Future Surveys

Fundamental Limits and Global Site Statistics

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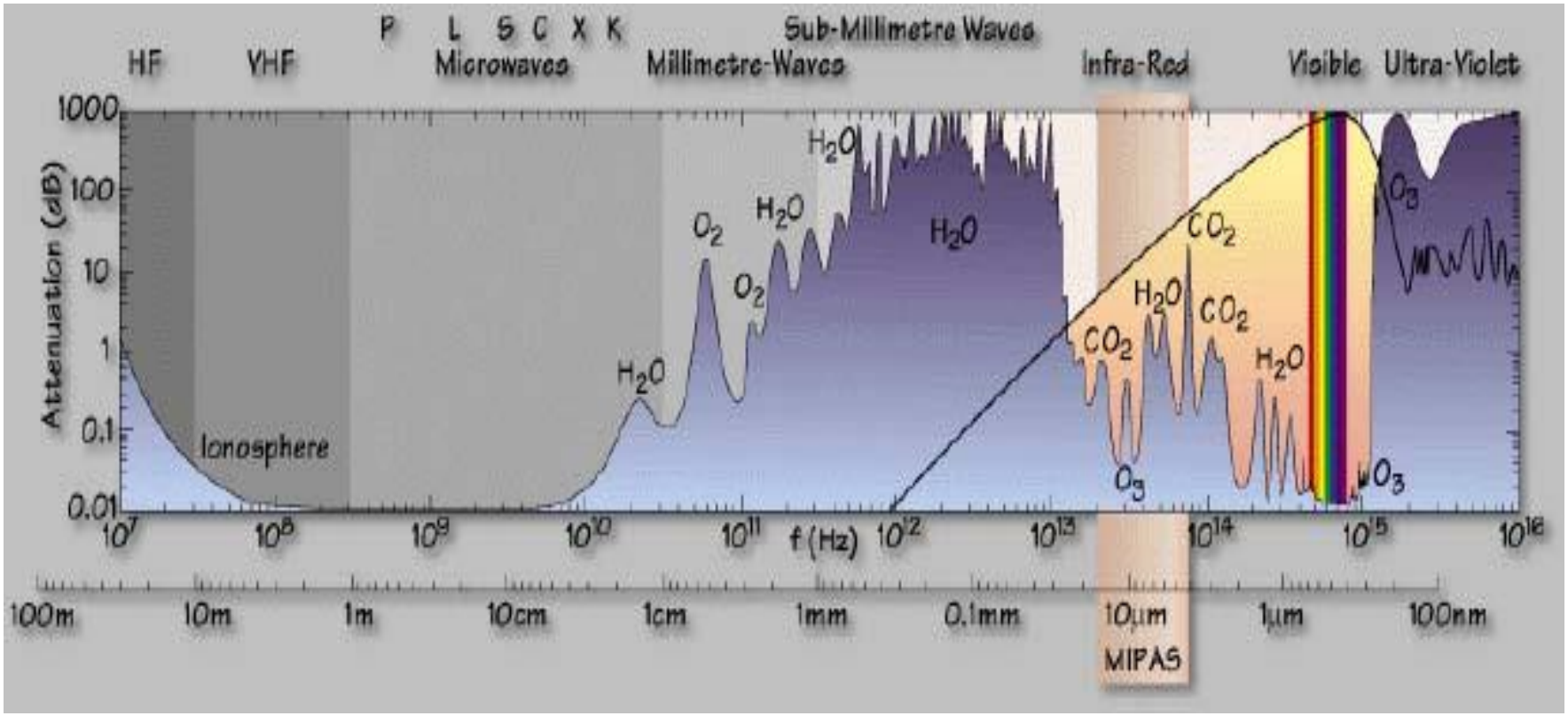
Recent Relevant Publications

- Fundamental Limits of Detection in the Far IR, S. Denny, J. Suen and P. Lubin New Astronomy 25,114, 2013.
- Global Distribution of Water Vapor and Cloud Cover - Sites for High performance THz Applications , J. Suen, M. Fang, and P. Lubin, IEEE Trans. THz Science and Technology, Vol. 4, 1, 86, 2015.
- Modeling of Terabit Geostationary Terahertz Satellite Links from Globally Dry Locations, J. Y. Suen, M. T. Fang, S. P. Denny, P. M. Lubin , IEEE Trans. THz Science and Technology, Vol 5, Issue 2, 2015.

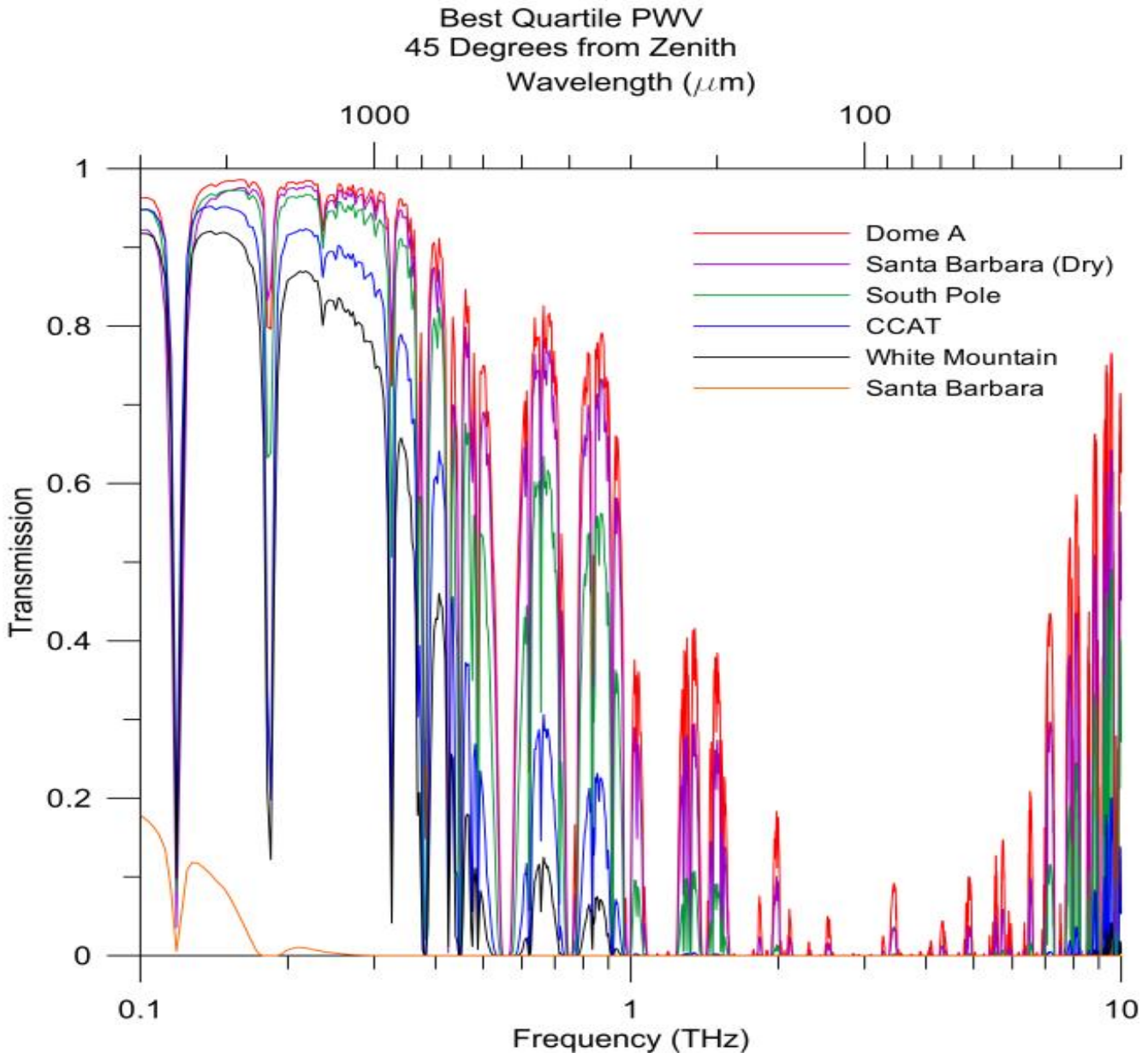
Sufficiency and Necessity

- What is good enough
- What is necessary and what is sufficient
- Lets rank some potential sites:
  1. Extragalactic – clearly desired
  2. Outside the solar system
  3. Moon
  4. L2
  5. LEO, GEO
  6. Balloon
  7. Dome A
  8. S. Pole
  9. Greenland/ Tibet
  10. ALMA/ Chile
  11. White Mountain, Mauna Kea etc
  12. Kona

