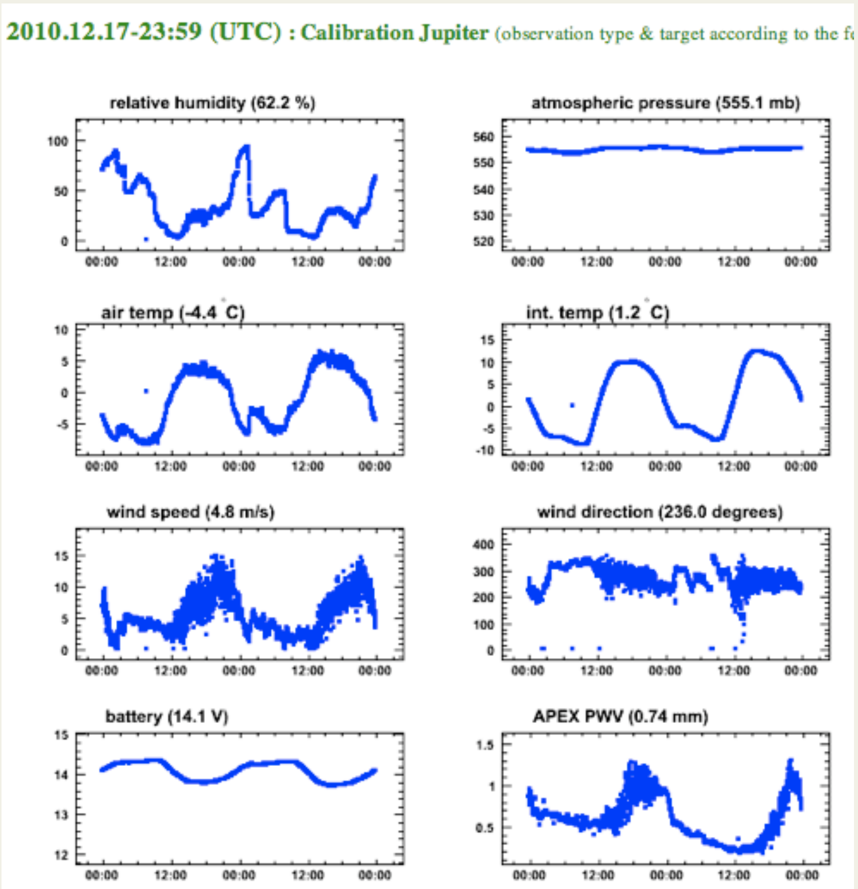
QUIET Season End Calibrations
December 9-23, 2010

Donna
05Feb2010

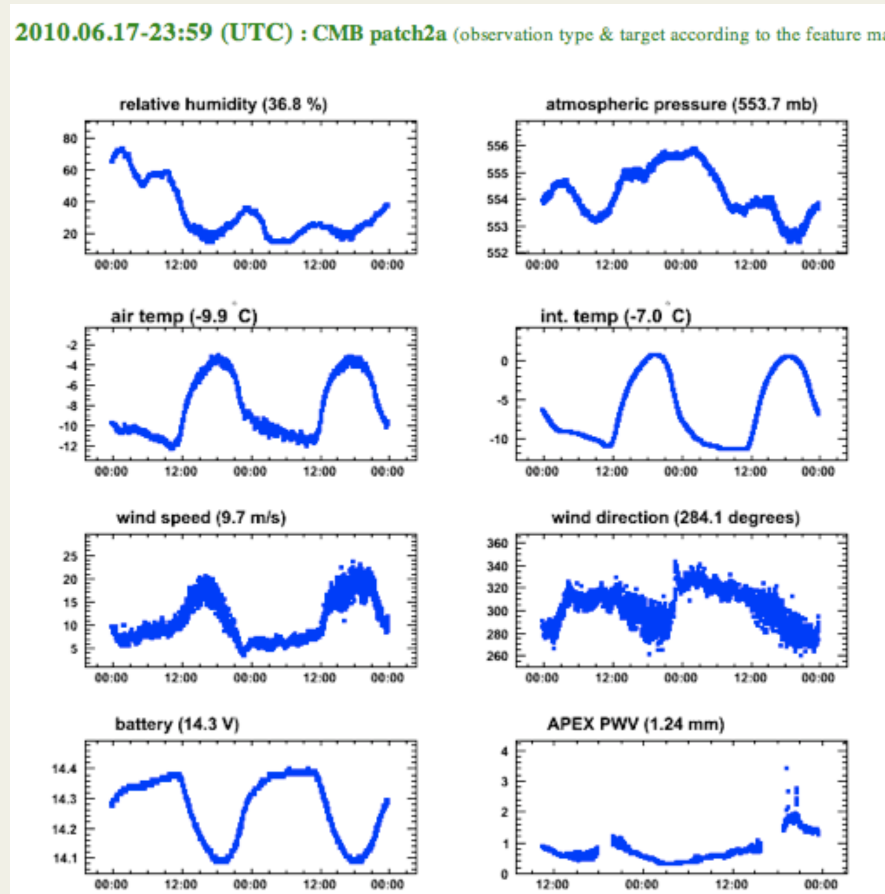
Chajnantor Plateau

- The Chajnantor Plateau is the site for many astronomical observatories
- It is located at an altitude of ~5100 meters in the Chilean Atacama desert, 50 kilometers to the east of San Pedro de Atacama
- It is a very dry site, somewhat inhospitable to humans, but an excellent site for millimeter and submillimeter astronomy.
- Water vapour absorbs an attenuates submillimetre radiation and thus a dry site is required for short-wavelength radio astronomy.

Weather



Summer (December)



Winter (June)

Chronology of telescopes on the Chajnantor Plateau

- 1994-present Atacama “pioneers” study observing conditions at the Chajnantor Plateau
- 1997-1998, Mobile Anisotropy Telescope on Cerro Toco (MAT/TOCO)
- 1999, Cosmic Background Imager (CBI)
- 2002, Atacama Submillimeter Telescope Experiment (ASTE) installed at Pampa La Bola
- 2003, Atacama Pathfinder Experiment (APEX)
- 2004, NANTEN2 Observatory (NANTEN2)
- 2007, Atacama Cosmology Telescope (ACT)
- 2008, Q/U Imaging ExperimenT, (QUIET)
- 2009, University of Tokyo Atacama Observatory (TAO)
- Under construction: Atacama Large Millimeter Array (ALMA)
  - The first antennas installed in 2009
- 2011, POLARBEAR
- 2017, Cornell Caltech Atacama Telescope (CCAT)

Red indicates CMB polarization experiment

Atacama pioneers*

- At millimeter and submillimeter wavelengths, the Earth's atmosphere presents a limitation to the sensitivity and resolution of astronomical observations.
- In 1994 May, Paul Vanden Bout and Bob Brown (NRAO), Riccardo Giovanelli (Cornell), and Geraldo Valladares visited San Pedro looking for suitable sites for the mmA.
- They drove up the (then dirt) highway to the Paso de Jama and made water vapor measurements with an IR solar absorption instrument.
- *From personal correspondence with Simon Radford

Atacama pioneers*

- Simon Radford first visited the Chajnantor plateau in 1994 November with Peter Napier and Fraser Owen (both NRAO), and Angel Otarola (then ESO, now TMT).

- They made measurements of the atmospheric optical depth at 225 GHz from a location a couple km north of where APEX is now.

- *From personal correspondence with Simon Radford

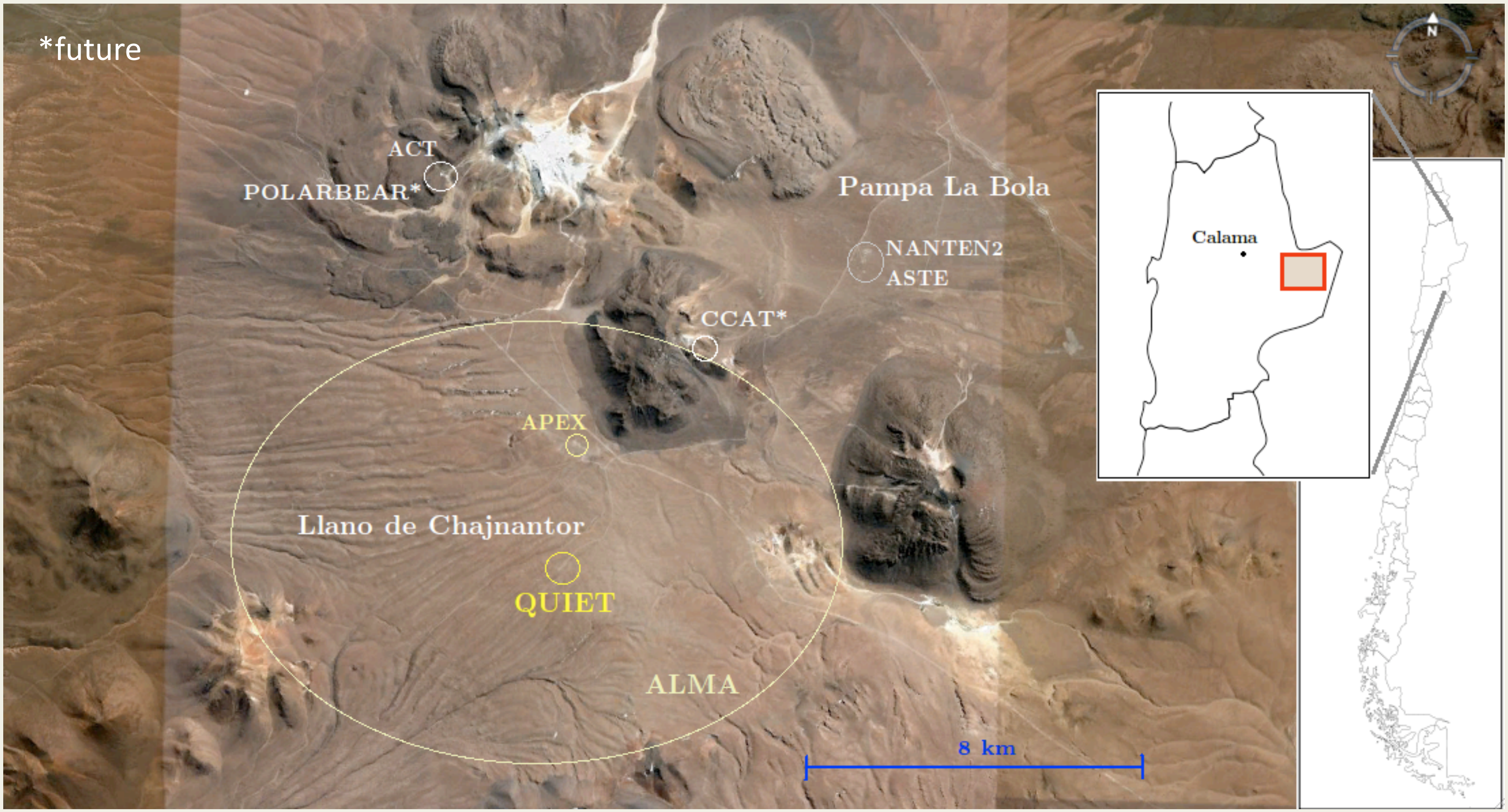
APEX

Atacama pioneers*

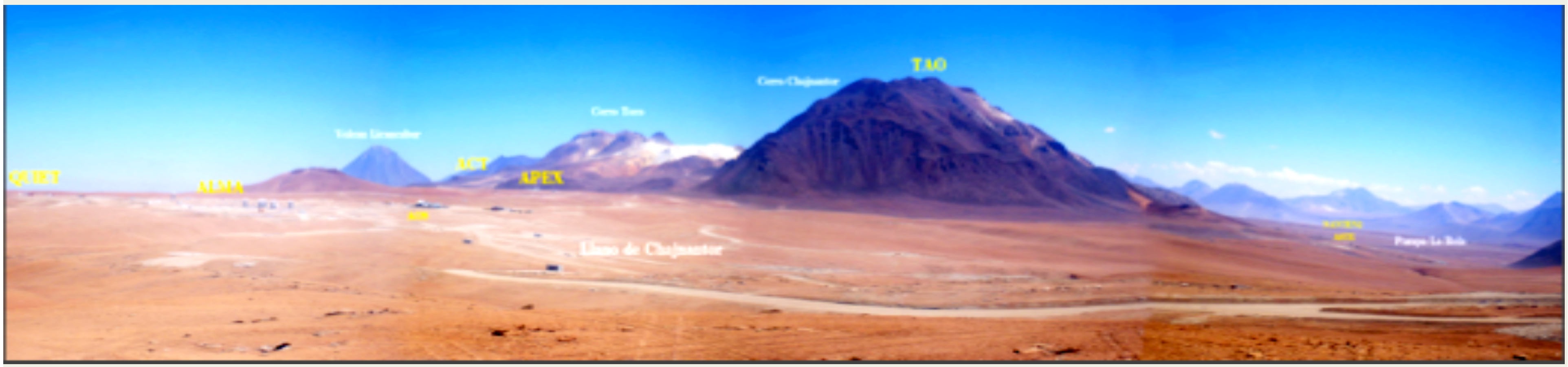
- In 1995 April, they (NRAO) set up a container with solar panels and started monitoring the 225 GHz optical depth and the atmospheric phase stability.
- Those measurements continued until 2005 (225 GHz) and 2008 (phase stability).
- They were joined by NAOJ on Pampa la Bola in ~1996 and by ESO in 1998.
- *From personal correspondence with Simon Radford

Site testing instruments and containers at the 4800 m site of Pampa la Bola, Region II, Chile. Two containers equipped with solar panels and one of the element antennas of the radio seeing monitor can be seen in the background. Three weather stations under cross calibration are seen in the foreground. Credit: NAOJ

Telescopes in the Atacama Desert



Thank you to Felipe Bustos for this image and for many other images used in this presentation.


