Ground-based temperature and humidity profiling using microwave radiometer retrievals at Sydney Airport.

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ABSTRACT
The aim of this study was to verify whether the ground based Radiometer Physics GmbH (RPG) Humidity And Temperature PROfiler (HATPRO) microwave radiometer (MWR) is suitable for use in Australian conditions. The reliability and accuracy of the atmospheric temperature and relative humidity profiles retrieved by the MWR were assessed.

A comparison of the MWR profiles with radiosonde soundings (RS) was conducted at Sydney Airport, Australia. The HATPRO has two measurement modes: full troposphere temperature and humidity profiles, up to 10km; and a boundary layer temperature profile, up to 1.2km. Each of the variables and measurement modes were analysed separately.

WMO requirements for observation of physical variables were used to assess the usefulness of the HATPRO profiles for specific purposes. When there is no precipitation, the HATPRO relative humidity profile below 800m is useful for local observations, forecasts and synoptic aerological observations. The HATPRO boundary layer temperature profile has some value for assimilation into Global Numerical Weather Prediction (NWP) models below 3km; additionally, the boundary layer temperature profile would also benefit aviation services, particularly below 3km.

1 Introduction
Temperature and humidity profiles play an important role in meteorological forecasts and the safety and efficiency of aviation services. Currently most major Australian airports rely on radiosonde (RS) flights to provide this information. RS flights provide accurate and reliable measurements of atmospheric temperature and relative humidity. However due to limitations in frequency, RS are released twice daily at most sites, they are inadequate to detect changing conditions.

The HATPRO MWR's can provide almost continuous temperature and humidity profiles of the lowest 10km of the atmosphere. This can be useful for the detection of changes in local conditions such as temperature inversions and fog. Various studies have evaluated the accuracy of MWR profiles (Hewison & Gafford, 2003) (Lohnert, et al., 2009) (Lohnert & Maier, 2012) (Xu, et al., 2015) however as the performance of any MWR is location specific, these results cannot be taken as representative of the HATPRO MWR's performance in Australian conditions.

2 Description of Radiometer
MWRs perform measurement of thermal emission from the down welling brightness temperature in the atmosphere. Most commercial units operate in the 20–60 GHz frequency range, in which atmospheric thermal emission is influenced by atmospheric temperature, humidity and the presence of hydrometeors. Atmospheric thermodynamic profiles can be retrieved using a variety of inversion methods, such as multivariate regression and neural networks (Cimini, et al., 2014). The HATPRO MWR has a steerable parabolic mirror, covered by a microwave transparent radome; this ensures that radiation from ±90° elevation can be received by the MWR.
2.1 Retrieval of Atmospheric Variables

The RPG HATPRO provides temperature and humidity profiles in the lowest 10km of the atmosphere. The HATPRO samples the brightness temperatures within two bands: 7 channels in the water vapour band (22-28 GHz); and 7 channels in the oxygen band (50-59 GHz). An artificial neural network (ANN), trained using RS atmospheric profiles, retrieves the humidity profile and temperature profiles (RPG, 2014). The performance of ANN is limited by the quality and range of atmospheric conditions in the training data set. The Sydney ANN retrievals algorithms were produced from the ~2 500 low-resolution RS flights. The Sydney retrieval algorithms, and hence the performance of the HATPRO MWR, could be improved by acquiring retrieval algorithms produced by a larger, and/or a higher resolution, set of RS flights.

2.2 Measurement Modes

The HATPRO has two measurement modes: Full Troposphere (TR) profiling; and Boundary Layer (BL) profiling. Both profiling modes output Air Temperature (AT), Absolute Humidity (AH) and Relative Humidity (RH) measurements at 93 heights between 0 and 10km. The resolution of the profile decreases with height.

2.2.1 Full Troposphere Profiling

Full troposphere profiling uses brightness temperatures taken from the zenith angle only. It provides AT, AH and RH profiles, below 10km, approximately every 90s. The AH profiles were not used in this study.

