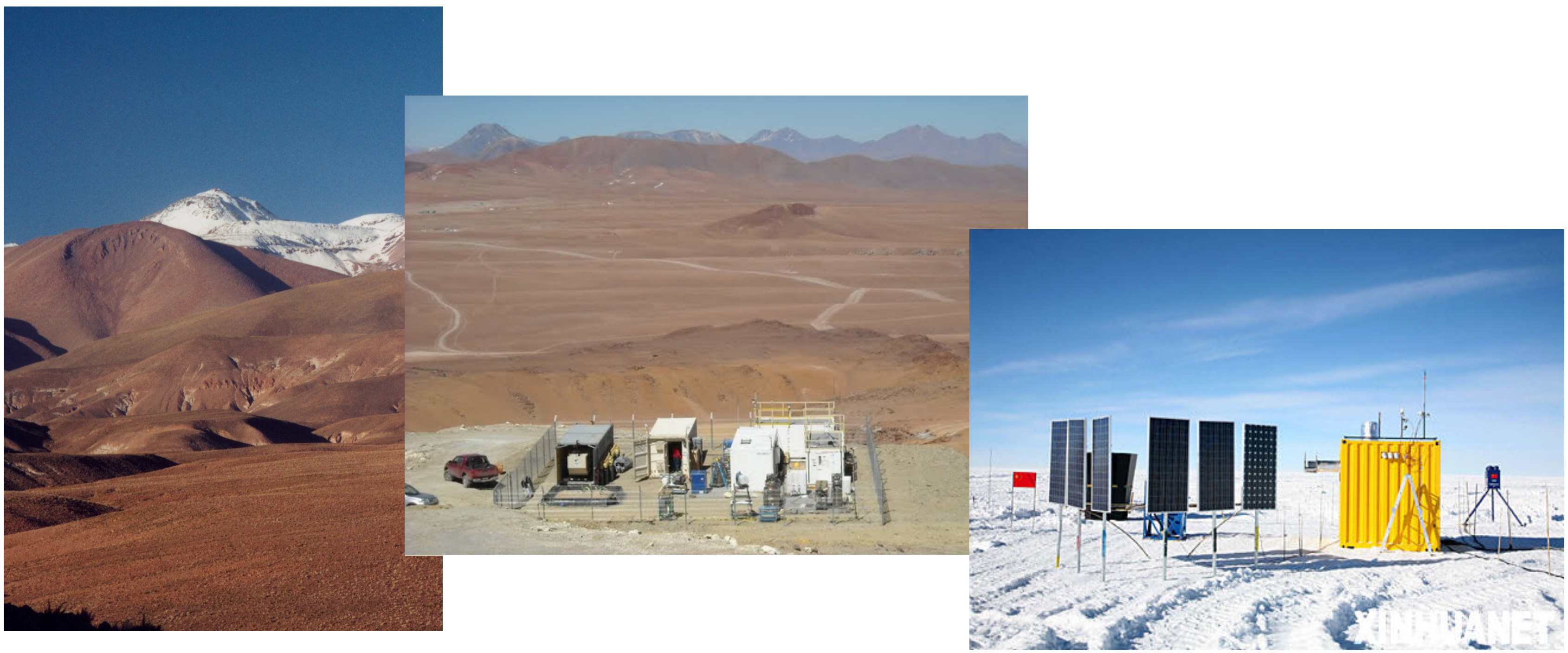
Atmospheric Radiometry for Astronomy and Climate Science



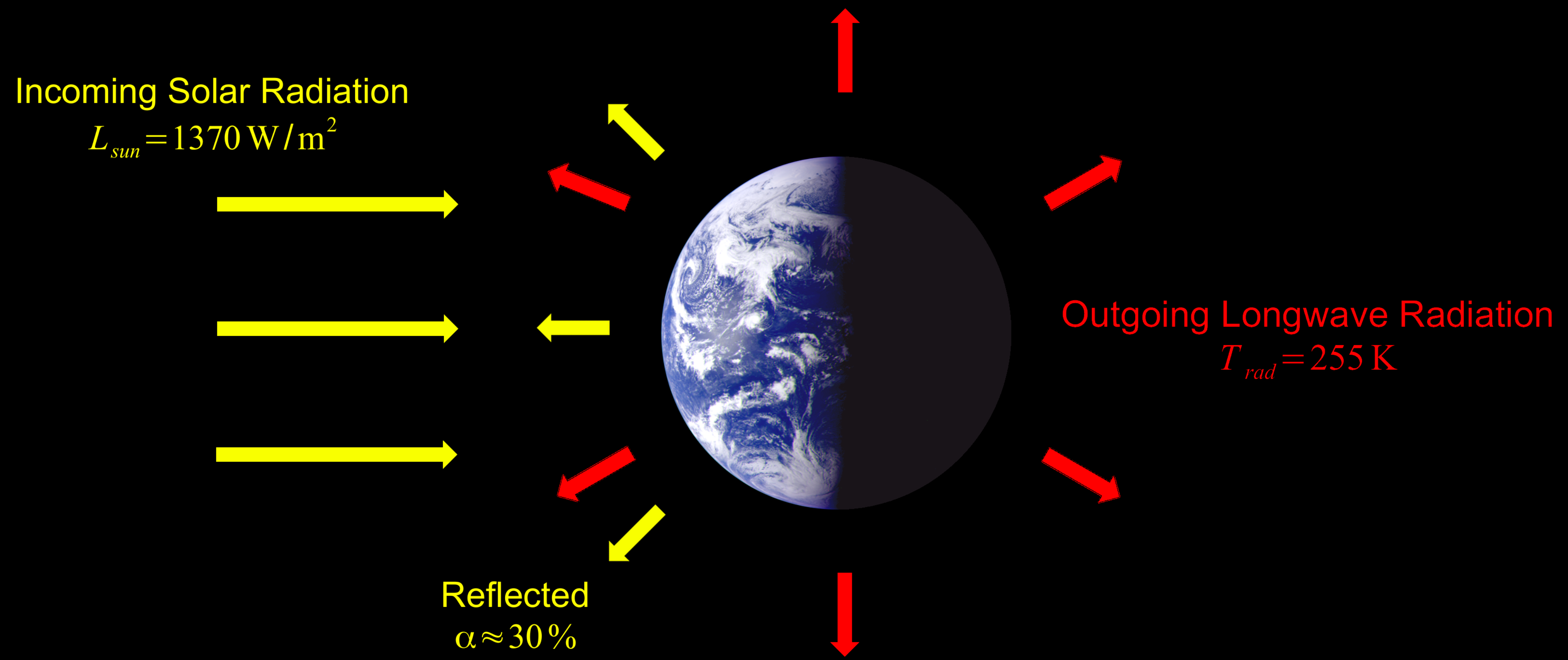
Scott Paine, SAO Submillimeter Receiver Laboratory

Smithsonian Climate Change Research Symposium – 2011 May 24

Outline

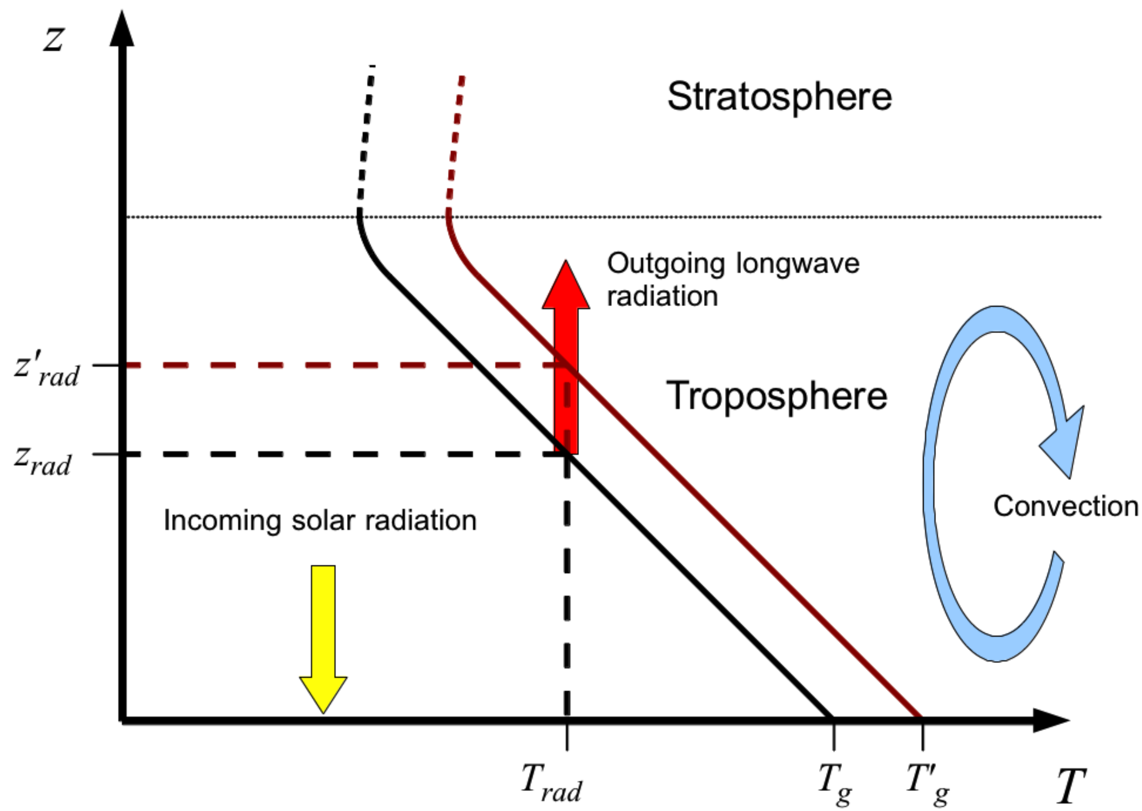
- Background – atmospheric radiation and climate
- Why astronomers care also
- Radiometric site testing for astronomy in northern Chile
- Radiometry for climate science – SAO participation in RHUBC-II
- Dome A, Antarctica

