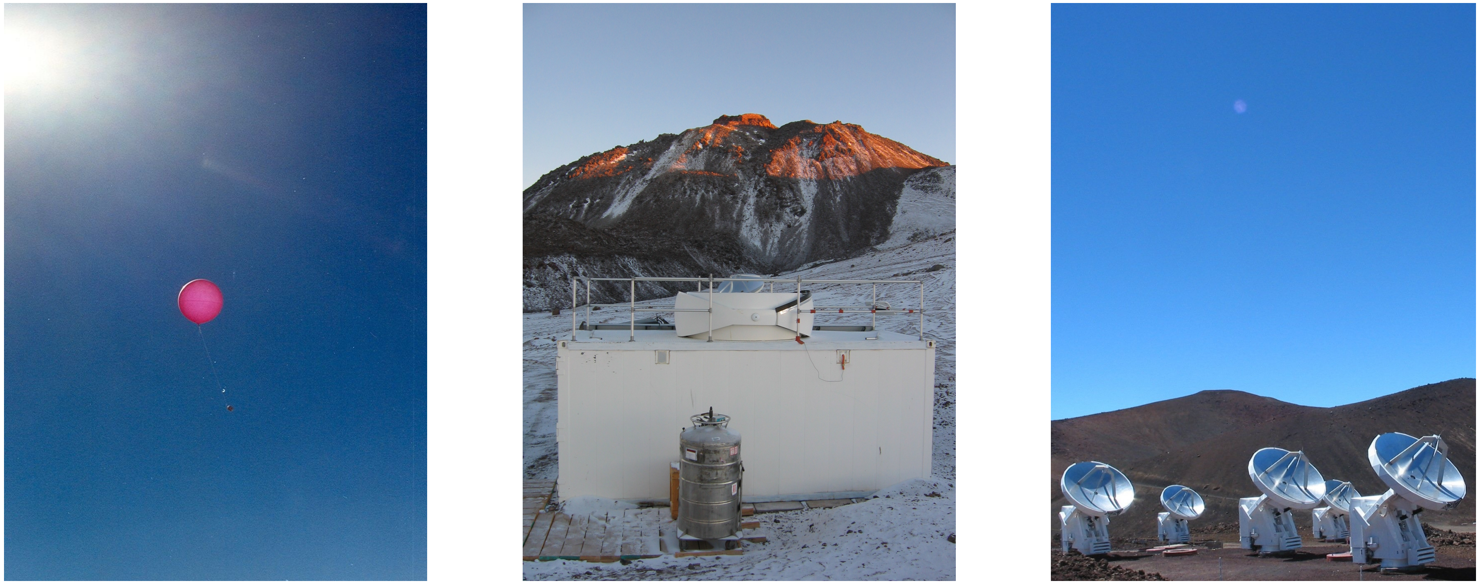
Atmospheric Propagation Studies for Submillimeter Radio Astronomy



Scott Paine
Smithsonian Astrophysical Observatory
Submillimeter Receiver Laboratory

Outline

- Introduction – Submillimeter Astronomy and the SAO Submillimeter Receiver Laboratory
- Atacama Site Testing – FTS and Radiosonde observations
- The Receiver Lab Telescope on Sairecabur
- Phase Correction for Submillimeter Interferometry

Submillimeter Astronomy

- Molecular clouds, star formation
  - Continuum emission – 10 K – 200 K
  - Rotational lines – excitation and dynamics
- Accretion disks
- High-redshift universe – submillimeter galaxies
- Galactic center
- Planetary Science

SAO Submillimeter Receiver Lab

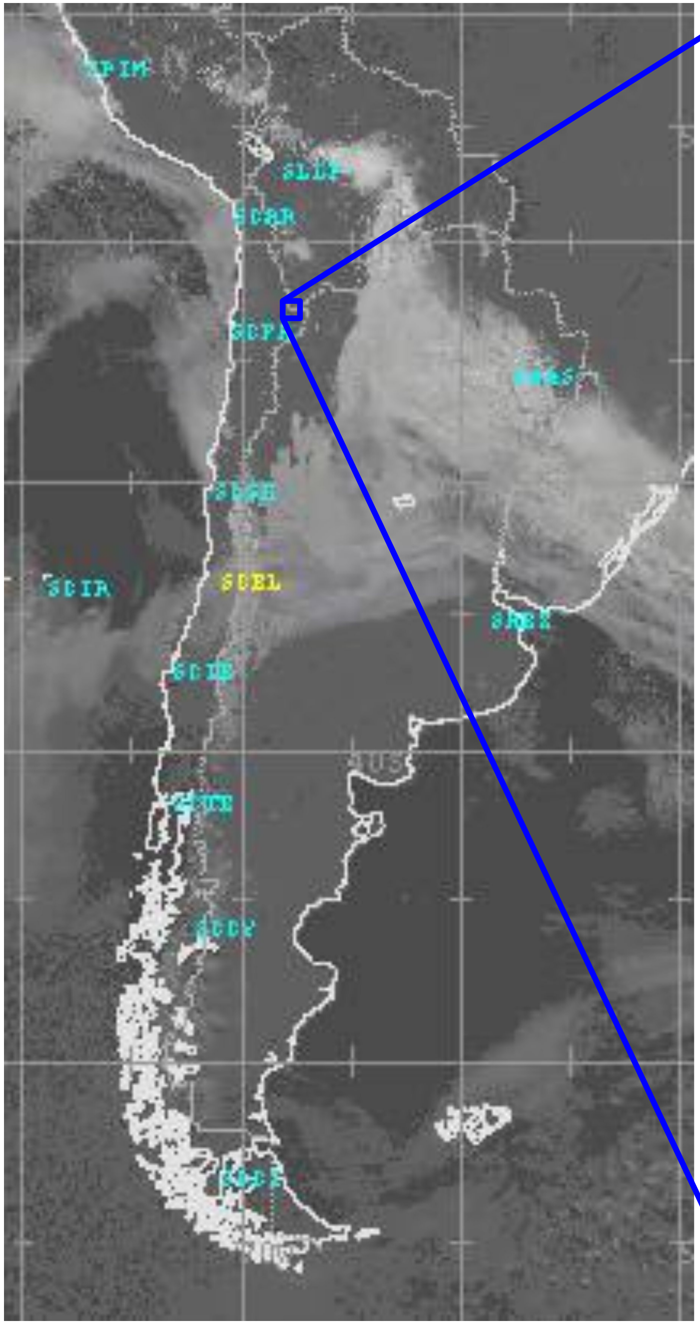
- Established 1988 to support submillimeter astronomy
- Receiver and associated technology development
  - SIS mixers to 900 GHz
  - HEB mixers to 1.5 THz
- Propagation studies
  - Site testing
  - Water vapor radiometry

Submillimeter Telescopes

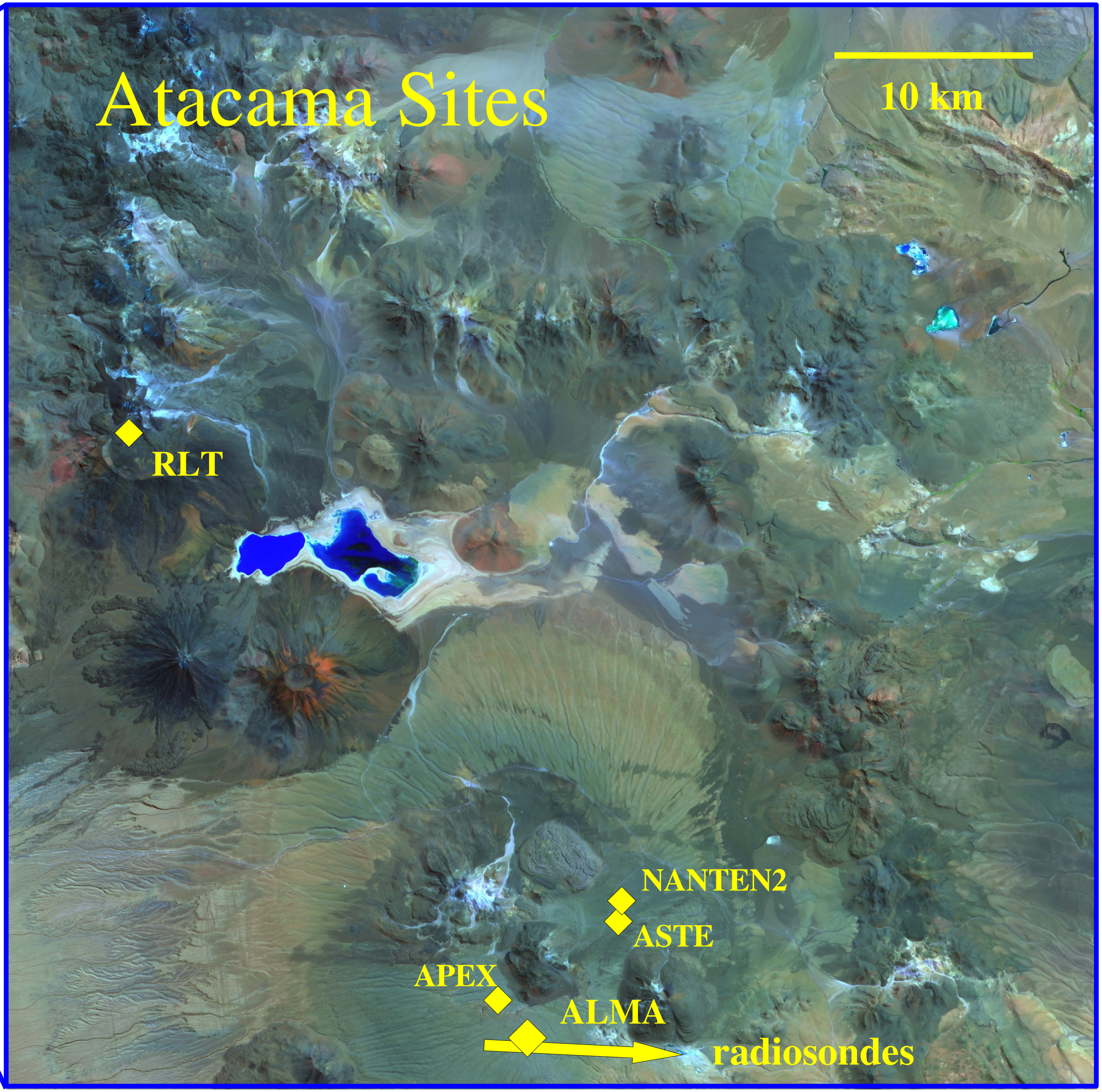
Telescope	Diameter		Location	Altitude	Date
CSO	10.4 m		Mauna Kea	4100 m	1986
JCMT	15 m		Mauna Kea	4100 m	1987
AST/RO	1.7 m		South Pole	2800 m	1995
KOSMA (upgraded)	3 m		Switzerland	3100 m	1995
HHT	10 m		Arizona	3200 m	1997
SWAS	0.55 x 0.71 m		650 km Earth orbit		1998
RLT	0.8 m		Atacama	5500 m	2002
ASTE	10 m		Atacama	4800 m	2002
APEX	12 m		Atacama	5100 m	2003
NANTEN2	4 m		Atacama	4800 m	2004
SPT	10 m		South Pole	2800 m	2007
HERSCHEL	3.5 m		L2 orbit		2007
CCAT	25 m	(proposed)	Atacama	5600 m	2012
Interferometers					
SMA	8 x 6 m	$B \leq 0.5$ km	Mauna Kea	4100 m	2003
ALMA	50 x 12 m	$B \leq 10$ km	Atacama	5000 m	2013

Site Testing

- Several ground-based telescopes now equipped (or instruments planned) for observations above 1 THz
- Feasibility was not widely recognized 10 years ago
- Requires unusual conditions, such as South Pole or high Atacama



