

The SOFIA Water Vapor Monitor

Tom Roellig

With contributions from

- Allan Meyer, Jeff Van Cleve, Lunming Yuen, and Len Pfister (Ames)
- Dale Hurst and Emrys Hall (NOAA-Boulder)
- Ed Teets and Fran Becker (NASA-Armstrong Meteorology)
- Thierry Leblanc (JPL Table Mountain)

*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, Infrared Astronomer of Denmark*

SOFIA Teletalk July 6, 2016

Talk Outline

- Introduction to water vapor in the stratosphere
- The design of the SOFIA Water Vapor Monitor
- Calibrating the WVM
- Use of WVM data in the SOFIA data pipelines
- Plans forward

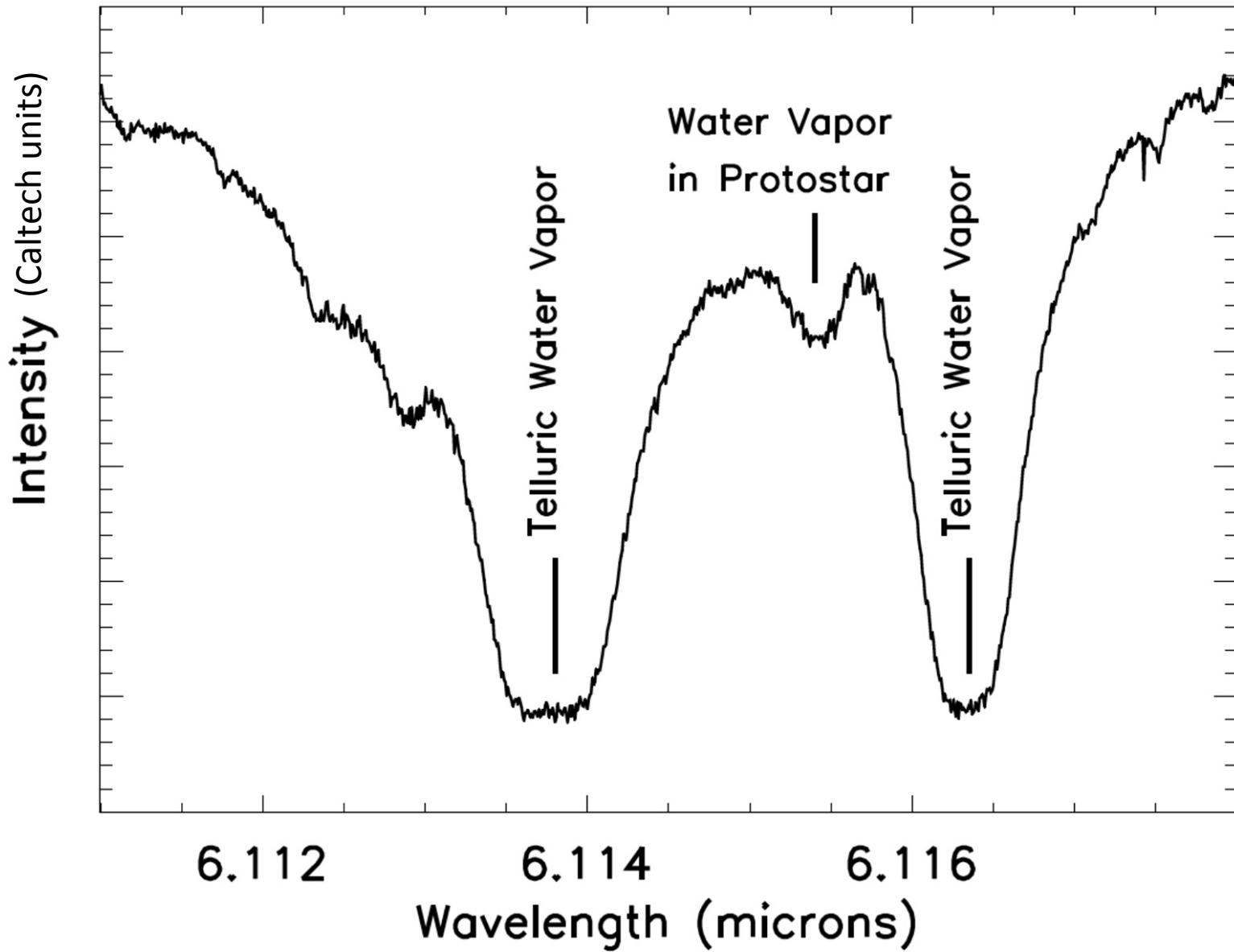
Water Vapor: As Above, So Below

- SOFIA, the *Stratospheric* Observatory for Infrared Astronomy, flies between 35-45 kft to get above most of our atmosphere's water vapor (WV)
 - 20x times more WV above the best Chilean ground-based sites on a median night than above SOFIA on a poor night.
- Often, we are interested in precisely those wavelengths where the small amount of WV above SOFIA (“zenith WV” or zWV) is still important, because WV itself is so important in the cosmos
 - Atmospheres of exoplanets
 - Star and planet formation regions
- On many flights, especially summer and in the tropics, the tropopause is so high that our stratospheric observatory can't reach the stratosphere
- So there's often “weather” above SOFIA's flight altitude, and zWV needs to be measured at the time and place of the observation in order to efficiently calibrate SOFIA's data and achieve our required 20% photometric accuracy.



Tropopause – altitude at which air temperature stops decreasing with height, forming a barrier to WV and weather
zWV -- the depth of water in a column of the atmosphere above a certain altitude, same as “precipitable water” or “water vapor overburden”

H₂O detected by EXES in the high-mass protostar AFGL 2591

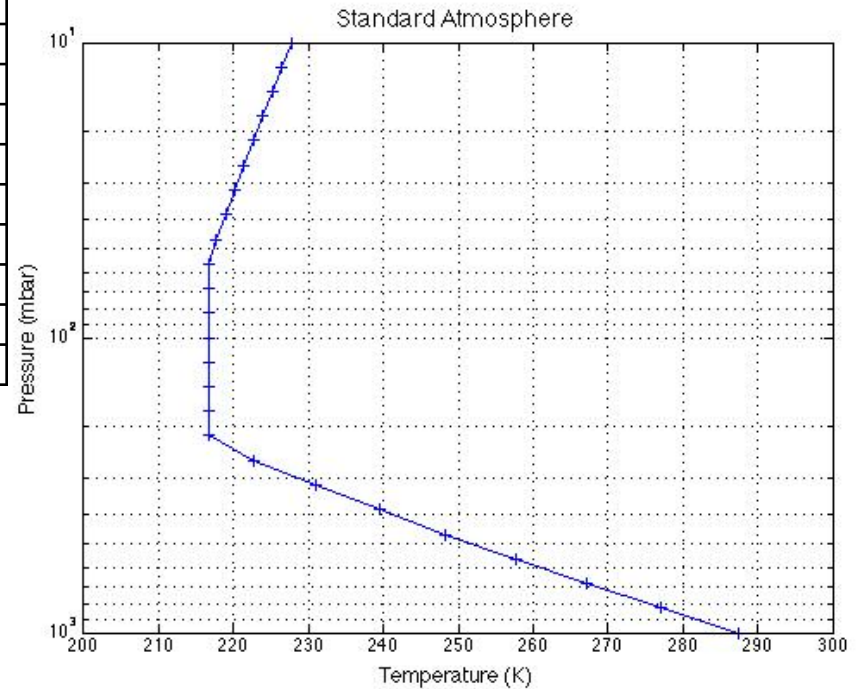
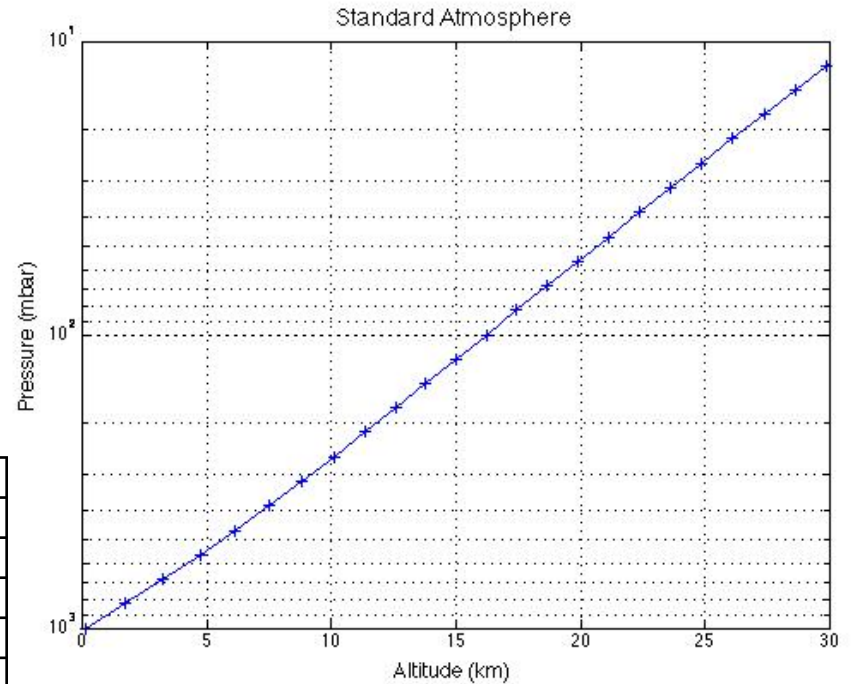