QUIET
ALMA
ACT
APEX
TAO
Llano de Chajnantor

Telescopes in the Atacama Desert

- Telescopes on the Llano de Chajnantor site
  - Cosmic Background Imager (CBI)
  - Atacama Pathfinder Experiment (APEX) 12-meter at 5105 meters
  - Atacama Large Millimeter Array (ALMA) 54 12-meter & 12 7-meter at ~5000 meters
  - Q/U Imaging ExperimenT (QUIET) 1.4 meter at 5080 meters

- Telescopes on the adjacent Pampa La Bola site
  - Atacama Submillimeter Telescope Experiment (ASTE) 10-meter at 4865 meters
  - NANTEN2 Observatory (NANTEN2) 4-meter at 4865 meters

- Telescopes on Cerro Toco
  - Mobile Anisotropy Telescope on Cerro TOCO (MAT/TOCO)
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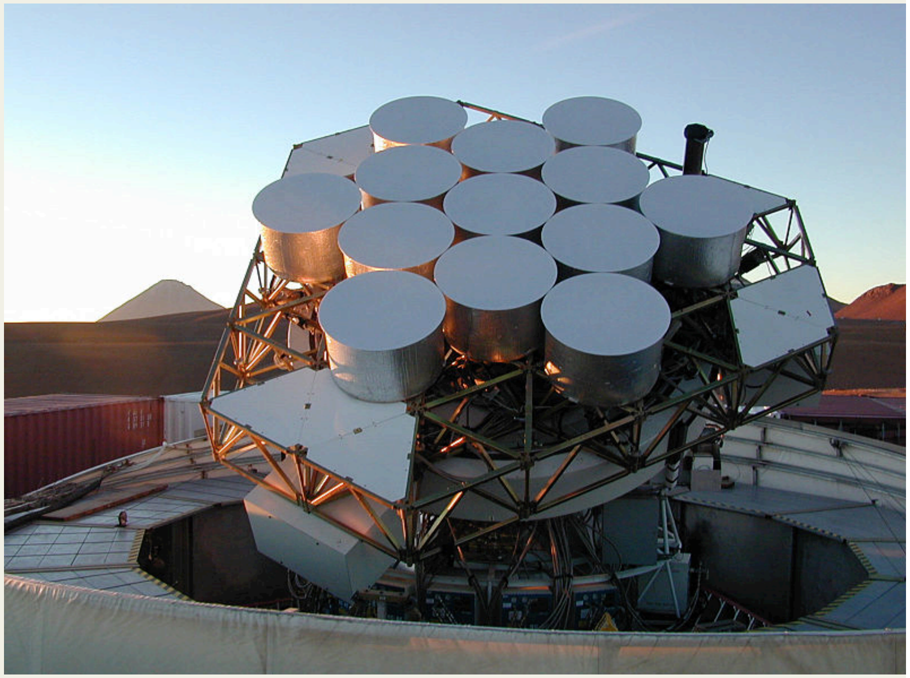
CBI

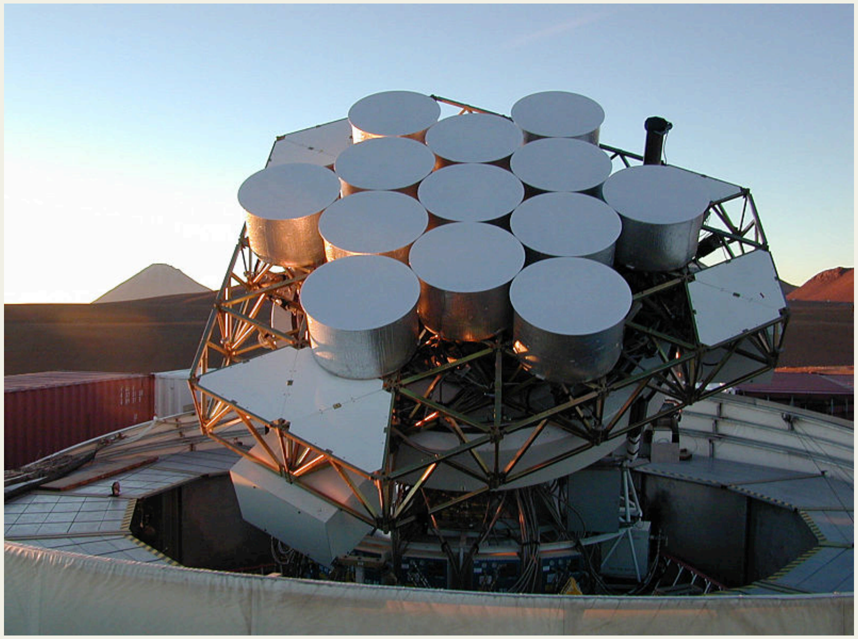
- Operated 1999-2008
  - QUIET moved to the CBI site in 2008 and uses CBI mount
- 13-element interferometer
- Conducted measurements at frequencies between 26 and 36 GHz in ten bands of 1 GHz bandwidth.
- It had a resolution of better than 1/10 of a degree.
- CBI was the first experiment to detect intrinsic anisotropy in the microwave background on mass scales of galaxy clusters
- Detailed E-mode spectrum



CBI

QUIET

- QUIET is at the site CBI was at and uses CBI's mount



CBI

QUIET uses CBI's mount

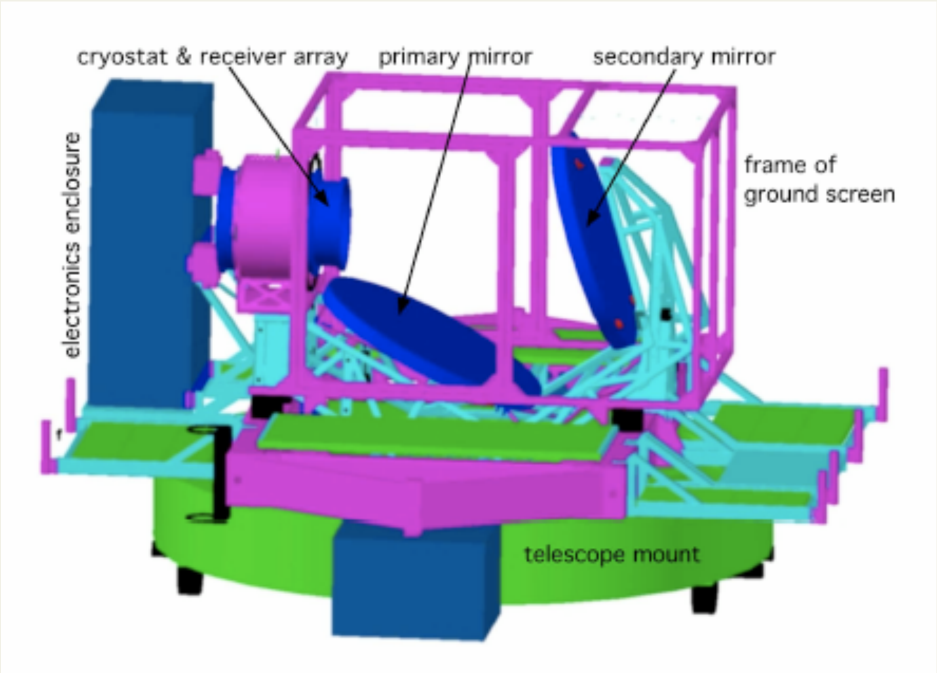
QUIET control room

QUIET site

Inside the QUIET control room

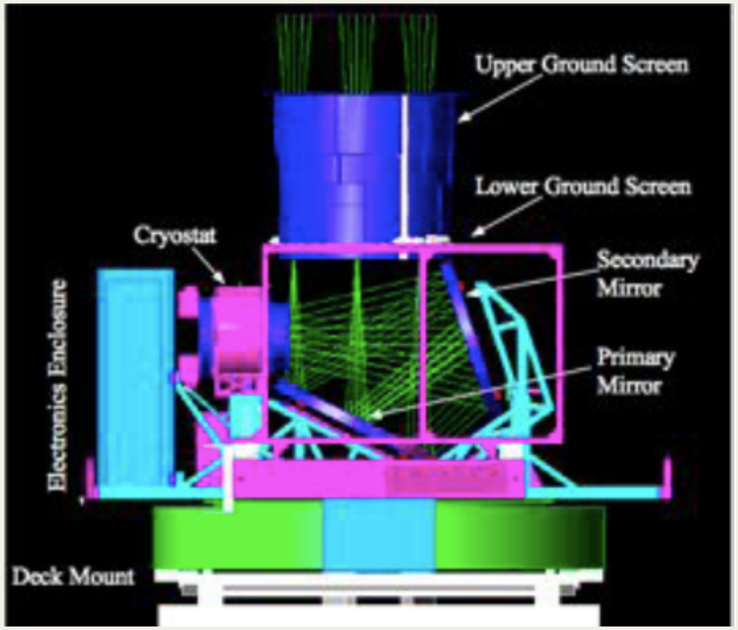
QUIET

- QUIET uses a 1.4-meter crossed Mizuguchi-Dragone (MD) dual reflective telescope
- An co-moving ground screen prevents radiation from the ground from entering the receivers



Mitsuguchi-Dragone optics

- MD optics
  - Are compact
  - Provide low cross polarization
  - Provide large diffraction-limited field of view



APEX

- The Atacama Pathfinder Experiment is a modified ALMA prototype antenna and is located at the future site of the ALMA observatory.
- It is designed to work at sub-millimetre wavelengths, in the 0.2 to 1.5 mm range.
- The main dish has a diameter of 12 meters (like the ALMA dishes)
- Uses both bolometer-based and heterodyne instrumentation

APEX

APEX and QUIET

ALMA

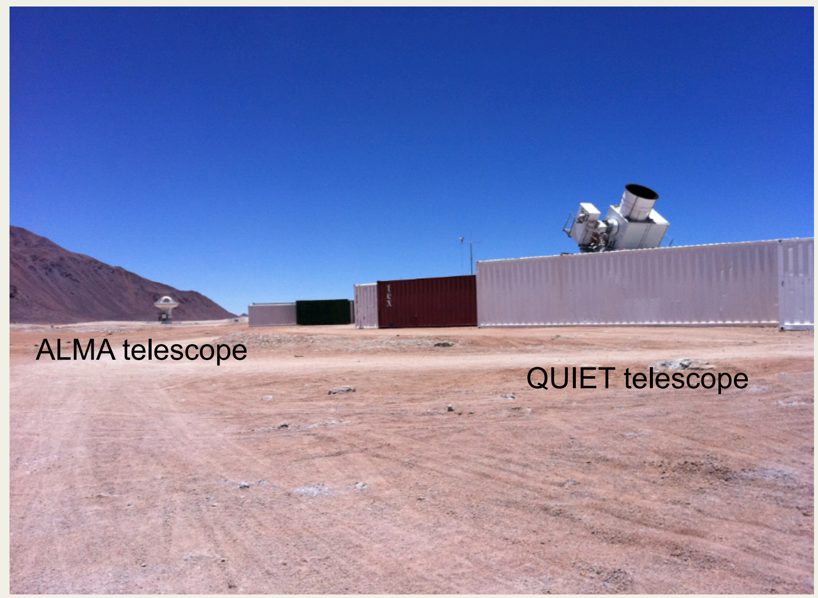
- When ALMA is fully operational a couple of years from now, it will be comprised of 66 antennas
  - 54 12-meter dishes
  - 12 7-meter dishes
- Array configurations will have baselines from approximately 150 meters to 15 km

ALMA today (plus one more – see next slide)

ALMA antenna being moved to location near QUIET

- We saw an ALMA antenna being driven up to the site on the transporter.
- It was located apart from the array, quite near to QUIET.

ALMA telescope on transporter



ALMA

- ALMA will combine the signals from its array of antennas as an interferometer
- Using the antenna transporters, astronomers will be able to reposition the antennas according to the kind of observations needed.
- So, unlike a telescope that is constructed and remains in one place, the antennas are robust enough to be picked up and moved between concrete foundation pads without this affecting their precision engineering.

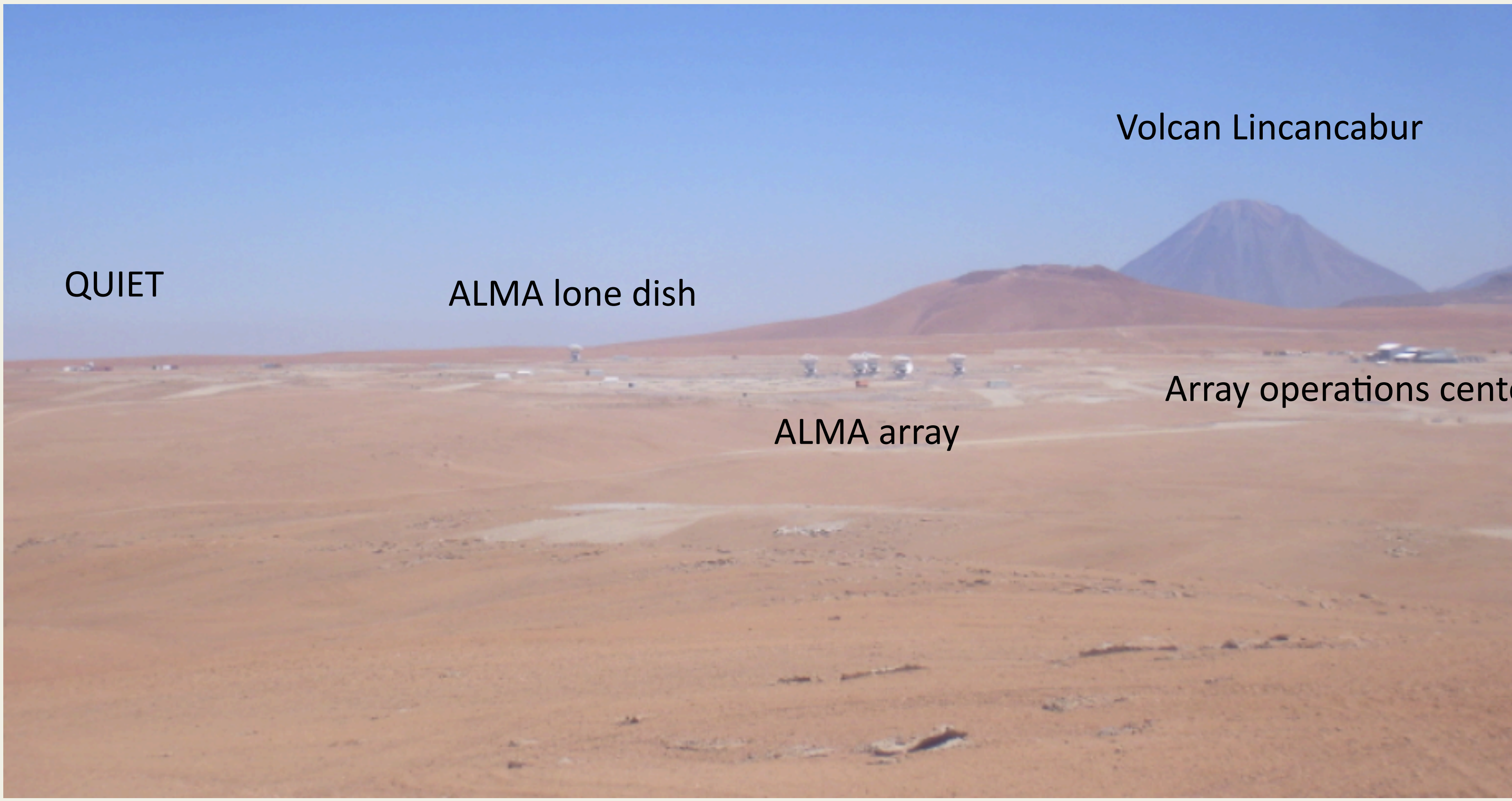
ALMA today (plus one more)

