CONGREGATION OF VAPORS:
TOWARDS A SYNOPTIC VIEW OF WATER VAPOR IN SUPPORT OF AIRBORNE IR ASTRONOMY

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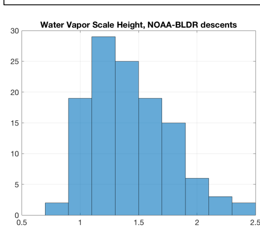
SOFIA, THE FLYING ASTRONOMICAL OBSERVATORY

- •SOFIA, the Stratospheric Observatory for Infrared Astronomy, flies between 10.7 and 13.7 km to get above most of our atmosphere's water vapor. Operational in 2014.
- •Precipitable water above flight level is typically <20 um, compared to >400 um at the best (non-Antarctic) ground-based sites in Chile
- •Besides SOFIA, only short-lived balloons or sounding can observe between wavelengths between 30 and 300 um
- •Science is to study star and planet formation, water in the cosmos, cold dust, and Solar System events for which a mobile observatory is essential.

WHY SOFIA NEEDS TO MEASURE WATER VAPOR IN FLIGHT

If the water vapor near the top of the troposphere could be seen, it might appear to the pilot or passenger of an aircraft flying just above the tropopause like the top of a fog bank – Meyer (2013)

- We're often observing WV in the cosmos while peering through the WV in our own atmosphere!
  - Atmospheres of exoplanets
  - Star and planet formation regions
- Often the tropopause is so high that SOFIA can't actually reach the stratosphere
- Nadir sensors, limb sensors, and in-situ radiosonde measurements cannot simultaneously provide the sensitivity and temporal, spatial, and vertical resolution required to calibrate SOFIA data
  - WV scale height is 1.3 +/- 0.1 km (Haas & Pfister, 1998 – HP98; our results below) so <650 m sampling is required to integrate PWV
  - WV correlation time and length at these altitudes TBD but less than several hours/few 100 km (Hurst et al., 2014)
- Goal is to apply model-based calibration to IR data using TPW measured by an on-board 183 Ghz radiometer (WVM) (Roellig et al., 2010)



HP98 UNIVERSAL MODEL

Haas & Pfister (HP 98) present a simple and universal model of MMR which we used as our starting point :

$$q(h) = \max(q_0 e^{-h/h_0}, 2.5)$$

Where
q = mass mixing ratio (MMR) in ppm
h = altitude
h_0 = WV scale height
q_0 can be calculated from the MMR at a single altitude, then the expression integrated to give TPW
-change integration variable to pressure using the standard atmosphere
-Assume h_0 = 1.3 km since this can't be measured using a single point and FPH data (left) show this to be a reasonably good value

ACKNOWLEDGEMENTS

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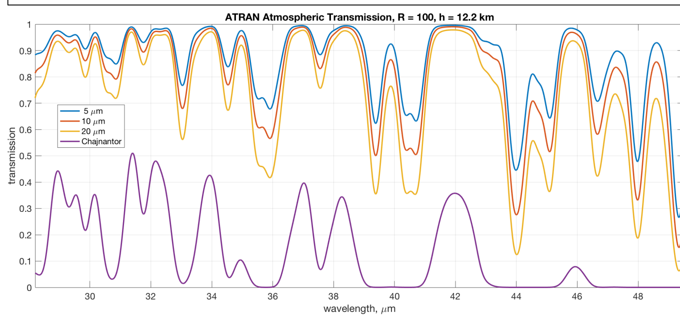
Atmospheric Science and IR astronomy Meet in the Study of Water Vapor above 9.1 km



WHY SOFIA MUST FLY HIGH AND DRY, AND MEASURE THE REMAINING TOTAL PRECIPITABLE WATER VAPOR (TPW): Atmospheric transmission to the zenith at an altitude of 12.2 km (40 kft) with varying amount of TPW smoothed to a spectral resolution R = $\lambda/\Delta\lambda$ = 100, compared to that calculated for TPW = 400 um (1st quartile winter) at the driest non-Antarctic ground-based site, the ALMA-APEX site in Chajnantor, Chile The wavelength range extends just beyond the 28 um long-wavelength cutoff of the James Webb Space Telescope (JWST), due to launch in late 2018,. The calculations were done with the ATRAN program (Lord, S. D., 1992, NASA Technical Memorandum 103957) which is made publicly for SOFIA planning https://atran.sofia.usra.edu. More advanced models which also include collision-induced absorption (Guan et al, 2012, S. Paine 2011) are used in attempts at model-based calibration.

