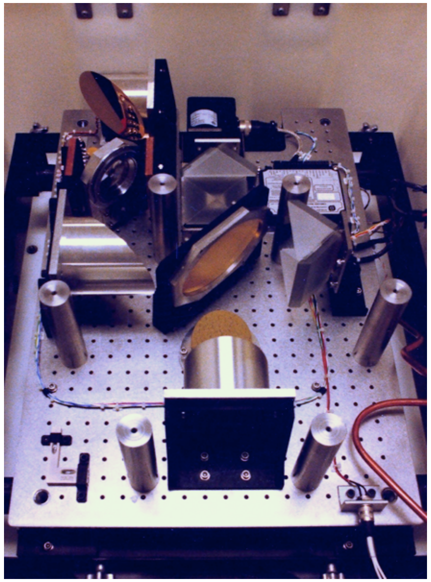
A Fourier Spectrometer for Dome A – Atmospheric Modeling and Design Issues



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Dome A Astronomy – Beijing – 2008 June 12

Outline

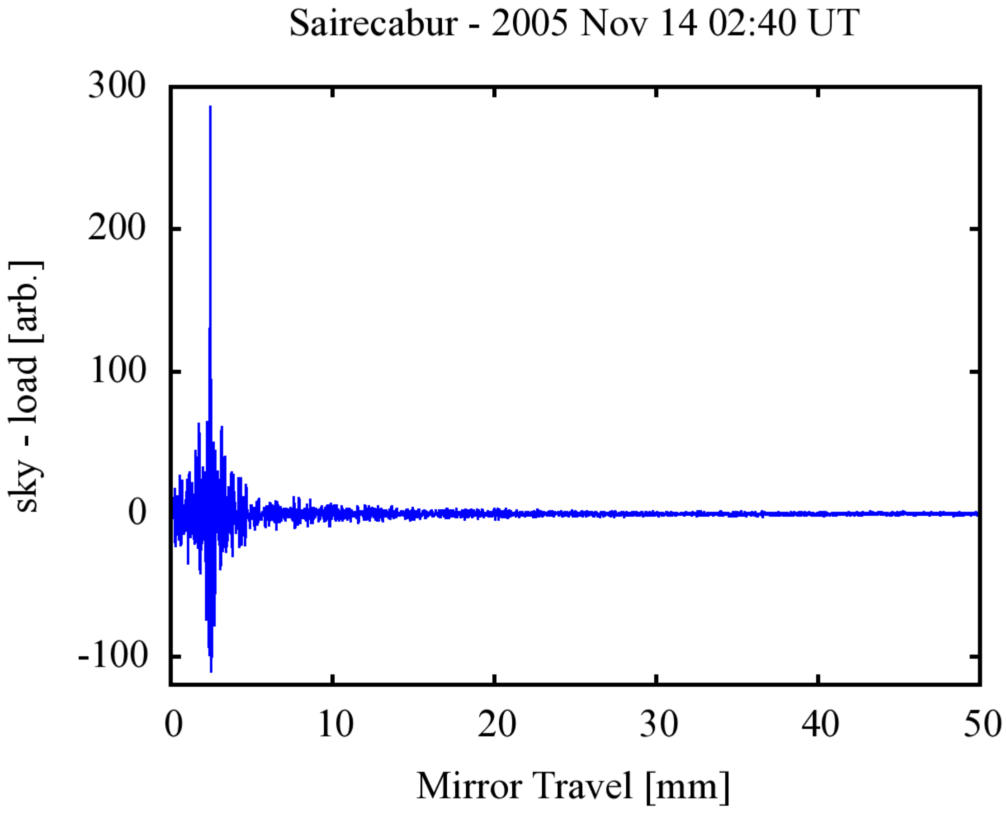
- Why deploy a Fourier Transform Spectrometer (FTS)?
- FTS measurement example
- An atmospheric model for Dome A
- FTS design issues
  - Experience with SAO site-testing FTS
  - Design constraints and sensitivity estimates for Dome A

Why deploy an FTS?

- Broad spectral coverage (e.g. 200 μm to 20 μm) gives tightly-constrained atmospheric transmission
- Eliminates modeling uncertainty associated with H_2O continuum absorption at low temperature
- FTS spectra combined with atmospheric sounding data can validate absorption models
- Probes boundary layer in optically-thick spectral range

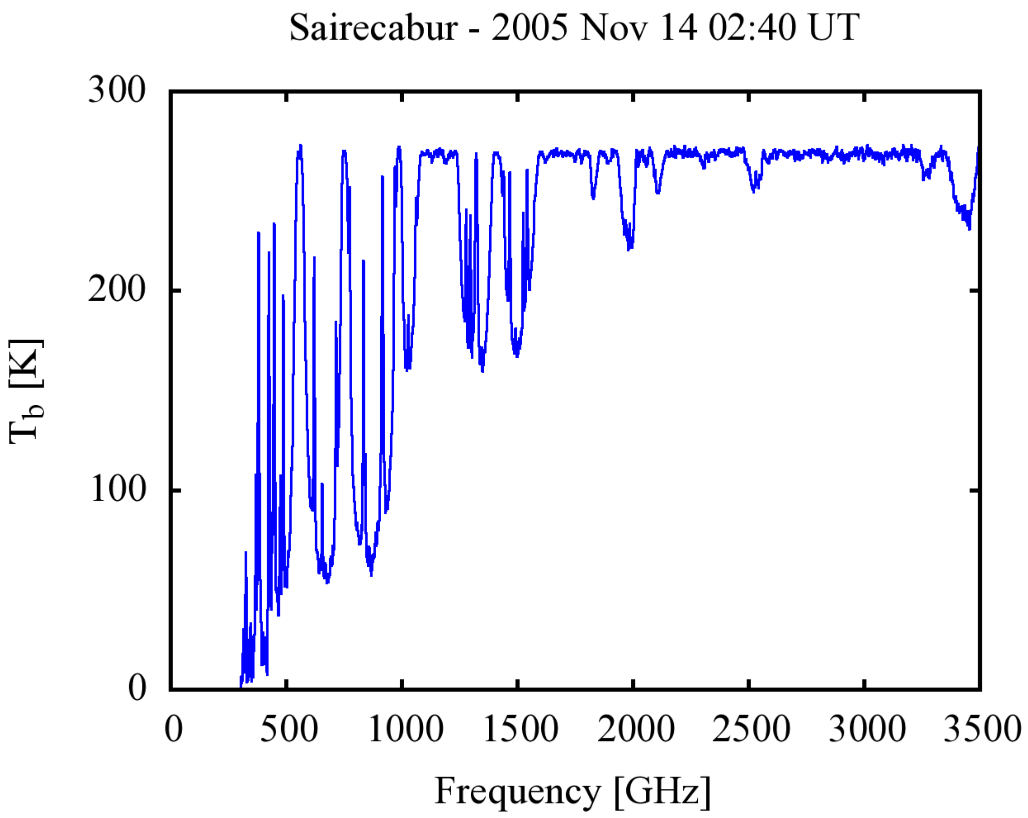
Example of an FTS interferogram – Sairecabur, Chile

- Polarizing Michelson interferometer with He-cooled bolometers
- Interferogram acquired in 10 minutes
- ~50 mm mirror travel (100 mm delay)
- ~3 GHz resolution
- Things to note:
  - Large dynamic range
  - Effect of flicker noise



