Development of ngVLA Tropospheric Calibration

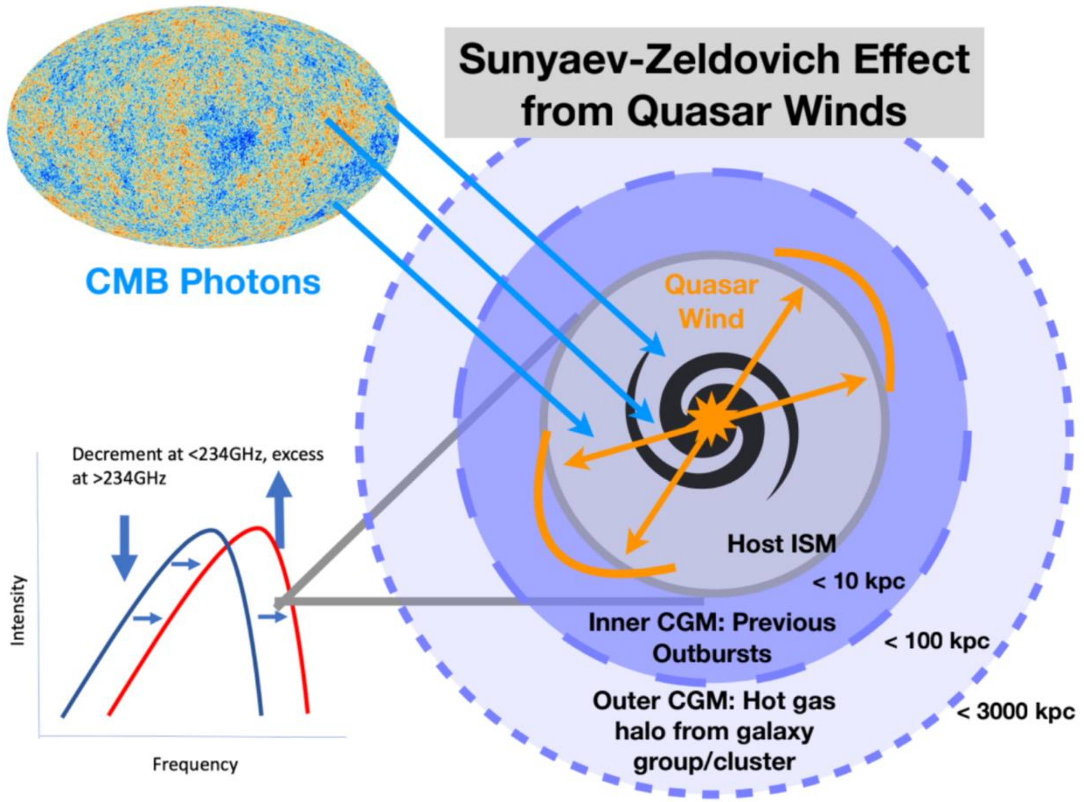
Kyle Massingill, Jansky Fellow
National Radio Astronomy Observatory (NRAO)

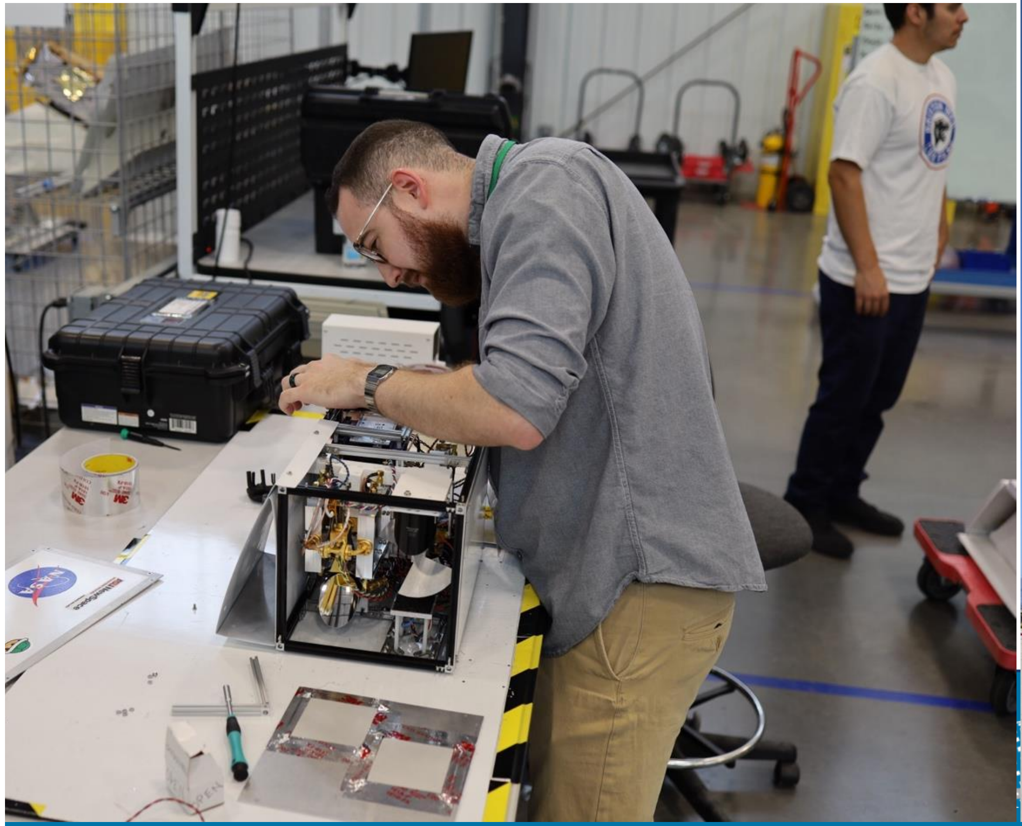
University of New Mexico, CART Seminar,
Jan 2025, Albuquerque, NM

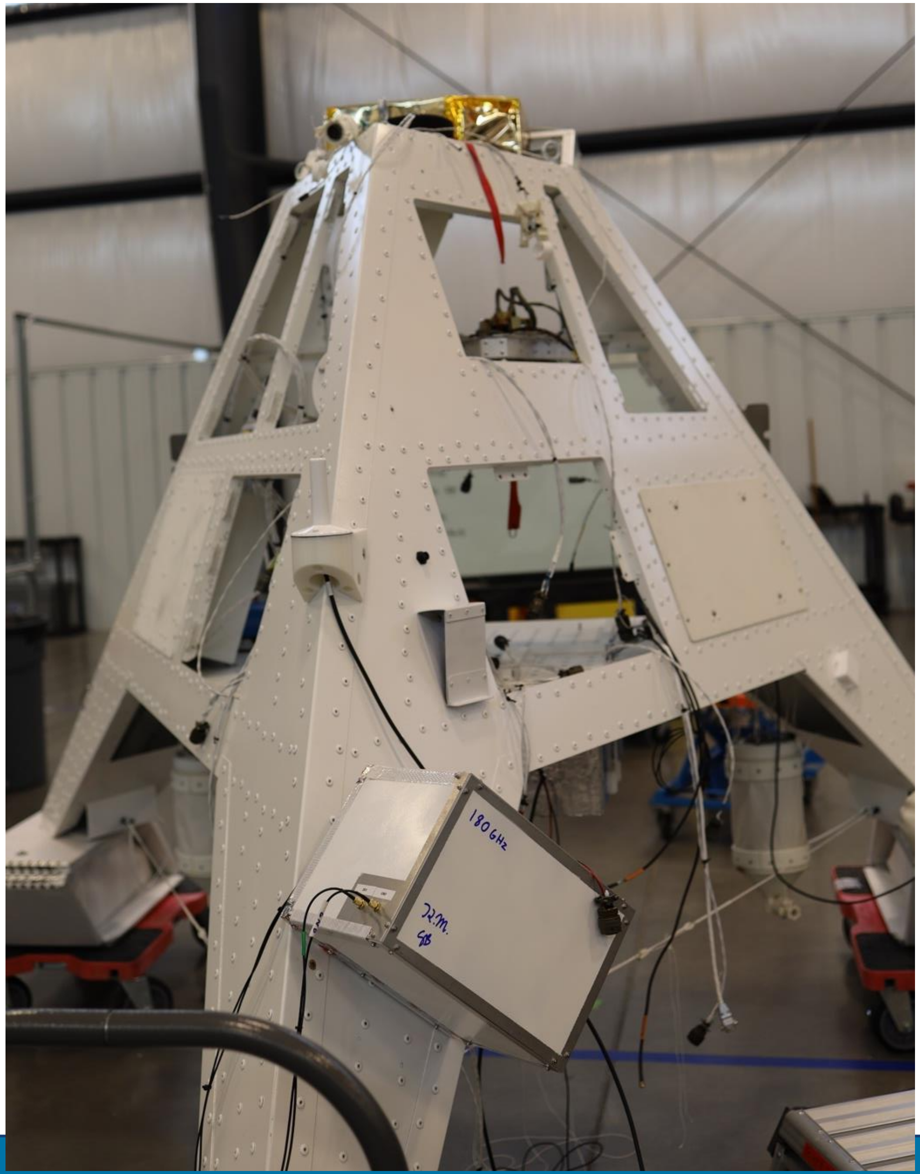
Introduction

- *U-grad: University of Arizona*
- *PhD: Arizona State University*
- *Quasar SZE halo constraints*

- *Weather sensors on high-altitude balloons*






180GHz

Outline

- ***Role of the atmosphere in astronomical observing***
- *Brief introduction to ngVLA*
- *Interferometry and time delay calibration*
- *Water vapor radiometer instruments and interpreting them*

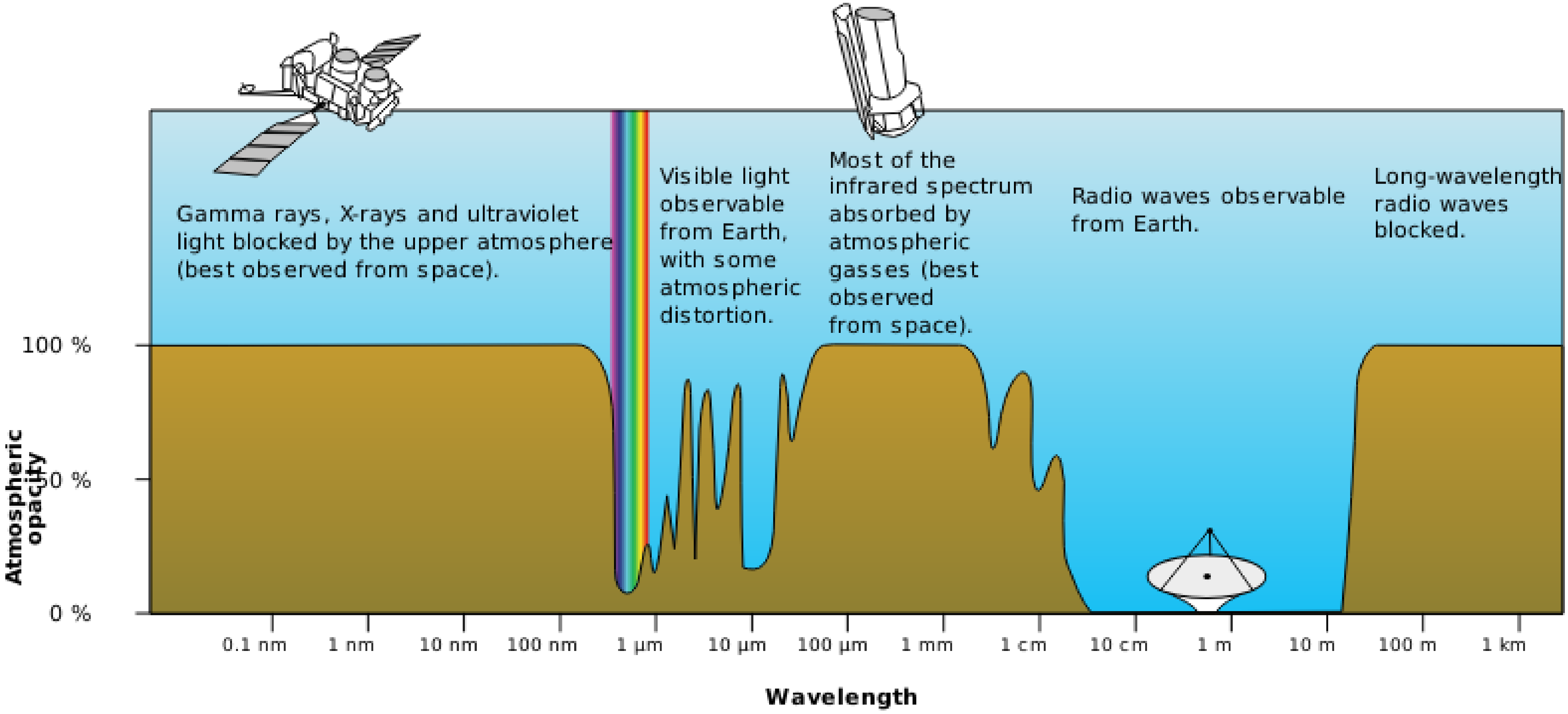
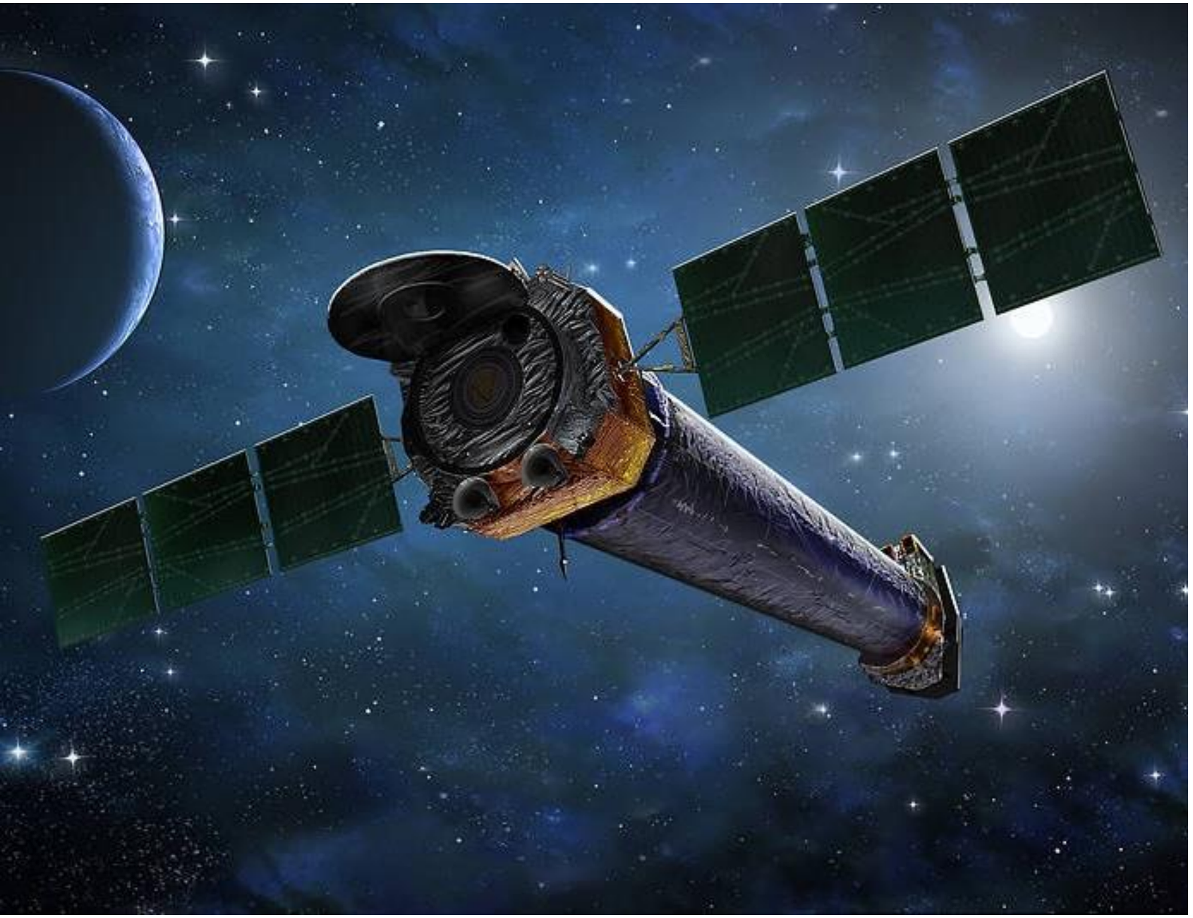


