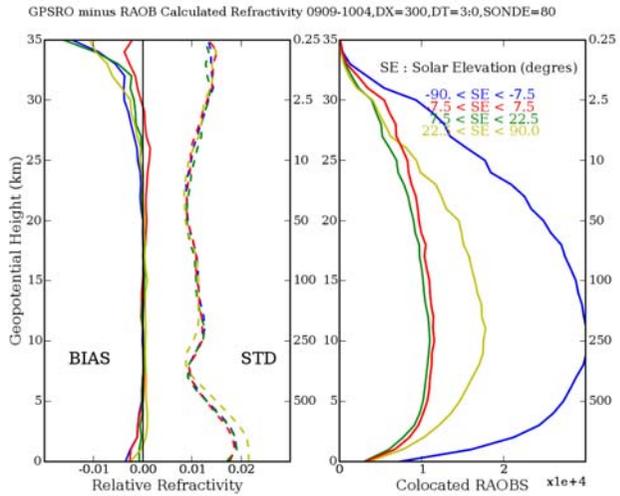
Estimated bias?

- GPSRO is very precise

enough to be limited by systematic biases in the links



Agreement of several « anchors »



The Refractivity-Atmosphere link

- Measurement is $N(\vec{x})$
 - Or equivalent $N(h)$, $\alpha(a)$ or other
- Interpreted as field of (P,T,q)
- Required
 - Refractivity expression $N \leftrightarrow (P,T,q)$
Local relationship (thermodynamic)
 - Structure of the atmosphere $\vec{x} \leftrightarrow (P,T,q)$
Nonlocal (hydrostatic eqn, etc)

Note: NWP Obs operators must include **both relationships**



Current situation

- Standard procedures accurate to $\sim 0.1\%$
 - Differences between expressions are of this size
 - Raw measures' precision not fully exploited
 - Except known low tropo bias ($\sim 10x$)
- Verified that GPSRO is beneficial
 - Operational in many NWP centers
 - In most cases, assumed unbiased
 - Naively, if std $\sim 0.5\%-1\%$, a bias $\sim 0.1\%$ may seem ok

BUT

- Verified that it is not yet optimal
 - Choosing one or another procedure impacts fcst performance
 - Not only a constant bias, but **also long term std**
 - Hint: millions of data/day: std disappears, bias accumulates
 - Not negligibly small compared vs benefit of GPSRO
- Objective: revise procedures
 - New target: systematic bias $\sim 0.01\%$
 - Would be safe for full exploitation of raw data

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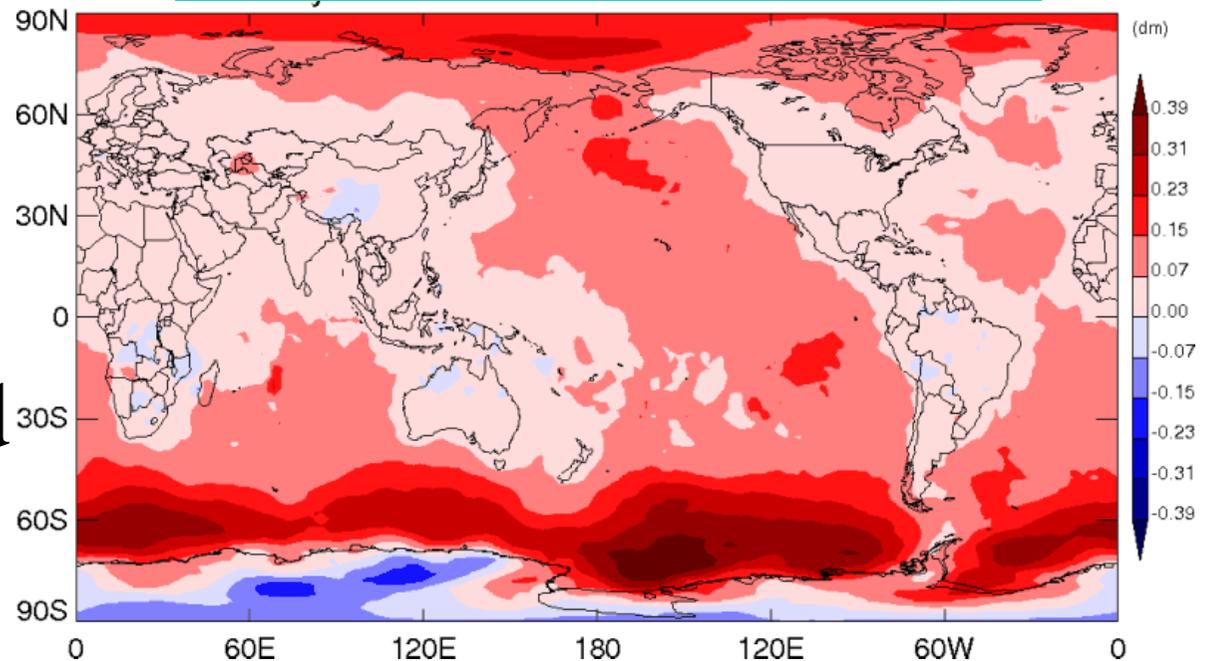
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Variability