Earth Radiation Balance



$$\sigma T_{rad}^4 = \frac{1}{4}(1-\alpha) L_{sun}$$

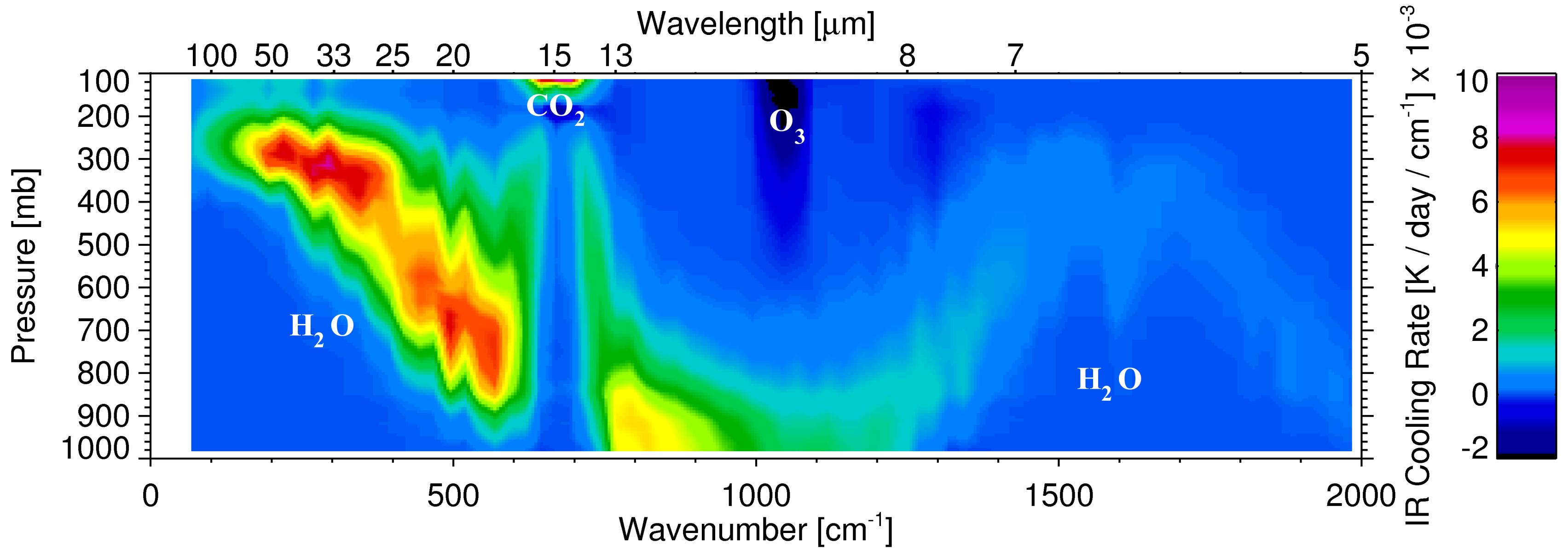
Gray gas greenhouse effect



- Consider an atmosphere transparent to solar radiation, gray in thermal IR.
- Solar radiation heats the surface and drives convection in the troposphere.
- Convection establishes adiabatic temperature lapse with height.
- Height of the effective radiating layer governs the surface temperature.

Infrared spectral cooling rate

(Midlatitude summer – Turner and Mlawer 2010, after Clough and Iacono, 1995)



- Real gas is more complicated, but the same principles apply.
- Far-IR radiation from mid- to upper troposphere accounts for about half of longwave cooling.
- Water vapor line and continuum radiation play a central role.
- Need for accurate spectral data drives radiometric studies.

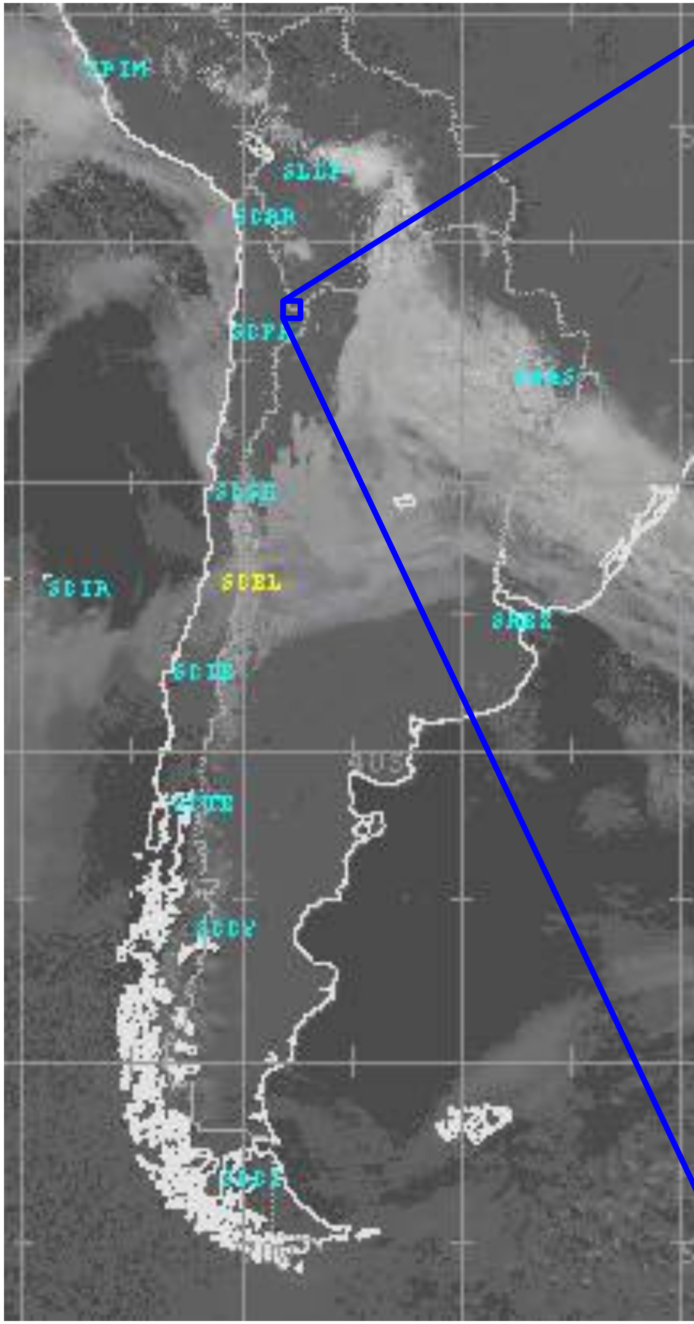
Radiometry of the mid- to upper troposphere

For climate models:

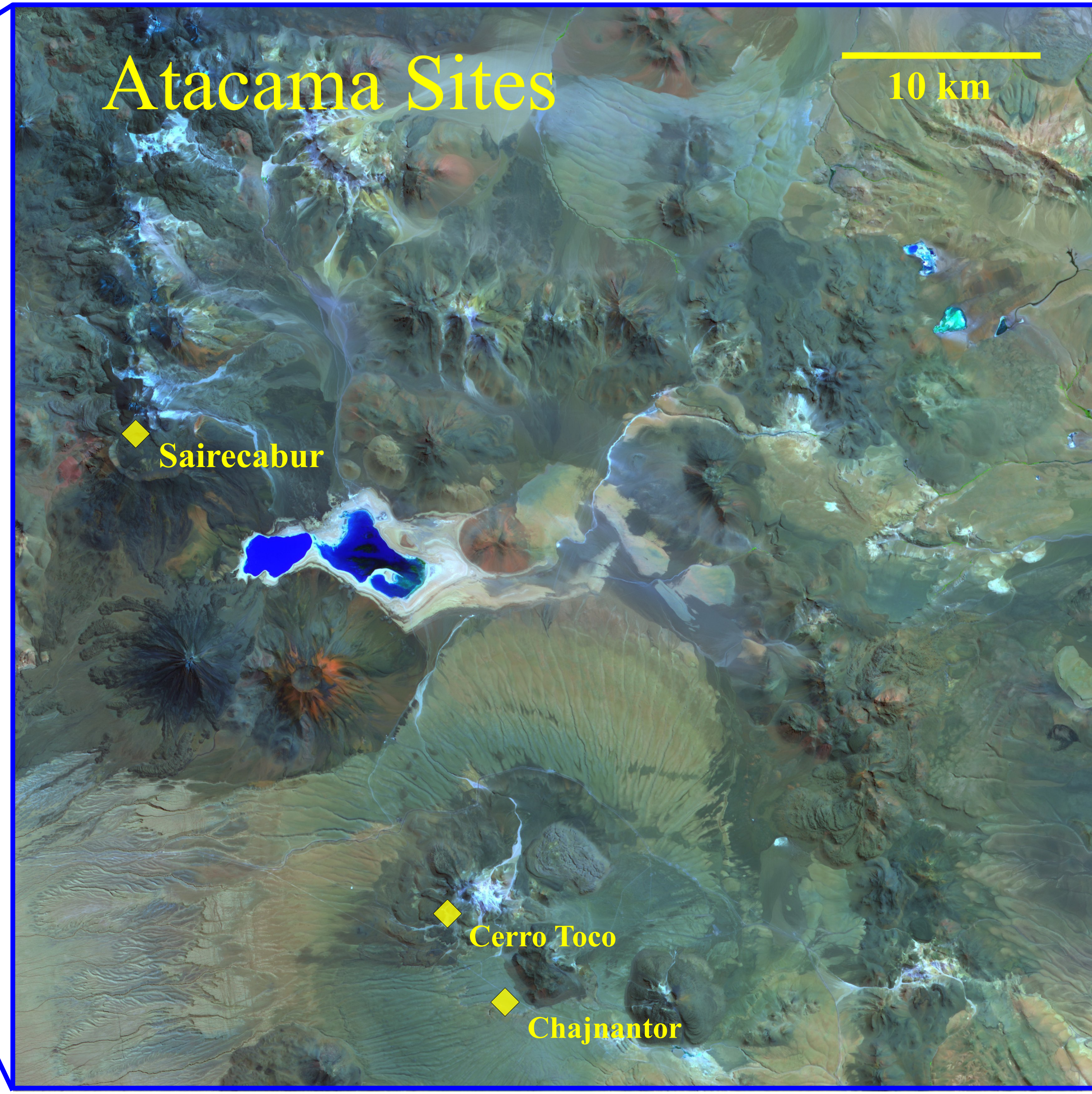
- Water vapor dominates radiative heat transfer and OLR, but spectral validation for relevant P, T conditions is very difficult in the laboratory.
- Solution – use the atmosphere as a natural laboratory, combining radiometry with independently-obtained atmospheric state data.
- Need high, dry vantage point to avoid tropospheric absorption.

For astronomy:

- Water vapor is the primary source of opacity and background emission.
- Radiometric site testing identifies and characterizes telescope sites
- High, dry sites like Mauna Kea, Atacama desert, Antarctica.



NOAA GOES-12 / Direccion Meteorologica de Chile

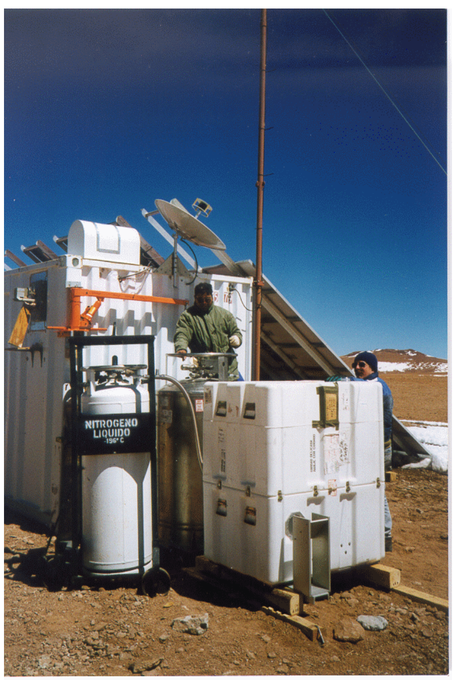


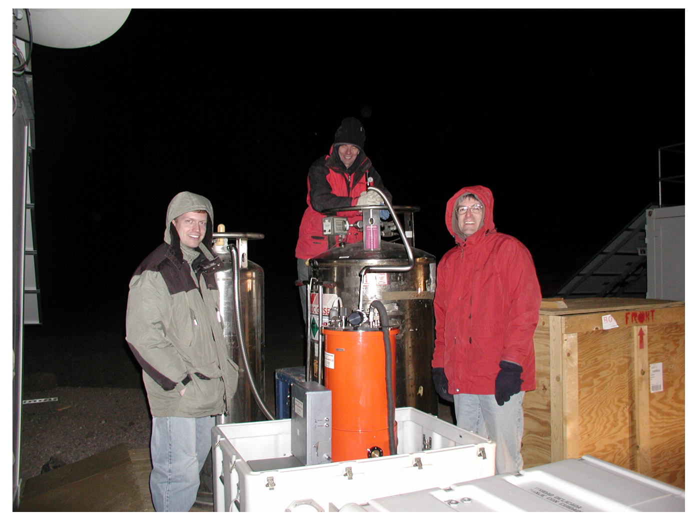
NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team

SAO submillimeter site testing

- Motivated by unusual dry climate of Atacama desert, potential for THz astronomy
- Purpose-built Fourier Transform Spectrometer (FTS) measuring zenith sky radiance
- Spectral coverage 300 GHz – 3.5 THz (1000 μm – 85 μm)
- Helium-cooled detector
- Up to 30 days unattended operation

