Radio Telescopes and Fundamentals of observations

III. mm-astronomy

Alex Kraus

September 2025

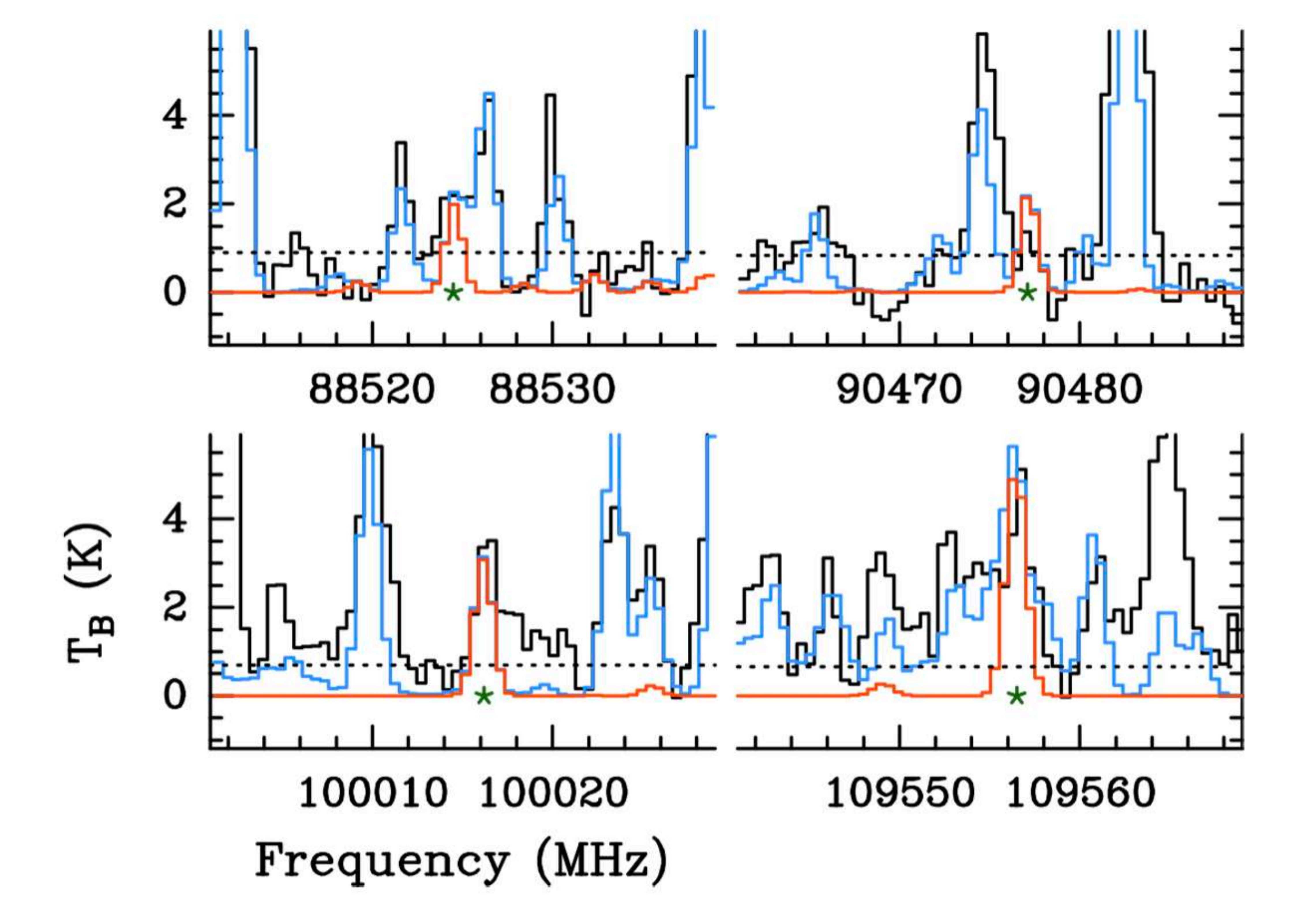
XIX IAG/USP Advanced School on Astrophysics