Standard Atmosphere

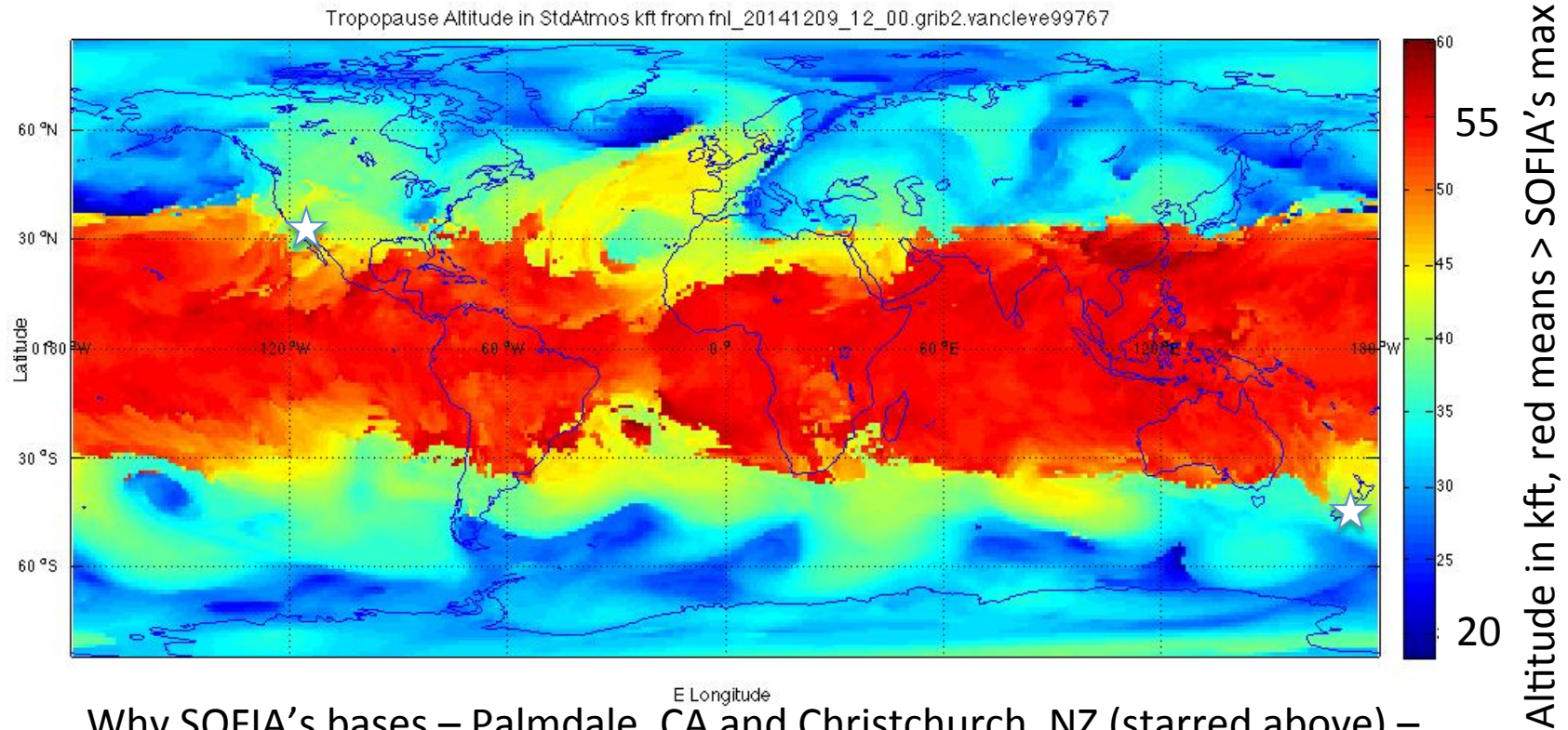
from MATLAB program stdatmo by Sky Sartorius

GOES levels			
km	kft	P (mbar)	T
16.22	53.2	100	217
15.33	50.3	115	217
14.31	46.9	135	217
13.64	44.7	150	217
11.81	38.7	200	217
10.38	34.0	250	221
9.18	30.1	300	229
8.13	26.7	350	235

SOFIA flight levels			
km	kft	P (mbar)	T
9.1	30.0	301	229
9.5	31.0	288	227
9.8	32.0	275	225
10.1	33.0	263	223
10.4	34.0	251	221
10.7	35.0	239	219
11.0	36.0	228	217
11.3	37.0	217	217
11.6	38.0	207	217
11.9	39.0	197	217
12.2	40.0	188	217
12.5	41.0	179	217
12.8	42.0	171	217
13.1	43.0	163	217
13.4	44.0	155	217
13.7	45.0	148	217



The Tropopause is Above SOFIA in Almost Half the World!



Why SOFIA's bases – Palmdale, CA and Christchurch, NZ (starred above) – are > 30 degrees from the Equator

Tropopause Height Varies with Latitude and Season

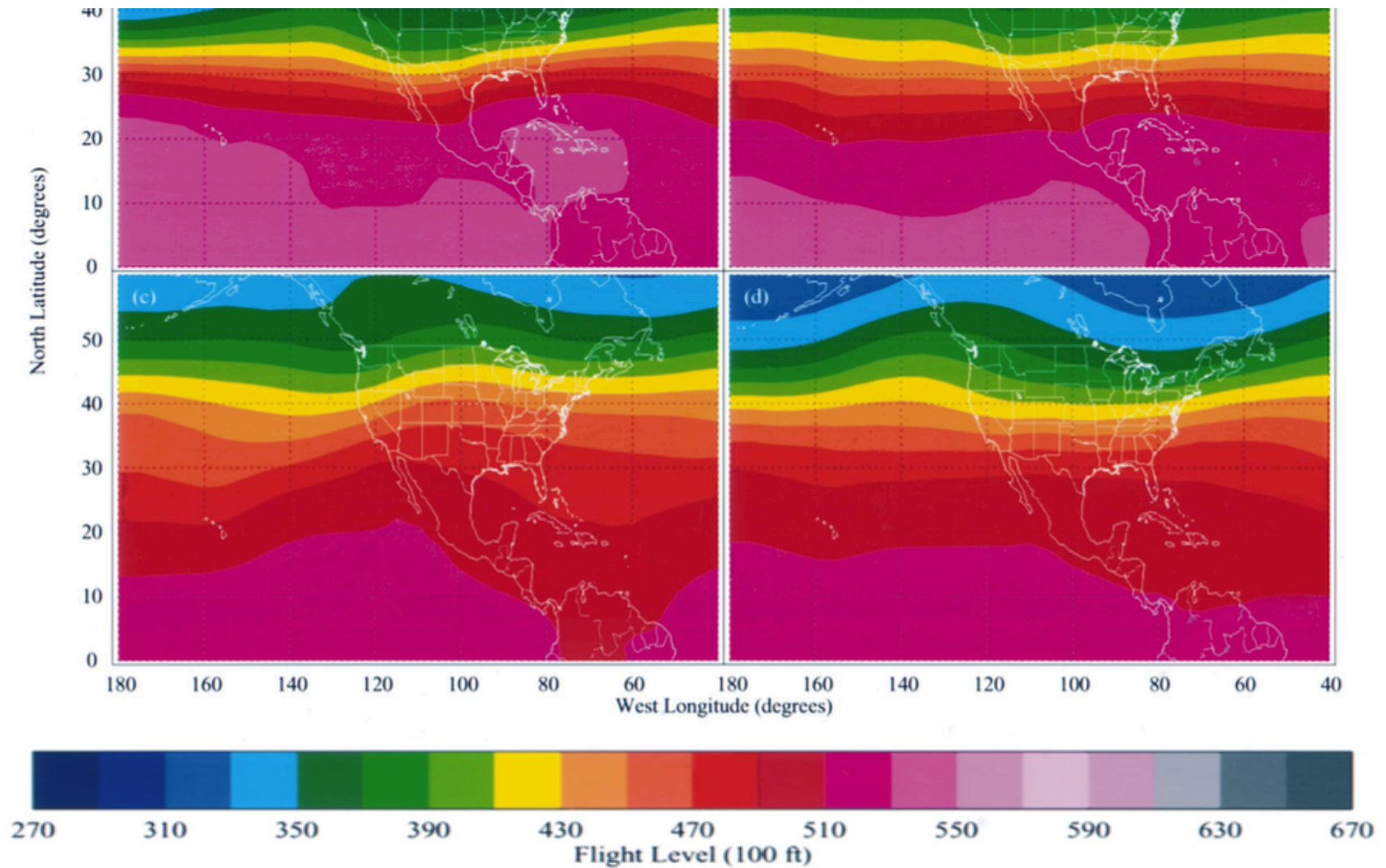


FIG. 6.—Average GDAS tropopause height for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON)

Overburden at 41,000 ft.

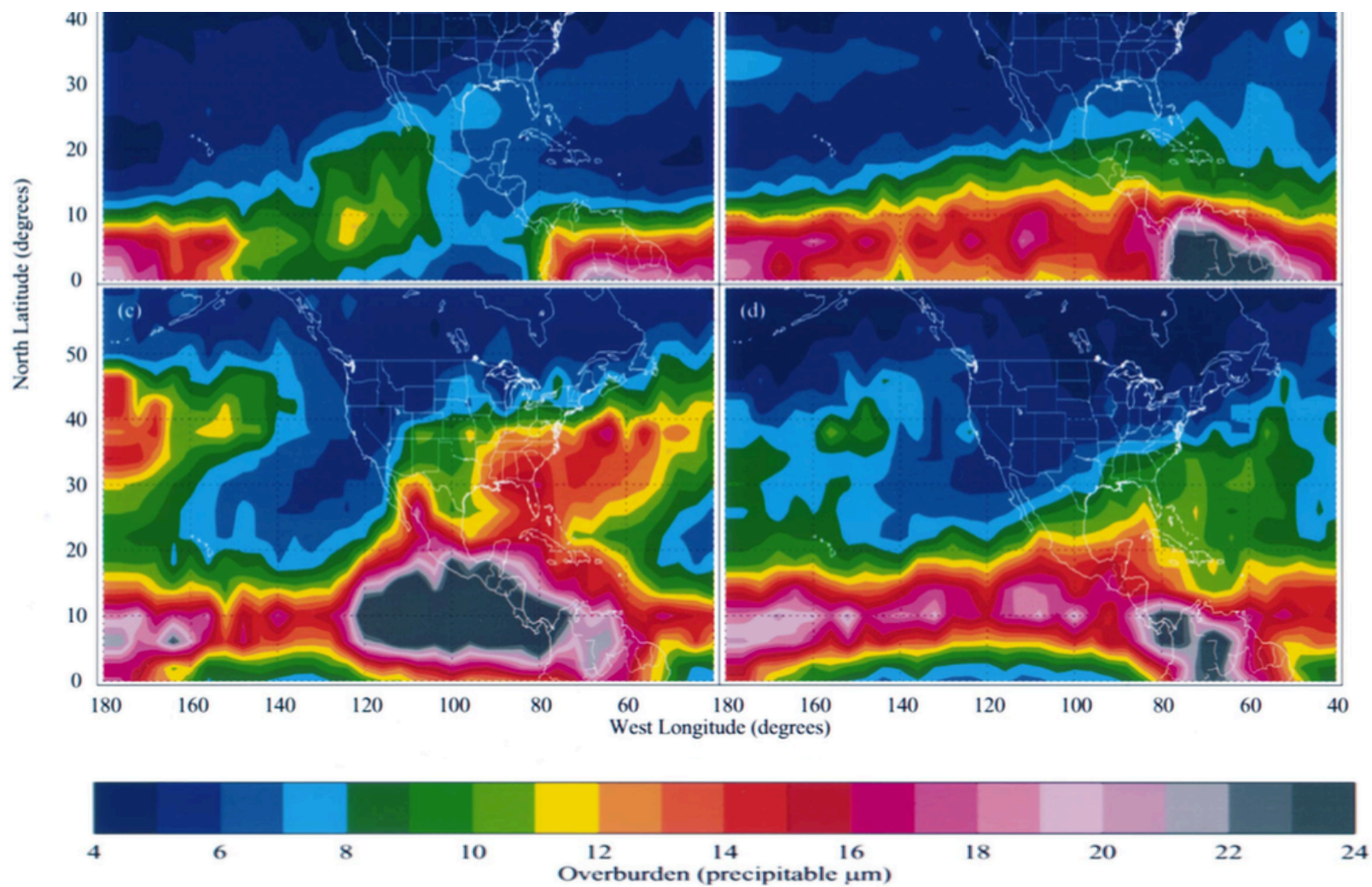
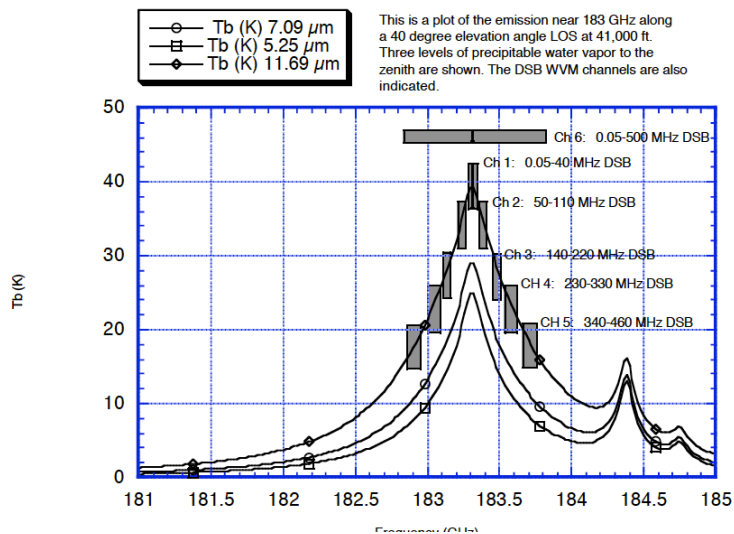