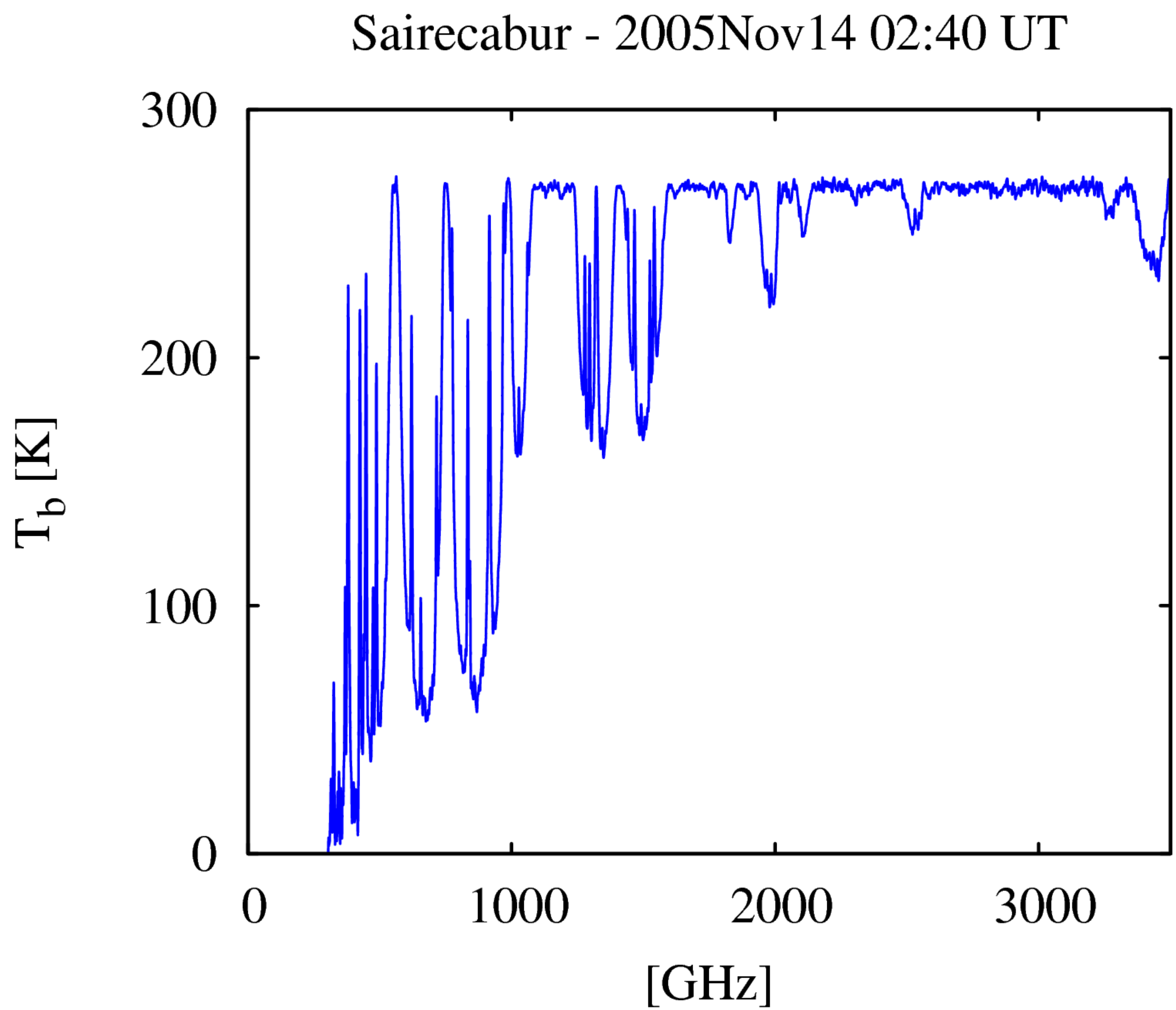
Chajnantor, 5000 m.a.s.l.
1997 – 1999



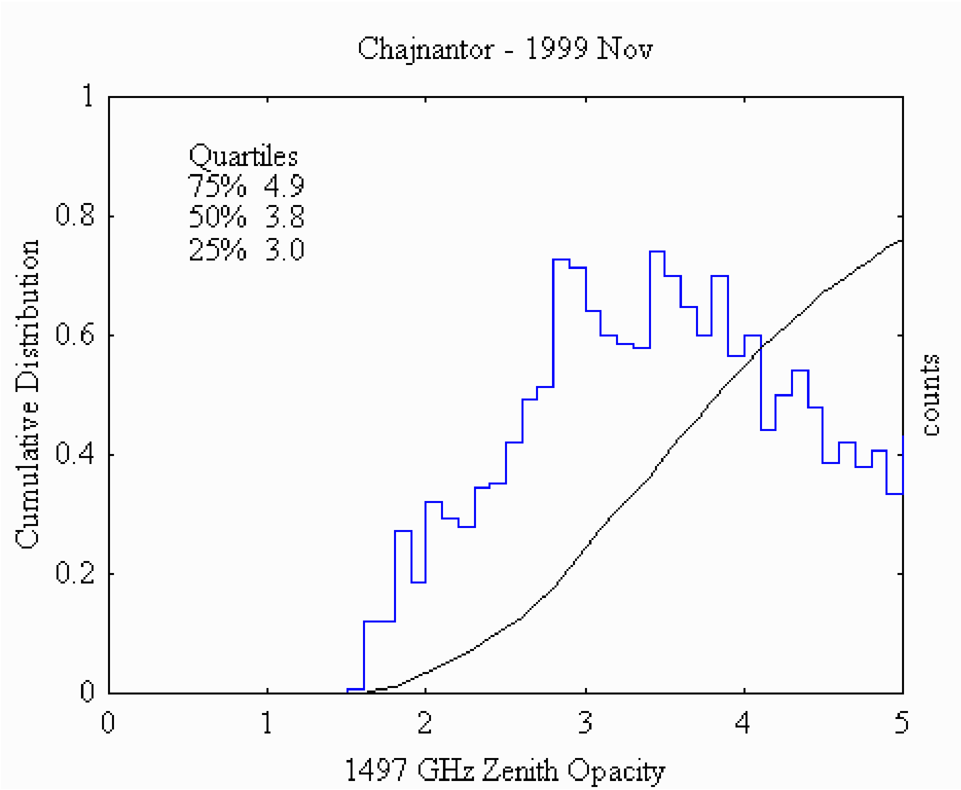


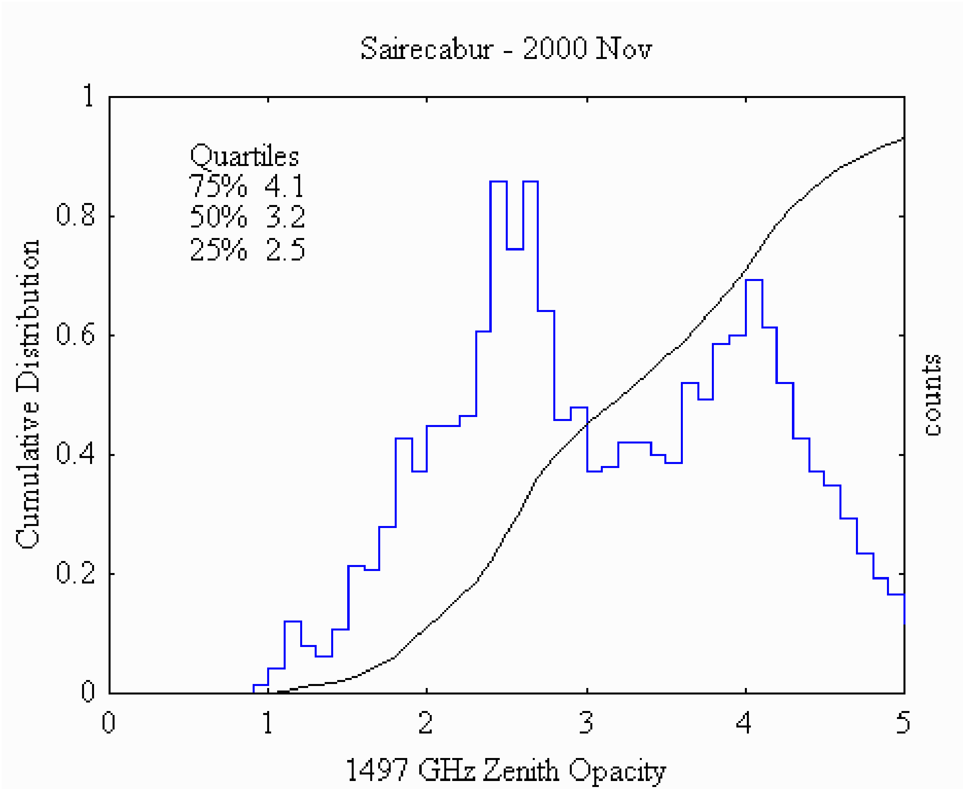
Sairecabur, 5500 m.a.s.l.
2000 – 2009

SAO submillimeter site testing – zenith T_b spectrum



SAO submillimeter site testing – comparative statistics





Key impacts:

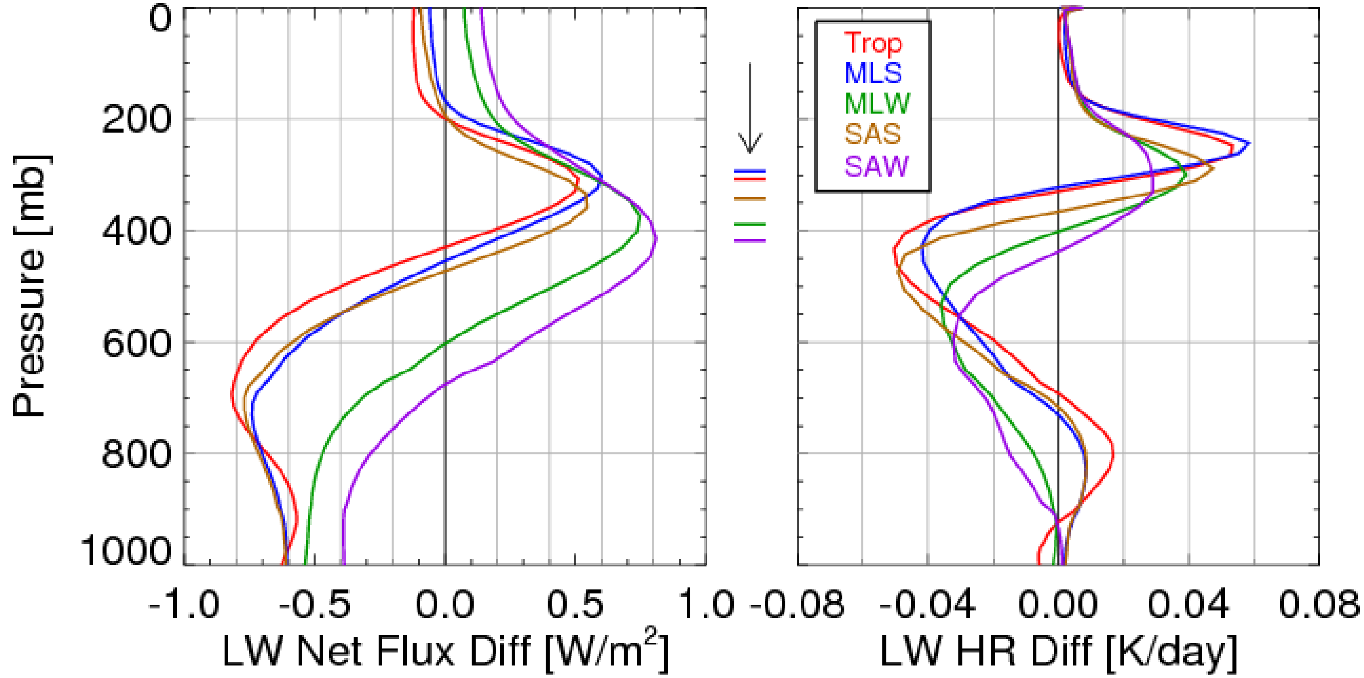
- Demonstrated feasibility astronomical observations in windows above 1 THz.
- Confirmed altitude dependence suggested by radiosonde measurements.
- Followed by RLT telescope on Sairecabur, THz receiver for APEX at Chajnantor.