Max-Planck-Institut

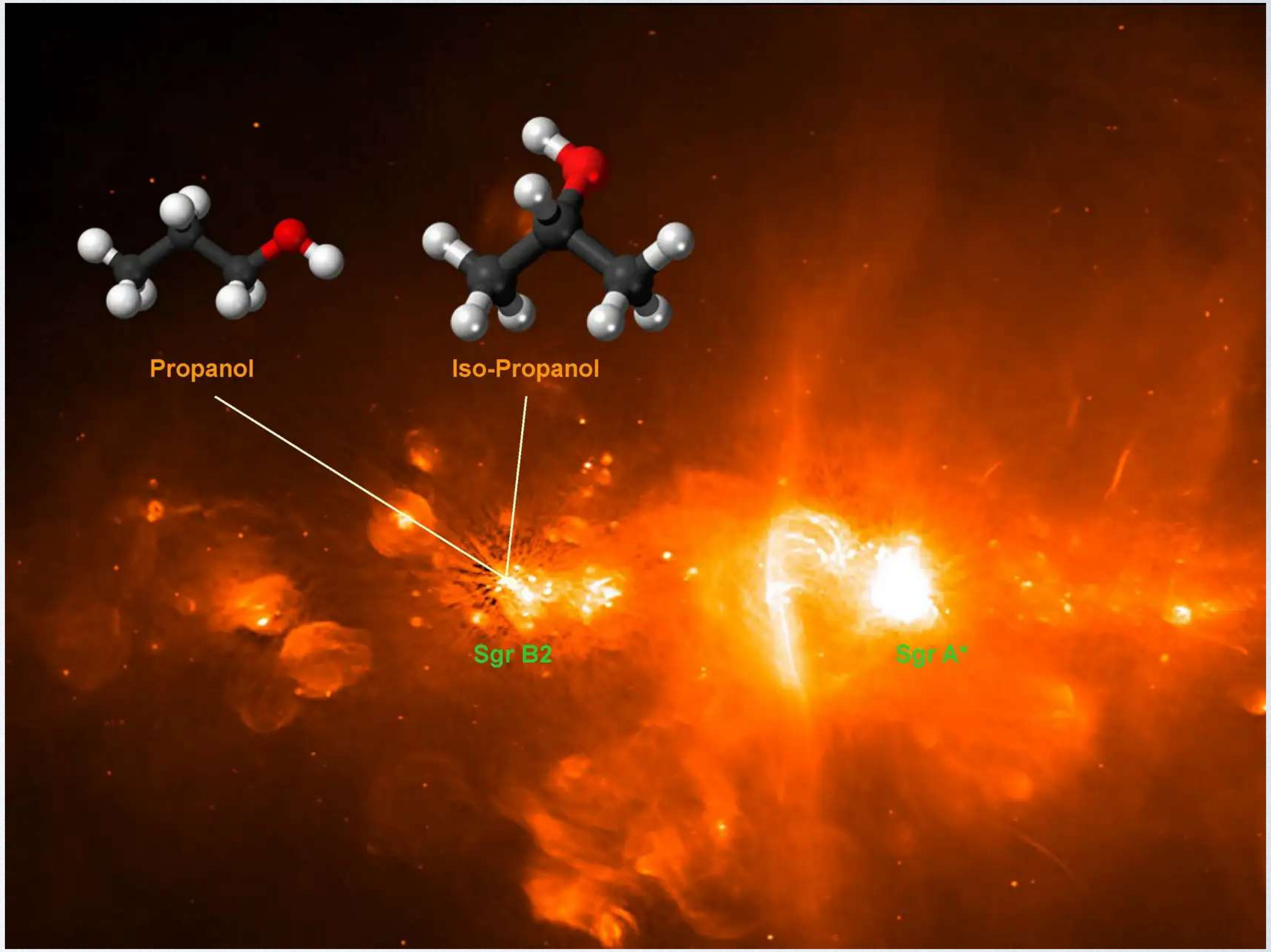
MM / SUB-MM TELESCOPES

ORGANIC MOLECULES

Detection of iso-Propanol (C_3H_7OH)
close to the Galactic center
by ALMA



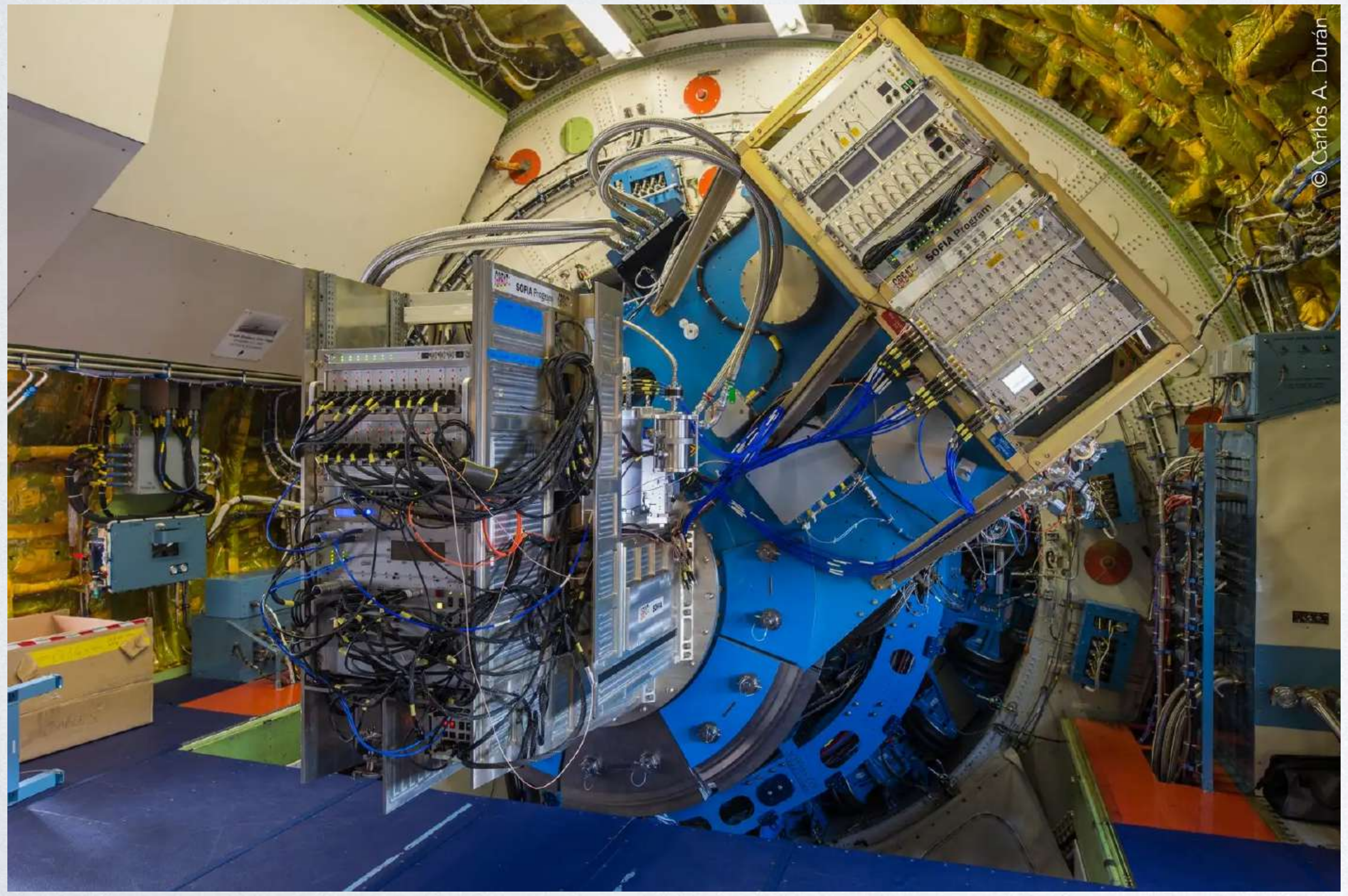
Belloche et al., 2022



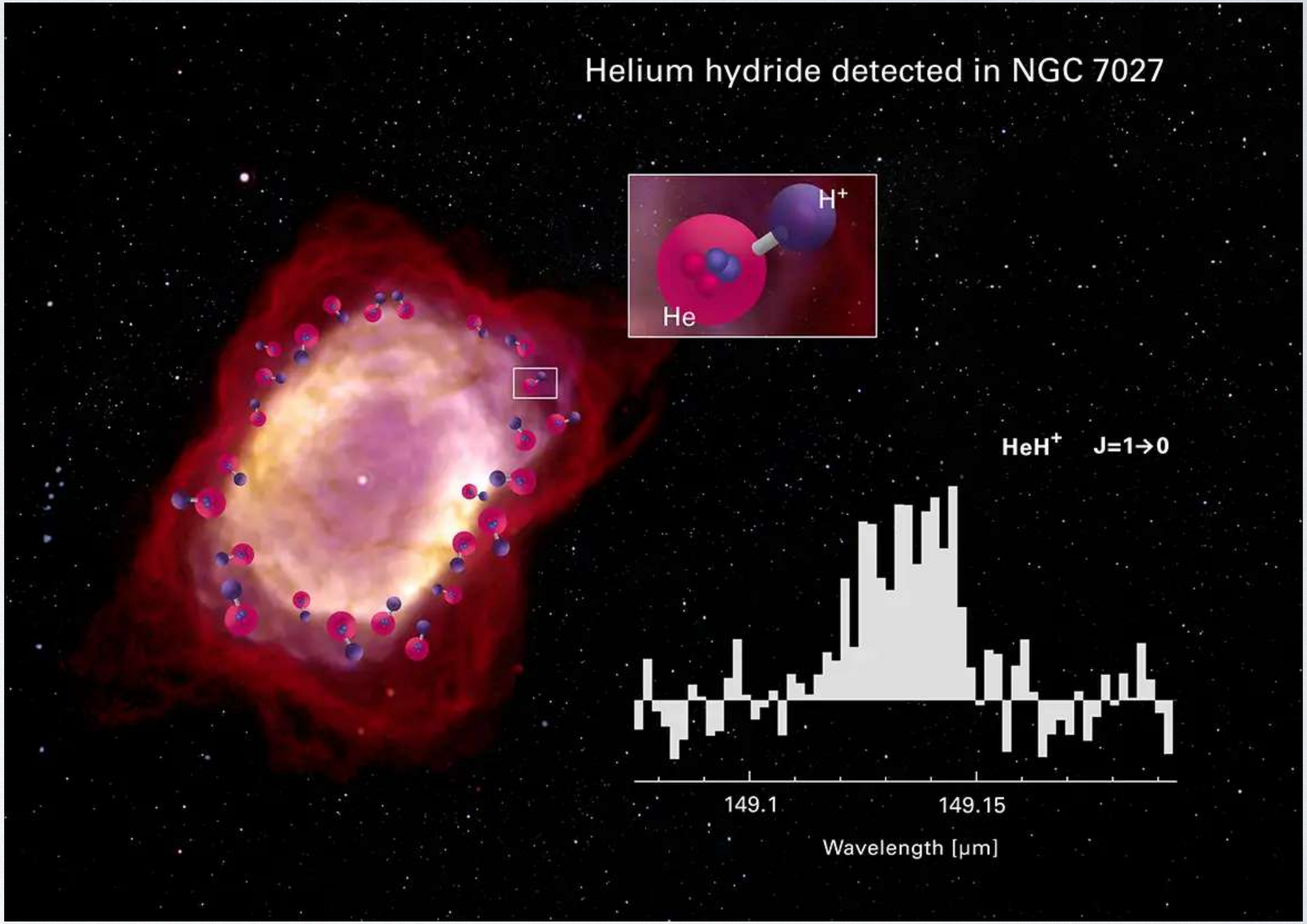
GLOSTAR collaboration (background image). Wikipedia/public domain (molecule models)

HELIUMHYDRIDE IN NGC7027

SOFIA:
Detection of HeH^+
at 2.01 THz
($\lambda = 0.149$ mm)



Carlos Duran/MPIfR



Composition: NIESYTO design; Image NGC 7027: William B. Latter (SIRTF Science Center/Caltech) and NASA/ESA;
Spectrum: Rolf Güsten/MPIfR (Nature, April 18, 2019)