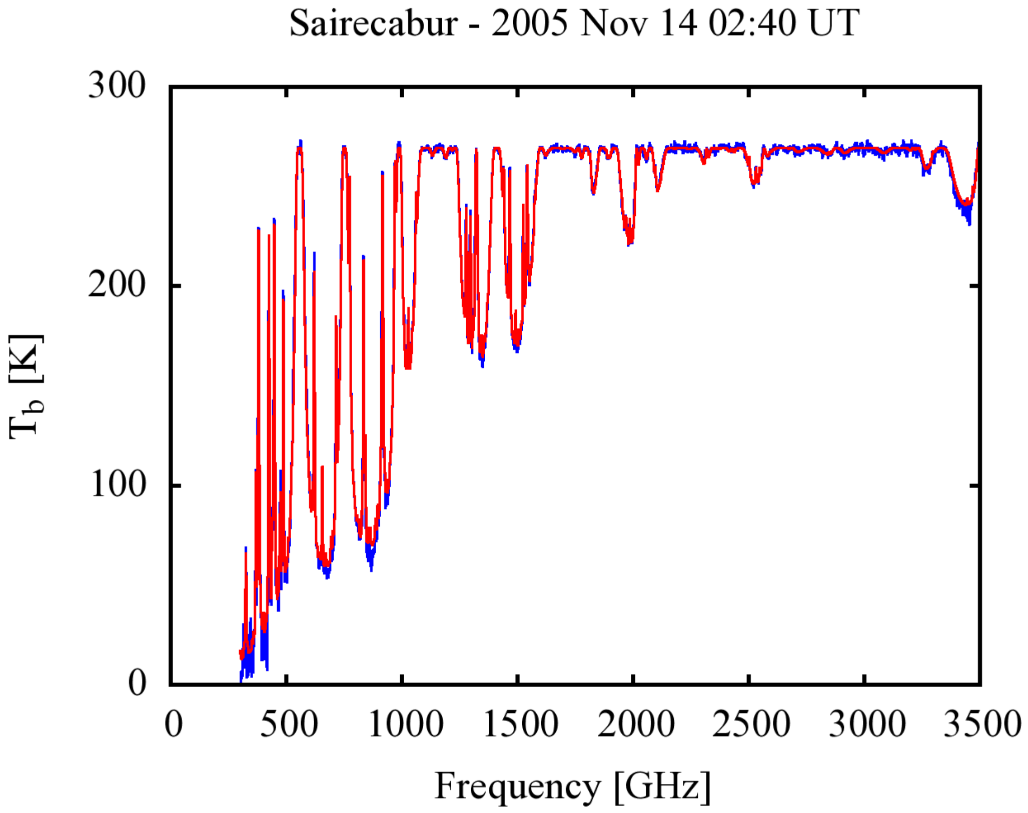
Example of an FTS spectrum – Sairecabur, Chile

- Fourier transformation and calibration produces T_b spectrum.
- SNR degrades rapidly towards low frequency: ~30 for 650 GHz, 100 K
- Note baseline at boundary layer temperature.



Example of an FTS spectrum – Sairecabur, Chile

- Model fit with *am*
- Initial profiles based on Chajnantor radiosonde archive
- Fit four parameters:
  - H_2O profile scale factor
  - T in two layers for $440 \text{ mbar} < P < 530 \text{ mbar}$
  - H_2O mixing ratio in bottom layer

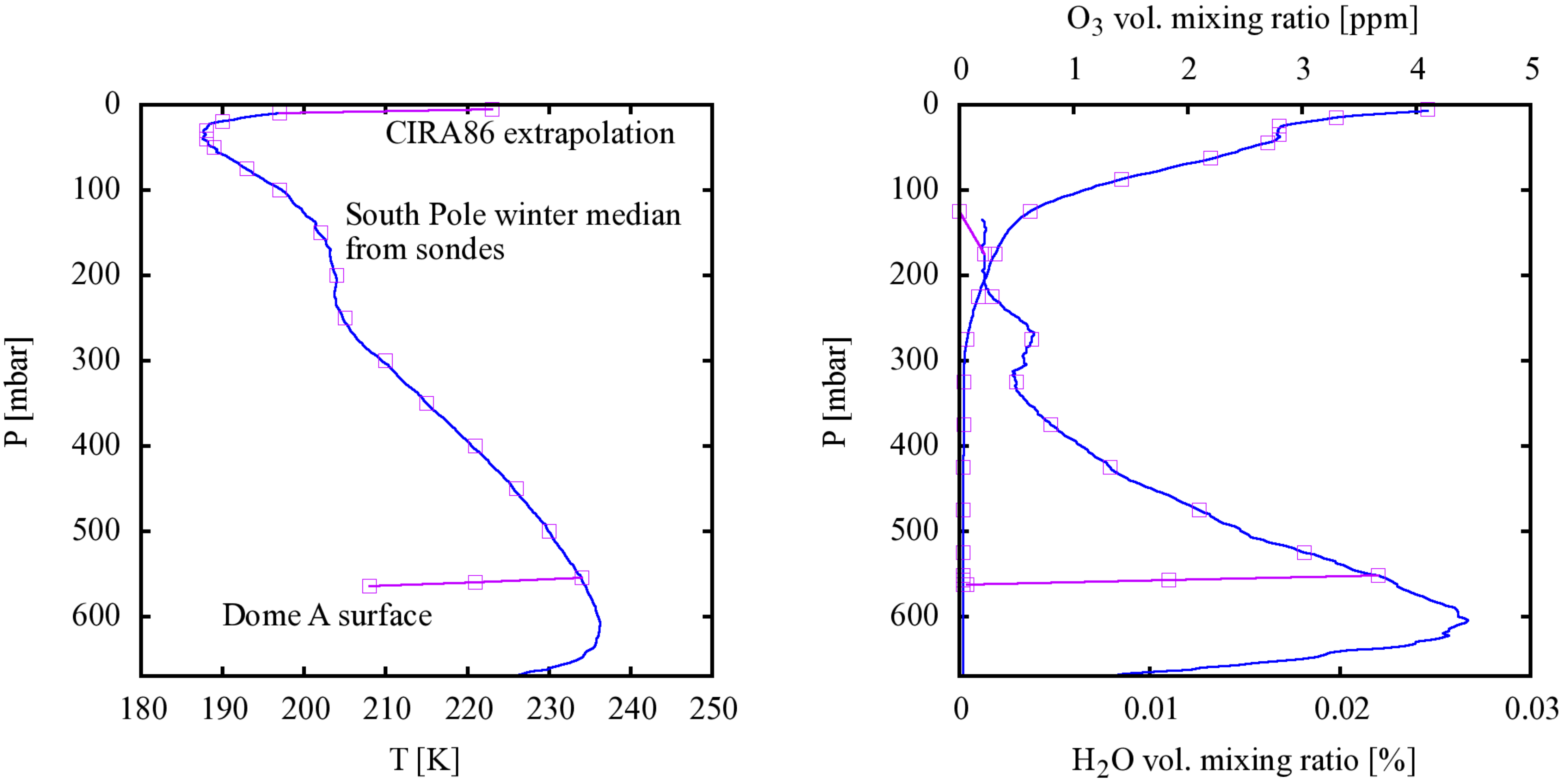


H_2O continuum (MT_CKD) works well here, where $T_{H20} > 260$ K

An atmospheric model for Dome A

- Serves as a starting point for instrument design
- Use median winter profiles from NOAA CMDL South Pole ozonesondes, which carry chilled-mirror hygrometers.
- Ground point based on Dome A weather station data
- Look at contributions from various constituents

Dome A model profiles (winter median)



- Model surface inversion is 10 mbar thick (e.g. J. S. Lawrence, PASP **116** 482)
- Symbols indicate points used for *am* winter median model profiles.
- Model winter pwv quartiles are 115 µm, 180 µm, 270 µm – this is probably an upper bound.