- Different setup shows where GPSRO has more impact, and its size

- CNTL RU02
- RES0: Proposed refractivity

Average GZ 850hPa (RES0-CNTL)

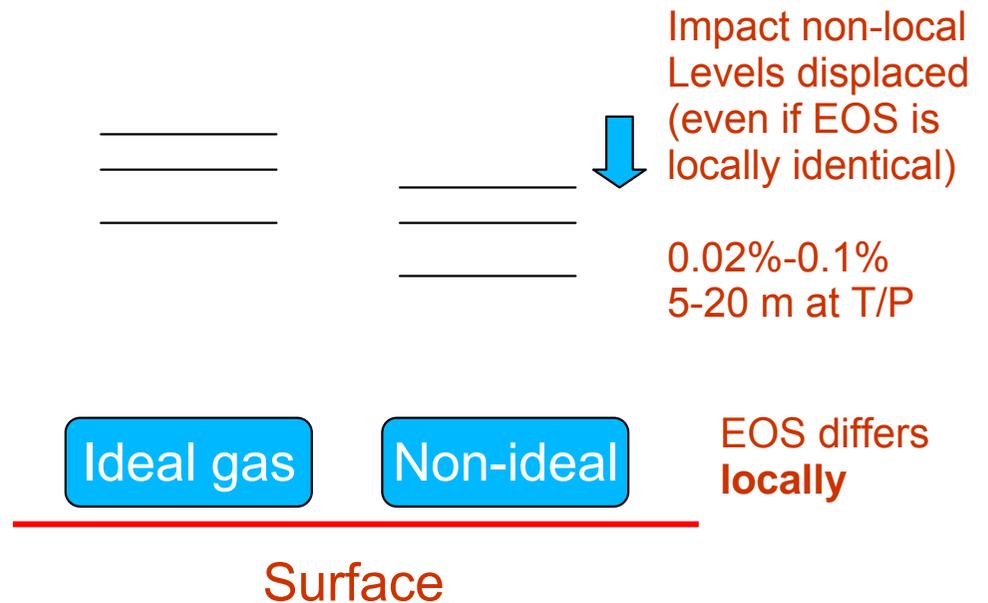


1: Structure of the atmosphere

- Essentially, the hydrostatic equation
- We need there the equation of state (EOS)
- Already found that the deviation of EOS from ideal is non-negligible
- **Non-local**
- 0.05% relevant for NWP if **systematic** (affects the anchor of radiances)

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

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



2: Refractivity expression

- Local $N(P,T,x)$
- Band of expressions within 0.1%
 - We already know that systematic biases of [0.01%-0.1%] do not simply translate to small fcst bias but **affect fcst precision**
(long term accuracy, tested with GPSRO by EC, ECMWF, NCEP)