ALMA

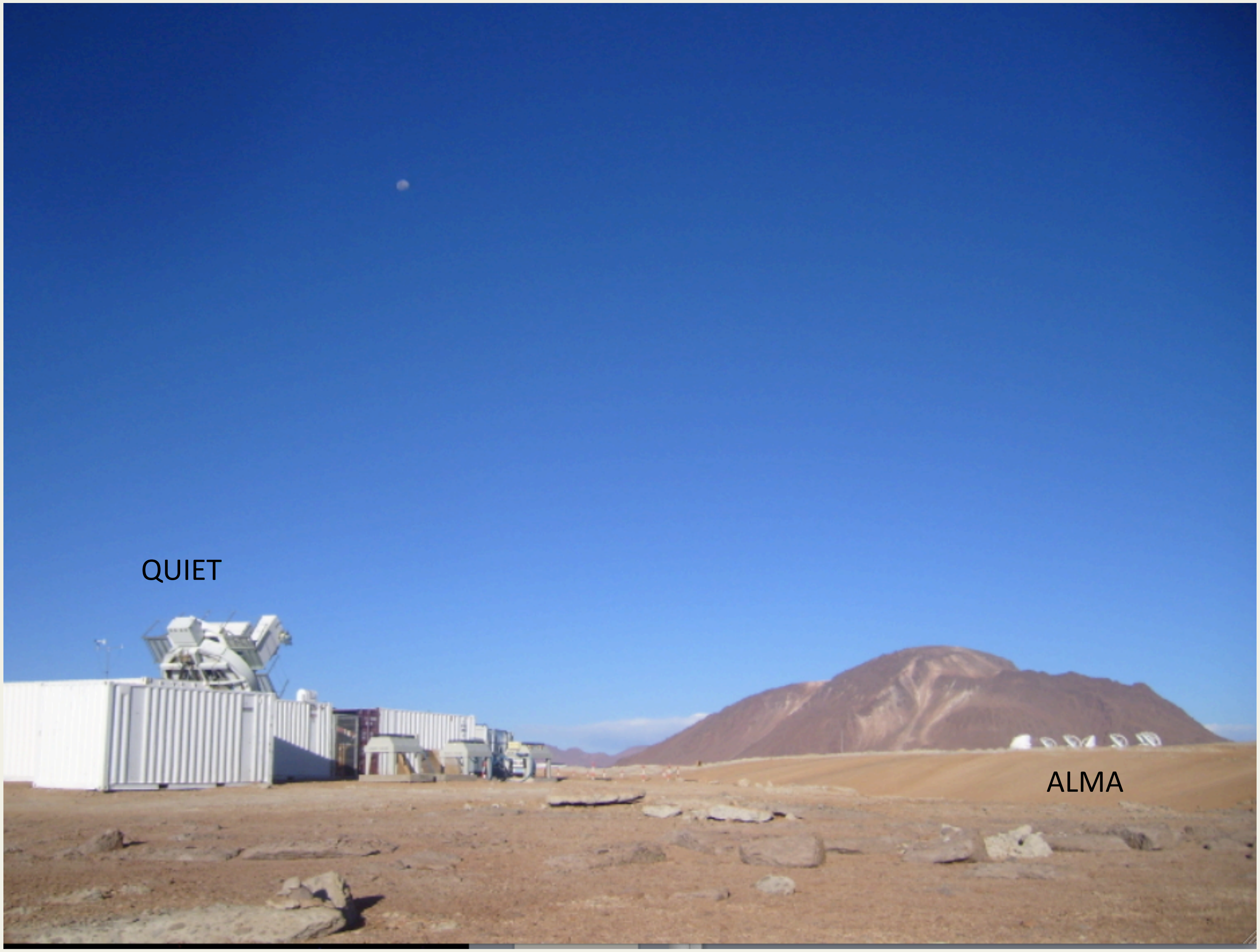
- ALMA will be the forefront instrument for studying the cool universe: the CMB and the molecular gas and dust that constitute the very building blocks of stars, planetary systems, galaxies, and life itself.
- This material typically resides at temperatures of 3-100 K, resulting in spectral energy distributions peaking at submillimeter through to far-infrared wavelengths.

ALMA today (plus one more)

ALMA is close to QUIET



ALMA is close to QUIET



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ASTE

- The Atacama Submillimeter Telescope Experiment is a 10 m submillimeter telescope

- The purposes of the project are to explore the southern sky with submillimeter waves up to 900 GHz, as well as development and on-site evaluation of observation techniques and methods for submillimeter observations.

- Led by NAOJ

ASTE

NANTEN2

- NANTEN is Japanese for “southern sky”
- NANTEN was first at Las Campanas
- In 2004 moved to Pampa La Bola
- The telescope is a 4 m Cassegrain
- NANTEN2 is equipped with coherent receivers covering frequencies from 110 to 345 GHz, 460-490 GHz, and 809-880 GHz.

NANTEN2 (left) ASTE (right)

NANTEN2 (left) ASTE (right)

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MAT/TOCO

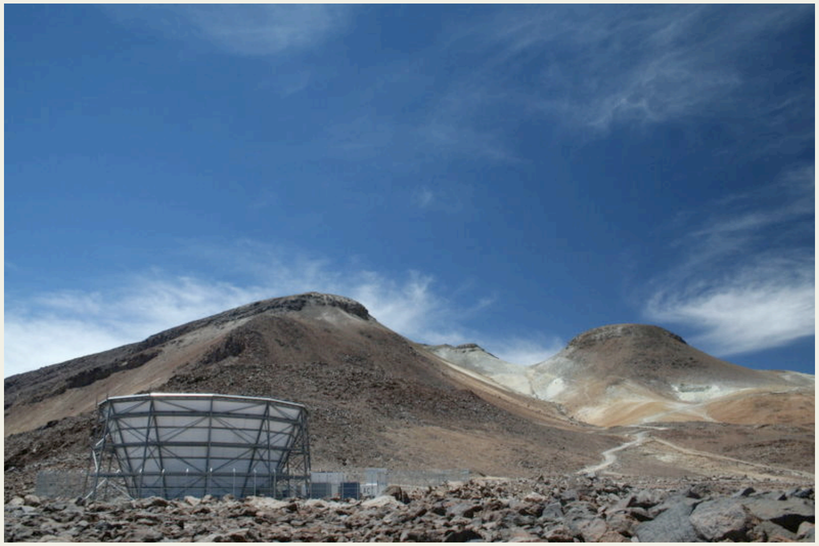
- MAT/TOCO was the first experiment to localize the position of the first acoustical peak in the CMB.

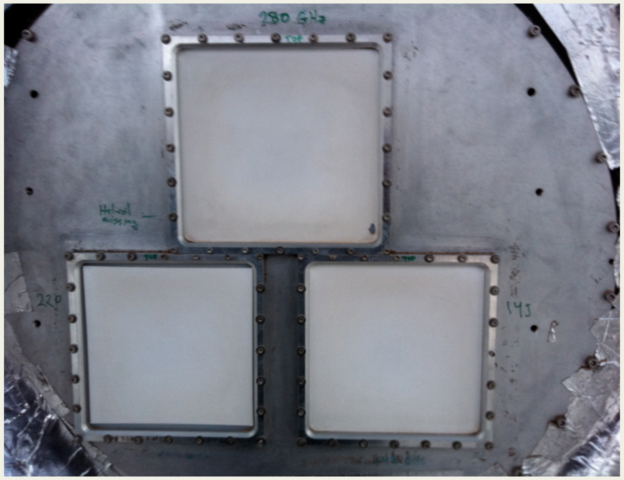
- It was comprised of five cooled corrugated feeds that under-illuminated a fixed off-axis parabolic mirror of 0.85m diameter.

- TOCO used the QMAP gondola (QMAP was a balloon-based CMB experiment).

ACT

- The Atacama Cosmology Telescope (ACT) is a six-meter telescope on Cerro Toco.
- ACT is looking for SZ clusters at 145 GHz, 215 GHz, and 280 GHz
- Uses TES bolometers

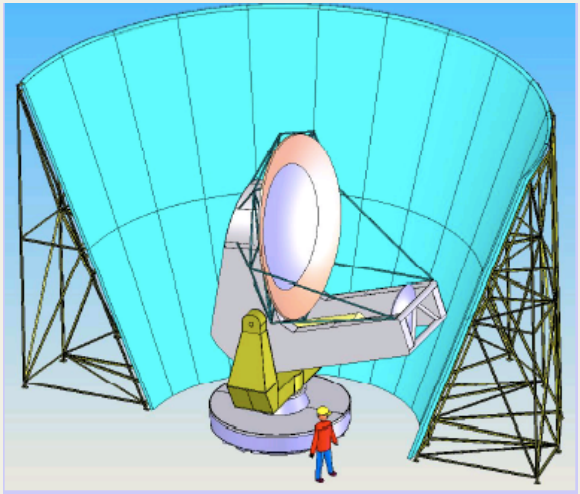




POLARBEAR

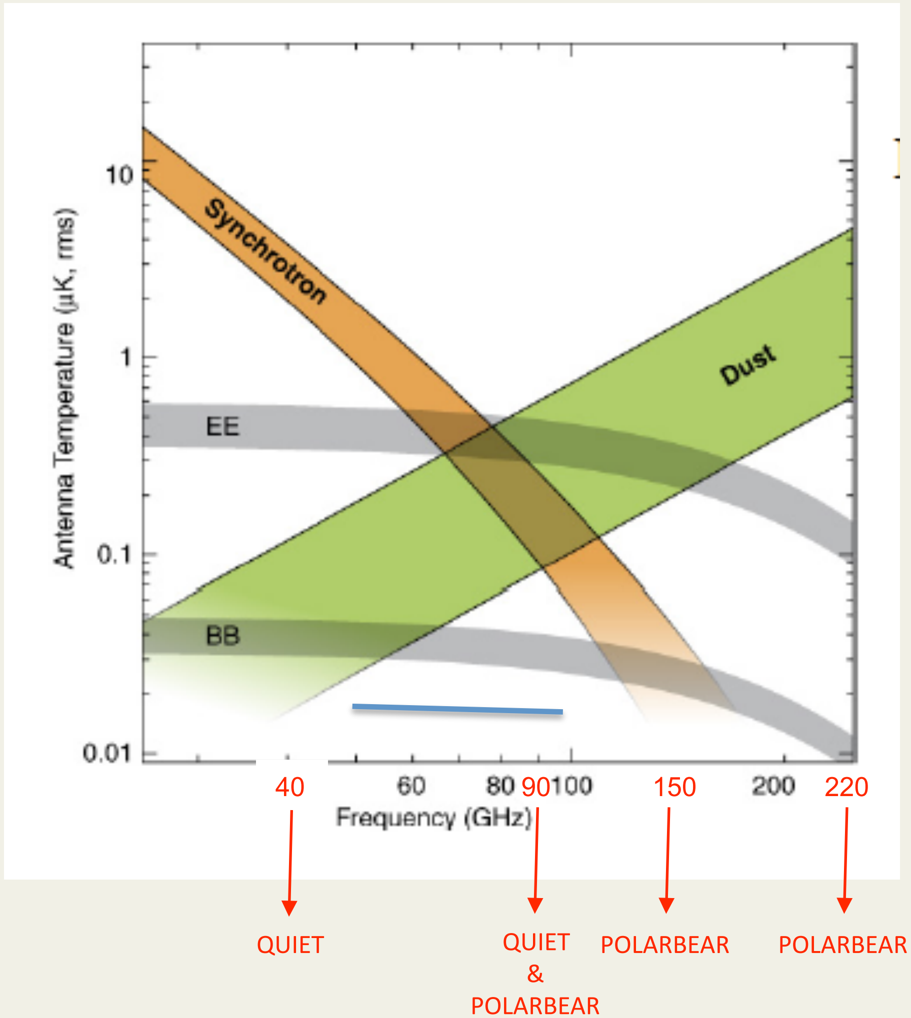
- POLARBEAR is a 3.5-meter off-axis Gregorian telescope that will be sited on Cerro Toco near ACT.
- POLARBEAR has been designed specifically to search for the B mode signal from both gravitational waves and from gravitational lensing.
- The focal plane houses ~1000 polarization sensitive antenna-coupled TES detectors read out with the Digital Frequency Domain Multiplexer.

POLARBEAR at Cedar Flat, CA. CARMA in background.
Now waiting in Antofagasta, Chile to be installed on Cerro Toco



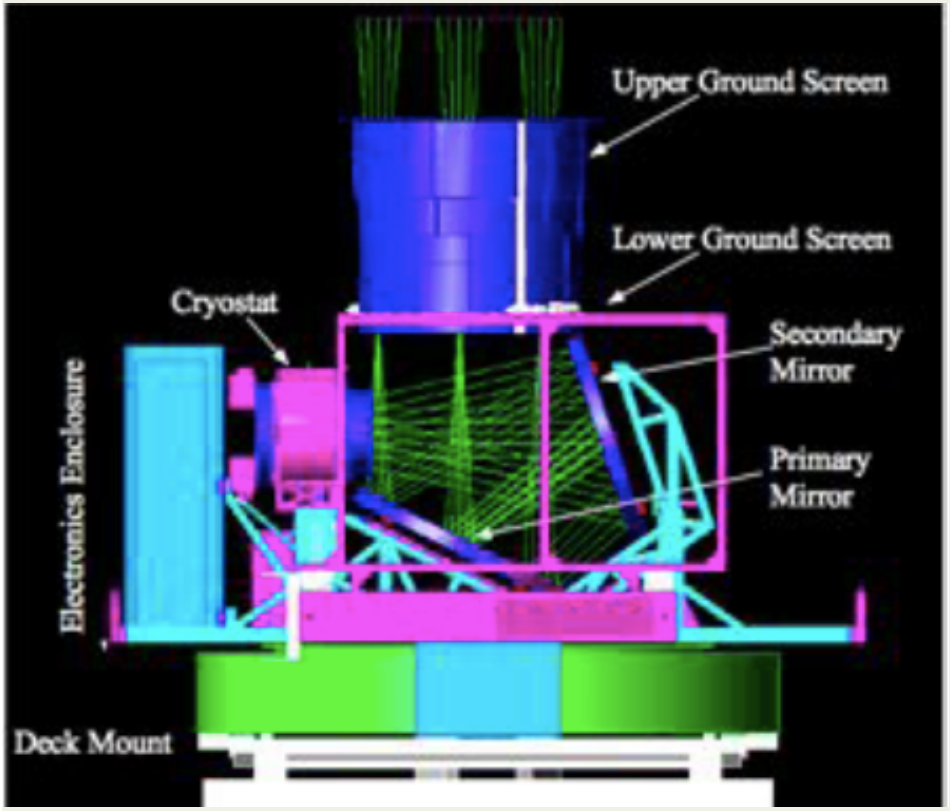
POLARBEAR

- POLARBEAR and QUIET will observe the same sky patches.
- Together they will have frequency bands at 40, 90, 150, and 220 GHz giving broad coverage of galactic foregrounds and a valuable cross-check by comparison of polarization maps.
- QUIET (40 and 90 GHz)
- POLARBEAR (90, 150 and 220 GHz)

