Calibration of the Atacama Large Millimeter Array

North American ALMA Science Center

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Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Large Baseline Array

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ALMA Design

- Continuous Frequency Coverage: 100 to 1000 GHz
- >6600 m^2 Collecting Area
- Baselines: 15 m to 16 km
- Ability to Process 16 GHz of Bandwidth
- 24 Hour Operation
- Continuum Sensitivity: 0.05 to 1 mJy in 60 seconds
- Spectral Line Sensitivity: 7 to 62 mJy in 60 seconds at 1 km/s resolution

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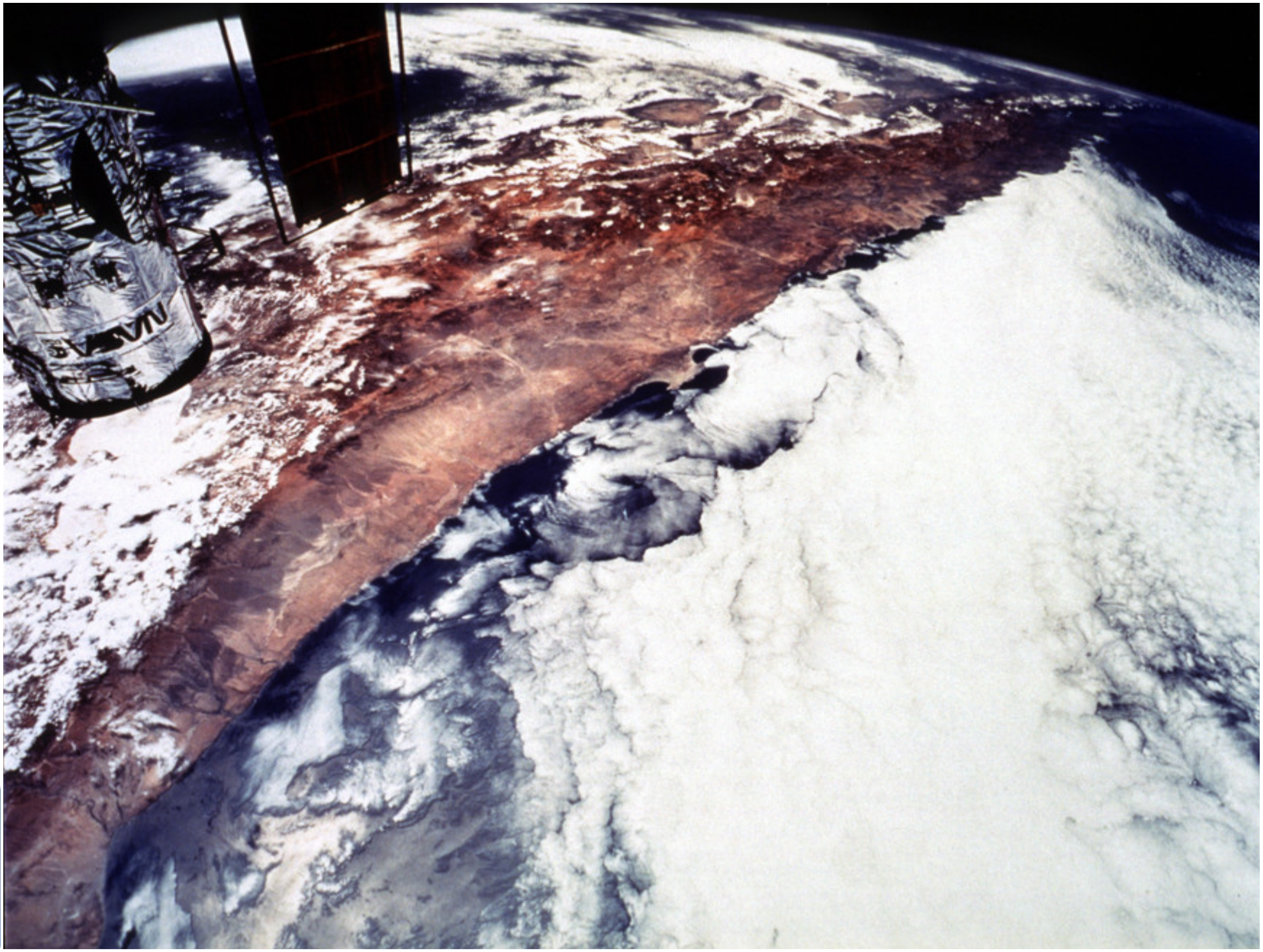
Atacama Desert as Seen from Shuttle/HST



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ALMA Site Location

ALMA Site

- Chilean Andes at altitude 5050 m (Array Operations Site: AOS)
- Operations Support Facility (OSF) at 2900 m

ALMA Antennas

- 54 12m antennas
- ACA adds 12 7m antennas
- Performance Requirements
  - Surface Accuracy: 25µm RMS (20µm goal)
  - Absolute Pointing Accuracy: 2 arcsec all-sky
  - Offset Pointing Accuracy: 0.6 arsec over 2 degree radius
  - Fast Switching
    - 1.5 degree move in 1.5 seconds
    - Settle to 3 arcsec peak pointing error at 1.5 seconds after start of switch
    - Settle to 0.6 arcsec RMS tracking error over 2 to 4 seconds after start of switch
- Path Length Stability: 15µm / 20µm (non-repeatable / repeatable)
- Primary Operating Conditions
  - T_{amb} = -20 to +20 C
  - $\Delta T_{amb} \leq 0.6 / 1.8$ C over 10 / 30 minute durations
  - $V_{wind} \leq 6 / 9$ m/s (day / night)

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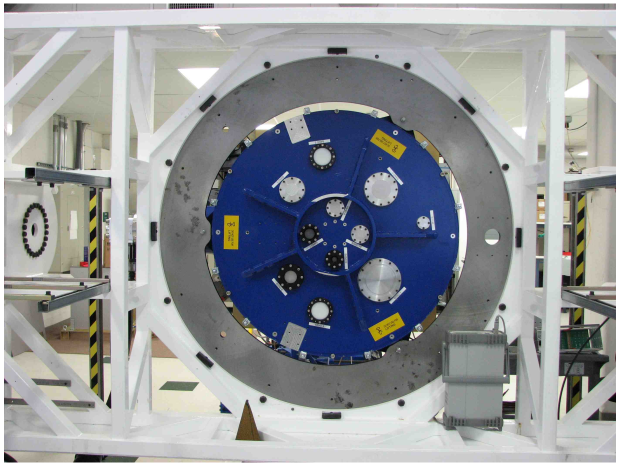
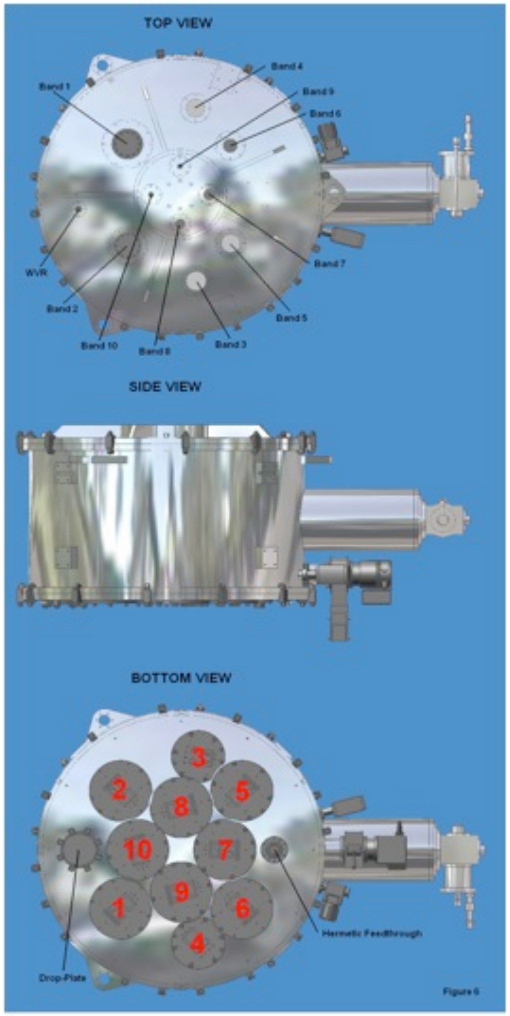
ALMA Antennas Delivery Status