EM spectrum from the Ground – The Big Picture

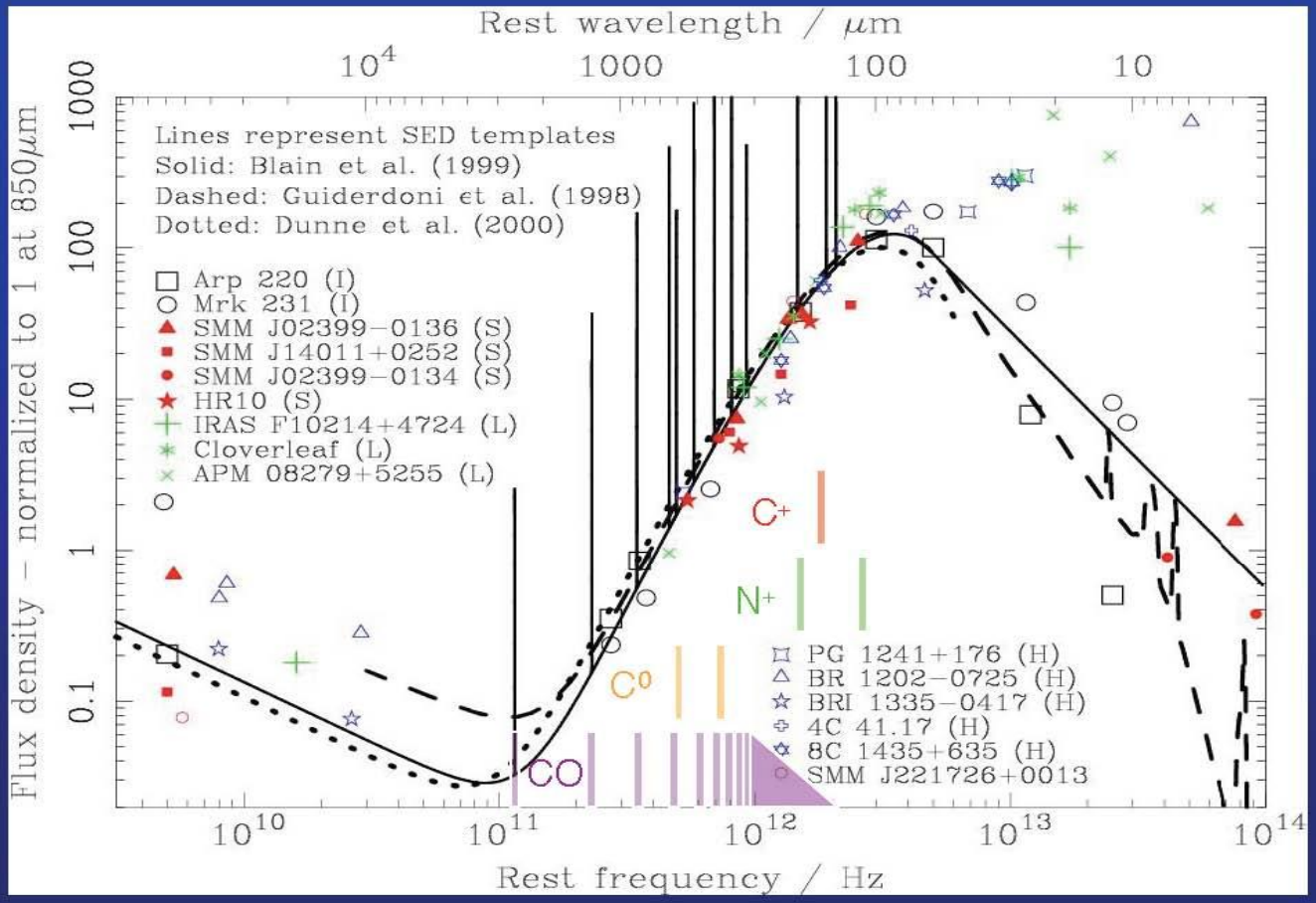


Far IR Transmission vs Frequency - Ground



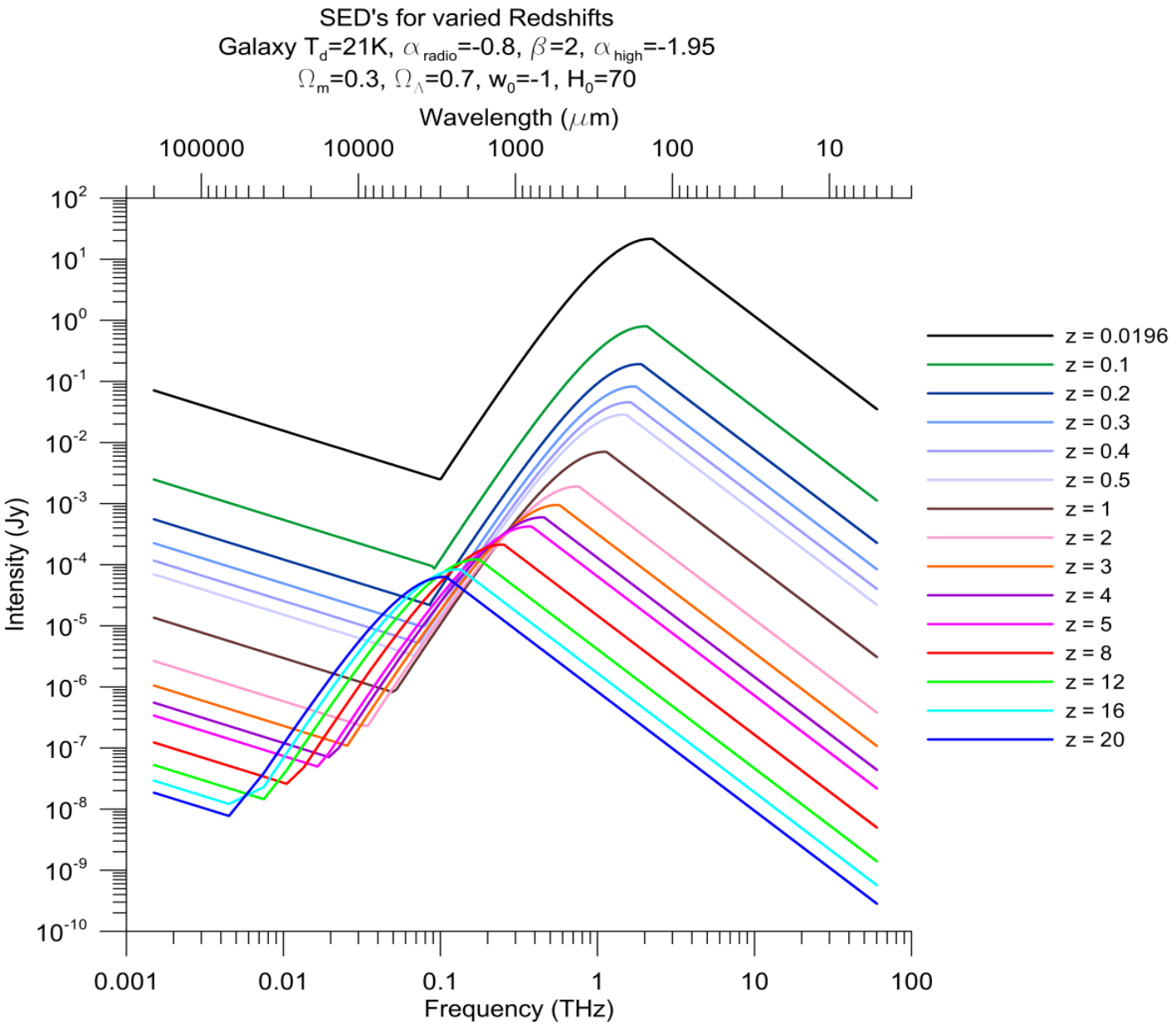
SED with Lines

Extragalactic spectroscopy beyond 100 microns

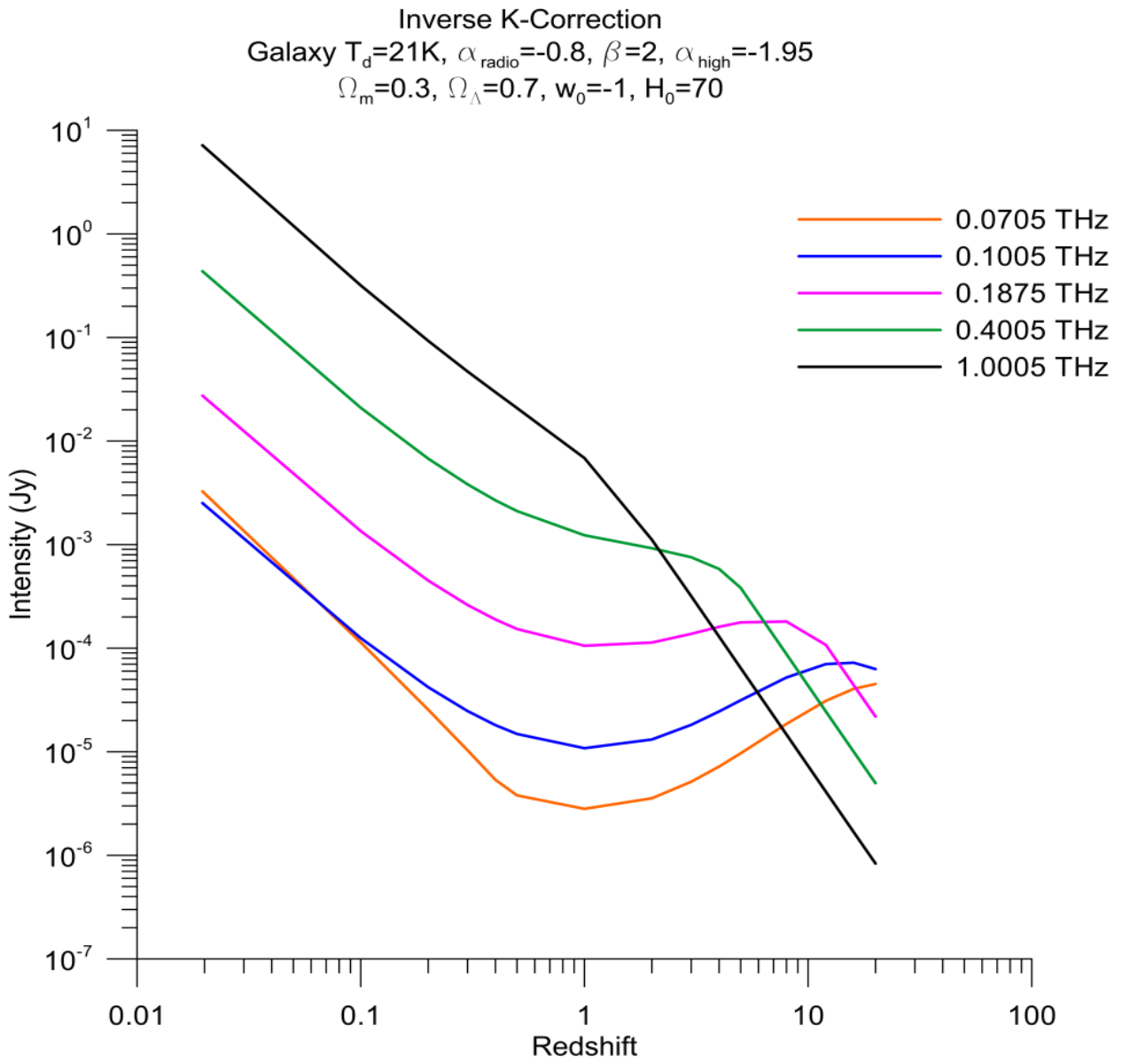


SED courtesy A. Blain

SED vs Redshift

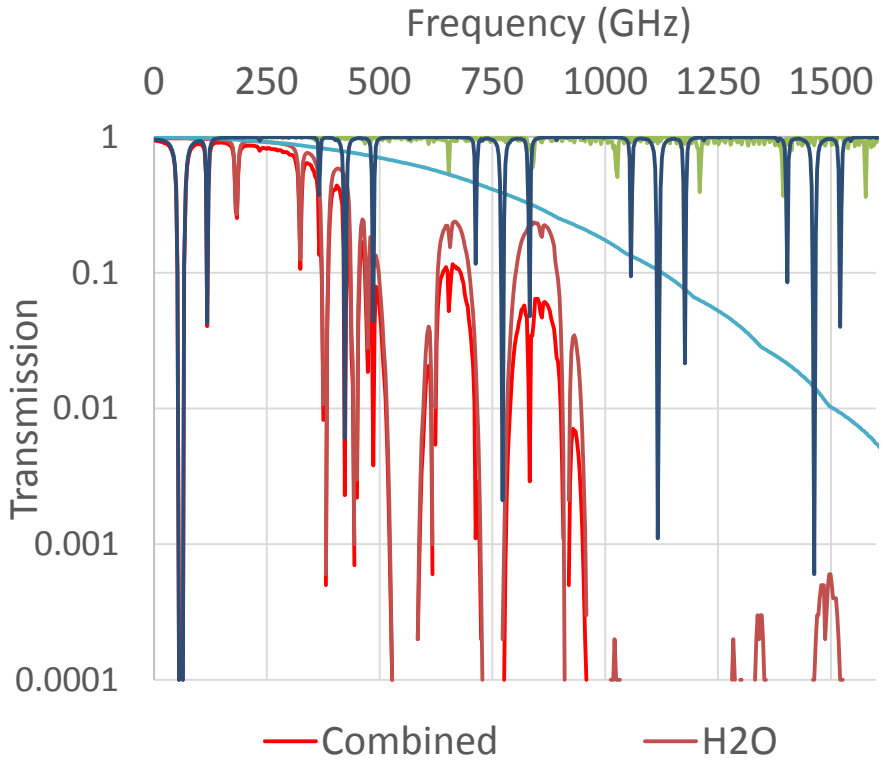


Strong Inverse K Correction



Water Vapor – The Enemy

- Most of the atmospheric lines in the THz regime are from water vapor.

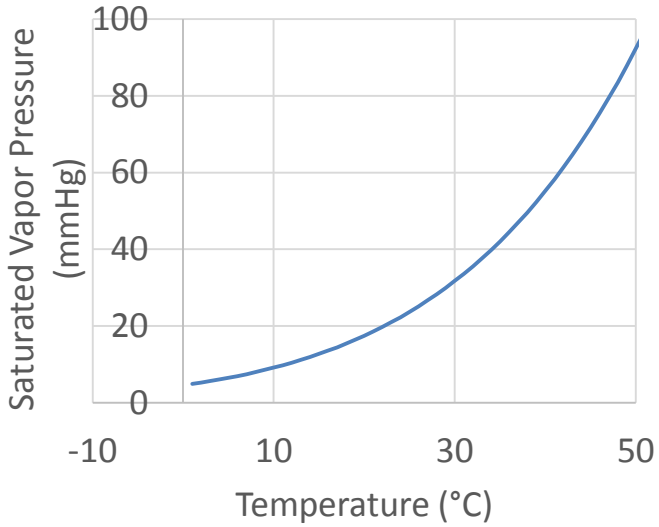


- Oxygen has a number of discrete lines
  - 60 GHz band (Magnetic dipolar)
  - Regular structure

- Negligible until the IR: CO, CO_2, CH_4, NOX (N_2O, $HNO_{3,4}$, NO, NO_2…), NH_3
- (in gas phase)

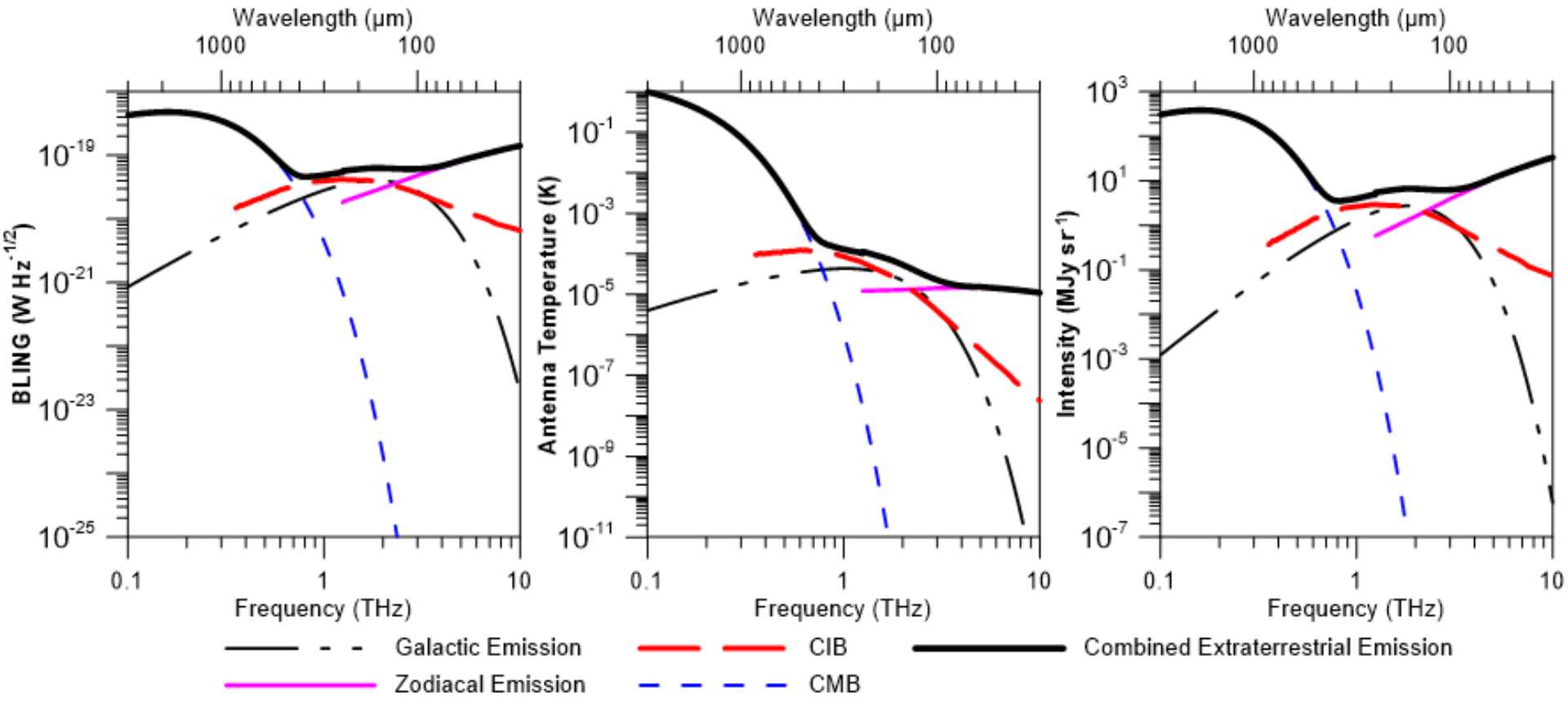
Distribution of Gasses

- Water distribution is a strong function of temperature.



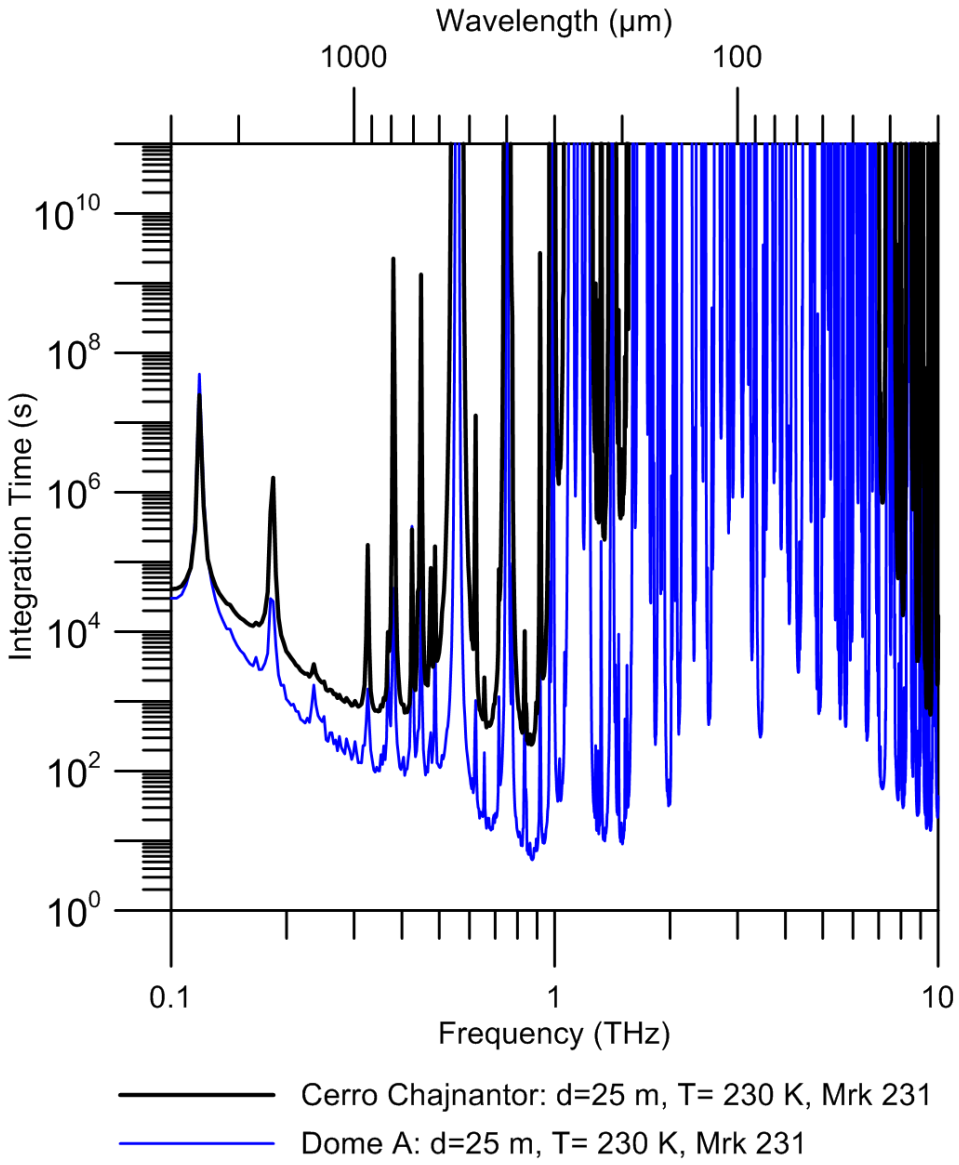
- Scale height (1/e distance) of water is much smaller than other atmospheric gasses
  - H2O = 1.5 km
  - O_2, N_2 = 7.6 km
- Mixing of O_2, N_2, Ar uniform until ~80 km.
- Very little atmosphere by 100 km.