NOAA GOES-12 / Direccion Meteorologica de Chile



NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team

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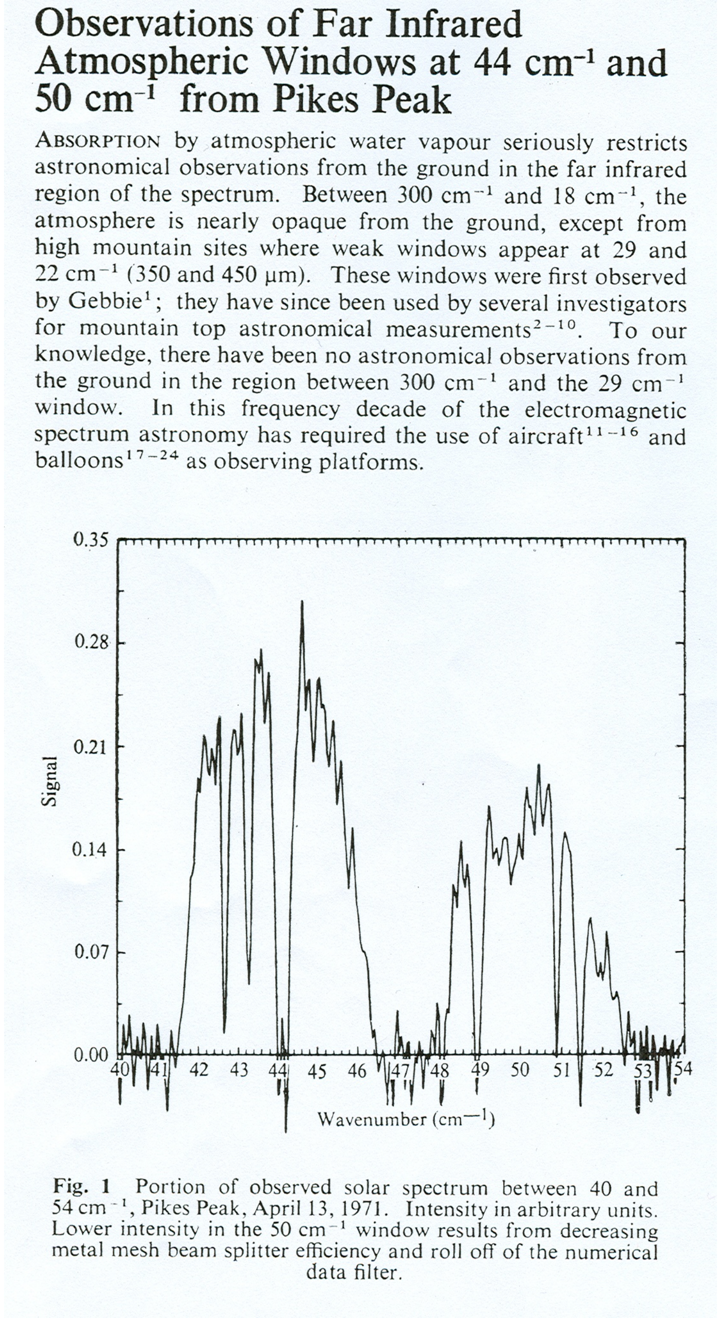


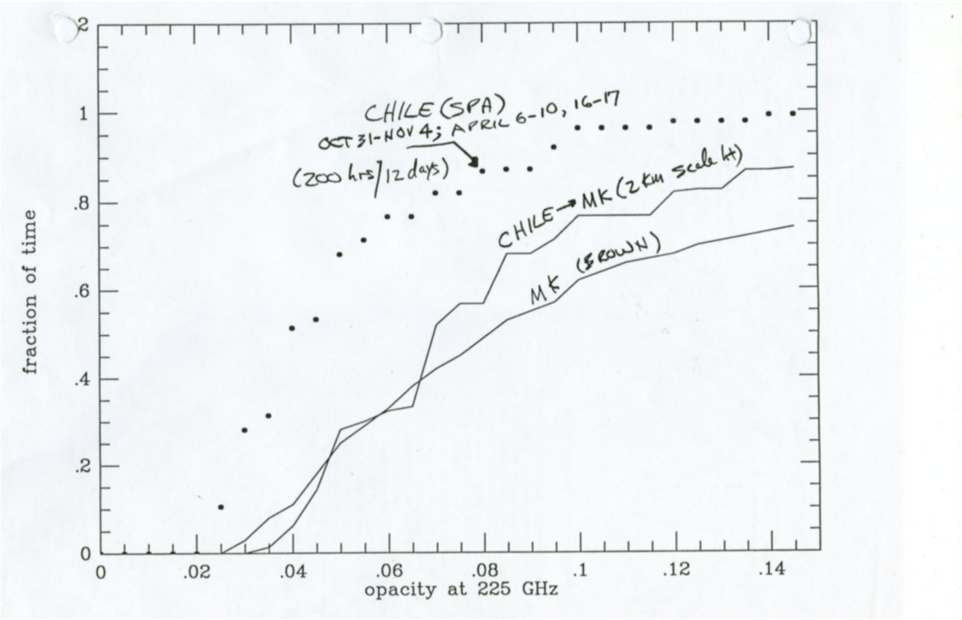
Observations of Far Infrared Atmospheric Windows at 44 cm^{-1} and 50 cm^{-1} from Pikes Peak

ABSORPTION by atmospheric water vapour seriously restricts astronomical observations from the ground in the far infrared region of the spectrum. Between 300 cm^{-1} and 18 cm^{-1}, the atmosphere is nearly opaque from the ground, except from high mountain sites where weak windows appear at 29 and 22 cm^{-1} (350 and 450 µm). These windows were first observed by Gebbie[1]; they have since been used by several investigators for mountain top astronomical measurements[2-10]. To our knowledge, there have been no astronomical observations from the ground in the region between 300 cm^{-1} and the 29 cm^{-1} window. In this frequency decade of the electromagnetic spectrum astronomy has required the use of aircraft[11-16] and balloons[17-24] as observing platforms.

Fig. 1 Portion of observed solar spectrum between 40 and 54 cm^{-1}, Pikes Peak, April 13, 1971. Intensity in arbitrary units. Lower intensity in the 50 cm^{-1} window results from decreasing metal mesh beam splitter efficiency and roll off of the numerical data filter.

NCAR solar spectrum from Pikes Peak
Mankin, et al. Nature Phys. Sci. 245 8 (1973)

NRAO 225 GHz tipping radiometer data
from future ALMA site (1995)



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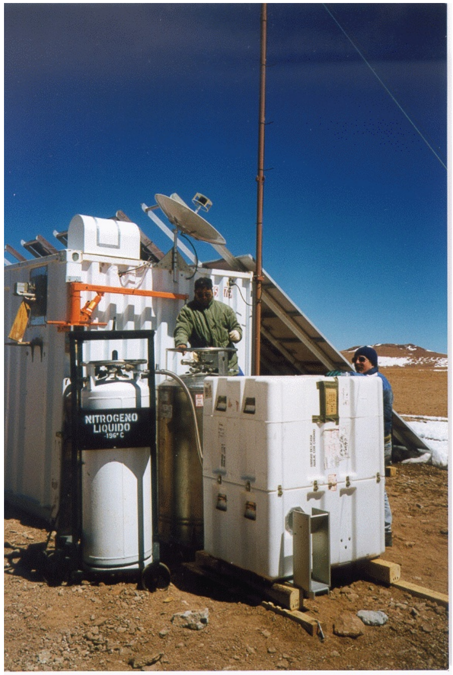
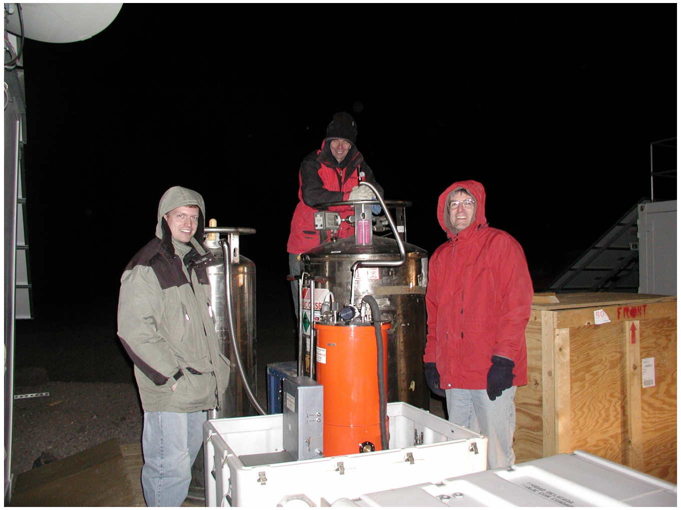
SAO Site Testing FTS

- Proposed collaboration with NRAO in 1995
- Frequency coverage 300 GHz – 3.5 THz
- Apodized resolution 3 GHz
- Zenith viewing, 3° beamwidth
- 10 minute scans
- 100 W power consumption
- 35 days Helium hold time, LN2 auto fill
- Unattended operation