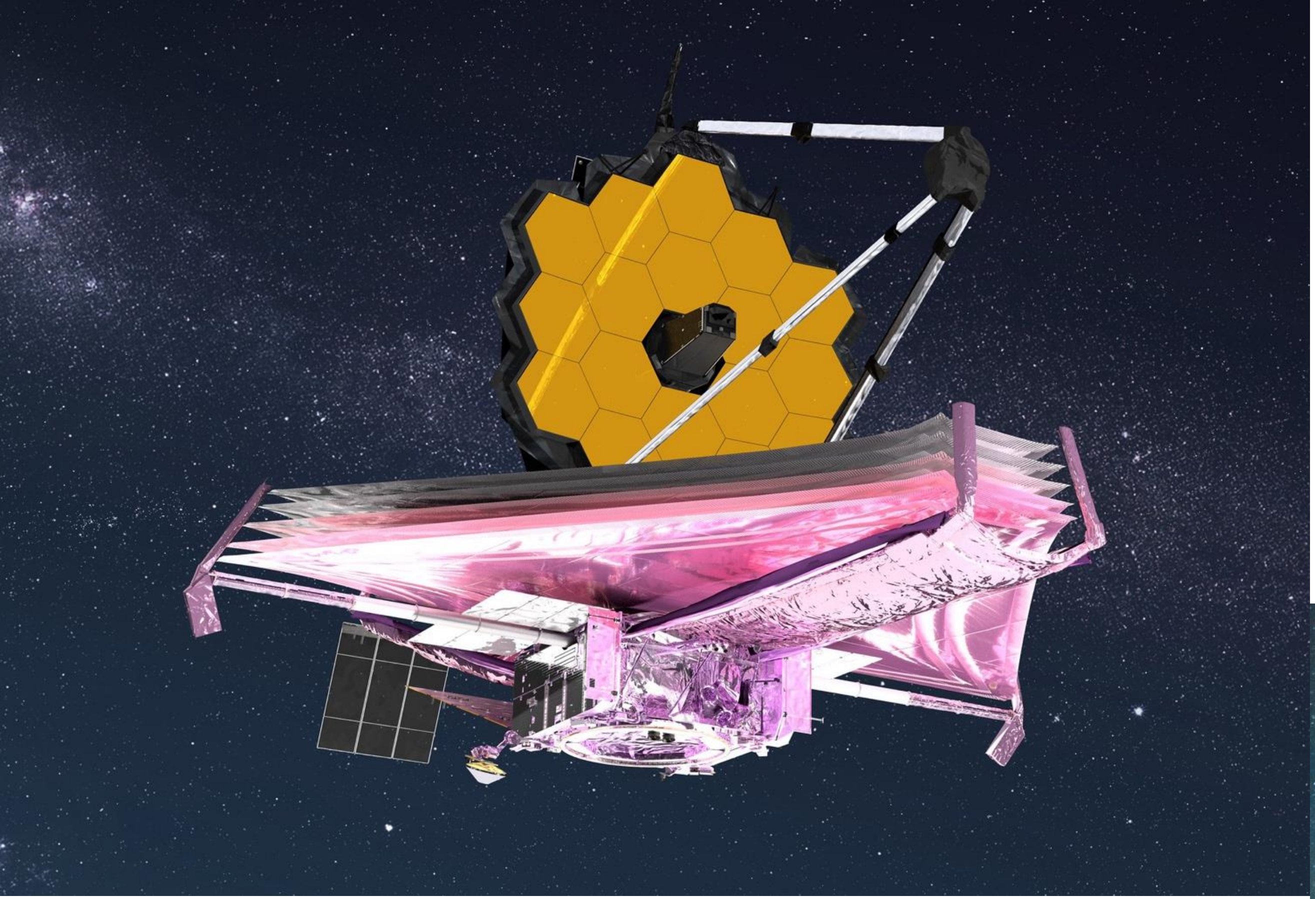
Image credit: NASA

Optical



X-ray

Image credits: Left, Top Right: NASA; Bot. Right: KECK OBSERVATORY



mm-wave

Infrared

Image credits: Left: NASA; Right: NRAO

Radio

Image credits: Right: NRAO

Chemical makeup of the atmosphere EXCLUDING water vapor

GAS	SYMBOL	CONTENT
Nitrogen	N_2	78.084%
Oxygen	O_2	20.946%
Argon	Ar	0.934%
Carbon dioxide	CO_2	0.042%
Neon	Ne	18.182 parts per million
Helium	He	5.24 parts per million
Methane	CH_4	1.92 parts per million
Krypton	Kr	1.14 parts per million
Hydrogen	H_2	0.55 parts per million
Nitrous oxide	N_2O	0.33 parts per million
Carbon monoxide	CO	0.10 parts per million
Xenon	Xe	0.09 parts per million
Ozone	O_3	0.07 parts per million
Nitrogen dioxide	NO_2	0.02 parts per million
Iodine	I_2	0.01 parts per million
Ammonia	NH_3	trace

Chemical makeup of the atmosphere INCLUDING water vapor

WATER VAPOR	NITROGEN	OXYGEN	ARGON
0%	78.084%	20.947%	0.934%
1%	77.30%	20.70%	0.92%
2%	76.52%	20.53%	0.91%
3%	75.74%	20.32%	0.90%
4%	74.96%	20.11%	0.89%

Image credit: NOAA

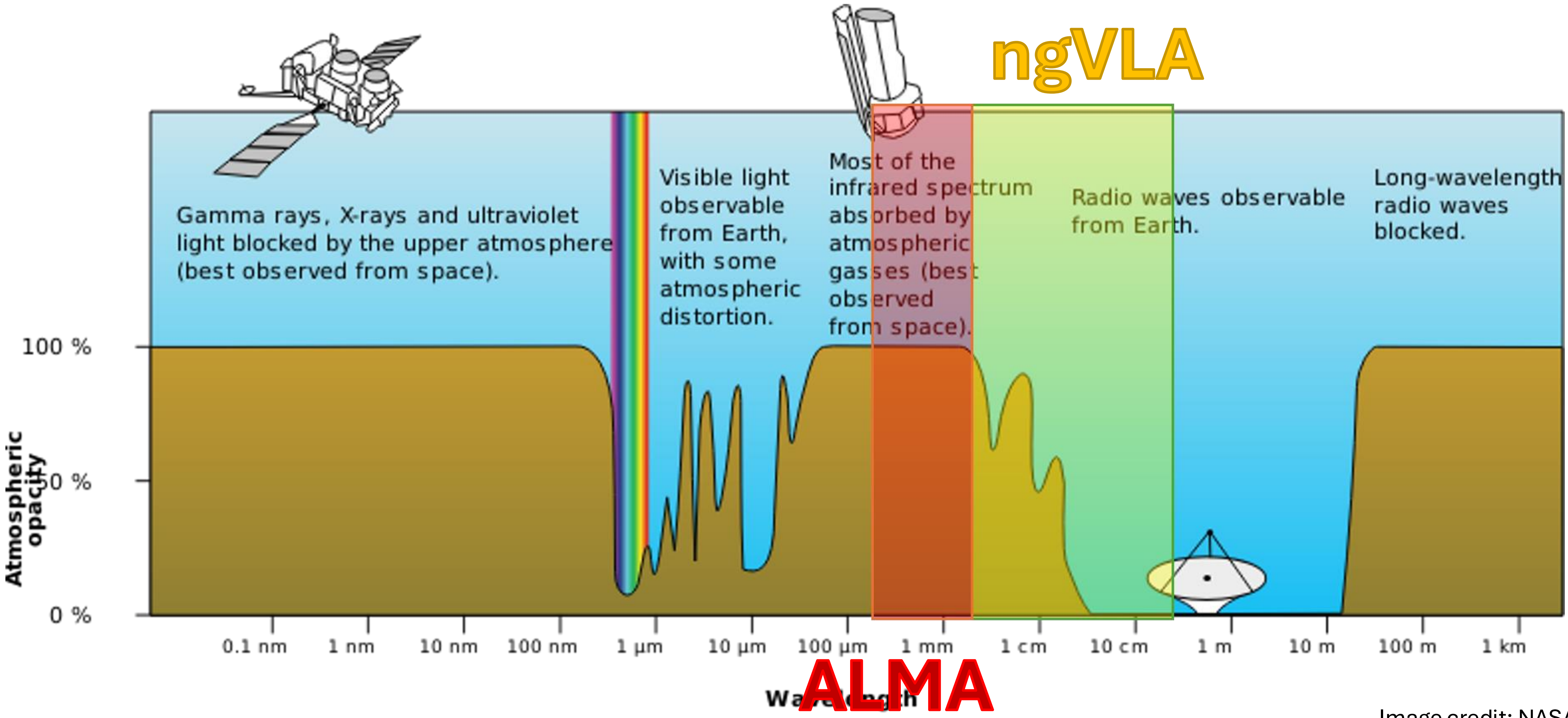
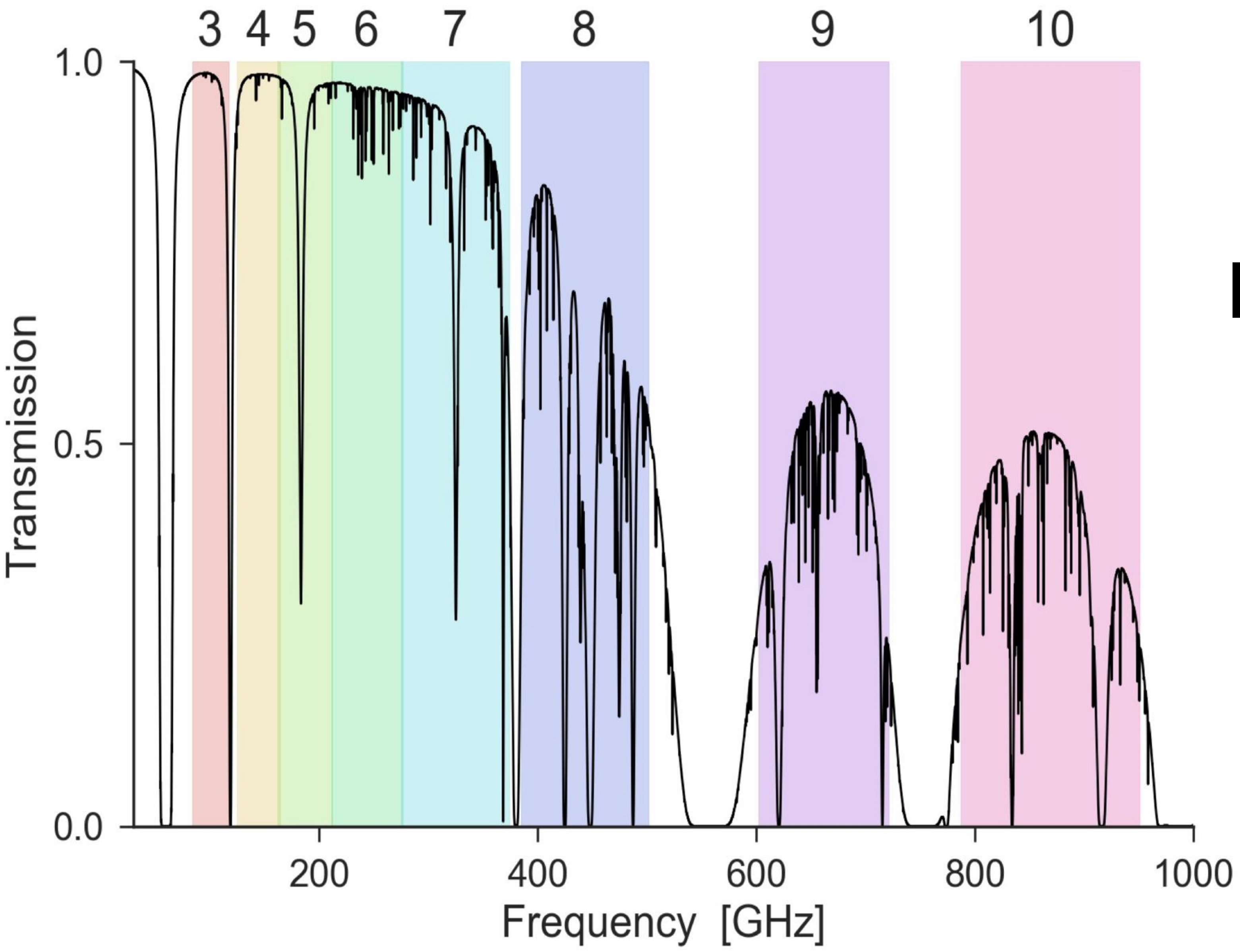
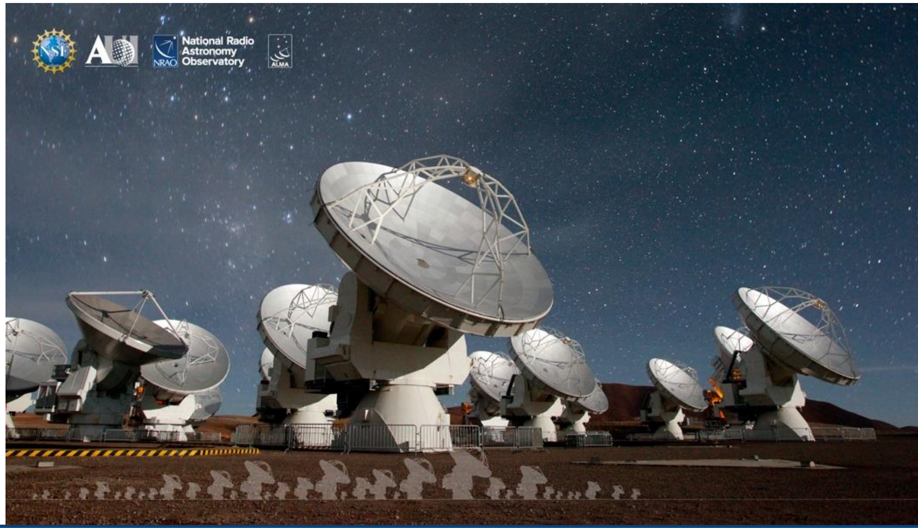


