Water Vapor Monitor Performance and Calibration

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With contributions from

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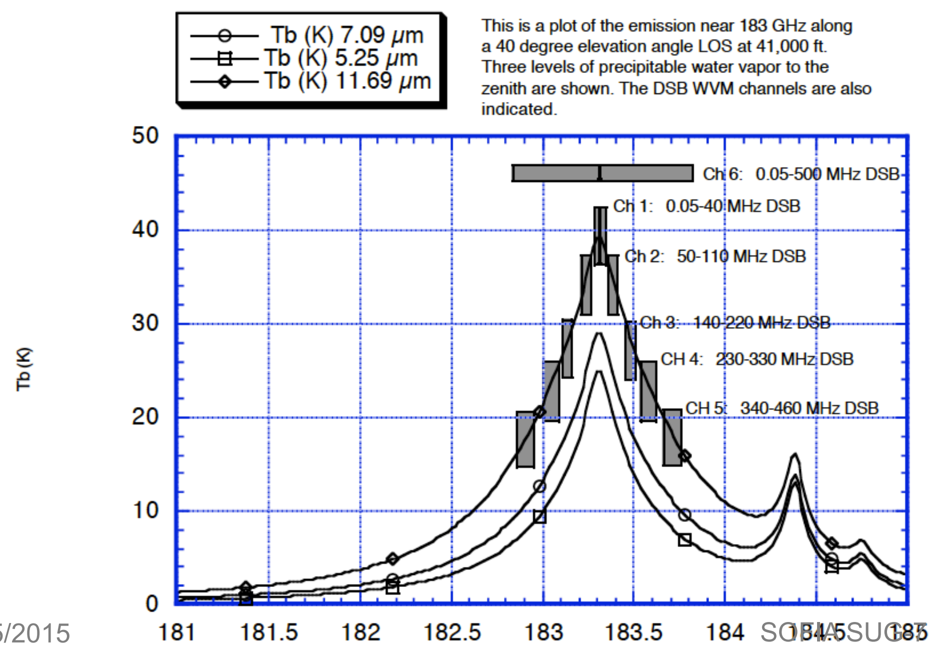
- Ed Teets and Fran Becker (NASA-Armstrong Meteorology)
- Thierry Leblanc (JPL Table Mountain)

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

SUG 7: 4/15/2015

Review of the SOFIA Water Vapor Monitor

- **The microwave Water Vapor Monitor (WVM) 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**
- **Software calculates zWV and WV along telescope line-of-sight to write into FITS headers of science data and engineering housekeeping archive**



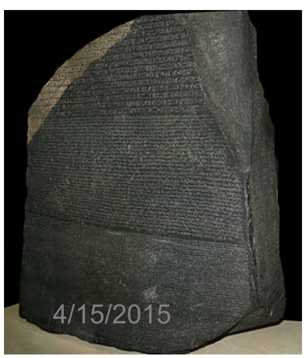
- Developed by SOFIA instead of commercially purchased because of unique airworthiness, sensitivity, and accuracy requirements

Steps to Reaching the "Rosetta Stone" of SOFIA Calibration

1. **Produce stable, high SNR data – enables all subsequent steps**
2. **Build up a database of the relationship between WVM measurements and the received calibrator signals from all the SIs (with each mode, filter, grism)**
3. **Use WVM data as a temporal bridge between SI calibrations (calibrator objects and sky dips)**
4. **Correlate WVM vs. meteorology (MET) to identify anomalous WVM output to exclude from calibration dataset -- (our "Science Jamboree" talk)**
5. **Use WVM zWV as input to an atmospheric IR transmission model to correct water absorption in SI data (ongoing "science project")**

-- reducing the time collecting calibration data with SIs.

"tactical" → "strategic"



"This is not completely desperate" – Urs Graf 10/21/2014

Examples of WVM Calibration at Other Observatories

LABOCA Zenith opacities

(APEX Submm bolometer camera)

LABOCA zenith opacities as a function of time. For each entry in the output table, we provide three values for the zenith opacity:

- tau_sd, derived by reducing a Skydip scan with redsky(scannr).
- tau_rm, computed from the precipitable water vapour (PWV) and an atmospheric model.
- A linear combination of these two: tau_mean = (1.3*tau_sd + 0.9*tau_rm)/2.0

The latter usually provides the best estimate of the true zenith opacity; but users are strongly encouraged to carefully and critically check all these values and their variations during the time interval covering their science observations.

Download all opacities (BoA format) which is generated automatically using a pipeline reduction.
Need help using these pages ?