The Radiative Heating in Underexplored Bands Campaigns (RHUBC)

- Intensive ground-based radiometry campaigns, combined with radiosonde flights, to improve atmospheric radiation models in the thermal infrared.
- PI's: Eli Mlawer (AER, Inc.), Dave Turner (U. Wisconsin / NOAA)
- RHUBC-I (2007) conducted from DOE ARM site in Barrow, Alaska.

RHUBC-I impact

- Improved water vapor spectroscopy, including significant change in water vapor continuum absorption model.
- Impact on radiation models for mid- to upper troposphere:



- Modeling depends on interpolation of measurements into H_2O rotation band, which was not fully covered by RHUBC-I.
- Motivated search for higher, drier site, and increased spectral coverage.

The RHUBC-II Campaign

Cerro Toco, Chile, 2009

Principal Investigators

Eli Mlawer, Atmospheric and Environmental Research, Inc.
Dave Turner, NOAA

Collaborating Institutions / Instrument PI's

NASA Langley Research Center, USA / Marty Mlynczak

Instituto de Fisica Applicata, Italy / Luca Palchetti

University of Denver, USA / Tom Hawat

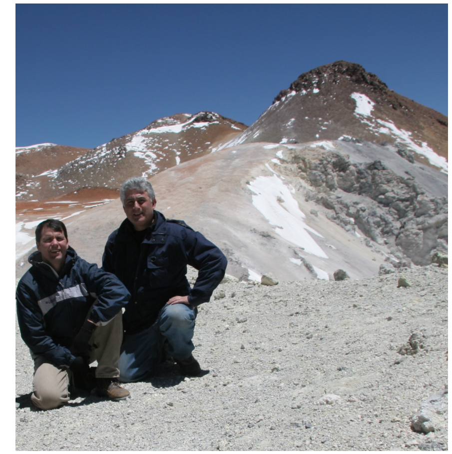
University of Cologne, Germany / Susanne Crewell

Smithsonian Astrophysical Observatory / Scott Paine

Argonne National Laboratory / Maria Cadeddu, Rich Coulter

Supported by DOE ARM program, with additional support from institutional collaborators.

SAO supported in part by SI endowment funds.

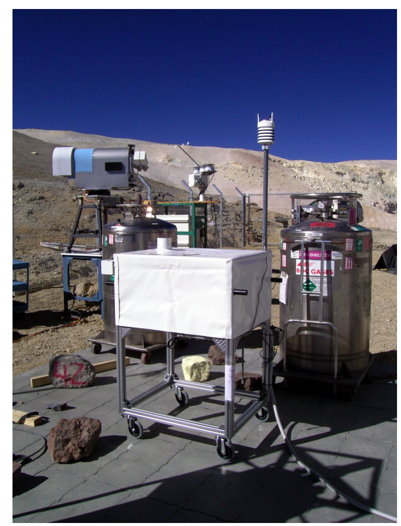


RHUBC-II Instruments (1)

- Fourier transform spectrometers spanning entire thermal infrared:
  - AERI (ARM / Turner) 3.3 µm – 25 µm
  - FIRST (NASA / Mlynczak) 6.3 µm – 100 µm
  - REFIR-PAD (IFAC – CNR / Palchetti) 7 µm – 100 µm
  - SAO-FTS (SAO / Paine) 85 µm – 1000 µm

AERI

FIRST



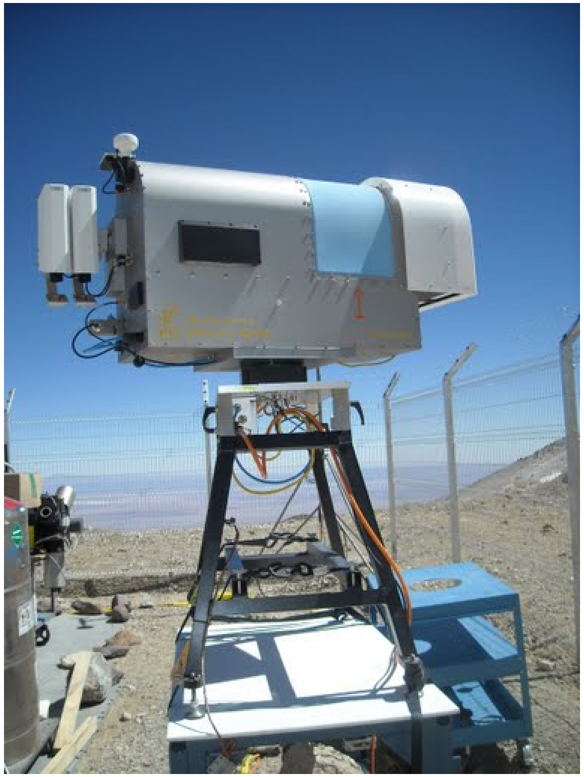
REFIR

SAO-FTS

RHUBC-II Instruments (2)

- Multi-channel radiometers:
  - GVRP 15-channel 183 GHz radiometer (ARM / Cadeddu)
  - HATPRO 22 GHz / 60 GHz radiometer (Cologne / Crewell)

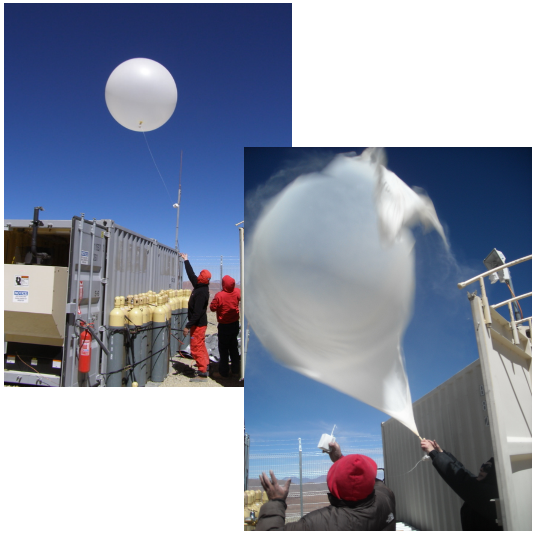
GVRP



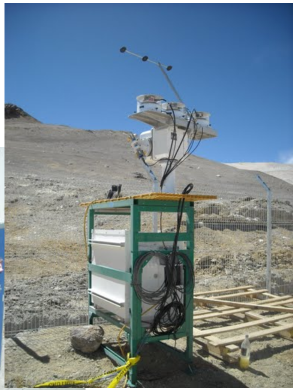
HATPRO

RHUBC-II Instruments (3)