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DIFFERENCES CM-MM

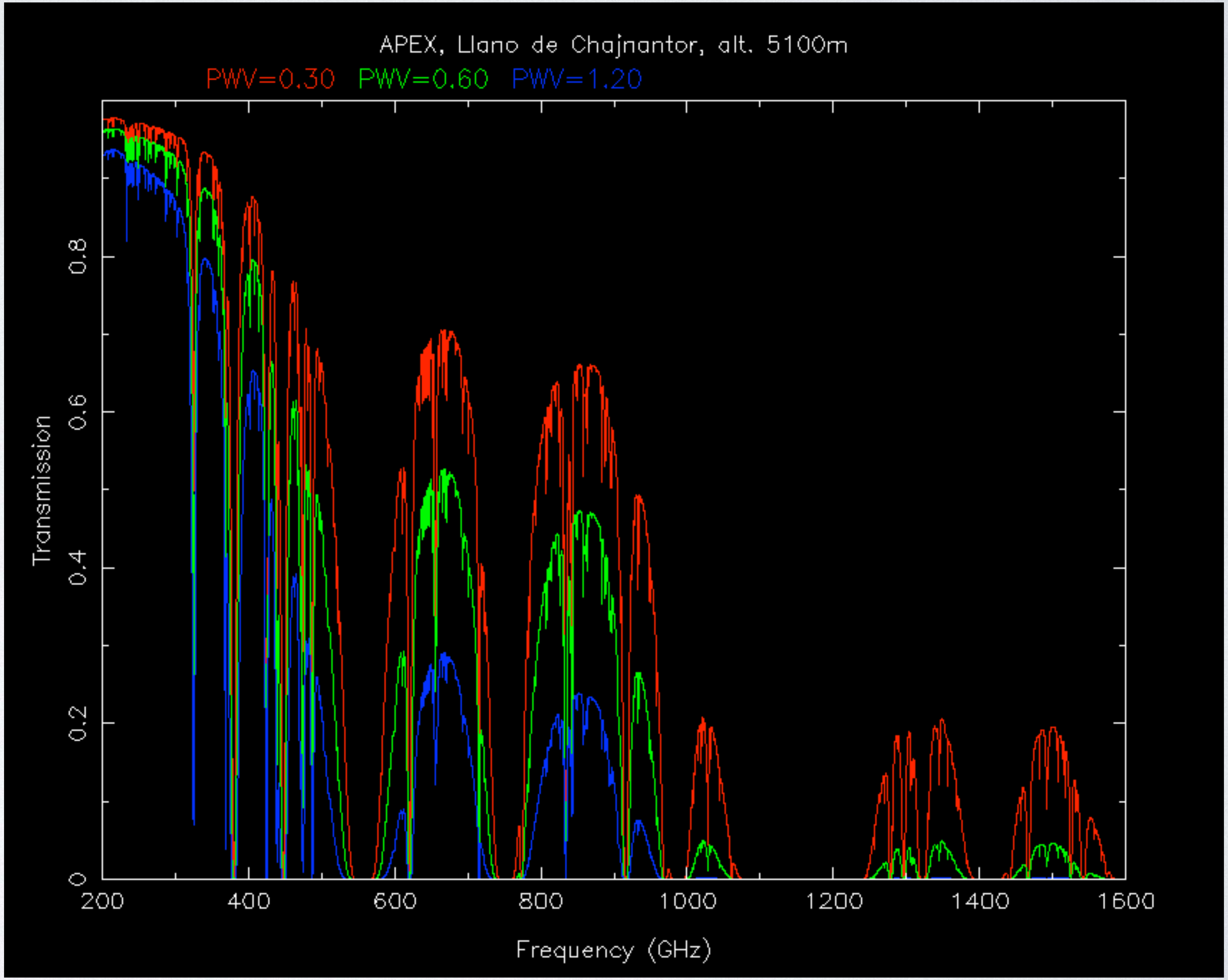
cm-wavelengths	mm-wavelengths
Sky is rather cold and mostly transparent	High absorption, significant emission
Atmosphere is stable	fast changing conditions
Receivers stable, noise diode sufficient for calibration	less stable, more sensitive to weather influences
Receiver dominates noise	Atmosphere dominates noise
Strong calibrator sources available	Difficult to find calibrators