- 39 antennas delivered and integrated
  - North American (Vertex): 20 of 25
  - European (AEM): 7 of 25
  - East Asian (Melco): 4 of 4 (12m) and 8 of 12 (7m)
- 36 antennas in use at the AOS (April 2012)
- Performance based on contractor acceptance testing meets specifications

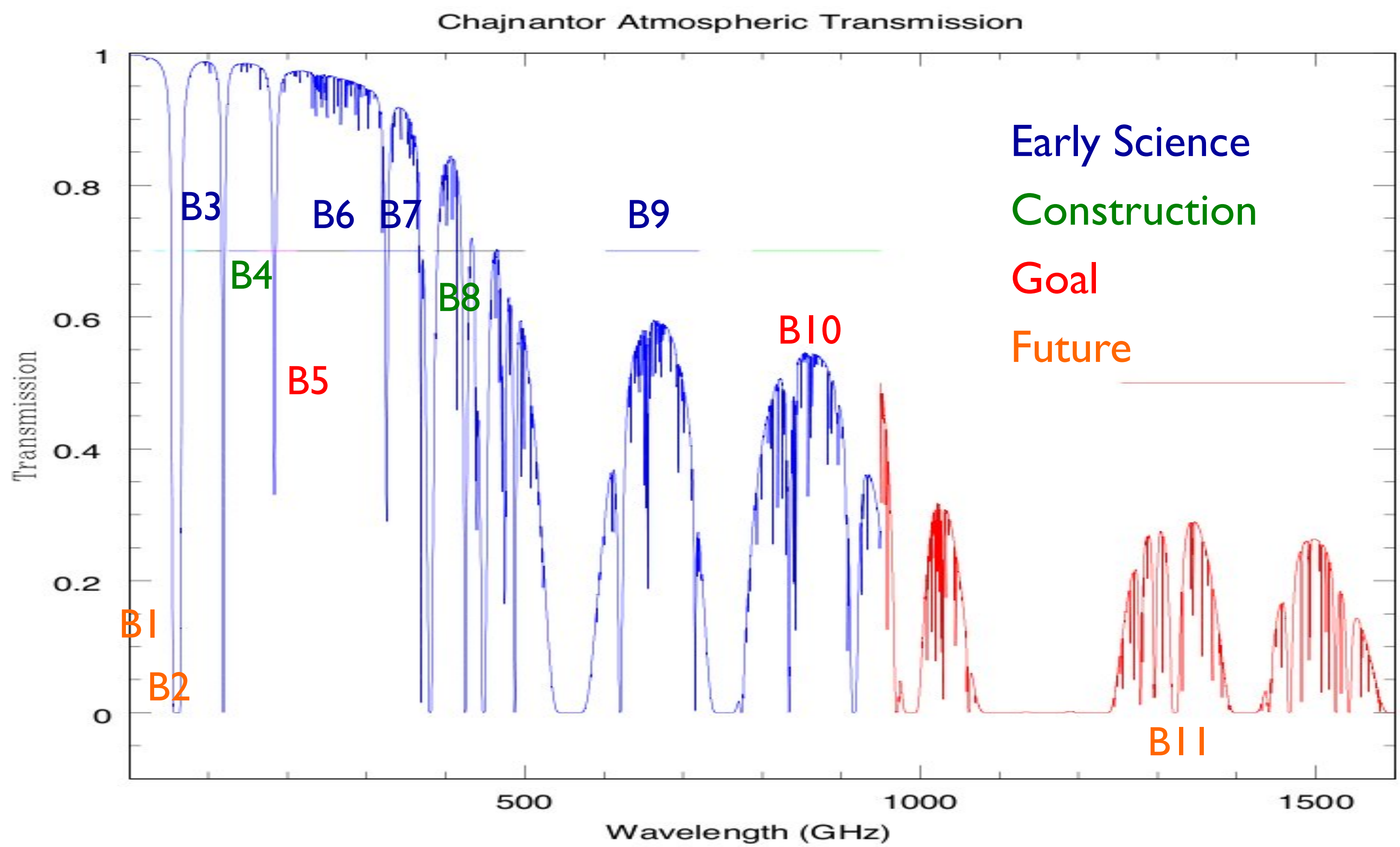
ALMA Receivers

- Ten Receiver Bands
  - All antennas equipped with
    - Band 3: 84-116 GHz
    - Band 6: 211-275 GHz
    - Band 7: 275-373 GHz
    - Band 9: 602-720 GHz
  - Six antennas equipped with Band 5 (163-211 GHz)
  - Bands 4 (125-163 GHz) and 8 (385-500 GHz) delivered by end of construction
  - Bands 1 (40 GHz), 2 (80 GHz) and 10 (787-950 GHz) will be developed in the future
- Bandwidth: 8 GHz at each of two polarizations