SAO Site Testing FTS

Llano de Chajnantor (5050 m) – 1997 – 1999
Note NRAO 225 GHz and 350 μm tippers

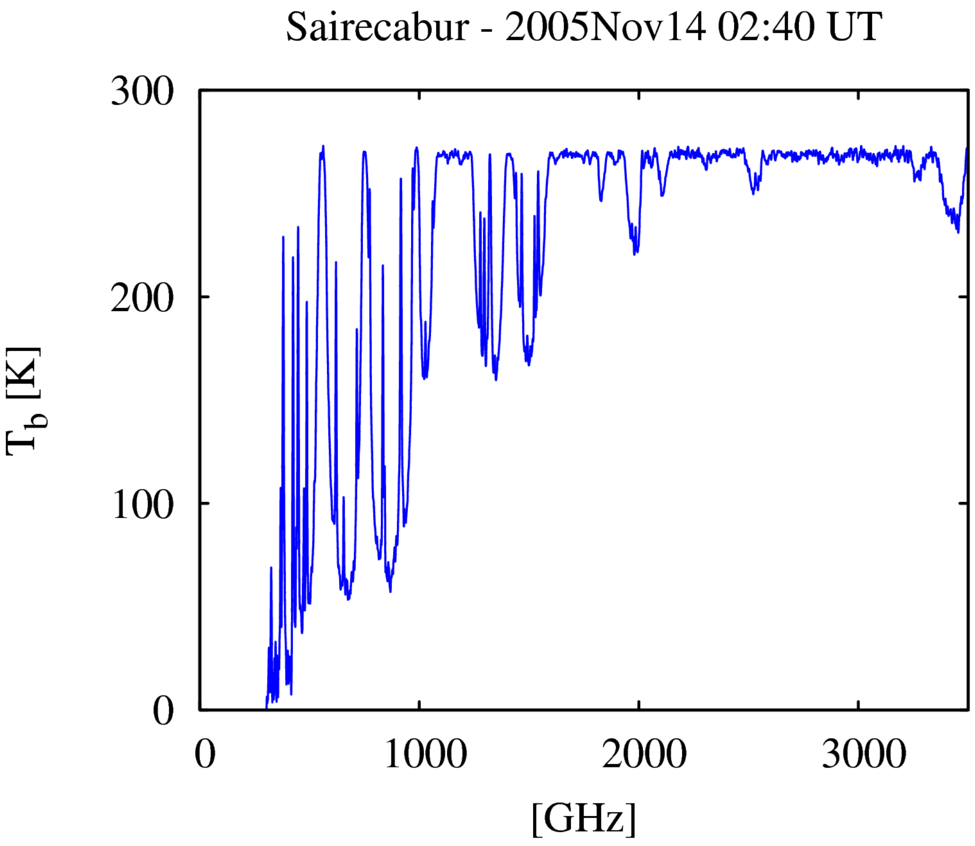




Sairecabur (5525 m) – 2000 – present
Comparison with Chajnantor
RLT calibration

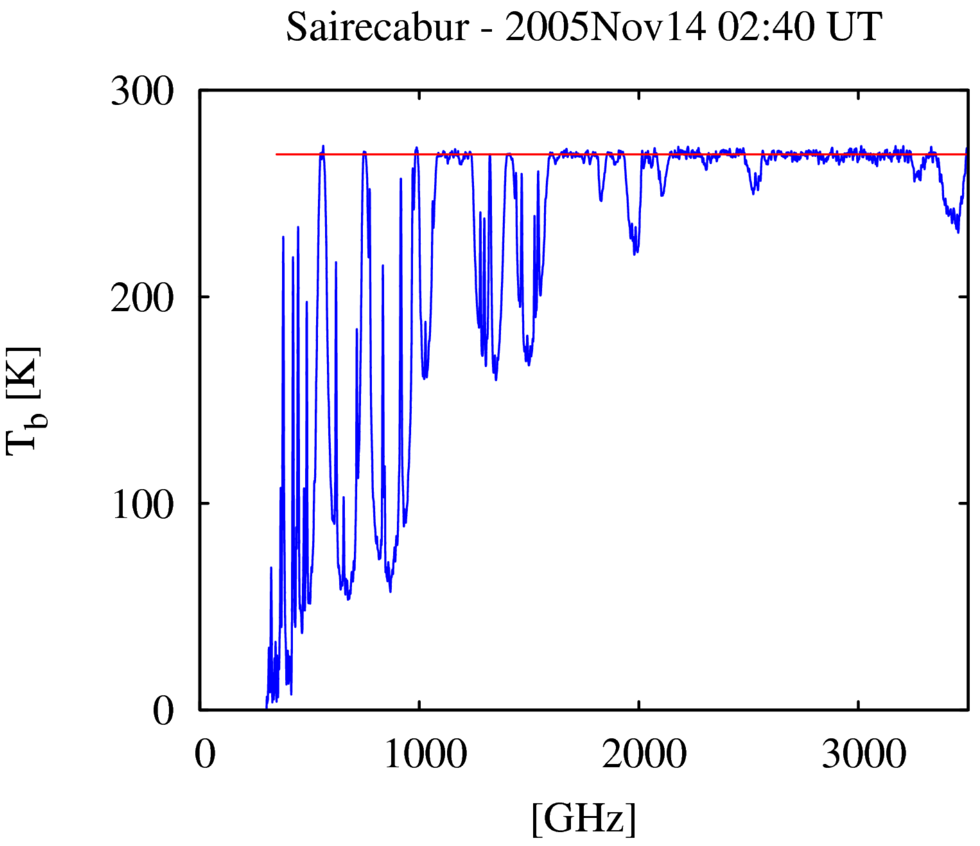
FTS Spectra

- Calibrated data product is T_b



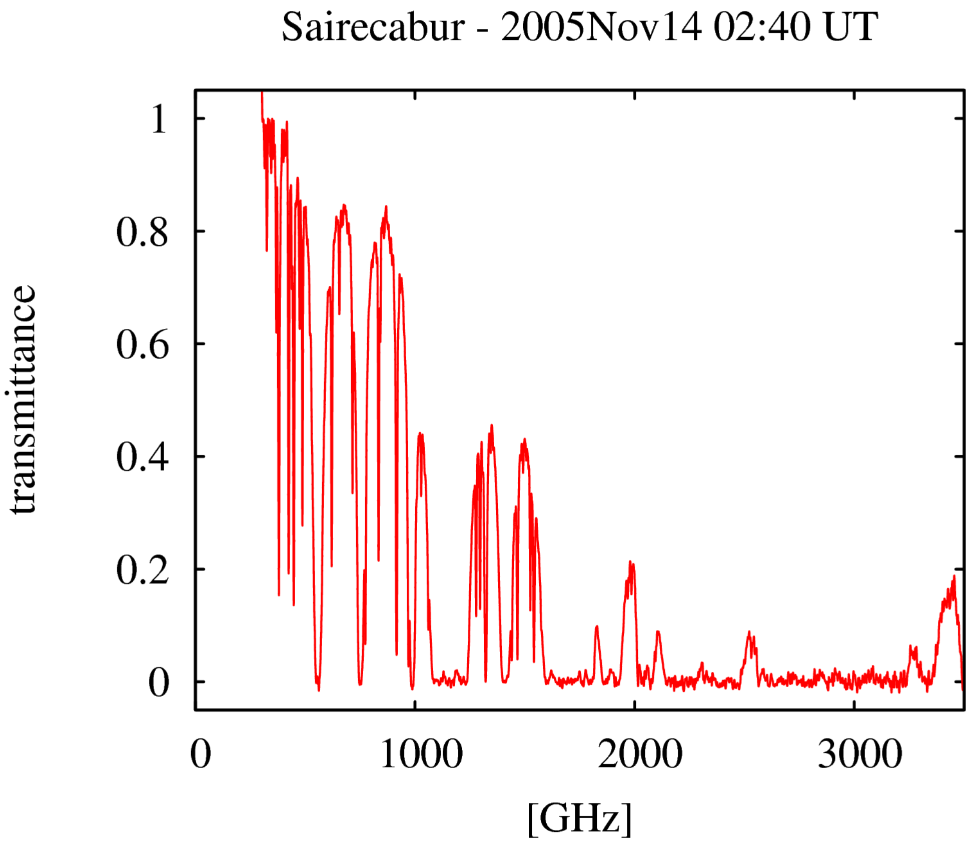
FTS Spectra

- Calibrated data product is T_b
- Simple transmittance
  - T_{atm} from baseline



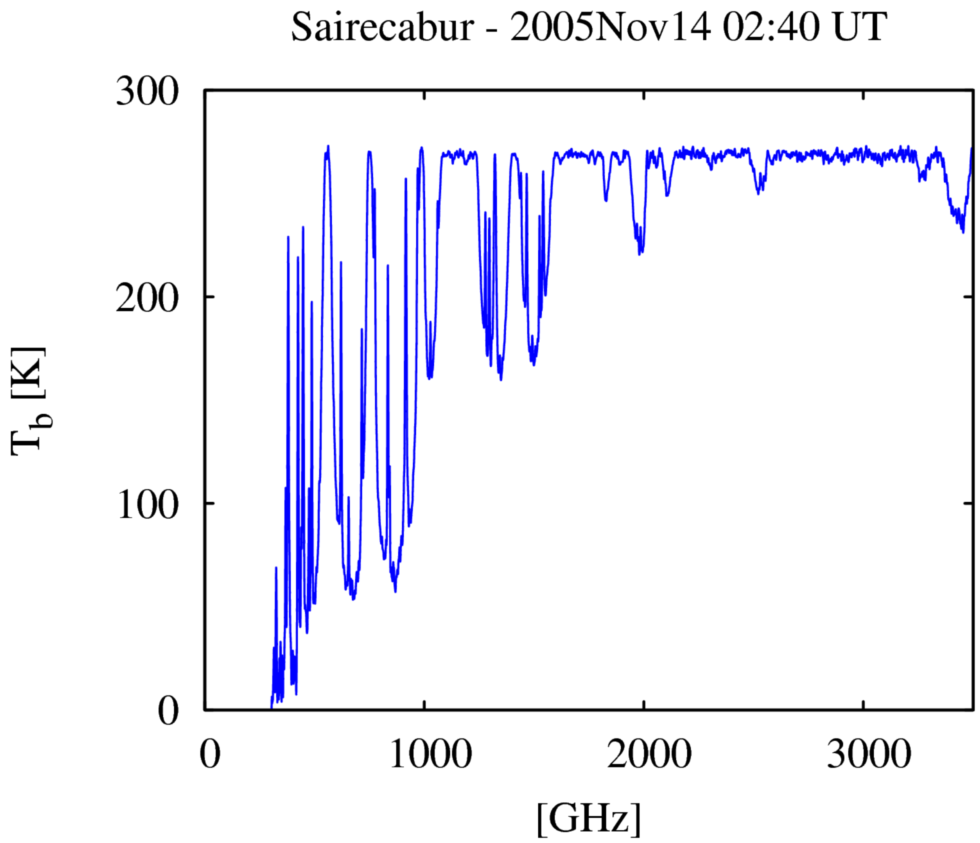
FTS Spectra

- Calibrated data product is T_b
- Simple transmittance
  - Effective T_{atm} from baseline
  - Isothermal transmittance



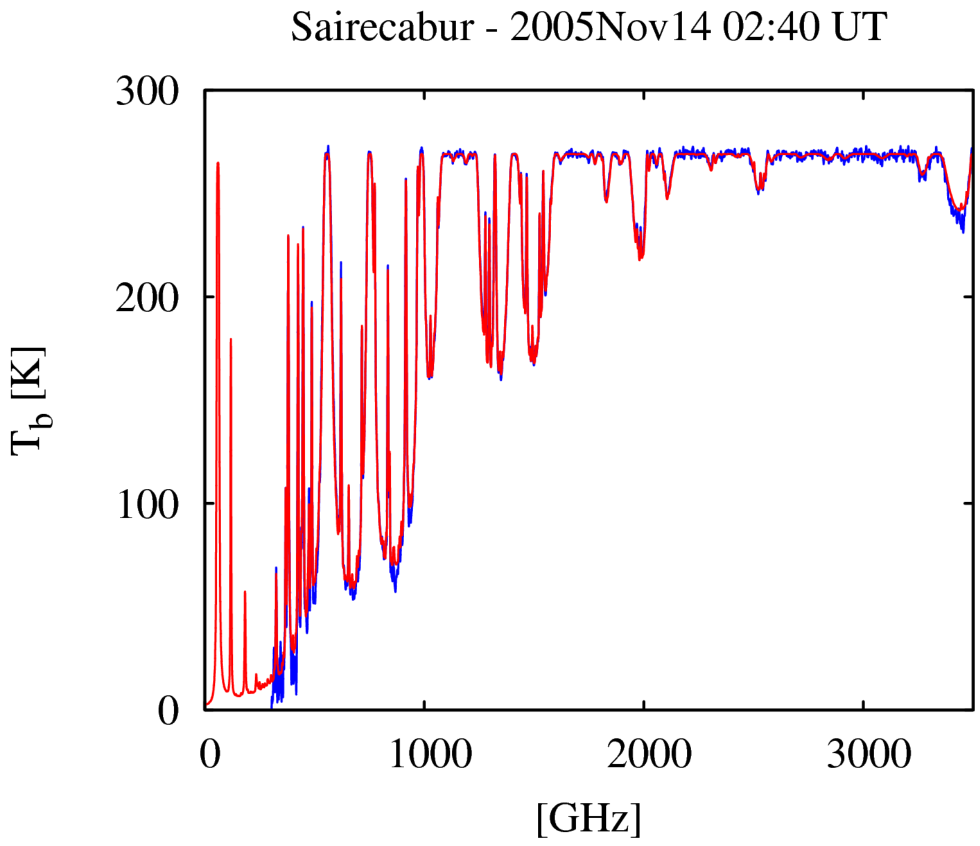
FTS Spectra

- Calibrated data product is T_b
- Simple transmittance
  - Effective T_{atm} from baseline
  - Isothermal transmittance
- Model transmittance



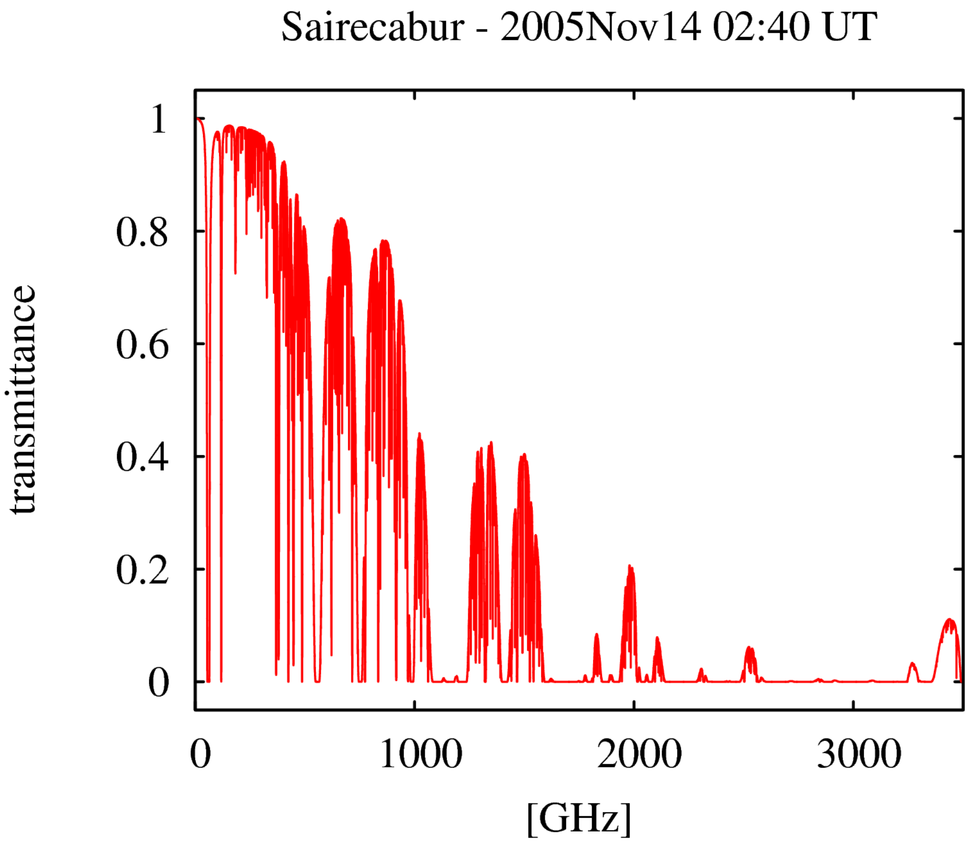
FTS Spectra

- Calibrated data product is T_b
- Simple transmittance
  - Effective T_{atm} from baseline
  - Isothermal transmittance
- Model transmittance
  - *am* fit to T_b



FTS Spectra

- Calibrated data product is T_b
- Simple transmittance
  - Effective T_{atm} from baseline
  - Isothermal transmittance
- Model transmittance
  - *am* fit to T_b
  - Fully-resolved model transmittance; useful near O_3 lines