UT Date start [yyyy-mm-dd] 2015-03-15

UT Date stop [yyyy-mm-dd] 2015-04-14

Scan quality factor Ok

Submit Reset

See also
SHARC2 at CSO
SCUBA at JCMT

Common Features:

- Queryable database of WV data
- Real-time WV result written to FITS headers sometimes erroneous, data reprocessed and correlated in pipeline processing
- Sanity check (and occasional rejection) of WVM data
- Weighted mix of instrumental opacity measurement and WV data
- Use of more frequent WV data as temporal bridge between SI calibration points

Is the WVM data stable with good SNR?

DATA QUALITY ASSESSMENT

Near-Term Need for DQA and Reprocessing

- **WVM data *as reported by MCCS* experienced intermittent data quality issues for about from Jan 2013 to April 2014**
  - High noise. Noise requirement is 0.67 um zenith water vapor (ZWV), 1-σ 1-minute
  - Dropouts
  - Nonsense numbers
  - Unphysically quantized results
- **Post-HMV WVM repair has eliminated problems caused by hardware**
- **On-aircraft algorithm still fails to converge much of the time**
- **Data can be reprocessed with new algorithm ("diff6 method 2") using raw data**
  - Voltages to brightness temperature
  - Brightness temperatures to zWV
- **Installation of new algorithm on aircraft before deployment (TBR)**

WVM Data Quality Metrics

Functionality

- **Plot time series**
  - Do brightness temperatures of channels come together at low altitude & diverge at high altitude?
  - Proxy for line broadening at lower altitudes
  - Calculate difference of Ch1-Ch5 brightness temperatures
- **Plot ZWV vs altitude**
  - Does ZWV decrease during climbs and increase during descents?
  - Calculate slope and WV scale height
- **Is output zero, constant, or quantized?**