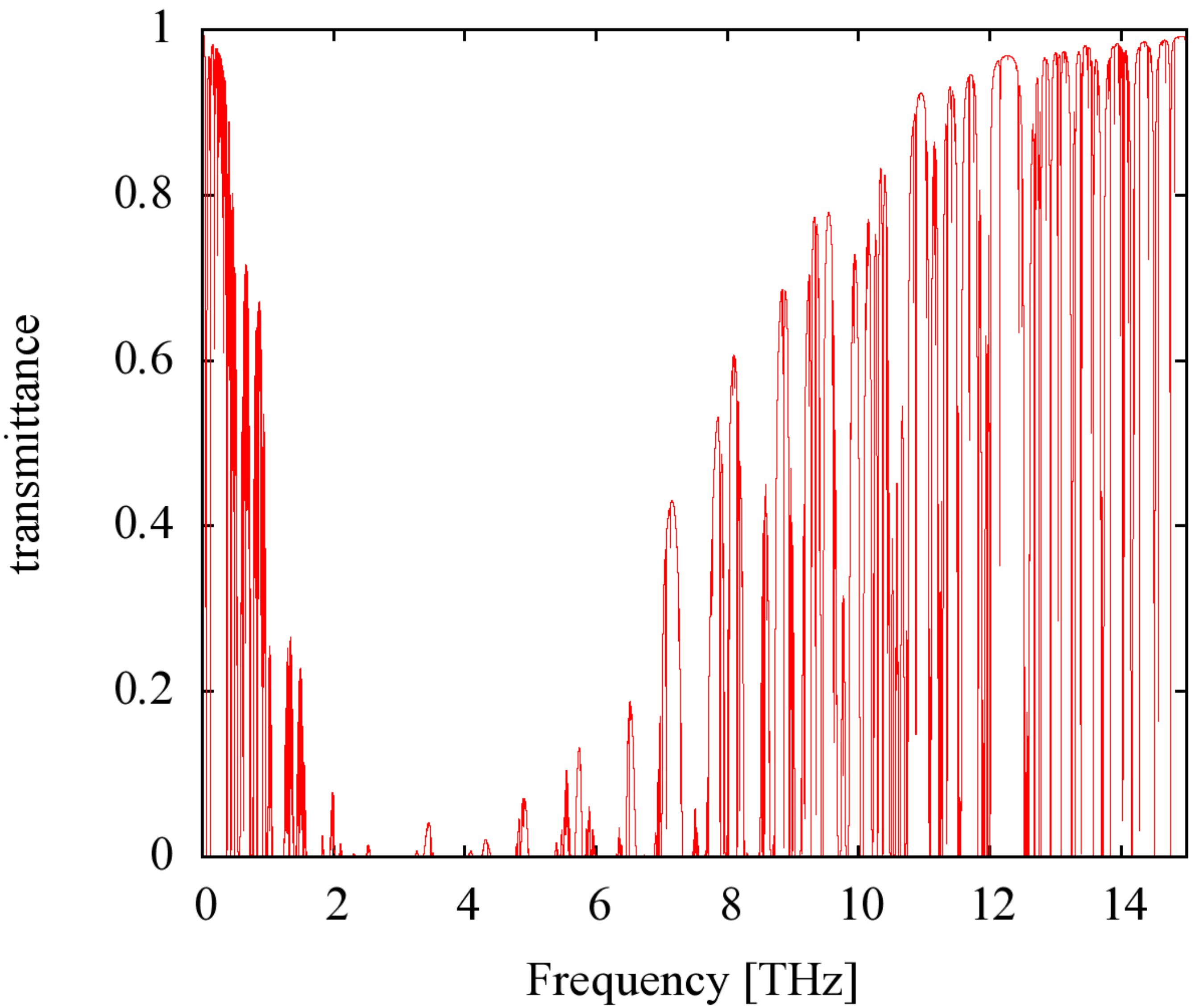
Atmospheric model components

Use model profiles in radiative transfer model with:

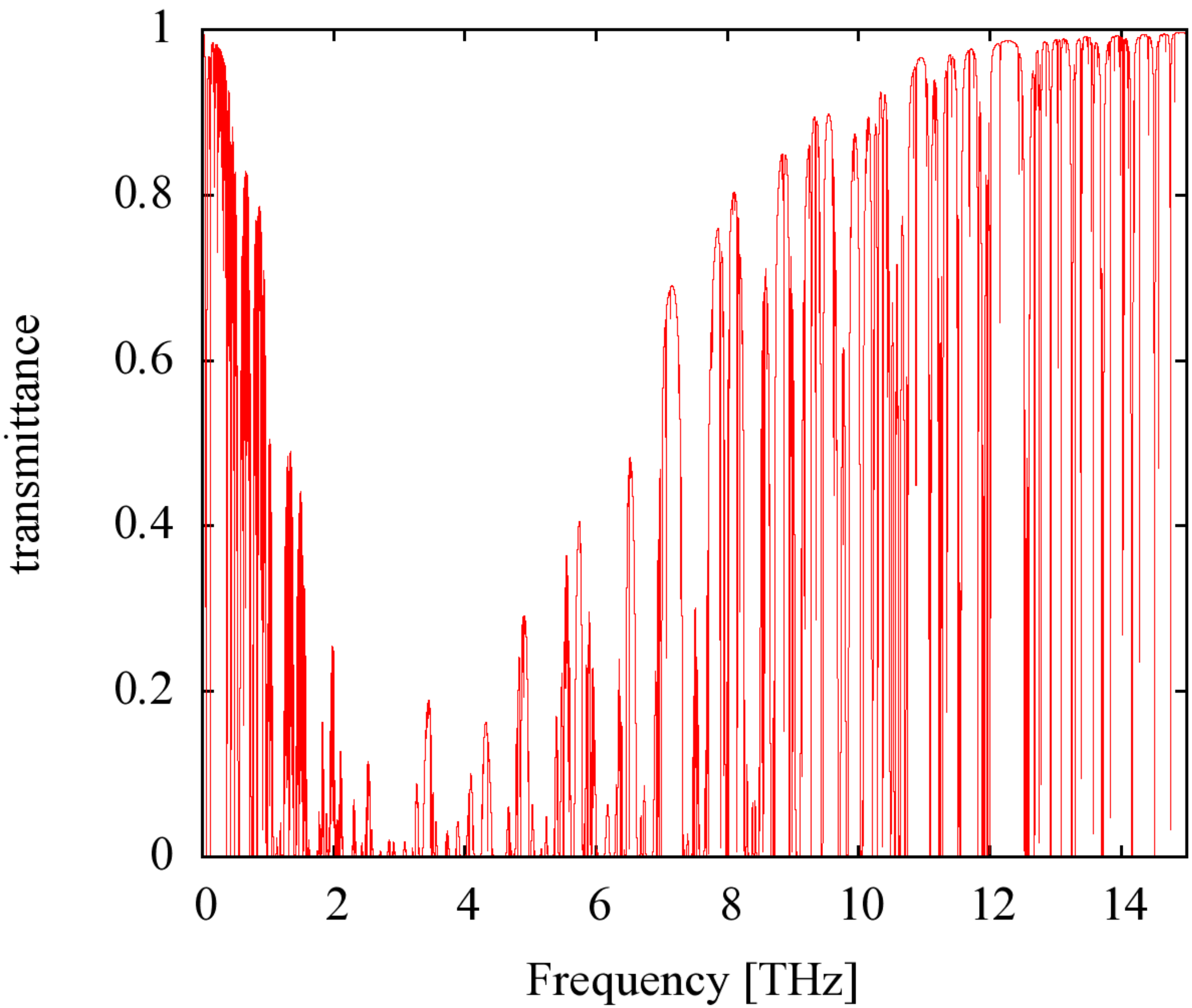
- Line absorption from H_2O, O_2, O_3, N_2O, CO, CH_4
- H_2O continuum absorption
- Dry collision-induced absorption

