Representation of vertical atmospheric structures by RO observations –
Comparison of high resolution RO and radiosonde profiles

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Outline

• Representation of vertical structures above the tropopause

• Representation of vertical structures at the tropopause

• Representation of vertical structures with L2C
Vertical resolution of RO data

Geometric Optics (GO): diffraction limitation

A ray is refracted according to Snell’s law.

\[ d_F = \frac{2\sqrt{\lambda D}}{\sqrt{1 - D \frac{d\alpha}{da}}}, \quad D \sim 30020 \text{ km} \]

\[ \Rightarrow d_F \sim 0.5 - 1.5 \text{ km} \]

Wave Optics (WO): sub-Fresnel Resolution

Principle of synthetic aperture, \( f(t) = \sum_j A_j(t)\exp(i\Psi_j(t)) \)

Mortensen et al. [1999]: \( \sim 100 \text{ m (simulation)} \)

Gorbunov et al. [2004]: \( \sim 60 \text{ m (analytical estimation)} \)

Tsuda et al. [2011]: \( \sim 150 \text{ m (spectral analysis)} \)
Motivation

Question:
Down to what scale the GPS RO realistically represents the vertical structure in the UTLS?

Plan:
To compare the UTLS temperatures retrieved by WO from GPS RO with those from high resolution RAOBs,
i) By applying high-pass filtering and calculating the cross-correlation between filtered RO and RAOB;
ii) By testing different approaches for ionospheric correction (IonCorr) (including the use of L2C).
High-resolution dataset - RAOB

- Vertical Resolution: 5 – 10 m
- Temperature accuracy: 0.5 °C

<table>
<thead>
<tr>
<th>Type</th>
<th>Manufacturer</th>
<th>Temperature Sensor</th>
<th>Site Radiation Correction</th>
<th>Native Resolution (s)</th>
<th>Temperature Resolution (°C)</th>
<th>Temperature Accuracy (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMS Mark IIA</td>
<td>Sippican</td>
<td>Chip thermistor</td>
<td>Solar</td>
<td>1</td>
<td>0.1</td>
<td>±0.5 (2σ)</td>
</tr>
<tr>
<td>RS06G</td>
<td>Meisei</td>
<td>Rod thermistor</td>
<td>Solar</td>
<td>1</td>
<td>0.1</td>
<td>±0.5 (2σ)</td>
</tr>
<tr>
<td>RS92</td>
<td>Vaisala</td>
<td>Thin-wire F-Thermocap</td>
<td>Solar &amp; IR</td>
<td>1-2</td>
<td>0.1</td>
<td>±0.5 (2σ)</td>
</tr>
<tr>
<td>M2K2-DC</td>
<td>Modem</td>
<td>Bead thermistor</td>
<td>Solar &amp; IR</td>
<td>1</td>
<td>0.1</td>
<td>±0.5 (2σ)</td>
</tr>
</tbody>
</table>
**RO data sets and processing schemes**

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>V13 (Standard)</th>
<th>V16 (high-res)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>GO</td>
<td>GO</td>
</tr>
<tr>
<td></td>
<td>WO for L1 (100m)</td>
<td>WO for L1 (100m)</td>
</tr>
<tr>
<td>20</td>
<td>GO</td>
<td>LC = L1 + c₄⟨L4⟩</td>
</tr>
<tr>
<td></td>
<td>WO for L1 (500m)</td>
<td>LC = L1 + c₂⟨L4⟩_{ext}</td>
</tr>
</tbody>
</table>

where \( c₁ = \frac{f₁^₂}{f₁^₂ - f₂^₂} \approx 2.5457, \quad c₂ = \frac{f₂^₂}{f₁^₂ - f₂^₂} \approx 1.5457, \langle \rangle \) means smooth, L₄=L₁-L₂
High-resolution dataset – RO V16

For different collocated RO and collocated RO & RAOB:

- well agreement achieved on the large-scale structures (tropopause, inversion layer @ 12 km);

- correlation for small-scale structures decreases with height
Correlation of highpass filtered temperatures from RAOB and RO_V16
Lagged correlation coefficient between high-pass filtered RO and RAOB

Cross-correlation coefficients between high-pass filtered temperature profiles at 20-27 km for collocated RO and RAOB, as functions of lag (-0.5, 0.5 km) and filter window (0.1, 2.0 km)
Maximum correlation coefficient (COEF) between high-pass filtered RO and RAOB

293 RO and RAOB pairs @ 100 km & 1 hr

Accepting COEF > 0.5 as statistically significant, filter window **0.5 km is optimal** in the sense:

- $w > 0.5$ km would result in degradation of the resolution in **some** ROs;
- $w < 0.5$ km would result in excessive noise propagation in **all** ROs.
Impact of the vertical resolution on the cold point tropopause parameters

When filter window width increases from 0.01 to 1 km:
- Tropopause temperature increases linearly with the increase of filter window width (up to ~ 1.4 K).
- For multiple local temperature minima, this may result in jumping of the tropopause height between the minima.
- Tropopause height is slightly changing with the filter window.
Impact of the vertical resolution on the cold tropopause parameters