Galaxy-Zodi-CIB-CMB Foregrounds

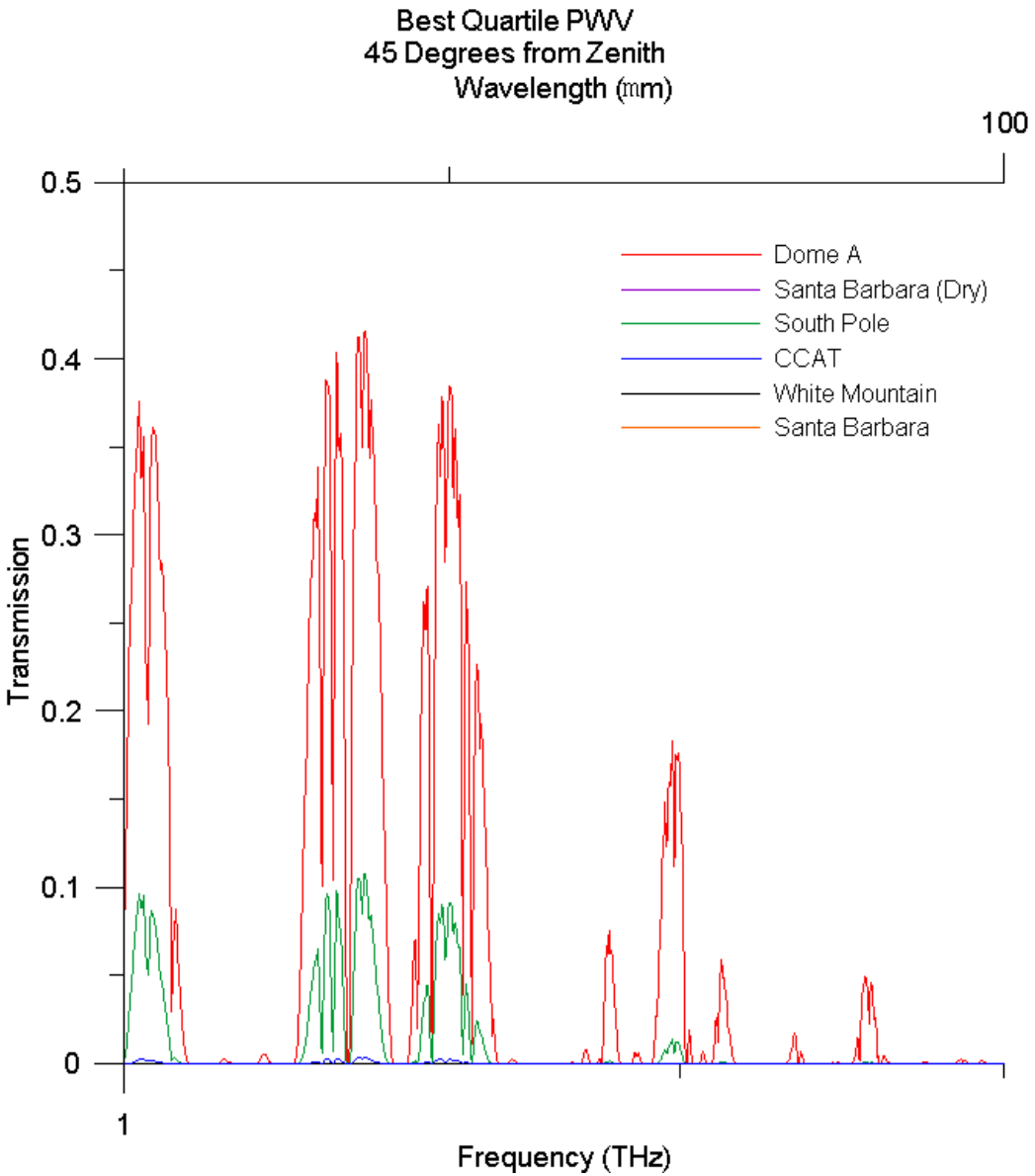


CCAT Class (25m) Integration vs Site - FIR

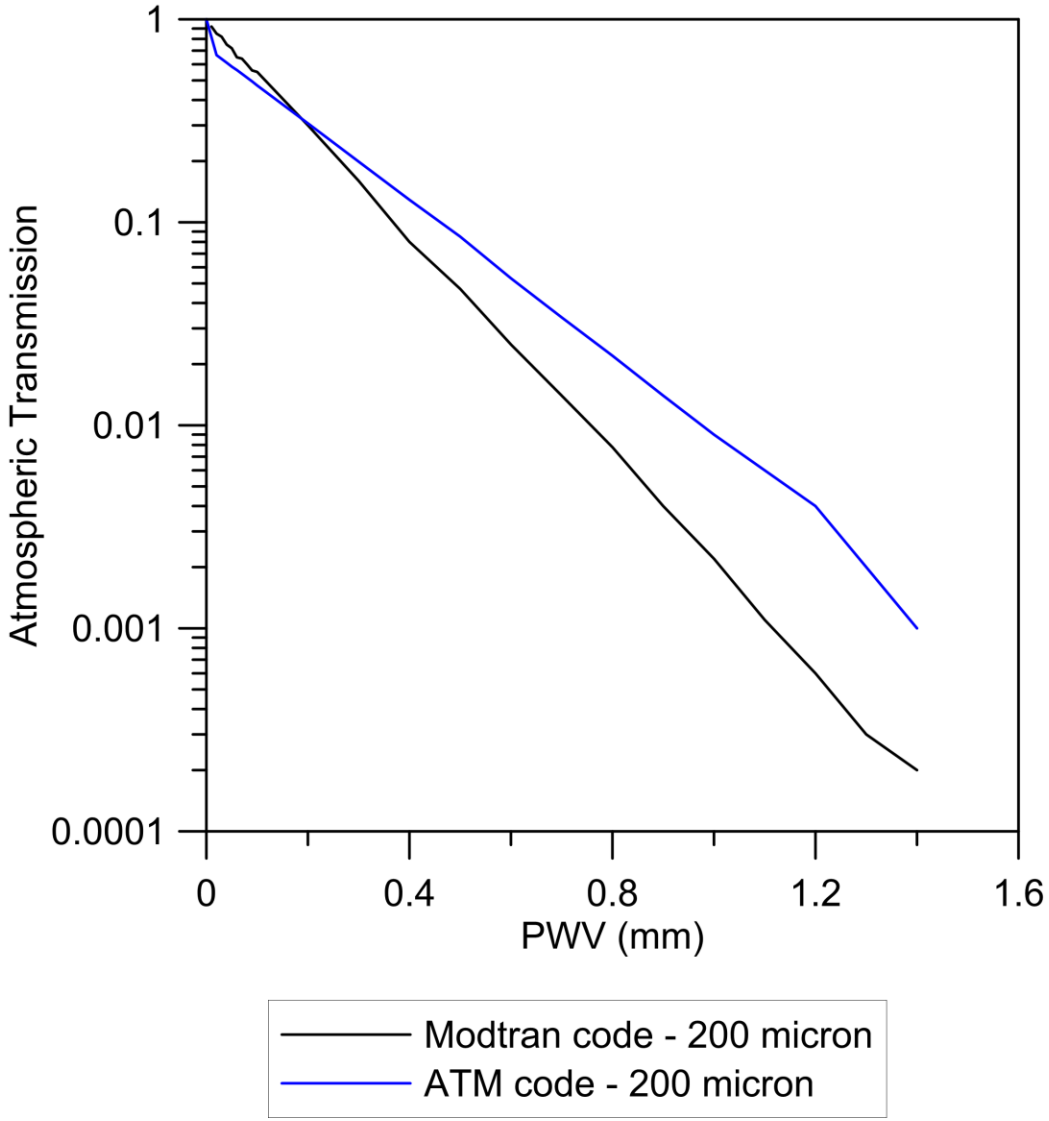
Mk231@ z=1 SNR=5 R=1000



Extreme Sensitivity to PWV (Ex: λ = 100-300μ)
Dome A (0.1 mm), SP (0.23 mm), CCAT site (0.73 mm)



Extreme Sensitivity to PWV for Sub mm Windows
Shown for 200 micron window (1.5 THz)



PWV (g/cm^2)– Best 25 and 50%

% Time with PWV	Dome A (4100m)	Dome C (3250m)	South Pole (2850m)	CCAT (5600m)	White Mountain (3800m)	Mauna Kea (4100m)
25%	0.010	0.015	0.023	0.0732	0.115	0.10
50%	0.014	0.024	0.032	0.0978	0.175	0.15

Dome A, Dome C, South Pole, and Mauna Kea values are from Yang et al. 2010. CCAT values are for Chajnantor in Herter and Radford 2005. White Mountain values are from Marvil et al. 2005.

Characterizing water vapor

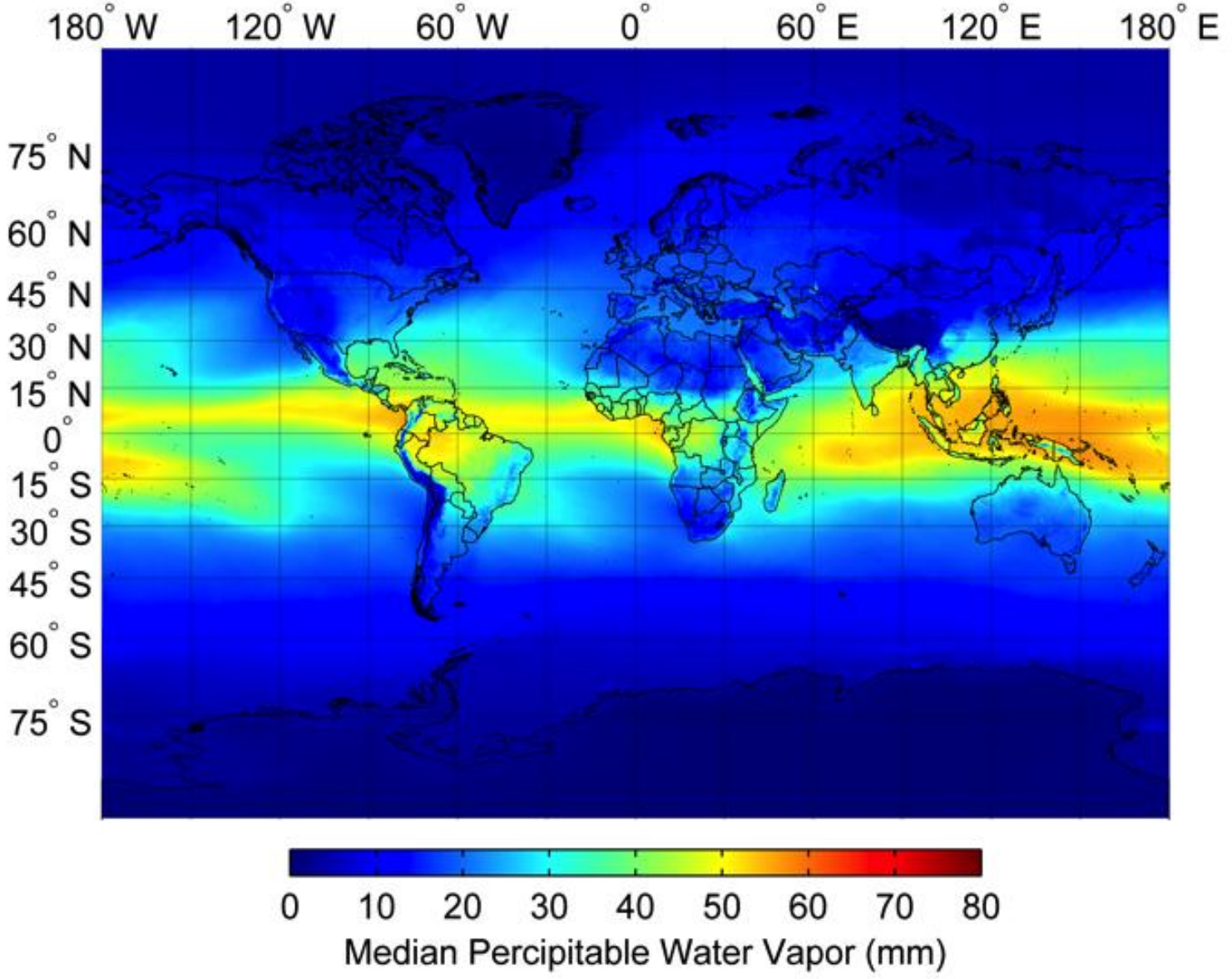
- Dependence of transmission to water column is basically Beer-Lambert

Freq. (GHz)	α (Exp,/mm)
30	0.0232
275	0.162
404	0.560
667	1.50
847	1.89
925	4.12
1015	8.08
1336	8.70
1500	8.45

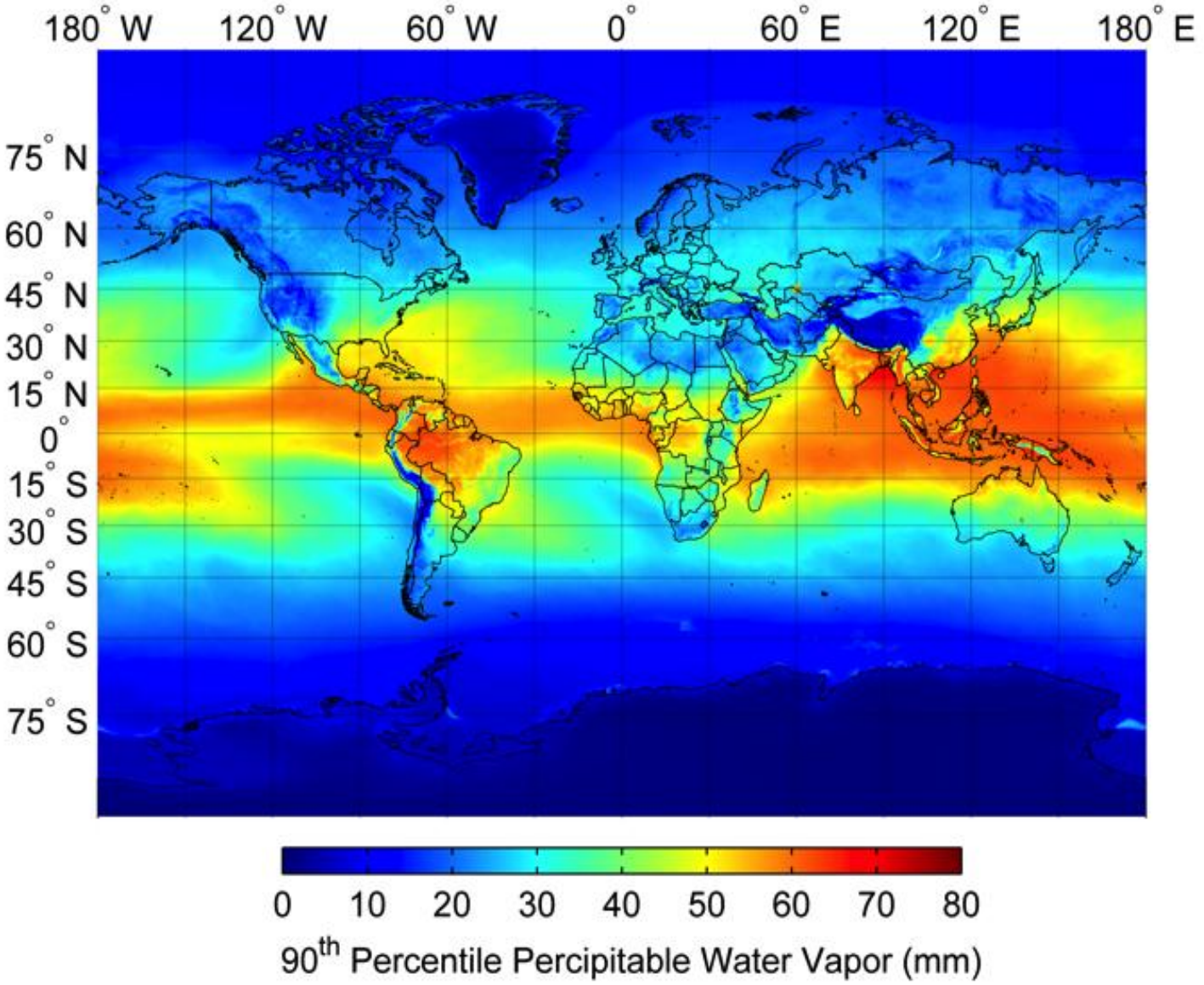
- 86, 225, 857 GHz Tipping radiometers
- Availability limited
- Clouds have low water vapor (0.2 mm) but high scattering