The greatest uncertainty arises from H_2O continuum

Dome A winter model (180 μm pwv)



Dome A winter model (75 μm pwv)



Collision-induced absorption (CIA)

- Broadband dry THz absorption is mainly N_2-N_2, N_2-O_2 CIA.
- Forbidden electric quadrupole and 16-pole rotational transitions acquire dipole coupling via polarization of collision partner.
- Binary process, so absorption depends on density squared.
- Collisions are brief (~10^{-12} s), so broad lines blend into an unresolved band.
- N_2-N_2 lab data is available to 90 K. O_2-x is less well-studied, but contribution to atmospheric opacity is small.

Laboratory N_2-N_2 CIA spectrum

(Stone, et al. 1984)

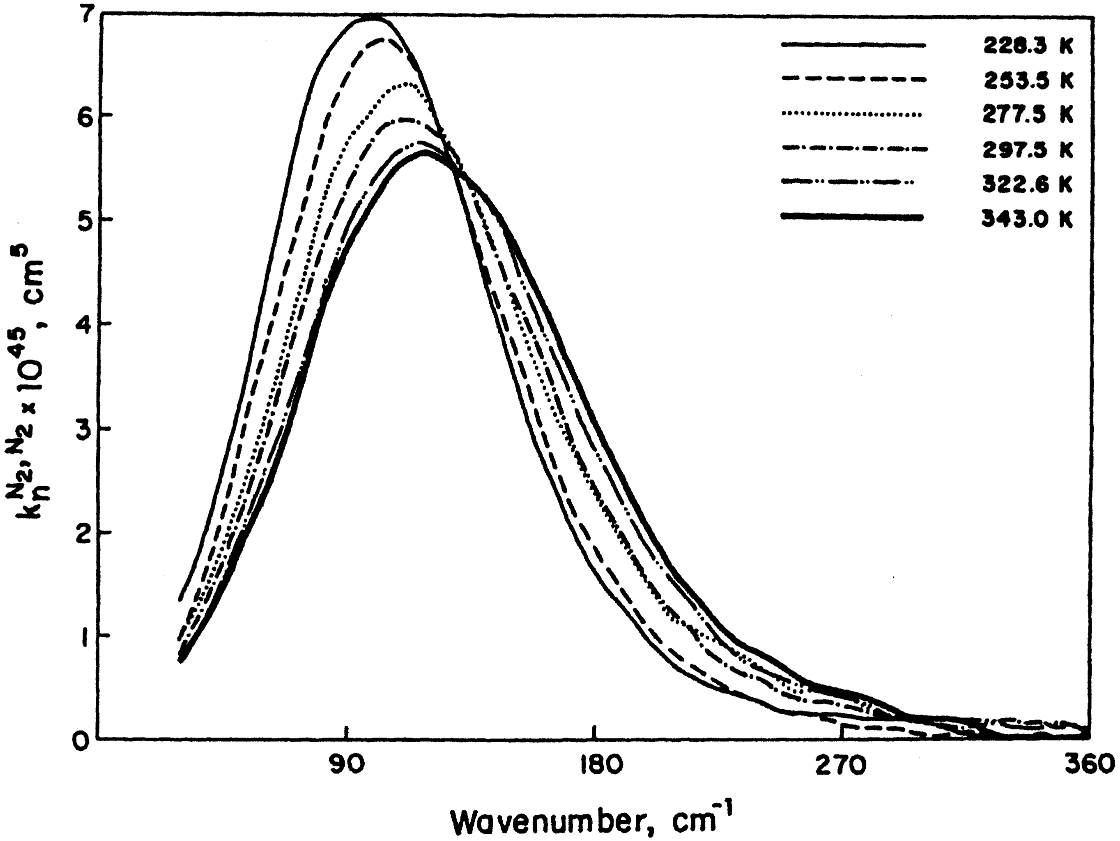
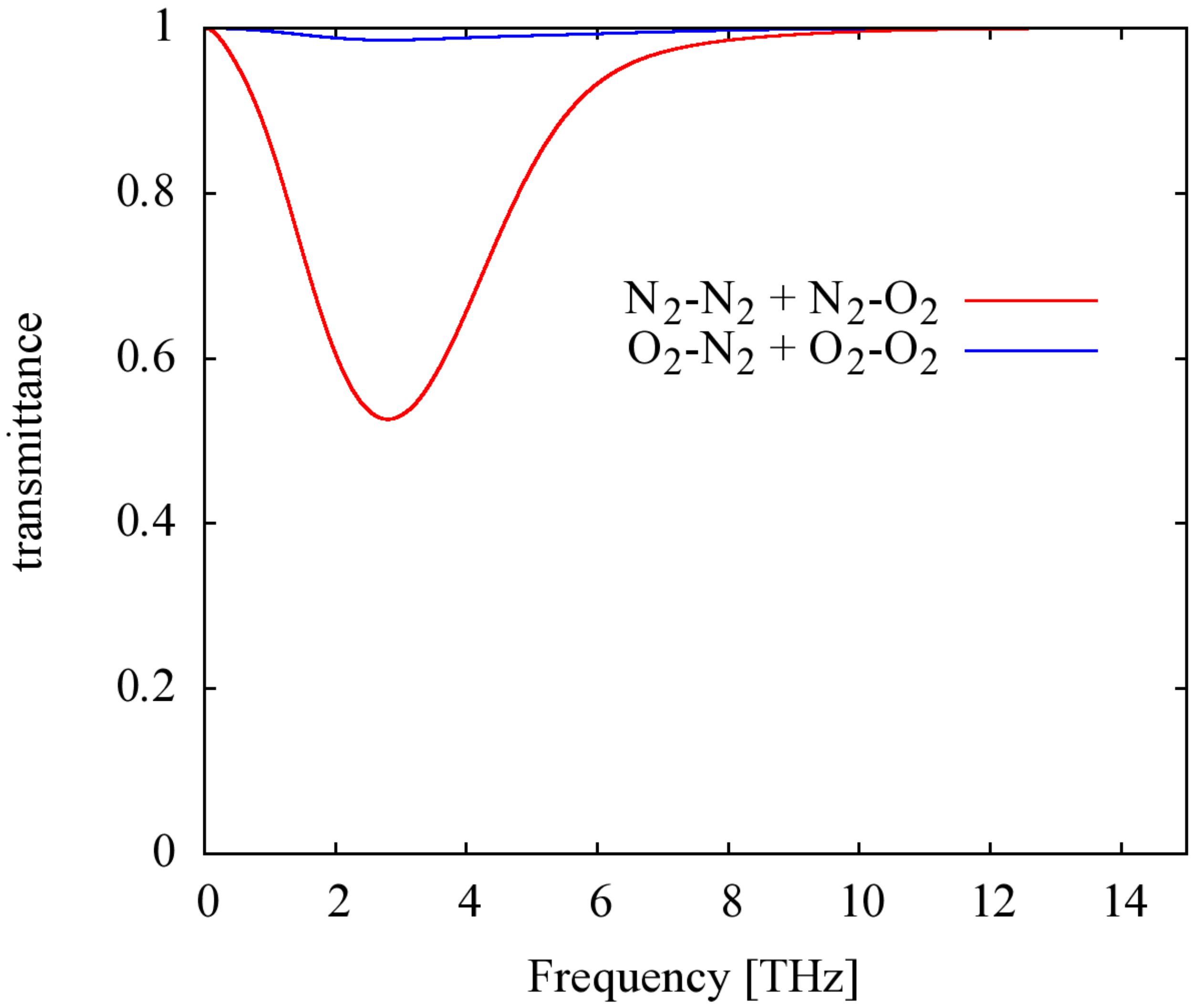


Fig. 5.2. The collision-induced rotation band of pure nitrogen (nitrogen–nitrogen collisions). The vertical axis is the binary absorption coefficient, as defined in (3.88). After Stone et al. (1984).