ALMA Frequency Coverage

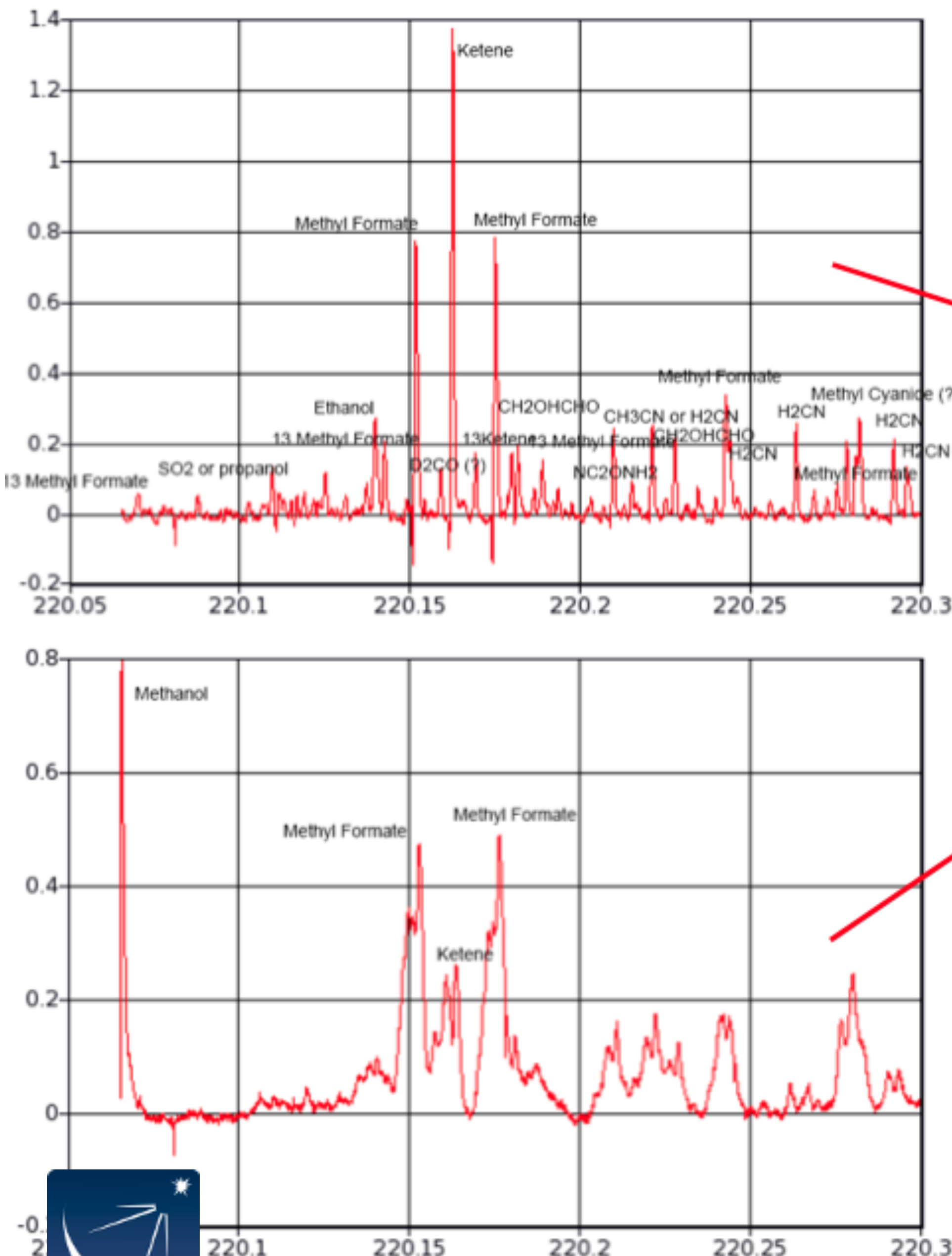


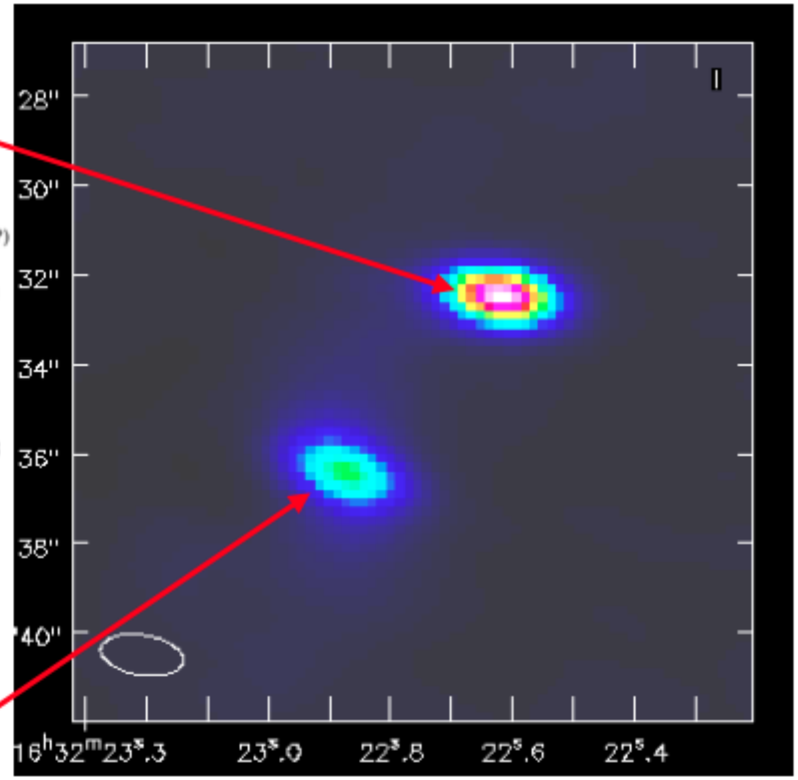
Early Science

The Antennae Galaxies

Blue = visible (HST)
Red = CO 1-0 (Band 3)
Yellow = CO 3-2 (Band 7)