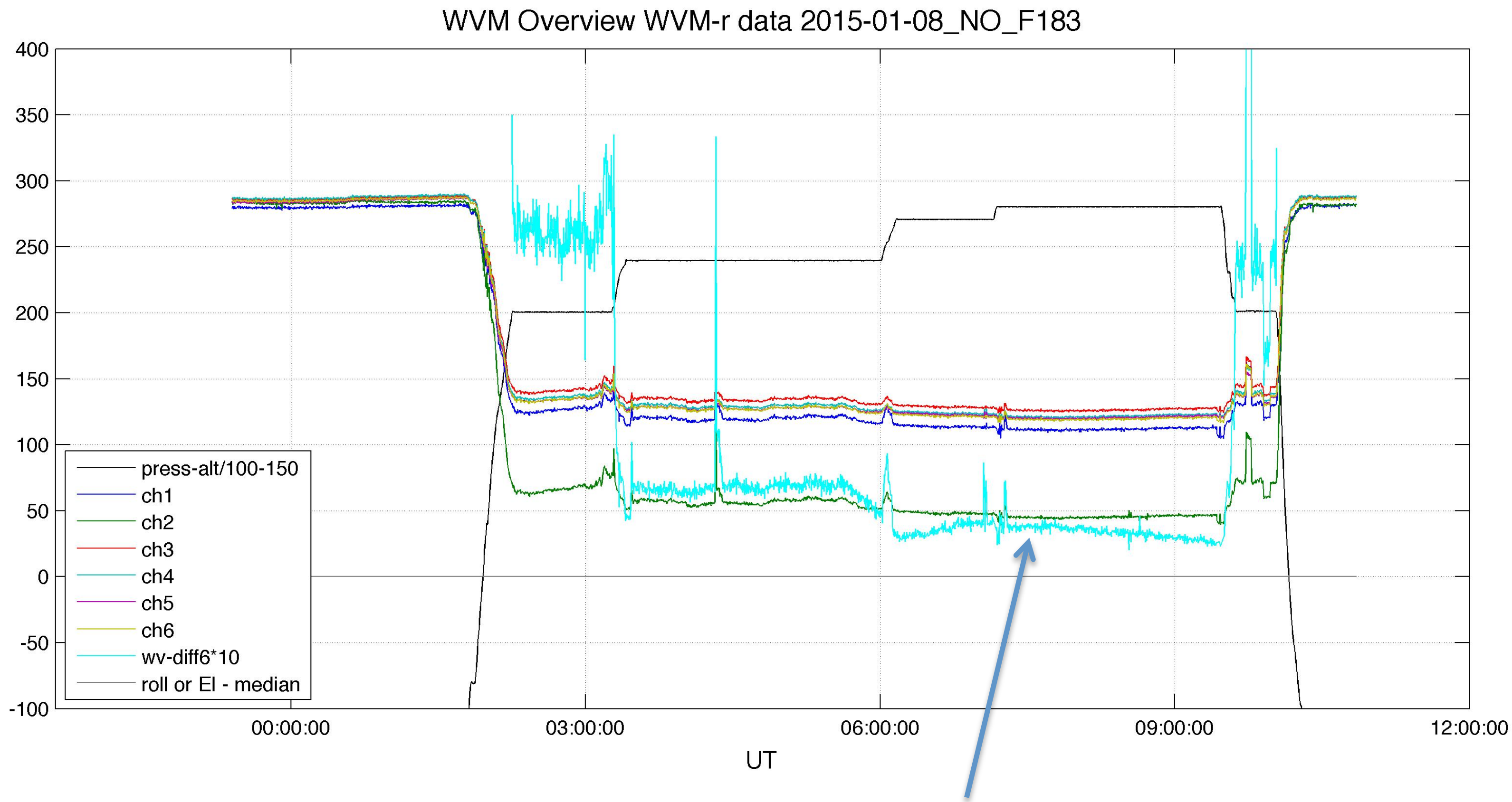
Noise

- **Select level flight segment from time series, without rolls or data spikes**
- **Remove 2nd order polynomial trend**
- **Calculate robust standard deviation of detrended data**

Output stored as text files suitable for ingestion into spreadsheet or Engineering Data Analysis database

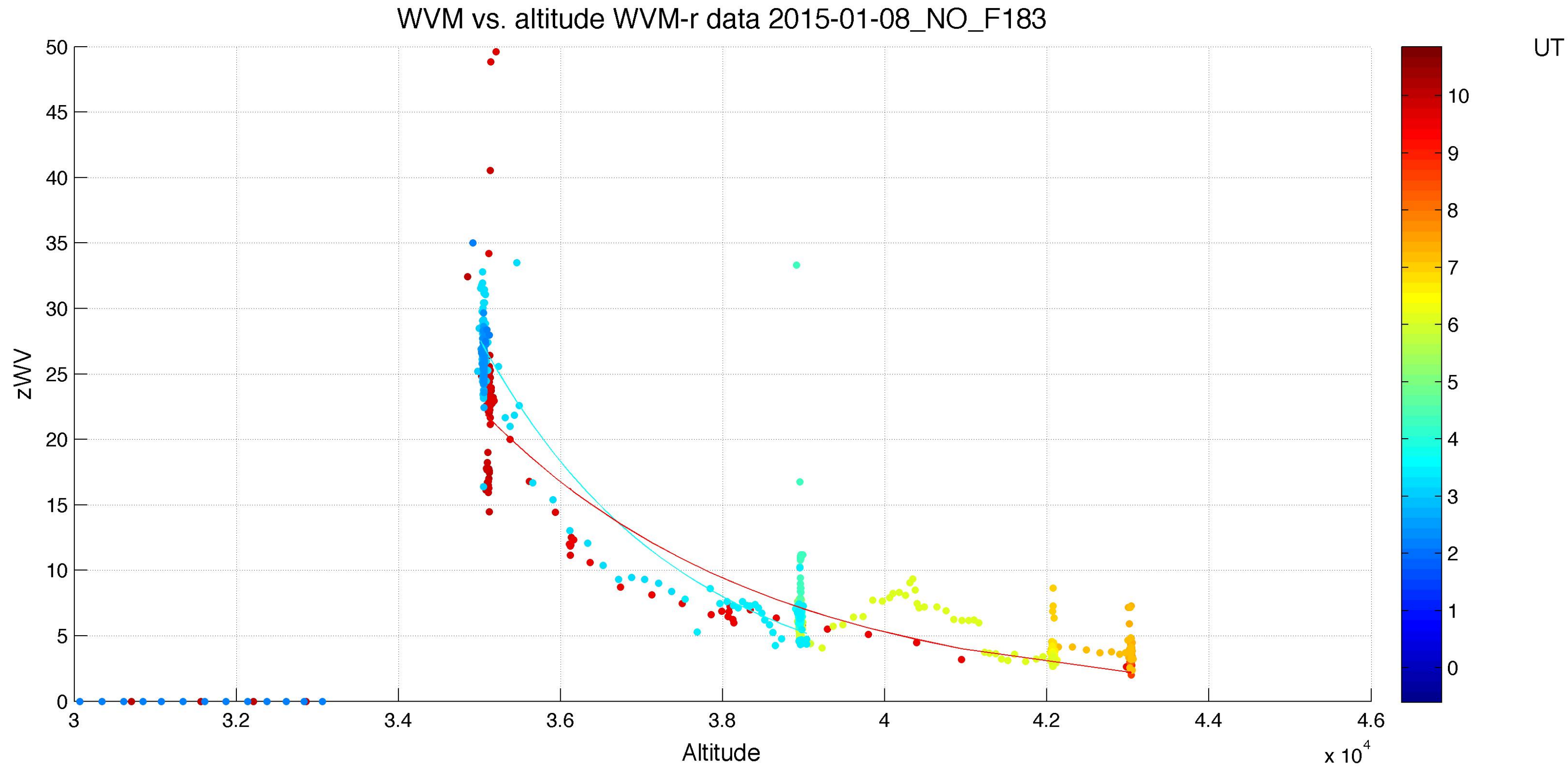
MATLAB Analysis Program `wvm_noise_level_flight_dualformat.m` posted on on EDA WVM Wiki
https://wiki.sofia.usra.edu/bin/view/EngDataAnalysis/WaterVaporMonitor