Suspected (ECMWF, NCEP) that the classical expression

requires recalibration

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

- We undertook this recalibration with
 - Theoretical modeling (microscopic/macroscopic relationships)
 - Selection of high precision data (broad range of measurements)

Refractivity expression

- Refraction index:
$$n = \sqrt{\epsilon_r \mu_r}$$
 - Function of the electric and magnetic responses of the material
 - Molecular polarizability
 - Electric dipoles
 - Molecular magnetizability
 - Magnetic dipoles
$$\epsilon_r \equiv 1 + \chi_e \approx 1.0006 - 1.0009$$
$$\mu_r \equiv 1 + \chi_m \approx 1.0000004$$
- Approximately:
 - Rough estimates:
 - Electric refractivity:
 - Magnetic refractivity:
$$N \equiv 10^6(n-1) \approx \frac{1}{2}10^6(\chi_e + \chi_m)$$
$$N_e \approx 300 - 450$$
$$N_m \approx 0.2$$

Dry air refractivity

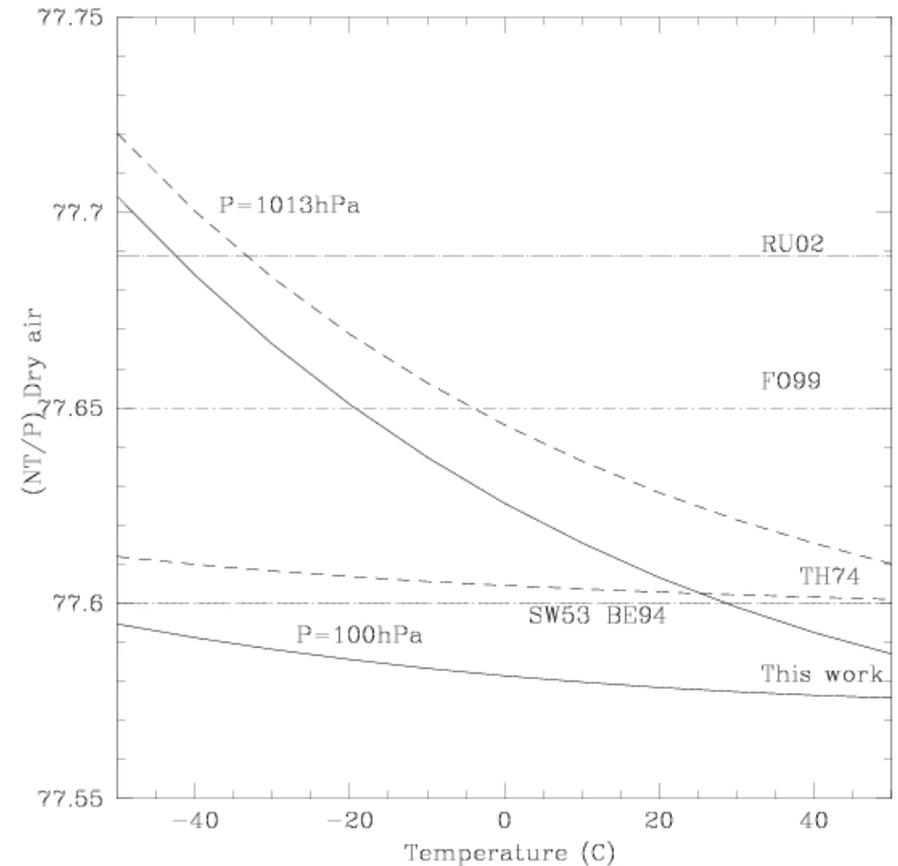
What is normally called k_1
(NT/P for dry air)

Not a constant

No constant would fit to
better than 0.1% rms
(max err up to 0.2%)