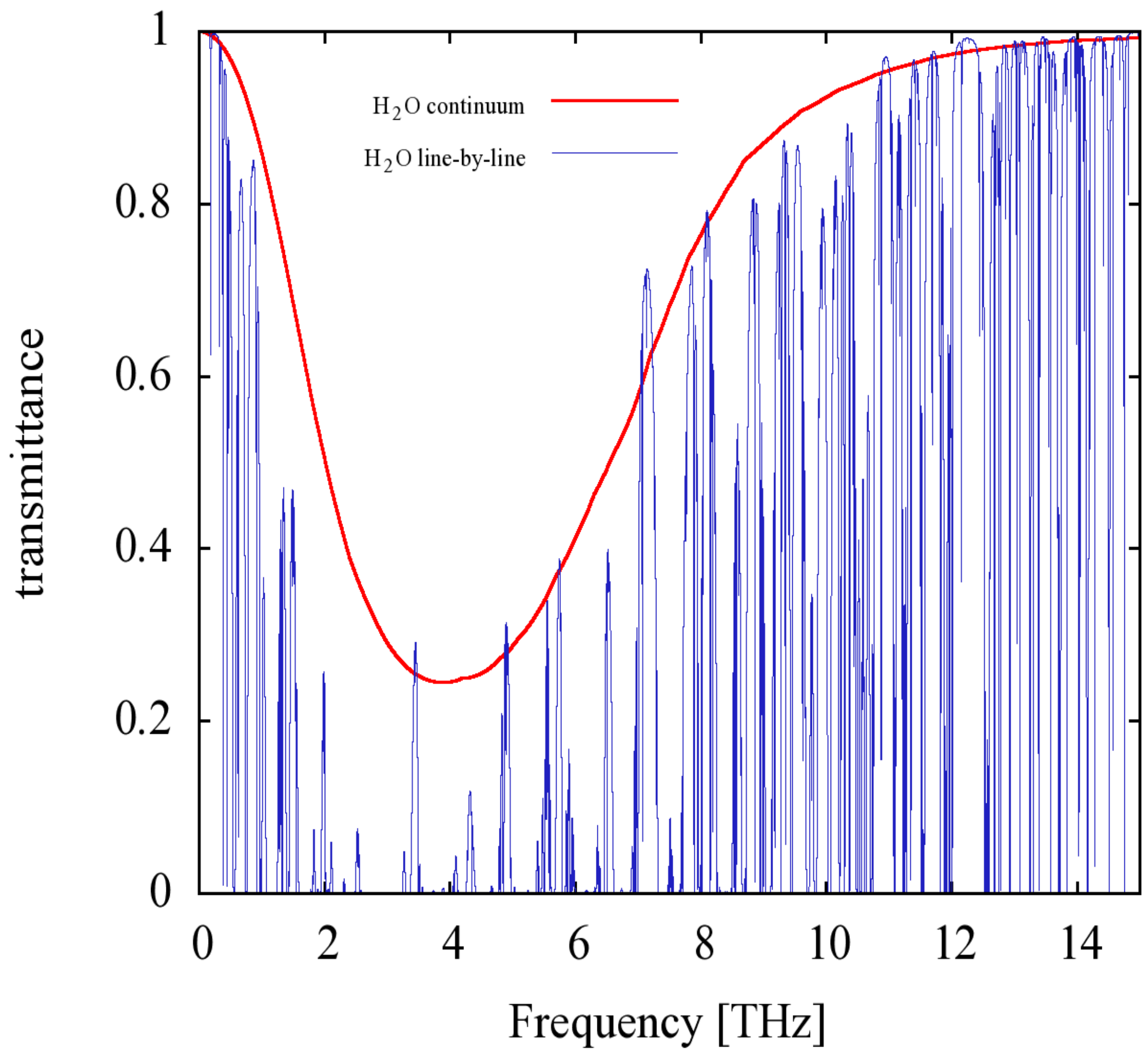
Dome A winter CIA transmittance



H_2O Continuum

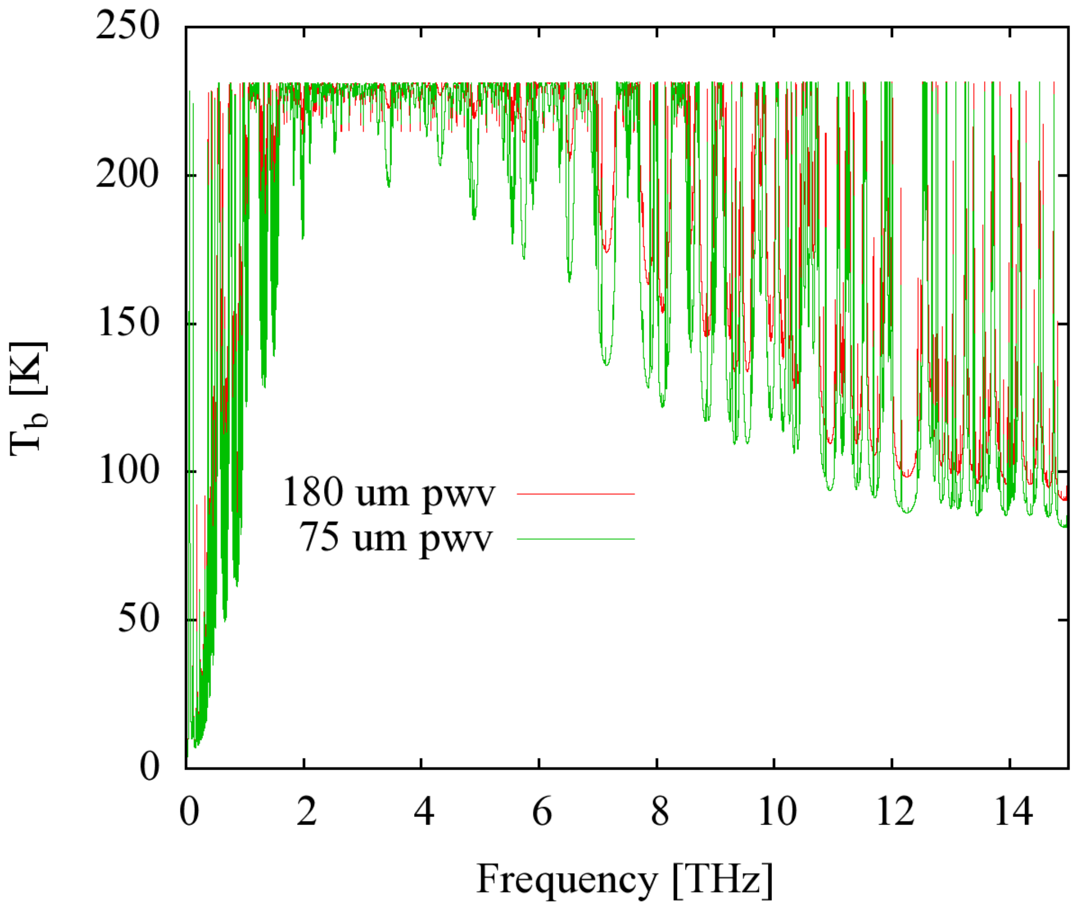
- Associated with short-range collisions
- Dipole-allowed transitions are affected, may also have a CIA component
- Difficult to study experimentally
  - Hard to disentangle from allowed line spectrum
  - H_2O vapor hard to control experimentally at low T
- Best model is MT_CKD (Mlawer, et al., see rtweb.aer.com)
  - Self-continuum defined for $260\ \mathrm{K} < T < 298\ \mathrm{K}$
  - T-dependence not developed for air-induced continuum, which dominates in the dry conditions at Dome A