DQA Example, Time Series: post-HMV Engineering Flight 2015-01-08_NO_F183



Bumps like this will be compared to Meteorology data

DQA Example, Variation with Altitude: post-HMV Engineering Flight 2015-01-08_NO_F183



Single-scale height fits show plausible dependence on altitude

WVM Summary Statistics Kept in "WVM Monitoring Spreadsheet"

Water Vapor Monitor Monitoring
Jeffrey Van Cleve, USRA
3/24/15

Quality Summary Terms
GOOD = valid ascent, level flight, and descent data available

ATRAN defaults zWV
H2O scale height 7.70 kft 2.35 km See also We
value at 41 kft 7.30 um
Scale Height in Red if disagrees with ATRAN by >3x
ZWV in Red if >90 Observed/ATRAN in y
Noise in Red if > 3 um 1-sigma
-999.0 numerical error or N/A code for float format data

Mission ID	strument	Quality Summary	da Stamp	taFormat	filename	ve	entStartTime(12:16)	centEndTime(12:16)	ntCh1Ch5Diff	ntScaleHeight (kft)	ne1(12:16)	ti 2(12:16)	levelFlightLat	levelFlightLon	le lFlightAlt	L elFlightSegmentCh1Ch5Diff	lFlightMedian	w mS
Good values		mean							42.8	11.6					42.2	44.3	20.8 (ZWV)	1.9 (sig-ZWV)
		std							8.9	4.7					2.3	8.9	6.6	0.3
2013-07-17_GR_F115	GR	FAIR	7/17/13	WVM-r	wv_m1_2013-07-17_GR_F115_Z.txt	wvm_0.4	7:22	7:38	41.9	22.6	11:31	12:44	-60.7	171.6	42.0	42.4	80.7	1.63
2013-07-18_GR_F116	GR	FAIR	7/18/13	WVM-r	wv_m1_2013-07-18_GR_F116_Z.txt	wvm_0.4	6:30	6:34	93.7	46.8	8:50	9:58	-56.6	175.9	40.8	88.7	74.7	1.75
2014-02-13_FP_F144	FP	FAIR	2/13/14	WVM-r	wv_m1_2014-02-13_FP_F144_Z.txt	wvm_0.3	6:21	6:24	10.9	4.8	7:57	8:27	42.8	-105.1	40.8	55.0	30.1	1.91
2014-02-15_FP_F145	FP	GOOD	2/15/14	WVM-r	wv_m1_2014-02-15_FP_F145_Z.txt	wvm_0.3	7:19	7:28	45.4	9.3	11:18	12:38	42.7	-109.9	45.6	48.5	18.6	1.66
2014-02-19_FP_F146	FP	GOOD	2/19/14	WVM-r	wv_m1_2014-02-19_FP_F146_Z.txt	wvm_0.3	2:17	2:26	48.3	13.6	3:18	4:37	37.4	-134.8	39.6	48.1	27.4	2.23
2014-02-21_FP_F147	FP	GOOD	2/21/14	WVM-r	wv_m1_2014-02-21_FP_F147_Z.txt	wvm_0.3	5:23	5:34	48.2	15.5	3:50	5:10	38.2	-135.0	39.6	48.5	26.9	2.24
2014-02-25_FP_F148	FP	GOOD	2/25/14	WVM-r	wv_m1_2014-02-25_FP_F148_Z.txt	wvm_0.3	6:51	7:03	47.4	17.3	8:33	10:13	36.6	-127.3	42.0	46.9	21.3	2.02
2014-02-27_FP_F149	FP	FAIR	2/27/14	WVM-r	wv_m1_2014-02-27_FP_F149_Z.txt	wvm_0.3	4:41	4:53	45.1	6.1	7:20	8:03	42.4	-101.4	39.6	44.4	23.9	1.64
2014-04-08_EX_F158	EX	GOOD	4/8/14	WVM-r	wv_m1_2014-04-08_EX_F158_Z.txt	wvm_0.4	2:30	2:46	25.1	5.0	6:12	7:26	35.2	-132.1	43.2	26.1	9.3	1.53
2015-01-08_NO_F183	NO	GOOD	1/8/15	WVM-r	F183_wv_m2_Z.txt	wvm_1.0	3:09	3:31	-7.7	2.4	4:33	5:23	33.8	-98.9	39.0	-7.7	6.9	0.32
2015-01-14_GR_F184	GR	GOOD	1/14/15	WVM-r	F184_wv_m2_Z.txt	wvm_1.0	5:33	5:56	-6.4	3.1	9:33	10:40	32.7	-130.3	41.1	-5.0	5.4	0.23
2015-01-15_GR_F185	GR	GOOD	1/15/15	WVM-r	F185_wv_m2_Z.txt	wvm_1.0	2:12	2:25	-4.9	2.2	3:01	3:40	41.2	-117.8	39.1	-5.0	8.4	0.32
2015-01-21_GR_F187	GR	GOOD	1/21/15	WVM-r	F187_wv_m2_Z.txt	wvm_1.0	5:25	5:45	-6.1	4.3	7:07	7:44	25.9	-132.1	41.1	-7.7	3.9	0.21
2015-01-23_GR_F189	GR	GOOD	1/23/15	WVM-r	F189_wv_m2_Z.txt	wvm_1.0	2:20	4:30	-5.4	3.4	5:07	6:17	36.3	-116.2	41.1	-6.8	3.3	0.23
2015-03-12_FI_F199	FI	GOOD	3/12/15	WVM-r	F199_wv_m2_allcols_newline_ISO.txt	wvm_1.0	2:09	2:32	-8.2	2.5	5:54	7:22	38.8	-137.3	41.1	-5.4	3.5	0.24
2015-03-13_FI_F200	FI	GOOD	3/13/15	WVM-r	F200_wv_m2_allcols_newline_ISO.txt	wvm_1.0	2:44	3:03	-5.7	1.7	6:00	6:58	43.3	-118.7	40.1	-4.1	6.1	0.24