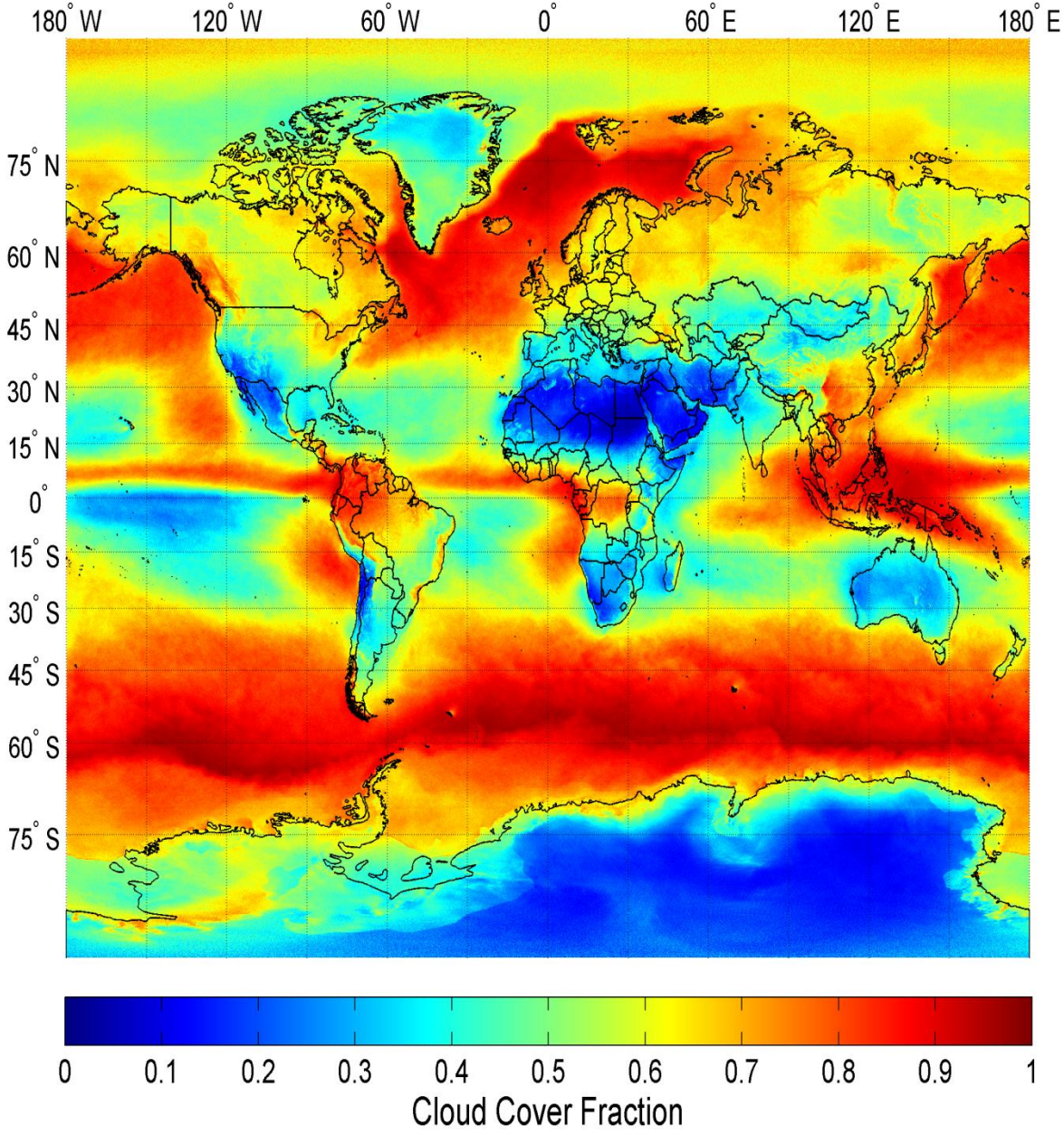
- Desired Coverage:
- Global Scale
- High Resolution
- Continuous Coverage
- Cloud Information

Median (50%) PWV



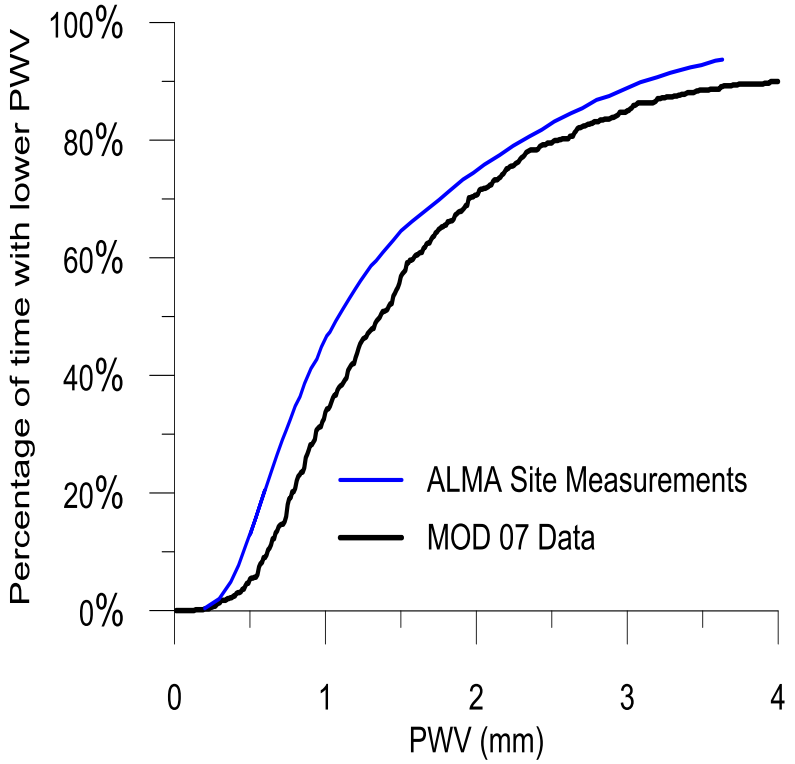
90% PWV

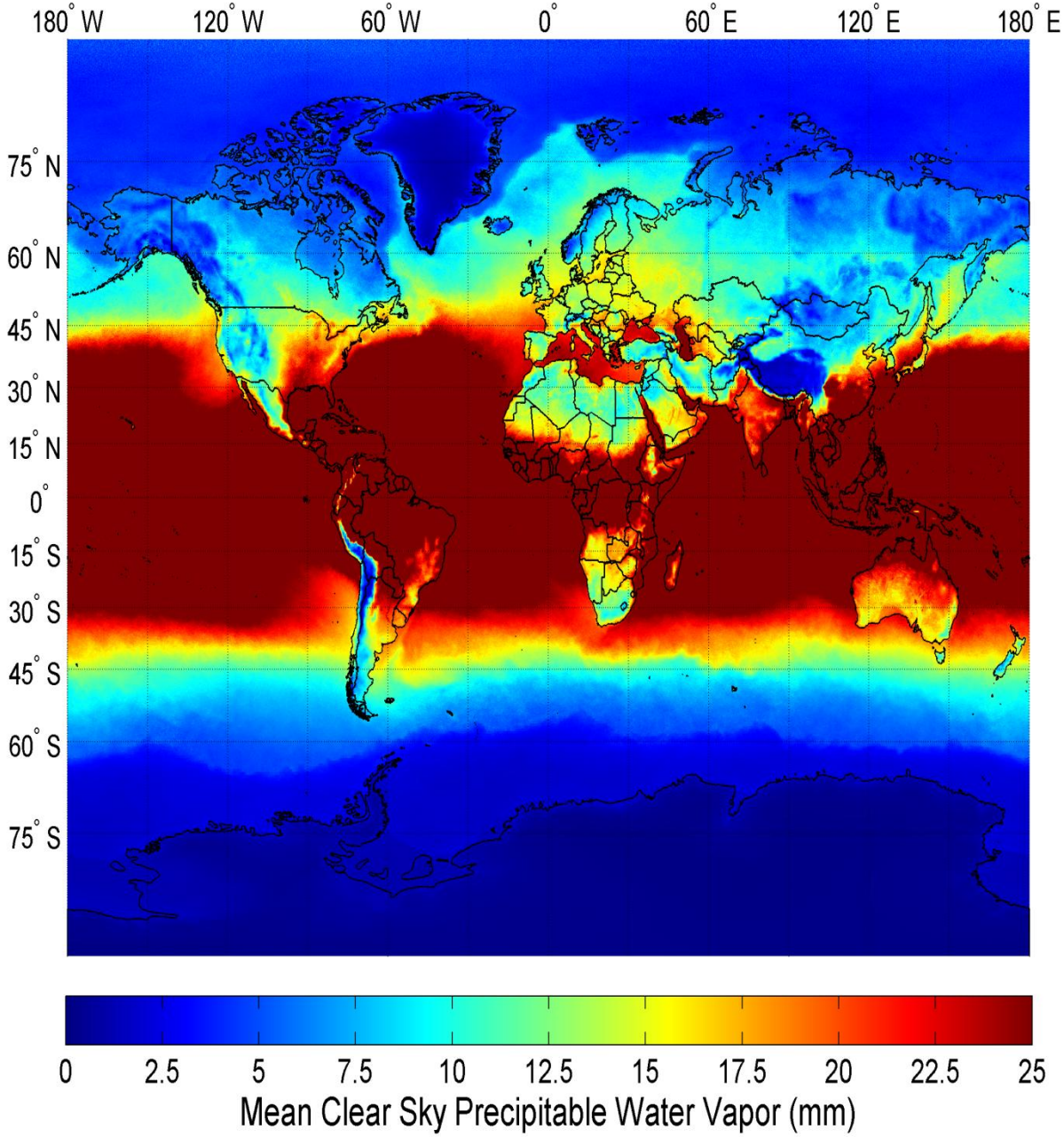

180° W
120° W
60° W
0°
60° E
120° E
180° E
75° N
60° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
60° S
75° S
0
10
20
30
40
50
60
70
80
90th Percentile Percipitable Water Vapor (mm)

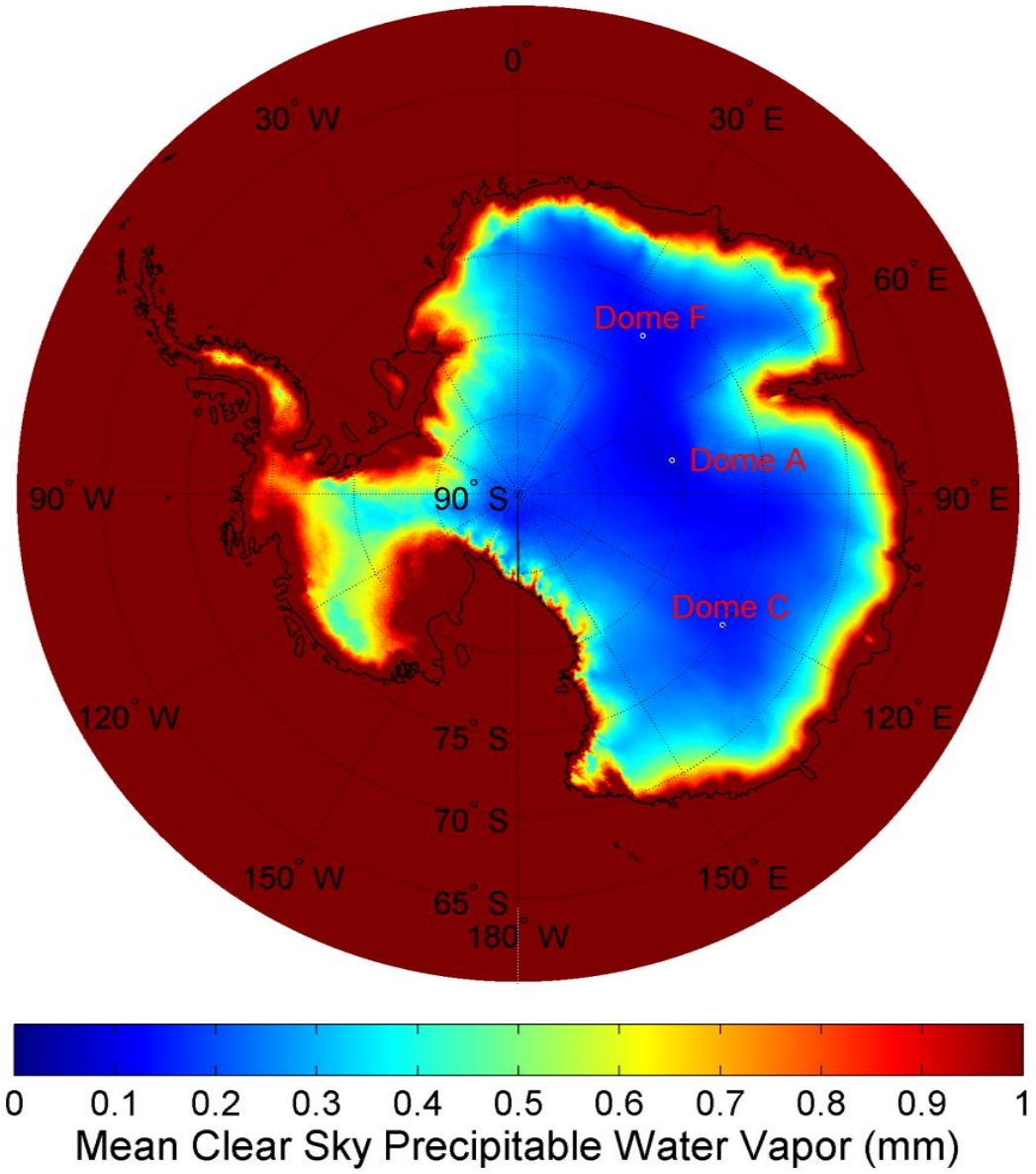

180° W
120° W
60° W
0°
60° E
120° E
180° E
75° N
60° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
60° S
75° S
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Cloud Cover Fraction