- Atmospheric state:
  - Vaisala RS-92 radiosondes
  - Met tower



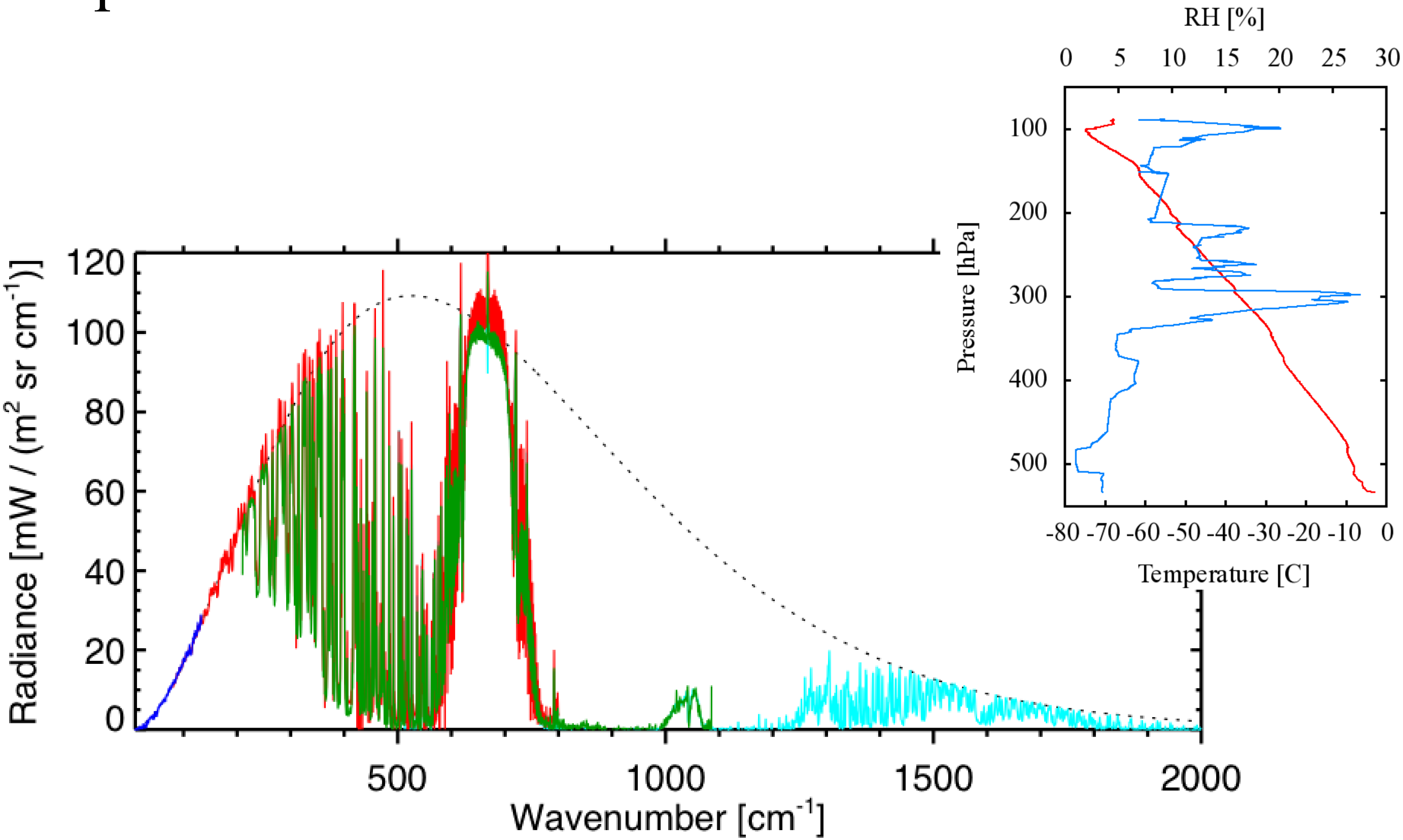
- Sun / Scattered light
  - ASTI solar tracking FTS (U. Denver / Hawat) 1 µm – 5 µm
  - ARM MFRSR shadow band radiometers



MFRSR

ASTI

Example of RHUBC-II data



(Preliminary data from 2009 Sep 19, 15:30 UT)

Problem: Sondes aren't perfect

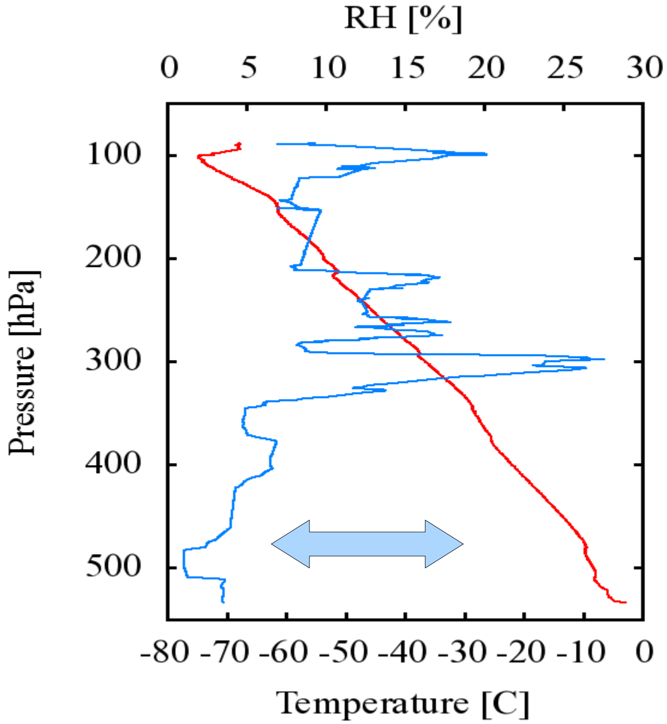
- Sondes give high-resolution profiles for temperature and humidity, but humidity accuracy under dry conditions can be poor.
- This is a key problem for upper troposphere studies.
- Various causes:
    - Dry calibration error
    - Response lag
    - Solar heating
    - Data processing
    - Manufacturing variations

- Solution – iterative radiative closure analysis, using data from multiple radiometers.

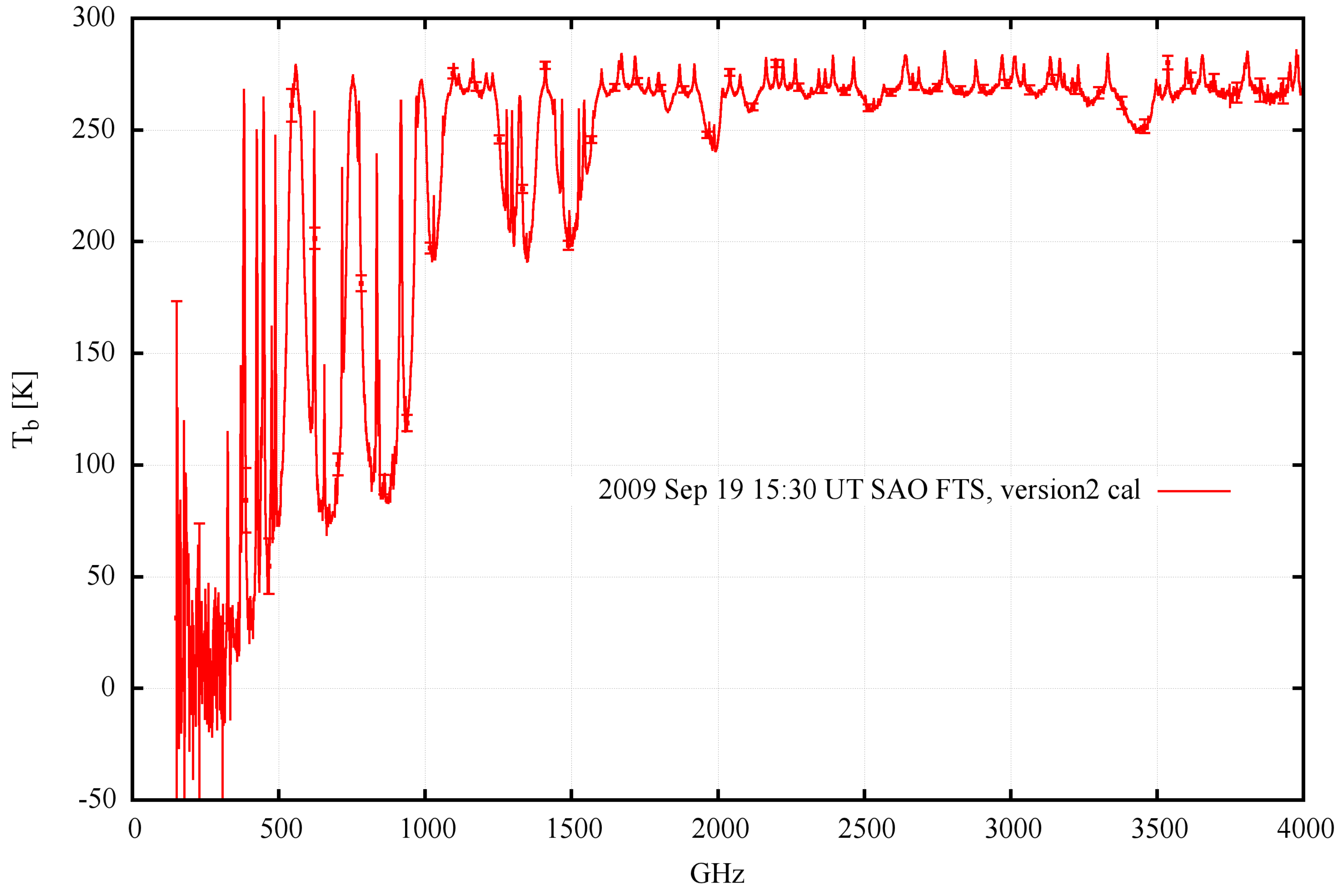
Correcting sonde profiles – a simple example

Fit radiative transfer model to measured spectrum from SAO FTS, using just two adjustable parameters:

- Scaling factor on sonde humidity profile
- Water vapor column in instrument enclosure (~ 1 μm PWV)