<table>
<thead>
<tr>
<th></th>
<th>V13 (Standard)</th>
<th>V16 (High-resolution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition height between GO &amp; WO</td>
<td>20 km</td>
<td>30 km</td>
</tr>
<tr>
<td>Filter window for L1 BA (WO)</td>
<td>500 m</td>
<td>100 m</td>
</tr>
</tbody>
</table>

- **Tropopause Temperature**
  - R13 = 0.971, M13 = 0.593, STD13 = 1.089
  - R16 = 0.970, M16 = -0.009, STD16 = 1.122

- **Tropopause Height**
  - R13 = 0.817, M13 = -0.073, STD13 = 0.595
  - R16 = 0.809, M16 = -0.010, STD16 = 0.614
The use of L2C signal (pros and cons)

- less noisy, less susceptible to tracking errors than L2P in the presence of scintillation.
- In V13/V16 may result in slightly smaller noise.
- In VL2C with the application of WO processing for both L1 and L2 at 100 m resolution:
  -- May allow better elimination of the small-scale ionospheric effects using the classical IonCorr without additional smoothing of L4;
  -- May result in larger errors due to diffraction effects by the small-scale structures;
  -- The overall error balance is not clear (under investigation)

<table>
<thead>
<tr>
<th>Signal</th>
<th>SNR (V/V)</th>
<th>Type</th>
<th>Tracking Mode</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1CA</td>
<td>800</td>
<td>Un-encrypted</td>
<td>PLL above &amp; OL below</td>
<td>Stable</td>
</tr>
<tr>
<td>L2P</td>
<td>200</td>
<td>encrypted</td>
<td>Semi-codeless PLL above &amp; not tracking below</td>
<td>Noisy, unstable</td>
</tr>
<tr>
<td>L2C</td>
<td>500</td>
<td>Un-encrypted</td>
<td>PLL above &amp; OL below</td>
<td>More stable</td>
</tr>
</tbody>
</table>

Sokolovskiy et al. [2014]
## RO data sets and processing schemes

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>V13 (Standard)</th>
<th>V16 (high-res)</th>
<th>VL2C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L2P &amp; L2C</td>
<td>L2P &amp; L2C</td>
<td>L2C only</td>
</tr>
<tr>
<td>80</td>
<td>Go</td>
<td>Go</td>
<td>WO for L1 &amp; L2C (100m)</td>
</tr>
<tr>
<td>30</td>
<td>Go</td>
<td>Go</td>
<td>WO for L1 (100m)</td>
</tr>
<tr>
<td>20</td>
<td>Go</td>
<td>( LC = L1 + c_2 (L4) )</td>
<td>( LC = L1 + c_2 (L4) ) or ( LC = L2 + c_1 (L4) )</td>
</tr>
<tr>
<td></td>
<td>WO for L1 (500m)</td>
<td>( LC = L1 + c_2 (L4)_{\text{ext}} )</td>
<td>N/A (in this study)</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where \( c_1 = \frac{f_1^2}{f_1^2 - f_2^2} \approx 2.5457 \), \( c_2 = \frac{f_2^2}{f_1^2 - f_2^2} \approx 1.5457 \), \( \langle \quad \rangle \) means smooth, L4=L1-L2
Filter window for L4=L1-L2

Two schemes:

(1) \( \alpha = \alpha_1 + c_2(\alpha_1 - \alpha_2) \)

(2) \( \alpha = \alpha_2 + c_1(\alpha_1 - \alpha_2) \)

With the increase of filter window width for L4:

- STD of ion-free BA (1) generally continuously decreases;
- STD of ion-free BA (2) quickly drops to its minimum @ w=0.3 km, then slightly increases and remains about constant

- Effect of thermal Noise: decrease
- Small-scale ionospheric residual: increase
- Diffraction effect caused by the small-scale ion structure: increase

(1) gives a smaller minimum STD compared to (2)
Filter window for L4=L1-L2

Two schemes:

1. \( \alpha = \alpha_1 + c_2(\alpha_1 - \alpha_2) \)

2. \( \alpha = \alpha_2 + c_1(\alpha_1 - \alpha_2) \)

- STD of (1) persistently decreases with filter window for L4
- STD of (2) constantly reaches the minimum @ w=0.3 km and shows slightly fluctuation after that
- Minimum STD of (1) is typically smaller than the one from (2)
- Optimal filter window for L4 would be 700 m if using (1) or 300 m if using (2) for ion_corr

Maximum correlation coefficient (COEF) between high-pass filtered RO (VL2C) and RAOB

20 RO with L2C and RAOB pairs @ 100 km & 1 hr

\[ \alpha = \alpha_1 + c_2(\alpha_1 - \alpha_2) \] with filter window for \( \alpha_1 - \alpha_2 \) of 700 m
Conclusions

• Based on comparison to high resolution RAOBs, we found that the effective resolution in the UTLS is \(\sim 500\) m, lower than the physical vertical resolution of WO-processed RO \(\sim 100\) m.

• At the tropical tropopause, the effective resolution of RO is close to the physical resolution, \(\sim 100\) m.

• When using RO data for monitoring the tropopause or GWs above the tropopause, the data should be smoothed (filtered) with windows of \(100\) m or \(500\) m.

• The use of RO with L2C, by applying WO processing for both L1 and L2, does not improve the effective resolution in the UTLS.