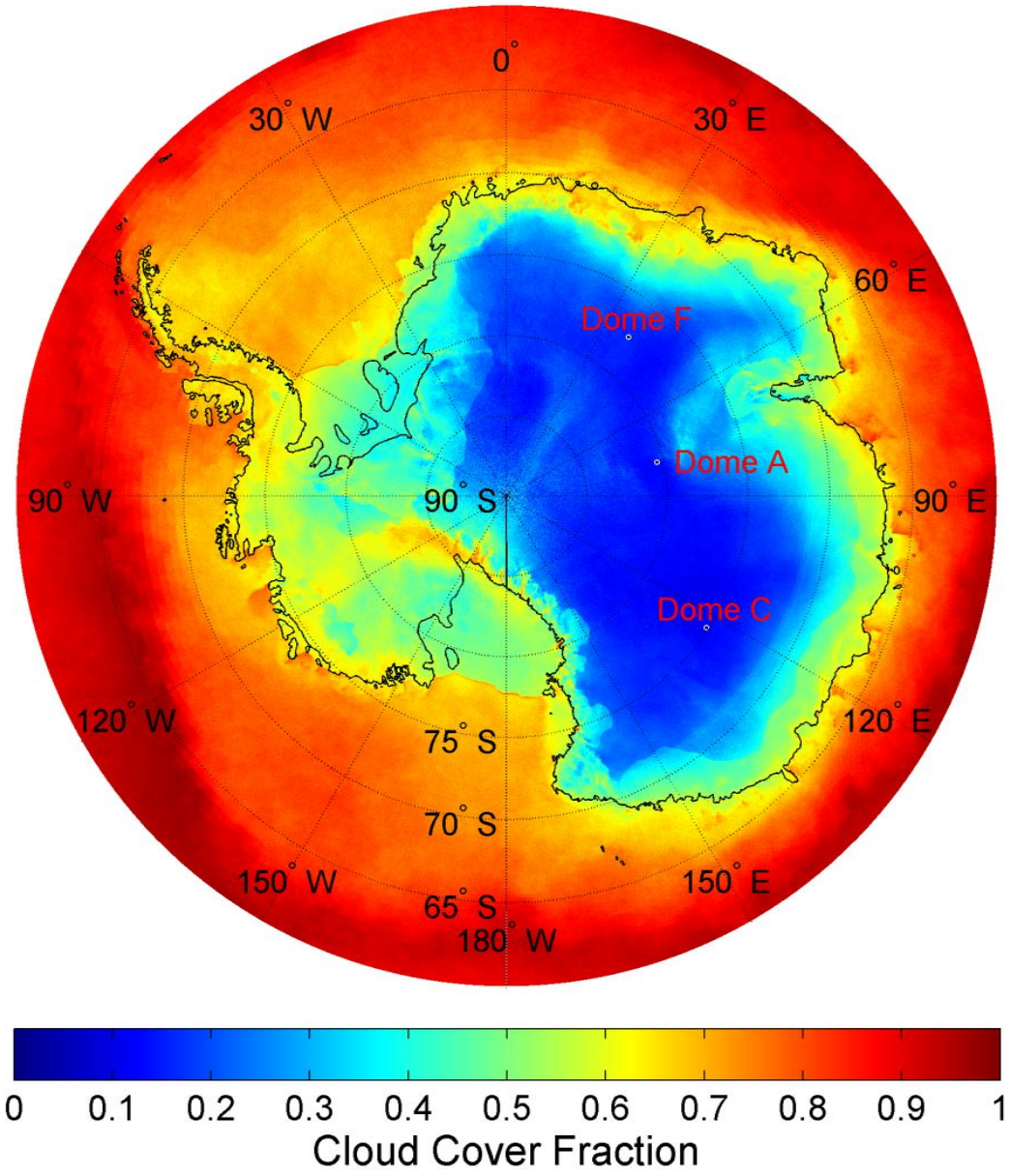
MOD07 Profile vs Ground Measure

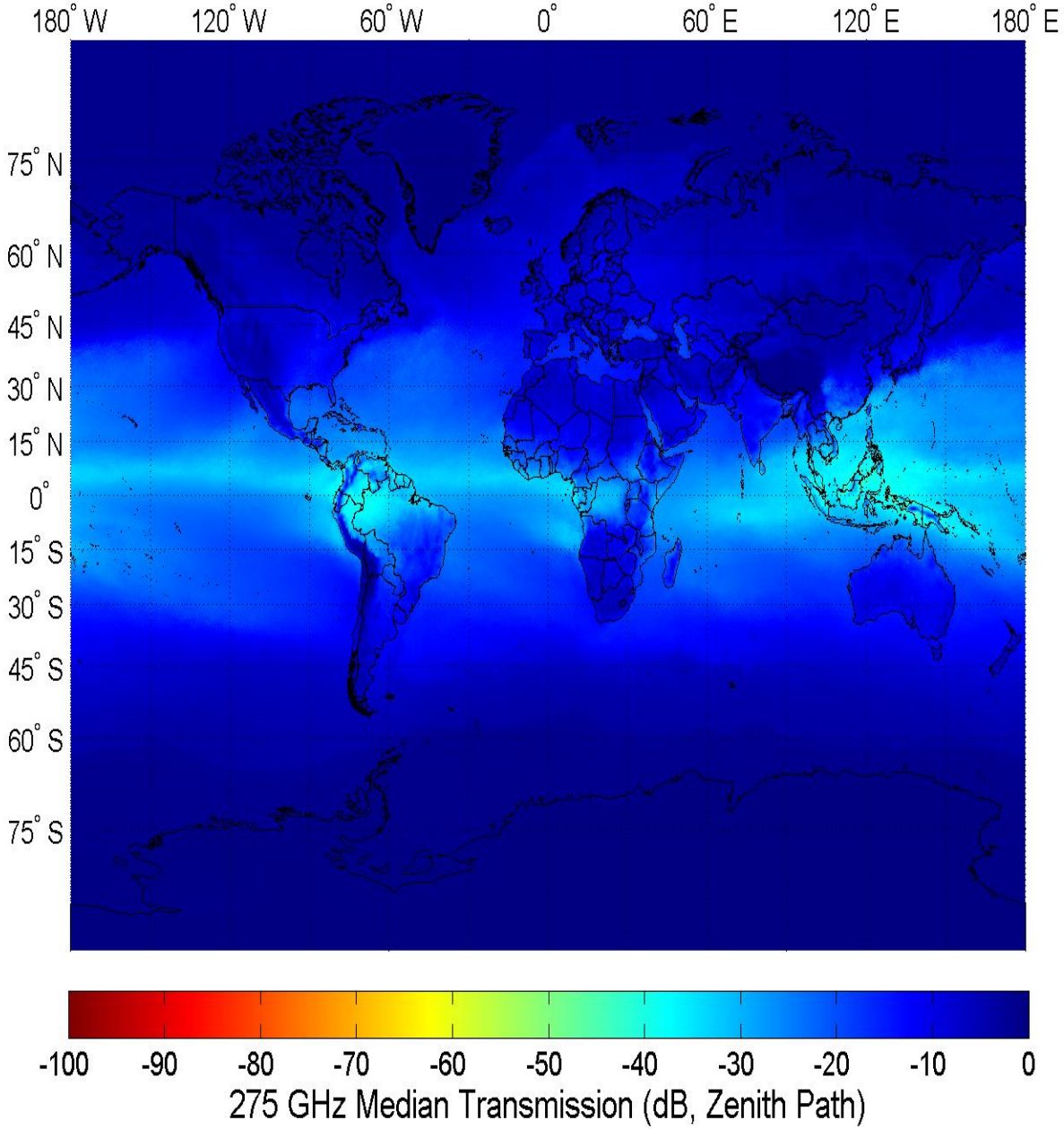
- Dataset used was CY 2011
- MOD07 Validation (ATBD)
  - RMSE (<15 mm) = 2.2 mm
  - Bias 0.7 mm mornings, 0.3 mm afternoons
- Difficult to get exactly the same data
  - Dome A, Antarctica 0.07 mm median MOD07 vs. 0.14 mm site
  - South Pole 0.10 mm MOD07 vs 0.24 mm site
  - ALMA 1.37 mm MOD07 vs 1.1 mm site
  - OVRO 5.36 mm MOD07 vs 5 mm site
  - Mauna Kea, 14.55 mm vs 1.5 mm site

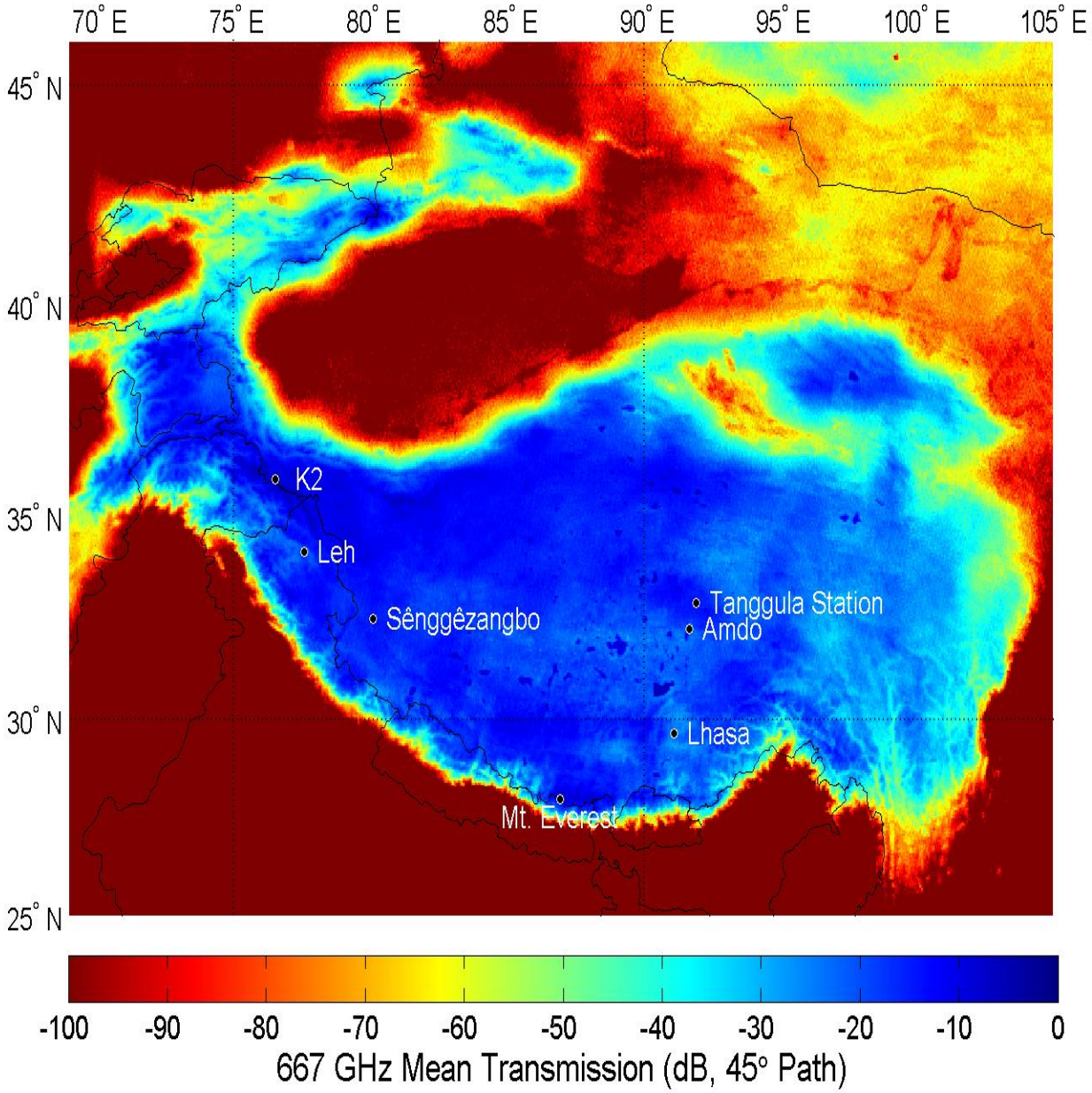


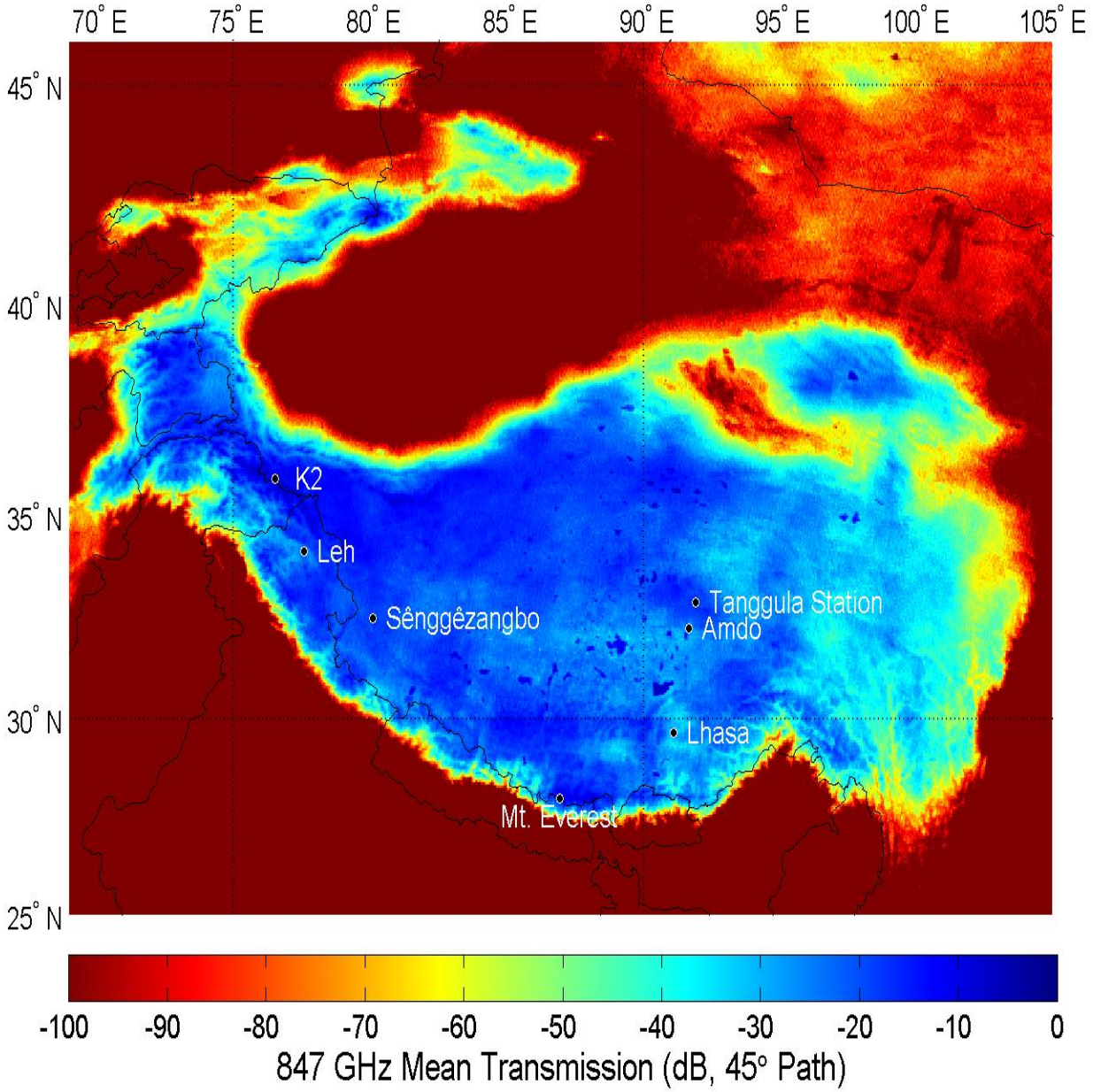

180° W
120° W
60° W
0°
60° E
120° E
180° E
75° N
60° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
60° S
75° S
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Mean Clear Sky Precipitable Water Vapor (mm)