Image credit: NASA



Elevation: 16,500 ft or 5 km



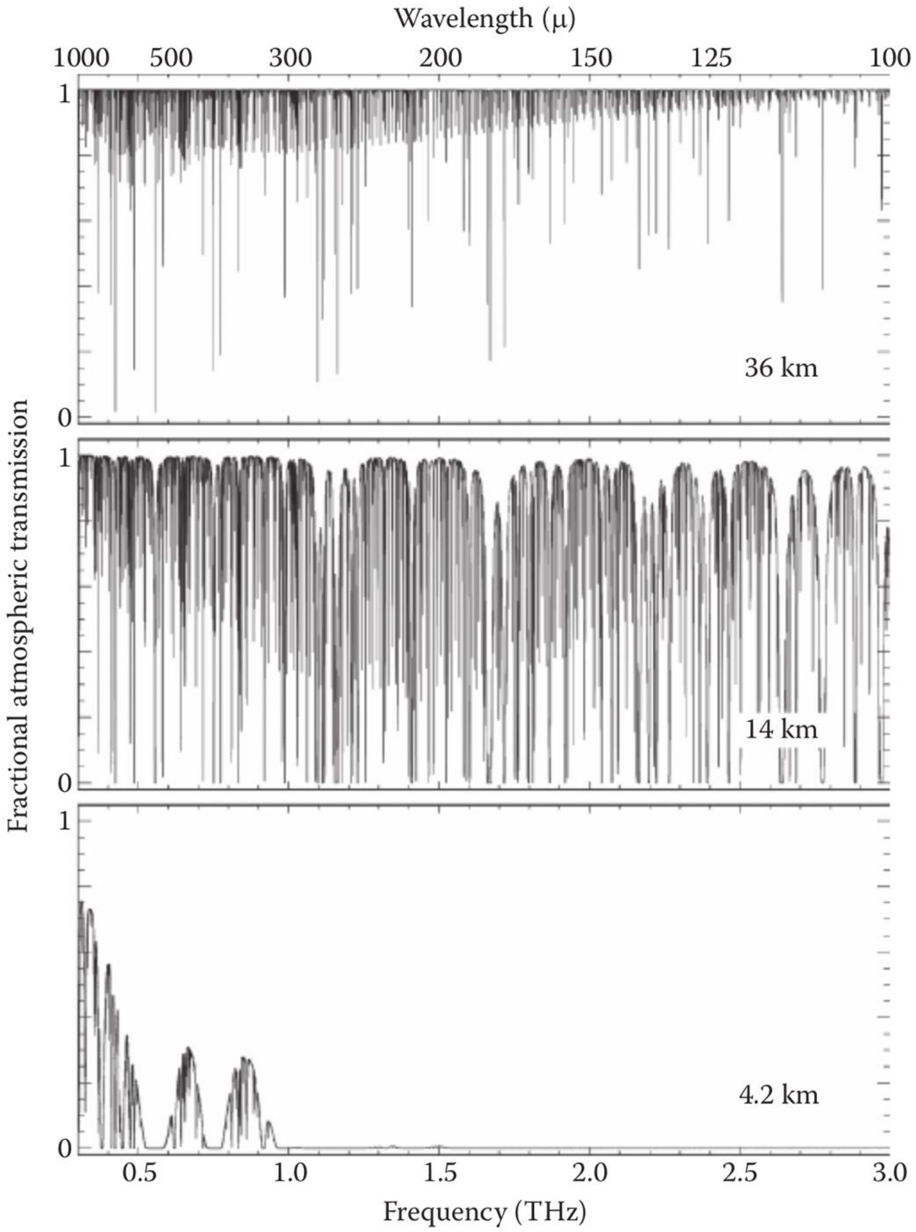


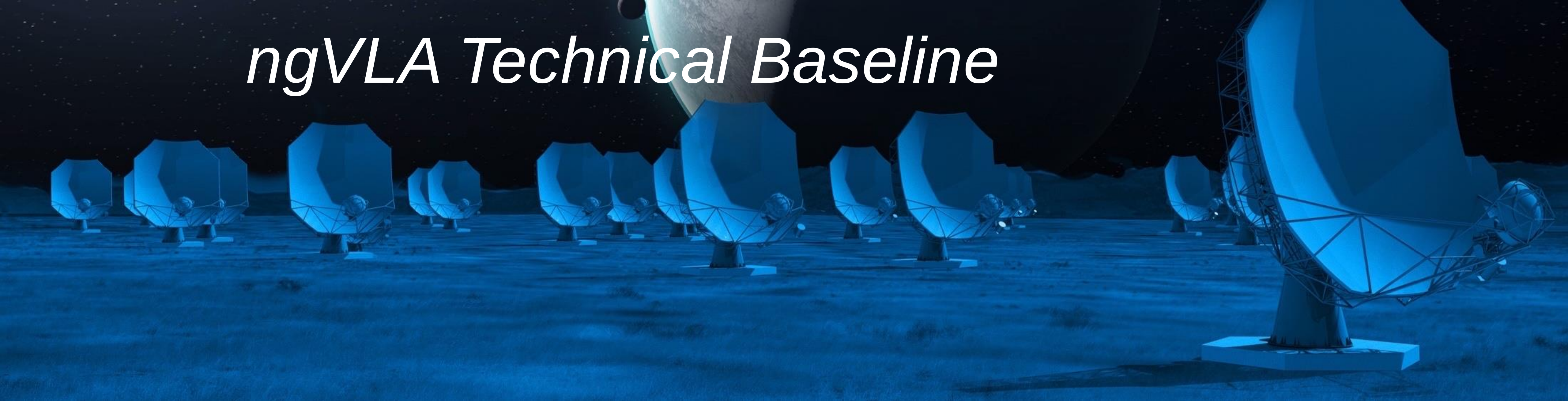
FIGURE 1.1 THz atmospheric transmission for typical weather conditions from mountaintop site (4.2 km), airborne altitudes (14 km), and balloon-borne altitudes (32 km). (Atmospheric model courtesy G. Melnick; see also Melnick (1988).)

Image credit: Walker 2015

Outline

- *Role of the atmosphere in astronomical observing*
- ***Brief introduction to ngVLA***
- *Interferometry and time delay calibration*
- *Water vapor radiometer instruments and interpreting them*

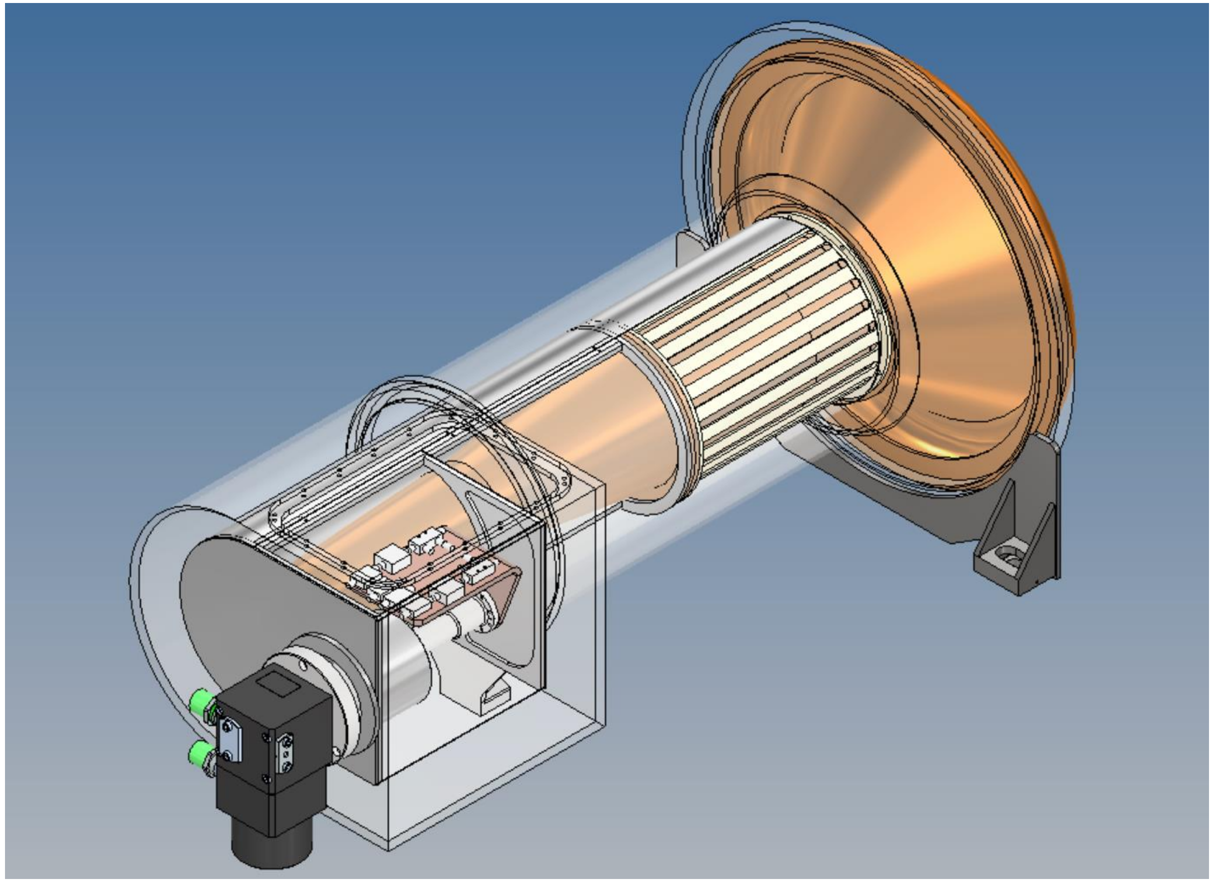
ngVLA Technical Baseline

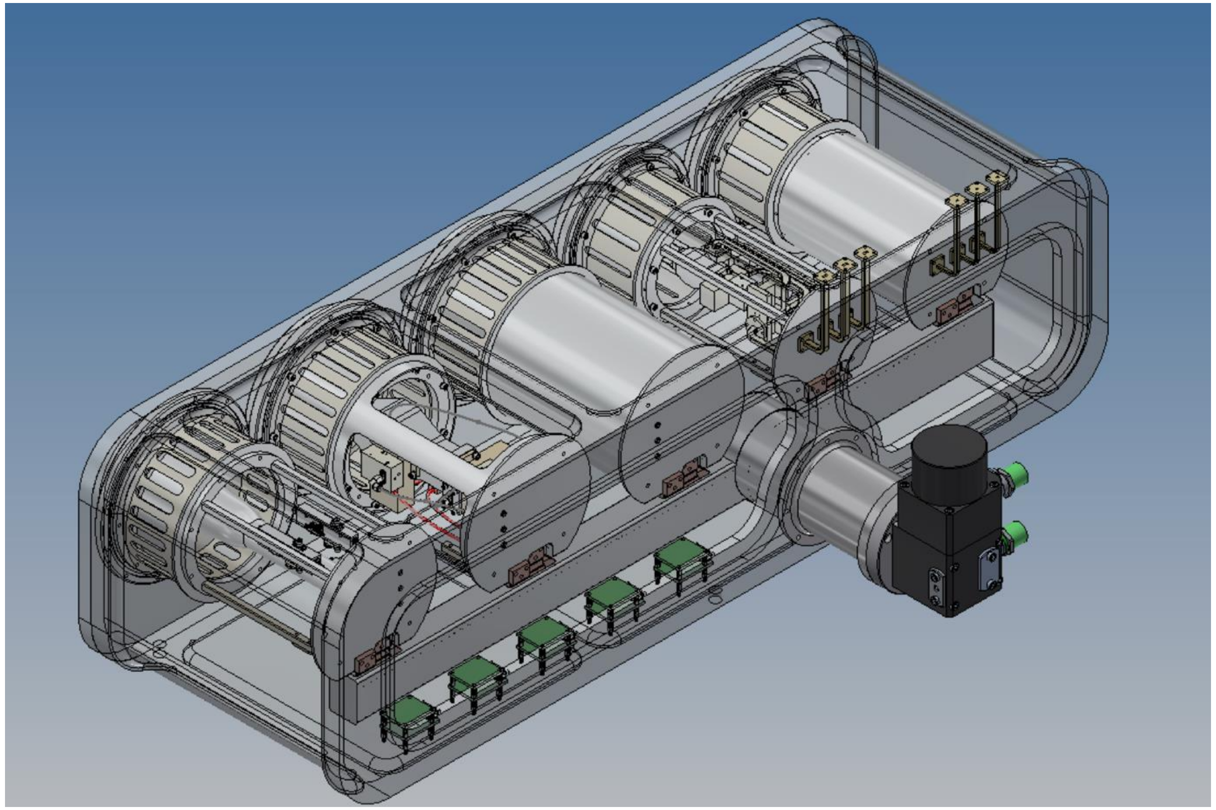


- *Frequency Range: 1.2 - 116 GHz*
- *Main Array: 244 x 18m offset Gregorian Antennas*
  - *Core: 114 antennas; B_{max} = 4.3 km*
  - *Spiral: 54 antennas; B_{max} = 39 km*
  - *Mid: 46 antennas in NM, AZ, TX, MX; B_{max}=1070 km*
  - *Long: 30 antennas across continent; B_{max}= 8860 km*
- *Short Baseline Array: 19 x 6m offset Greg. Antennas*
  - *Use 4 x 18m in Total Power mode to fill (u,v) hole*