Early Science

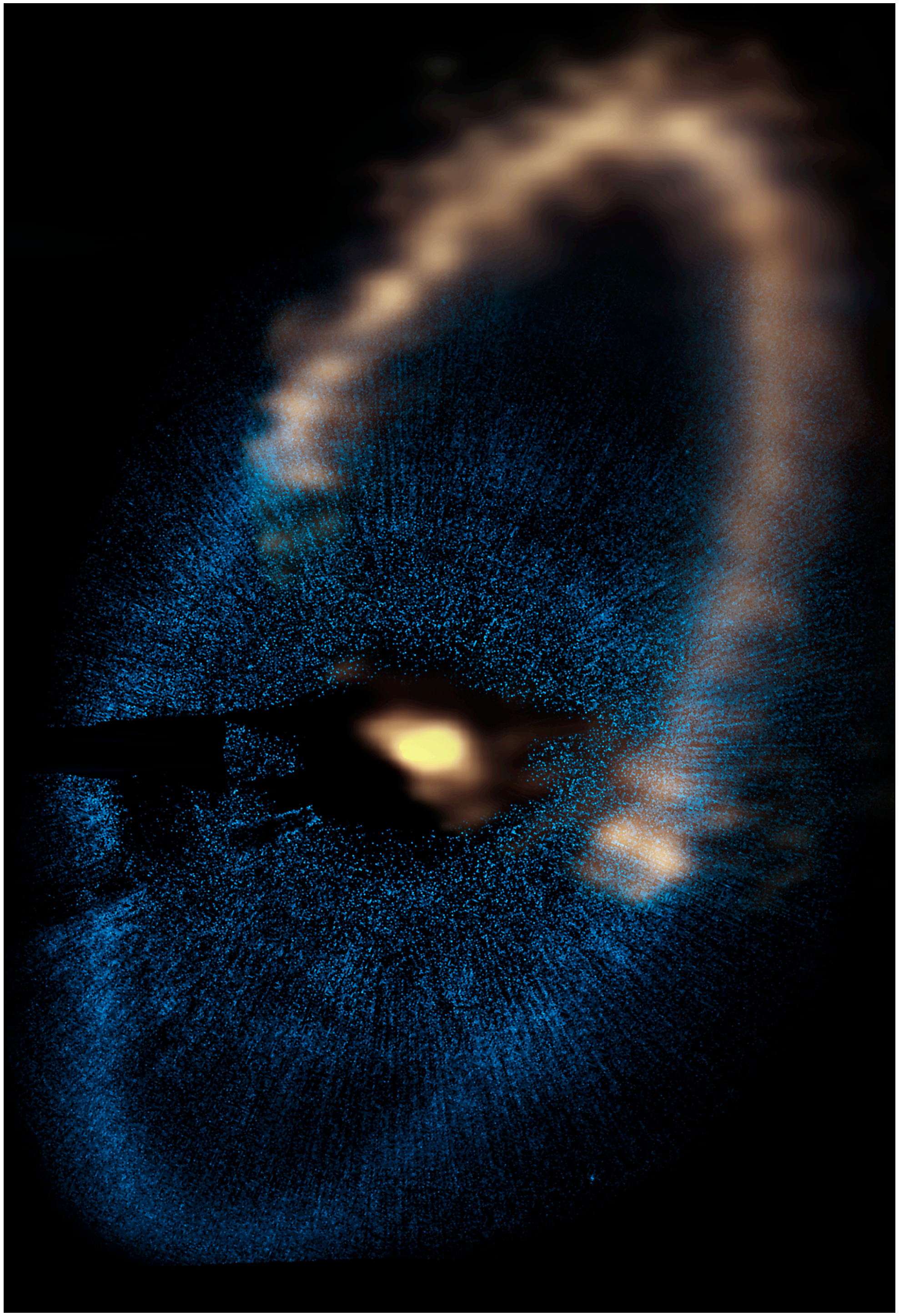




IRAS16293

Early Science

Fomalhaut (Boley etal. 2012)
• 345 and 357 GHz continuum
• θ = 1.2 x 1.5 arcsec
• Total flux = 45.5 mJy
• Supports "shepherd planets" formation mechanism for ring



ALMA Operations Timeline 2012-2013

- May 2012: Cycle 1 Call for Proposals
- July 2012: Cycle 1 Proposal Deadline
- January 2013: Cycle 1 Observing Begins
- October 1, 2012: Antenna DV25 Delivered

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ALMA Calibration Specs and Reqs

Specification	Requirement
Antenna Pointing (All-Sky/Offset)	2.0/0.6 arcsec
Primary Beam Characterization	6% in power out to 10% on the primary beam
Feed Setting	280 µm vertical / 3200 µm lateral
Subreflector Setting	28 µm vertical / 140 µm lateral / 1.7 arcmin rotational
Antenna Motion	1.5 deg in 1.5 seconds settling to 3 arcsec peak pointing error
Antenna Location	65 µm
Geometric Delay	5 fs systematic
Atmospheric Delay	10 fs systematic / 40*(1.25 + PWV) fs fluctuating
Antenna Delay	7 fs systematic / 50 fs fluctuating
Electronic Delay	7 fs systematic / 30 fs fluctuating
Bandpass	10000:1
Polarization	0.1% in amplitude / 6 deg in position angle
Sideband Gain Ratio	0.1%
Amplitude (Relative)	1% / 3% (ν < 370 GHz / ν ≥ 370 GHz)
Amplitude (Absolute)	5% (all frequencies)
Corrected Visibility Phase	< 57 deg at 950 GHz for timescales < 10 seconds

ALMA Calibration Types

Operations/Maintenance Calibration

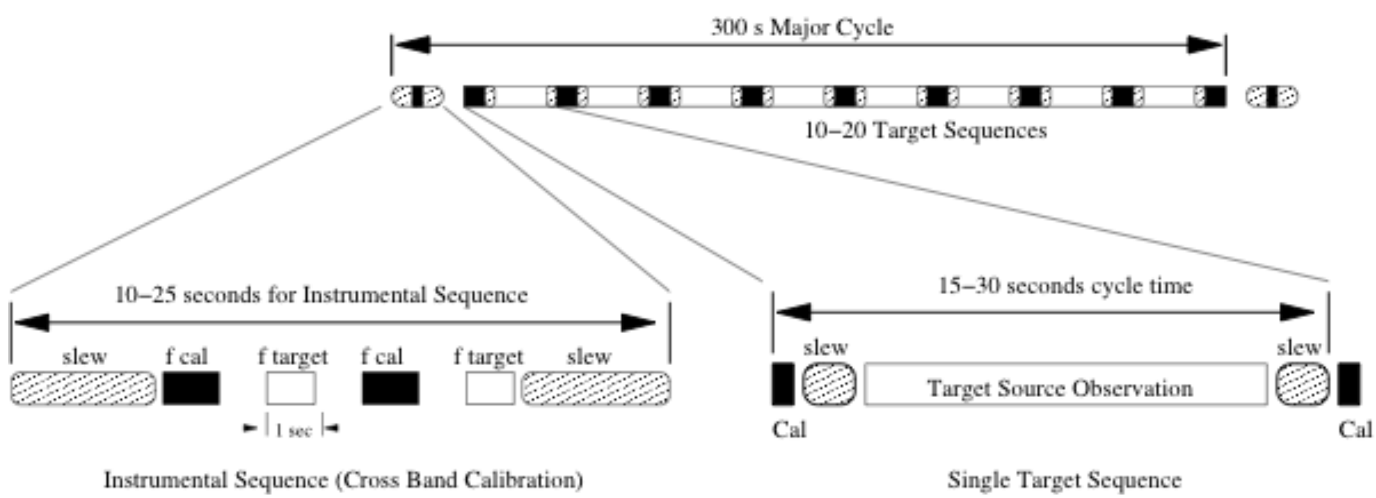
- Pointing
- Polarization
- Antenna Location
- Antenna and Electronic Delay
- Optics
- Primary Beam

User Calibration

- Reference Pointing
- Amplitude
- Phase
- Bandpass
- Polarization

Phase Calibration Sequence

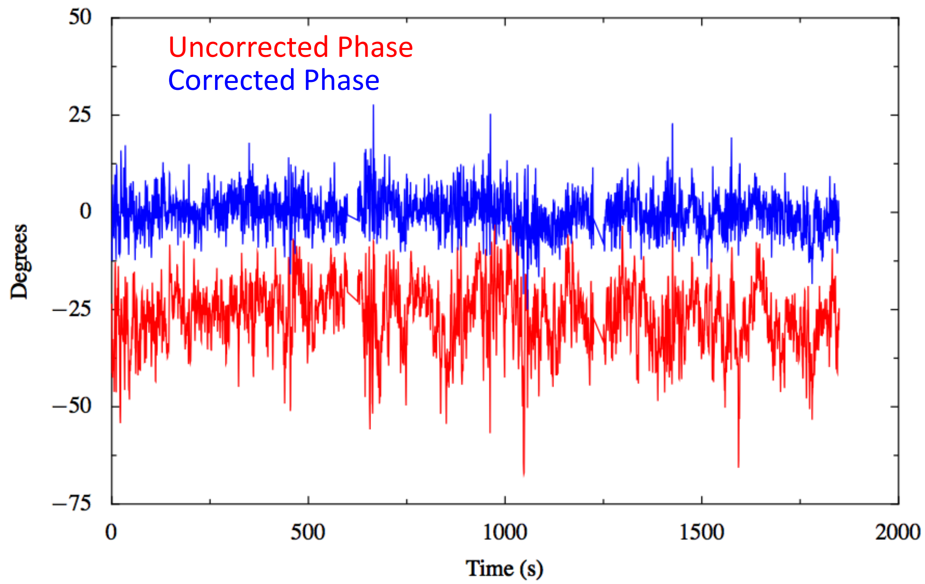
- Measure system phase by monitoring a relatively strong phase-stable signal outside the Earth's atmosphere (i.e. quasar).
- Monitor phase stability as a function of time on both short (fast switching) and long (phase monitoring) timescales.
- For higher frequency bands (> 350 GHz) calibrator availability might require phase referencing to measurements at 230 GHz.
- Instrumental Sequence:
  - Required for cross-band calibration of dual-frequency fast switching measurements
  - Calibrator measured at both calibration (90 GHz) and target frequencies
- Target Sequence:
  - Measure target and phase calibration source separated by ≤ 2 degrees