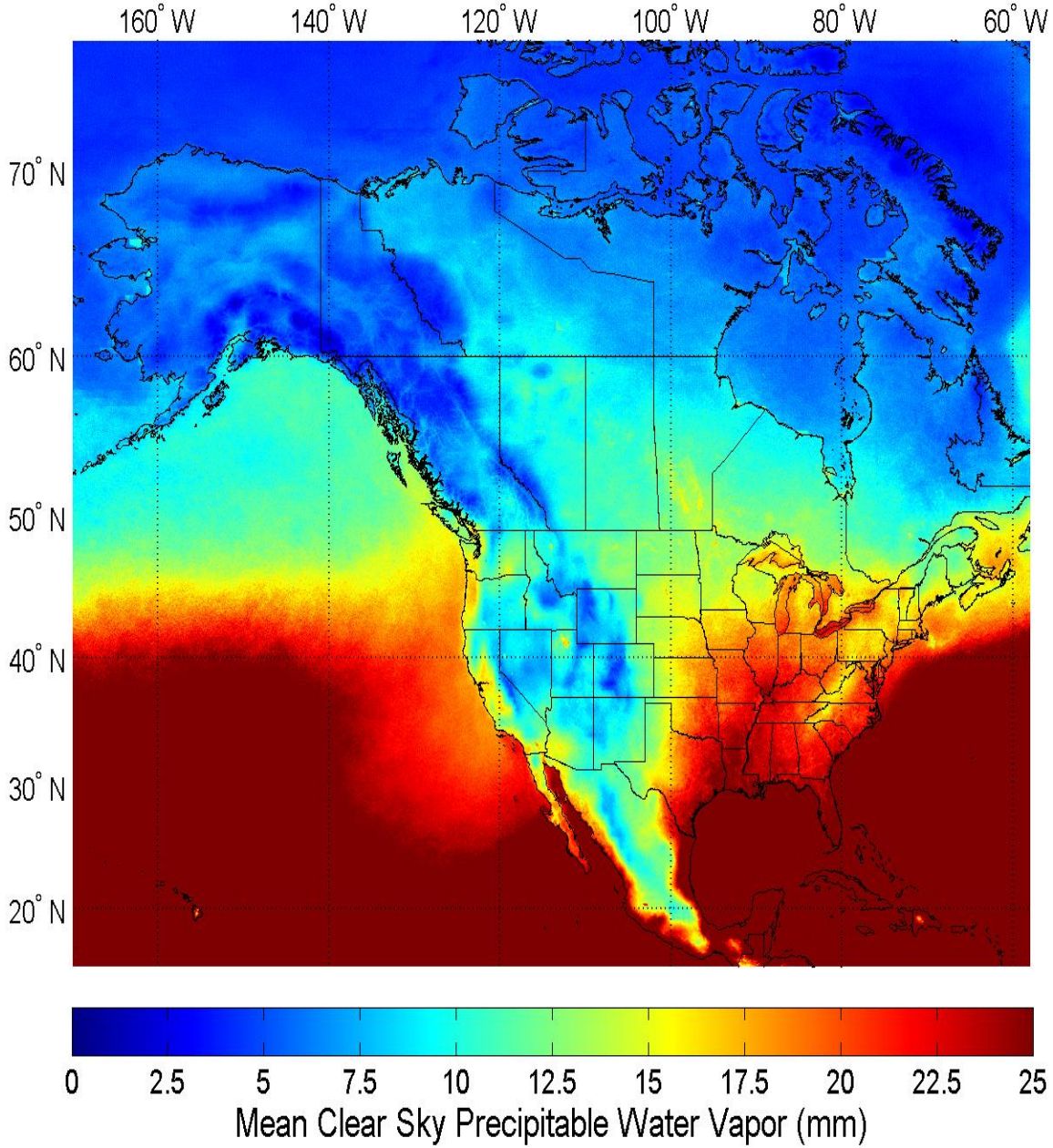

0°
30° W
30° E
60° E
Dome F
Dome A
90° W
90° S
90° E
Dome C
120° W
120° E
75° S
70° S
150° W
150° E
65° S
180° W
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Mean Clear Sky Precipitable Water Vapor (mm)

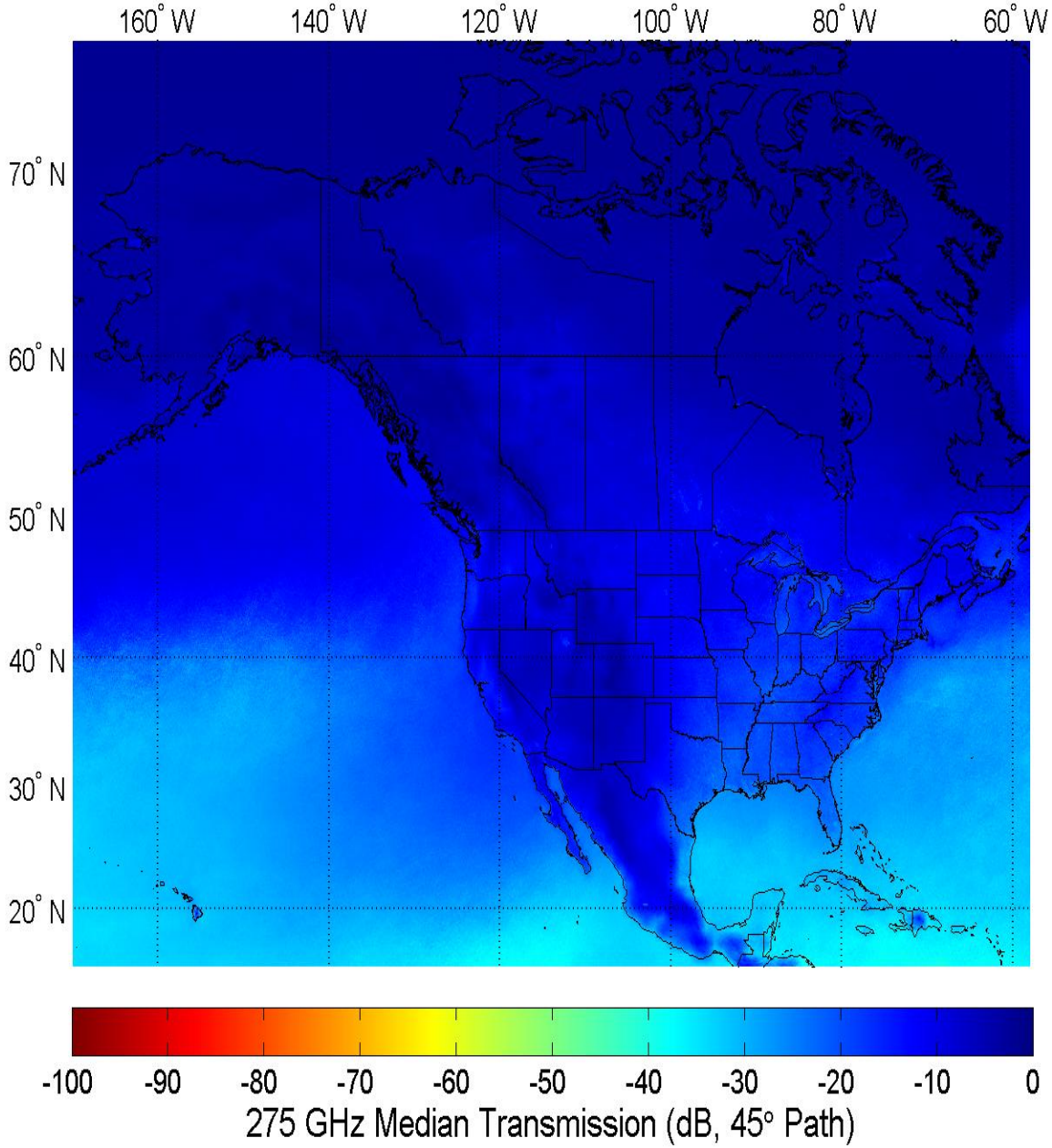

0°
30° W
30° E
60° E
Dome F
Dome A
90° W
90° S
90° E
Dome C
120° W
75° S
120° E
70° S
150° W
65° S
150° E
180° W
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Cloud Cover Fraction


180° W
120° W
60° W
0°
60° E
120° E
180° E
75° N
60° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
60° S
75° S
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
275 GHz Median Transmission (dB, Zenith Path)

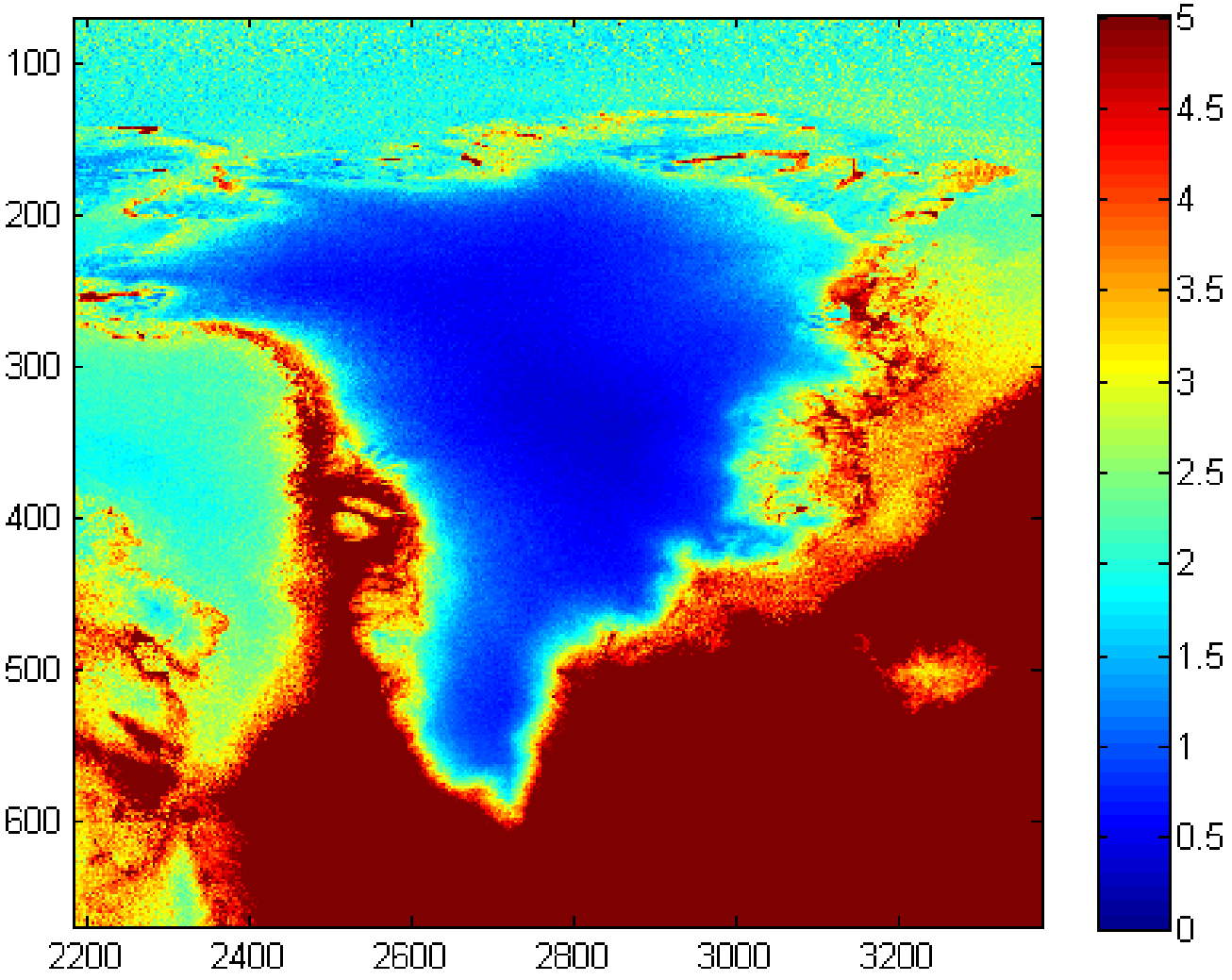

70° E
75° E
80° E
85° E
90° E
95° E
100° E
105° E
45° N
40° N
35° N
30° N
25° N
K2
Leh
Sênggêzangbo
Tanggula Station
Amdo
Lhasa
Mt. Everest
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
667 GHz Mean Transmission (dB, 45° Path)


70° E
75° E
80° E
85° E
90° E
95° E
100° E
105° E
45° N
40° N
35° N
30° N
25° N
K2
Leh
Sênggêzangbo
Tanggula Station
Amdo
Lhasa
Mt. Everest
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
847 GHz Mean Transmission (dB, 45° Path)