2.2.2 Boundary Layer Profiling

Boundary layer profiling scans angles between 5° and the zenith. The brightness temperature measurements from the various angles are combined to provide an AT profile below 1.2km. The AT profile from the BL scan (0 - 1.2km) and the most recent TR scan (0-10km) are combined and smoothed to produce a composite temperature profile (0-10km). The BL scan takes approximately 5 minutes. In this study, BL scans were taken once every 15 minutes.

3 Data

The study was conducted at Sydney Airport from 18 August 2015 to 29 February 2016. The HATPRO was located at an elevation of 9m and 50m from the coast.

Radiosonde flights are release from Sydney Airport daily at 6am local time, occasionally a second RS is release later in the day on forecaster request. A typical RS flight takes a Pressure, AT and RH reading every 2s (10-15 metres). The RS takes approximately 30 minutes to reach 10km, during this period the HATPRO takes approximately 13 TR and 2 BL profiles.

RS measurements were matched both spatially and temporally to the HATPRO measurements. This ensured that no measurements are used twice, and there is approximately the same number of data points for each HATPRO profile height.
4 Methodology

The analysis of each atmospheric variable (AT and RH) was conducted separately. The HATPRO uses a rain sensor to detect a reduction in the quality of data caused by intense rain. This information is coded into the rain flag variable (RPG, 2014). All measurements with an active rain flag were excluded from this study.

4.1 Bias and RMS

RS data is used to calculate the Mean Difference (Bias) and Root Mean Square Difference (RMS) of HATPRO measurements for AT and RH at each HATPRO profile height (H_MWR). The calculations of Bias and RMS for AT profiles are shown below.

\[
Bias = \frac{1}{n} \sum_{1}^{n} (AT_{HATPRO} - AT_{RS})
\]

\[
RMS = \sqrt{\frac{1}{n} \sum_{1}^{n} (AT_{HATPRO} - AT_{RS})^2}
\]

4.2 Accuracy Requirements

The WMO Observation Requirements outline three levels for uncertainty:

- "Threshold" (minimum requirement for useful data)
- "Goal" (ideal requirement above which further improvement is not required)
- "Breakthrough" (intermediate level which results in significant improvement)

The uncertainty requirements are dependent on the intended application. The uncertainty requirements for AT for: Aeronautical Meteorology; and Global NWP in the lower troposphere; are shown in Table 1.

The RH uncertainty requirements are included in the WMO Observation Requirements. The Goal and Threshold values for RH are taken from WMO CIMO Guide (WMO, 2008) performance limits for aerological instruments measuring humidity. These values are the same for local weather dependent operations, forecasts and synoptic observations. The Breakthrough value for RH has been set at a reasonable value between the Goal and Threshold values.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Use</th>
<th>Goal</th>
<th>Breakthrough</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>Aeronautical</td>
<td>2K</td>
<td>3K</td>
<td>5K</td>
</tr>
<tr>
<td>AT</td>
<td>Global NWP</td>
<td>0.5K</td>
<td>1K</td>
<td>3K</td>
</tr>
<tr>
<td>RH</td>
<td>Aerological</td>
<td>3%</td>
<td>10%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Table 1: WMO uncertainty requirements (WMO, 2016)
5 Results

5.1 Bias and RMS

The study includes 214 RS flights. Figure 1 shows the biases and RMSs for HATPRO RH and AT measurements compared to RS measurements.

5.1.1 Relative Humidity
The HATPRO TR RH plots in Figure 1 show that:

- the RH biases are smaller than ±5% below 4.5km;
- the RH RMSs are never better than 5%;
- the RH RMSs increase rapidly in from 8% to ~18% between 0 and 1.5km;
- the RH RMSs increase slowly from 18% to 25% between 1.5 and 4.5 km; and
- the RH RMSs decreasing slightly between 4.5 and 10km.

5.1.2 Atmospheric Temperature

The HATPRO TR AT plots in Figure 1 show that the:

- the biases are smaller than ±0.5K between 0.5 and 5km;
- the RMS are between 1.0K and 1.5K below 3km; and
- the RMSs steadily increase from 1.5K (at 3km) to 3K (at 10km).