FIG. 7.—The MLS-determined zenith water vapor overburden for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON)

Introducing the SOFIA Water Vapor Monitor

- In order for SOFIA's science instruments (SIs) to spend most of their time observing science targets instead of calibrator targets, SOFIA is equipped with a microwave Water Vapor Monitor (WVM), which continually measures zWV using the 183 GHz WV absorption line while the astronomical instruments are collecting data.
- Looks out same side of aircraft as the telescope, at a fixed elevation angle of 40 degrees
 - Not mounted to moving mass of telescope as in some other observatories
- Software calculates zWV and WV along telescope line-of-sight to write into FITS headers of science data and engineering housekeeping archive



- Developed by SOFIA instead of commercially purchased because of unique airworthiness, sensitivity, and accuracy requirements

WVM Overview

- The WVM measures the integrated water vapor along its line of sight by measuring the strength and shape of the emission from the 183 GHz rotational line of water
- On the aircraft, the WVM hardware consists of:
 - The radiometer head (RHD)
 - Which is mounted inside a pressure confinement structure (green box)
 - Is attached to the inside of the fuselage in the rear upper deck area
 - Observes the sky at a 40° elevation angle relative to the aircraft
 - Looks out through a custom window
 - Contains two calibration black bodies and two stepper motors that direct the radiometer field-of-view among the sky to the black bodies
 - Includes an inclinometer for registering the WVM bore-sight to the aircraft autopilot frame of reference
 - The IF Control box (IFC)
 - Is mounted in a 19" electronics rack near the RHD (underneath the SkyNet hardware)

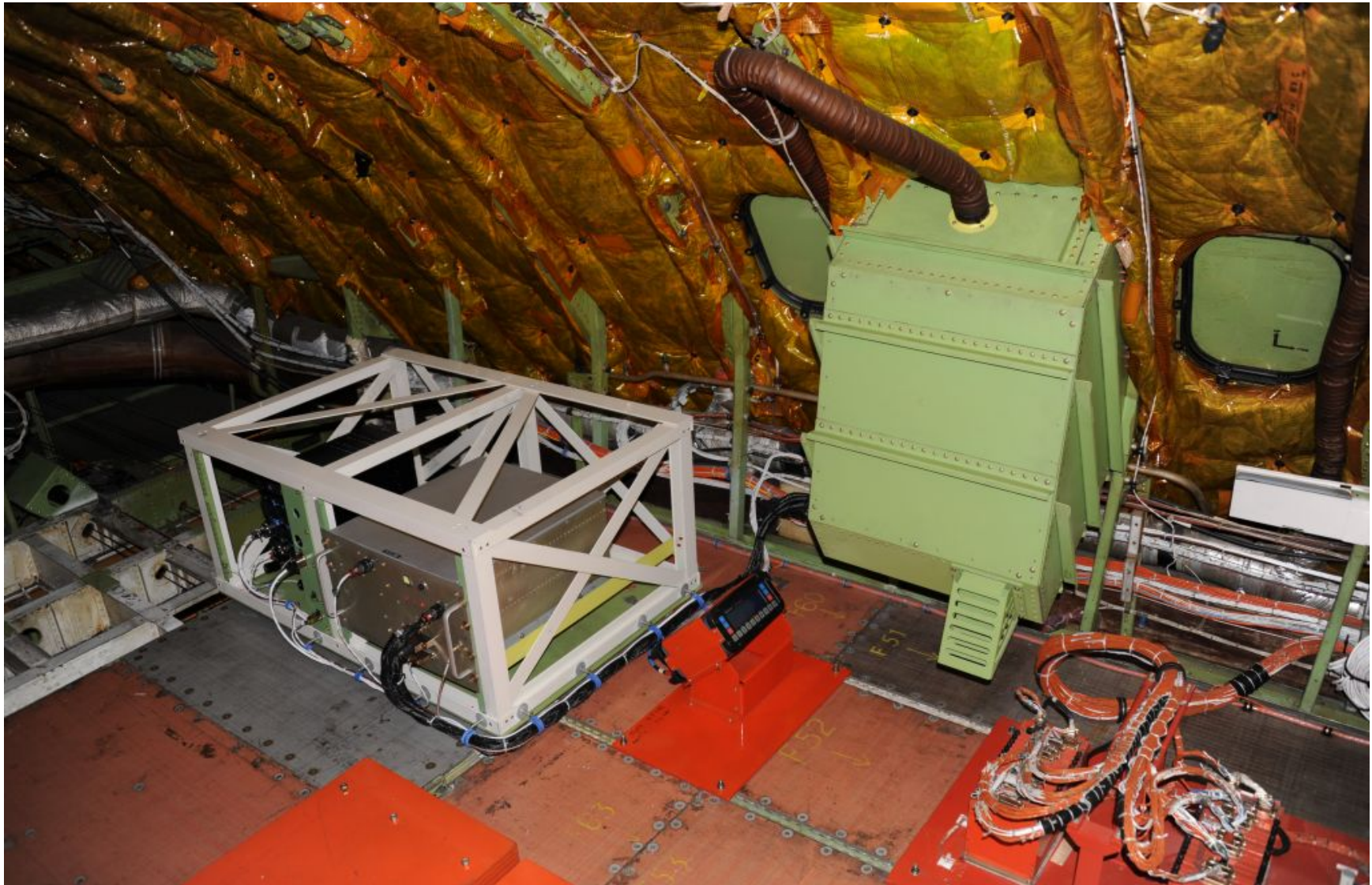
WVM Overview (2)

- WVM Hardware (cont.)
 - IFC (cont.)
 - Separates the mixed-down RF signal into 6 frequency bands and measures the power in each band
 - Conditions and digitizes all the analog signals and then sends these data to the WVM CPU
 - Provides DC power to the RHD
 - Controls the actions of the calibration stepper motors in the RHD
 - WVM CPU
 - Consists of a single board computer, I/O board, SS memory board
 - Resides in an ATR chassis mounted in the same electronics rack as the IFC hardware
 - Communicates with the IFC over an RS232 serial line
 - Communicates with the MCCS through an Ethernet cable

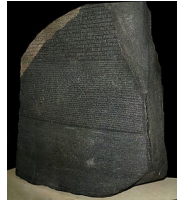
WVM Overview (3)

- WVM Software
 - In the IFC
 - Relatively simple assembly language program running on a 68HC11 microprocessor
 - Even more simple programs in the calibration stepper motor controller boards
 - In the WVM CPU
 - More complex C-language program that handles
 - Communication with the MCCS, including response to commands and packaging of WVM data
 - Quick-look calculation of the water vapor overburden from the WVM measurements
 - Fault detection and response
 - In the MCCS
 - WVM command and response window
 - WVM GUI page providing real-time performance display
 - Storage of WVM data, including raw data, on the Archiver
 - Publication of selected WVM data to SCL subscribers (SI's)
 - Conduit of needed aircraft state data (aircraft roll and pitch angles, outside air temp and pressure) to WVM CPU

And This is What it Looks Like on the Plane



Steps to Reaching the “Rosetta Stone” of SOFIA Calibration



1. Produce stable, high SNR data – enables all subsequent steps
2. Calibrate WVM vs. meteorology (MET) – requires understanding strengths and weaknesses of MET data sources (what is truth?)
3. Use WVM zWV as input to an atmospheric IR transmission model to correct water absorption in SI data without needing the SI itself to do WV measurements at several airmasses for each wavelength. Requires a good model correlating water vapor to its effects in the IR.
4. Alternatively, build up a database of the relationship between WVM measurements and the received signals from all the SIs (with each mode, filter, grism) as they look at calibration objects– costly in terms of in-flight calibration time.

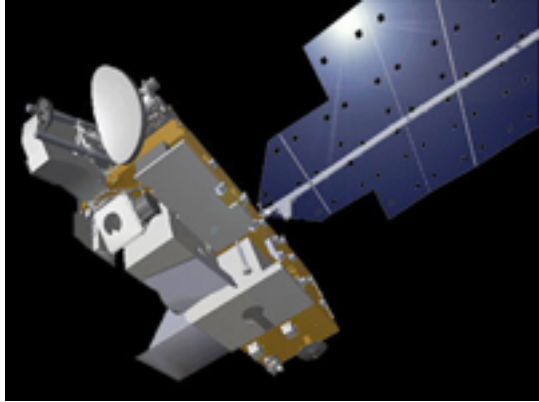
Measuring the Water Vapor in the Stratosphere

What is Truth?