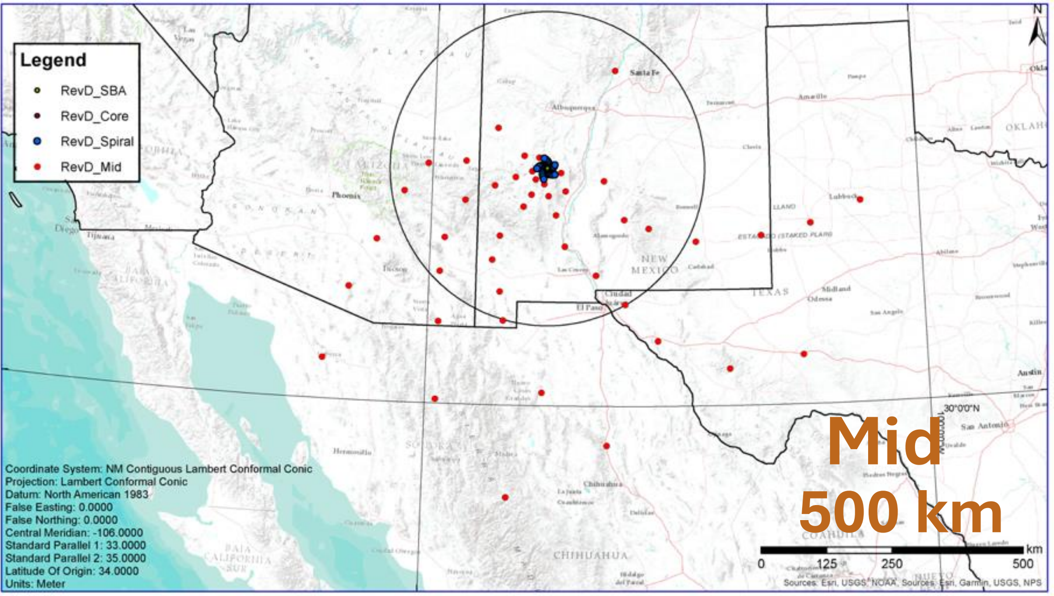
Band #	freq. range (GHz)
1	1.2 - 3.5
2	3.5 - 12.3
3	12.3 - 20.5
4	20.5 - 34
5	30.5 - 50.5
6	70 - 116

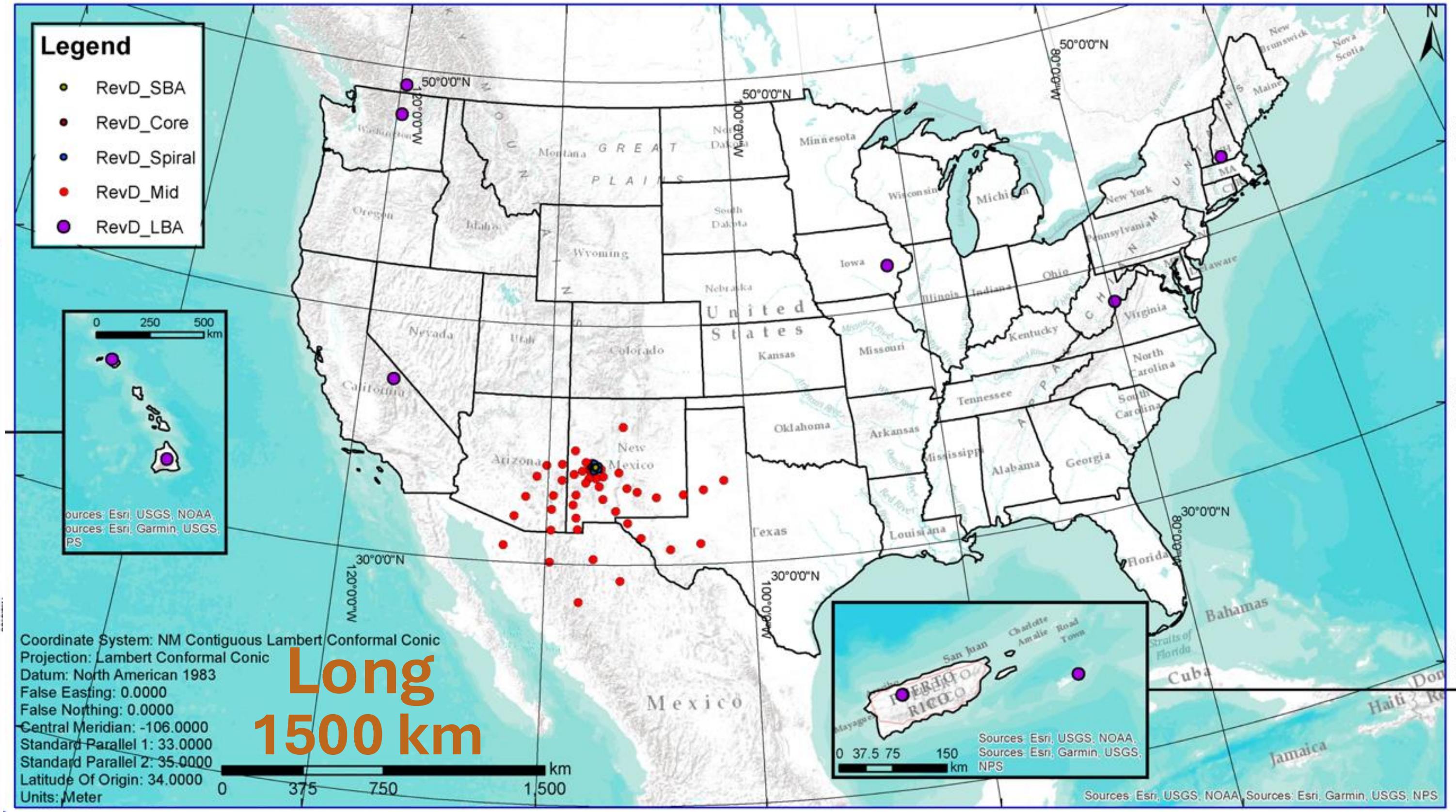
Correlator / Beamformer	Requirement (design)
digital efficiency	>95%
narrowest channel	<1 kHz
total # channels	>240,000
sub-band width	<250MHz (218.75)
total bandwidth	>14GHz/pol (20)
# formed beams	10

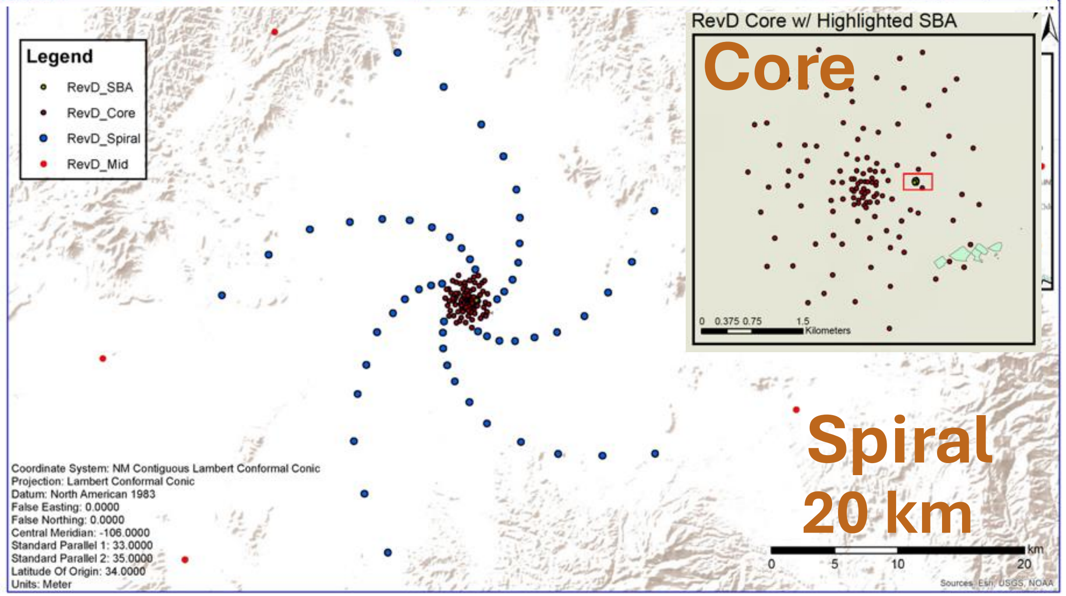




Distribution of Antennas







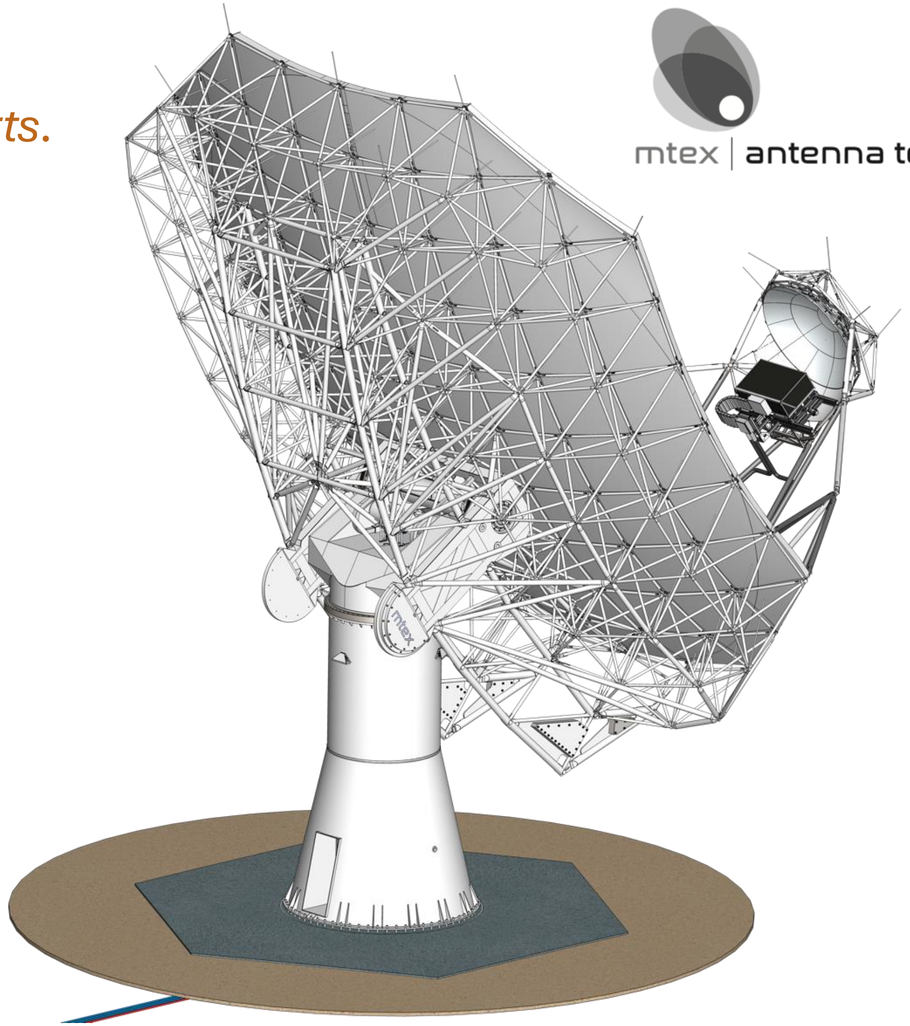
Long Baseline Antenna Locations

Qty	Location	Notes
3	Puerto Rico	Arecibo Site
3	St. Croix	VLBA Site
3	Kauai, HI	Kokee Park Obs.
3	Hawaii, HI	not Mauna Kea
3	Hancock, NH	VLBA Site

Qty	Location	Notes
3	Green Bank, WV	GBO
3	Brewster, WA	VLBA Site
3	Penticton, BC	DRAO
3	North Liberty, IA	VLBA site
3	Owens Valley, CA	VLBA site

18m Prototype Antenna

- *76 Al. Main Reflector Panels, 5-pt supports.*
- *19 Al. Sub Reflector Panels w/ Hexapod*
- *Tube and Node BUS*
- *Steel Pedestal*
- *RFI Chamber w/ Electronics/servo*
- *CFRP Feed Arm*
- *Metrology (Tilt meter, temp sensors)*



mtex | antenna technology

Status:
- *Prototype under construction at VLA site.*
- *2025 Testing at 3 cm and 7 mm, including correlation with VLA antennas*

Key Specifications	
18m Aperture	Offset Gregorian
Shaped Optics	3° Slew & Settle in 7 sec
Surface: 160 µm rms	Reference pointing: 3” rms
Precision conditions:	Total efficiency >80% (X..Q)


2025-01-07 11:14:50

Outline

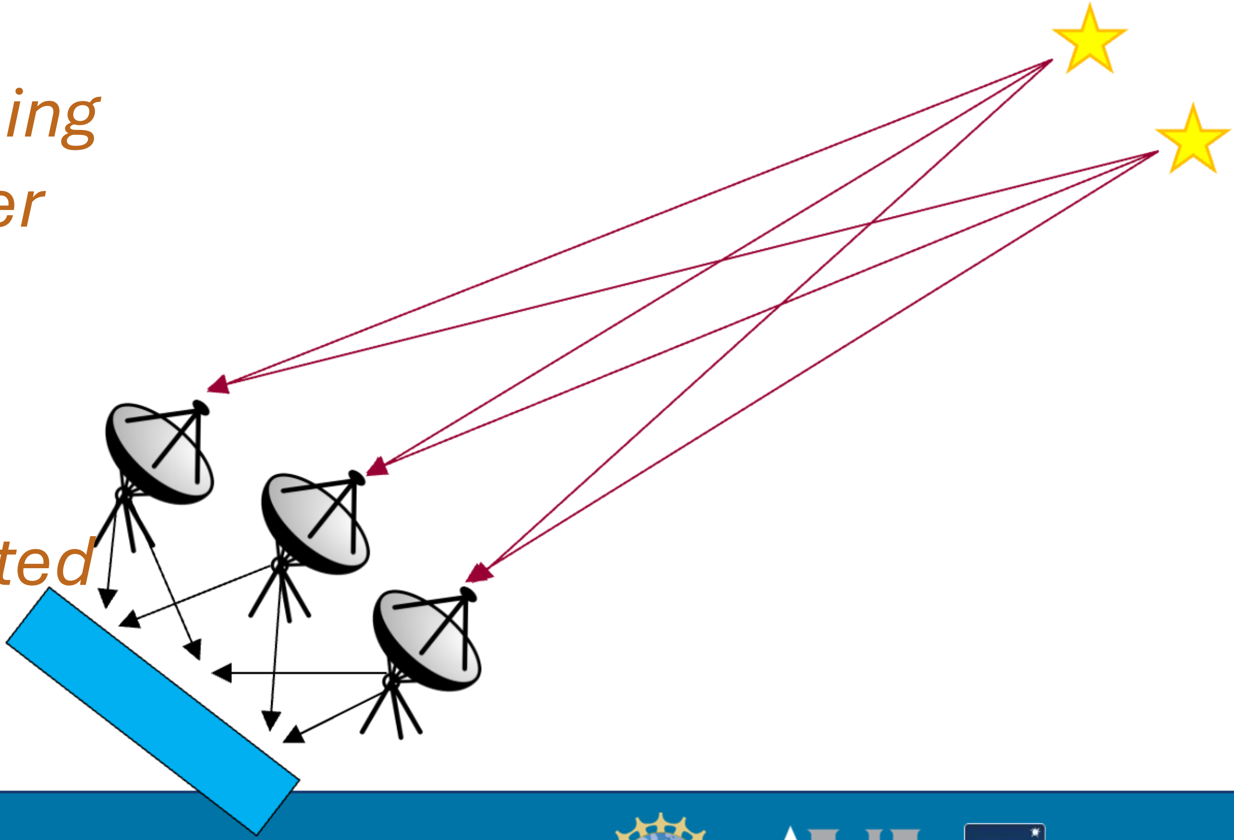
- *Role of the atmosphere in astronomical observing*
- *Brief introduction to ngVLA*
- ***Interferometry and time delay calibration***
- *Water vapor radiometer instruments and interpreting them*