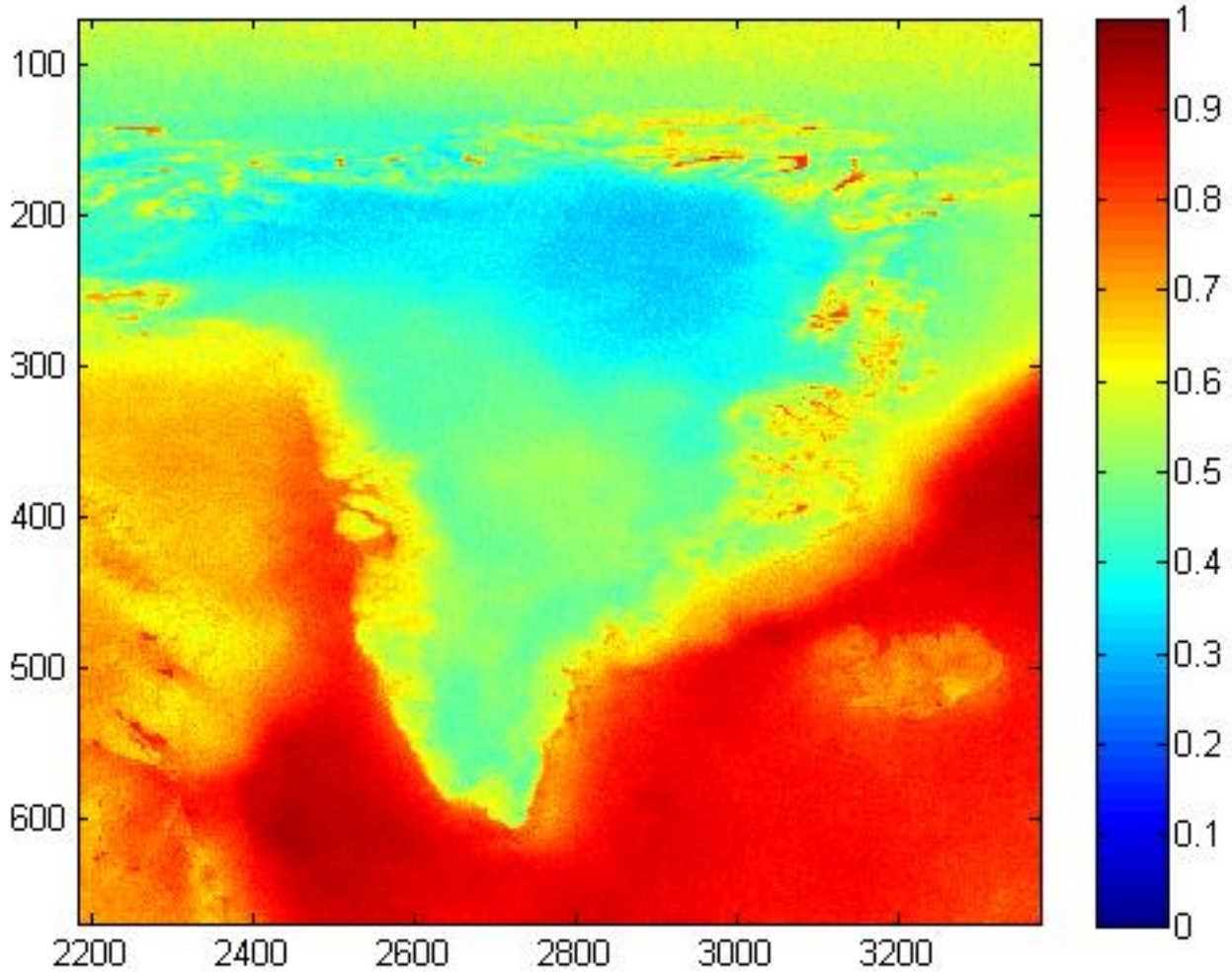

160° W
140° W
120° W
100° W
80° W
60° W
70° N
60° N
50° N
40° N
30° N
20° N
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Mean Clear Sky Precipitable Water Vapor (mm)


160° W
140° W
120° W
100° W
80° W
60° W
70° N
60° N
50° N
40° N
30° N
20° N
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
275 GHz Median Transmission (dB, 45° Path)

