Remote Sensing of Cloud Top Heights using the Research Scanning Polarimeter

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Motivation

- Cloud top height (CTH) is critical for the Research Scanning Polarimeter (RSP) when studying:
  - cloud thermodynamic phase
  - particle size distributions
  - asymmetry parameter
- Interested in exploring the RSP’s ability to sense multiple cloud layers
- Models indicate that cloud height increases in a warming climate result in a positive cloud-height feedback
- Global-scale observations of CTH changes have yielded uncertain results

IPCC, 2013
Research Scanning Polarimeter

• Prototype for Aerosol Polarimetry Sensor on the Glory satellite (2011)
• Along track scanning - 152 viewing angles per scene (±60°)
• 14 mrad field of view (~280 m on ground from 20 km alt.)
• Polarimetric and full intensity measurements in the visible and shortwave infrared over 9 bands:
  • 410, 470, 555, 670, 864, 960, 1593, 1880, 2263 nm for aerosols and clouds
  • 1880 nm for high-altitude measurements
Measurements

- **RSP:** using 2 channels: 1880 nm & 670 nm
- **Cloud Physics Lidar (CPL)**
  - 30 m vertical resolution
  - Accurate up to an optical depth of ~3.0
- Data products used: cloud top height, cloud bottom height, extinction, layer classification (aerosol, cloud, PBL)
- Data used in this analysis was collected over 9 days during the NASA SEAC^4RS experiment
  - August 6\(^{th}\), 21\(^{st}\) and September 2\(^{nd}\), 4\(^{th}\), 11\(^{th}\), 13\(^{th}\), 16\(^{th}\), 18\(^{th}\) and 22\(^{nd}\) 2013

Photo credits (top): Carla Thomas
• Uses the concept of *parallax*.
• Distance from a stationary object is related to the displacement when observed from different viewing angles.
• Accurate knowledge of the geometry of the instrument and position of the aircraft is essential for stereo reconstruction.
RSP Measurements

Viewing Angle

Time
Multilayer Sensing

- Take a set of consecutive measurements
- Calculate the correlation between this set and equal sized sets at other viewing angles
Multilayer Sensing

• Take a set of consecutive measurements
• Calculate the correlation between this set and equal-sized sets at other viewing angles
• Calculate the same correlation for aggregated offsets ranging from 0-20 km
**Multilayer Sensing**

- Take a set of consecutive measurements
- Calculate the correlation between this set and equal sized sets at other viewing angles
- Calculate the same correlation for aggregated offsets ranging from 0-20 km
Multilayer Sensing

- Take a set of consecutive measurements
- Calculate the correlation between this set and equal-sized sets at other viewing angles
- Calculate the same correlation for aggregated offsets ranging from 0-20 km
Multilayer Sensing

• Take a set of consecutive measurements
• Calculate the correlation between this set and equal-sized sets at other viewing angles
• Calculate the same correlation for aggregated offsets ranging from...
Results

1880 nm channel
Results

670 nm channel
Results

Dual channel
Results

Differences and Cloud Height

- Abs RSP CLH Difference [km]
  - CPL CTH

- Number of Points
  - CPL CTH [km]

Legend:
- Layer 1
- Layer 2
- Layer 3
- 1880 nm band
- 670 nm band
- Dual band
Correlation for 1\textsuperscript{st} and 2\textsuperscript{nd} peaks
Results

1880 nm band

- Correlation cutoff: 0.0, 0.35, 0.60
- 5-17 km
  - 1\textsuperscript{st} peak median error: 0.43 km
  - 2\textsuperscript{nd} peak median error: 1.71 km
  - 3\textsuperscript{rd} peak median error: 2.49 km
670 nm band

• Correlation cutoff: 0.0, 0.45, 0.60
• 1-13 km
  • 1<sup>st</sup> peak median error: 0.57 km
  • 2<sup>nd</sup> peak median error: 2.16 km
  • 3<sup>rd</sup> peak median error: 3.02 km
Results

Dual band

- Correlation cutoff: 0.0, 0.25, 0.60
- 1-15 km
  - 1<sup>st</sup> peak median error: 0.45 km
  - 2<sup>nd</sup> peak median error: 1.67 km
  - 3<sup>rd</sup> peak median error: 2.66 km
Summary

• Possible to use the RSP to retrieve multilayered cloud scenes
• Method works well for optically thin clouds (<0.05)
• The 1880 nm, 670 nm and dual bands consistently retrieve primary layer heights
• The dual band method is the most robust at determining multilayered scenes

Future Work
• Study the effect of using less angular measurements and degrading the spatial resolution
• Determine the magnitude of the effect of the object changing shape or position during the overpass (~3 minutes)
### Thresholds