Interferometry

- To achieve arcsecond resolution in radio need km-scale antenna

- Synthesize large aperture by combining signal detected from multiple smaller apertures

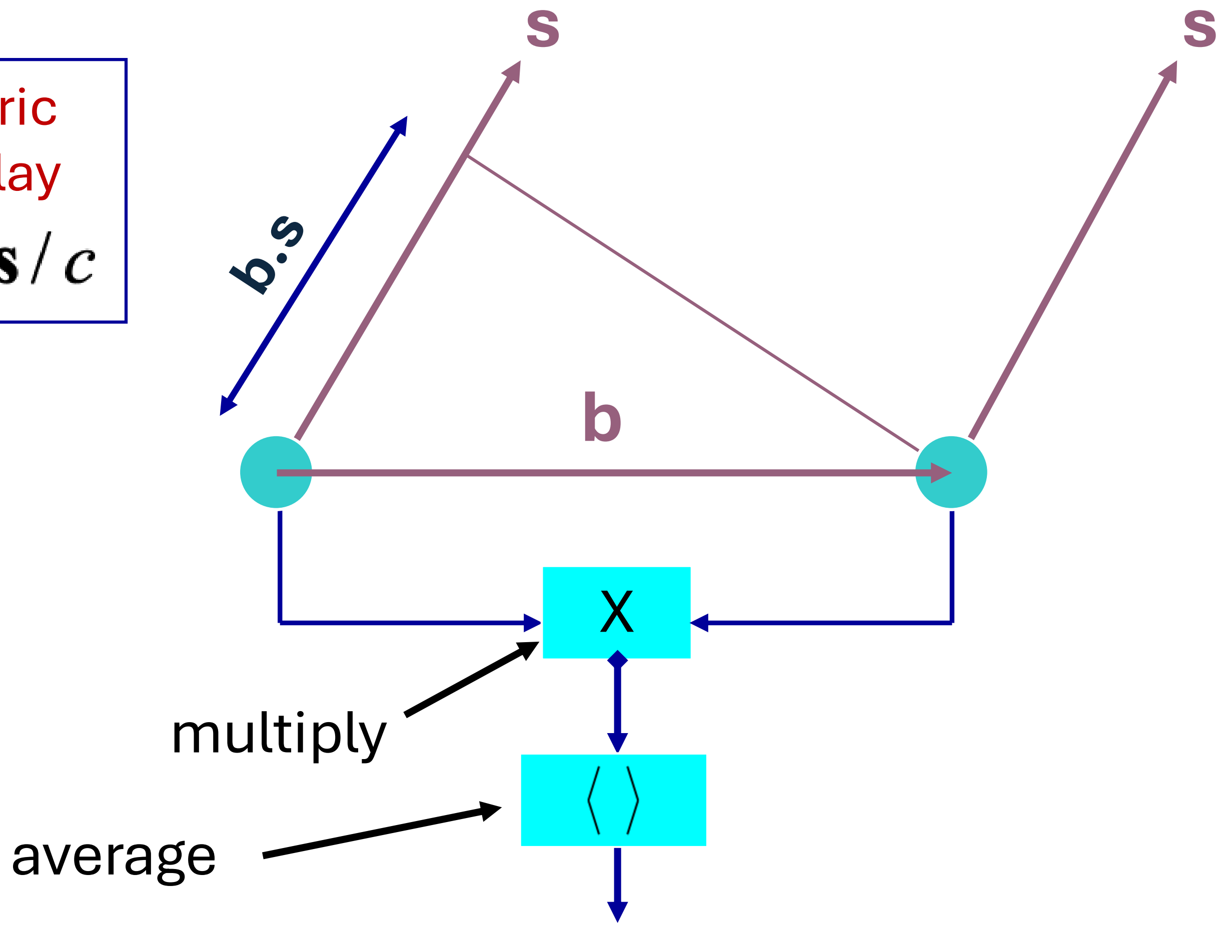
- Combined in correlator
  - Time delay measured and corrected



Interferometry

Geometric Time Delay

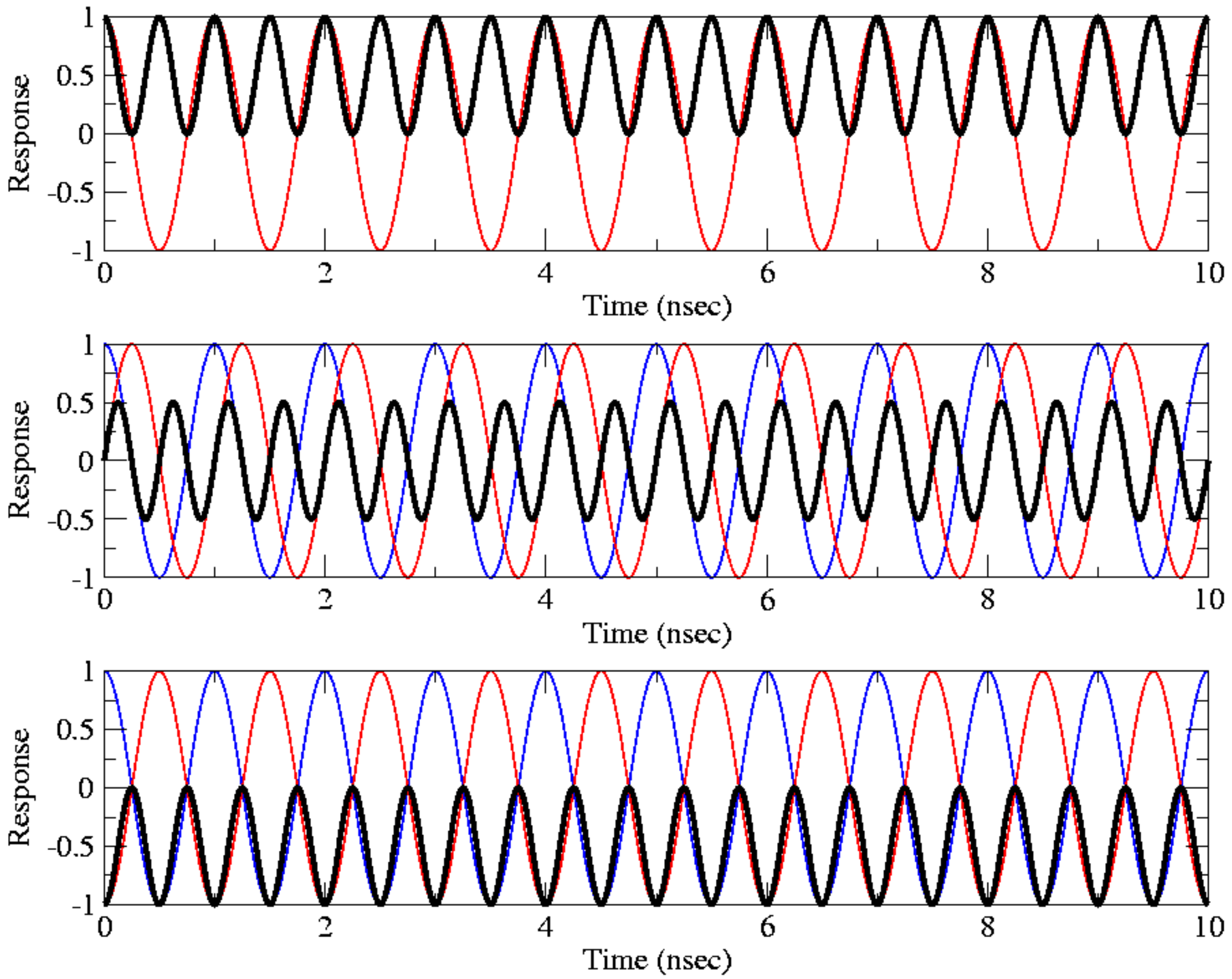
$$\tau_g = \mathbf{b} \cdot \mathbf{s} / c$$



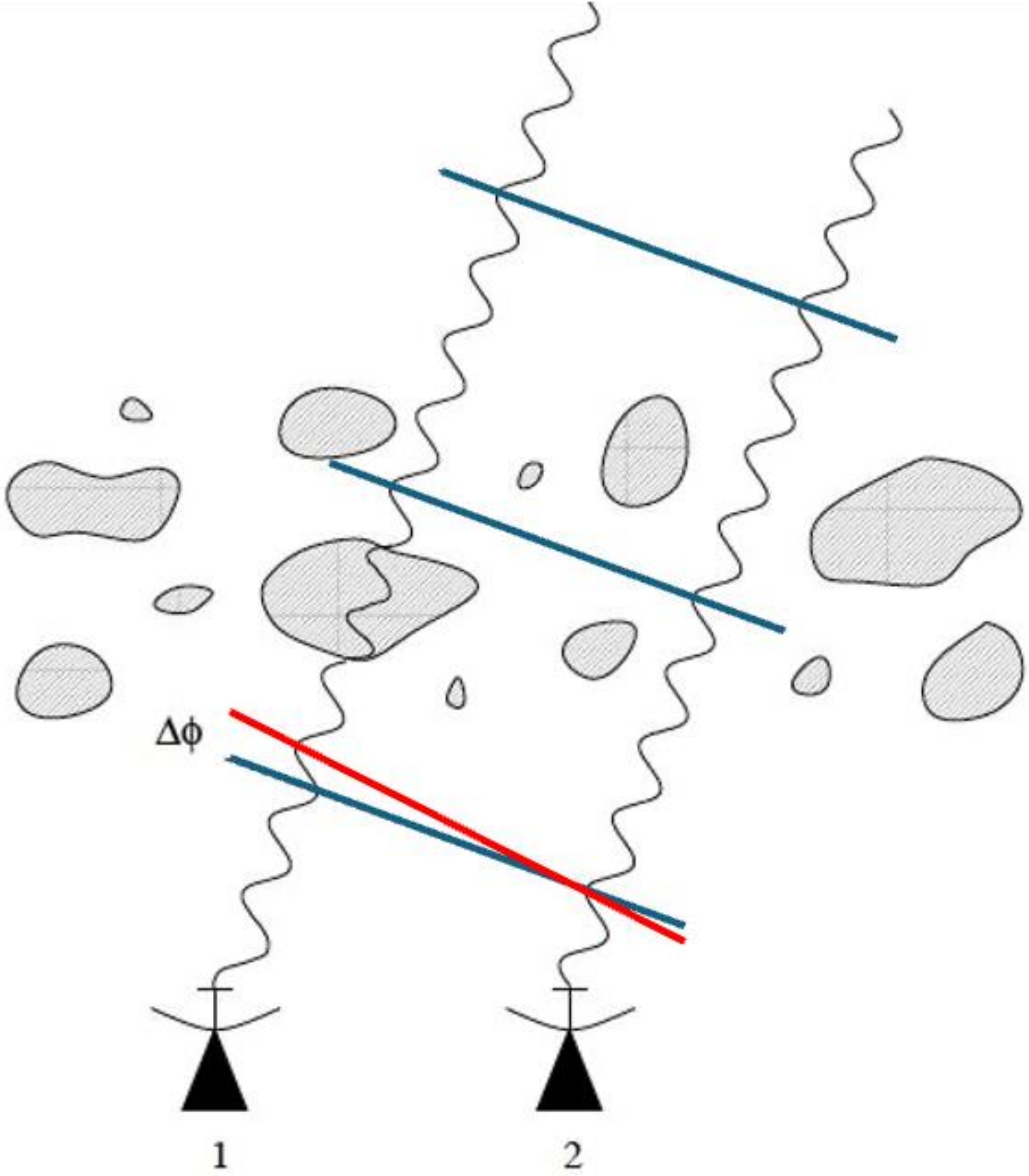
Credit: Rick Perley, NRAO

Examples of the Signal Multiplications

- *The two input voltages are shown in red and blue, their product is in black.*
- *The output is the average of the black trace.*



Credit: Rick Perley, NRAO



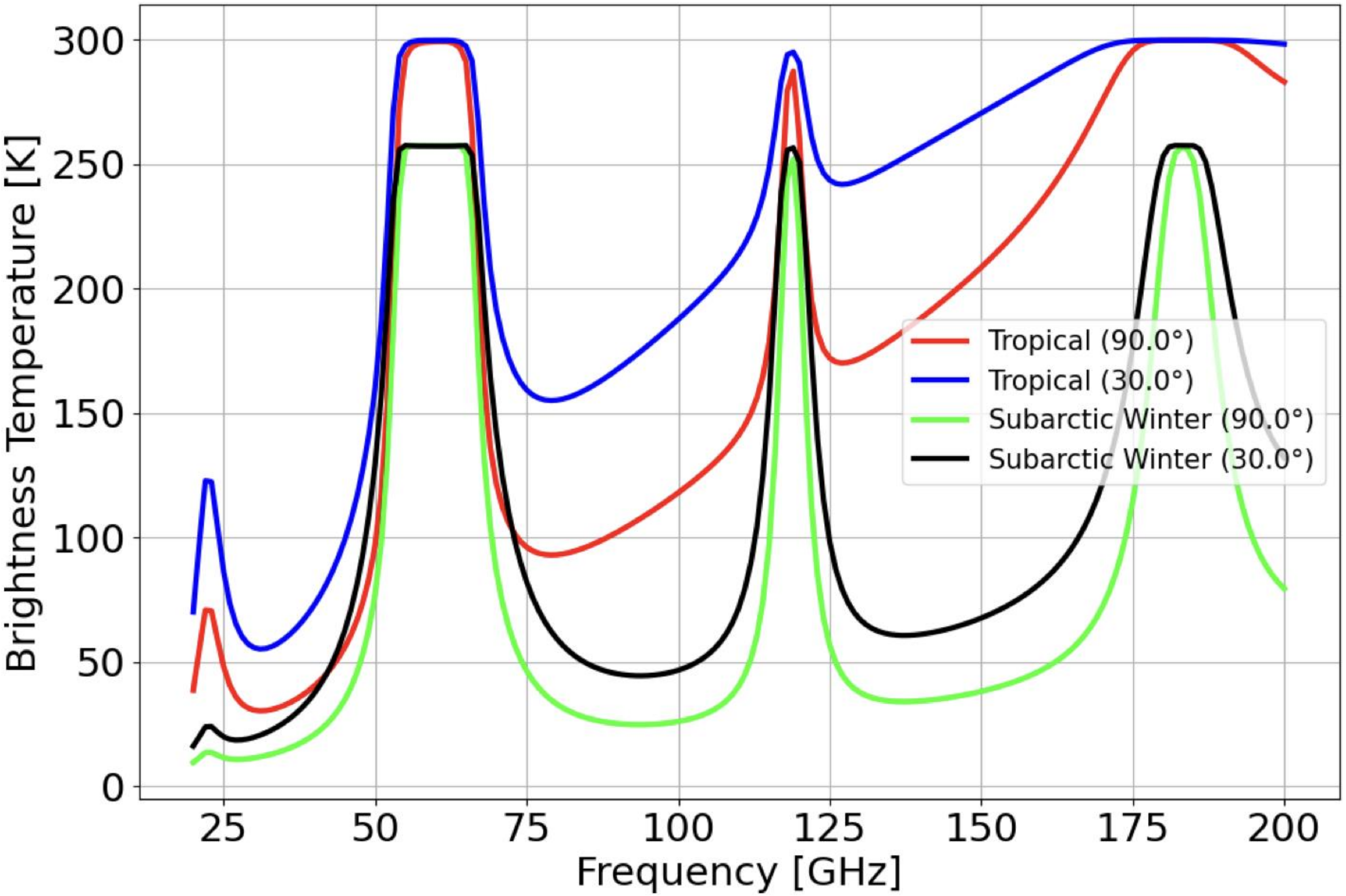
Δφ
1
2

How Do We Calibrate Atmospheric Fluctuations?