FTS Spectra

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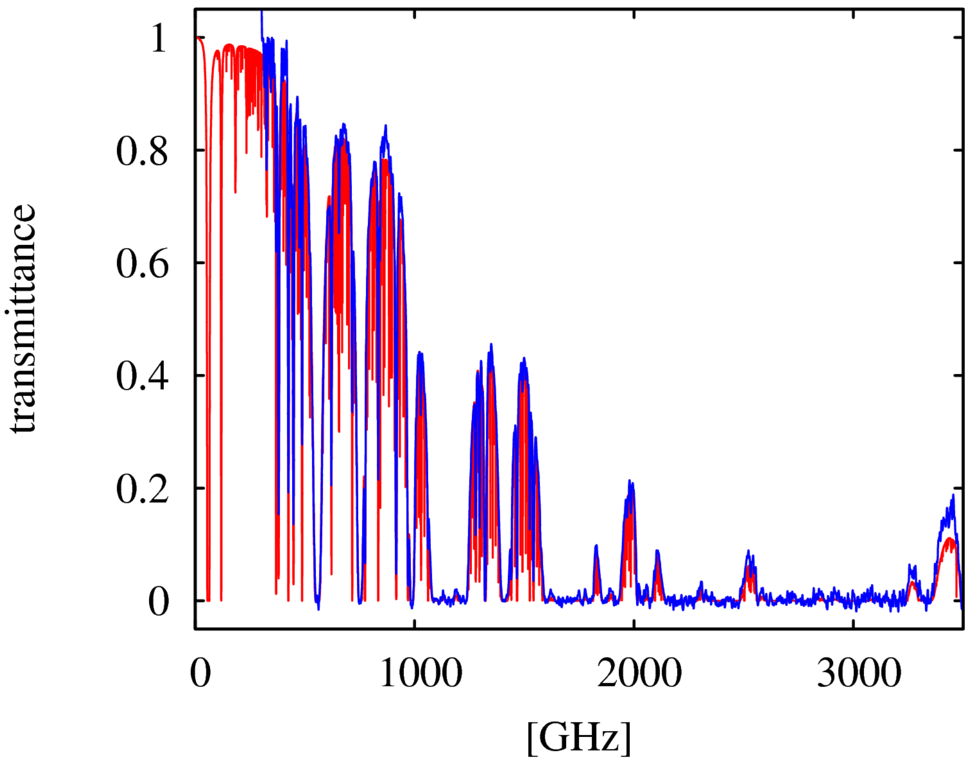
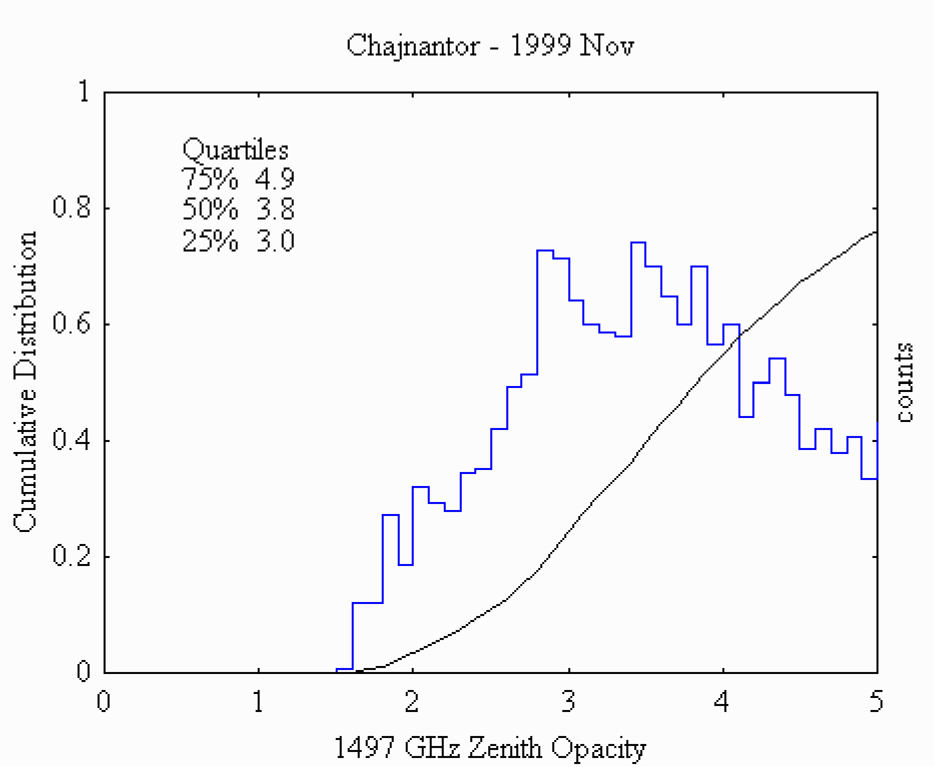
Sairecabur - 2005Nov14 02:40 UT

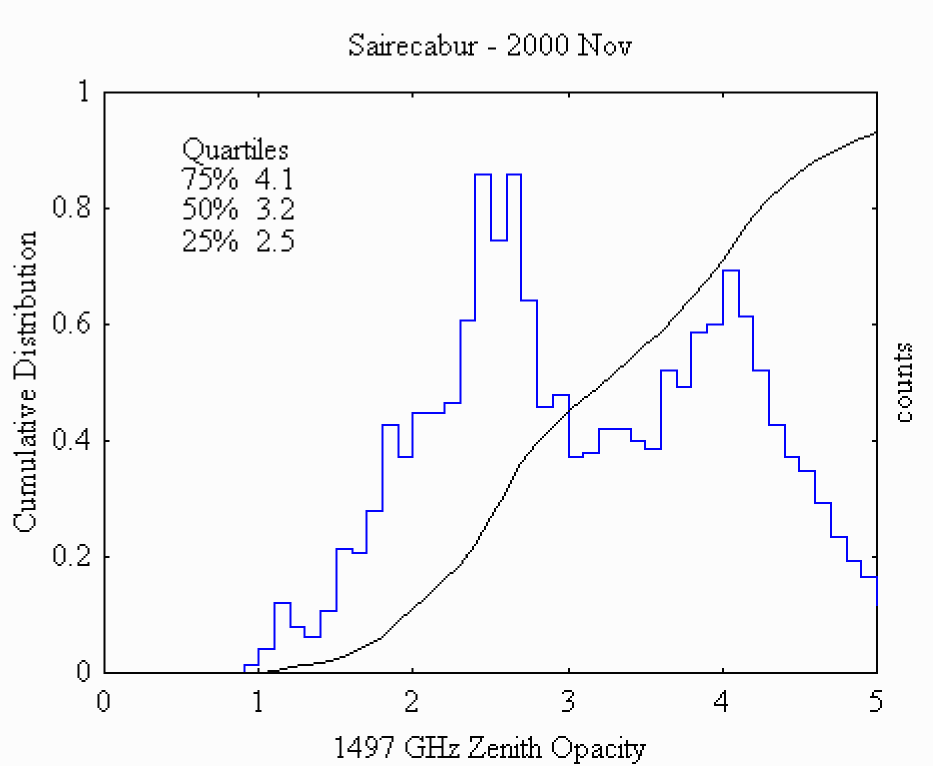


Chajnantor Plain (5000 m) vs. Sairecabur (5525 m)

- Only one FTS, so comparison is indirect
- Use 1999 Nov and 2000 Nov, which had similar τ_{225} quartiles at Chajnantor, and good FTS coverage
  - 1999 Nov: 0.026 / 0.035 / 0.049
  - 2000 Nov: 0.027 / 0.037 / 0.054
- 2000 Nov was slightly worse