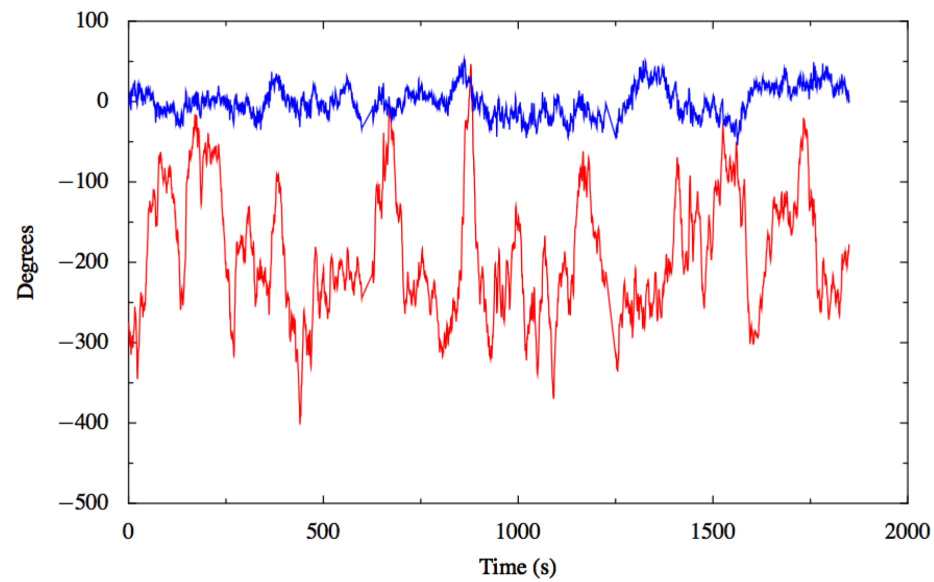
Water Vapour Radiometers (WVR)

- Omnisys Radiometers
- 8 filters measuring 177 to 195 GHz total power centered at 183 GHz water line.
- Sensitivity: 0.08 to 0.1 K per channel.
- Stability: 0.1 K peak-to-peak over 10 minutes.
- Absolute Accuracy: 2 K maximum error.
- All 58 systems delivered to ALMA.
- System developed by University of Cambridge (Bojan Nikolic)

Nikolic (2011)



Short Baseline (≈50m)



Longer Baseline (≈300m)

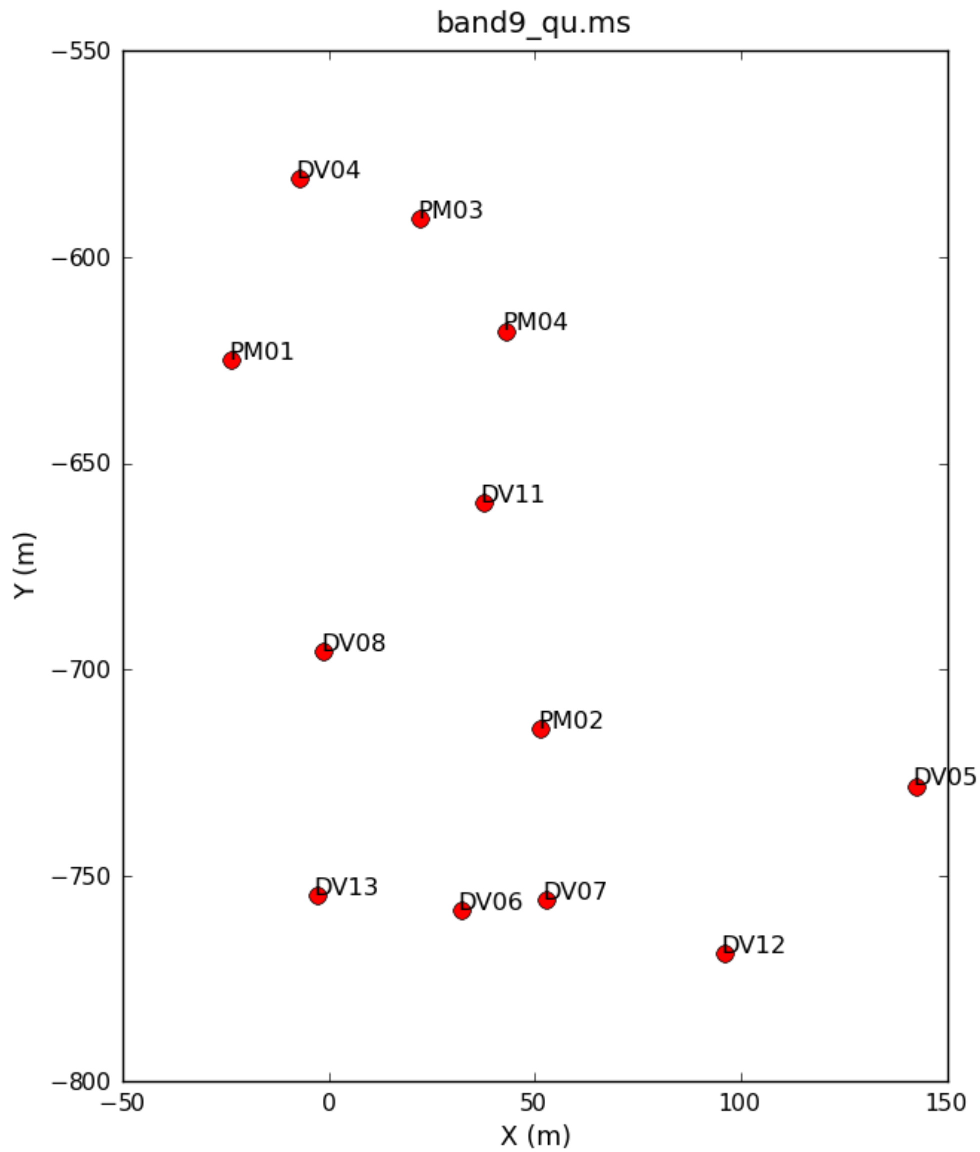
ALMA Phase Calibration at 660 GHz

- Data taken August 31, 2011.
- Four ICRF quasars were observed alternately for one minute over a 70-min period.
- WVR corrections made virtually no difference in the phase data and were not applied.
- PWV measured to be ≈ 0.2 mm.
- Four correlator spectral windows (spw), each with 2 polarizations and a useable bandwidth of 1.7 GHz. The spw frequencies were 687, 689, 691 and 693 GHz.
- All four Stokes parameters were measured and each spw had 64 channels.
- Rule-of-thumb: 1 deg phase error ≅ 2% amplitude error.