- *Fast Switching (sometimes referred to as standard calibration)*
  - *Array slews between science target and known calibrator source*
    - *Visibilities are compared to model of calibrator to solve for phase fluctuations*
  - *Cons: reduces on target time (observing efficiency)*

- *Self-Calibration*
  - *Develop model of science target by imaging, then compare visibilities to model to solve for phase fluctuations*
  - *Cons: Target must have significant SNR*

- *Other option: Observe atmosphere directly*



PyRTlib: Larosa et al. 2024

Outline

- *Role of the atmosphere in astronomical observing*
- *Brief introduction to ngVLA*
- *Interferometry and time delay calibration*
- ***Water vapor radiometer instruments and interpreting them***

ALMA Water Vapor Radiometer (183 GHz)

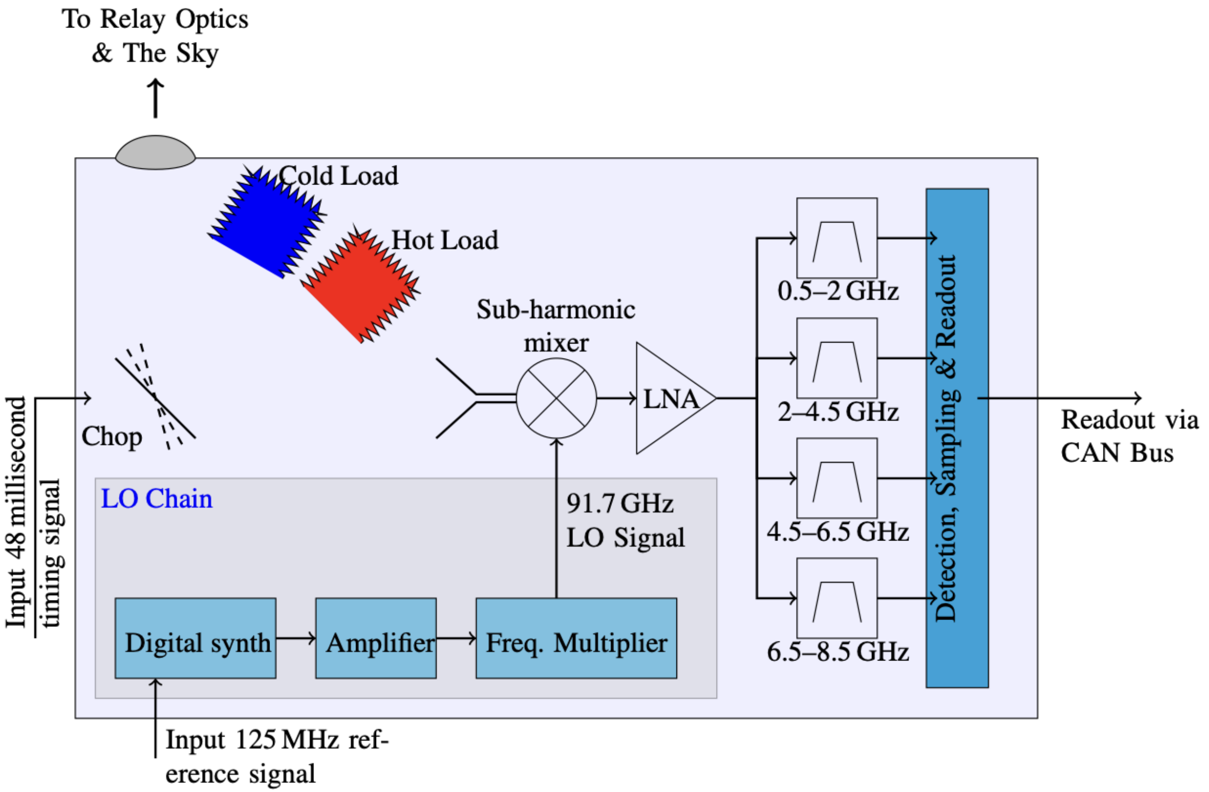


Fig. 1. Conceptual design of the water vapour radiometers.

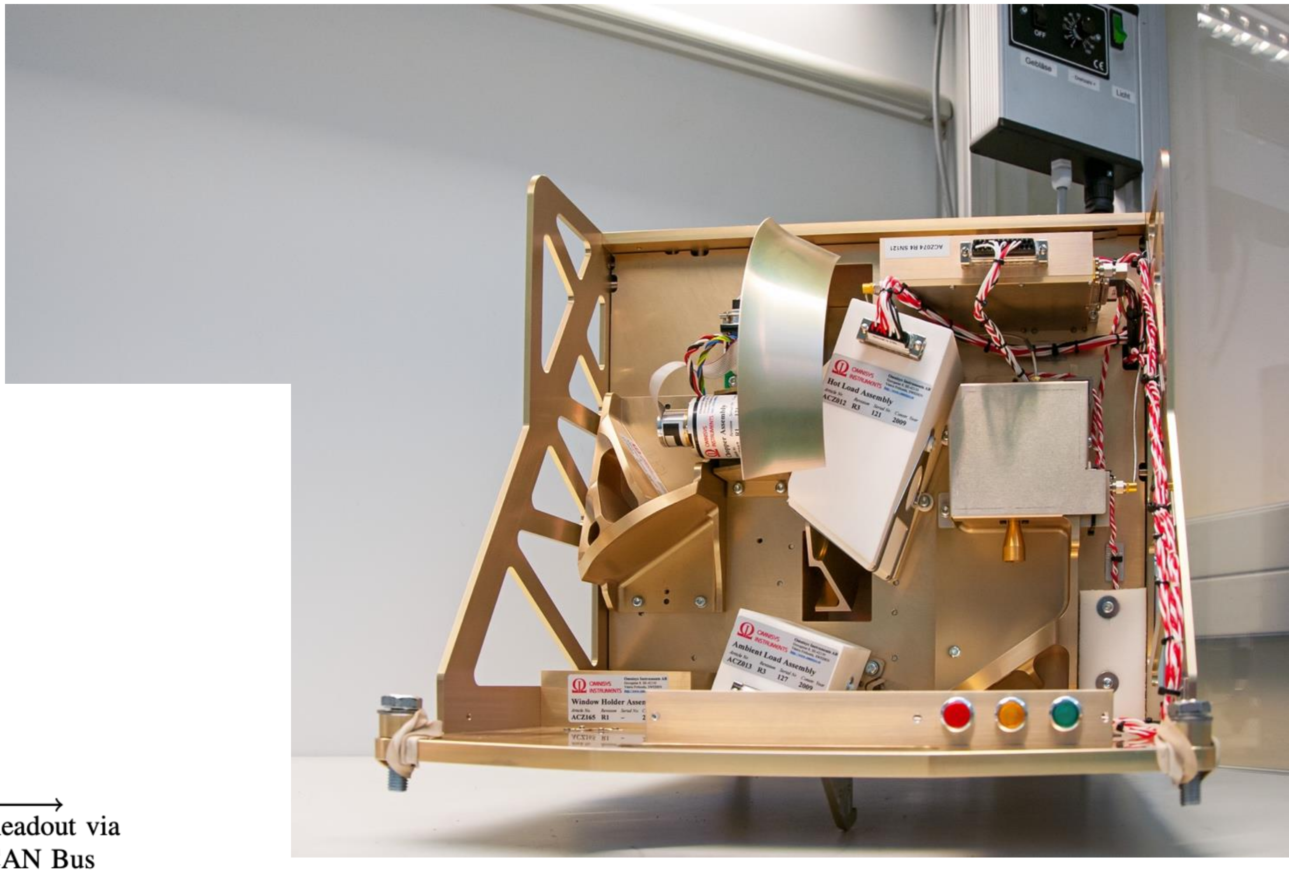


Image credits: Left: Nikolic et al. 2013; Right: ESO

Nikolic et al. 2013

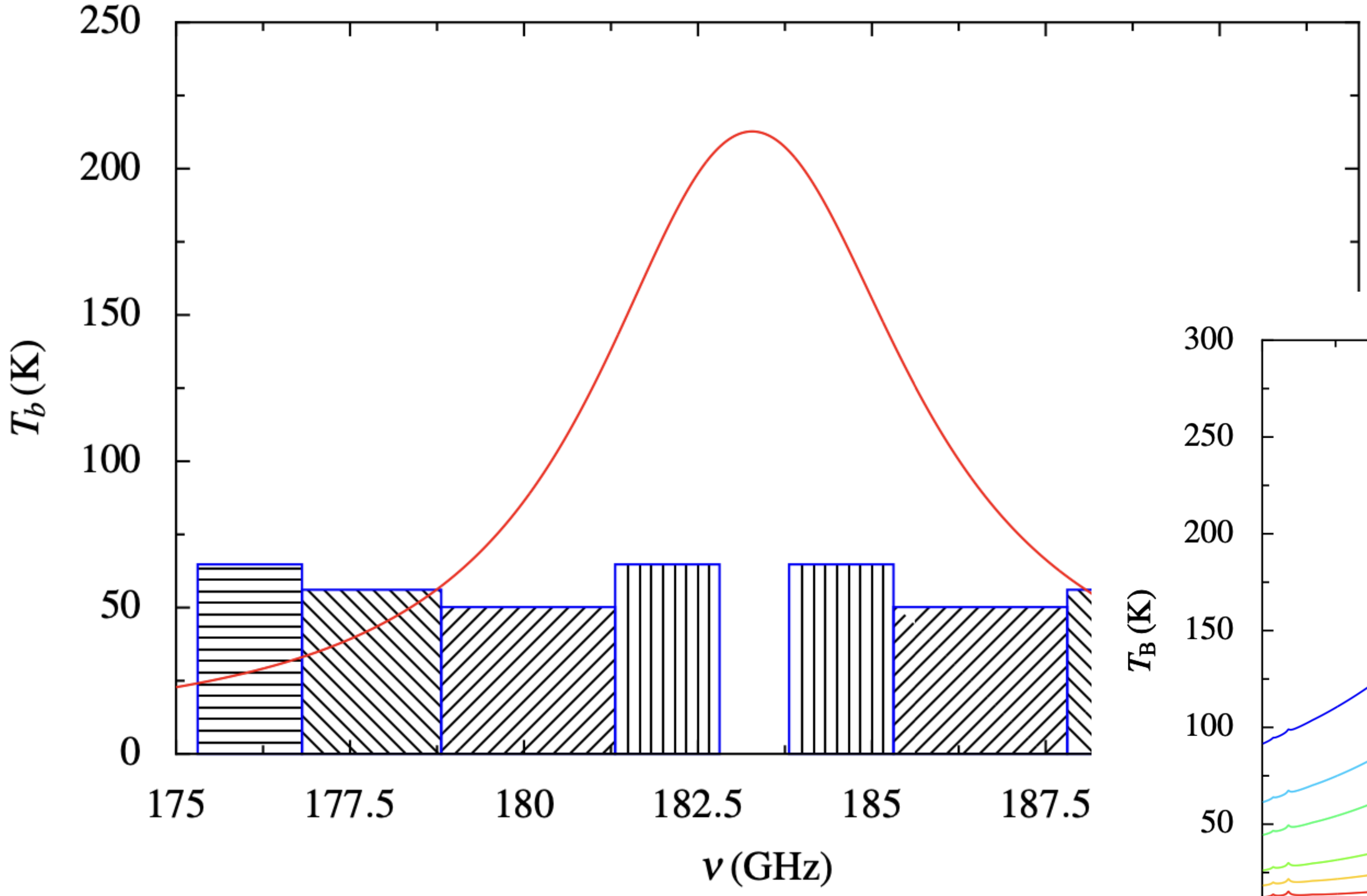


Fig. 4. Design band-passes of the four channels of ALM
gether with a plot model brightness temperature for 1 mr