…

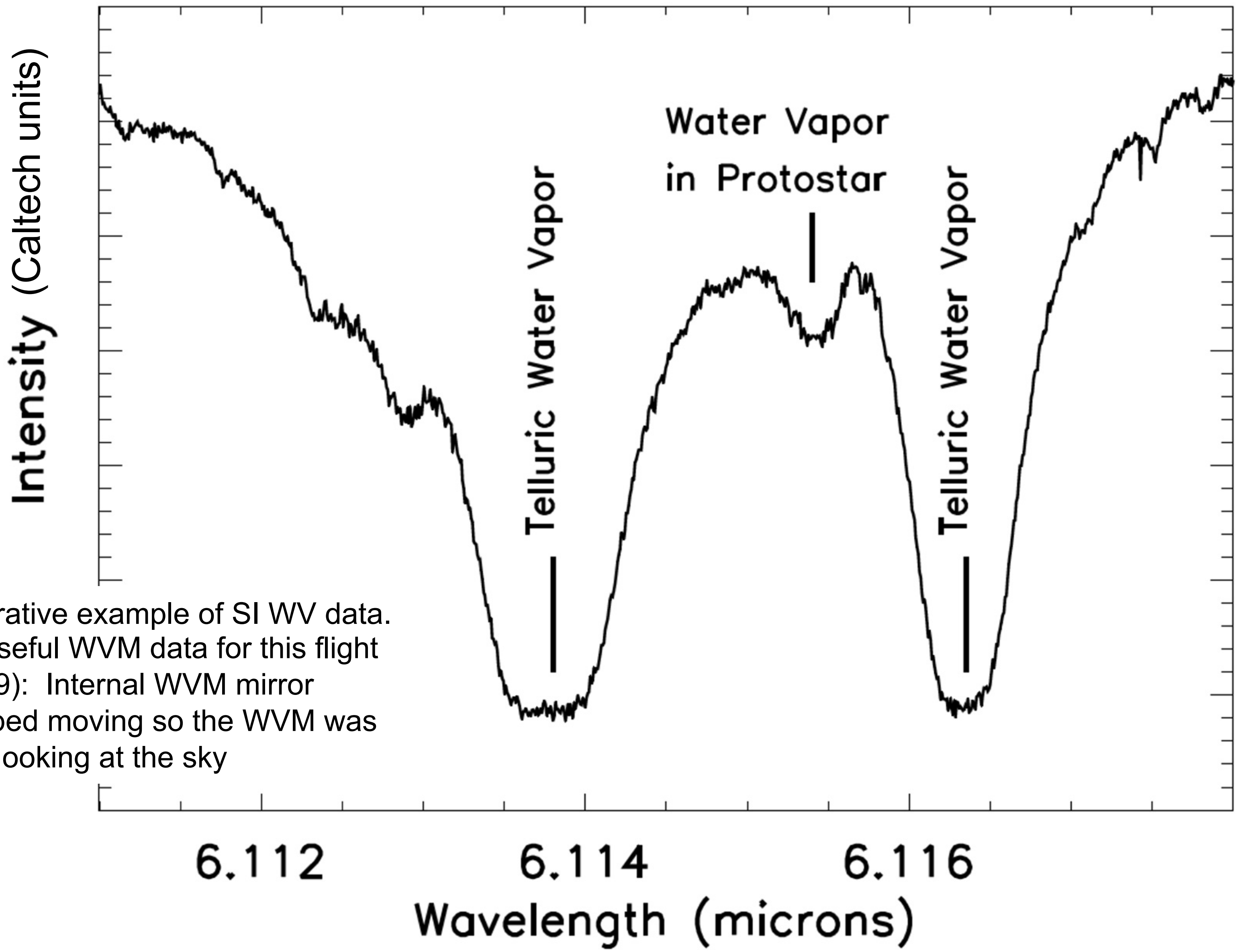
GOOD =
- Level flight value agrees with ATRAN to 3x
- noise meets requirements
- either ascent or descent scale height agrees with ATRAN and MET