—> a special calibration scheme is needed: **Chopper-Wheel-Method**

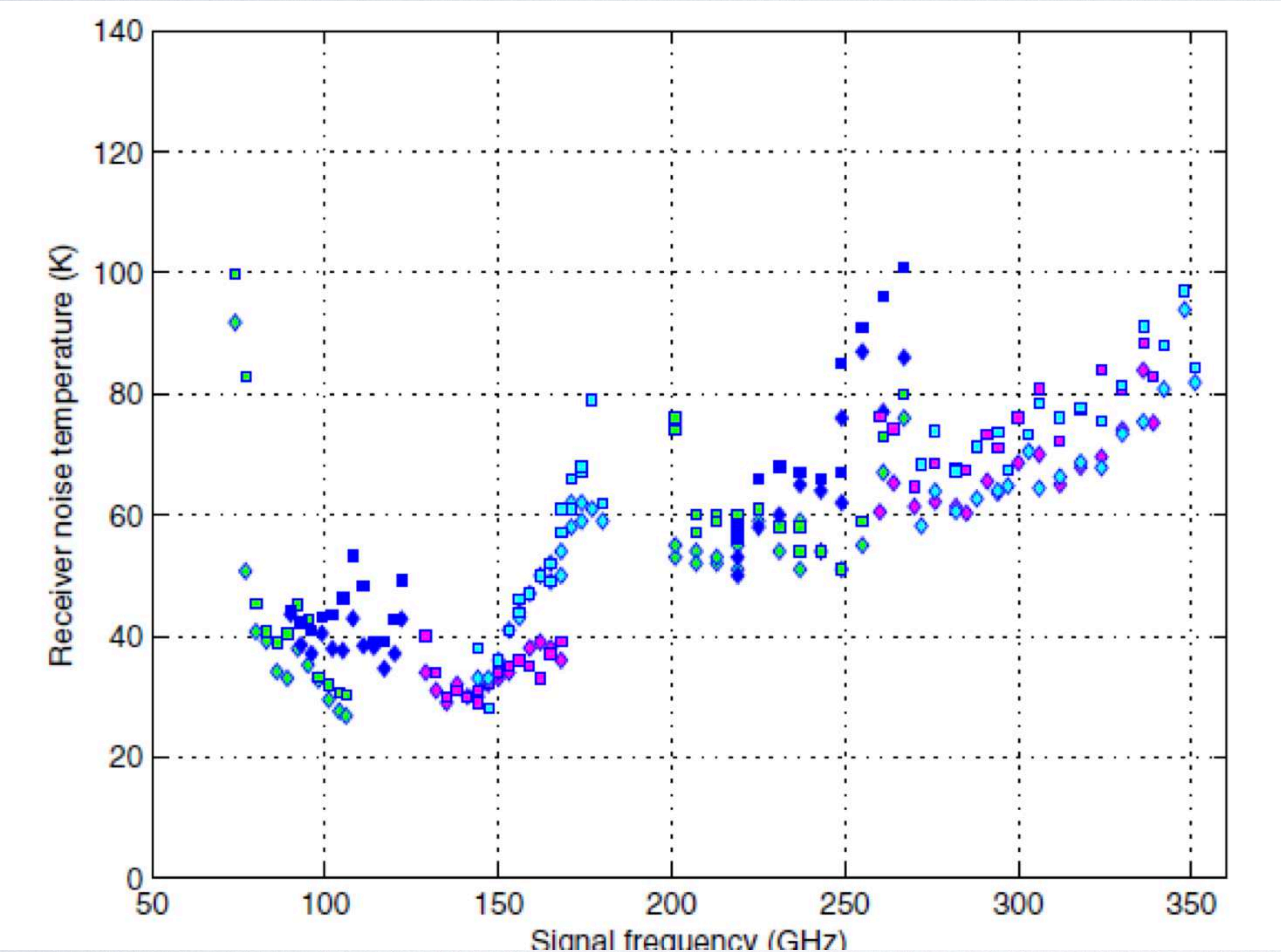
MM-SKY

Transmission / Absorption strongly depends on the water in the atmosphere

pwv - precipitable water vapor



RECEIVER NOISE TEMPERATURES



Compare to cm-regime:
Trec ~ 5-30 K

C. Kramer, IRAM
mm Interferometer School,
2018

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CHOPPER-WHEEL-METHOD

see e.g. Penzias & Burrus, ARAA, 1973, Ulich & Haas, ApJ1976

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 30:247–258, 1976 March

ABSOLUTE CALIBRATION OF MILLIMETER-WAVELENGTH SPECTRAL LINES

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Received 1975 March 17

ABSTRACT

A detailed analysis of the chopper-wheel method of calibrating the intensity of a millimeter-wavelength spectral line is presented. Special techniques were used to construct a receiver which eliminates most of the usual calibration difficulties. The zenith atmospheric extinction between 3.5 mm and 2.6 mm wavelength was measured, and the intensities of six spectral lines in this range were absolutely calibrated with an estimated uncertainty (1 σ) of 7 percent. The effects of the antenna power pattern on the corrected antenna temperature T_A* are calculated for several simple models of the source brightness distribution.
Subject headings: interstellar: molecules — radio sources: lines

Atacama Pathfinder EXperiment
APEX

Atacama Pathfinder EXperiment

User Manual

APEX-MPI-MAN-0012	
Revision:	1.4
Release:	March 28, 2023
Category:	4
Author:	D. Muders, H. Hafok

APEX Calibration and Data Reduction Manual

https://www3.mpifr-bonn.mpg.de/staff/dmuders/APEX/APECS/APEX-MPI-MAN-0012-R1_4.pdf

CHOPPER-WHEEL-METHOD

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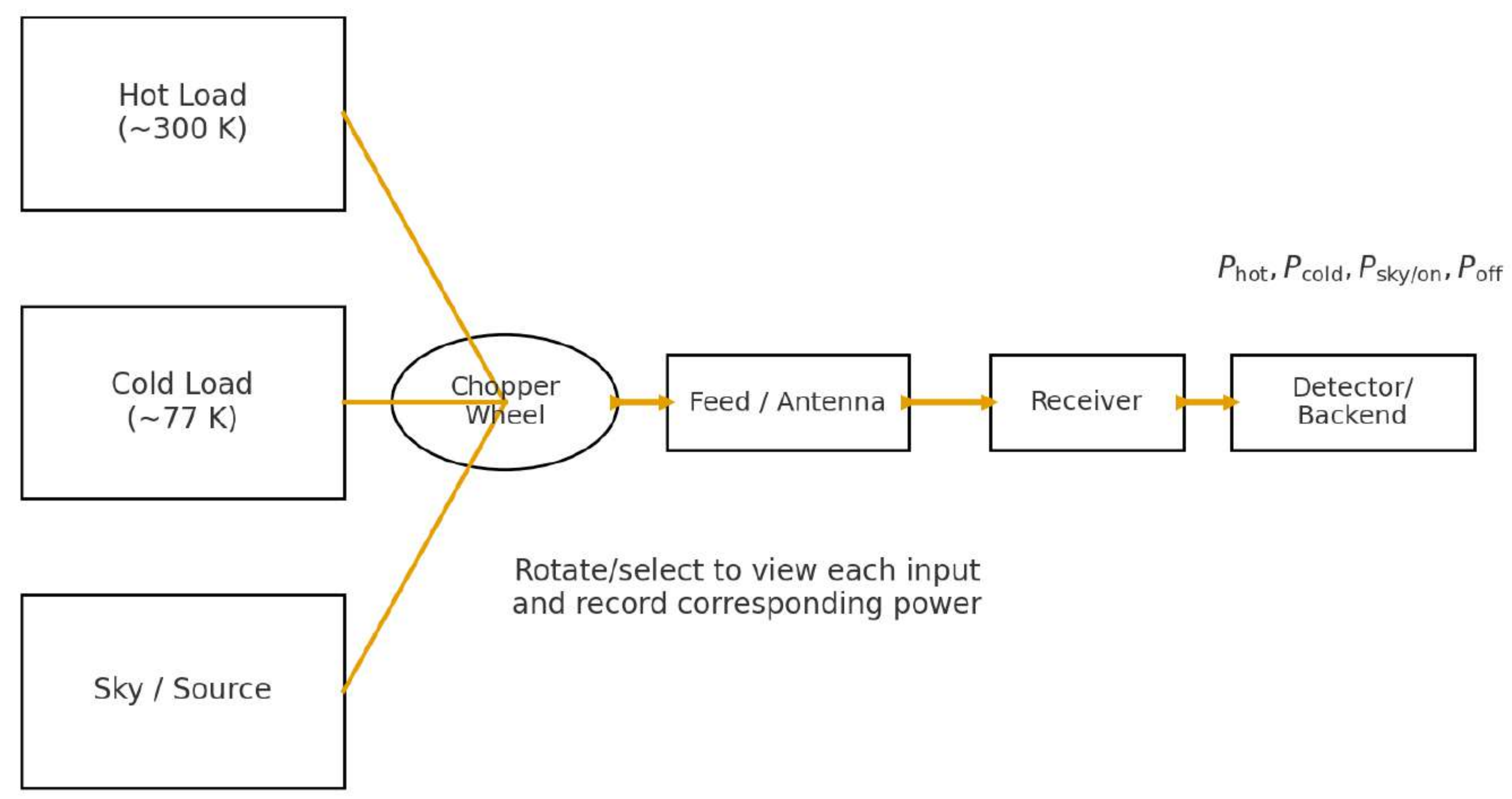
Main idea:
Compare the received signal frequently from the sky with various reference signals.