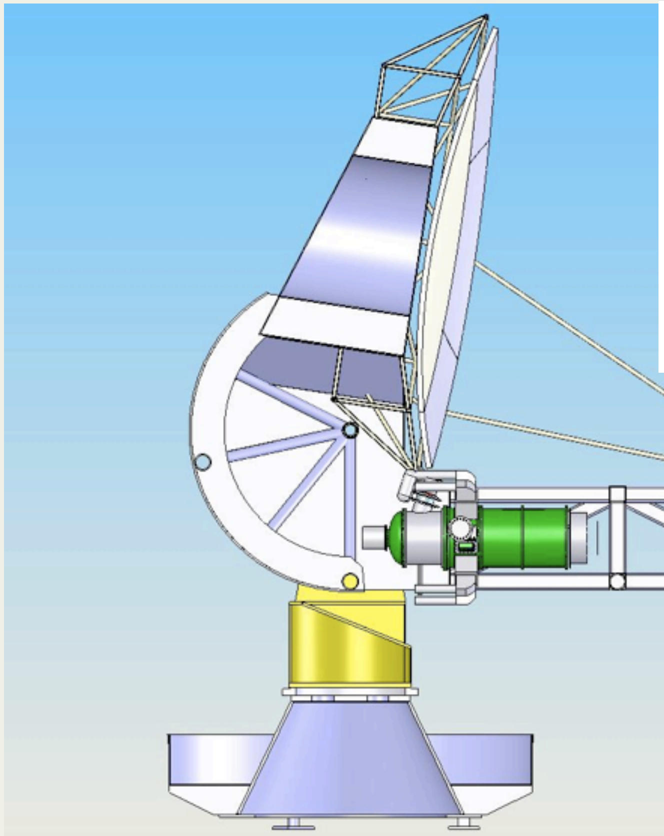


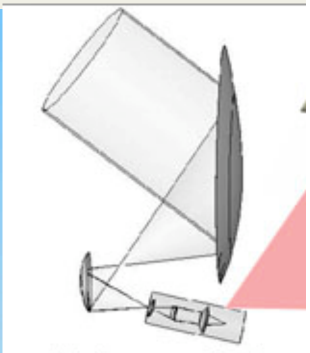
Compare POLARBEAR and QUIET optics

Both are offset dual-reflector antennas



QUIET
Crossed Mizuguchi-Dragone





POLAREAR
Gregorian Mizuguchi-Dragone

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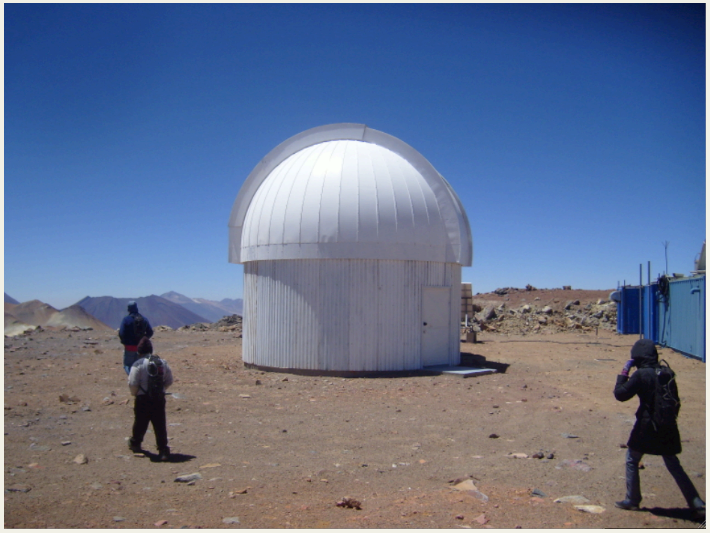
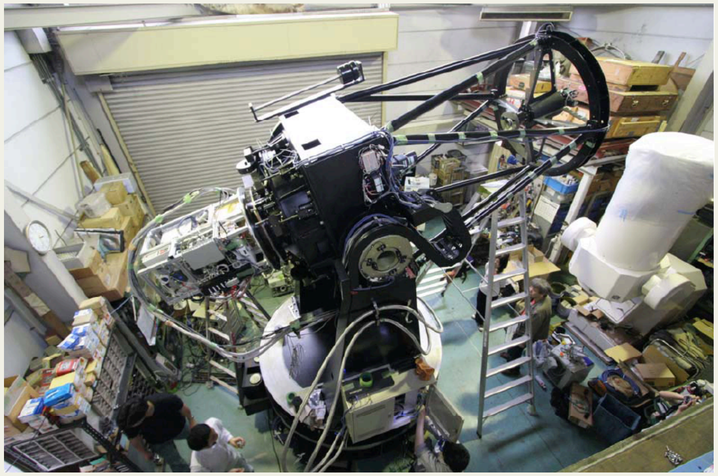
TAO

- MiniTAO, at 5640 meters at the summit of Cerro Chajnantor, is the highest telescope in the world.
- MiniTAO is a 1-meter telescope.
- The mid-IR camera on miniTao can access the 30-micron wavelength region from the ground for the first time.
- TAO, a 6.5-meter telescope, is planned for the future
- At summit, it's cold and windy (note we all have our O_2 on our backs).





miniTAO

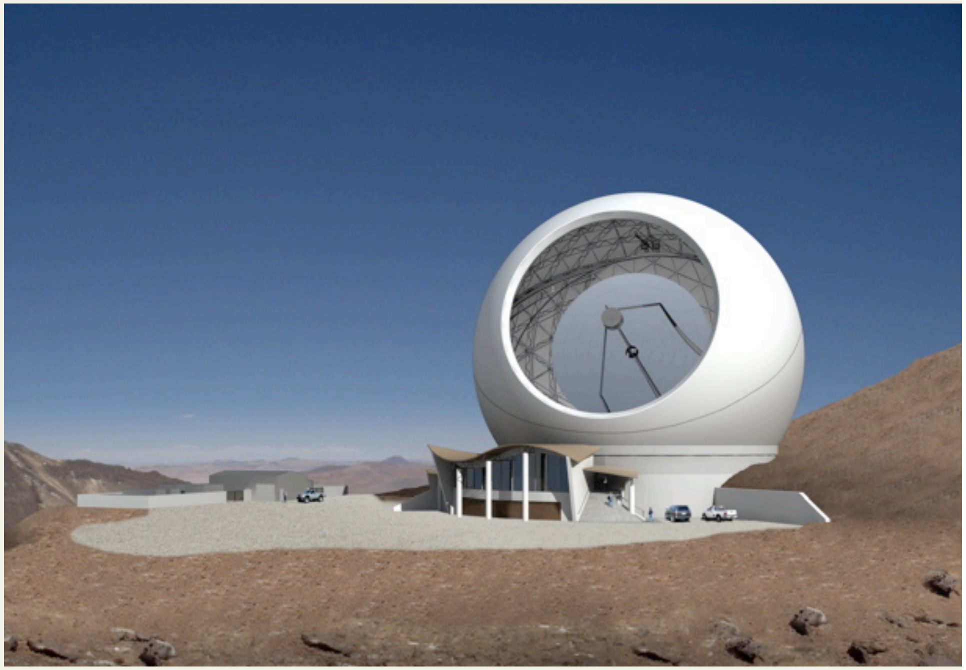
TAO

Chile issued a postage stamp commemorating the inauguration of mini TAO

CCAT

- CCAT will be a 25 meter telescope for submillimeter astronomy located at 5600 m altitude on Cerro Chajnantor in northern Chile.

- CCAT was ranked the highest priority among medium scale, ground based projects by the Astro2010 survey.

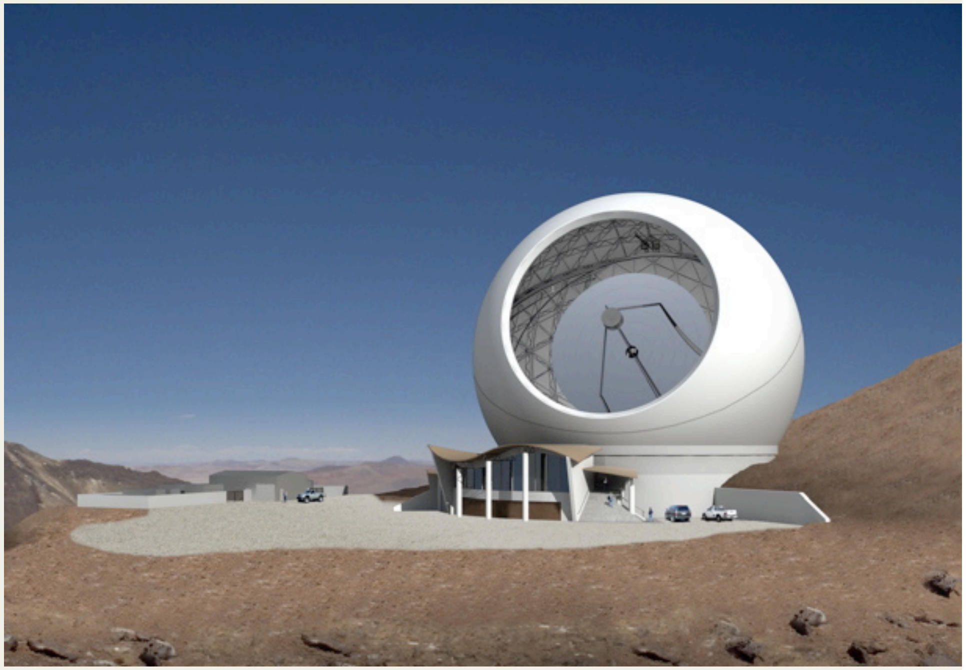


Artist's conception of CCAT

CCAT

- Science objectives include galaxy formation and evolution throughout the history of the Universe; the hot gas pervading clusters of galaxies; star formation, protoplanetary disks, and debris disks in the Milky Way galaxy; and Kuiper belt objects in the outer reaches of the Solar system.

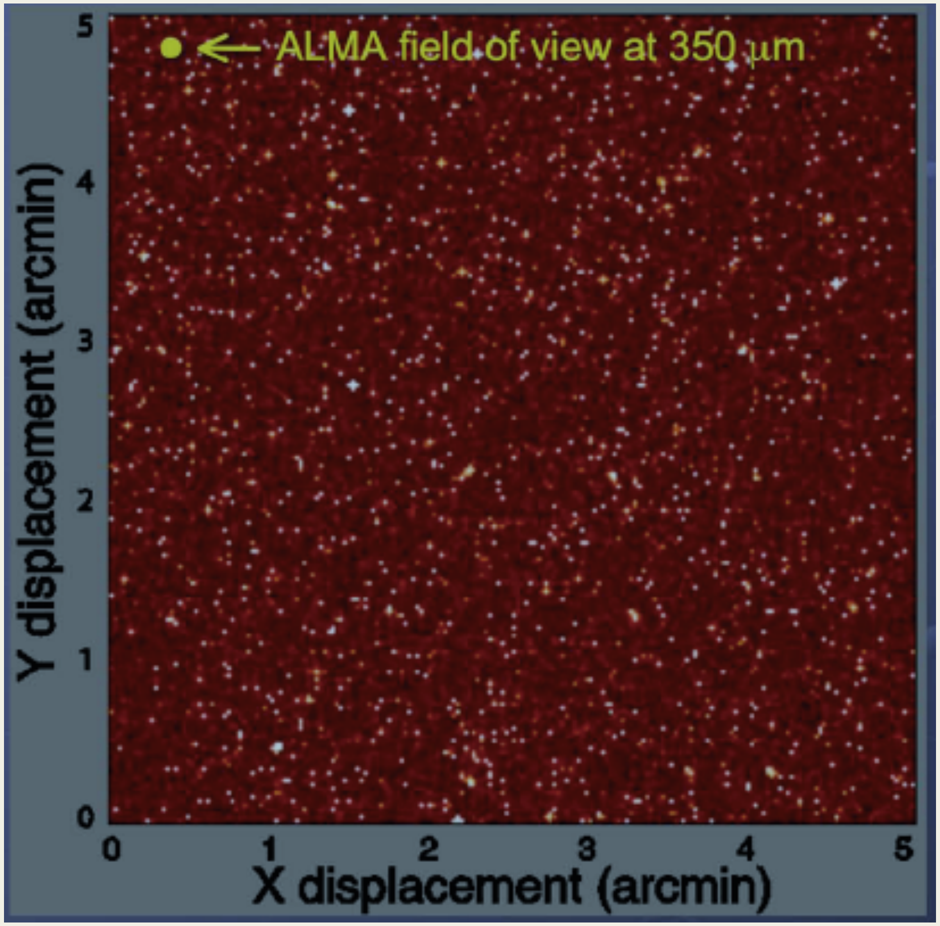
- Instrumentation will include bolometer cameras, direct detection spectrometers, and heterodyne receiver arrays.



Artist's conception of CCAT

CCAT

- Complementary to ALMA
- Detectors designs include MKIDs (Microwave Kinetic Inductance Detectors)



CCAT SITE

- To evaluate environmental and observing conditions at the CCAT site, a submillimeter tipper, a weather station, and other instruments were deployed there in 2006 May.

- We added another solar panel when I was there.

- The tipping radiometer measures the atmospheric transparency in the continuum at 350 um and 200 um.

- Estimating the transparency at other wavelengths requires a model, such as ATM.

Beautiful, but scary, drive up to CCAT site & TAO

Camaraderie

- Not only is it simply interesting to know that there are more and more telescopes at Chajnantor, it is also nice to know there is a strong camaraderie among projects.

- Just in the 2 weeks I was there, I saw at least 4 examples

    - QUIET used one of ALMA's truck cranes to remove the upper ground screen,
    - QUIET helped both ACT and APEX move a radiometer to their sites
    - QUIET routinely accesses APEX weather information

Removing QUIET's upper ground screen with an ALMA crane

Water-vapor measurement

- The line radiometers we delivered to ACT and APEX are different form the measurement made by the tipping radiometer.
- These measure the strength of the 183 GHz water vapor absorption line to determine the amount of precipitable water vapor.
- Then the transparency in the windows can be estimated with a spectral model, such as ATM.