ALMA Phase Calibration at 660 GHz

Array Configuration

- The band 9 antennas that were working well and used in the following analysis are DV11, DV12, PM01, PM02, PM03
- $B_{avg} \cong 150$ m

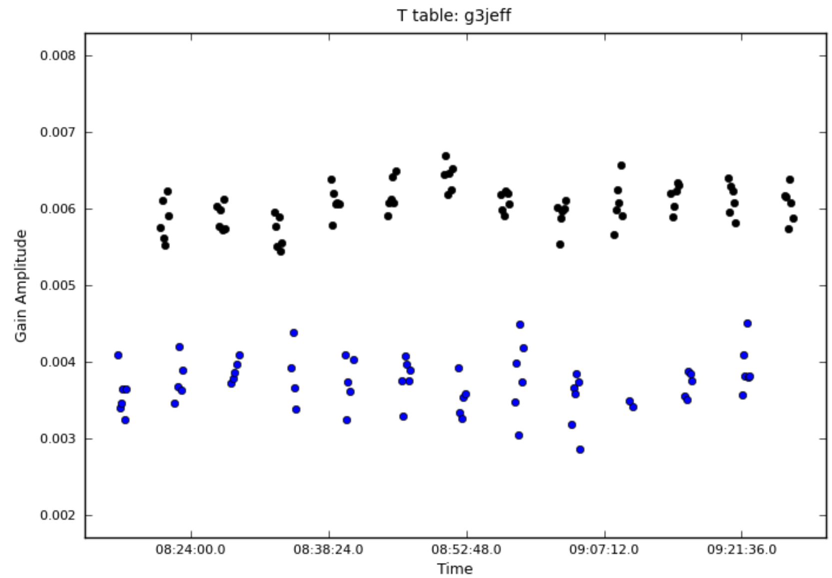


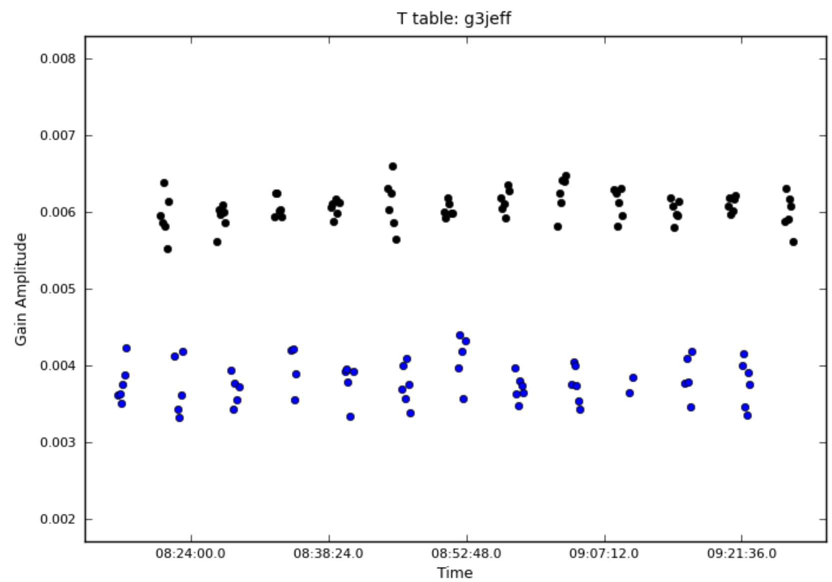
Fomalont (2012)

ALMA Phase Calibration at 660 GHz

Raw Amplitude

- Raw amplitude for three antennas: DV12, PM01 and PM03.
- Black dots are for the source J0522-364 and the blue dots are for the source J0538-440.
- The amplitude scale gives raw antenna-correlation with no amplitude correction applied.
- Each clump of points represents a one minute scan with each point a 10 sec integration.
- The amplitudes are the average of eight channels (2 pol and 4 spw).
- The approximate flux density at band 9 for the sources are 2.4 and 1.2 Jy.
- **Amplitude gain variations ≅ 7% over 1 to 70 minute timescales.**





Fomalont (2012)

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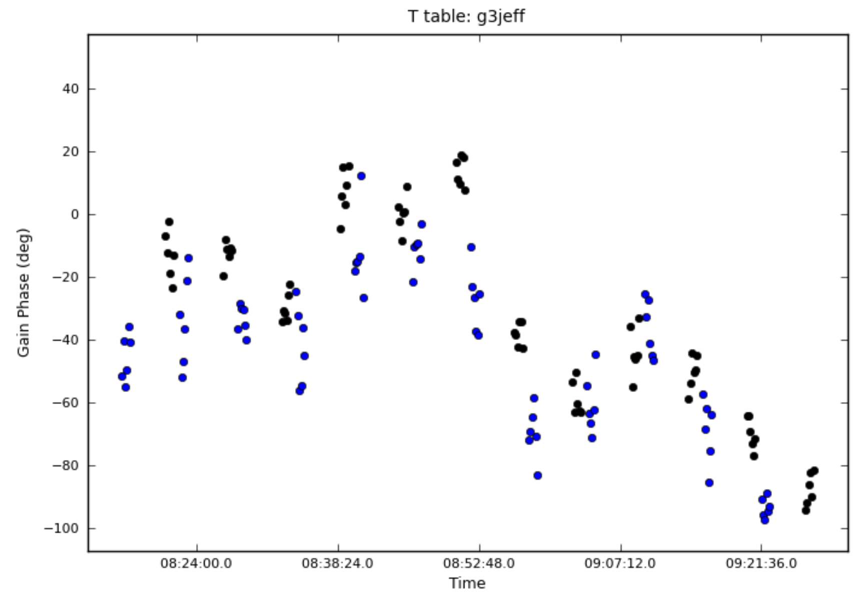
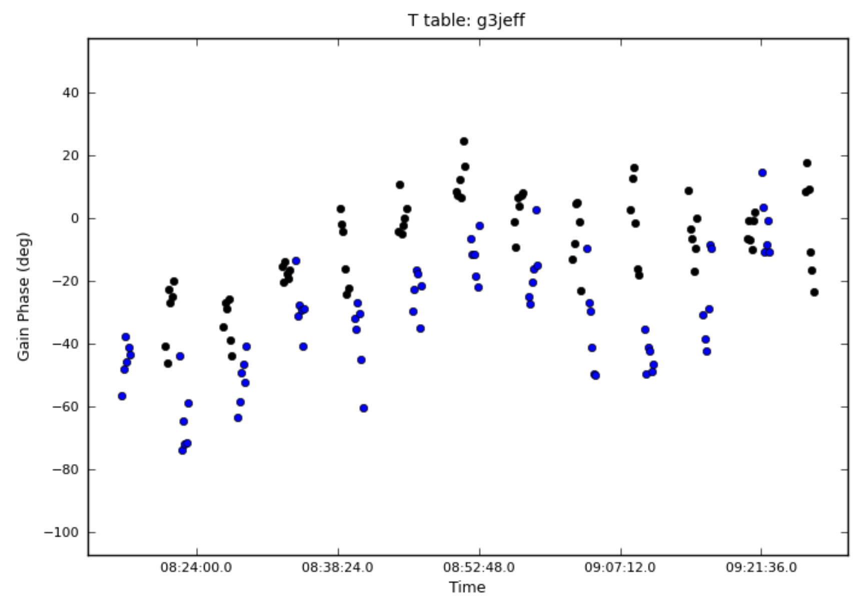
ALMA Phase Calibration at 660 GHz

Raw Phase

- Raw phases for three antennas: DV12, PM01 and PM03.
- The black dots are for the source J0522-364 and the blue dots are for the source J0538-440.
- The plotted phases are the combination of all eight streams (two polarizations and four spw) to minimize noise.
- Each clump of points represents a one minute scan with each point being a 10 sec integration.
- The only phase calibration used the J0522-364 scan near the middle of the run at approximately 08:50:00 to align all of the eight streams to zero.
- All other phase variations with time and the phases for J0538-440 are from the sky and the system.
- **Phase variations ≅ 10/25 deg over 1 to 70 minute timescales.**