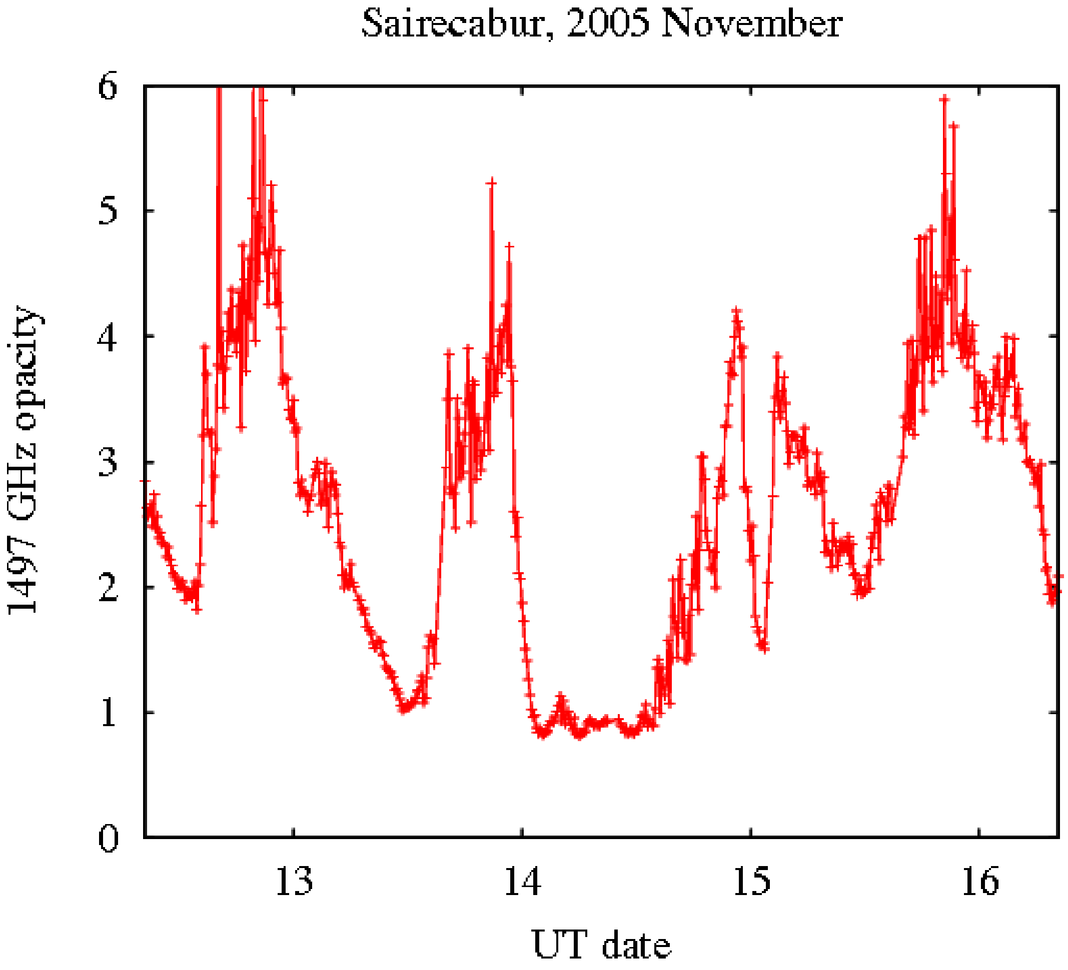
Llano de Chajnantor vs. Sairecabur





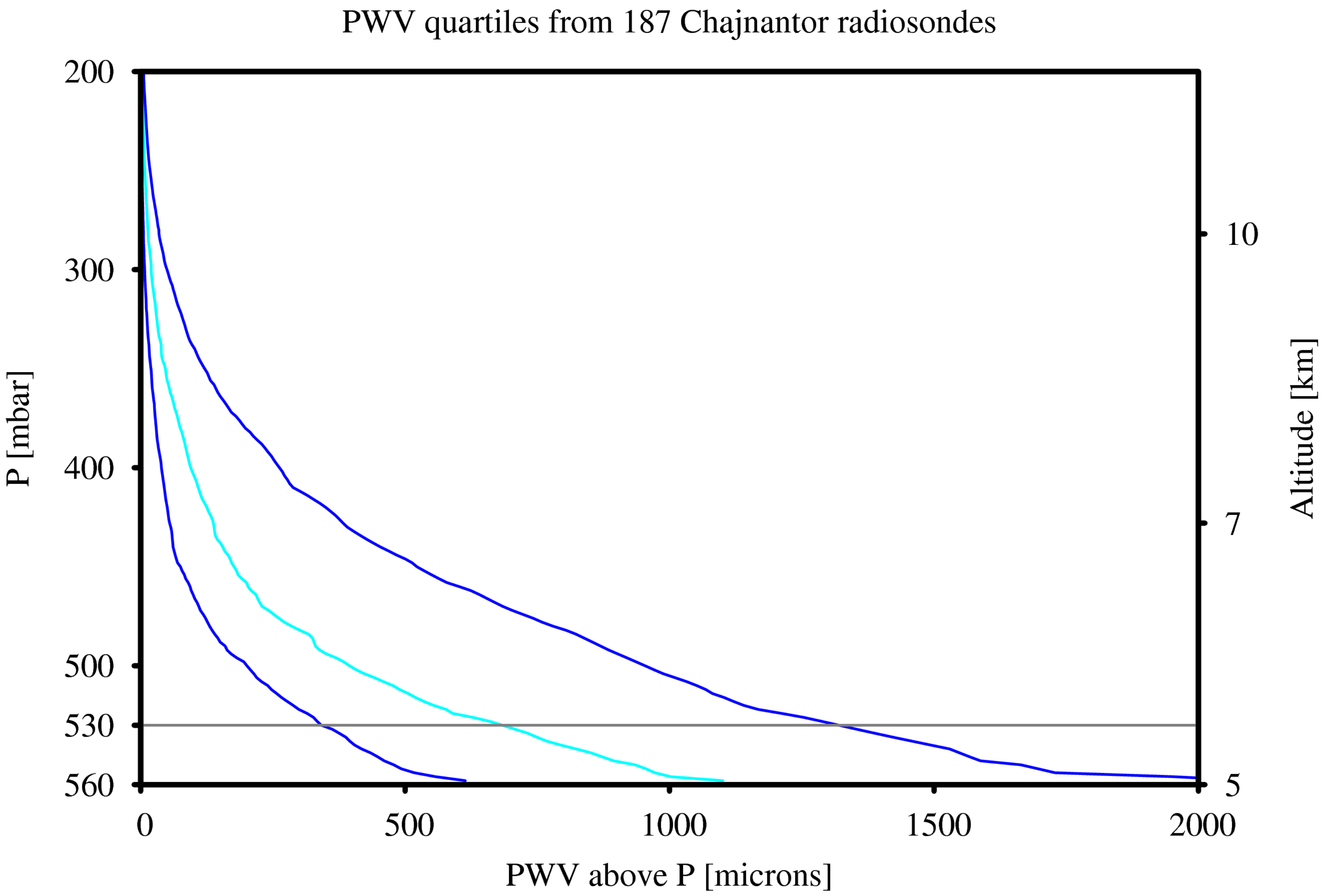
200 µm opacity lower by about 0.6, down to endpoint

Typical Diurnal Variability (good weather)



Chajnantor Radiosondes

- Initiated in 1998 by Cornell, NRAO, ESO, SAO
- Irregular time sample, but median pwv (1.1 mm) agrees well with median τ_{225} for Chajnantor (0.061)



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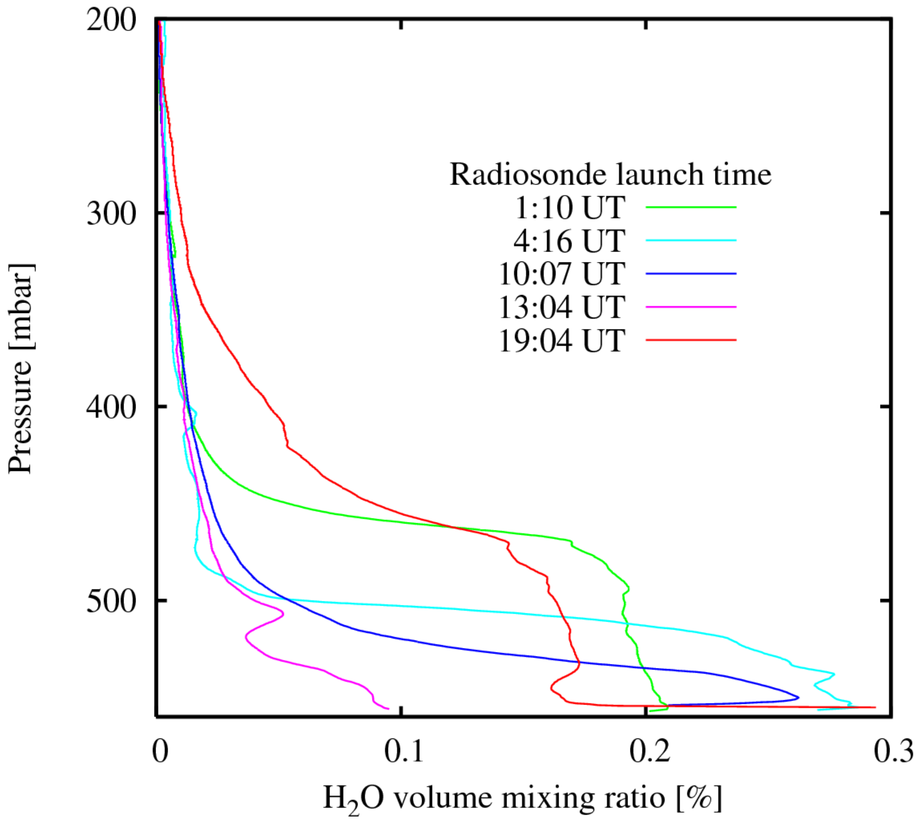
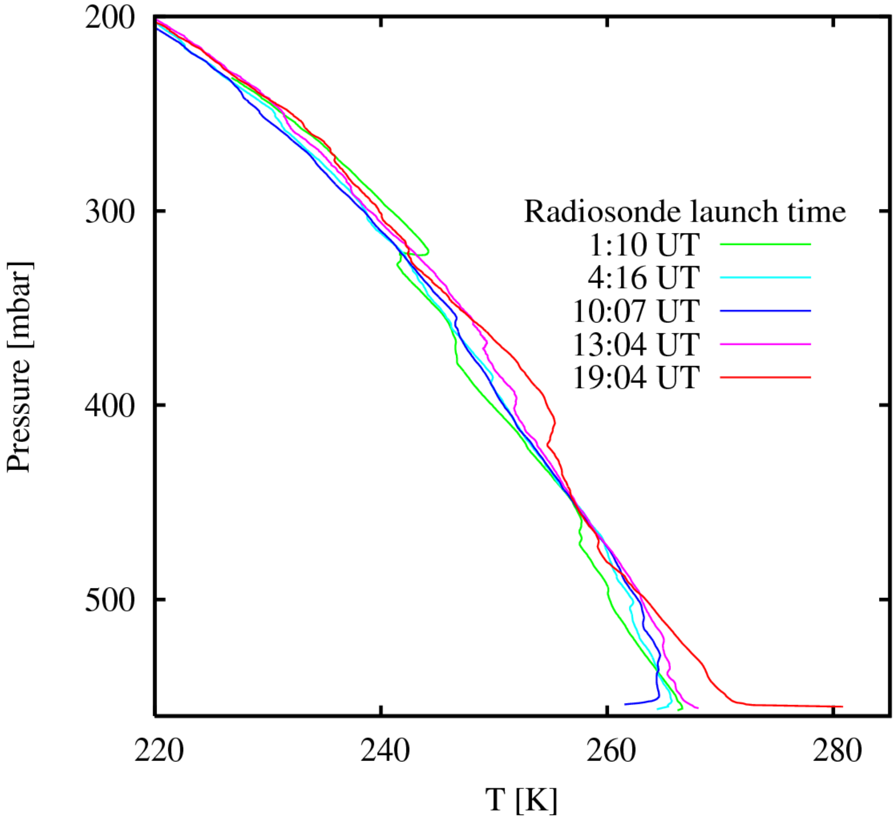
Radiosondes – diurnal cycle (1999 Nov 10)



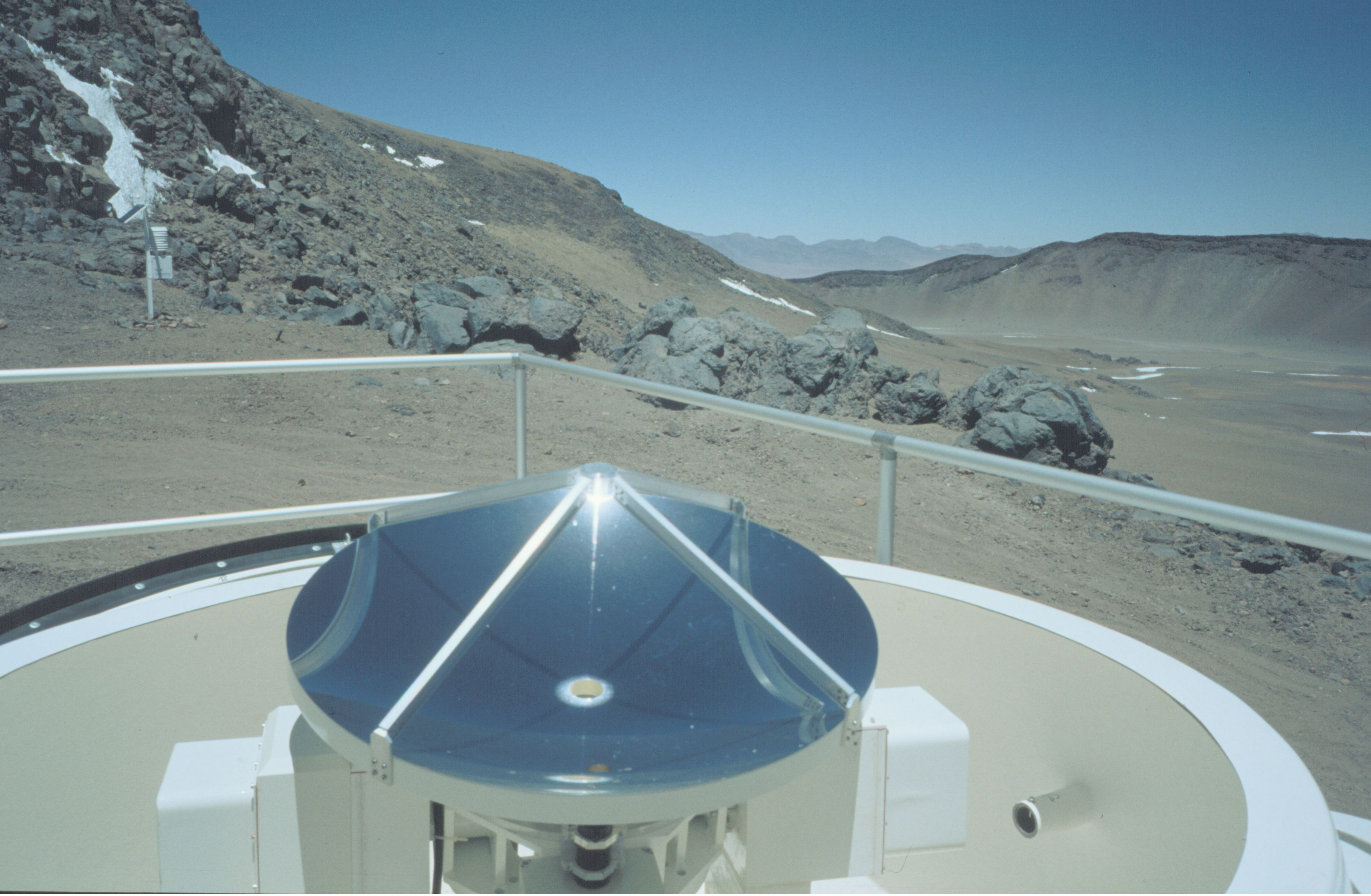


The RLT

- Encouraged by radiosonde and FTS data
- Goals
  - Test bed for THz receivers using HEB mixers
  - Spectroscopy – CO and isotopologues, N+
  - THz observing techniques
  - Propagation studies
- Deployed Nov 2002

RLT specifications

- 800 mm primary (1' at 1.5 THz)
- HEB mixer receivers
  - 850 GHz, ~900 K
  - 1.03 THz
  - 1.3 THz
  - 1.5 THz, ~ 1900 K
- Autocorrelating spectrometer, 1 GHz BW