Dome A H_2O transmittance (180 μm pwv)



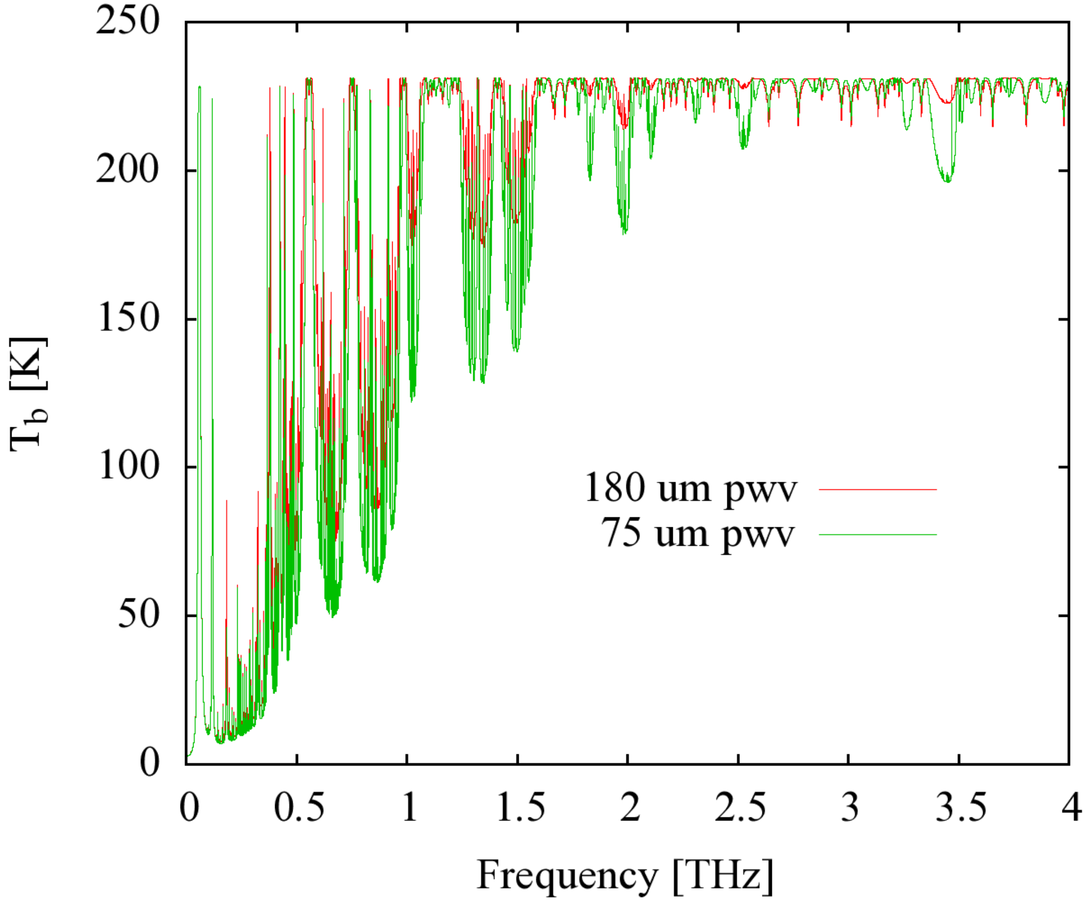
Accuracy of the T-independent MT_CKD self-continuum is questionable at such low temperatures (T < 240 K). The band can be expected to move down in frequency and sharpen. (Compare with line-by-line.)

Planck T_b for winter median P,T profile

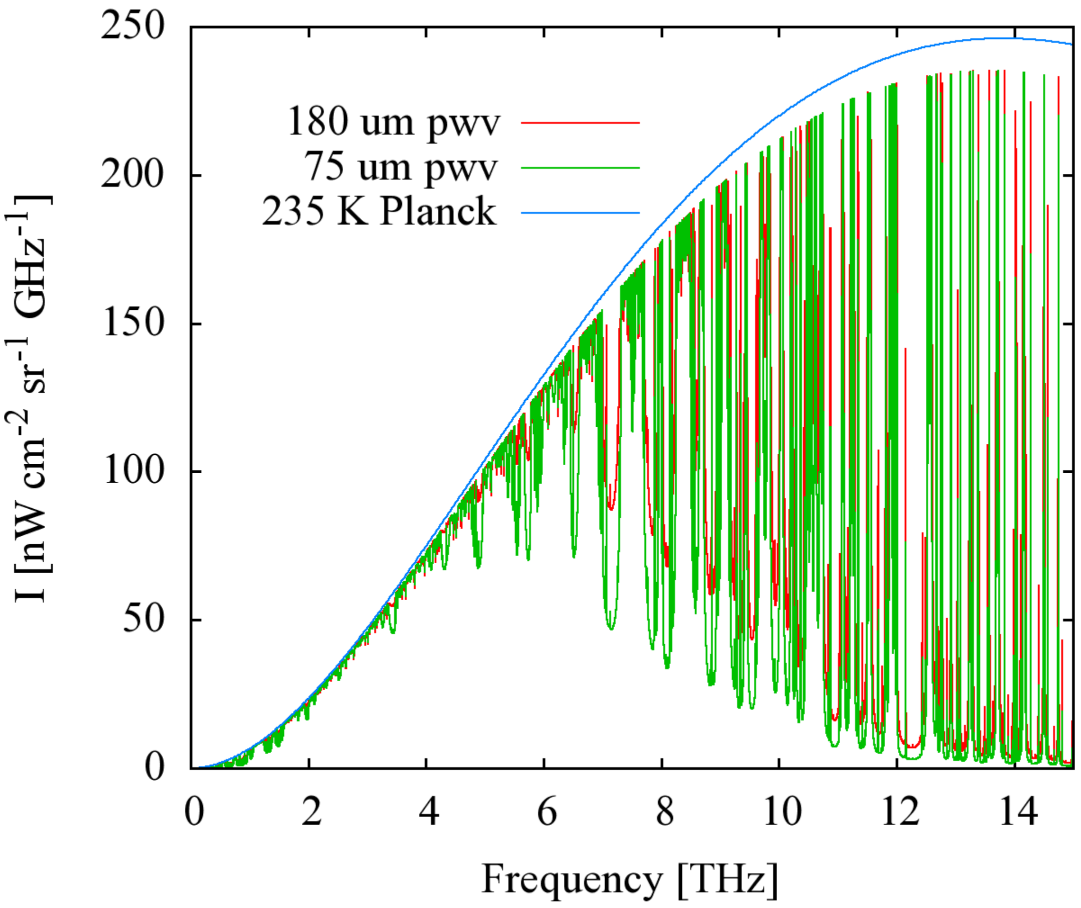


The optically-thick part of the spectrum gives some indication of the boundary-layer profile-- T_b at the center of strong lines is the surface temperature, baseline is T at top of inversion.