<table>
<thead>
<tr>
<th>Threshold</th>
<th>1880 nm</th>
<th>670 nm</th>
<th>Dual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Top or Middle</td>
<td>Middle</td>
<td>Middle</td>
<td>Middle</td>
</tr>
<tr>
<td>Minimum COT</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Minimum cloud height</td>
<td>5.0 km</td>
<td>1.0 km</td>
<td>1.0 km</td>
</tr>
<tr>
<td>Maximum cloud height</td>
<td>17.0 km</td>
<td>13.0 km</td>
<td>15.0 km</td>
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<tr>
<td>1st Peak Minimum Static Correlation</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>2nd Peak Minimum Static Correlation</td>
<td>0.35</td>
<td>0.45</td>
<td>0.25</td>
</tr>
<tr>
<td>3rd Peak Minimum Static Correlation</td>
<td>0.50</td>
<td>0.60</td>
<td>0.60</td>
</tr>
</tbody>
</table>

### Performance

<table>
<thead>
<tr>
<th></th>
<th>1880 nm band</th>
<th>670 nm band</th>
<th>Dual Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Median Error [km]</td>
<td>0.43</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Np</td>
<td>105467</td>
<td>107476</td>
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<td>2nd</td>
<td>Median Error [km]</td>
<td>1.71</td>
<td>2.16</td>
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<tr>
<td></td>
<td>Np</td>
<td>74170</td>
<td>75310</td>
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<tr>
<td>3rd</td>
<td>Median Error [km]</td>
<td>2.49</td>
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<tr>
<td></td>
<td>Np</td>
<td>40307</td>
<td>30805</td>
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</table>
## Cloud Top vs Cloud Middle

<table>
<thead>
<tr>
<th></th>
<th>1880 nm band</th>
<th></th>
<th>670 nm band</th>
<th></th>
<th>Dual Band</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
<td></td>
<td>2nd</td>
<td></td>
<td>3rd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CPL Cloud Top</td>
<td>CPL Cloud Middle</td>
<td>CPL Cloud Top</td>
<td>CPL Cloud Middle</td>
<td>CPL Cloud Top</td>
<td>CPL Cloud Middle</td>
</tr>
<tr>
<td>Median Error [km]</td>
<td>0.52</td>
<td>0.47</td>
<td>0.63</td>
<td>0.58</td>
<td>0.53</td>
<td>0.48</td>
</tr>
<tr>
<td>Mean Error [km]</td>
<td>1.07</td>
<td>1.00</td>
<td>1.67</td>
<td>1.52</td>
<td>1.19</td>
<td>1.08</td>
</tr>
<tr>
<td>Np</td>
<td>87447</td>
<td>87447</td>
<td>76262</td>
<td>76262</td>
<td>86223</td>
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<tr>
<td>Std. Dev.</td>
<td>2.03</td>
<td>1.91</td>
<td>2.91</td>
<td>2.83</td>
<td>2.28</td>
<td>2.18</td>
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<tr>
<td>Corr. Coeff.</td>
<td>0.86</td>
<td>0.86</td>
<td>0.79</td>
<td>0.79</td>
<td>0.85</td>
<td>0.86</td>
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</table>
Number of Cloud Layers

**Table 1: 1880 nm band RSP cloud scene fractions compared with CPL**

<table>
<thead>
<tr>
<th>RSP Scenes</th>
<th>Fraction</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 layer</td>
<td>0.32</td>
<td>0.1</td>
<td>0.46</td>
<td>0.27</td>
<td>0.12</td>
<td>0.04</td>
<td>0.01</td>
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<tr>
<td>2 layer</td>
<td>0.30</td>
<td>0.06</td>
<td>0.41</td>
<td>0.30</td>
<td>0.15</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>3 layer</td>
<td>0.37</td>
<td>0.05</td>
<td>0.40</td>
<td>0.31</td>
<td>0.16</td>
<td>0.07</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Table 2: 670 nm band RSP cloud scene fractions compared with CPL**

<table>
<thead>
<tr>
<th>RSP Scenes</th>
<th>Fraction</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 layer</td>
<td>0.37</td>
<td>0.11</td>
<td>0.48</td>
<td>0.25</td>
<td>0.11</td>
<td>0.04</td>
<td>0.01</td>
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<tr>
<td>2 layer</td>
<td>0.36</td>
<td>0.10</td>
<td>0.44</td>
<td>0.27</td>
<td>0.13</td>
<td>0.04</td>
<td>0.01</td>
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<tr>
<td>3 layer</td>
<td>0.27</td>
<td>0.04</td>
<td>0.41</td>
<td>0.31</td>
<td>0.15</td>
<td>0.04</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Table 3: Dual band RSP cloud scene fractions compared with CPL**

<table>
<thead>
<tr>
<th>RSP Scenes</th>
<th>Fraction</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 layer</td>
<td>0.31</td>
<td>0.12</td>
<td>0.53</td>
<td>0.23</td>
<td>0.08</td>
<td>0.03</td>
<td>0.01</td>
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<tr>
<td>2 layer</td>
<td>0.31</td>
<td>0.09</td>
<td>0.43</td>
<td>0.28</td>
<td>0.13</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>3 layer</td>
<td>0.38</td>
<td>0.05</td>
<td>0.40</td>
<td>0.31</td>
<td>0.16</td>
<td>0.07</td>
<td>0.02</td>
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