Hot load: Usually an absorber at ambient (room) temperature (~290 K).

Cold load: Sometimes a cooled absorber, and/or just looking at the sky, assuming known atmospheric attenuation (—> ATM model, WVR)

—> use the sky itself as calibrator!

Sky measurement: Looking at the blank sky and then on the source.



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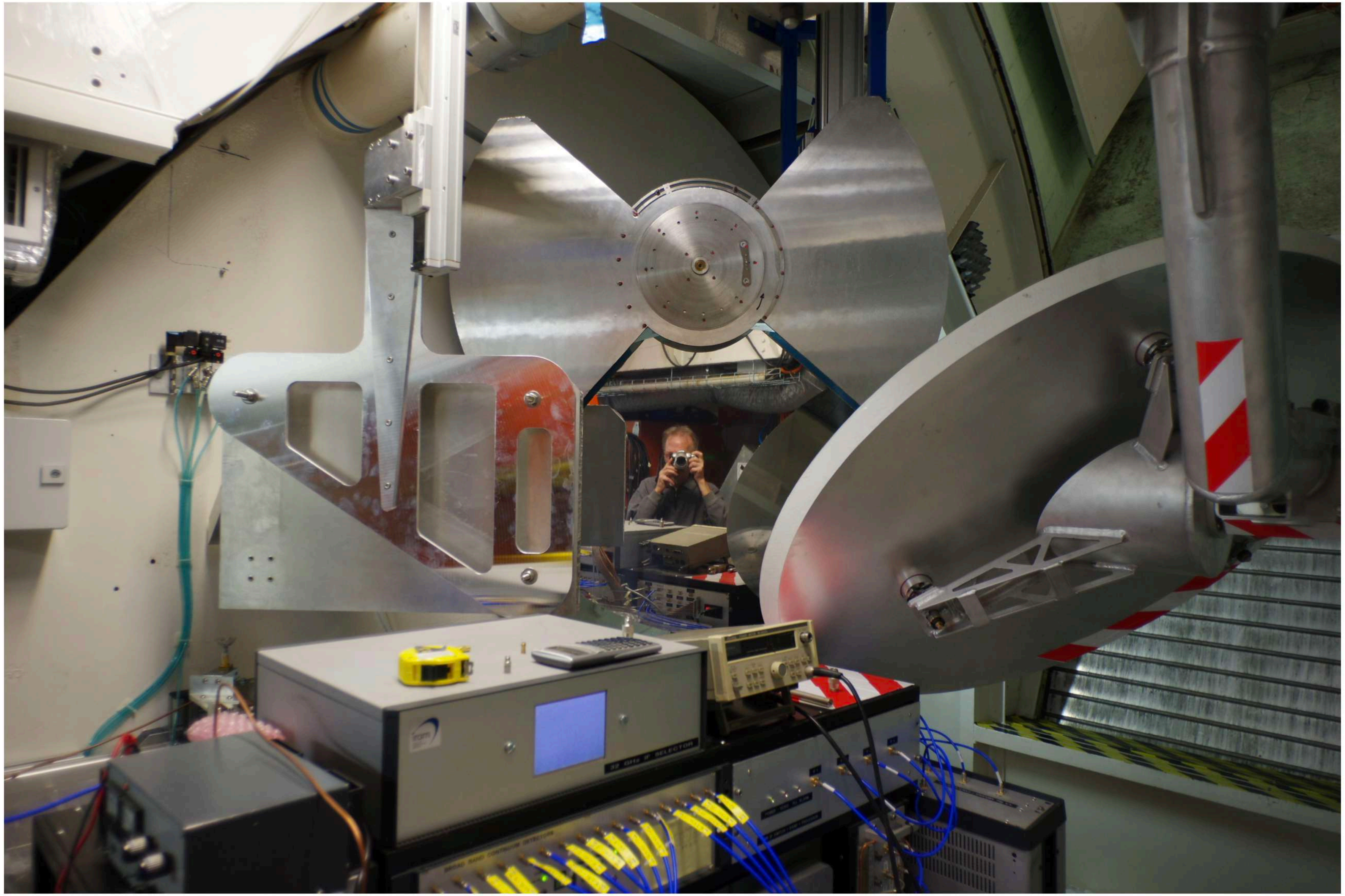
CHOPPER-WHEEL