Example Joint Question: How well can we predict Total Precipitable Water (TPW) above an altitude given only H_2O mass mixing ratio (MMR) measurements at that altitude?

- Using atmospheric models to convert WVM TPW to IR absorption corrections has not lived up to expectations.
- Cross-calibration between different bands of the same SOFIA instrument give inconsistent results (Guan et al., 2012).
- In search of new data or model insights, look for correlations between MMR and TPW in FPH data

METHOD

1. Select descent data with <10% gapped data (code -999), no gaps >= 1 km, and good data up to at least 23.5 km
2. Linearly fill gaps
3. At each altitude in a flight, Integrate MMR over pressure between the pressure at that altitude and 25 mbar and add a constant 0.8 um TPW above 25 km/25 mbar
4. For each altitude, select the MMR result at that altitude from each flight and plot TPW vs. MMR on a log-log scale.
5. After seeing that the universal HP98 model did not work well at higher altitudes, empirically fit the data to a power law (straight line on log-log plot)
6. Where HP98 gives a greater TPW at a given MMR then the power law, use HP98
7. Iterate the power law fit, excluding the points for which the power law was replaced by HP98 in the previous step
8. Fit the power low exponent and prefactor themselves to a linear function of altitude (uber fit)
9. Regression against ozone, tropopause pressure height, and temperature did not improve the results.

FUTURE JOINT QUESTIONS

1. MMR above clouds at FPH vertical resolution
2. Correlation length and time for WV between 10.7 and 13.7 km

APPLICATION to SOFIA

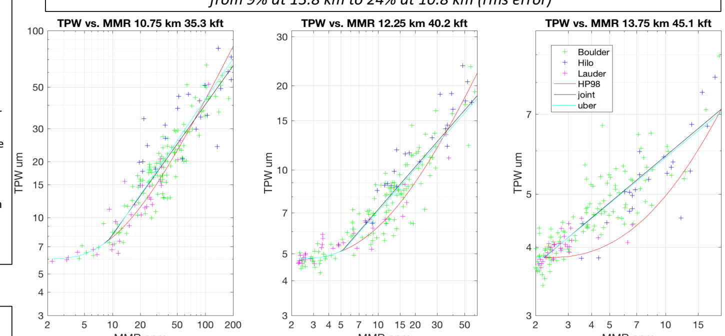
1. An aircraft FPH (Buck Instruments CR-2) and possibly other instruments, similar to the successful IAGOS-CARIBIC package (Brenninkmeijer , 2007) for commercial airliners, would allow SOFIA to serve atmospheric science as well as astronomy.
2. The FPH could serve as a backup and cross-check on the WVM microwave measurents
3. Having FPH and WVM data from the same flight could test atmospheric models to be used for calibration

NOAA FROST POINT HYGROMETER (FPH)

- FPH measures water vapor in-situ up to 28 km with a vertical sampling of 250 m
- Accuracy <0.5 ppm or 10% H_2O MMR under upper troposphere/lower stratosphere (UTLS) conditions
- Monthly launches from Boulder, Lauder NZ, and Hilo under mostly clear conditions.
- Use both ascent and descent data, but the descent is a little more trustworthy since then there is no condensation contamination from the balloon train.
- Ongoing reconsideration of ascent data cleanliness and launch weather criteria
- Data public at https://www.esrl.noaa.gov/gmd/ozwv/wvap/

RESULT

In clear skies or above light cirrus, TPW can be predicted from MMR and altitude to an accuracy from 9% at 13.8 km to 24% at 10.8 km (rms error)



Example plots for various altitudes showing correlation of TPW vs. MMR at fixed altitude for all FPH descent data from all 3 stations. The joint fit is the maximum of HP98 and a power-law fit to the data at fixed altitude. The uber fit reduces the number of free parameters in the joint fit by letting the power-law prefactor and exponent themselves be simple functions of altitude. The RMS scatter of the data around the uber fit in the middle panel is 15%. At the lowest MMRs, the uber, joint, and HP98 fits are indistinguishable and appear as the cyan line.

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this most excellent canopy the air, look you, this brave o'er hanging firmament, this majestical roof, fretted with golden fire: why, it appeareth no other thing to me, than a foul and pestilent congregation of vapours – Hamlet