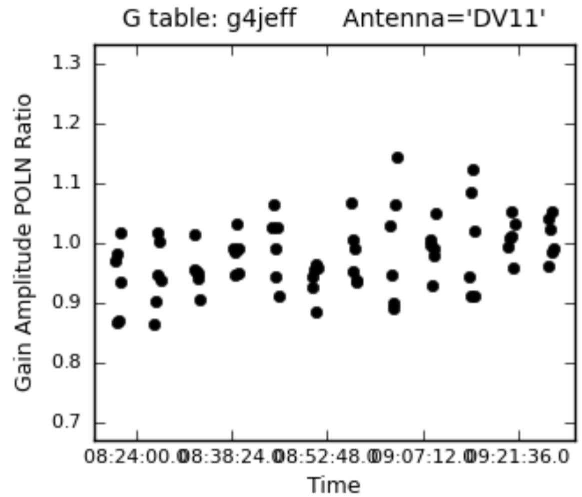


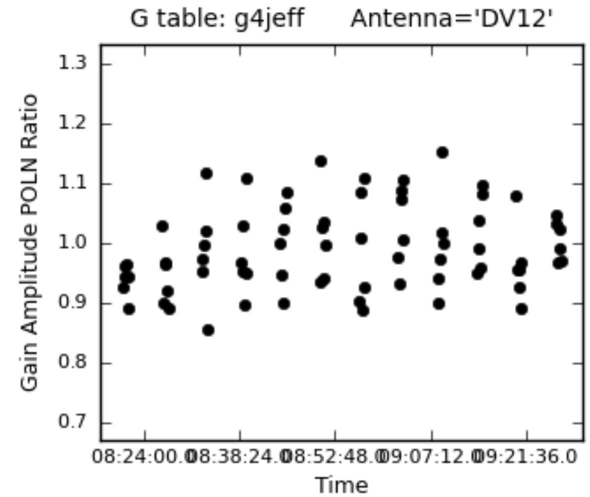
Fomalont (2012)

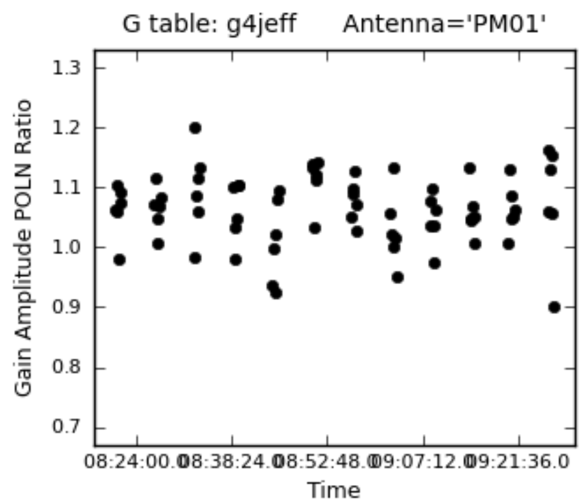
ALMA Phase Calibration at 660 GHz

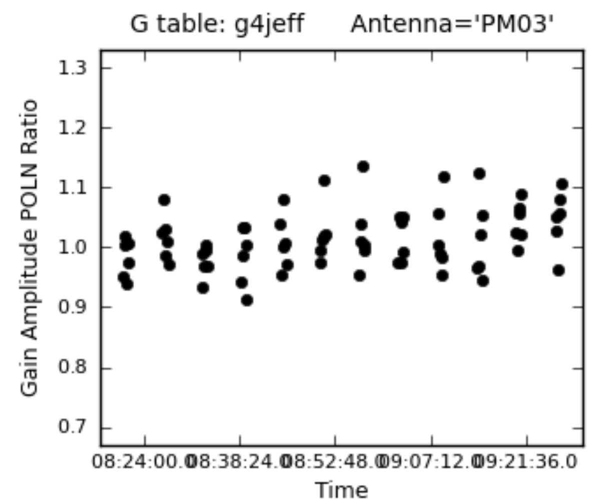
Amplitude Ratio XX/YY

- The amplitude ratio between XX and YY of J0522-364 for each antenna.
- The ratio is indicative of the SNR of each 10 second integration and differences in the instrumental gain of the XX and YY systems.
- Sky dependences should be removed.









Fomalont (2012)

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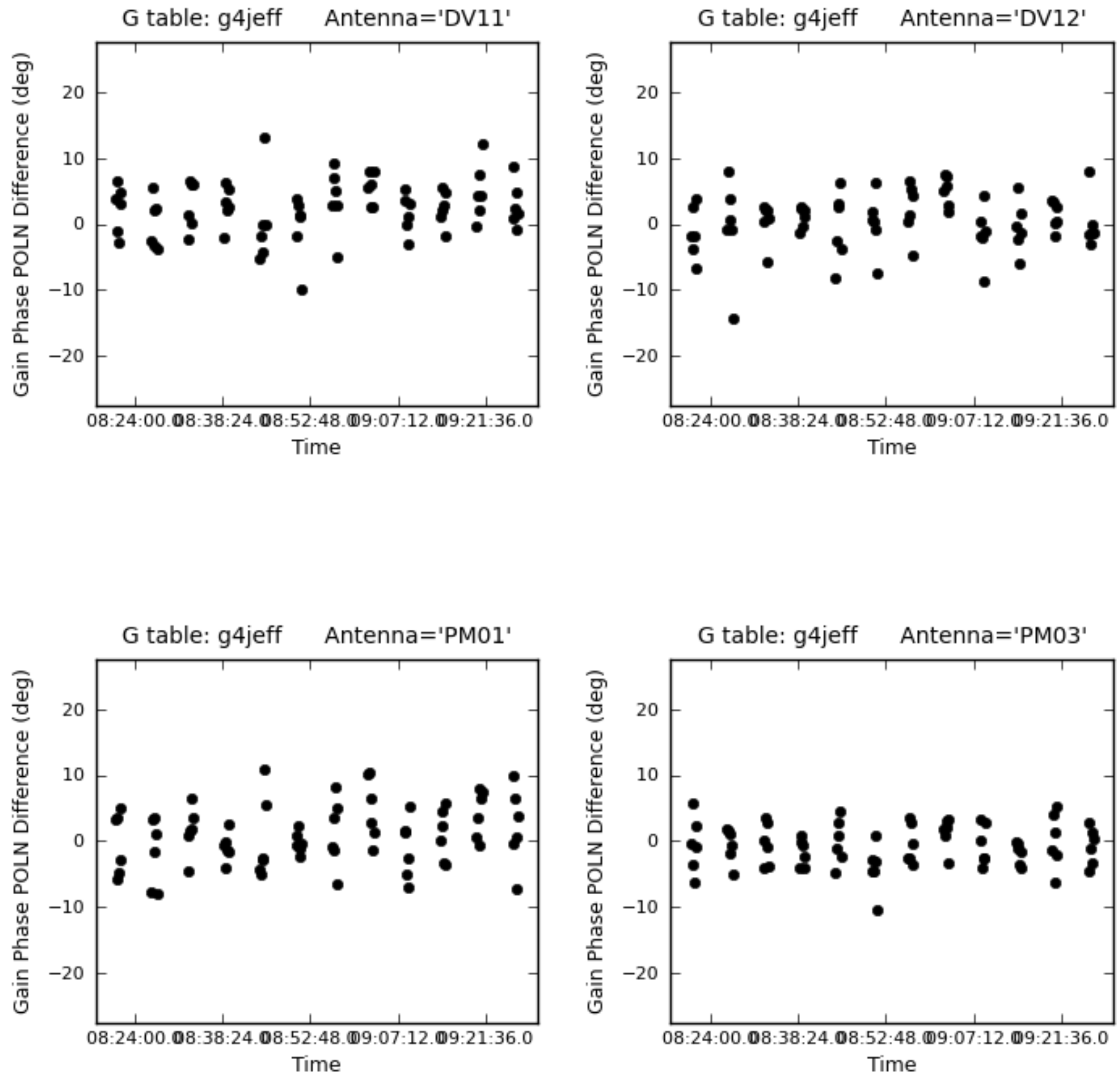
ALMA Phase Calibration at 660 GHz