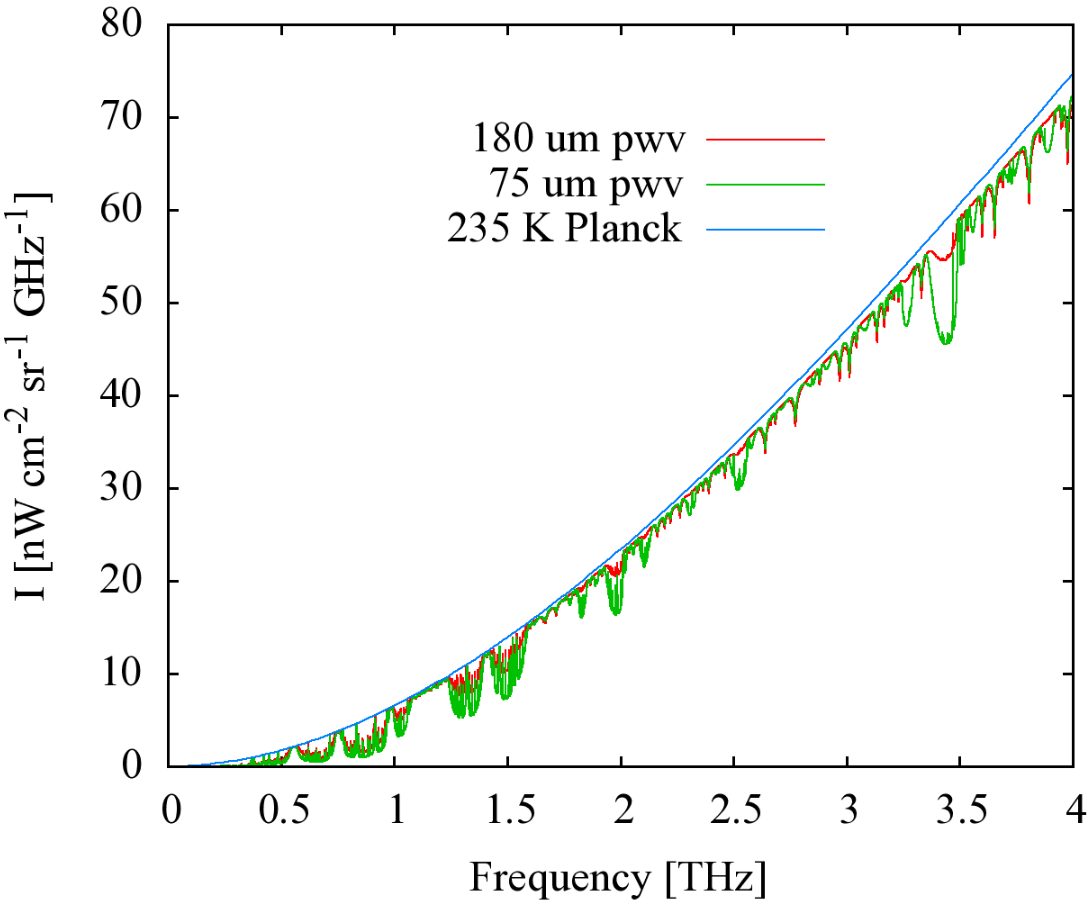
Planck T_b (submillimeter)



Radiance for winter median P,T profile



Submillimeter radiance



- Submillimeter radiance will drive instrument design

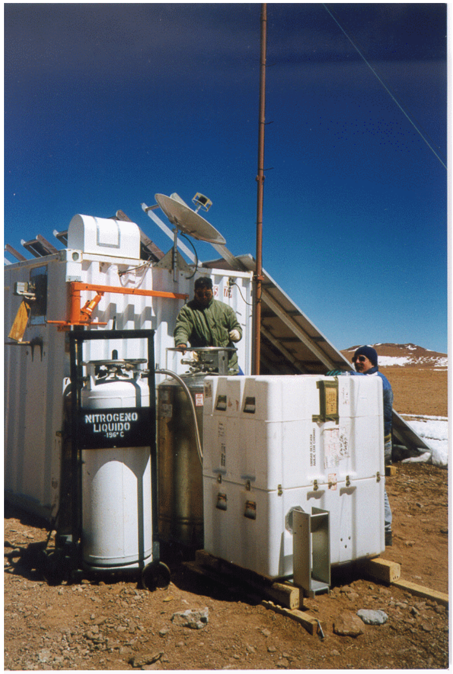
Instrument design issues

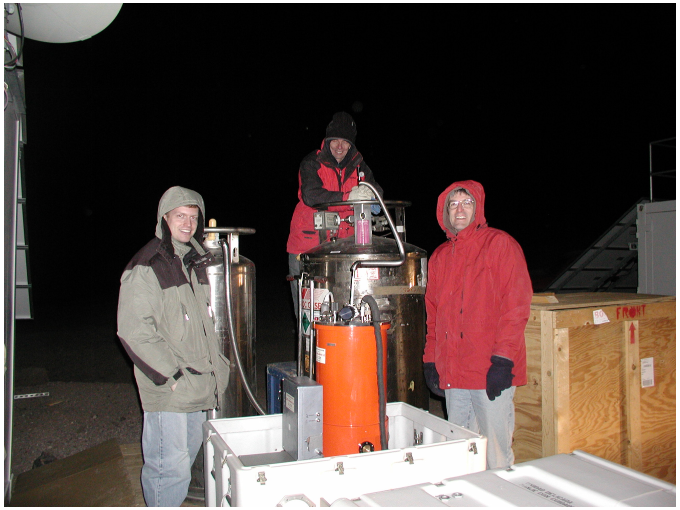
- SAO FTS summary
- Design constraints for Dome A
- Sensitivity estimates
- Other design issues