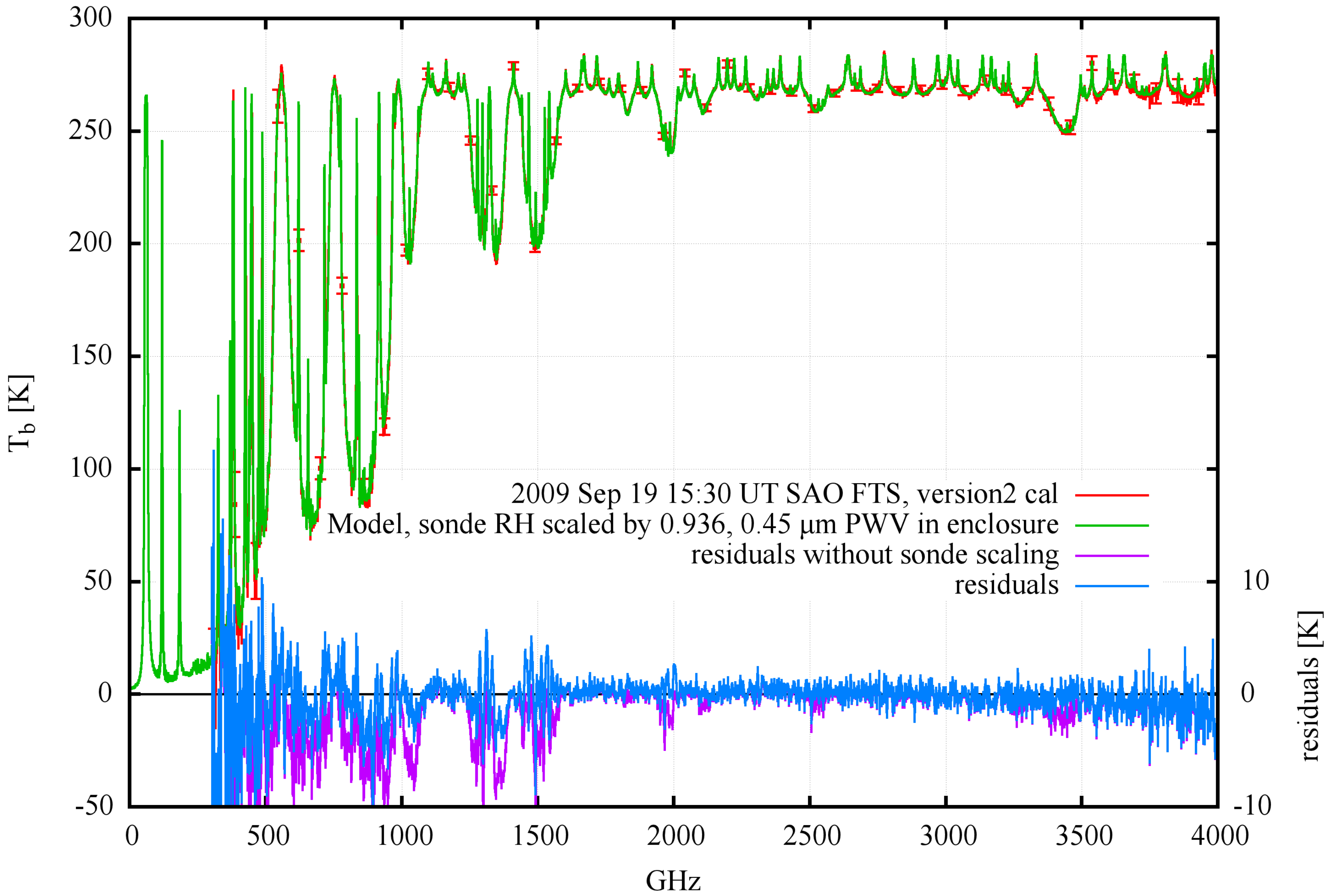


Zenith Planck T_b from SAO FTS



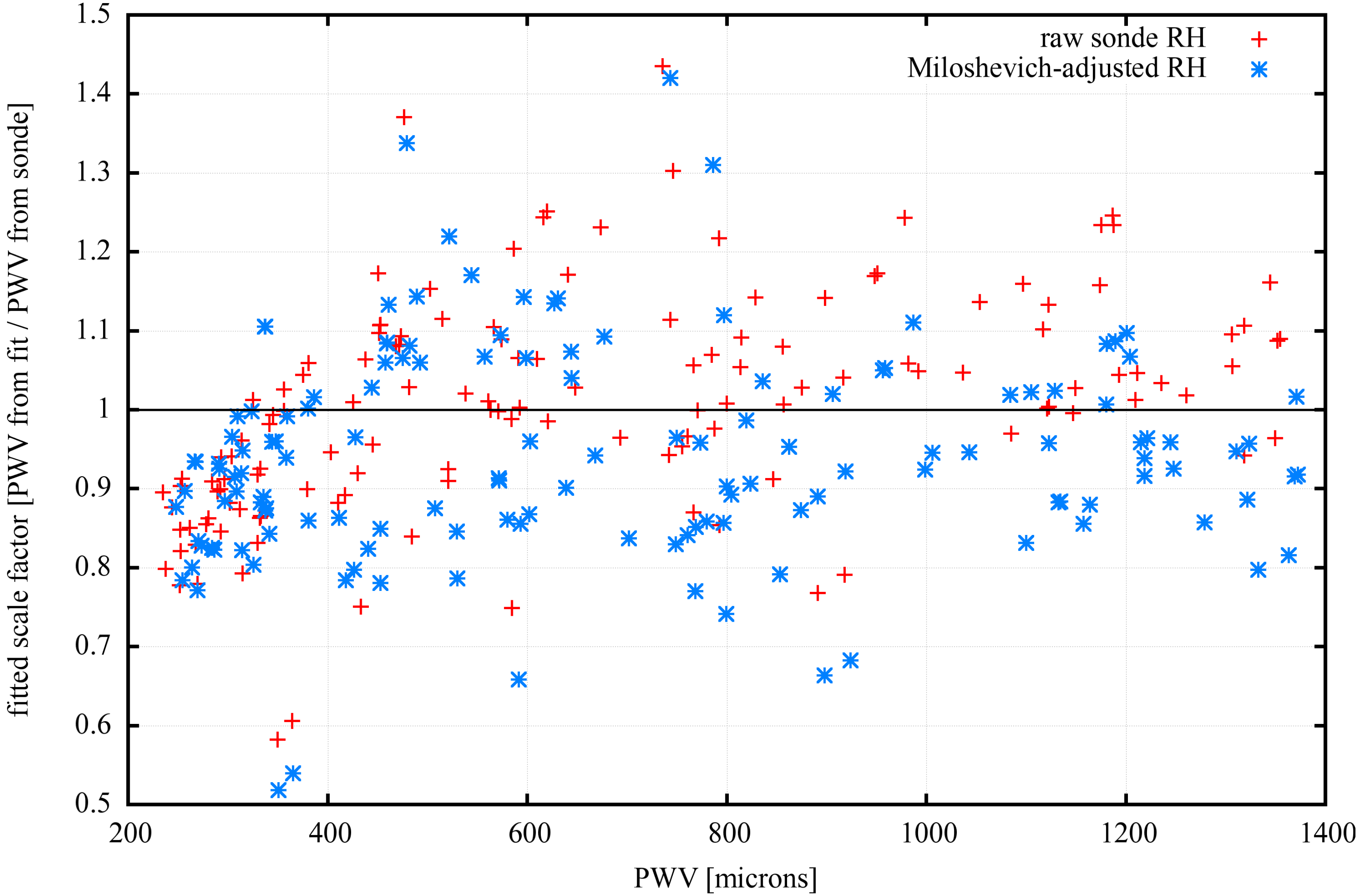
- Error bars (every 50th point) reflect cal error and quadrature noise spectrum

Two parameter model fit



- Fit scale factor on sonde RH, small H_2O layer inside instrument.
- Statistically significant residuals may impact models, after sonde adjustment.

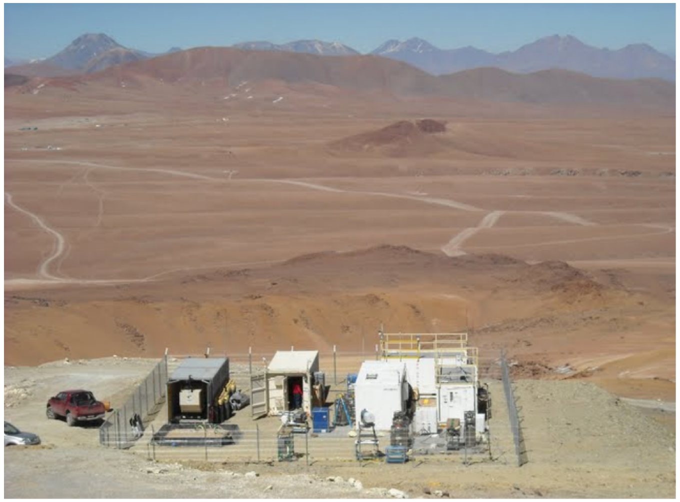
Fit all spectra with clear sky sonde profiles



- Note large corrections to total water vapor column.
- Statistical accuracy of correction factor is about 0.5%.