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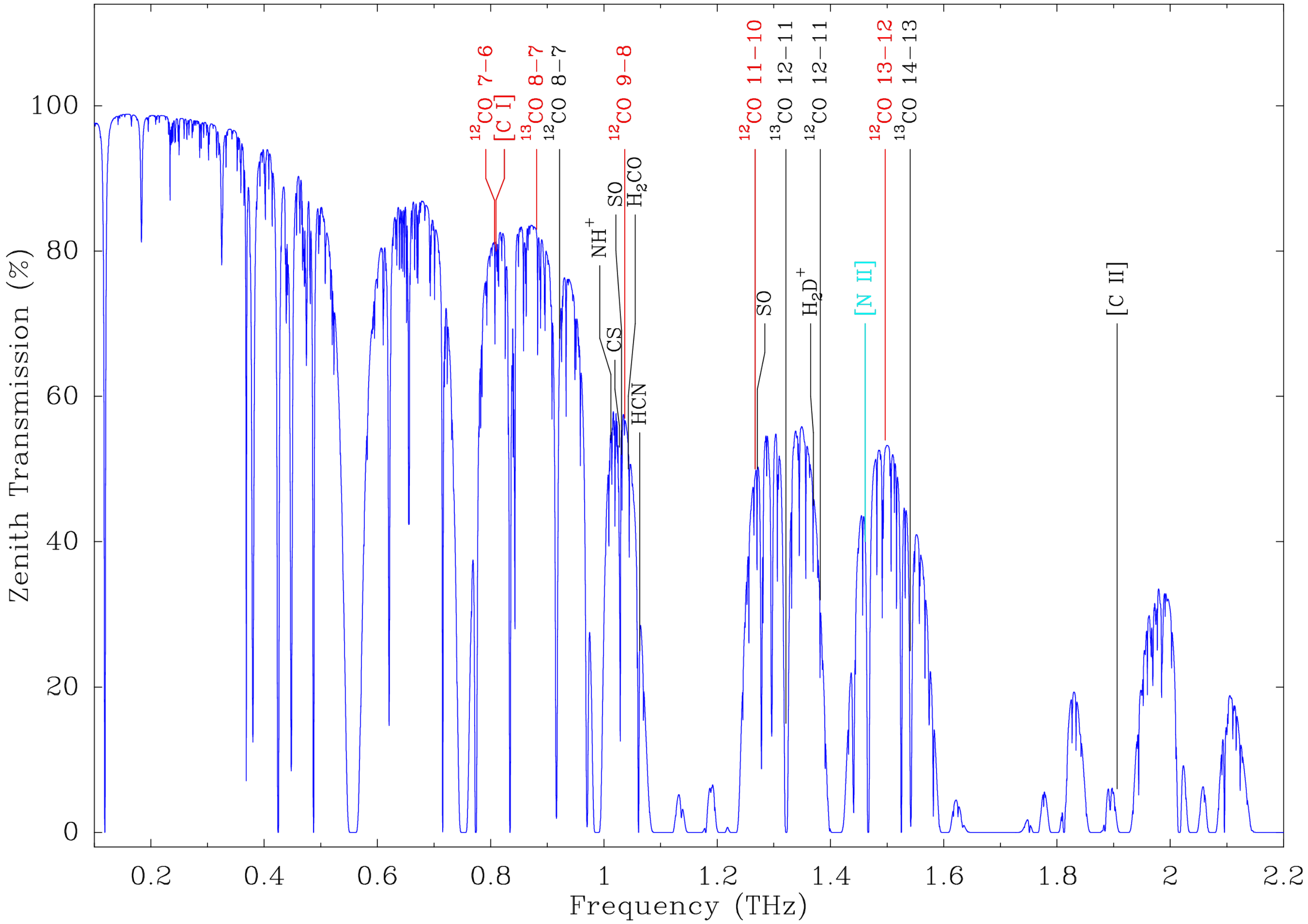
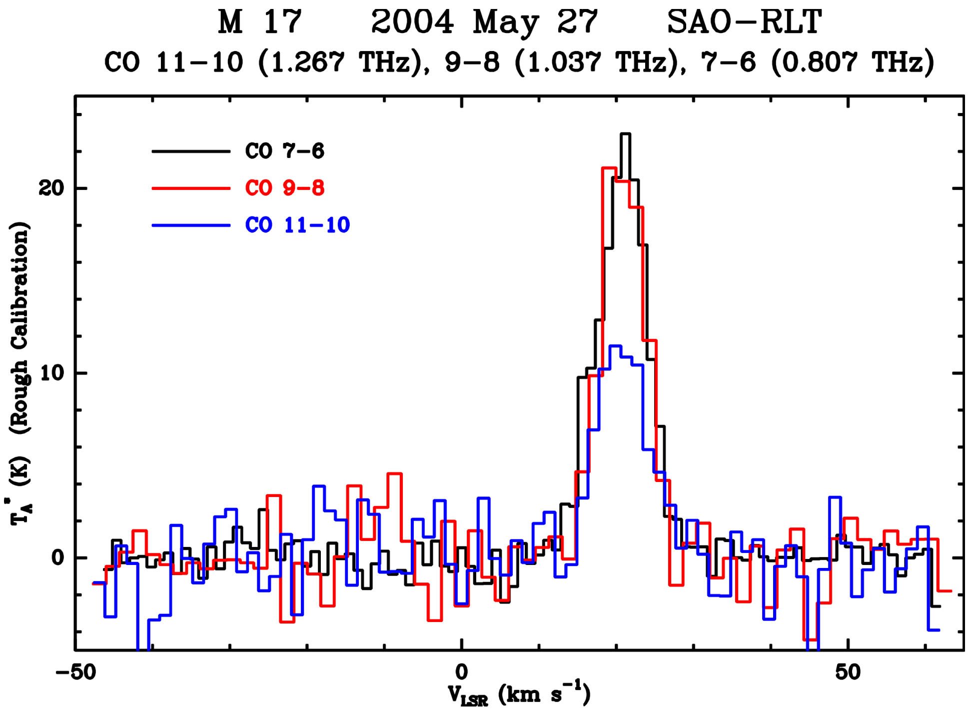
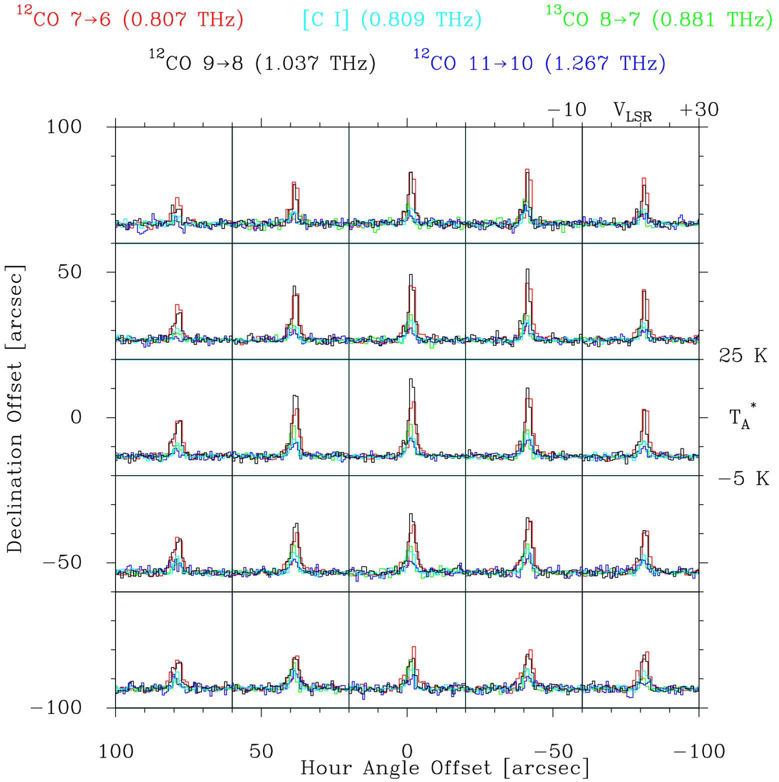
RLT Target Species



Multi-band observations

M 17



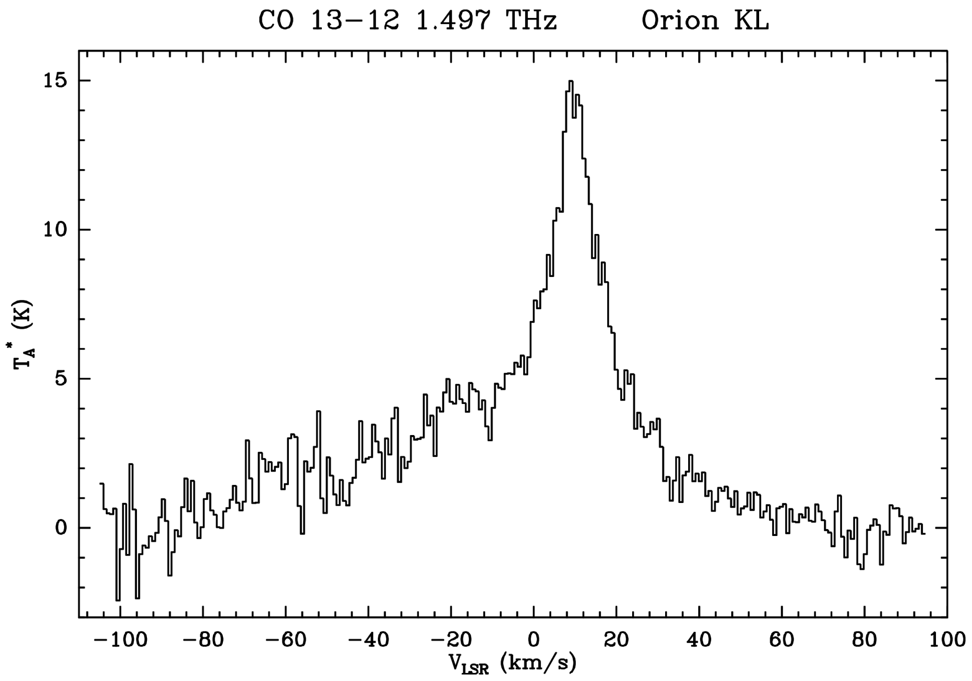


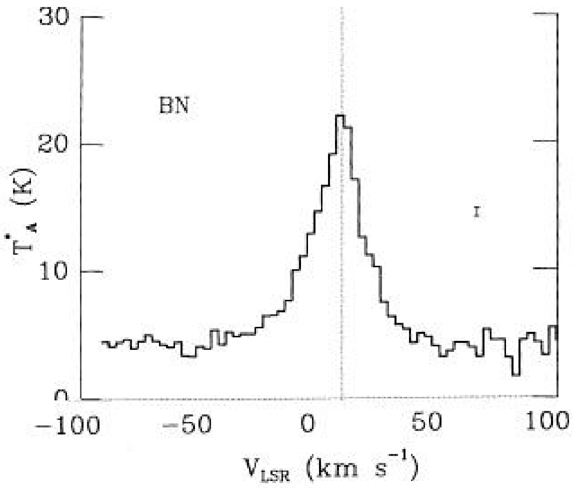
NGC 2024

(D. Marrone)

1.5 THz band

- 1.5 THz LO on loan from JPL since 2004 December



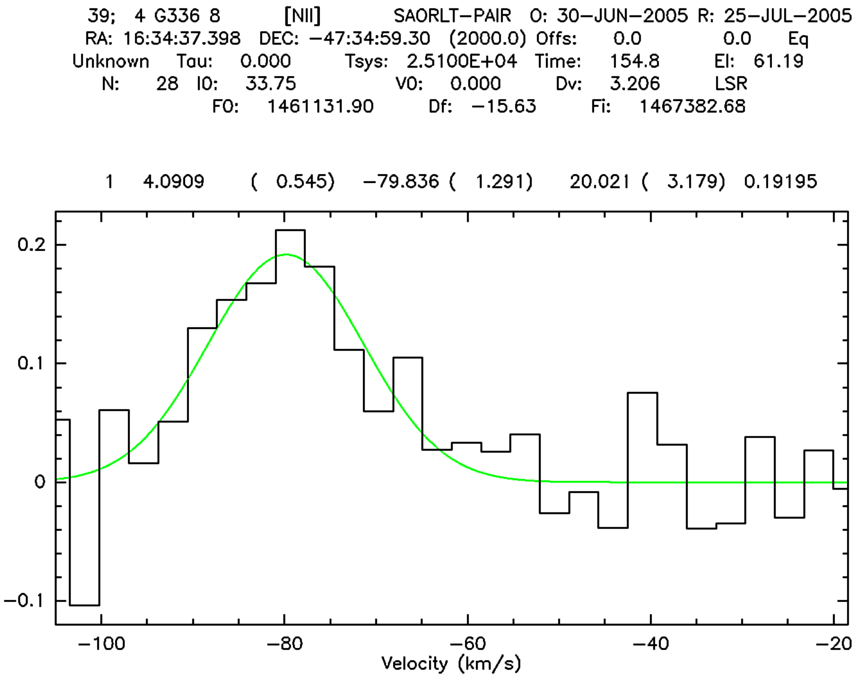


cf. CO 17-16 from KAO (Boreiko, Betz & Zmuidzinas 1989)

(D. Marrone)

N+ Observations (1461.1 GHz)