SAO Site Testing FTS

Llano de Chajnantor (5050 m) – 1997 – 1999

Note NRAO 225 GHz and 350 μm tippers





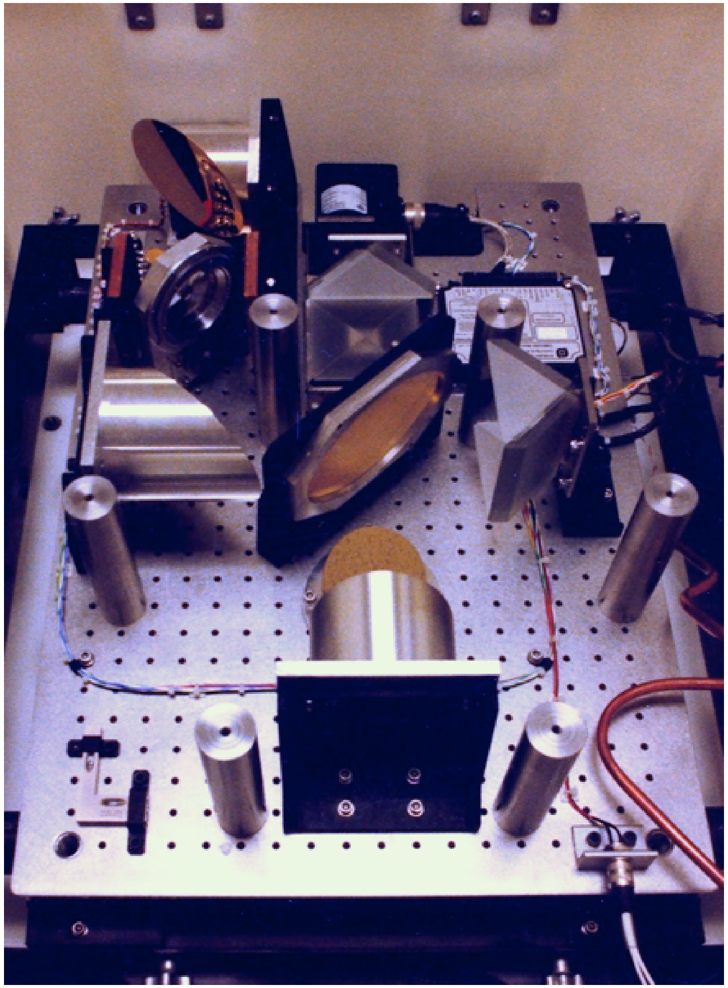
Sairecabur (5525 m) – 2000 – present

Comparison with Chajnantor, and

RLT calibration

SAO FTS Characteristics

- Polarizing Michelson FTS
- Polarization chopping @ 95 Hz
- 300 GHz – 3.5 THz
- He cryostat, 35 days hold time
- 100 W power consumption
- Outdoor operation to -25 C
- Biggest reliability issue has been the polarizing chopper



SAO FTS resolution and sensitivity

- Apodized resolution for 50 mm scan: 3 GHz
- Dual-polarized bolometers, NEP $1.2 \cdot 10^{-12}$ W $Hz^{-1/2}$
- Optical throughput per polarization channel: 0.11 cm^2 sr
- Efficiency ~20 %
- Typical SNR at 650 GHz, 100 K: ~30 in 10 minutes at full resolution, typically limited by flicker, not bolometer.

Design constraints for Dome A

- Frequency coverage to 15 THz (20 μm) is highly desirable
  - Cover entire H_2O rotation band and rotational continuum
  - Measure windows to $f \geq 7.5$ THz ($\lambda \leq 40$ μm)
- Liquid cryogens or closed-cycle fridge not practical in near term
  - Forces use of ambient temperature (pyroelectric) detector
  - NEP ~10^{-9} W/$\text{Hz}^{1/2}$, compared with ~10^{-12} W/$\text{Hz}^{1/2}$ for cryogenic bolometer

FTS sensitivity estimate

$$SNR = \frac{P}{NEP \cdot t^{-1/2}} \qquad P = I \cdot E \cdot \Delta f \cdot \eta$$

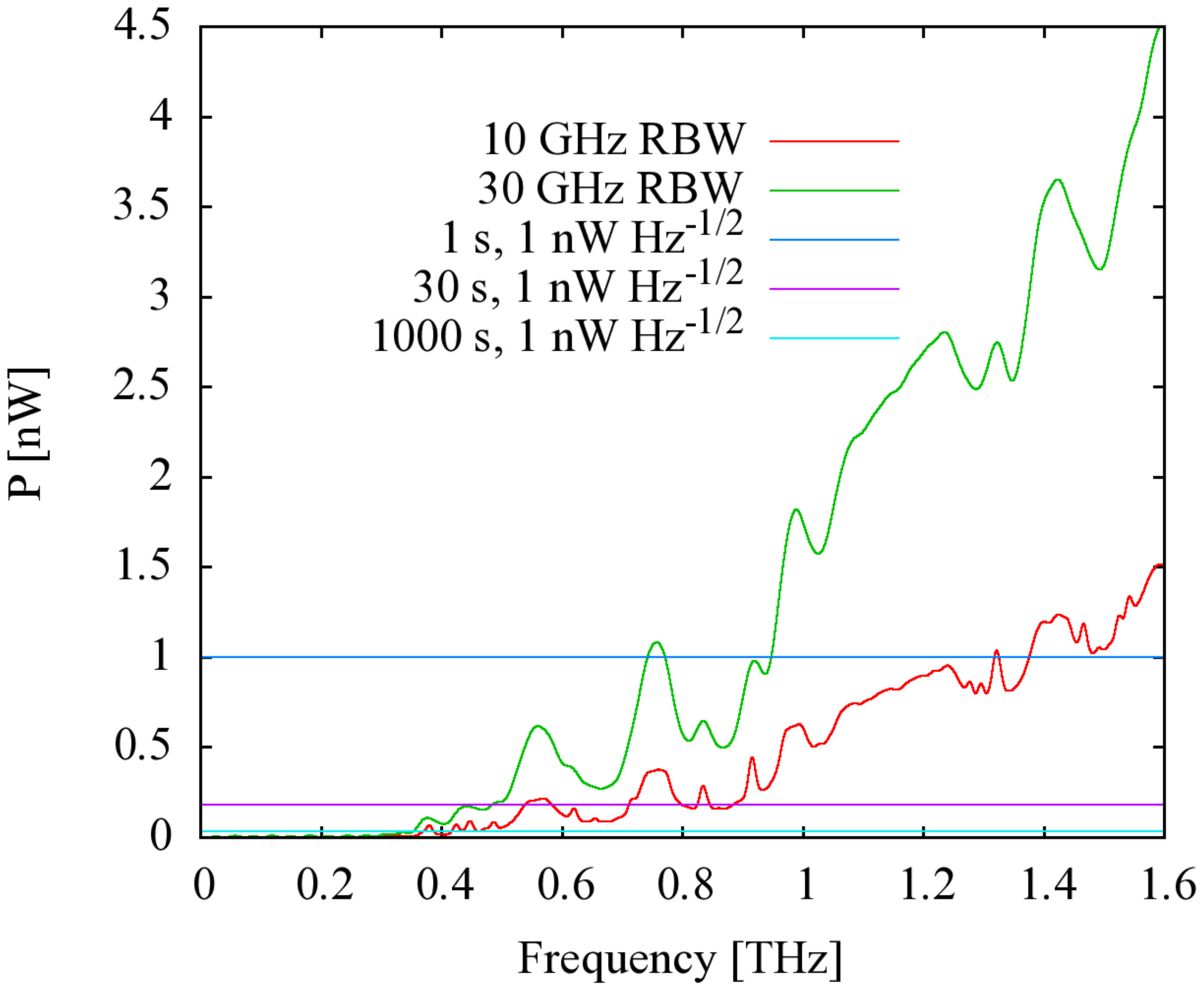
$I = \text{radiance}$

$\Delta f = \text{resolution bandwidth}$

$E = \text{optical throughput (assume } 0.1\,\text{cm}^2\,\text{sr)}$

$\eta = \text{efficiency (assume } 0.1)$

FTS sensitivity estimate



(Power spectra computed using median model radiance at 180 μm pwv)

Other design issues

- Two-mode operation
  - High throughput with long-pass filter ($\lambda > \sim 100\ \mu$m) for submillimeter measurement
  - Lower throughput mode for measurement to ~20 μm
- Calibration with no cryogens, limited power
  - May be able to use internal & external ambient loads
- Optimum measurement strategy
  - Mix of short vs. long scans, submillimeter vs. FIR spectral modes

Conclusion and next steps

- The concept of a site-testing FTS without cryogenics appears feasible.
- Having the capability to measure both ends of H_2O rotation band is desirable
- Next steps:
  - Refine understanding of design tradeoffs
  - Evaluate capabilities of commercial vendors