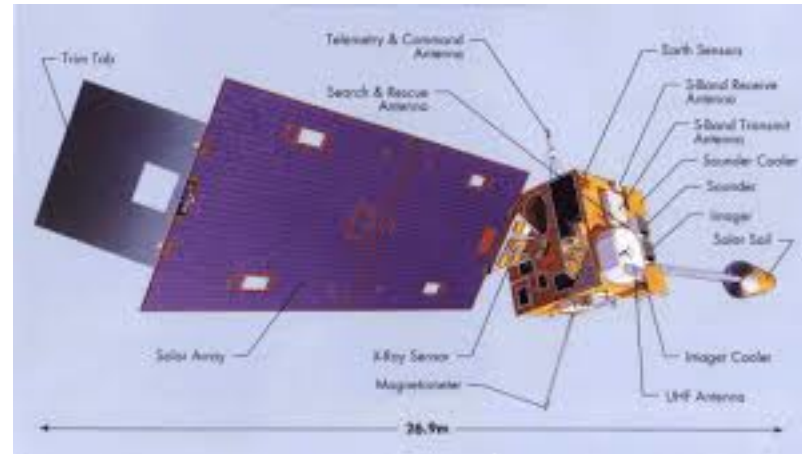
(P. Pilate, 36 CE)

Observation Systems Overview

AURA-Microwave Limb Sounder (MLS)



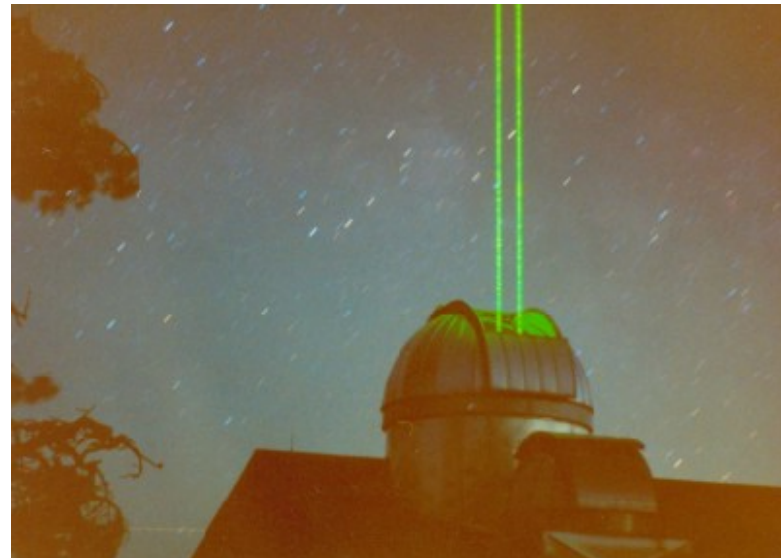
GOES Sounder
Multiband mid-IR



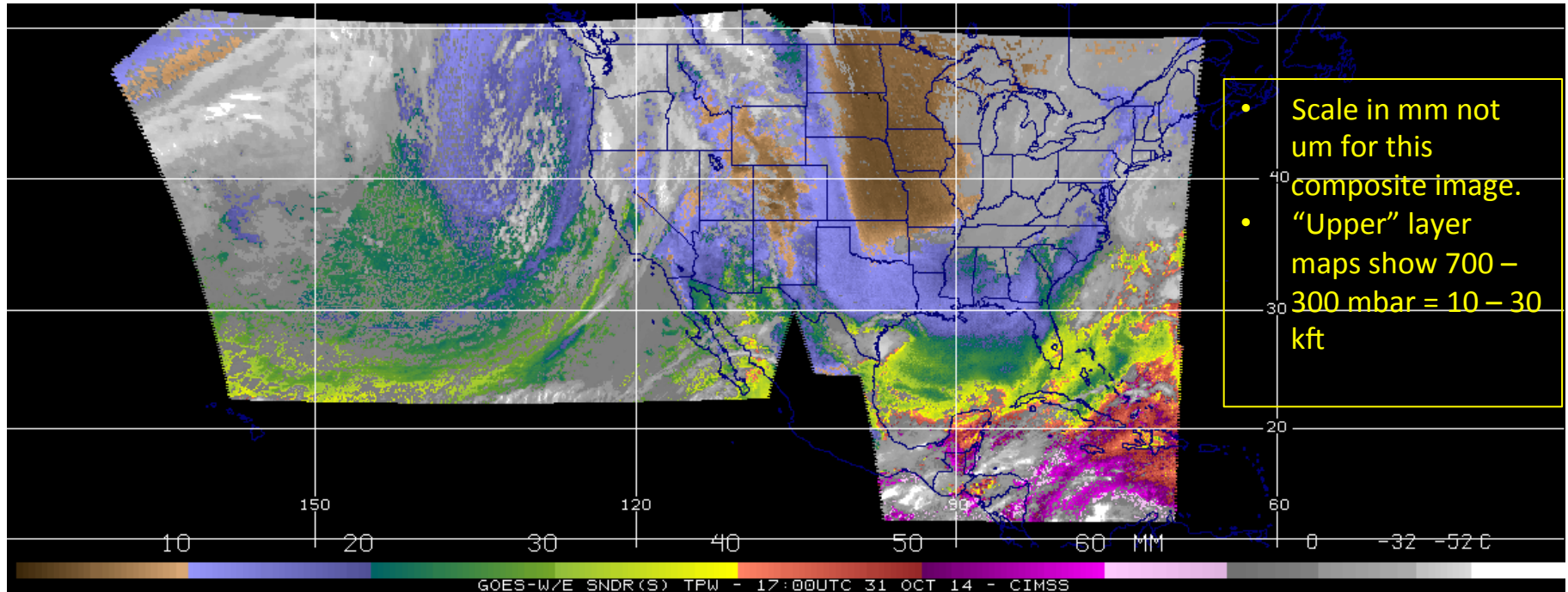
NOAA Frost Point
Hygrometer (FPH)



water vapor Raman LIDAR (JPL TMF and EAFB)



GOES Sounder



Platform: Geostationary satellites (2)

Coverage: E Pacific and CONUS

Horizontal Sampling: Variable. No data where cloudy. 15 km grid where clear

Cadence: Hourly

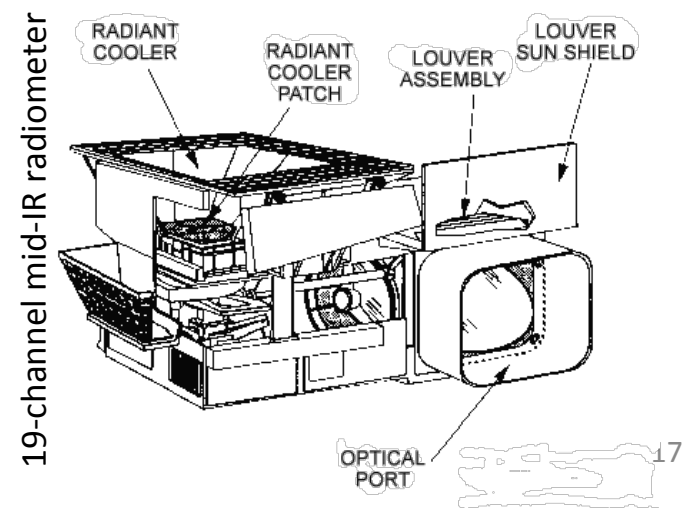
Sample Altitudes: Surface to 300 mbar = 30 kft

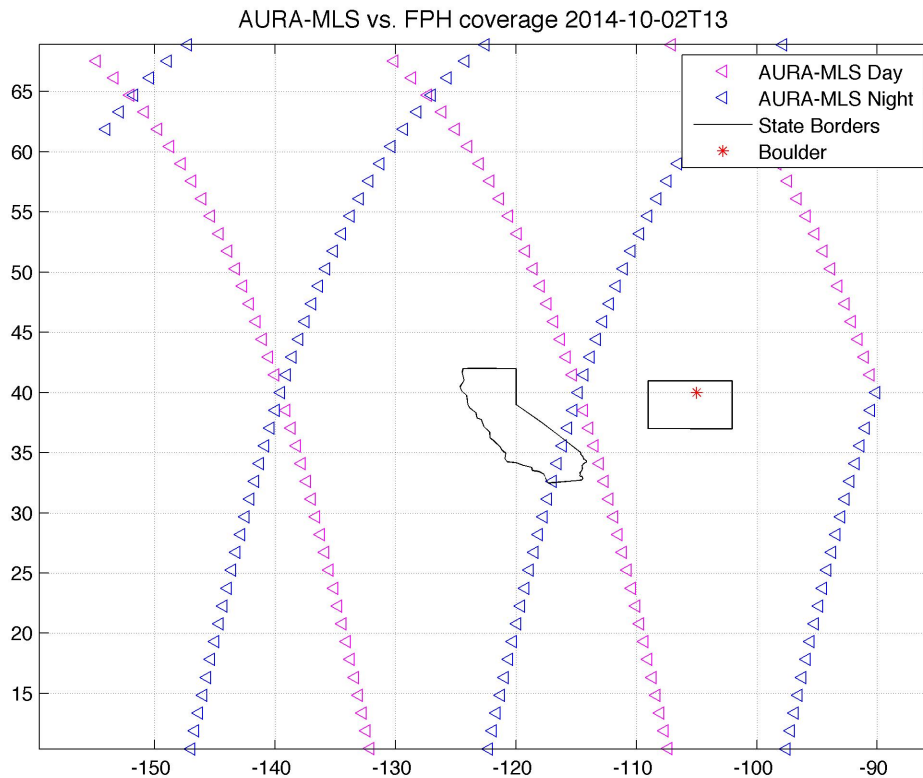
Retrieval Range: Surface to 100 mbar = 53 kft

Accuracy: Questionable > 30 kft

Data File Units: Dew point temperature vs. altitude, pressure, air temperature, lat, lon

Hardware





AURA-MLS

Coverage

- Flight path: Sun-synchronous orbit of 438 miles (705 kilometers)
- Period ~100 minutes
- 1:45 PM equator crossing time.
- Ground track repeats every sixteen days.

Hardware

The EOS MLS instrument contains three modules, one of which is the GHz radiometer module. The R2:190 band overlaps with the SOFIA WVM monitor and also uses the 183.3 GHz line

Platform: Sun-synchronous satellite

Horizontal Sampling: ~180 km in lat, ~1600 km in lon

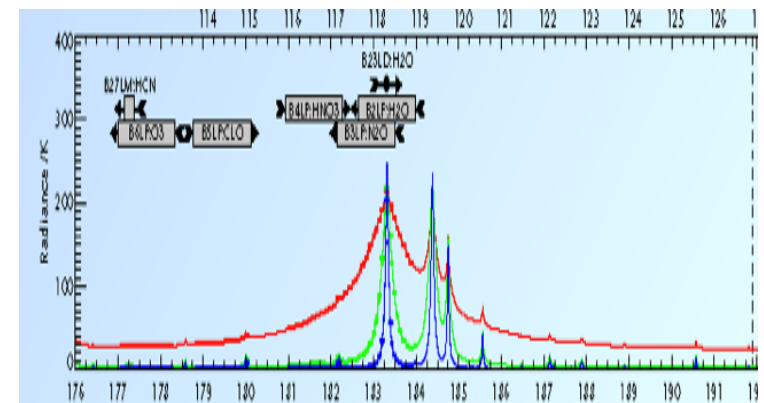
Cadence: Close approaches in time/space twice a day around noon (E and W passes)