The HATPRO BL AT plots in Figure 1 show that in general the HATPRO BL AT profiles are better that the TR AT profiles. The BL AT biases and RMSs are better than the TR AT profile at a majority of profile heights, the exception being between 1.8 and 3.0km. The BL AT profiles below 1.2km have biases smaller than ±0.5K and RMSs less than 1.0K, except close to the surface (H_MWR < 50m).

This is surprising as the HATPRO BL scan only provides additional data below 1.2km. As the BL profile is taken every 15 minutes, there is greater temporal difference for BL profiles. Hence, it was expected that the BL AT measurements would perform better than the TR AT measurements above 1.2km.
5.2 Accuracy Requirements

Figure 2 shows the percentages of HATPRO (TR) RH and (TR and BL) AT measurements at each HATPRO profile height (H_MWR) that meet the WMO uncertainty requirements (see Table 1) when compared to RS measurements.

Most of the WMO requirement plots follow the same general pattern for both RH and AT measurements. They are poor at the surface (H_MWR<50m); then improve between 50 and 400m; deteriorate between 400m and 1800m; briefly improve again between 1.8 and 2.0km; before slowly deteriorating between 2 and 10km.

The HATPROs retrieval algorithms use historical radiosonde data to produce weighting functions for the profiles. As the profile height increases, the retrieval algorithms have less direct inputs from the current brightness temperatures and rely more on the historical radiosonde data to estimate the atmospheric conditions. As the height increases the atmospheric profiles become based more on historical average condition than current conditions. This greatly affects the usefulness and accuracy of the HATPRO MWR with increasing height.

5.2.1 Aerological (RH)

The HATPRO RH profiles would provide some value for Aerological purposes below 800m. In this region, for each H_MWR: at least 95% of RH measurements meet the Threshold requirement; at least 50% meet the Breakthrough requirement; however, at best only 30% meet the Goal requirement.

5.2.2 Global NWP (AT) Requirements

The HATPRO TR AT profiles would provide some value to Global NWP below 3km. In this region, for each H_MWR: at least 90% of TR AT measurement meet Threshold requirement; and at least 50% meet the Breakthrough requirement.

In general the HATPRO BL AT profiles perform better that the TR profiles, especially below 1.2km. In this region, for each H_MWR: at least 50% of BL AT measurements meet the Goal requirement; at least 80% meet the Breakthrough requirement; and over 98% meet the Threshold requirement.

5.2.3 Aeronautical (AT) Requirements

The AT Aeronautical requirements are less stringent than the Global NWP requirements; hence the HATPRO AT profiles are more useful for this purpose. At the vast majority of H_MWR values over 60% of TR AT measurements meet the Goal Aeronautical requirement and over 80% meet the Breakthrough requirement. Below 3km over 80% of the TR AT measurements meet the Goal requirement.

The HATPRO BL AT profiles are even better than the TR AT profiles for Aeronautical purposes, especially below 1.2km. Between 50m and 1.2km, for each H_MWR, at least 98% of BL AT measurements meet the Goal Aeronautical requirement.

The HATPRO AT profiles below 3km are suitable for Aeronautical purposes. The HATPRO AT profiles above 3km are less reliable but are still beneficial for Aeronautical purposes.
6 Conclusions

The performance of the atmospheric profiles produced by the HATPRO microwave radiometer has been assessed by comparison to RS flights at Sydney Airport in non-precipitating conditions.

The HATPRO Full Troposphere RH profiles below 800m had biases smaller than ±5% and RMSs less than 15%; they have some value for local observations, forecasts and synoptic aerological observations.

The HATPRO Boundary Layer AT profiles performed better than the Full Troposphere AT profiles, especially below 1.2km. The HATPRO Boundary Layer AT profiles below 1.2km have biases smaller than ±0.5K and RMSs less than 1.0K; they would provide value to Global NWP and improve the safety and optimal efficiency of aviation services in this region. Despite the usefulness of the HATPRO AT profiles declining with height, they would provide benefit to Global NWP up to 3.0km and aviation services up to 10.0km.
7 References