Current version at
https://wiki.sofia.usra.edu/pub/EngDataAnalysis/WaterVaporMonitor/WV_monitor_monitoring.xlsx

Examples of WV measurements by SIs

SI – WVM CALIBRATION

H_20 detected by EXES in the high-mass protostar AFGL 2591



- Illustrative example of SI WV data.
- No useful WVM data for this flight (F159): Internal WVM mirror stopped moving so the WVM was only looking at the sky

GREAT/SOFIA atmospheric calibration

- **Guan+ (2012, Special Issue A&A GREAT Early Science) could not self-consistently fit the atmospheric emission simultaneously for the L1 and L2 bands**
  - independent fits to the individual receiver bands converge well, but on solutions with different values of zWV for each band
  - Typical science observations intentionally avoid strong water lines
- **Dedicated tests to directly calibrate the water vapor monitor (WVM) against GREAT on 2015-01-21_GR_F187 and 2015-01-23_GR_F189**
  - Deliberately centered the optical depth ~1 lines in the middle of GREAT band
  - Will use atmospheric models to deduce the precipitable water vapor along the line of sight (science team focusing on science papers right now)

Leg 10	engineering leg	to cross-calibrate WVMonitor		
		L1: H2O_1	L2: H2O_3	43 kft
12:11	19.47 elev	hot-cold-sky	11711-12	
12:12-15	21.32		11713 (went into local), repeat: 11715	
12:15	23.58		11716	
12:18	30.00		11717	
12:20	41.81		11718	
12:22	60.4		11719	

Snippet of Göran's log on Flight 187

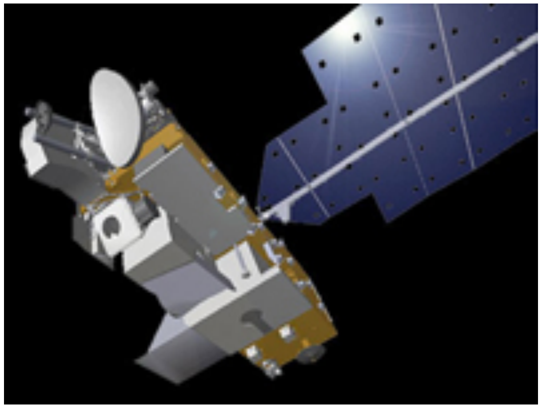
Is the zWV measured by the WVM related to that calculated from weather models used for forecasts and analysis?