Sample Altitudes: Above 300 mbar = 30 kft

Retrieval Range: 300 mbar (30 kft) to 300 kft

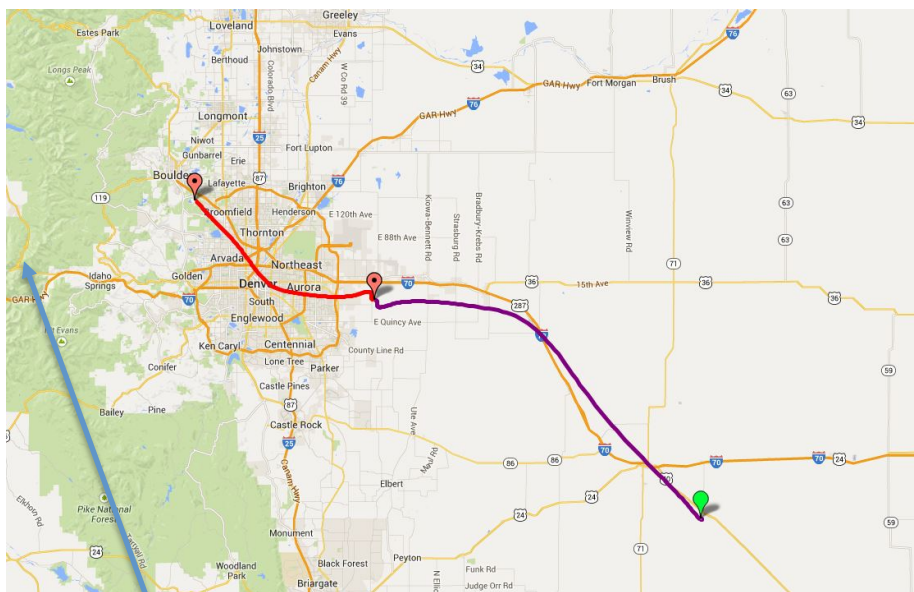
Accuracy: Agrees with FPH within 10% at > 53 kft (Hurst et al. 2103)

Data File Units: Water vapor mixing ratio vs pressure, lat, lon



NOAA-FPH

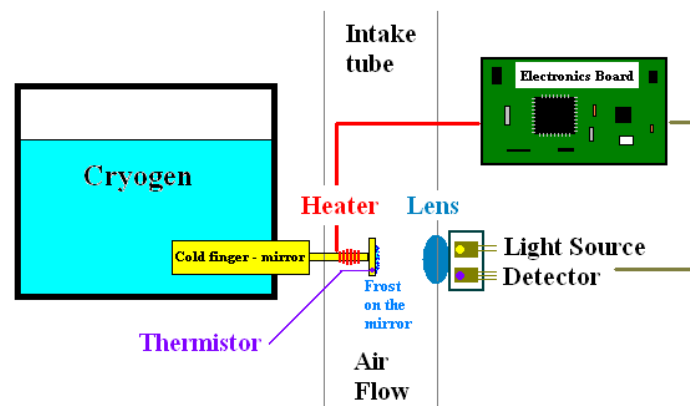
Coverage



- Flight Path: Typically between Boulder and ~200 km SW
- Lauder NZ and Hilo sites as well



Hardware



- The FPH uses active cooling and heating to maintain a thin layer of frost on a small polished metal mirror.

Platform: Balloon

Coverage: Boulder, CO

Horizontal Sampling: Single point

Cadence: Once a month around noon

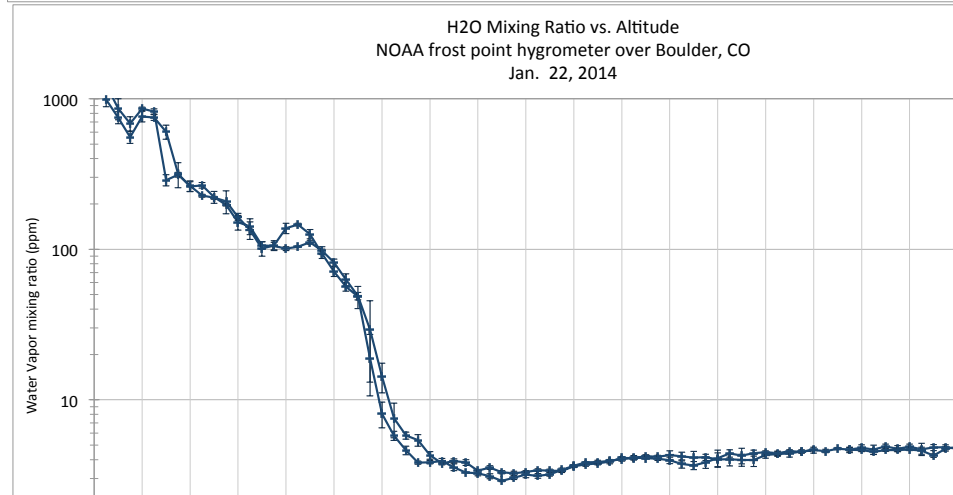
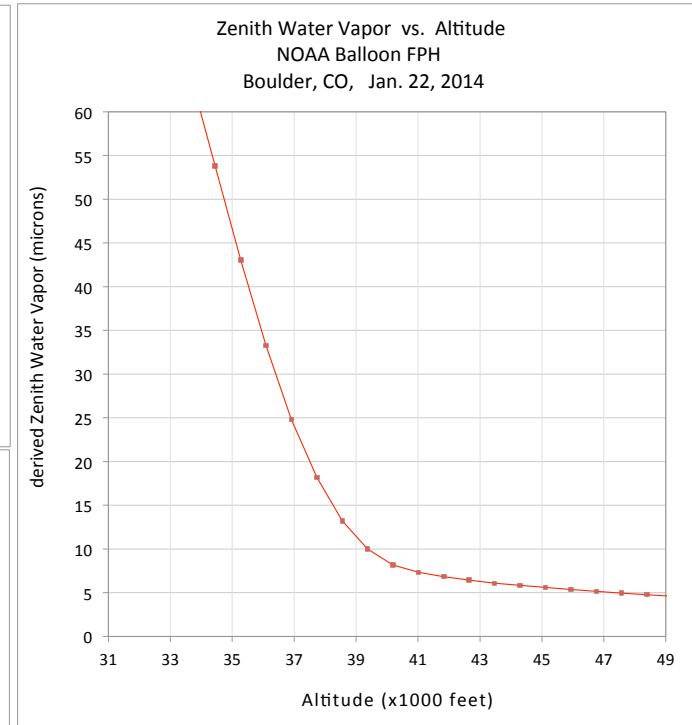
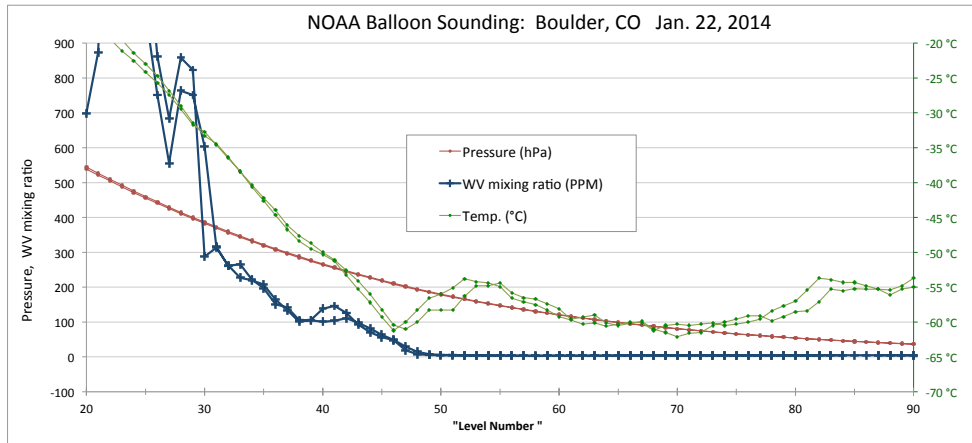
Sample Altitudes: 5 kft to 27 km = 90 kft = 18 mbar

Retrieval Range: 5 kft to 27 km = 90 kft = 18 mbar

Accuracy: 4% (Hurst et al. 2011) – GOLD STANDARD!

Data File Units: Water vapor mixing ratio vs pressure, altitude, air temperature

NOAA balloon FPH sounding example – Boulder CO Jan. 22, 2014



Note consistency of ascent and descent data, even though balloon was at high altitude for many hours, *even well below the tropopause*

Run of integral upward vs. starting altitude shows very typical zWV vs. altitude, zWV < 10 μm above 39K (January 2014)

NOAA balloon FPH sounding example – New Zealand, May, July, Aug, 2014

Synoptic balloon FPH soundings recently commenced over New Zealand (how convenient!)

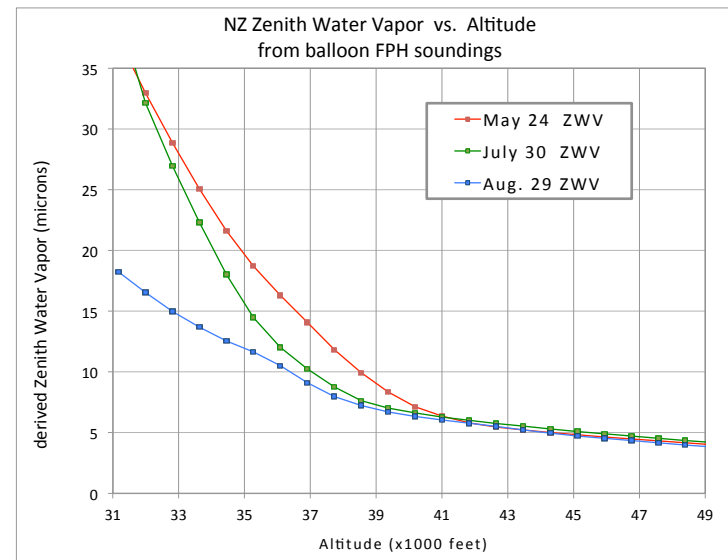
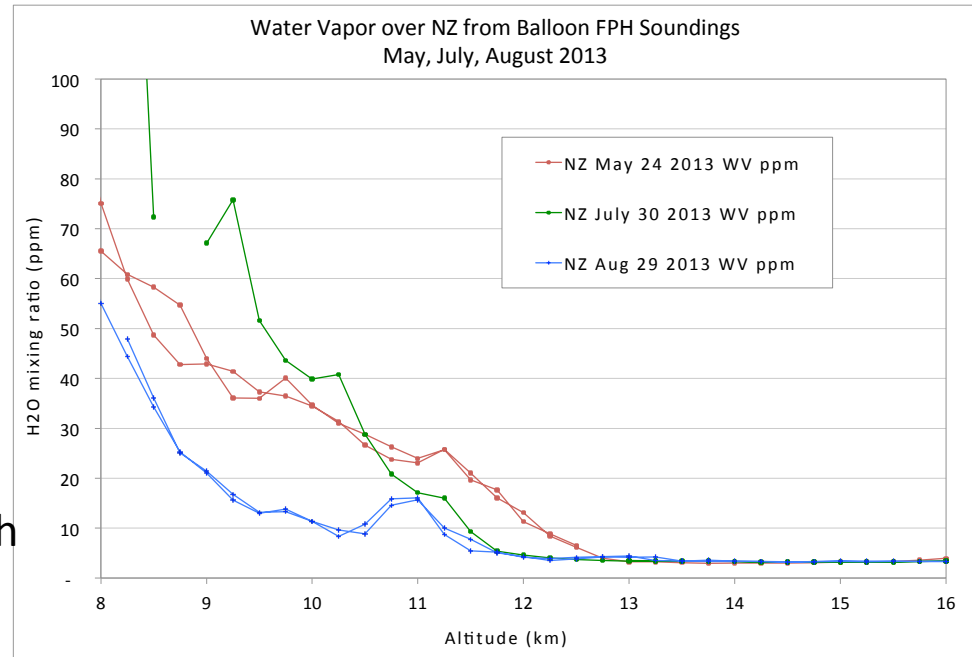
Most equipment lost at sea after descent.