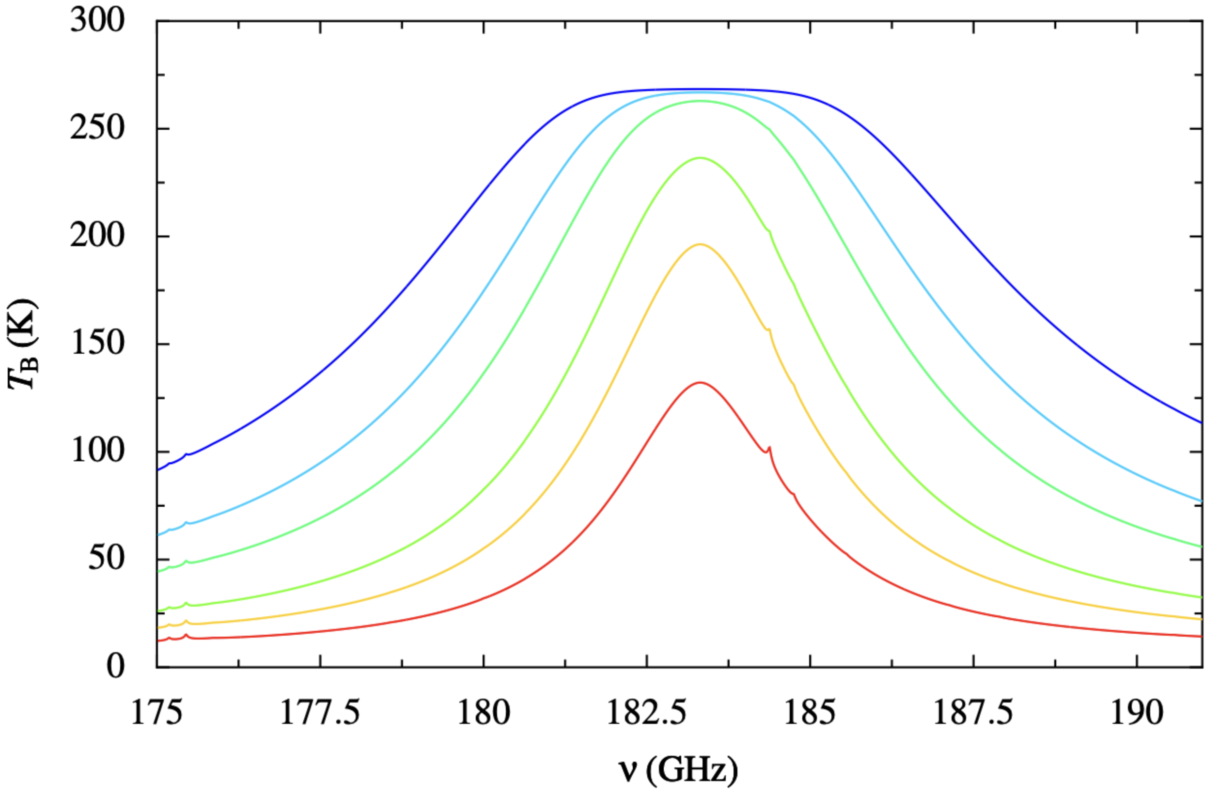
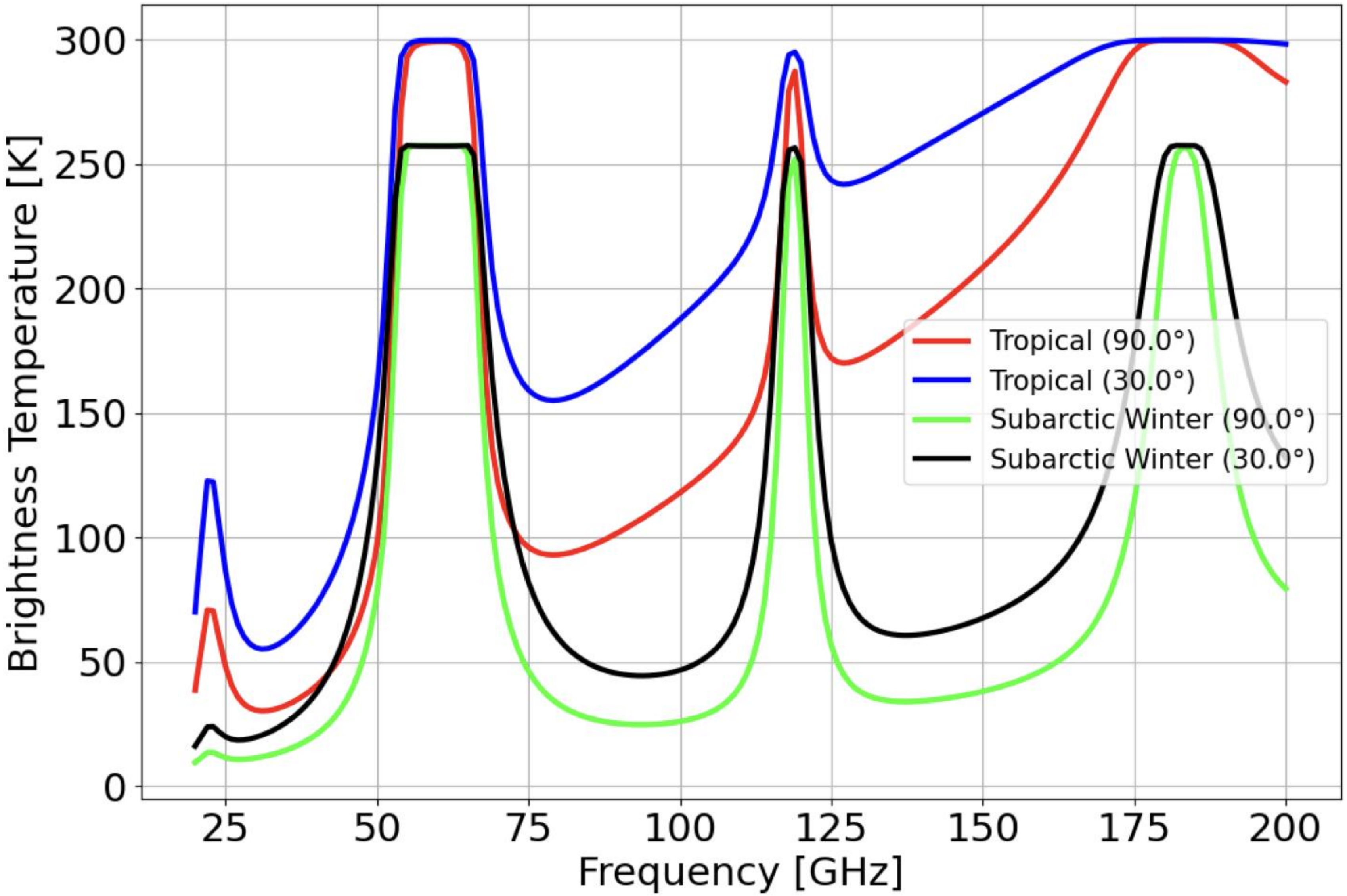


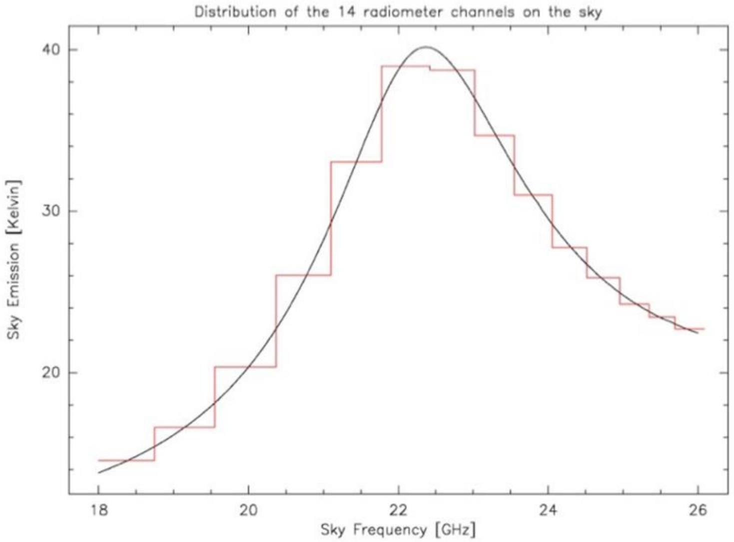
Fig. 2. Model brightness of the atmosphere at frequencies around the 183 GHz water vapour line for six values of PWV along the line of sight: 0.3, 0.6, 1, 2, 3 and 5 mm (from lowest red line to highest blue



PyRTlib: Larosa et al. 2024

22 GHz, Projects

- *NOEMA (Bremer 2018)*
  - *14 Channel*



- *COMAP (Kim et al. 2023)*
  - *Spectral and continuum measurement*

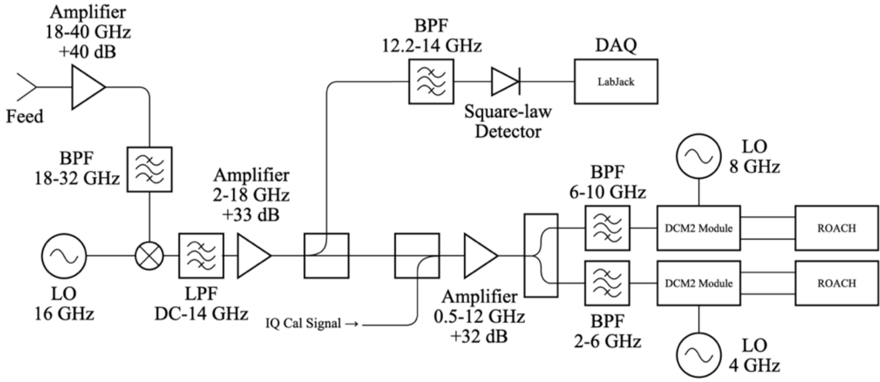


Fig. 2. Signal path for the WVR. The signals from the 18–26 GHz spectral and 28–30 GHz continuum channels are processed separately. For the detailed

- *JPL AWVR (Locke et al.)*
  - *3 Channel, Nested Temperature controllers*

Photographs of the Advanced Water Vapor Radiometer units next to the DSN 34-meter antennas.

- *ngVLA Baseline Design*
  - *19.7 – 31.0 GHz*
  - *Custom front end with discrete RF components*
  - *Modified ngVLA band 4 receivers*
  - *Requirement: $T_{atm,rms}$ <100 mK (2 sec.)*

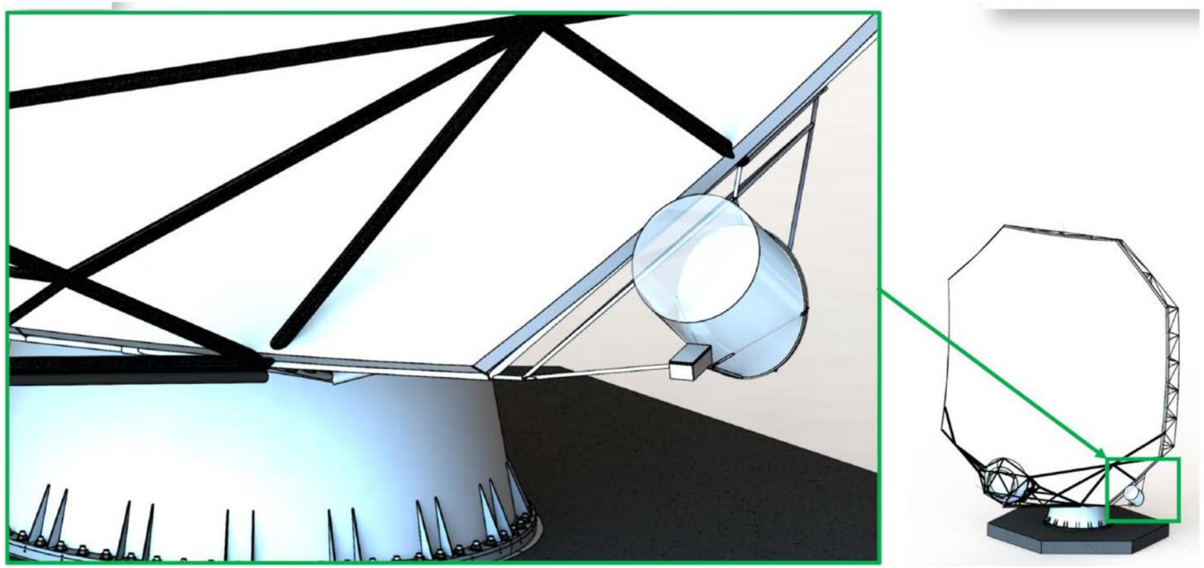


Figure 2: Location of WVR dish and F507 Module on main 18m antenna. The WVR optical beam is visualized.