Nasmyth cabin
30m telescope

(In reality, the wheel is not used for hot/cold calibration, but for very fast on/off observations.
But it gives the idea…)

C. Kramer,
IRAM mm
Interferometer School,
2018

CALIBRATION (SIMPLIFIED)

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$$V_{\text{load}} = G(T_{\text{amb}} + T_{\text{rec}})$$

Voltage due to the load

$$V_{\text{sky}} = G(T_{\text{sky}} + T_{\text{rec}}) = G(T_{\text{amb}}(1 - \exp(-\tau \text{AM})) + \text{T}_{\text{rec}})$$

Voltage on sky

Simplifications:
All power comes from the front,
no second sideband, $T_{atm} = T_{amb}$,
the atmosphere can be described
as a single layer.

τ is the optical depth in zenith

Airmass: $\text{AM} = \dfrac{1}{\sin \text{Elv}}$

Define the calibration signal: $V_{\text{cal}} := V_{\text{load}} - V_{\text{sky}} = GT_{\text{amb}} e^{-\tau \text{AM}}$

—> Contribution of the receiver deleted!

$$V_{\text{src}} = GT'_A e^{-\tau \text{AM}}$$

Voltage due to the source

ATMOSPHERIC MODELING

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$$V_{\rm cal} = G T_{\rm amb} e^{-\tau \rm AM}$$

Need good information about the atmospheric absorption —> water vapor radiometer, atmospheric modeling

A water vapor radiometer (WVR) measures the temperature profile of the water lines at 22.2 and / or 183.3 GHz to determine the amount of precipitable water (pwv).

Proceedings of the 7th European VLBI Network Symposium
Bachiller, R. Colomer, F., Desmurs, J.F., de Vicente, P. (eds.)
October 12th-15th 2004, Toledo, Spain

The Water Vapour Radiometer at Effelsberg

A. L. Roy, U. Teuber and R. Keller

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Abstract. We have installed a scanning 18 GHz to 26 GHz water vapour radiometer on the focus cabin of the Effelsberg 100 m telescope for tropospheric phase, delay and opacity correction during high-frequency VLBI observations. It is based on the design by Tahmoush & Rogers (2000) but with noise injection for calibration, weather-proof housing, and temperature stabilization. The radiometer is delivering data into an archive since July 2003, from which they are available for download. The data will be delivered automatically to PIs of EVN experiments in a calibration table attached by the EVN calibration pipeline. This paper describes the radiometer and its performance.

1. The Effelsberg Water Vapour Radiometer

Some views of the water vapour radiometer (WVR) are shown in Fig. 1. The radiometer is located on top of the prime focus cabin looking skyward along the optical axis. The basic parameters are given in Table 1, and the project status is maintained at `http://www.mpifr-bonn.mpg.de/staff/aroy/wvr.html` .

Table 1. Basic parameters of the Effelsberg WVR

Frequency	18.3 GHz to 26.0 GHz
Channels	25
Bandwidth	900 MHz
$T_{\rm receiver}$	200 K
Physical temperature	25 °C
Temperature stabilization	Peltier cooler
Thermal noise	61 mK in 0.025 s per spectrum (= 0.27 mm path length noise, assuming 4.5 mm K^{-1})
Absolute accuracy	~ 1 % of $T_{\rm sys}$ (= 9 mm path length systematic offset assuming 4.5 mm K^{-1})
Gain stability	2.7×10^{-4} over 400 s
Sweep Time	5 s
Beamwidth	1.3° for best main-beam overlap
Gain calibration	noise injection or measured $T_{\rm internal}$
Monitor and control	ethernet on optical fibre
Integrated water vapour retrieval	by fitting theoretical line profile to measured spectrum and frequency-squared term for cloud component and a constant term for calibration errors. Upgrade to *Atmospheric Transmission at Microwaves* (Pardo et al.) is pending.

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 49, NO. 12, DECEMBER 2001 1683

Atmospheric Transmission at Microwaves (ATM): An Improved Model for Millimeter/Submillimeter Applications