Three soundings shown here straddle the July, 2013 SOFIA deployment. The July 30 balloon sounding coincides with the last GREAT NZ flight.

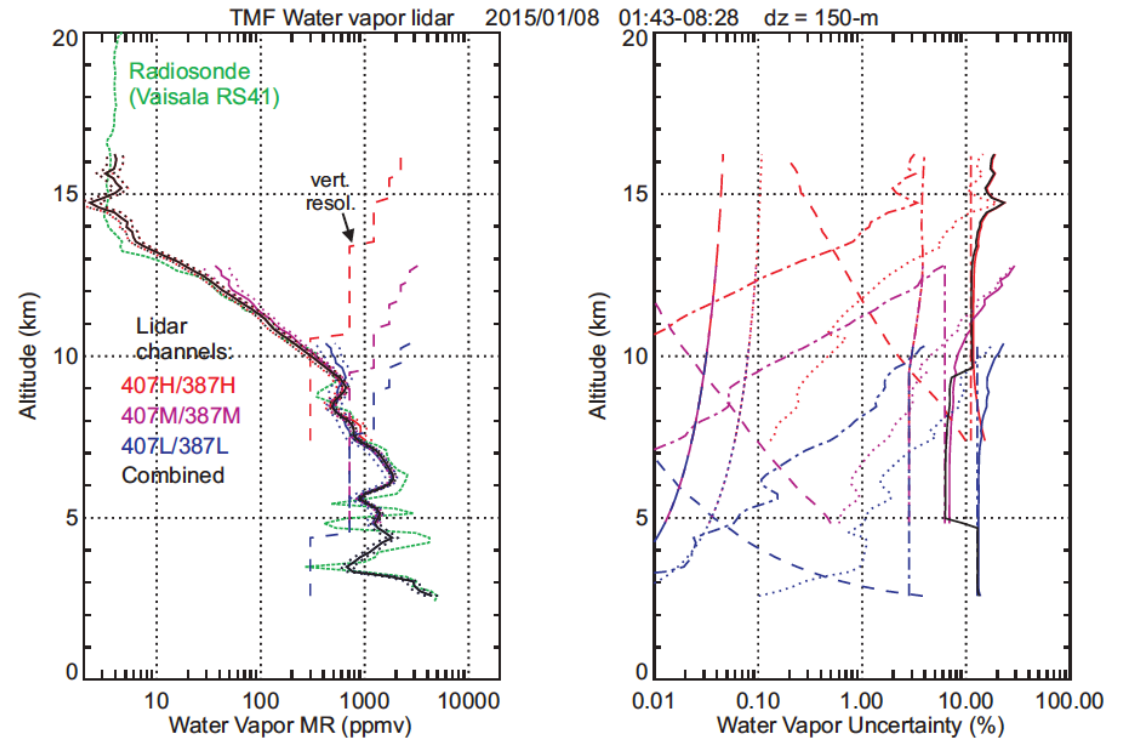
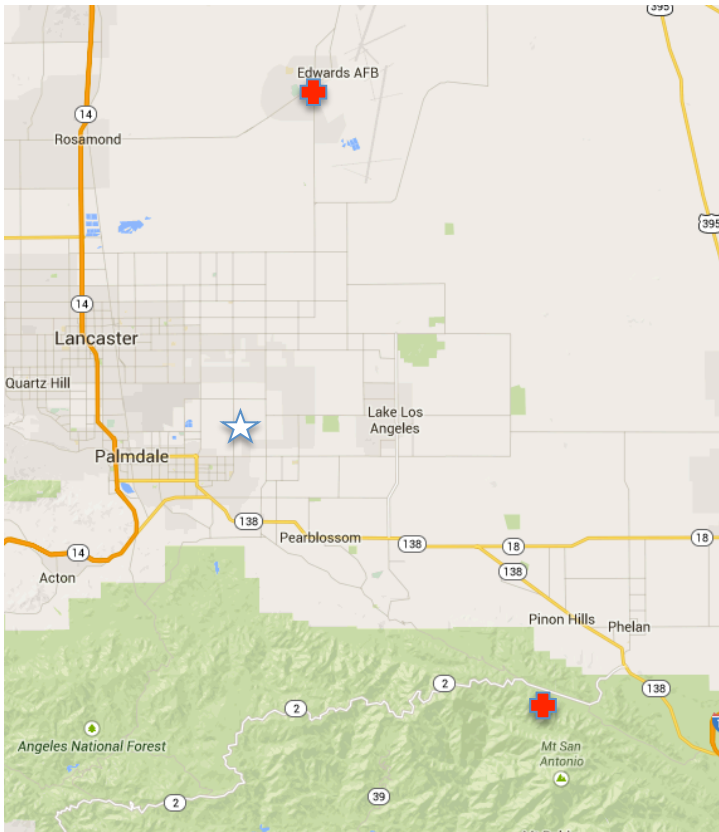
All three mixing ratio profiles converge at about 12.5 km, i.e. 41K, indicating 5 ppm

Integrals for precipitable water vapor show elevated zWV for alt. < 39K.

Note for $h > 40K$ tight agreement on zWV vs. altitude across 4 months at least, May – Aug.



Raman Backscatter LIDAR



Instrument description:

http://tmf-lidar.jpl.nasa.gov/instruments_intro.htm

Platform: Ground-based telescope

Coverage: Edwards AFB and Wrightwood, CA (Yes, two of them within 50 miles of SOFIA's Palmdale base)

Horizontal Sampling: Single point

Cadence: Most clear nights

Sample Altitudes: up to 16 km = 53 kft = 100 mbar

Retrieval Range: up to 16 km = 53 kft = 100 mbar

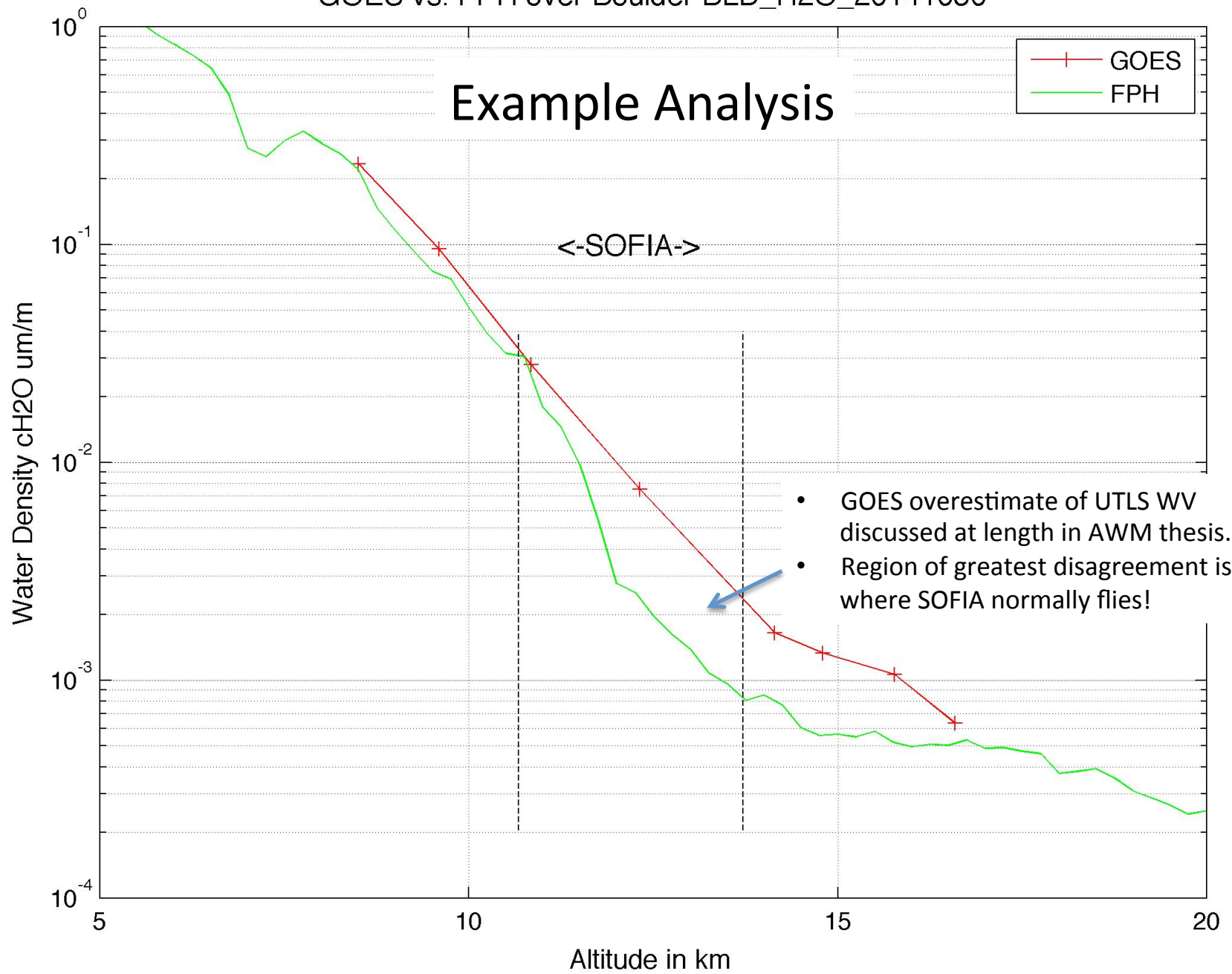
Accuracy: ~10% up to 14.5 km (see above)

Data File Units: Water vapor mixing ratio vs pressure, altitude, air temperature

zWV Forecasting (AFRC MET)