WVM VS. MET CORRELATION

See “Jamboree” presentation
https://wiki.sofia.usra.edu/pub/EngDataAnalysis/WaterVaporMonitor/vancleve_jambo3_vapours_2015030318.pptx
for a more detailed discussion of this specific topic

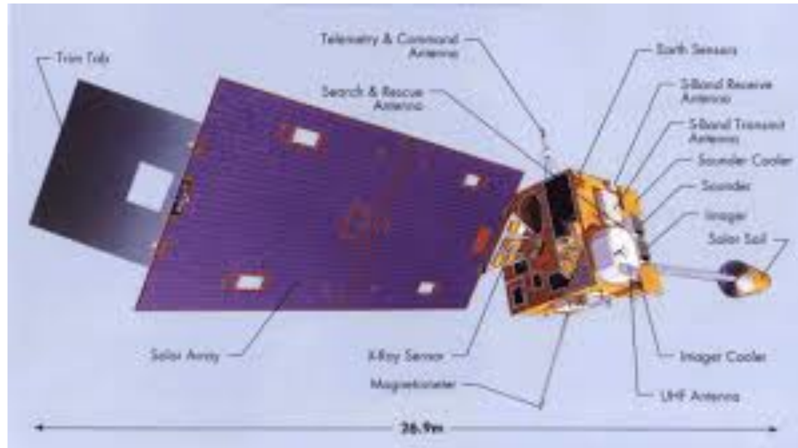
Observation Systems Overview

AURA-Microwave Limb Sounder (MLS)