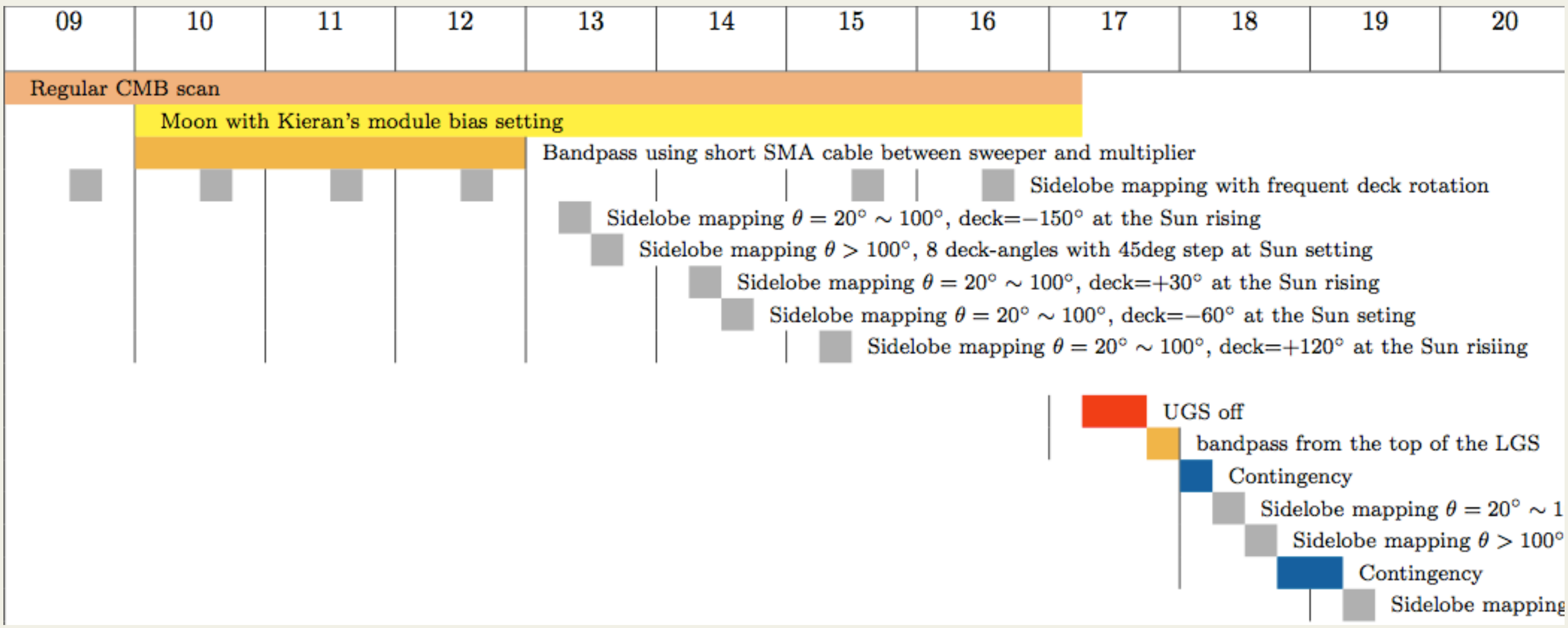
Removing QUIET's upper ground screen with an ALMA crane

Final 2 weeks of QUIET

End of season calibrations

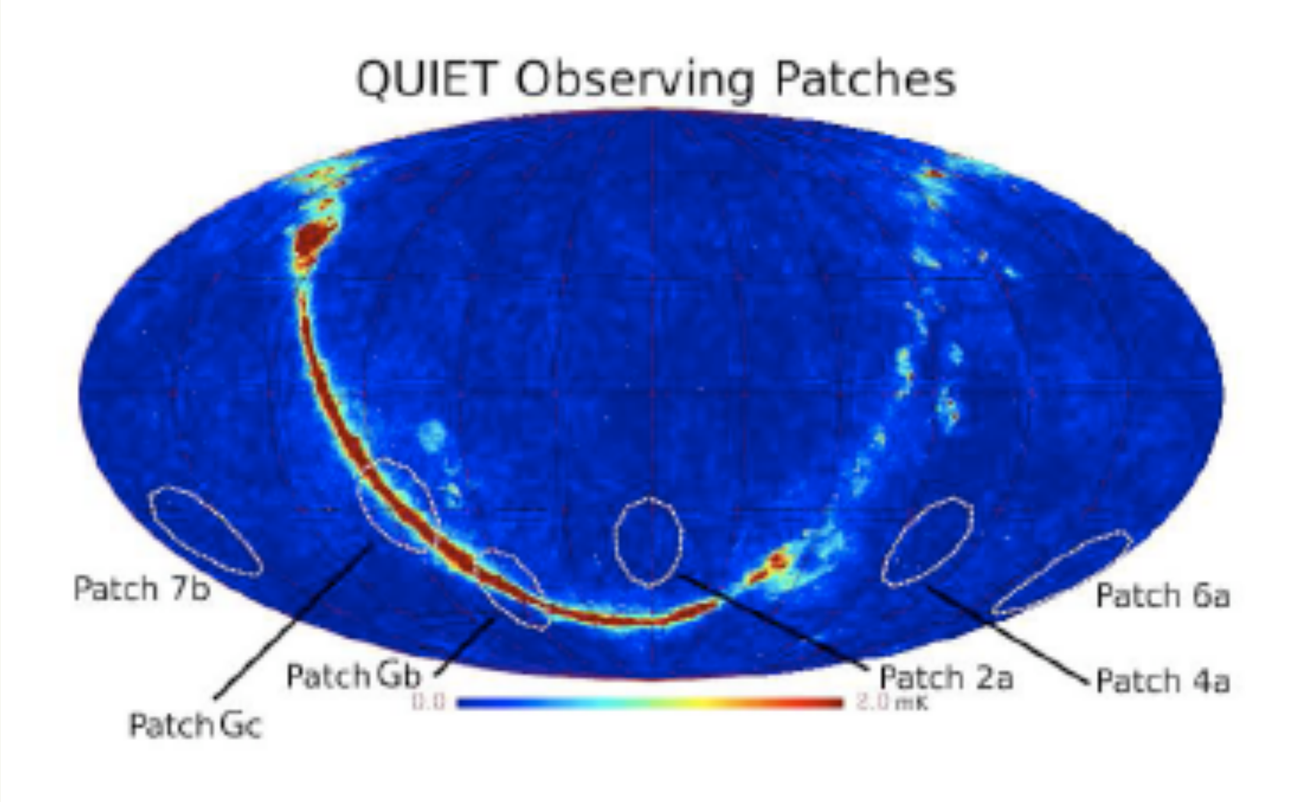
Dec 9-18

1. Finished up some regular CMB scans
2. Bandpass measurements
3. Sidelobe mapping with sun



1. Finish up CMB scans

- Goal: Finish up CMB scans



2. Measure bandpass of the receivers

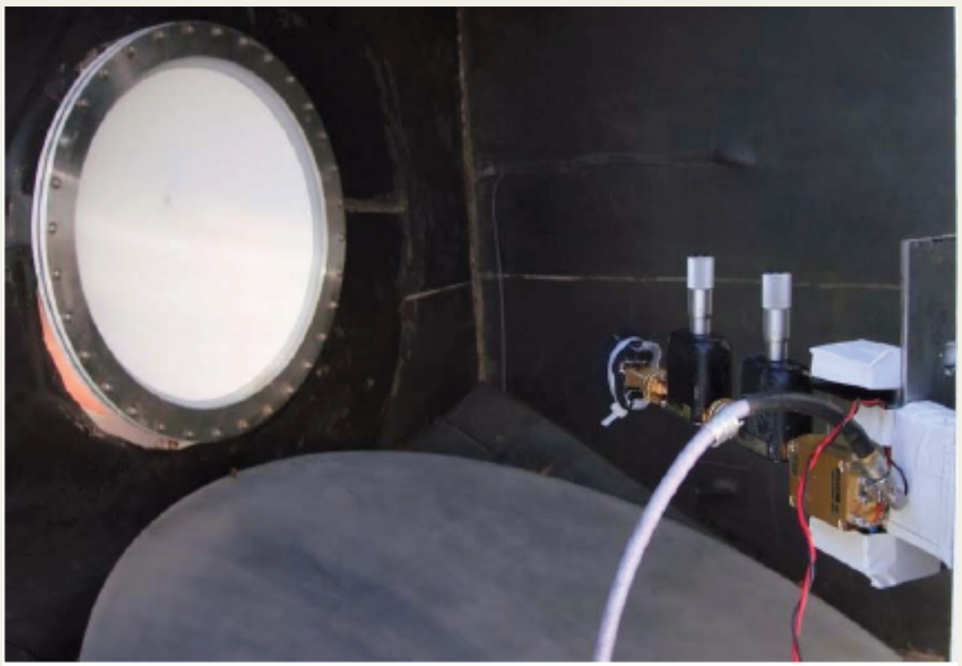
- Goal: Shine horn fed by swept oscillator onto receiver array to measure bandpass

Open this panel to get access to front of receiver

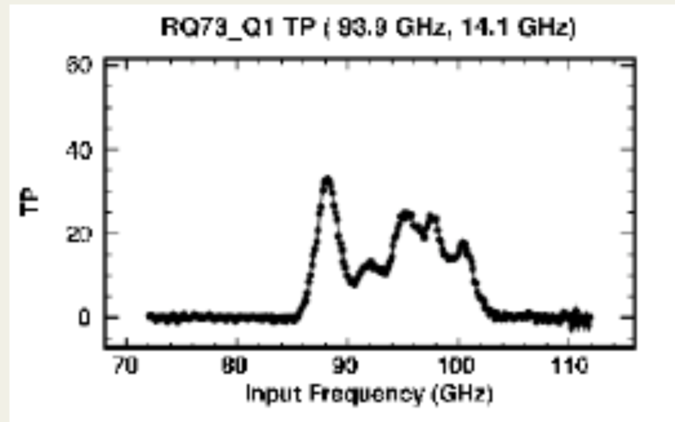
Bring oscillator, power supplies, horn, etc. up to the telescope via red ladder

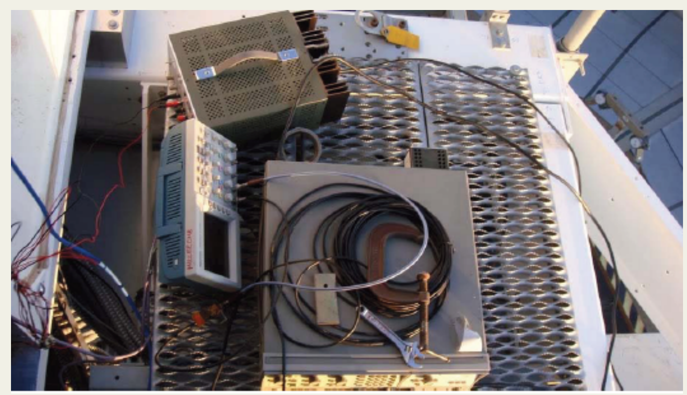
2. Measure bandpass of the receivers

- Goal: Shine horn fed by swept oscillator, multiplier, attenautor onto receiver array to measure bandpass
- Repeated after removing upper ground screen, IIlluminating primary mirror instead of directly illuminating cryostat.



Attach horn so that it is illuminating the array.
Repeat with horn rotated at different angles.





Instruments & cables used to power the horn.

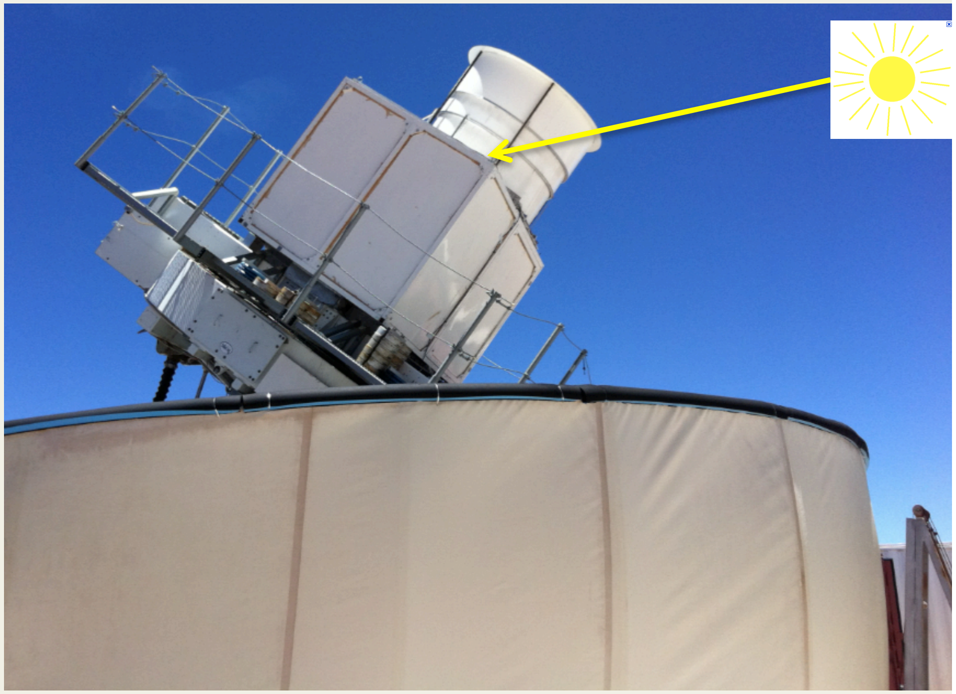
3. Measure sidelobes

- Goal: Use the Sun (a strong source) to probe sidelobes

- A small fraction of the detector response spills past the telescope mirrors to create sidelobe response at large angles from the main beams.

- Depending on their orientation, the sidelobes could terminate on the sky (T=~10 K or the ground (T=~270 K).