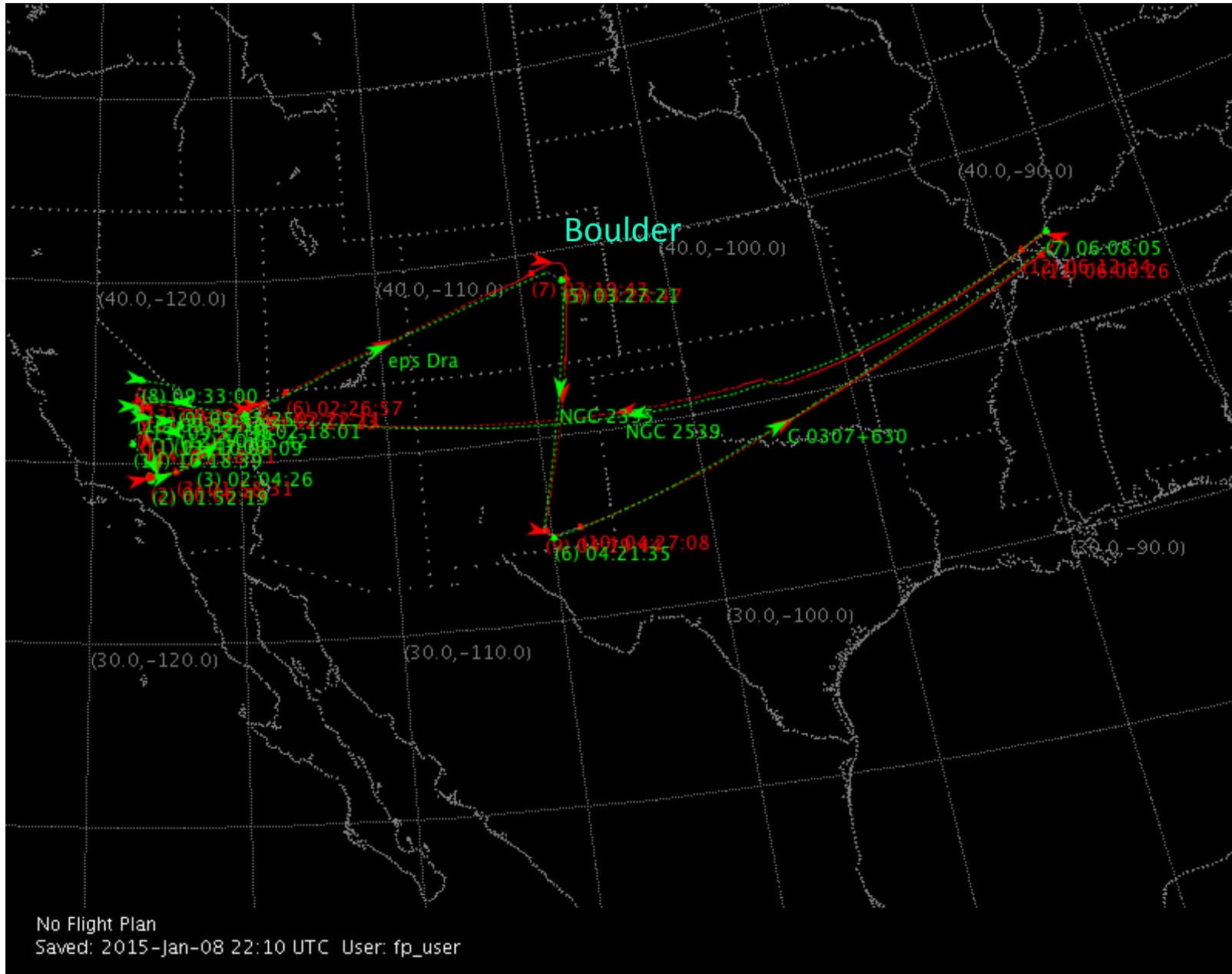
- Goddard's Earth Observing System Model, Version 5 (GEOS-5)
 - assimilation model that combines diverse in-situ and satellite data streams into a single analysis product.
 - Data are available in high-resolution horizontal grid spacing of $1/4^\circ$ latitude by $1/3^\circ$ longitude and 72 levels to 73km altitude.
- To compute the total water vapor loading, the precipitable water content for each model layer above the aircraft altitude is calculated and added together for the total loading at each aircraft waypoint.
- Note that the SOFIA flight planner uses a different data set maintained by the Navy FNMOC , which typically states that there is $\sim 2x$ more water than above. (See Allan Meyer thesis for more details)

GOES vs. FPH over Boulder BLD_H2O_20141030



THE STORY OF FLIGHT 183

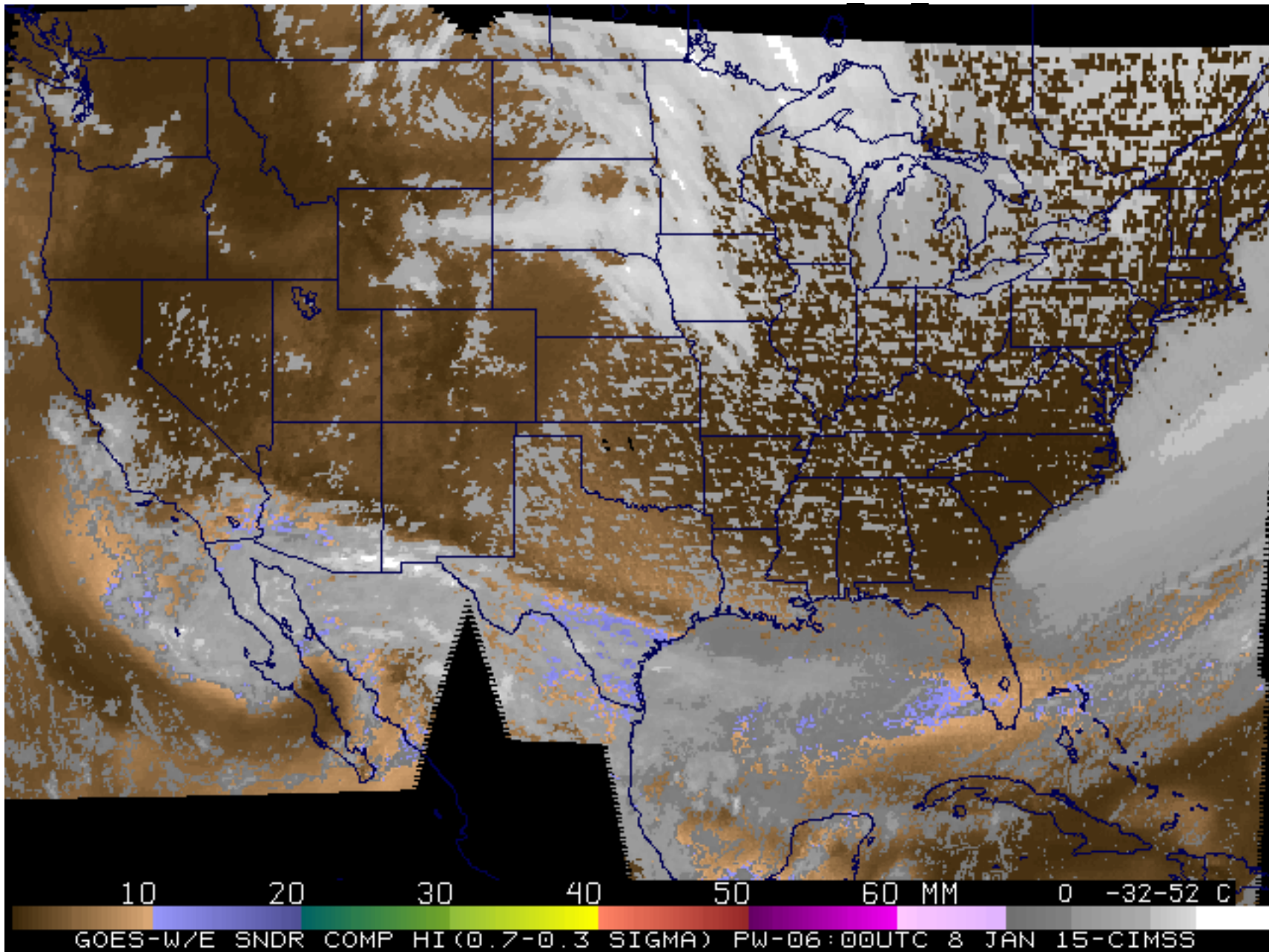
SOFIA Flight Path Detail



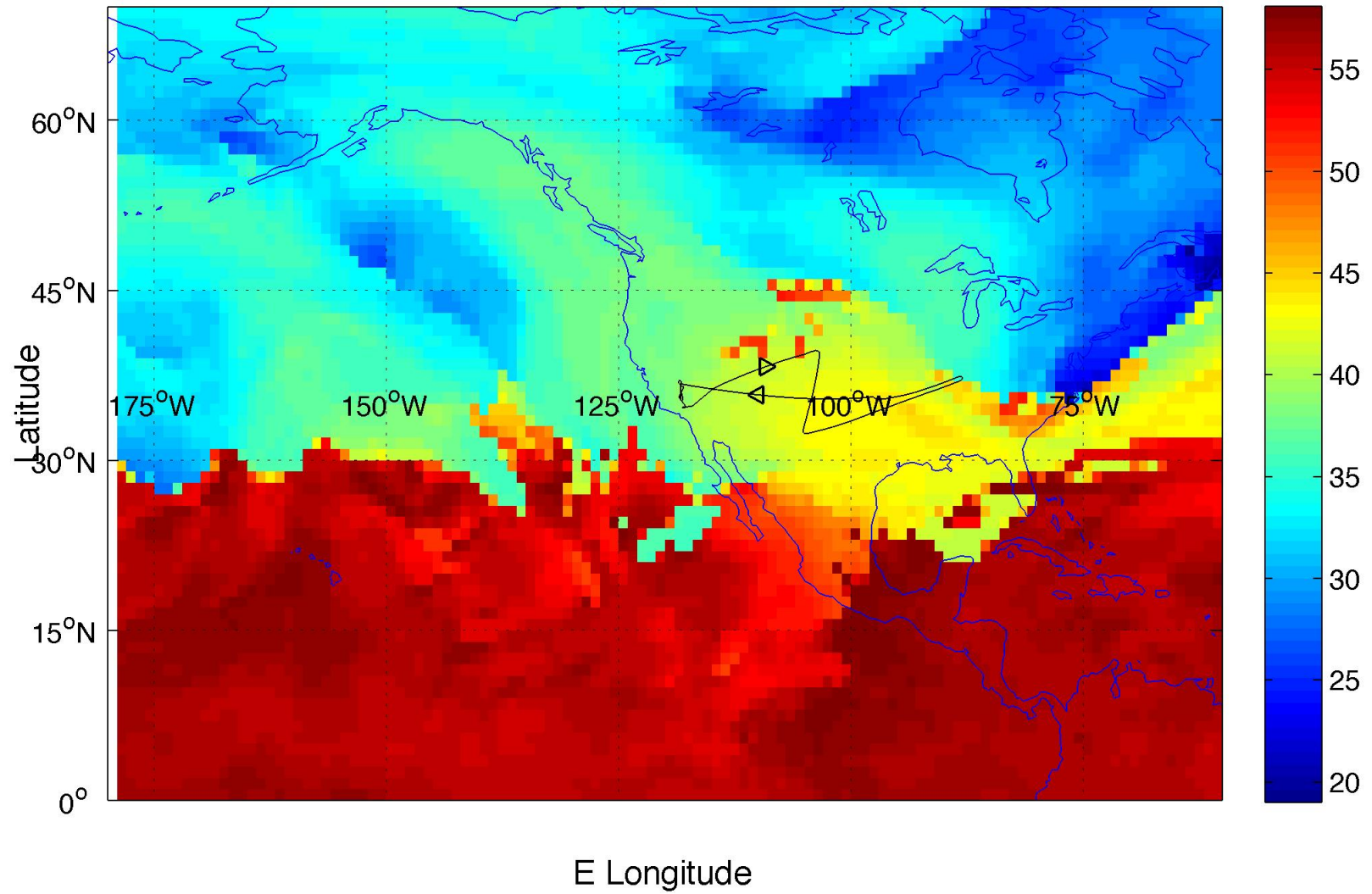
In the Right Place at the Right Time (However no SI on this V&V Flight)