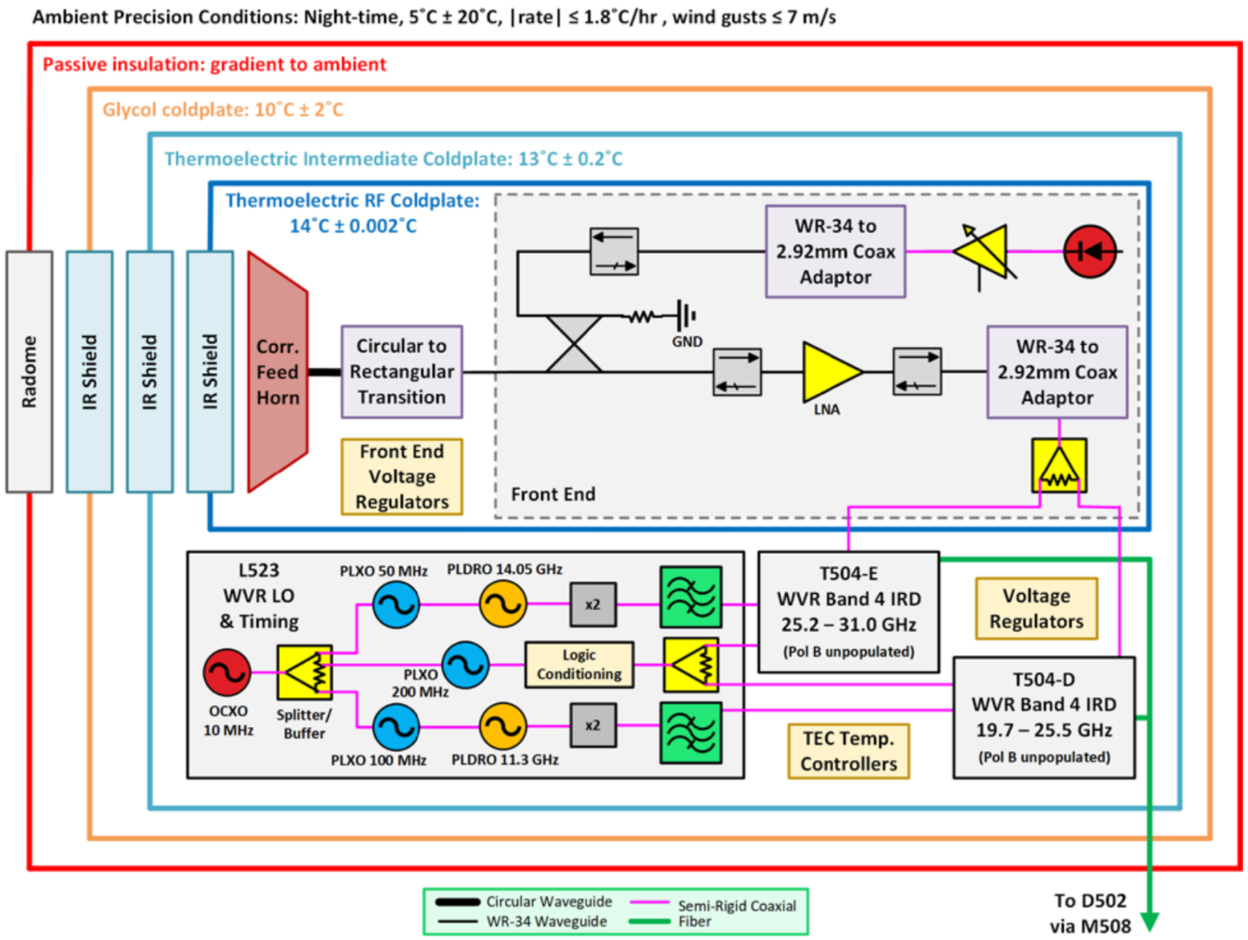
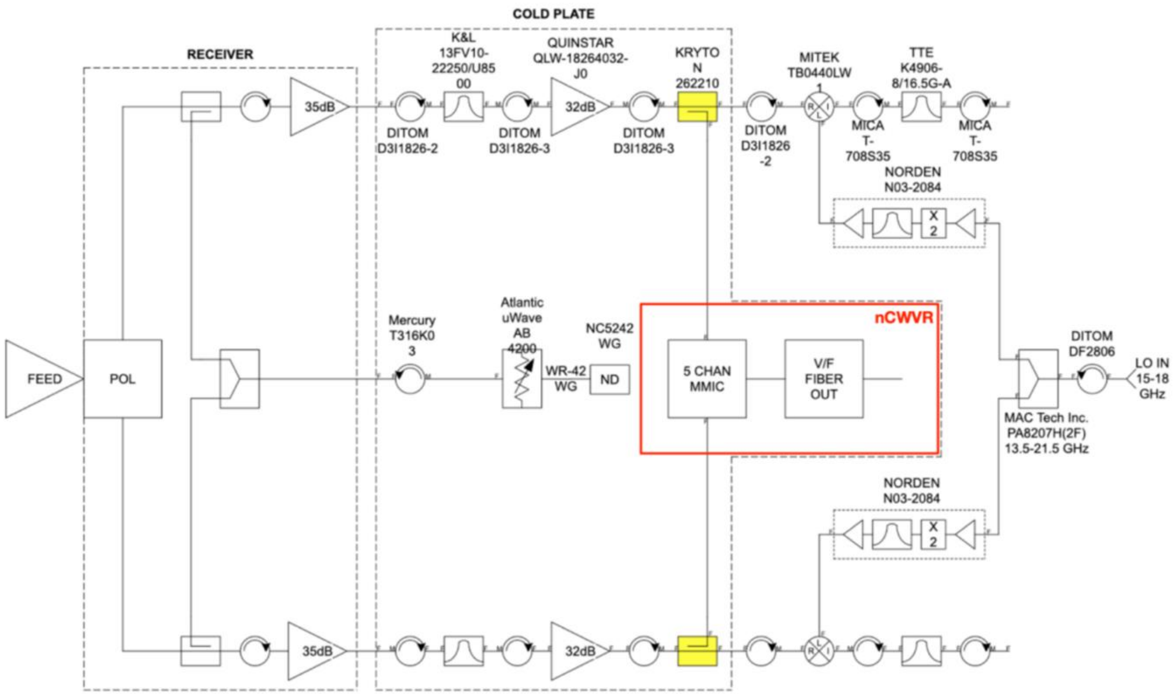
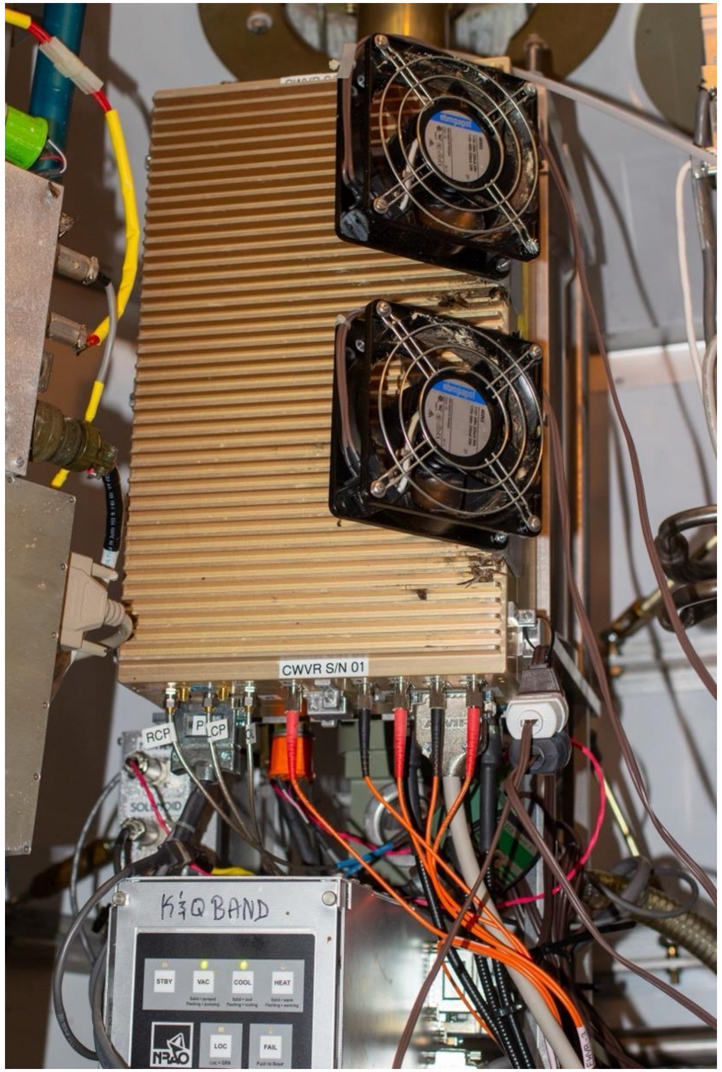


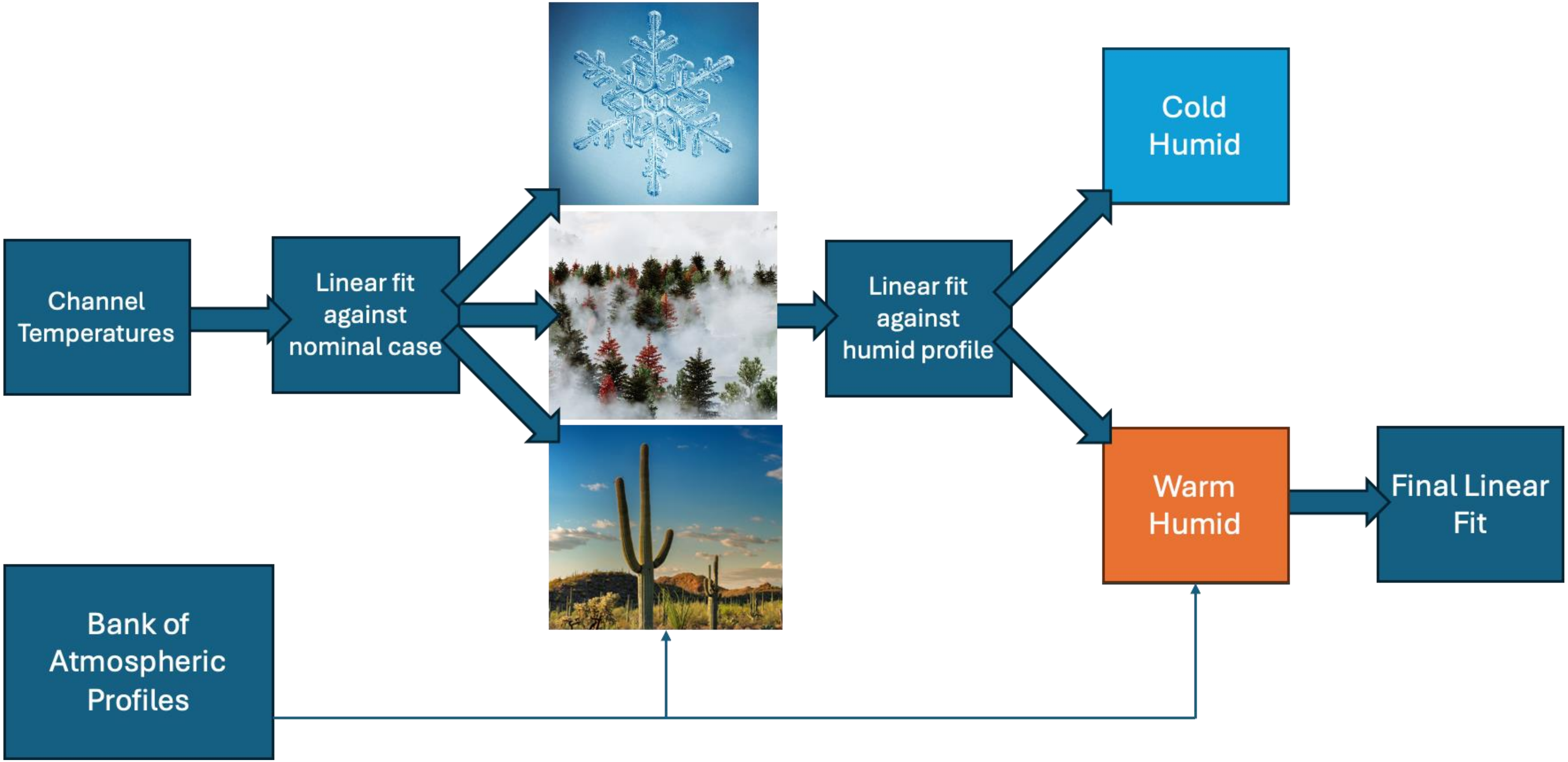
Fig 5. from NRAO Doc: 020.45.00.00.00-0002-DSN

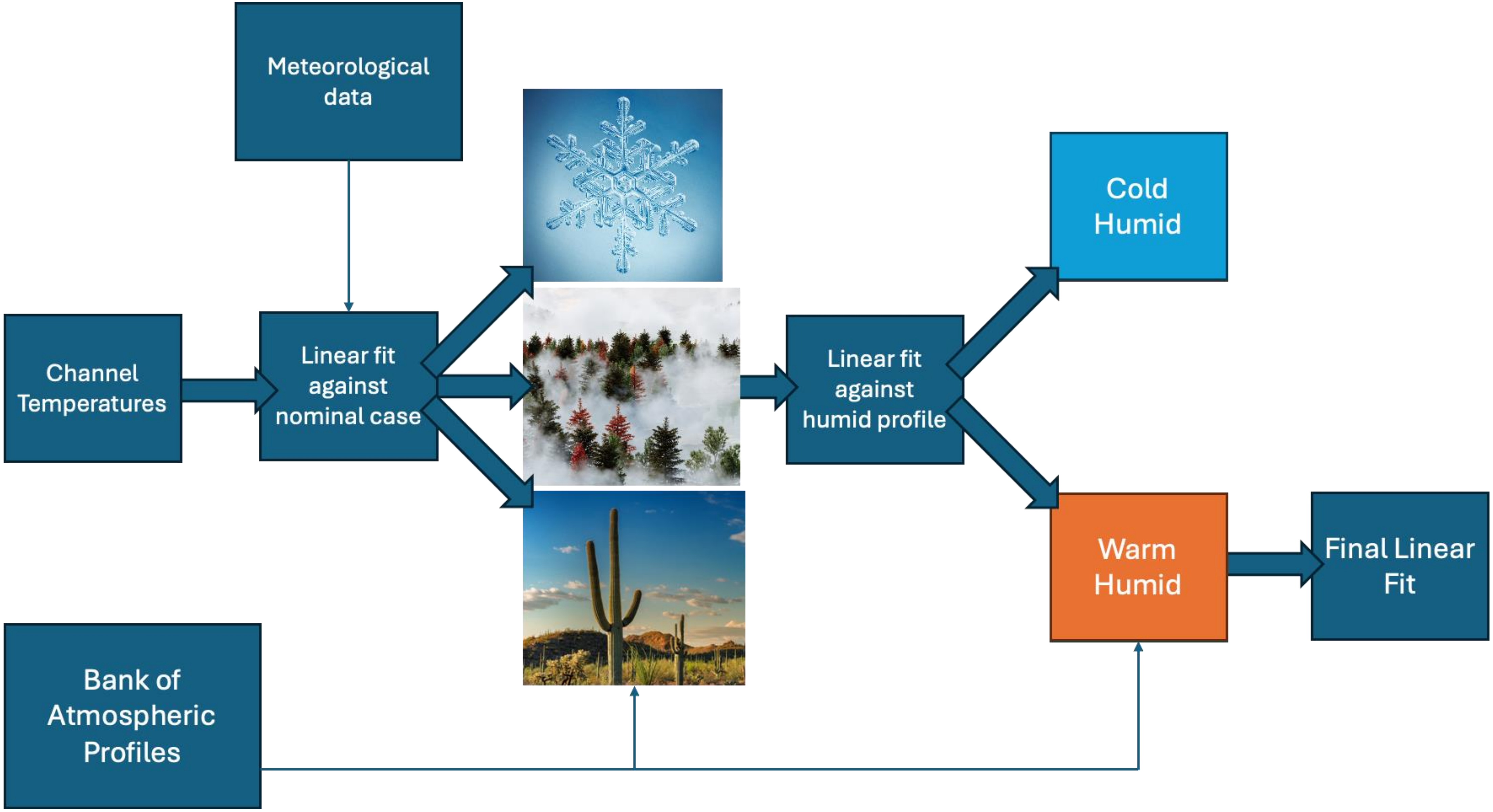
Current Hardware Work

- *VLA Water Vapor Radiometer*
  - *MMIC based, 5 channel*
- *Integrated into VLA k-band (~5 antennas)*
- *Recharacterization/calibration*






Channel Temperatures
Linear fit against nominal case
Linear fit against humid profile
Cold Humid
Warm Humid
Final Linear Fit
Bank of Atmospheric Profiles


Meteorological data
Channel Temperatures
Linear fit against nominal case
Linear fit against humid profile
Cold Humid
Warm Humid
Final Linear Fit
Bank of Atmospheric Profiles

Summary

- *ngVLA is a proposed large scale array based primarily in the Southwest*
  - *~1-100 GHz*

- *Variable water vapor in the troposphere will introduce delay error*

- *This error can be calibrated by measuring wet delay with water vapor radiometers*

- *We are currently developing analysis pipelines for WVRs at the VLA site and testing existing WVR hardware*

National Radio Astronomy Observatory

Summer Student Research Assistantships

Applications are now open for the 2025 summer student program at NRAO. The application deadline is February 1, 2025.

Please read the instructions before applying.

- **On-line Application Form**
- **Submit Reference Letter**

Reference letters may be submitted by faculty members or other contacts who feel qualified to recommend the student. Each application should include at least one reference letter, and as many as three may be submitted. We encourage those who are writing reference letters to submit by the Feb 1 deadline, but we will continue to accept reference letters after that date until all positions are filled.

Please direct questions to: sstudents at nrao dot edu.

Celebrating More Than Six Decades of Training Young Scientists

Since its inception in 1959, the NRAO Summer Research Assistantship program has engaged over 1,000 young people in scientific research, and many of our summer students have gone on to distinguished careers in astronomy, physics, and other sciences. The list of former NRAO summer students includes people who represent a wide range of careers, research interests, geographic locations, and backgrounds.

Thank you!

- Email: kmassing@nrao.edu
- Astro-Water Vapor: NRAO, Univ. of New Mexico, JPL, Univ. Nacional de Mexico, Univ. of Pretoria, etc.