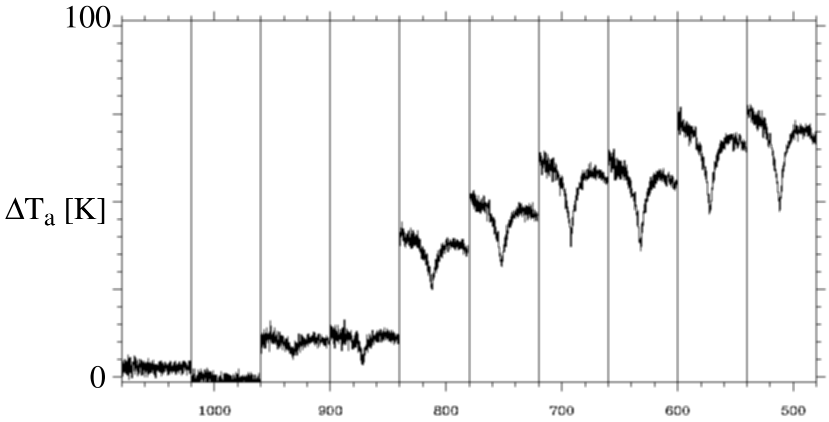
- Transmittance about 50% of window peak (O_2 line at 1466.8 GHz)
- Sources weak
- System inefficient



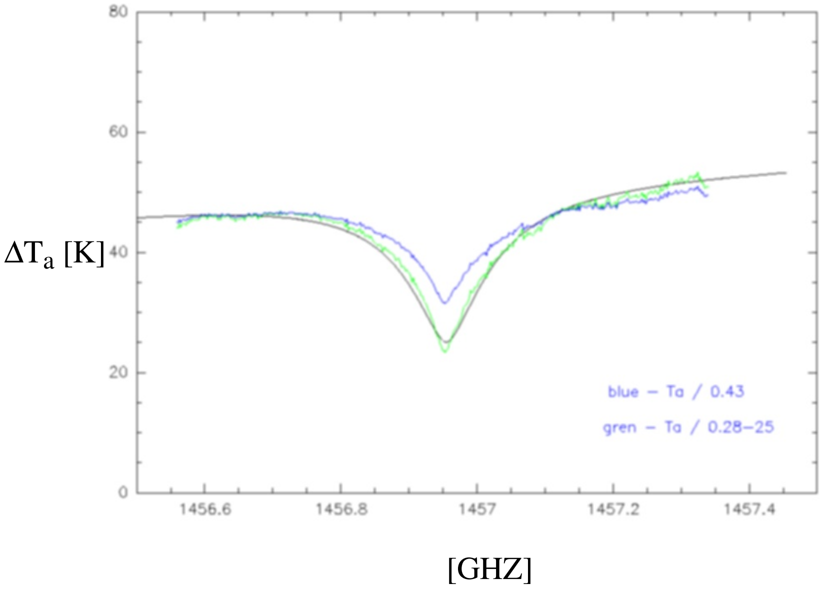
```
   39;  4 G336 8        [NII]         SAORLT-PAIR  O: 30-JUN-2005 R: 25-JUL-2005
  RA: 16:34:37.398  DEC: -47:34:59.30  (2000.0) Offs:     0.0          0.0     Eq
 Unknown    Tau:    0.000       Tsys:  2.5100E+04  Time:     154.8        El:  61.19
    N:      28  I0:    33.75              V0:    0.000      Dv:    3.206        LSR
                     F0:    1461131.90       Df:   -15.63        Fi:    1467382.68

    1   4.0909     (  0.545)   -79.836 (  1.291)    20.021 (  3.179)  0.19195
```

G336.84+0.05 Jun-Jul 2005 (D. Marrone)

O_3 against the Moon, 1457 GHz



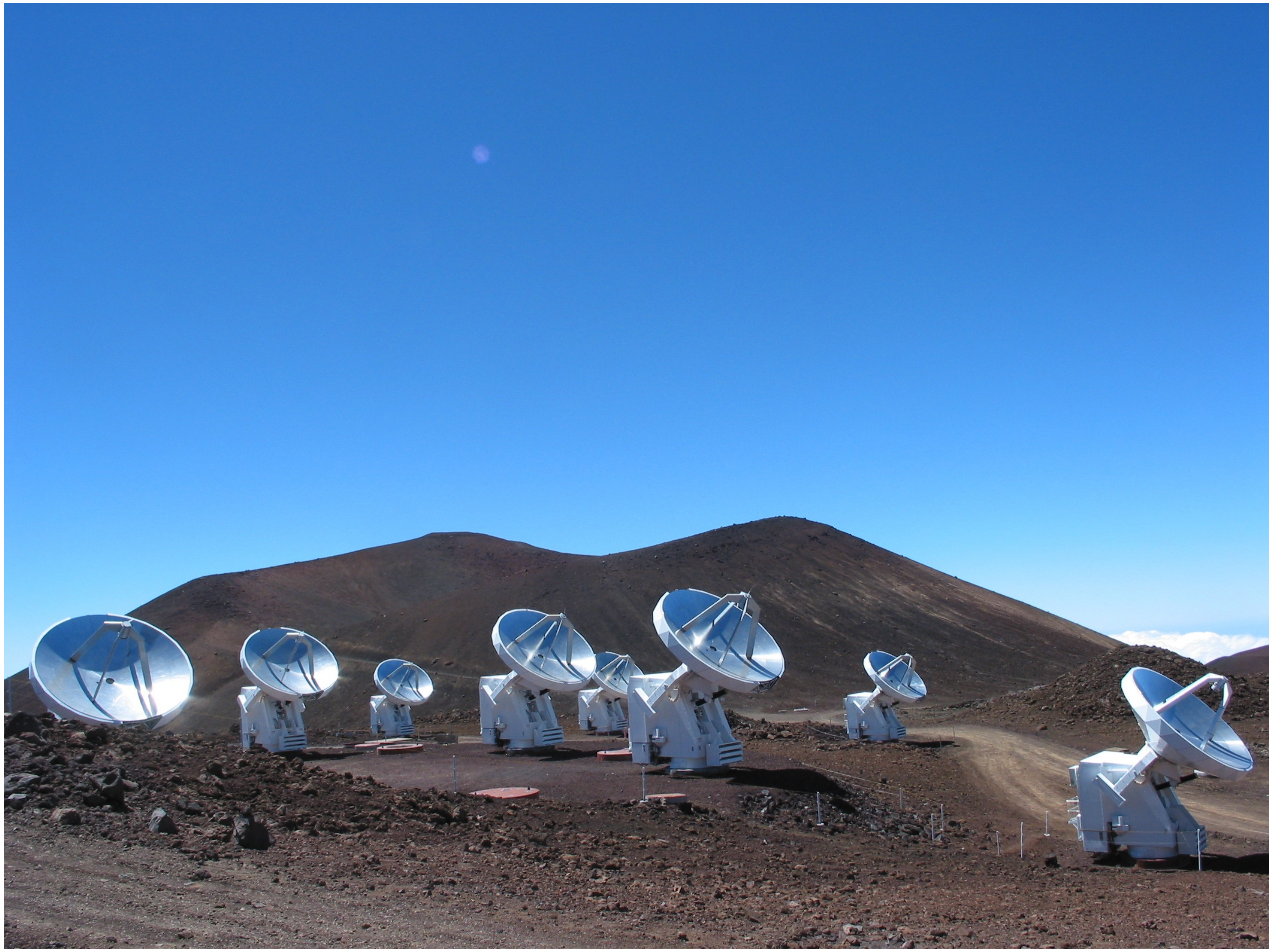
Scan across terminator



Fit to model spectrum

Combine with contemporaneous FTS data and TOMS ozone to determine telescope forward efficiency – about 30% at 1.5 THz

Phase Correction for Submillimeter Interferometry



The SAO/ASIAA Submillimeter Array (SMA)
Mauna Kea, Hawaii

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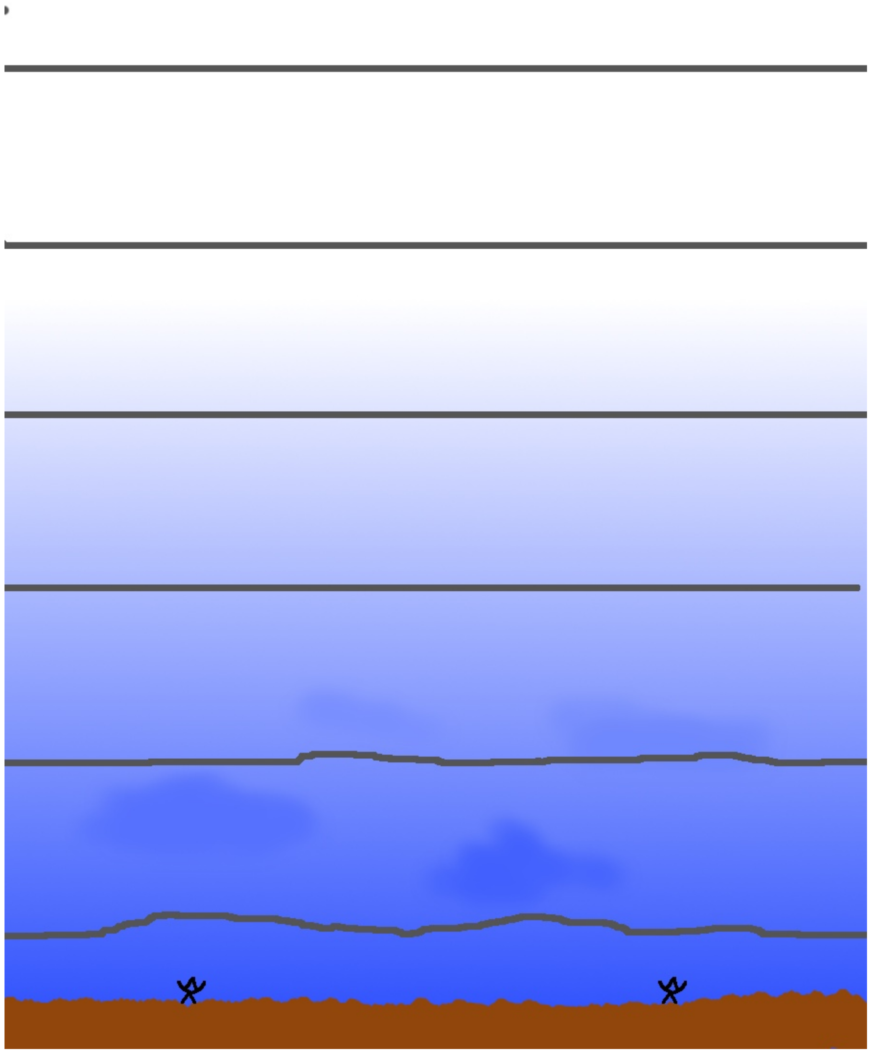
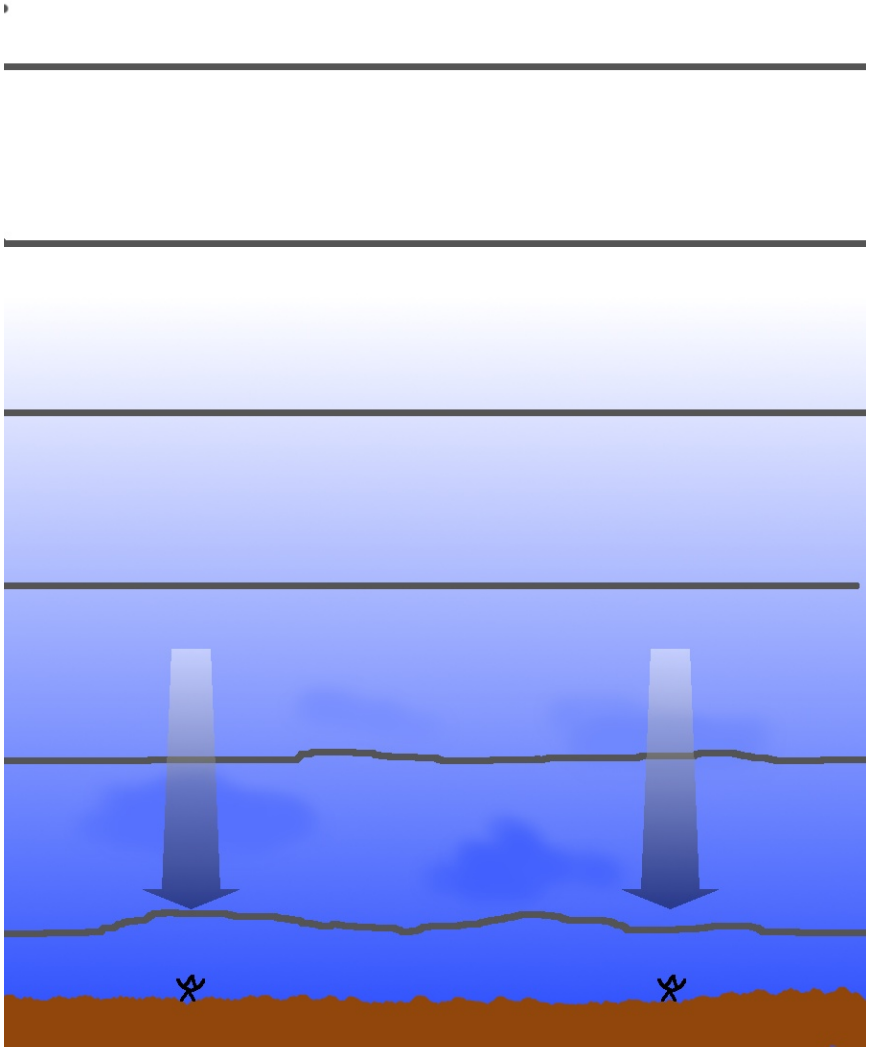
The Problem