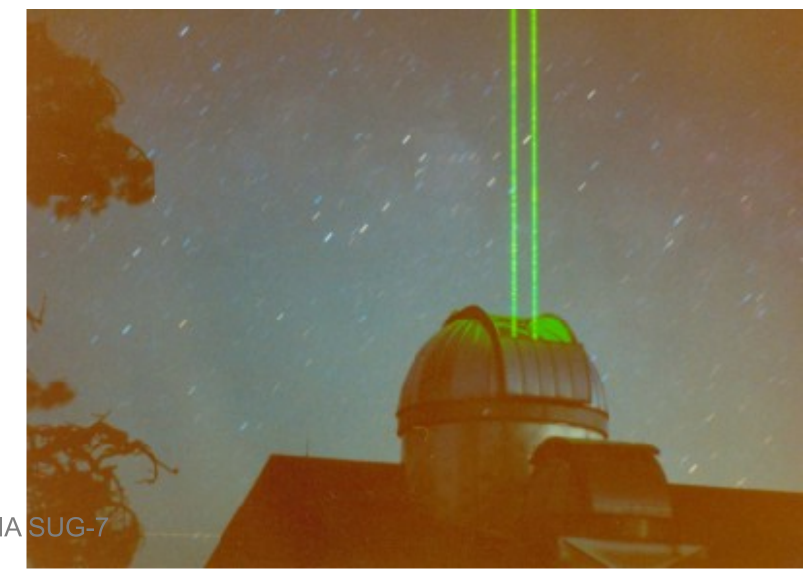
GOES Sounder

Multiband mid-IR

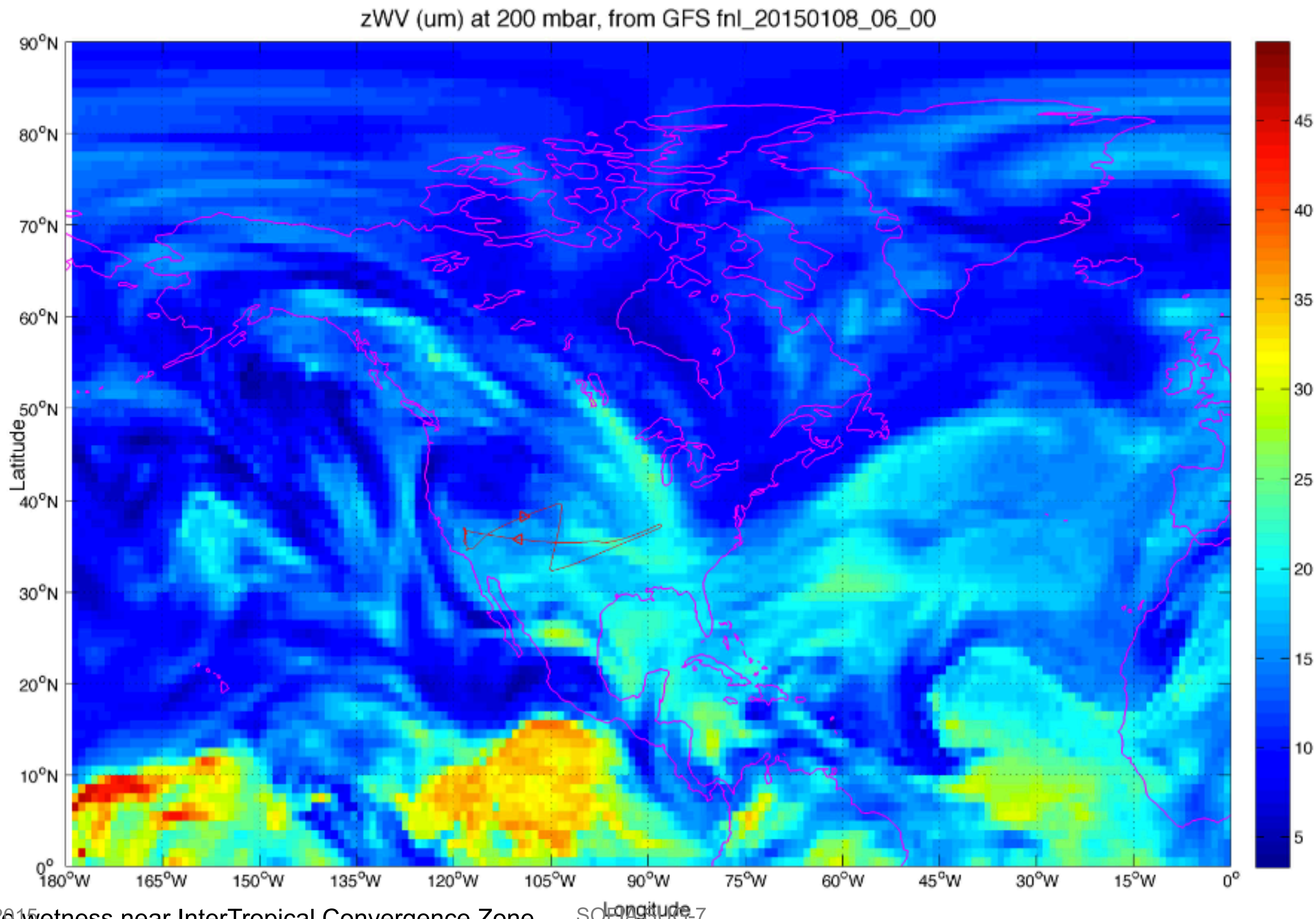


NOAA Frost Point Hygrometer (FPH) – "Gold Standard"

water vapor Raman LIDAR (JPL TMF and EAFB)



Example GFS Final Analysis Converted to zWV
with 2015-01-08_NO_F183 Flight Path Overlay



Note wetness near InterTropical Convergence Zone

References

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- LABOCA: http://www.apex-telescope.org/bolometer/laboca/calibration/opacity/
- SHARC-2: http://www.submm.caltech.edu/~sharc/
- SCUBA-2: http://www.eaobservatory.org/jcmt/instrumentation/continuum/scuba-2/calibration/#Standard_FCF_and_Tau_values

BACKUP SLIDES

Why Monitor Water Vapor?

- **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.
- **Residual WV is still the dominant cause of opacity and background noise over entire IR - FIR - submm range.**
- **Often interested in precisely those wavelengths where WV absorbs since we are looking at WV itself in the cosmos**
  - Atmospheres of exoplanets
  - Star and planet formation regions
- **Especially in summer and in the tropics, the tropopause is so high that our stratospheric observatory can't reach the stratosphere**
  - So there's "weather" above SOFIA's flight altitude, and zWV needs to be measured to 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"

WVM vs. MET Calibration Plan

- **Critically review observing systems to understand limitations – these are the inputs to weather analysis products (GIGO)**
  - Accuracy of WV measurements at SOFIA flight levels (35 – 45 kft)
  - Spatial and temporal sampling
    - *Sparse?*
    - *Irregular?*
- **Tools for converting all data (dew point, relative humidity, H2O mass or volume mixing ratios) to zWV**
- **Interpolation tools and usability criteria for sparse data**
- **Compare WVM to observations**
- **Compare WVM to MET pre-flight zWV forecasts extracted along as-flown flight path**
- **Compare WVM to zWV calculated from Global Forecasting System "Final Analysis"**

Next Steps

- **Use GFS Final Analysis (FNL) for MET data**
  - Uniform spatial and temporal sampling
  - Made with the same model which NCEP uses in the Global Forecast System (GFS)
  - Delayed so that more observational data can be used
- **Hire two summer interns for data quality assessment and calibration**
- **Work out empirical WVM-SI calibration plan using EXES and GREAT data as pathfinders**
- **Regularly use TMF or Edwards LIDAR**