Juan R. Pardo, José Cernicharo, and Eugene Serabyn

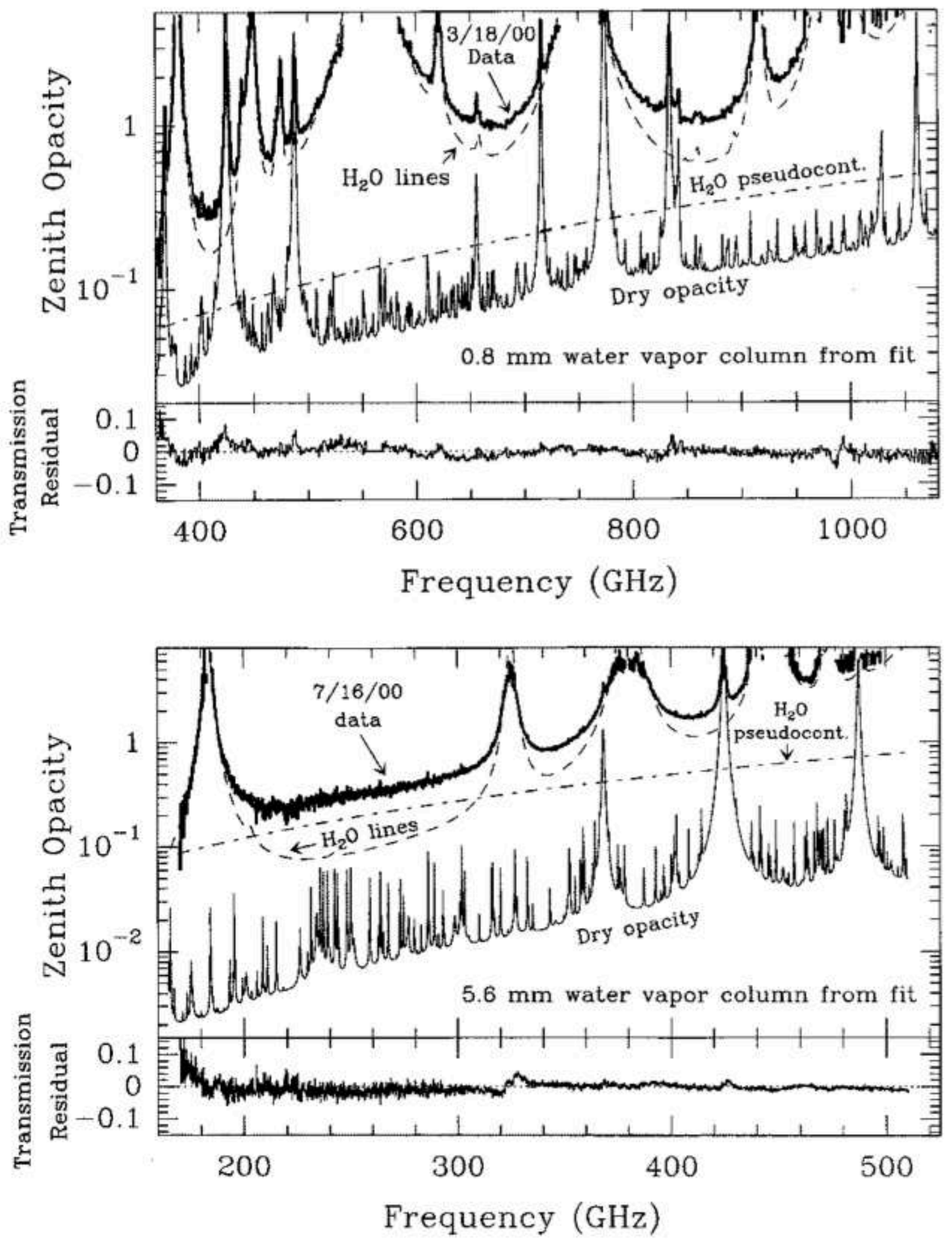

Fig. 1. FTS zenith atmospheric opacity spectra obtained on Mauna Kea in March and July 2000 and best fit opacity contributions. The estimated water vapor columns differ by a factor of seven. Because the curve $\tau_{fit}(\nu)$ matches the data so well, the fit residuals are shown as the transmission difference ($exp[-\tau_{\rm meas}] - exp[-\tau_{\rm fit}]$). The fitting routine that produced these results is based on the radiative transfer code described in this paper and uses only the precipitable water vapor column as a free parameter (P/T profile is fixed from the readings of the Mauna Kea weather station, our own handheld thermo/hygrometer, and Hilo airport radiosoundings).

CALIBRATION (SIMPLIFIED)

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Compare what we have so far: $V_{\text{cal}} = G T_{\text{amb}} e^{-\tau \text{AM}}$ $V_{\text{src}} = G T'_A e^{-\tau \text{AM}}$

and we get: $\frac{V_{\text{src}}}{V_{\text{cal}}} = \frac{T'_A}{T_{\text{amb}}} \Rightarrow T'_A = T_{\text{amb}} \frac{V_{\text{src}}}{V_{\text{cal}}}$

In somewhat more detail: $T_A = T_{\text{cal}} \frac{T_{\text{src}} - T_{\text{sky}}}{T_{\text{load}} - T_{\text{sky}}}$

With some calculations, on gets: $T_{\text{cal}} = (T_{\text{load}} - T_{\text{sky}})\, e^{\tau \text{AM}}$

Be aware that instrumental effects, like, e.g. the gain-elevation-effect still have to be corrected for!

CALIBRATION IN REALITY

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In reality, several effects have to be considered, e.g.:

* not all radiation comes from the source (define the „forward efficiency" as $T_A^* = T_A' / F_{eff}$)
* usually, signals from both sidebands mix (with different gains)
* in reality: $T_{amb} \neq T_{sky}$

—> things get more complicated:

$$
\begin{aligned}
T_{\rm cal} \;=\;& (1+G_{\rm im})\Big[J(\nu_{\rm s},T_{\rm ATM}) - J(\nu_{\rm s},T_{\rm bg})\Big] \\
&+(1+G_{\rm im})\Big[J(\nu_{\rm s},T_{\rm cab}) - J(\nu_{\rm s},T_{\rm ATM})\Big]\exp(\tau_{\rm s}A) \\
&+G_{\rm im}\Big[J(\nu_{\rm s},T_{\rm ATM}) - J(\nu_{\rm s},T_{\rm bg})\Big]\Big[\exp((\tau_{\rm s}-\tau_{\rm i})A) - 1\Big] \\
&+(1+G_{\rm im})/F_{\rm eff}\Big[J(\nu_{\rm s},T_{\rm chop}) - J(\nu_{\rm s},T_{\rm cab})\Big]\exp(\tau_{\rm s}A)
\end{aligned}
$$

C. Kramer,
IRAM mm
Interferometer School,
2018

Usually, the calibration is done by dedicated software.
(Still, it is good to know what happens „under the hood").

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SUMMARY

At mm-wavelengths:

* the atmosphere dominates the noise
* receivers are less stable than in the cm-range
* difficult to find calibrator sources

—> A Special calibration scheme is needed: „Chopper-Wheel-Calibration"

MPIfR

In reality, the observer does not have to deal with this on his own, the procedures are realized in dedicated software at the observatory.