- Water vapor causes variable delay, distorting wavefront
- Delay is approximately proportional to water vapor column density along boresight

Water Vapor Radiometry (WVR)

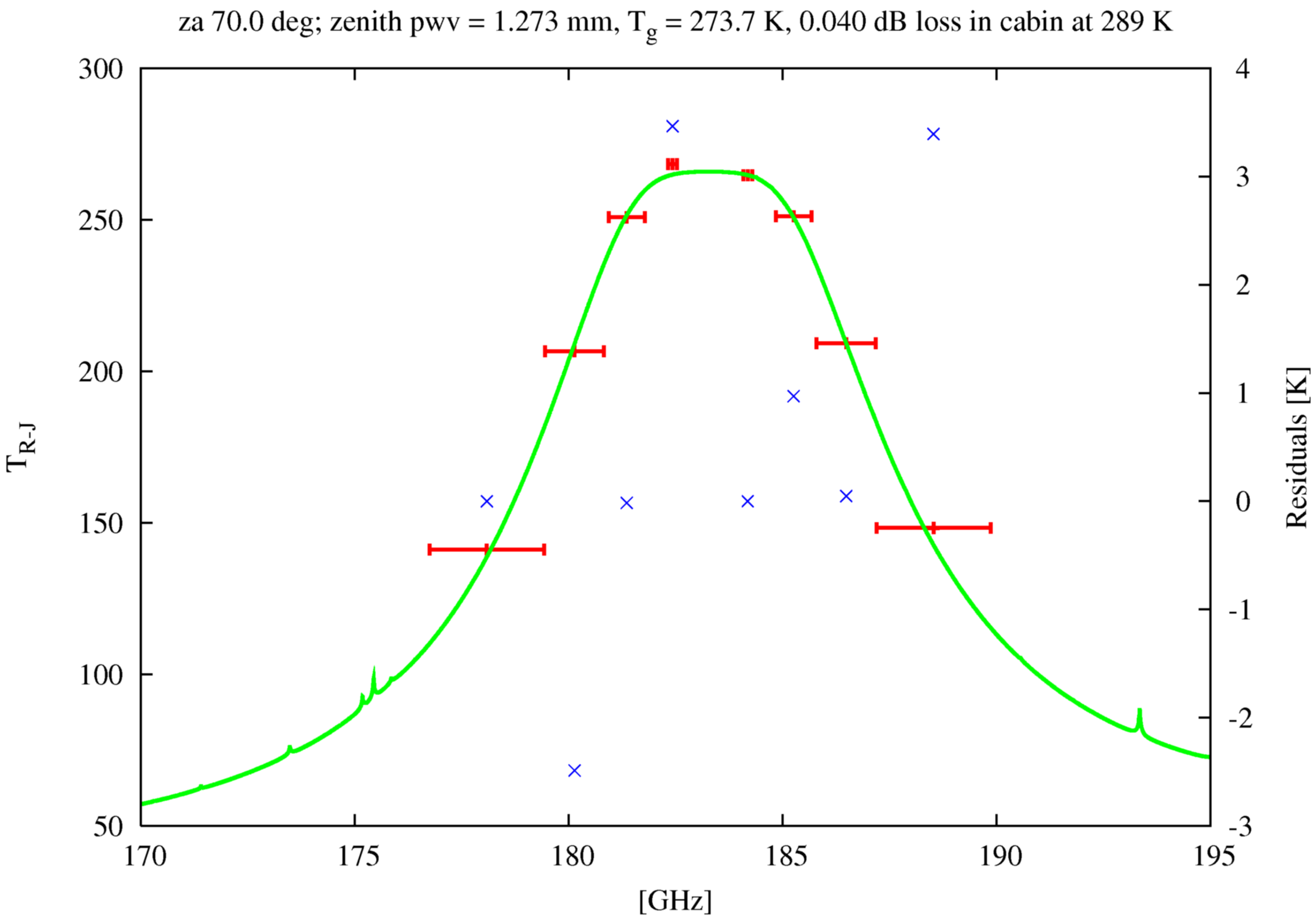
- Estimate column density from water vapor emission along each line of sight
- From high altitude, 183 GHz line is a good choice for sensitivity, using several channels across line



WVR at the SMA

- Prototype WVRs developed for ALMA jointly by Cambridge University and Onsala Space Observatory (R. Hills et al.)
- Eight channels across 183 GHz water line
  - Cambridge: Sideband-separated correlating radiometer
  - Onsala: Dual-Dicke DSB
- Installed for tests in two SMA antennas since January 2006
- Coaxial with astronomical beams
- Integrated with SMA software system

183 GHz line fit to WVR channels



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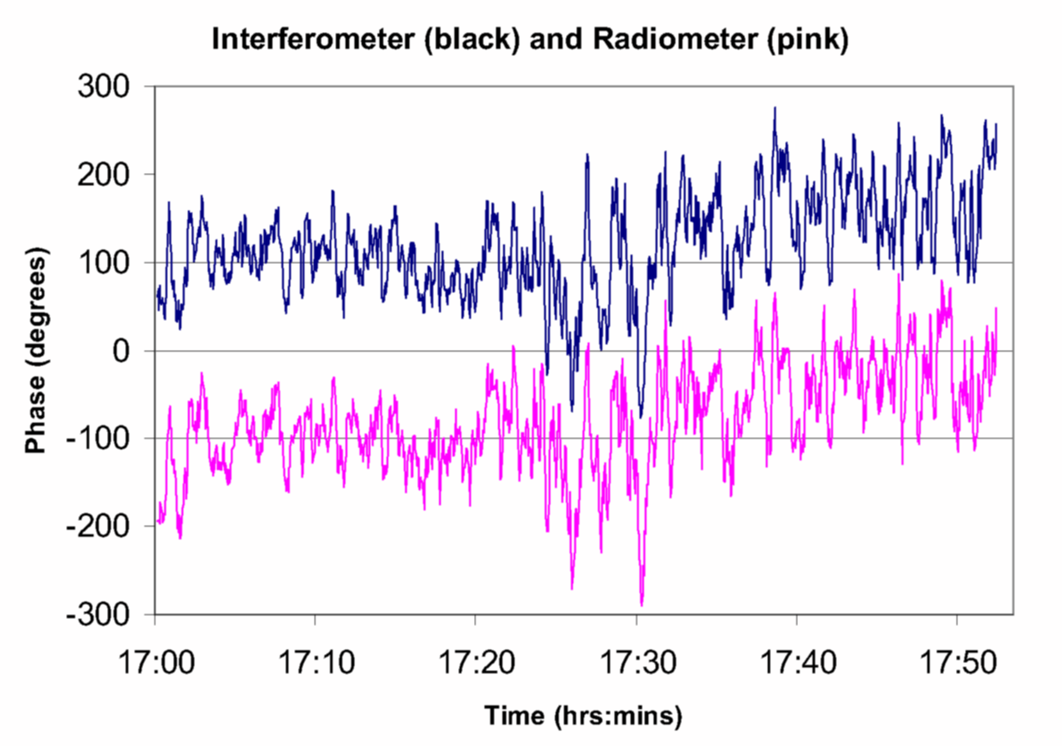
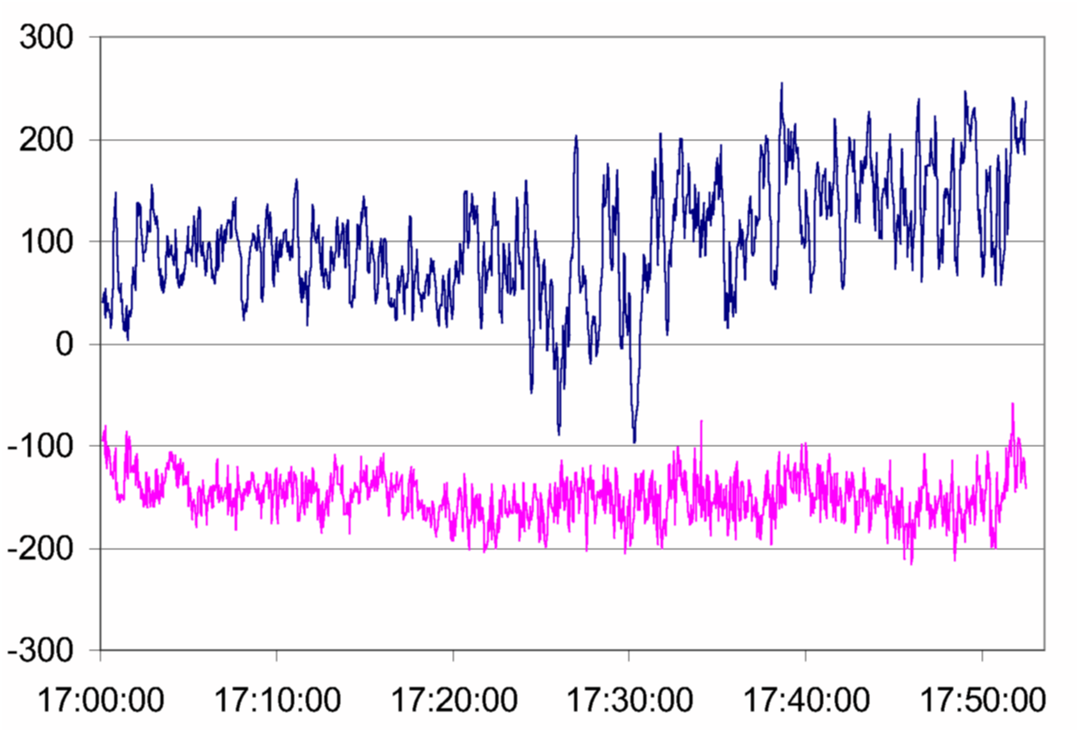
WVR phase vs. SMA phase, Feb 24 2006

- 200 m baseline
- SMA 230 GHz phase derived from bright quasar 3c273, averaged across sidebands
- WVR phase is delay, from pwv estimate, scaled to wavelength
- Special fast (2.5 s) SMA integration cycle



Corrected phase, Feb 24 2006

Phase [deg]



time

WVR, continued

- Not always effective...
  - Need to distinguish atmosphere from system issues
- but reliability is critical
  - Fluctuation time scale faster (~1 s) than normal astronomical integration times (~30 s). An erroneous correction applied on the fly will irreversibly corrupt data.
- Nevertheless, some phase correction scheme is essential for interferometers to reach full potential

Collaborators

Site Testing & RLT

R. Blundell, D. Marrone, E. Tong, D. C. Papa, T. Hunter, M. Smith, R. Plante, J. Battat, S. Leiker, T.K. Sridharan (CfA); J. Kawamura, J. Pearson, J. Stern, H. Yorke, I. Mehdi, J. Ward, S. Lord (JPL/Caltech), J. May, L. Bronfman, D. Luhr, C. Barrientos, W. Moerback (U. Chile); H. Gibson (RPG); B. Voronov, G. Goltsman (MSPU); M. Diaz (BU); D. Loudkov (Delft), D.Meledin (Chalmers), F. Bensch (Bonn); C. Groppi (NRAO); S. Radford (Caltech); A. Otarola, R. Rivera (ESO)

Phase Correction

R.E. Hills, R. Williamson, H. Smith, J. Richer (U. Cambridge); R. Booth, Magne Hagstrom, Leif Heldner, Lars Pettersson (Onsala); M. Reid, A. Schinckel, K. Young, A. Peck, T. Hunter, R. Christensen (SMA)