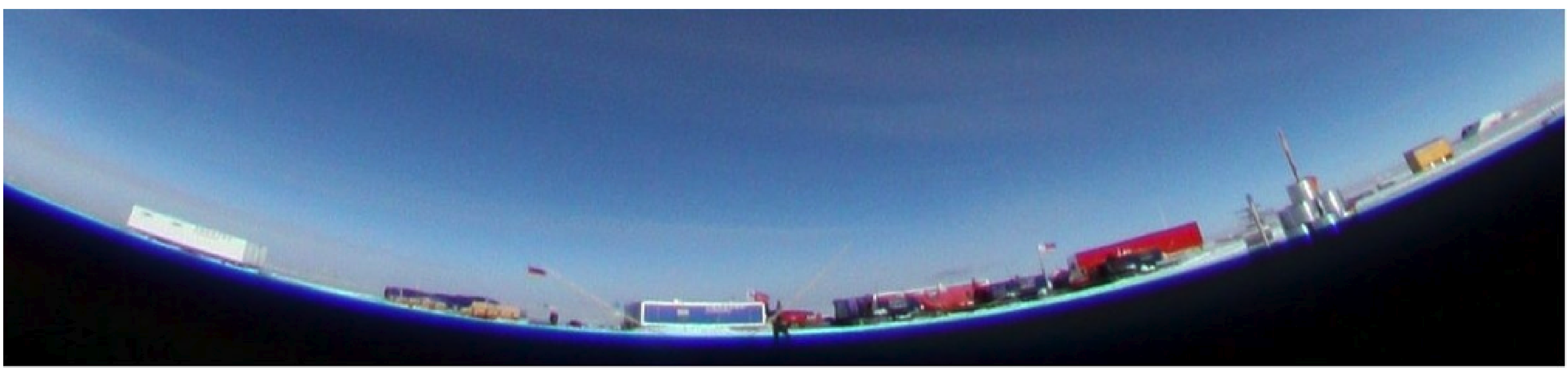
RHUBC-II status

- Three month campaign; much longer to analyze data.
- More sophisticated optimal sonde profile corrections currently under development (Mlawer et al.; Turner et al.), using data from multiple radiometers.
- Corrected profiles will support subsequent analysis of radiometric data to improve atmospheric radiative transfer models, particularly for water vapor.



Dome A, Antarctica

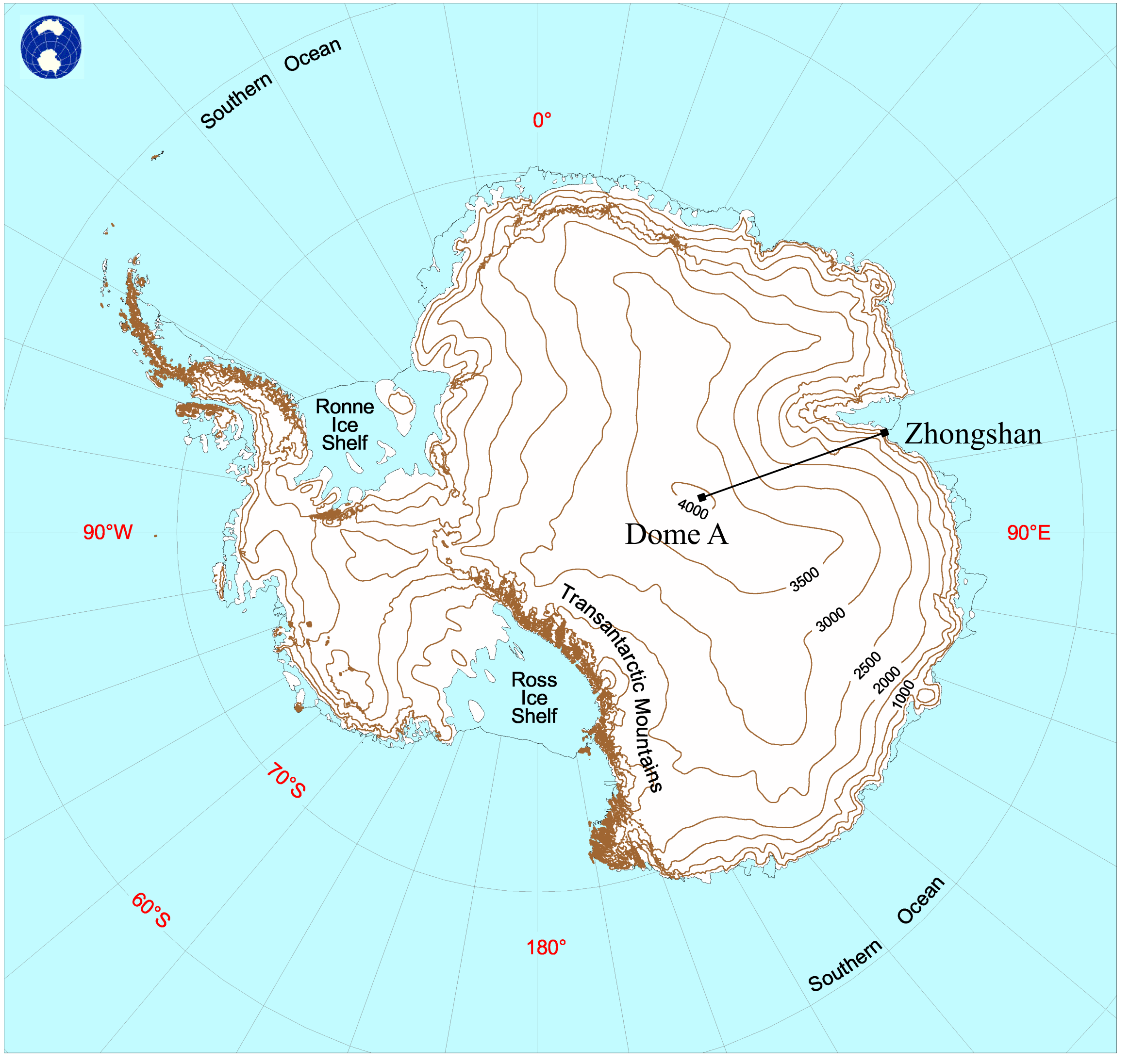
- Highest point on Antarctic Plateau (4100 m.a.s.l., 550 – 600 mbar)
- Cold (winter $T_g \sim 200$ K), extremely dry, low winds.
- Research station under development by Polar Research Institute of China.
- Instrument support module by UNSW (J. Storey, M. Ashley, et al.).
- Collaboration between SAO and Purple Mountain Observatory, Chinese Academy of Sciences, on site testing for a prospective Terahertz radio telescope.



Antarctica

500 metre contours

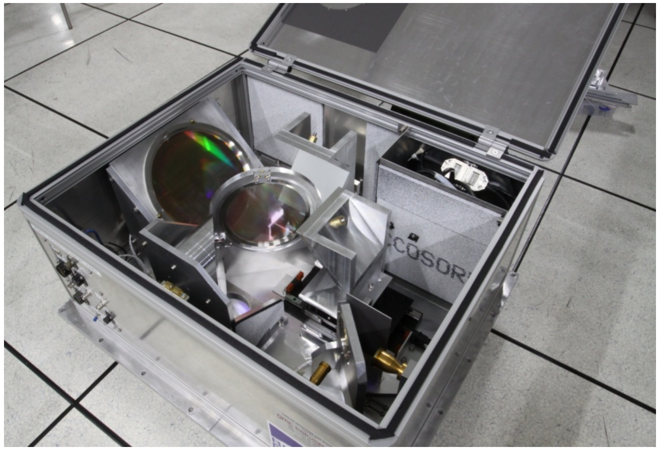
Produced by the Australian Antarctic Data Centre,
Australian Antarctic Division,
Department of the Environment and Heritage, January 2000

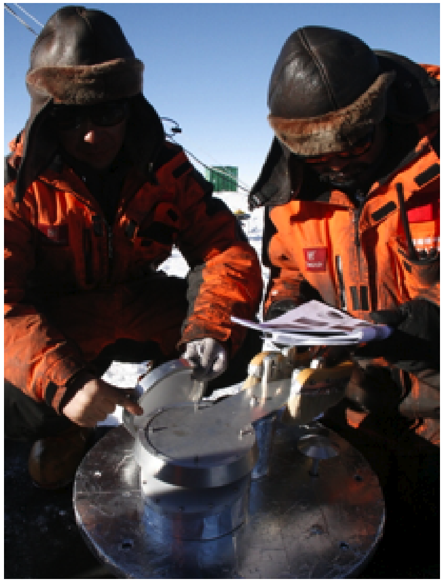


Projection: Polar Stereographic
True Scale at 71°S

Dome A site testing

- Fourier transform spectrometer developed in collaboration with PMO receiver group. (Shengcai Shi, et al.)
- SAO contributions include polarizing FTS optical design, data analysis, atmospheric modeling.
- Fabrication by QMC Instruments UK, Blue Sky Spectroscopy Canada.
- Spectral coverage 850 GHz – 15 THz (350 μm – 20 μm).
- Installed in UNSW PLATO module by PRIC 4th traverse team in Jan. 2010.





Dome A FTS status

- FTS ran successfully through austral winter, and continues to operate.
- First year's data set recovered last month, analysis under way.
- Present focus is on astronomical site testing, but potentially an excellent site for atmospheric studies as well.