Developments on the interpretation and assimilation of GPSRO data at Environment Canada

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Outline

• Considerations around unbiased observations
• Realization of GPSRO as a calibrated source
  – Quality of our knowledge
  – Air compressibility
  – Expression of refractivity
• Exploration of calibration’s forecast value
  – Direct value
  – Indirect value through radiance bias correction
The Numerical Weather Prediction (NWP) Objective

• To track the atmosphere numerically:
  – Atmospheric field (AF, external)
  – Numerical field (NF, we control it)

• Tools
  – Correction of the numerical field (=assimilation of measurements)
  – Time propagator of the numerical field (=forecast model)

• Therefore:
  – We have established a link AF→NF
    ▪ Actually (AF → Obs → NF)
  – We want this link to be as strong as possible
2 kinds of Observations

Absolute:
- We can state the accuracy of their calibration with high degree of confidence (more than our system)
  - Eg. Radiosondes, GPSRO, some aircraft and surface data
  - We tell the system to trust the observations (Obs → NF)
  - Strengthens coupling (AF → Obs → NF)

Relative:
- The calibration is less known (less than our system)
  - Notably, radiances (vast amount of data)
  - We establish a bias-correction procedure.
  - We tell observations to trust the system (NF → Obs)

Then:
- Radiances and numerical field end strongly coupled
  - Bidirectional coupling (Obs → NF) and (NF → Obs)
- But actual objective (Numerical Field and Atmosphere) more weakly coupled
  - Coupled by physics and absolute observations
Information flow from data

Atmospheric Fields

Absolute Data (eg GPSRO)

Relative Data (radiances)

Assimilation

\[ J_{\text{Obs}} = \sum \frac{1}{2} \left( \frac{O - B}{\sigma} \right)^2 \]

Background

Numerical Fields

Bias correction

Double path for impact:

Absolute Data (eg GPSRO)

Direct assimilation

Assimilation of Data impacted by bias correction loop

Numerical Fields
Absolute observations

Impact the numerical field directly
- numerical field should trust absolute observations
- \((\text{AF} \rightarrow \text{absObs} \rightarrow \text{NF})\)

Also impact indirectly:
- relative observations should trust the field
- \((\text{AF} \rightarrow \text{absObs} \rightarrow \text{NF} \rightarrow \text{relObs} \rightarrow \text{NF})\)
- Feedback loop

Then
- Absolute observations have
  - Larger impact
  - Higher responsibility
The tolerance to bias (in NWP) : 1

Standard view within the GPSRO community:
• “GPSRO is self-calibrating, unbiased”

But:
  – 1: Is it true?
  – 2: Is it verifiable?
  – 3: Does it require a careful procedure? (to realize the accuracy)

Most measurements in NWP (radiances) are more biased (10x-100x)
  – But nobody is claiming that they are not
  – They don’t receive the responsibility to calibrate other data
The tolerance to bias (in NWP) : 2

• From an **NWP user** perspective, the no-bias claim means:
  “Sufficiently unbiased to avoid degrading forecast performance”

• Window of optimum forecast quality is very narrow
  – Verified in different ways at EC, ECMWF, NCEP.
  – Width of this window about 0.05% \((O-B)/B\)

• Not so surprising:
  – GPSRO injects information at fractional levels around 0.5% \((O-B)/B\), leaving little room to accept a bias
Traceability of GPSRO

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

- For GPSRO:
  
  - 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

- GPSRO is very precise
  enough to be limited by systematic biases in the links
Agreement of several « anchors »

Coincident (>10^4) GPSRO vs several RS types, at several sun elevations
The Refractivity-Atmosphere link

- Measurement is \( N(\tilde{x}) \)
  - 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 \( \tilde{x} \leftrightarrow (P,T,q) \)
    - Nonlocal (hydrostatic eqn, etc)

Note: NWP Obs operators must include both relationships
1: Structure of the atmosphere

- Essentially, the hydrostatic equation
  \[ \nabla P = -g(\bar{x})\rho \]

- 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)

Impact non-local
Levels displaced (even if EOS is locally identical)
0.02%-0.1%
5-20 m at T/P

EOS differs locally

**Ideal gas**  **Non-ideal**

Surface
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

\[
N = k_1 \frac{P_d}{T} + k_2 \frac{P_w}{T} + k_3 \frac{P_w}{T^2}
\]

• We undertook this recalibration with
  – Theoretical modeling (microscopic/macroscopic relationships)
  – Selection of high precision data (broad range of measurements)
Dry air refractivity

What is normally called k1 (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 not even well-defined in a non-ideal gas

Is it:

\[ P_w = x_w P \]

\[ \text{or} \]

\[ P_w = P - P_{\text{dehydrated}} \]

Or even another?
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

**Proposal:**

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

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

\[ \tau = 273.15 / T - 1 \]
Forecast impact of the calibration I

- Different implementations of GPSRO calibration
  - Our first (RU02)
  - Our refined (see former viewgraphs, AL11)
  - Other tests (SW53)
- Good tropospheric temperatures at stake
Forecast impact of the calibration II

RS Temperatures (World AVG)

- **Bias correction**
  - Each RO implementation blocked/allowed to calibrate radiances

- Blocking/allowing (DYN) bias correction feedback loop between implementations

- Impact smaller, but comparable to differences between calibrations

- Indirect impact of RO assimilation comparable to direct impact
Forecast impact of the calibration III

- We use NO-GPSRO as reference
- Blocking/allowing (DYN) bias correction feedback loop between implementations
- Impact comparable to differences between calibrations
- Indirect impact of RO assimilation comparable to direct impact
GPSRO denial test

- **Cycles**
  - Best estimate, with its own bias correction
  - No GPSRO assimilation, but bias correction from best estimate retained
  - No GPSRO assimilation, and bias correction recalculated
Conclusion

• As calibrated data, GPSRO has
  – Direct impact (entered in the cost function)
  – Indirect impact (anchors radiance bias correction)

• Both impact paths have forecast value

• Different calibrations lead to different fcst performance

• Indirect impact smaller than direct, but comparable

For both reasons:
• A careful revision of intercalibration recommended for optimal results
Thank you!