- For QUET, which only measures anisotropies, the magnitude of this contribution is less important then its stability



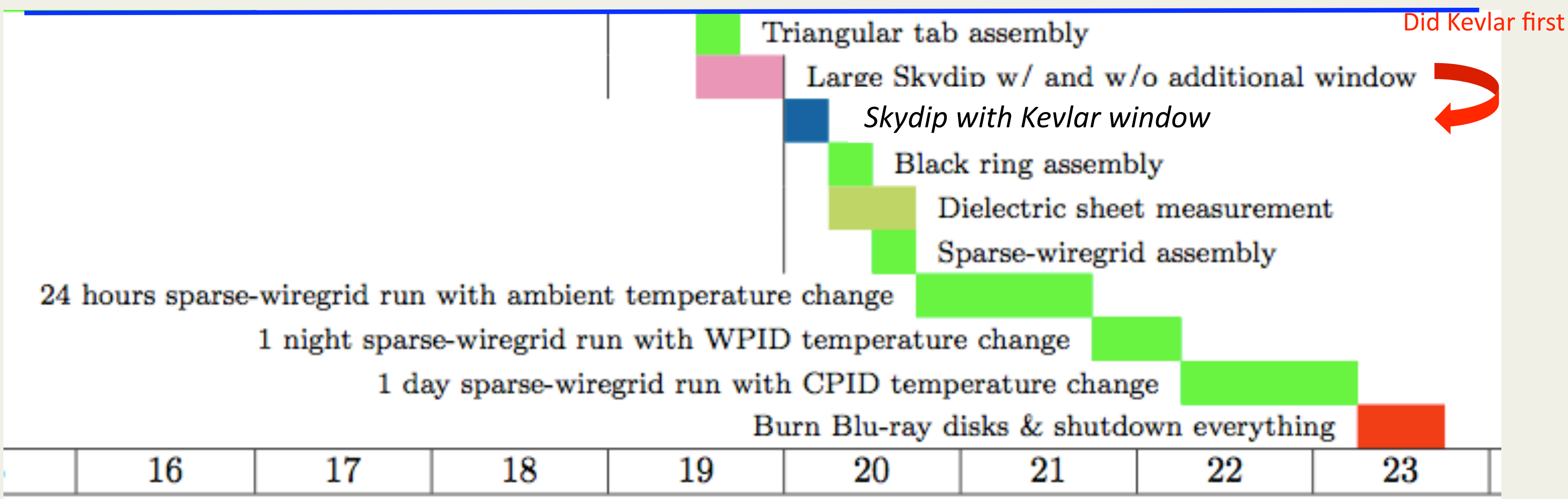
Dec 19-23

1. Kevlar window (Never done before) **Done on telescope (W-band) Dec. 19, 2010**

2. Additional HDPE window (Never done before) **Done on telescope (W-band) Dec. 19, 2010**

3. Dielectric sheet (Never done at the site) **Done on telescope (W-band) Dec. 19, 2010**

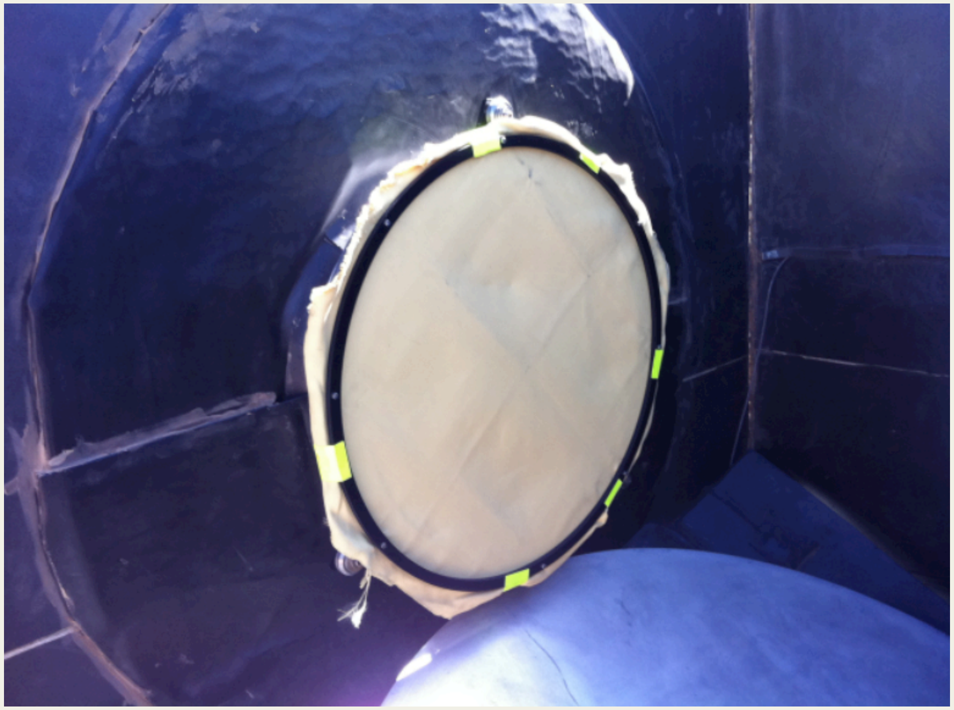
4. Sparse wire grid (Done in July 2009 without Upper Ground Screen) **Done on telescope (W-band) Dec. 19-22, 2010**



1. Kevlar window

- Goal: See if Kevlar might be a good material to use for a window

- Although Kevlar is floppy and cloth-like, we were able to make it quite smooth, holding it between the black ring and another black ring (seen in the image, which was part of the packing material for the wiregrid!), and screwing them tightly together.



Kevlar window on W-band receiver

2. Additional HDPE window

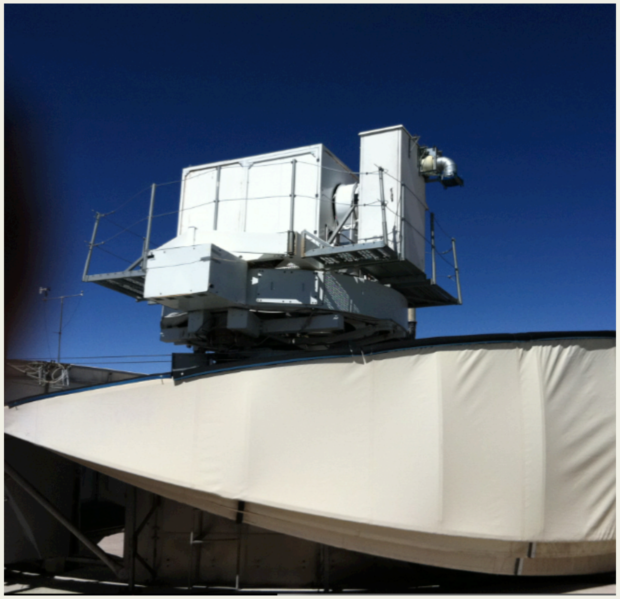
- Goal: Effective additional temperature measurement of the window

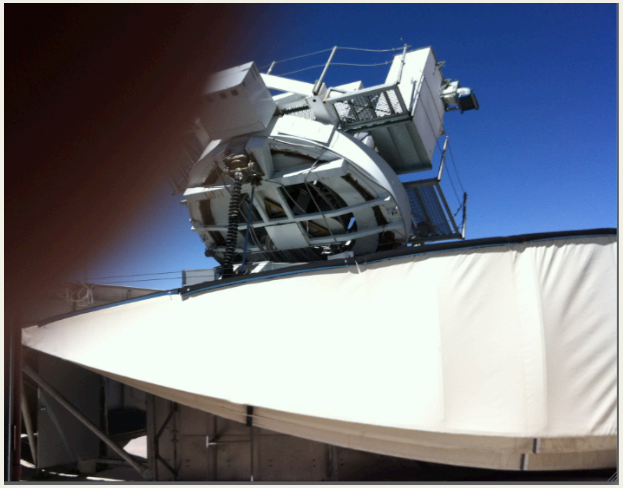
- The window, as we found it, was not flat.
- We screwed the window to the black ring at 7 points which helped flatten it a lot!

Additional HDPE window on W-band receiver

Large skydips with additional HDPE and Kevlar windows

- Did large skydip (without any additional material)
- Assembled Kevlar window
- Did large skydip
- Assembled additional HDPE window
- Did large skydip
- Disassembled additional HDPE window
- Did large skydip (without any additional material)



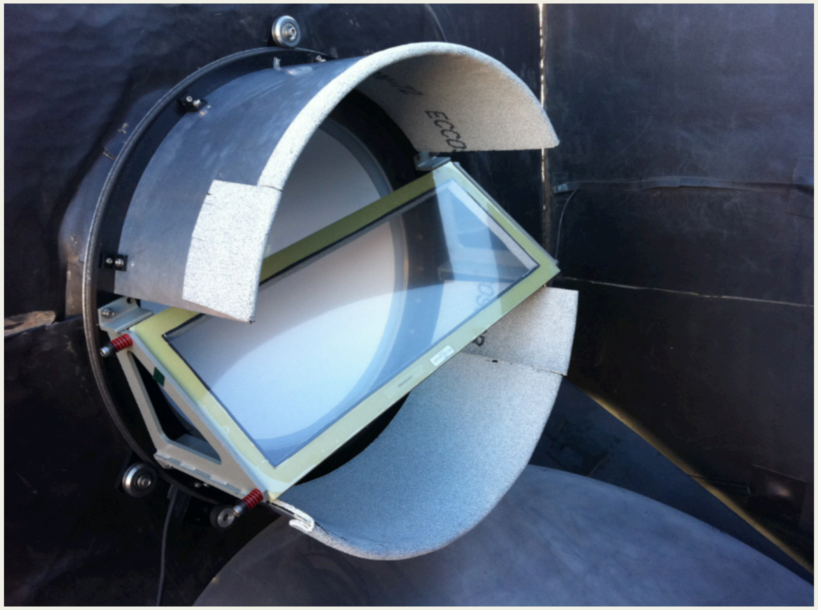


Large skydip

3. Dielectric sheet

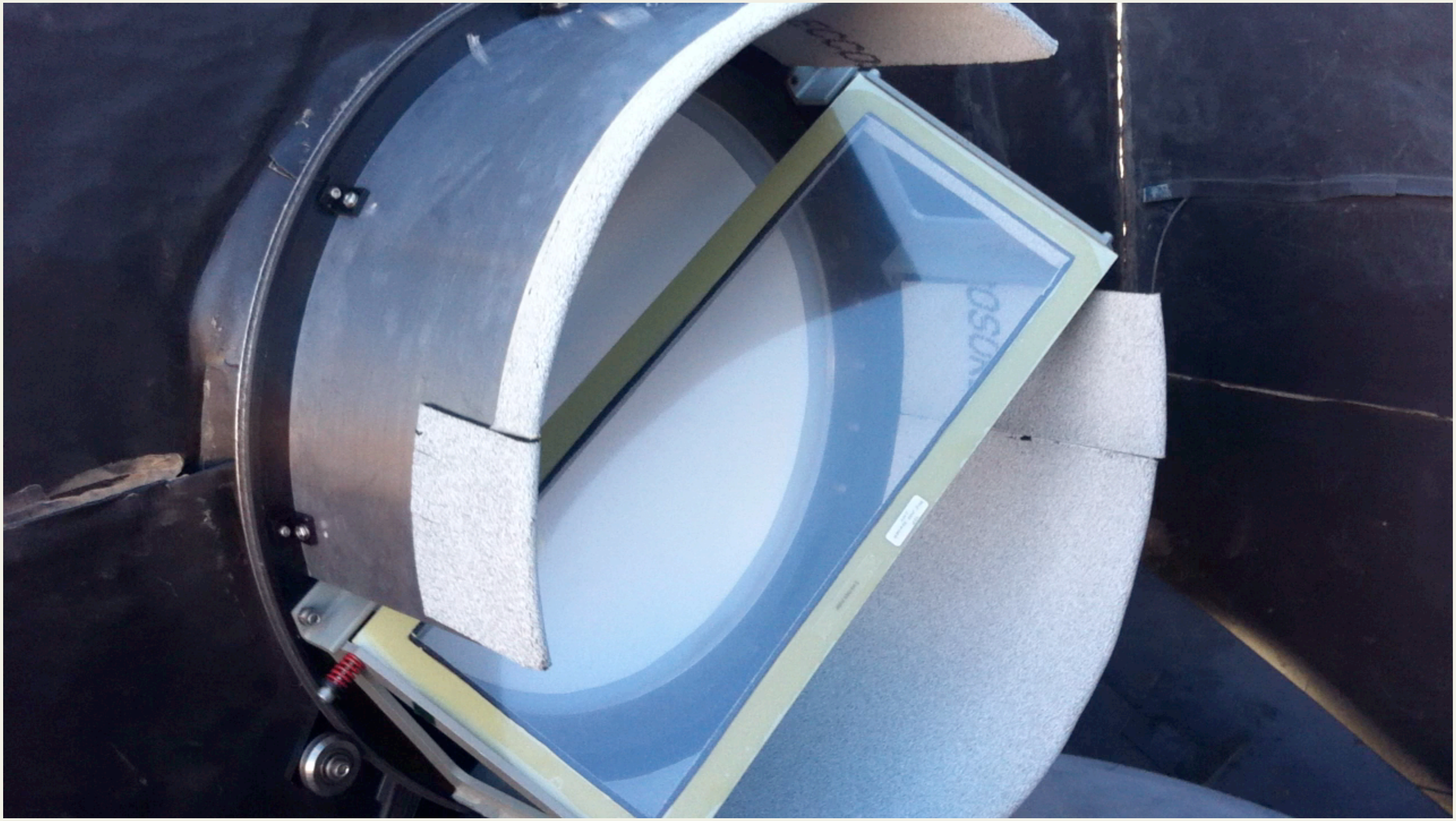
- Goal: Calibration of "absolute responsivity" (absolute gain) mainly for the center horn.

- Eccosorb was installed on the yellow G10 frame on the side facing the receiver.
- Rotation speed was ~8 seconds/rotation
- A movie of the rotating dielectric sheet can be viewed here:
  http://home.fnal.gov/~kubik/dielectricRotating.MOV



Rotating dielectric sheet installed on W-band receiver

Rotating dielectric



Estimated Q/U Signal for Dielectric Sheet Run

Expressions Taken From

http://cmb.physics.wisc.edu/
papers/cmb2009/ODelletal2002IEEE.pdf

$$I_x = T_C + (T_H - T_C) R_{\mathrm{TE}} + (T_S - T_C)\epsilon_{\mathrm{TE}} \quad (1a)$$

$$I_y = T_C + (T_H - T_C) R_{\mathrm{TM}} + (T_S - T_C)\epsilon_{\mathrm{TM}} \quad (1b)$$

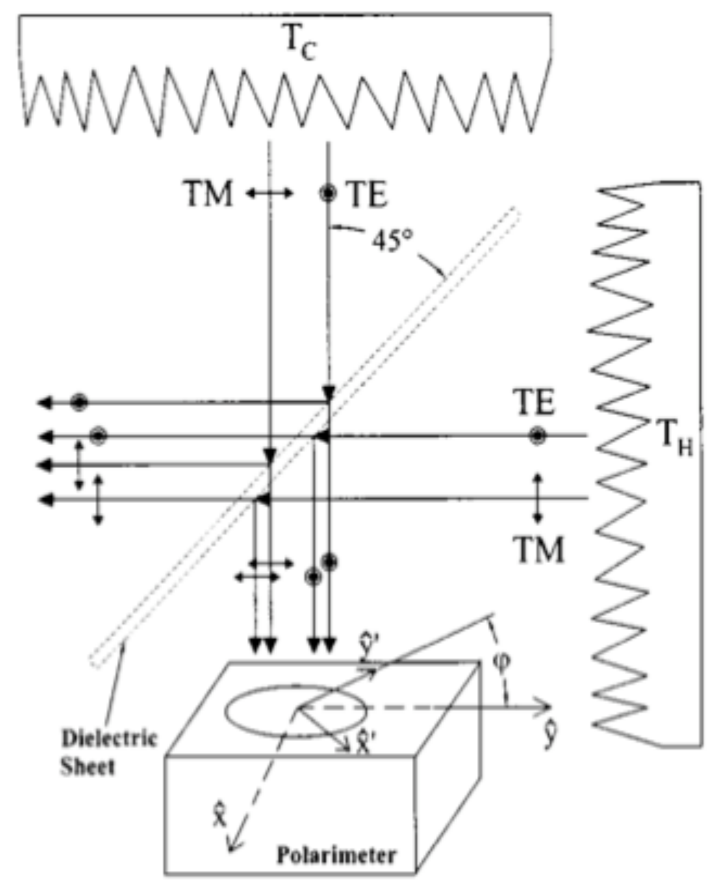
$$Q = (T_H - T_C)(R_{\mathrm{TE}} - R_{\mathrm{TM}}) + (T_S - T_C)(\epsilon_{\mathrm{TE}} - \epsilon_{\mathrm{TM}}) \quad (1c)$$

maximum
Q or U signal

T_H = 273 K (temperature of Eccosorb)