- SOFIA climbed from 35 kft to 39 kft within 50 miles of Boulder the night before a Frost Point Hygrometer (FPH) balloon flight
 - SOFIA flyover around 03:18 UT
 - Balloon launch 18:36 UT
- SOFIA also flew near Taos on the way back (around 08:05 UT)
 - Not sure this is close enough
- LIDAR data from Table Mountain for the departure and arrival legs (see slide 12)
- GOES data looks yukky because of weather that night

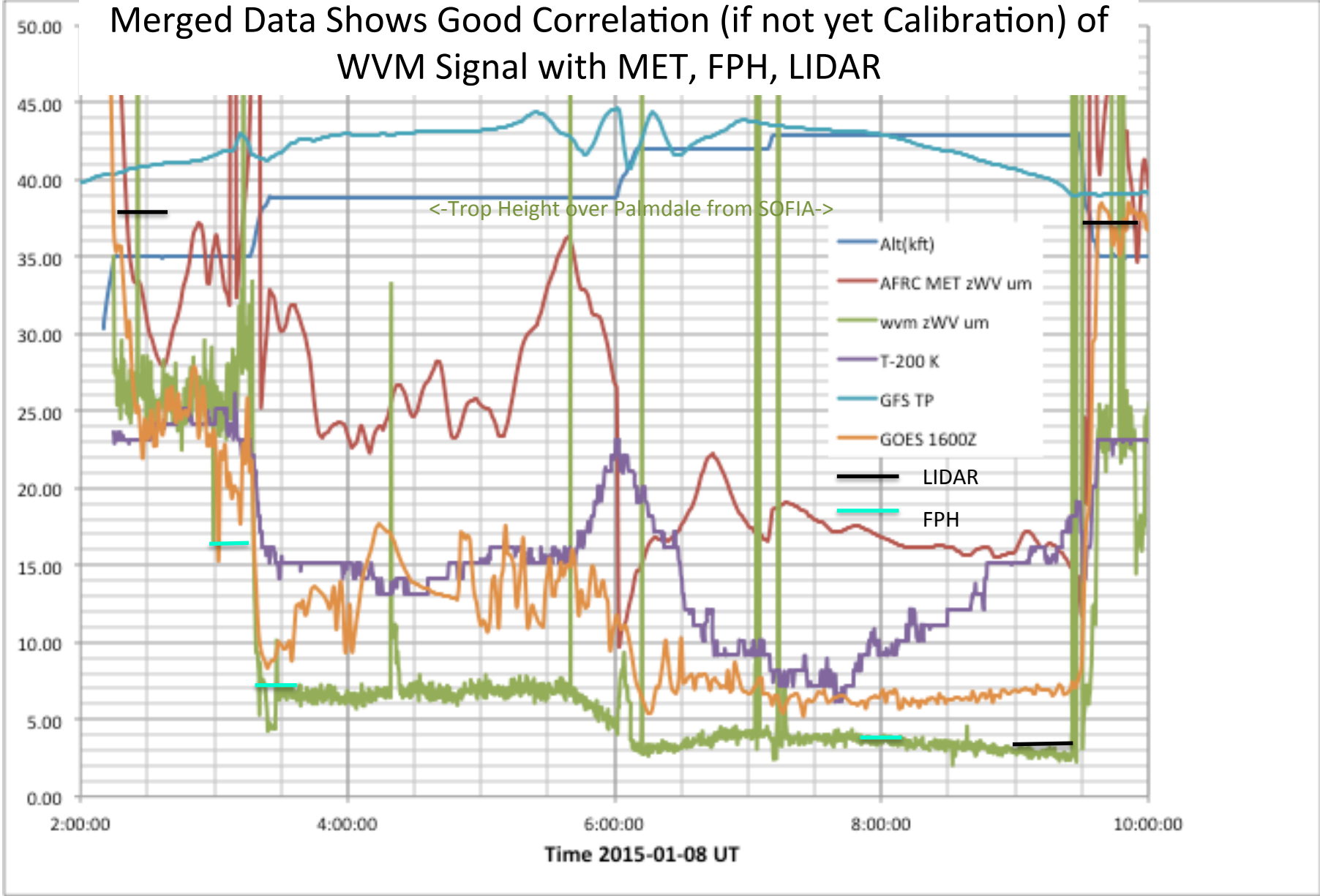
Weather Near Mid-Point of 2015-01-08 NO F183



Tropopause Altitude in StdAtmos kft from fnl_20150108_06_00.grib2.vancleve105783



Merged Data Shows Good Correlation (if not yet Calibration) of WVM Signal with MET, FPH, LIDAR



See backup slides for Flight 187 and 189 results

Thoughts From Flight 183

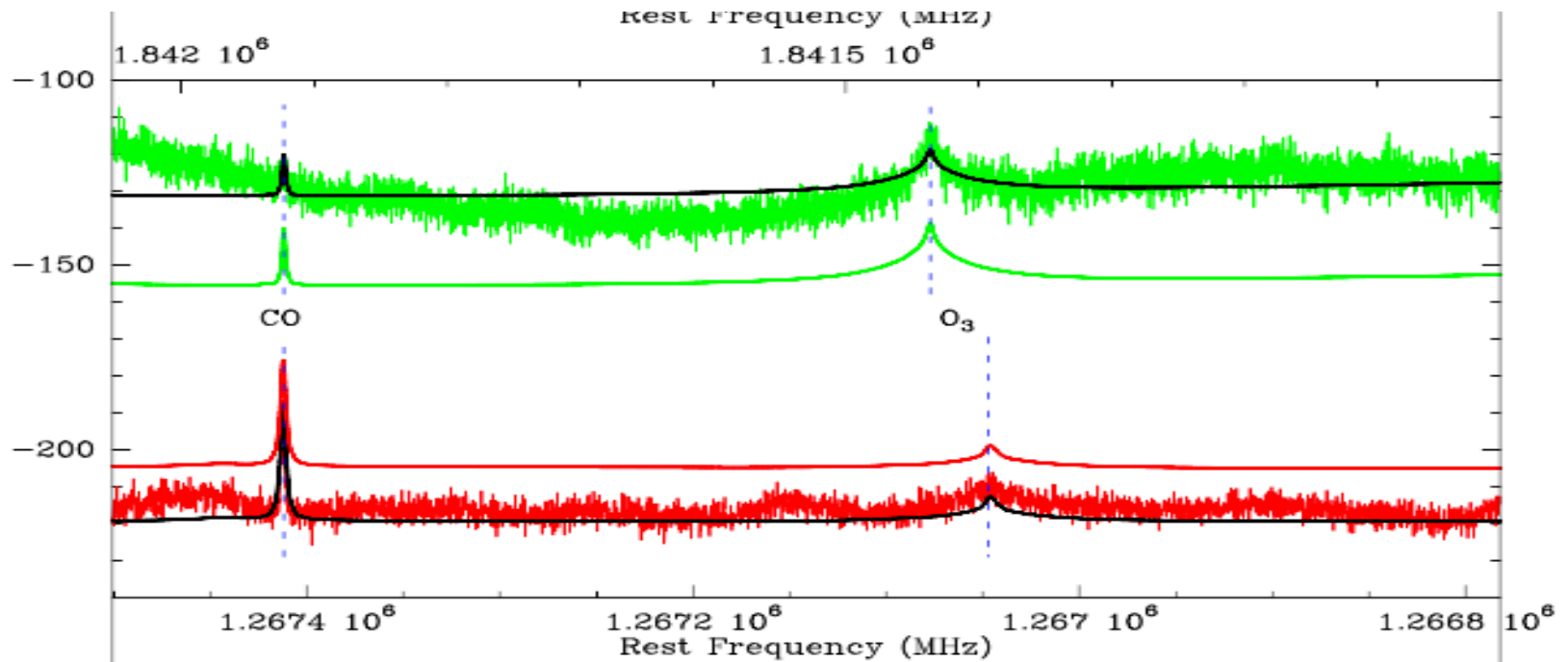
- TML, FPH, and WVM agree within a factor of 1.5 above the tropopause
- MET is consistently higher than FPH or WVM, which may be another aspect of AWM's observation that tropospheric weather data and derived products systematically overestimate ZWV,
- TML, FPH, and WVM agree within a factor of 1.6 below the tropopause.
 - Don't yet know what to say about agreement with FPH, because of the ~1300 km and 16 hr between Table Mountain and Boulder observations.

OK, So Even if We Know the Water
Vapor Truth, How Well Can We
Predict what this Means for Our IR
Signals?

Modeling the WV Effects

- There are a number of models out there
 - SOFIA has traditionally used ATRAN
 - ATRAN is used in the SOFIA proposals tools set
 - Is also currently used in the SOFIA data reduction pipelines
- However, there is evidence that there are problems with our current understanding
 - Concerns while using the CGS on the KAO
 - GREAT's experience (Guan et al., 2012, next slide)
 - GREAT finds ATRAN was the worst of the three models that were tried (not that the best model was very good!)
- So, we are stuck with the time-consuming effort of empirically relating the WVM signals to the measurements of astronomical standards.

The GREAT Experience



Same sky, same time, two frequencies -> different water

Black line fits are for 12.3 μm ppwv in L1 (Red), 35 μm ppwv in L2 (Green)

Red and green lines are for best fit for common value of 21.4 μm ppwv

Plans Forward

- Improve the reliability of the WVM hardware
 - Motor controllers used for calibration mirrors in the WVM have proven problematical. New controllers have been built and are being installed.
- Currently the SOFIA data pipelines use ATRAN. Near-term we therefore need to convert the WVM measurements to “ATRAN water units”, to get the best results with our current pipelines
- Long-term, need to build up a database of the relationship between WVM measurements and the received signals from all the SIs (with each mode, filter, grism) as they look at calibration objects at different altitudes, etc.

References

- Allan W Meyer (2001) “Preliminary ATRAN Modeling of Water Vapor Calibration via FLITECAM 2 to 5 μm Transmission Spectroscopy” (WVM-SYS-2001-01)
- Tom Roellig et al. (2010) “Measuring the water vapor above the SOFIA observatory,” SPIE 7733, Ground-based and Airborne Telescopes III, 773339
- Allan W Meyer (2013) “Airborne Astronomy: an Assessment of Some Aspects of the First Year of SOFIA Science Operations” Doktor der Ingenieurwissenschaften dissertation, U. Stuttgart
- Dale F. Hurst et. al (2013), “Validation of Aura Microwave Limb Sounder stratospheric water vapor measurements by the NOAA frost point hygrometer,” JGR
- Thierry Leblanc, I. Stuart McDermid, and Robin A. Aspey, 2008: First-Year Operation of a New Water Vapor Raman Lidar at the JPL Table Mountain Facility, California. *J. Atmos. Oceanic Technol.*, **25**, 1454–1462.