Higher at

- low T
- high P



WV refractivity

WV Partial pressures only well defined in an ideal gas

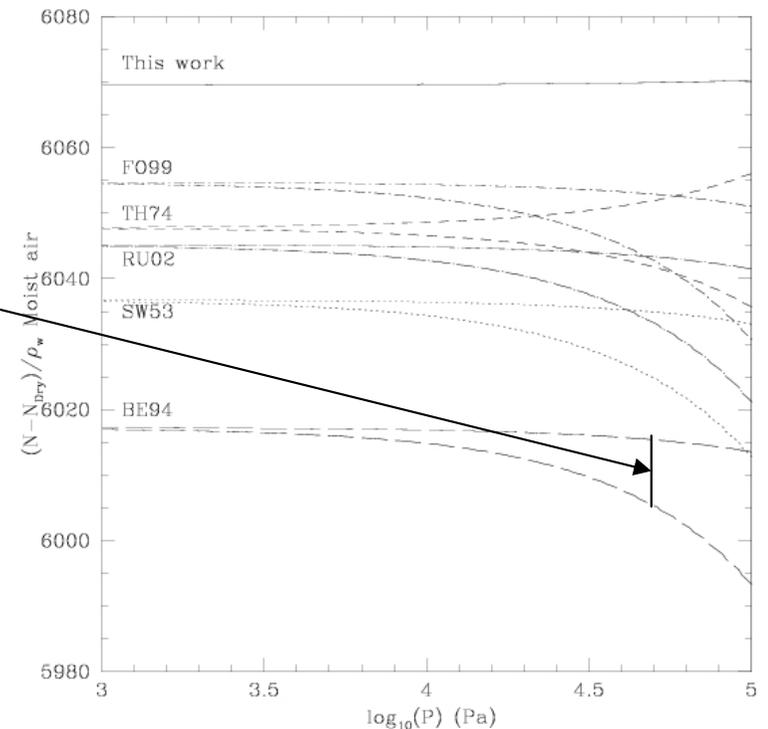
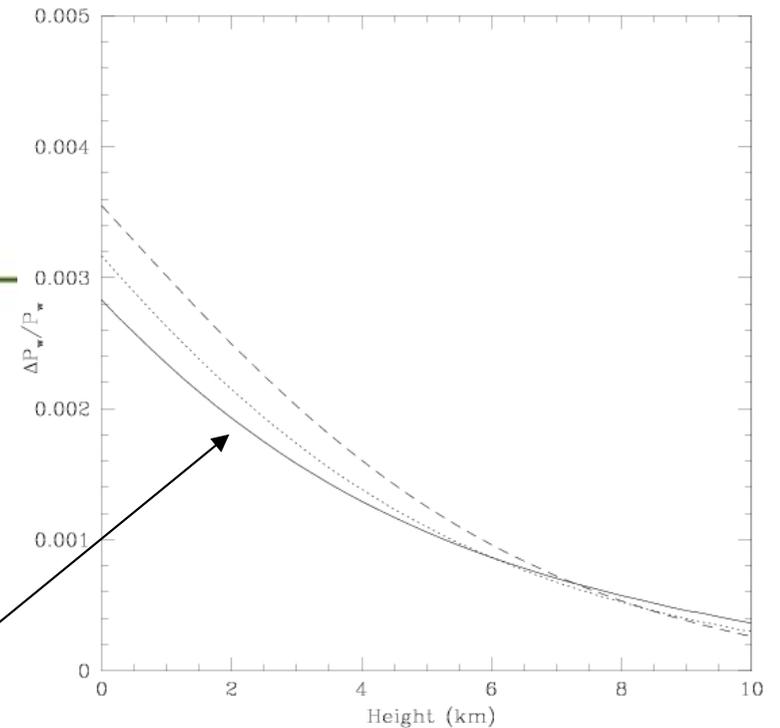
$$P_w = x_w P$$

$$P_w = P - P_{dehydrated}$$

Both amounts differ

Wet refractivity at 25C

Available expressions are not uniquely defined



Proposed setup

Hydrostatic equation

- Should consider
- EOS should include compressibility

$$g(\lambda, h)$$

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

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

Pr oposal :

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

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

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

Thank you!



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