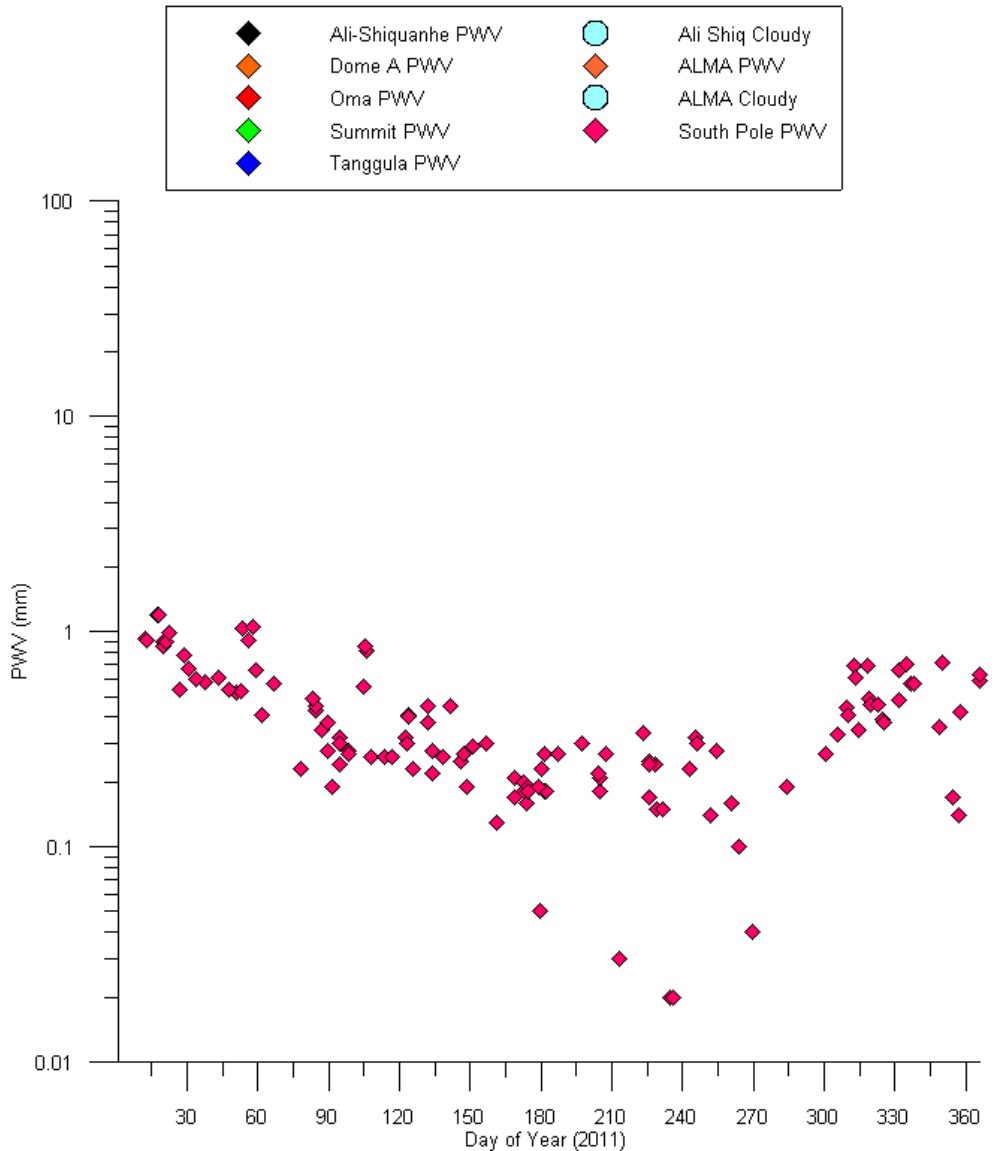
Greenland PWV



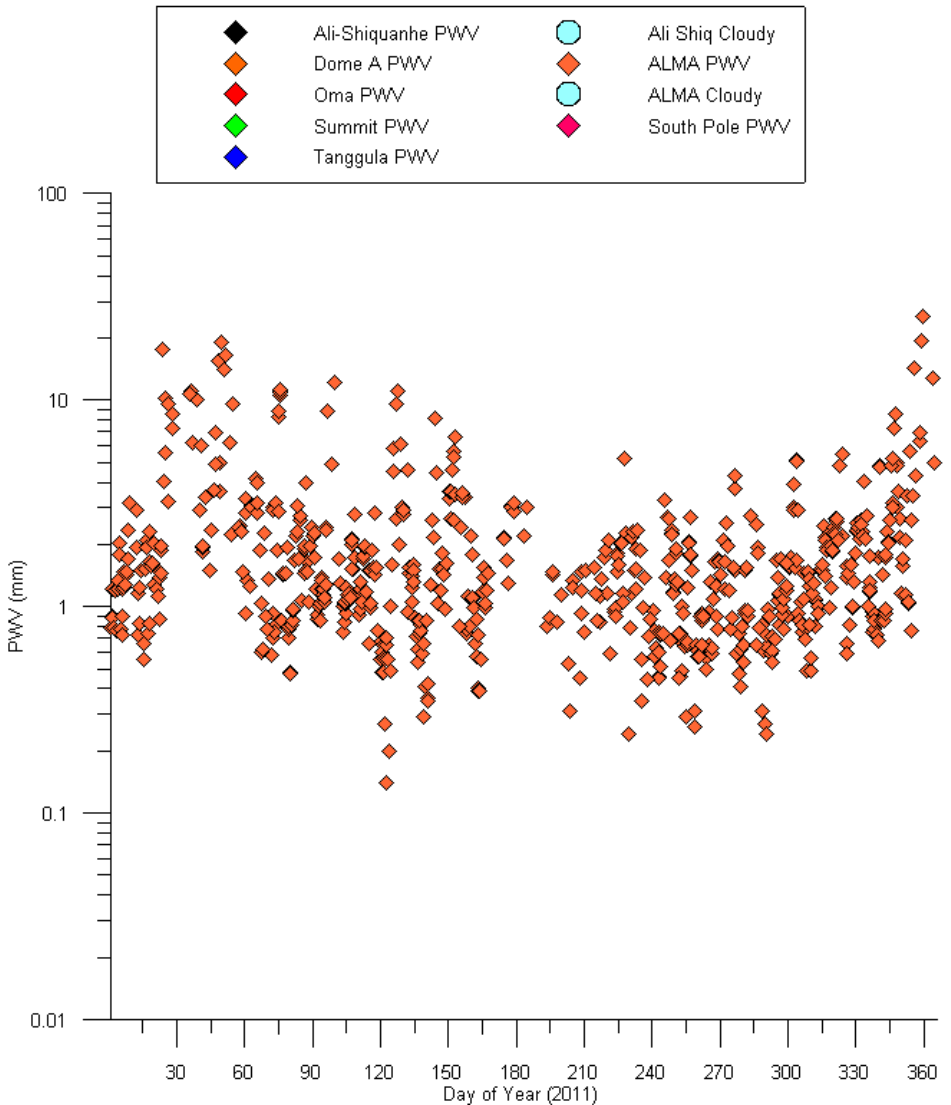
Greenland Cloud Fraction



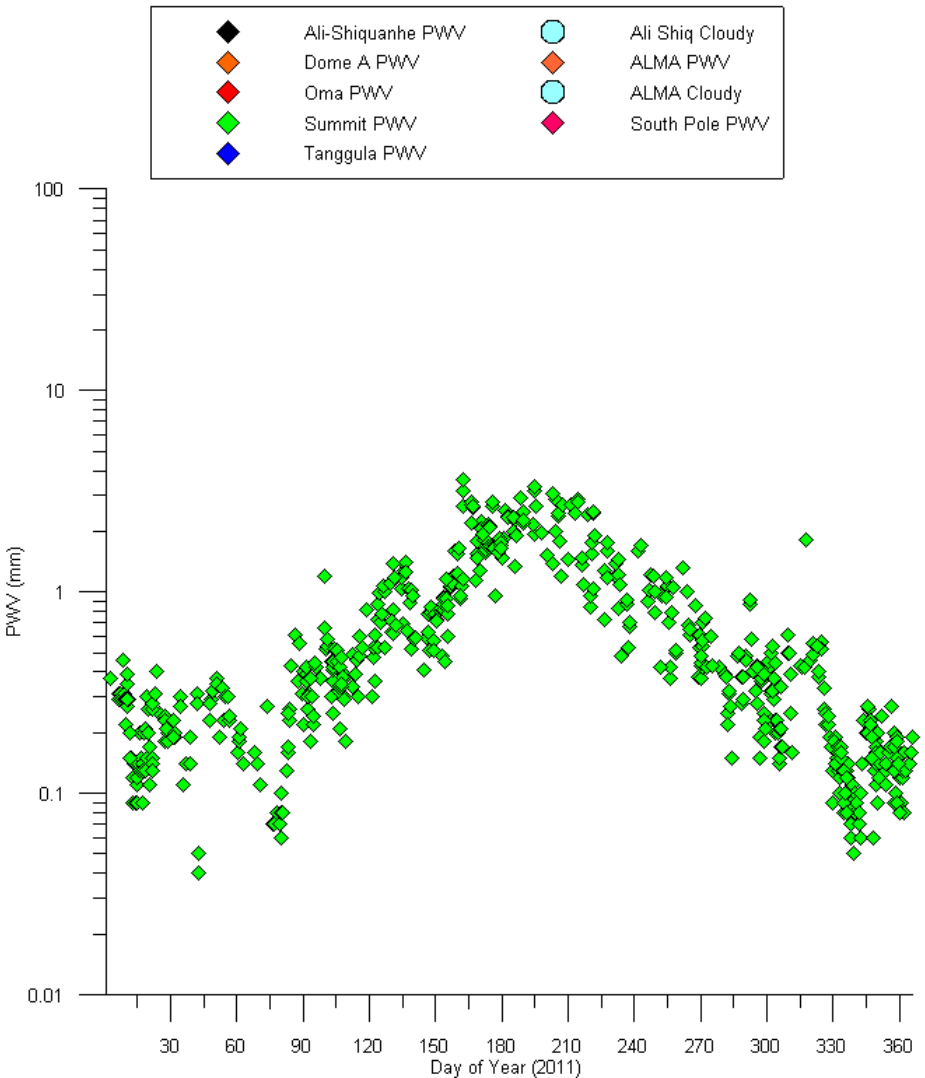
PWV Clear South Pole 2011 Time series



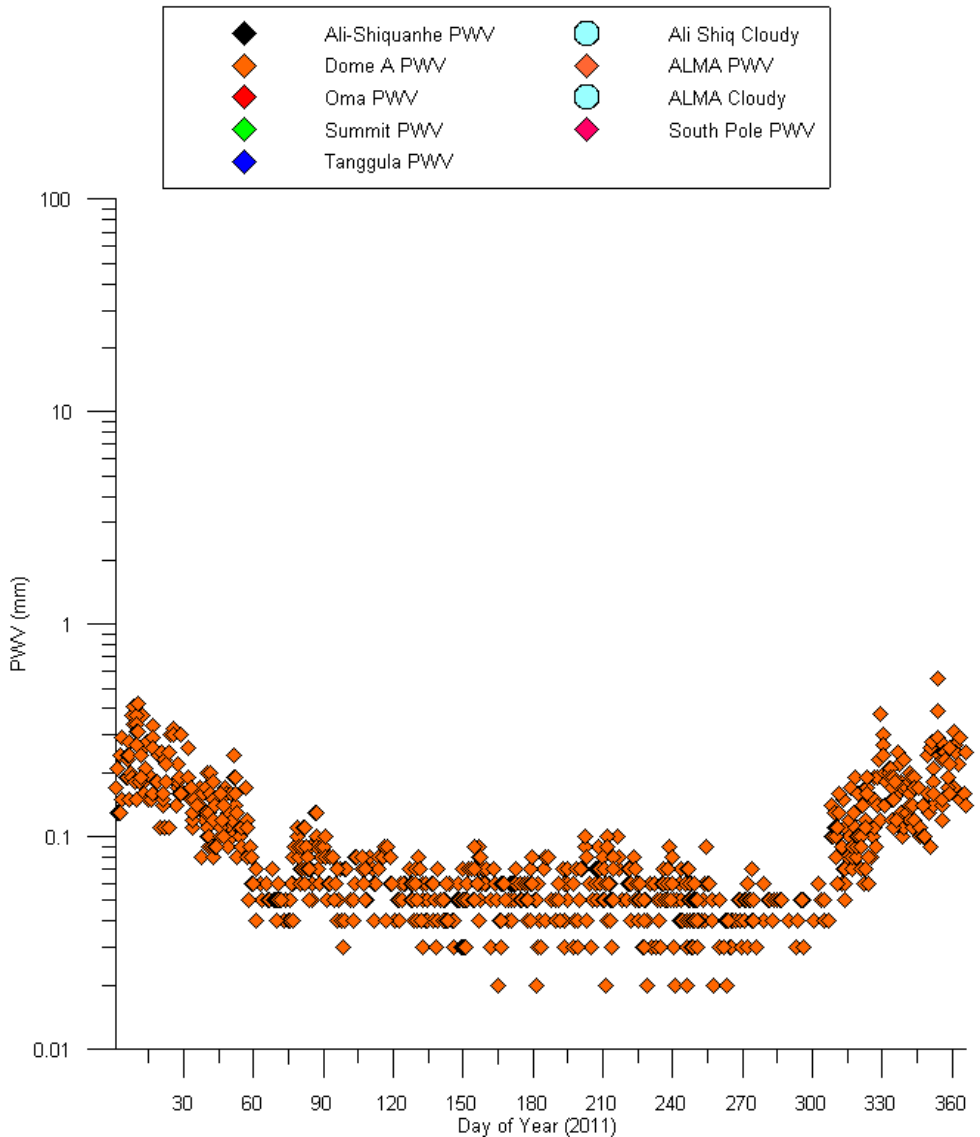
PWV Alma2011 Time series



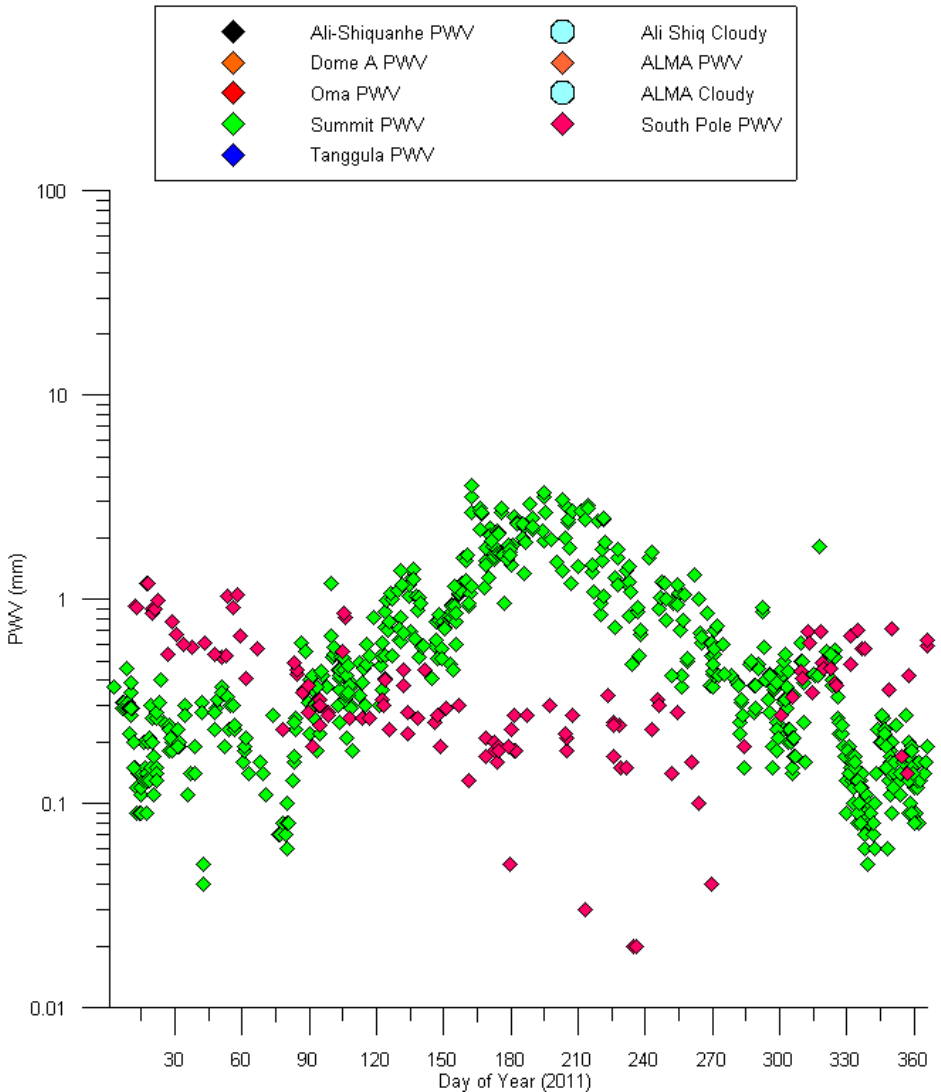
PWV Summit Greenland 2011 Time series



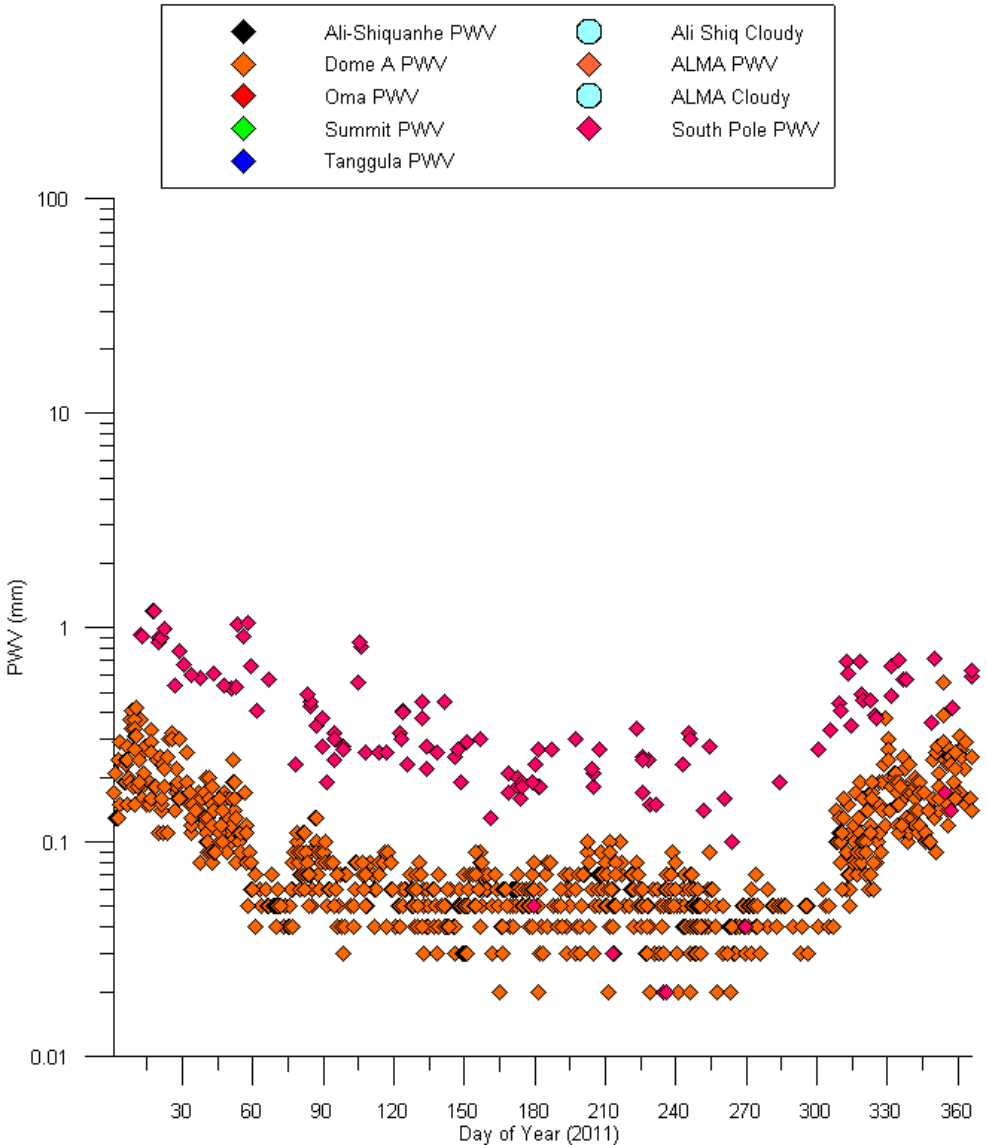
PWV Dome A 2011 Time series



PWV – Greenland Summit and S. Pole

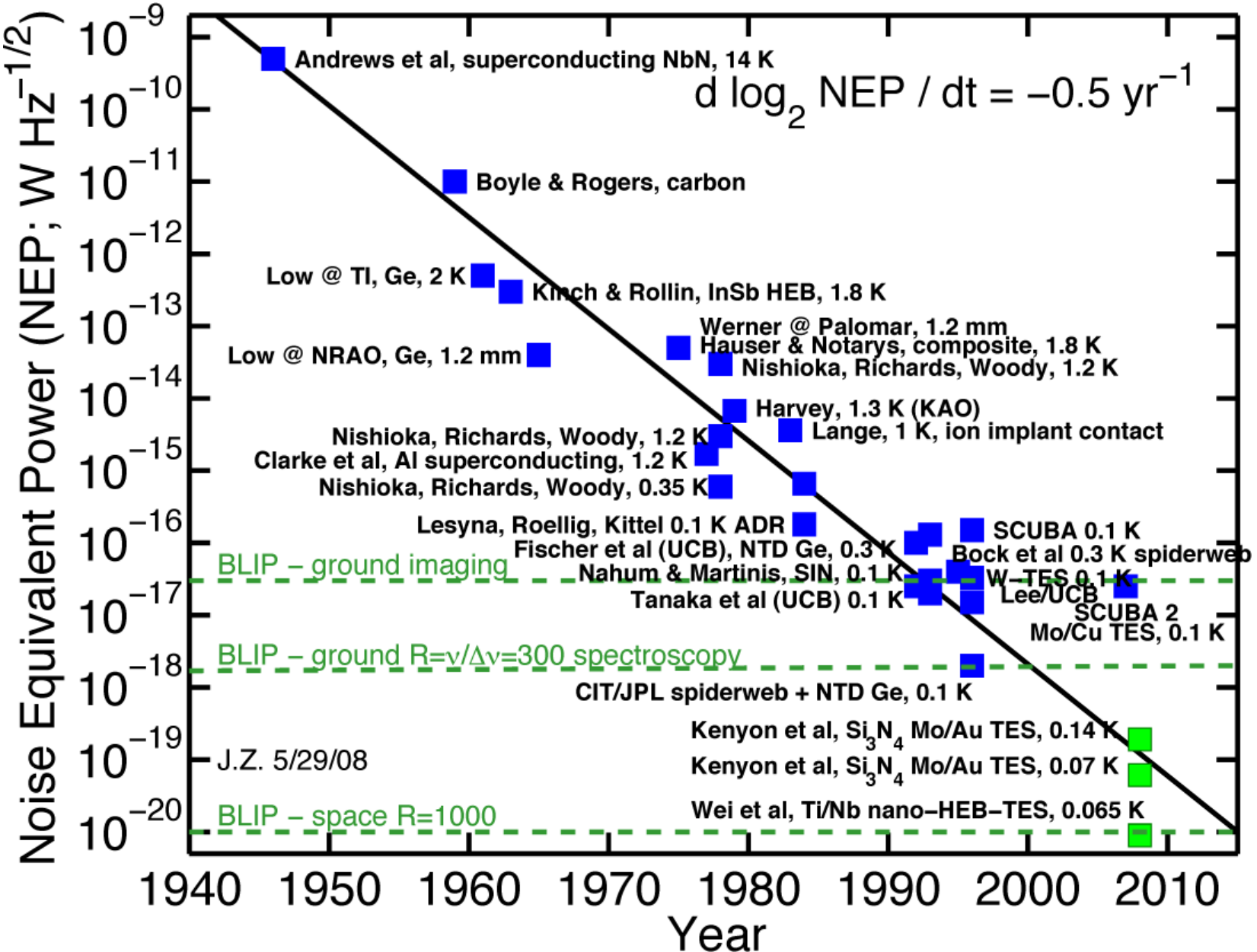


S. Pole and Dome A



Historical View- Moore would be proud

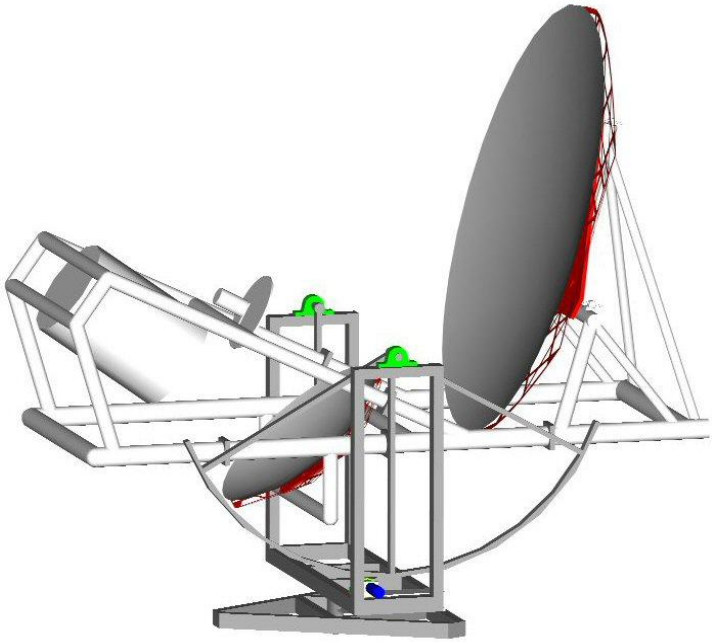
but reality intervenes

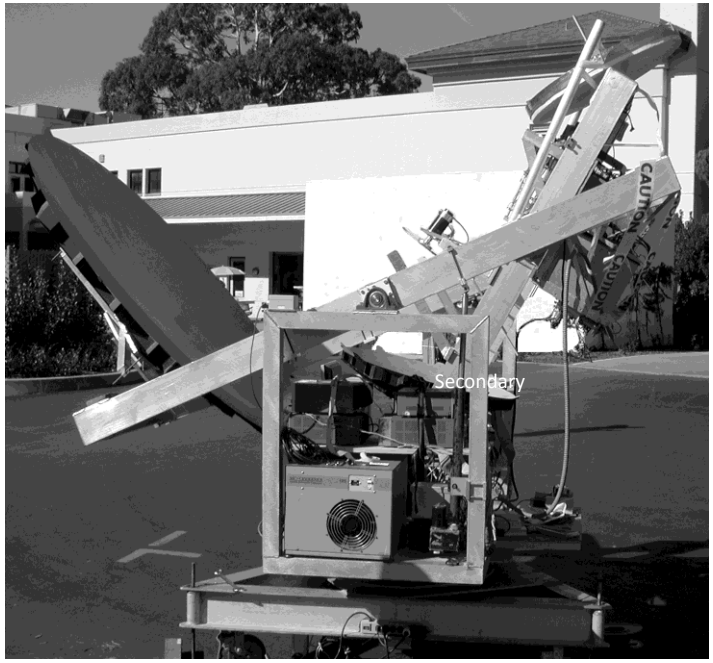


Very lightweight 2.2 meter telescope Hernia Operation 1 week later!


UCSB 'White
Mountain site'


UCSB 2.2 m
Telescope Dome




Secondary

Conclusions

- Everyone has a favorite poison
- We usually like to do what we did
- Scientists are not always so scientific
- Politics and money play a major factors in decisions
- Logic is not always operational
- WE have a problem now ->galaxy
- Extragalactic mission required -> will require some time
- Fallback -> space (is it needed?) -> we do not know
- Do not know the signal level for B modes from (IF) inflation
- Array of 2m telescopes – low cost high performance option to cover 10-1000 GHz with HEMT and MKID's