T_S= 273 K (temperature of dielectric sheet)

T_C = 5K (Chile Sky temp)

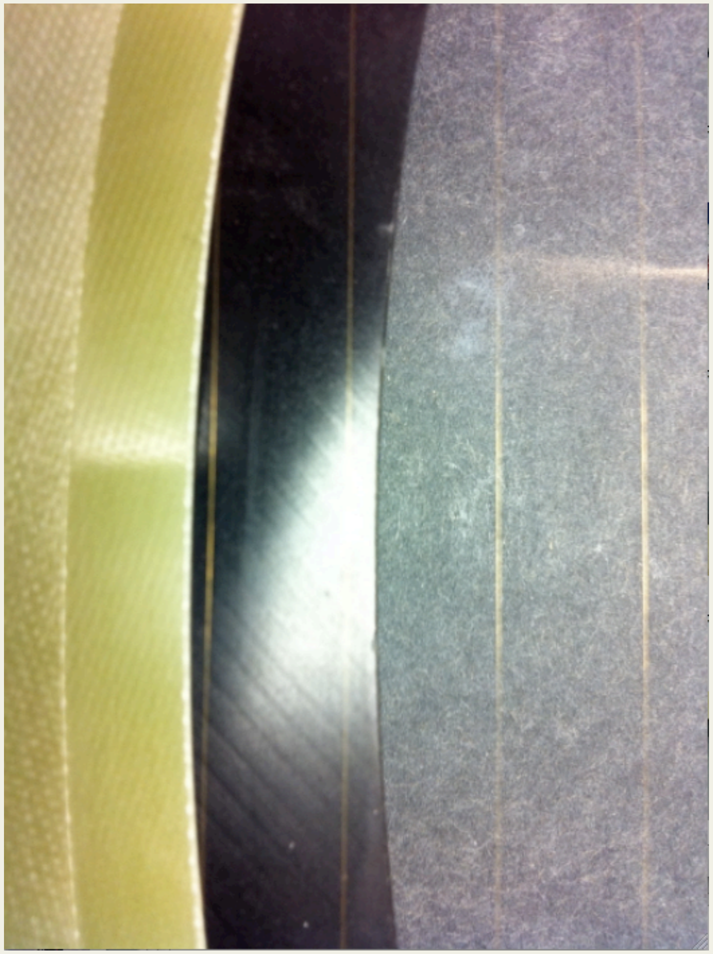
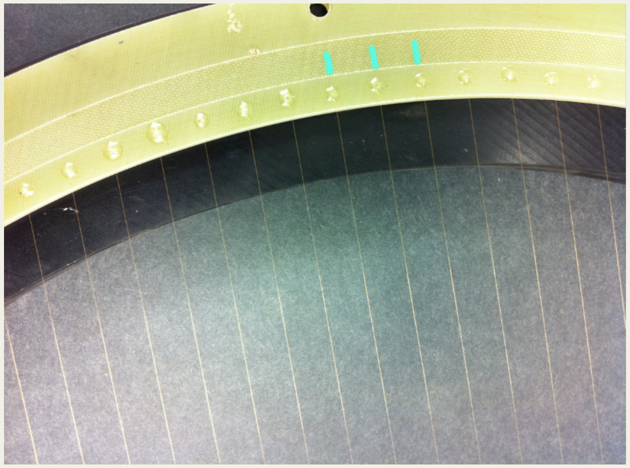


4. Sparse wiregrid

- Goals:
  - Simultaneous measurement of the relative responsivity (gain) and polarization angle for the full array.
  - Time variation with
    - Ambient temperature
    - Enclosure (bias boards) temperature
    - Cryostat temperature

Sparse wiregrid installed on W-band receiver

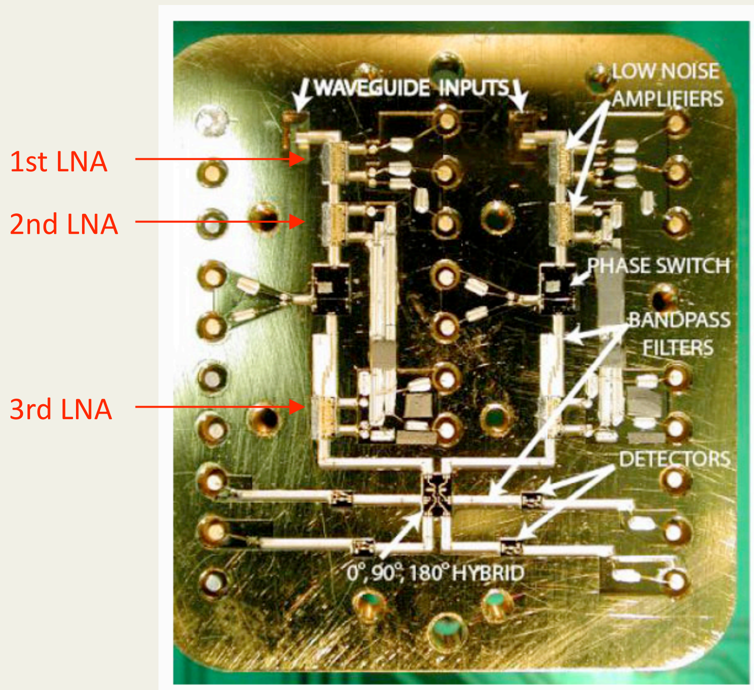
The sparse wiregrid was not damaged during installation, rotation for 3 days, and removal!

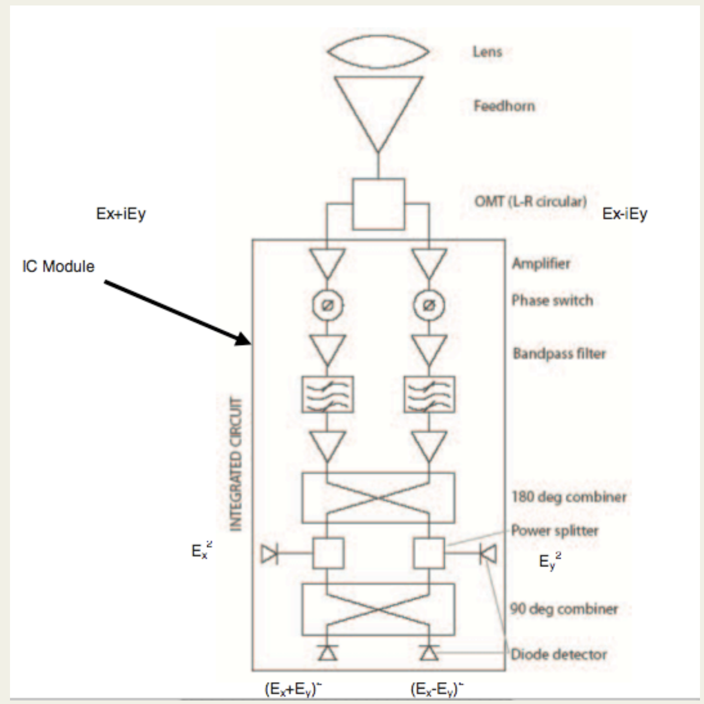




Close-up images showing wires intact

Temperature

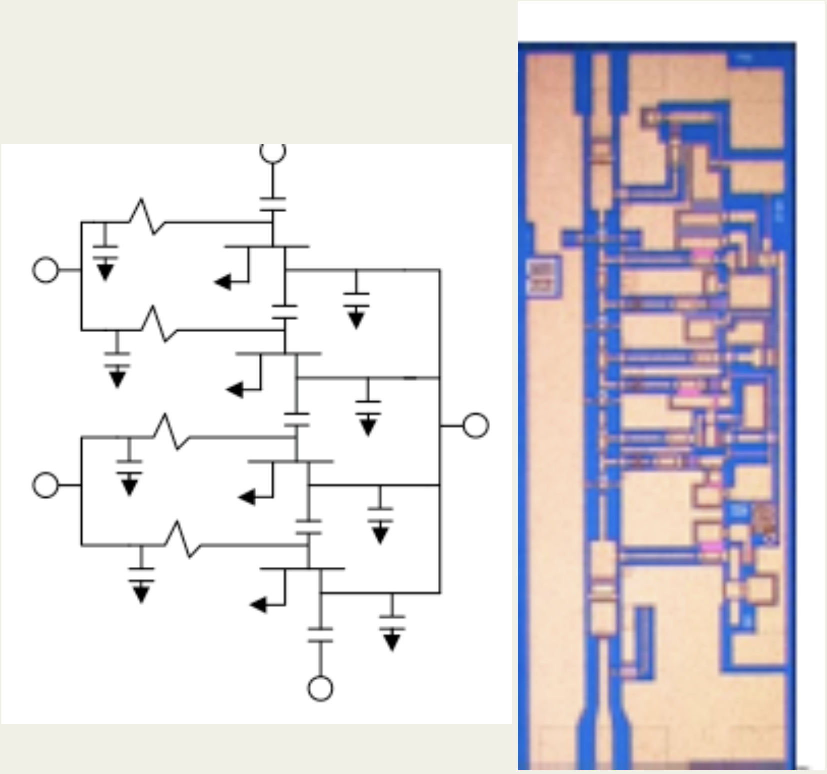
- The gain is determined by the biasing of the LNA which is temperature dependent
- Both warm and cold electronics are monitored





LNAs

- The purpose of the LNAs is to balance the amplitude and phase of the 2 legs
  - Adjust the gains by changing the bias of the LNAs
  - Adjust the phases by changing the bias of the LNAs
    - When the bias voltages are changed, parasitic capacitances and inductances change -> changes phase
    - Note: There is no other way to adjust the phase: *There is no phase shifter on the module.*

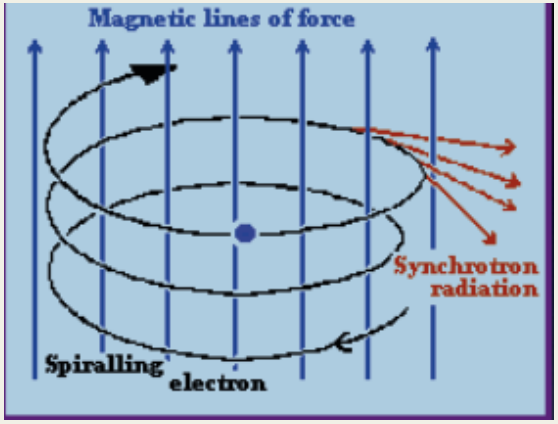


Block diagram and image of one of the three MMIC LNAs

Tau A

- Tau A (Crab Nebula) is a supernova remnant.
- Because the central pulsar is magnetized, the Crab Nebula is permeated by a magnetic field.
- This causes any electrons in the nebula, of which there are many, to spiral around the magnetic field lines and emit radiation known as synchrotron radiation.
- The polarization is perpendicular to the B fields.

HST image of Tau A



Radiation is perpendicular to B field

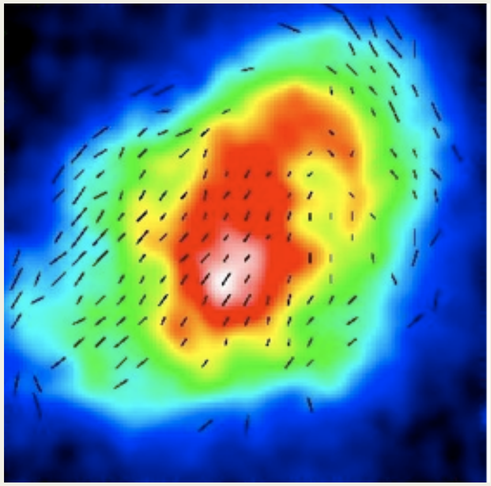
Tau A

- This radiation, which is brightest at radio wavelengths, but still very strong at millimeter and submillimeter frequencies, is polarized, which makes the Crab an ideal object for calibrating the polarization-sensitive detectors on QUIET.

- One of the properties of synchrotron radiation is that it varies in a fairly predictable way with frequency, so it is possible to tell from an observation at one frequency what it will look like at another.

- QUIET uses calibration data from WMAP.

HST image of Tau A



Polarization measured at 350 GHZ by JCMT

Tau A

- Tau A is around 7 arcmin across, which is about 1/4 the diameter of the full moon as seen from Earth.

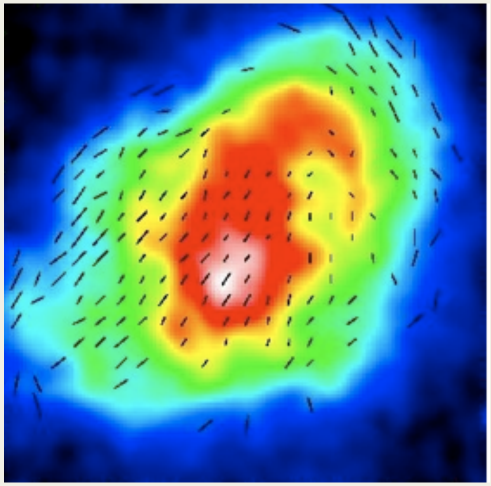
- The QUIET beams (for each horn) on the sky are
  - 27.3 arcmin for Q-band
  - 12.6 arcmin for W-band

  so the Tau A appears as a point source.

See next slide for more on array sizes

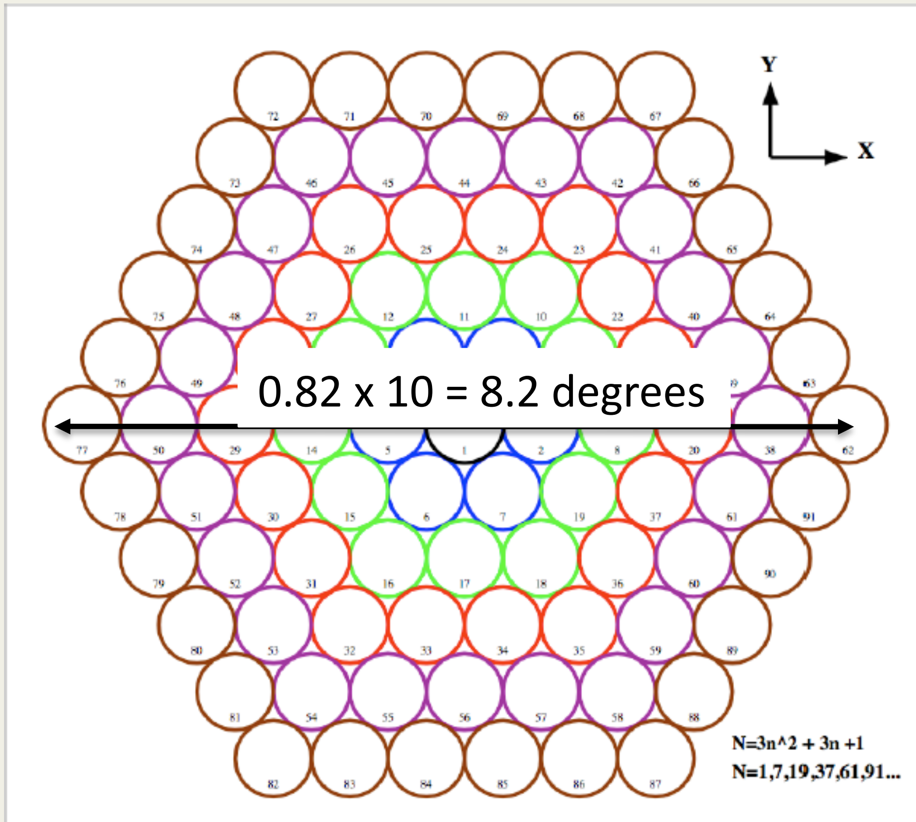
- However, it is so bright that it is very obvious.

HST image of Tau A



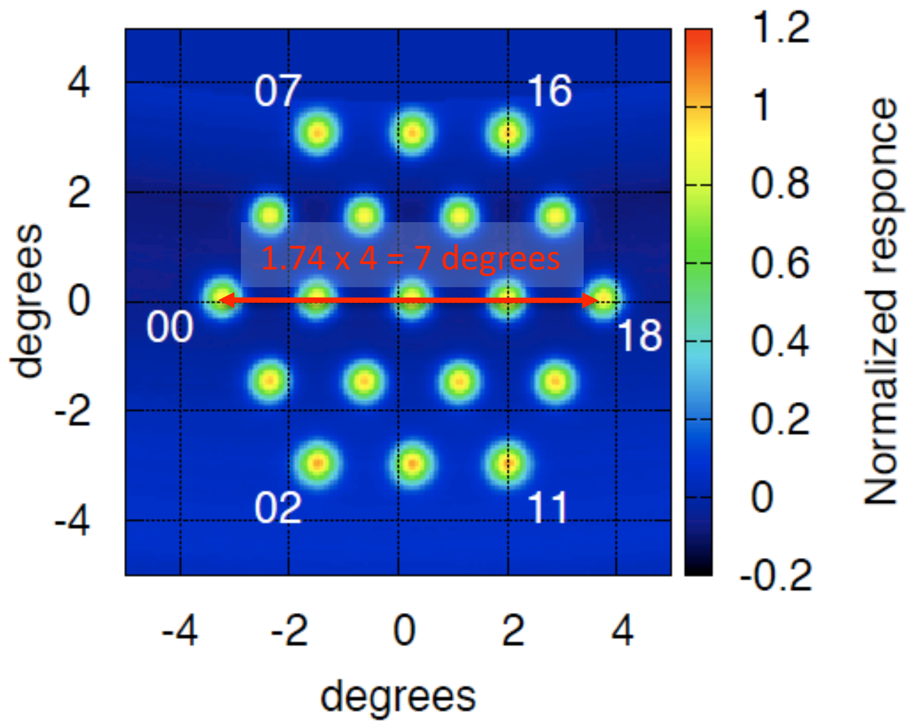
Polarization measured at 350 GHZ by JCMT

QUIET beam sizes



- The horn beam size is
  - 27.3 arcmin for Q-band
  - 12.6 arcmin for W-band
- The distance between the horn beams
  - 1.74 deg. for Q-band
  - 0.82 deg. for W-band
- Field of view of array
  - (1.74 deg between horns)*4 = 7 deg for Q-band
  - (0.82 deg between horns)*10=8.2 deg for W-band.

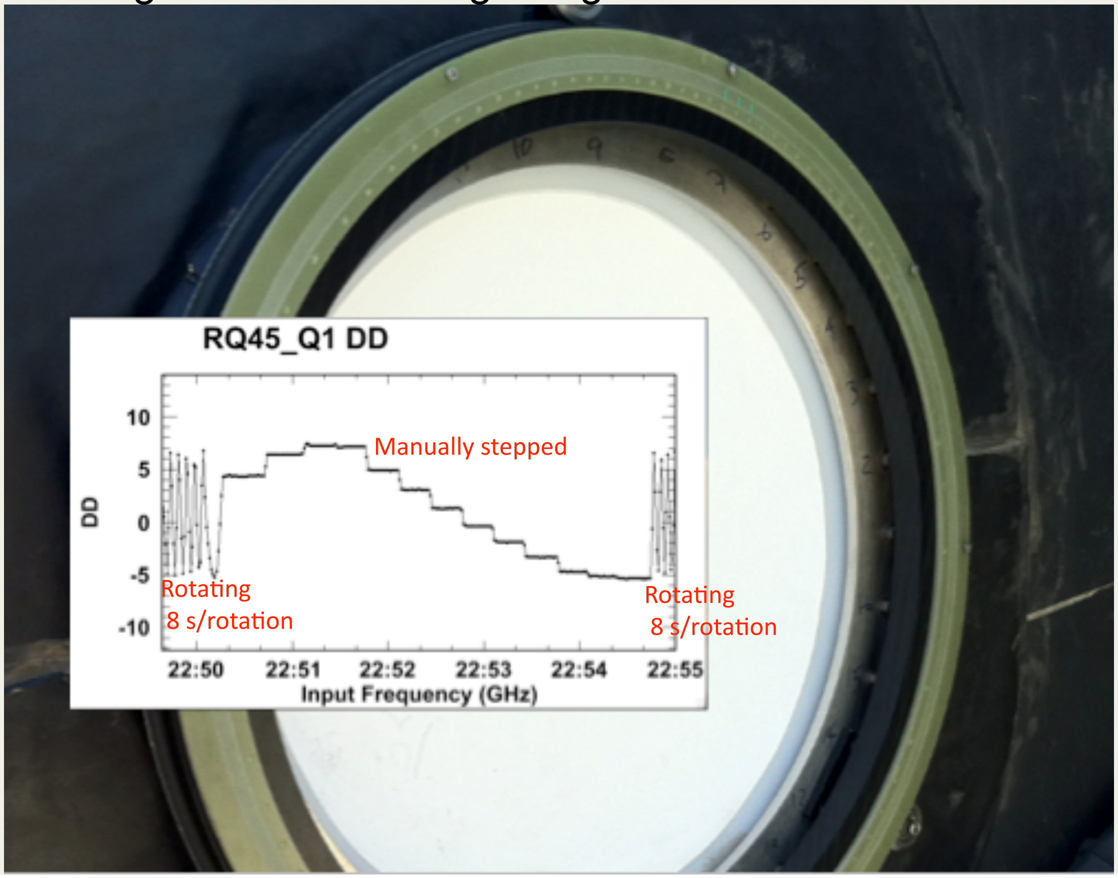
QUIET beam sizes



- The horn beam size is
  - 27.3 arcmin for Q-band
  - 12.6 arcmin for W-band
- The distance between the horn beams
  - 1.74 deg. for Q-band
  - 0.82 deg. for W-band
- Field of view of array
  - (1.74 deg between horns)*4 = 7 deg for Q-band
  - (0.82 deg between horns)*10=8.2 deg for W-band.

4. Sparse wiregrid

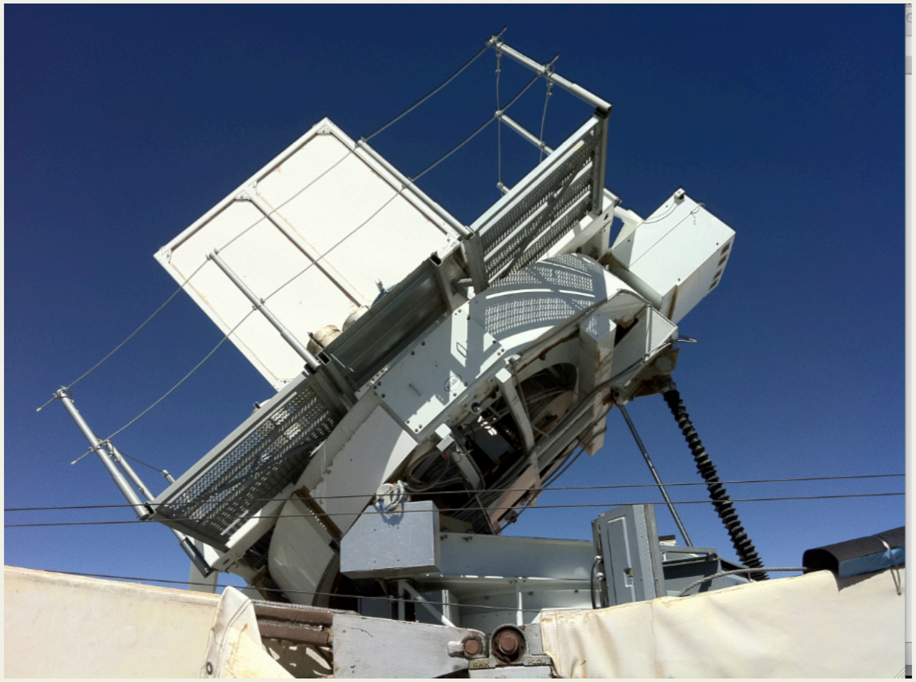
- The numbering of the window bolts can be seen in this image and may serve as documentation
- A movie of the rotating dielectric sheet can be viewed here: http://home.fnal.gov/~kubik/rotatingWiregrid.MOV



Rotating wiregrid

Telescope orientation during dielectric sheet and wiregrid tests

- Telescope position: Azimuth = 0 degrees
  Elevation = 50 degrees
  Deck = -60 degrees



Two views of the telescope's orientation during the dielectric sheet and wiregrid tests

Last two sets of measurements

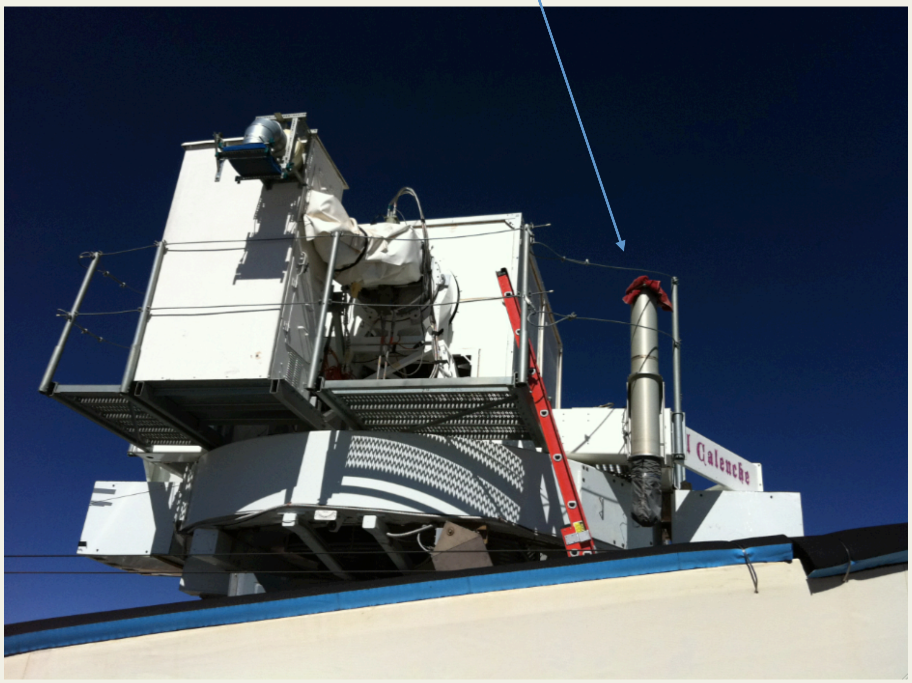
- After removing the wiregrid, two more sets of measurements were made
  - Cross talk
  - Noise vs. V_g
- The telescope's orientation for these tests was
  - Azimuth 180 degrees
  - Elevation 85 degrees
  - Deck -90 degrees

The telescope's orientation during the crosstalk and noise vs. V_g tests

Pointing studies

- There is an optical telescope that ride piggy-back on the QUIET telescope
- Pointing observations are done weekly to monitor any changes in the pointing model, problems with the drive motors, encoders, etc.
- We did extended pointing studies during the last week
  – Done at beginning, middle and end of season
  – And because the upper ground shield was removed

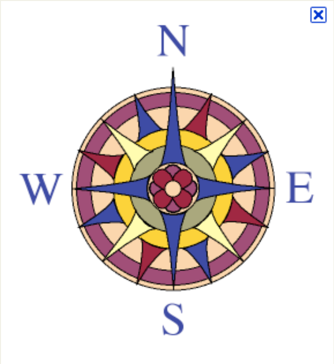
Optical telescope



There is an optical telescope used for pointing studies

Many thanks to Jose, Felipe, and Simon for their skill used to assemble all the instruments!

Hopefully, the sun will rise on QUIET again!



December 23, 2000

Future

Routine calibrations

	Precision	Typical Value	Calibrators
Beam			Jupiter, Tau A
Size (FWHM)	<0.1 arcmin	27/12 arcmin (Q/W)	
Ellipticity	–	<1.5%	
Pointing	4 arcmin	–	Moon, Jupiter, Patch Gc
Responsivity			
Polarization	7%	2 mV/K	Mini-sky-dips, Tau A, the Moon, polarizing grid
Intensity	5%	2 mV/K	Jupiter, Venus, RCW38
Polarization Angle	±2°	–	Mini-sky-dips, the Moon, Tau A, polarization grid
I → Q/U Leakage	±0.5dB	-20dB / -27dB (Q/U)	Skydips, the Moon, Tau A
Correlated Noise	±0.5%	30 %	Constant elevation CMB scan

Source	Schedule	Calibration
Tau A, central polarimeter	Once/two days	Beam size and ellipticity, absolute polarimeter responsivity, absolute polarimeter angles
Tau A, off-center polarimeters	Once/season	Absolute polarimeter responsivity, absolute polarimeter angles
Moon (full array scan)	Once/week	Relative polarimeter responsivity between polarimeters, pointing, leakage, absolute polarimeter angles
Jupiter, Venus, RCW38 (TT channels)	Once/week	Absolute TT responsivity, pointing, beam size and beam ellipticity
Sky dip	Once/scan	Relative TT and polarimeter responsivity, leakage monitoring
Polarized wire grid	Once/season	Relative polarimeter responsivity, relative polarimeter angles