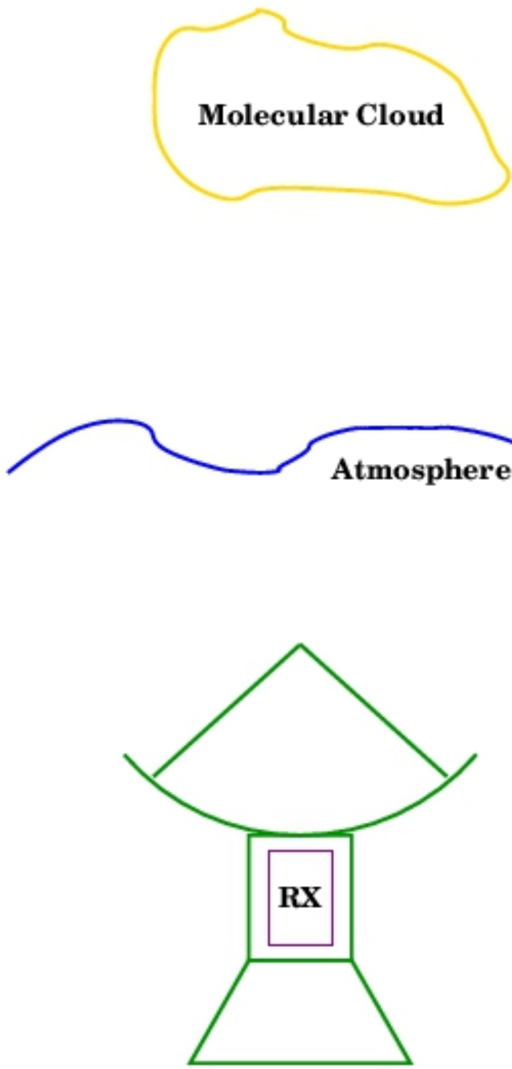
Phase Difference XX-YY

- The phase difference XX-YY for J0522-364 for each antenna.
- This difference is consistent with the expected noise for the source since tropospheric delay changes will cancel.



Fomalont (2012)

Amplitude Calibration

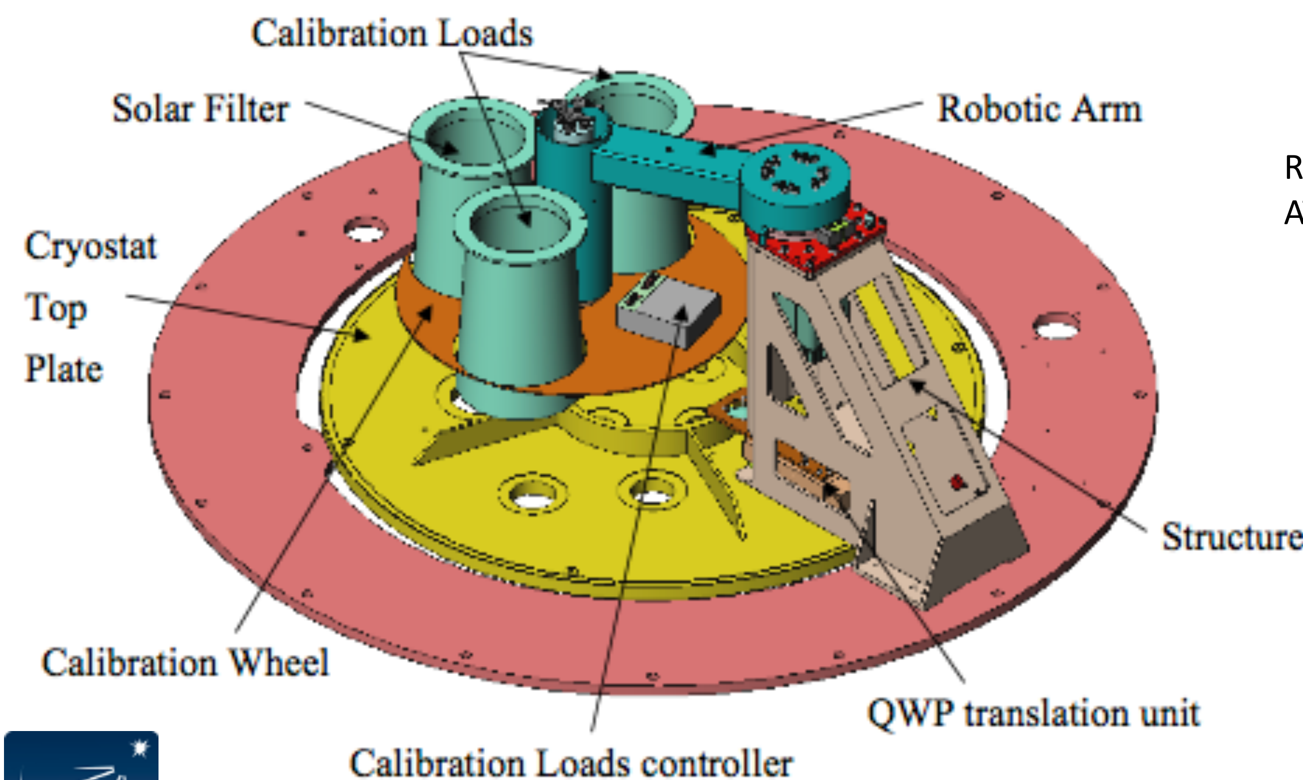


	Typical	ALMA Spec
$T_A^* \rightarrow T_R$ and S (Absolute)	>10%	5%
$T_A \rightarrow T_A^*$ (Relative)	5–10%	1% (< 370 GHz) 3% (> 370 GHz)
$TP \rightarrow T_A$ (Relative)	2%	<1%
Total Power (TP)	0.5%	0.01/0.3% over 1/300 sec

Dual-Load Amplitude Calibration System

Calibration Loads: T_{amb} and T_{hot} (50 – 100 C)
Solar Filter: Attenuator for solar observations
Quarter Wave Plate: For polarization calibration at Band 7 (optional)

$\sigma(T_L)$ = 0.3 K (amb) 0.5 K (hot)
$\sigma(\tau)$ = 1%
RF Mismatch < -60 dB



Requires measurement of τ_{atm}
ATM model and WVR input

Absolute Amplitude Calibration

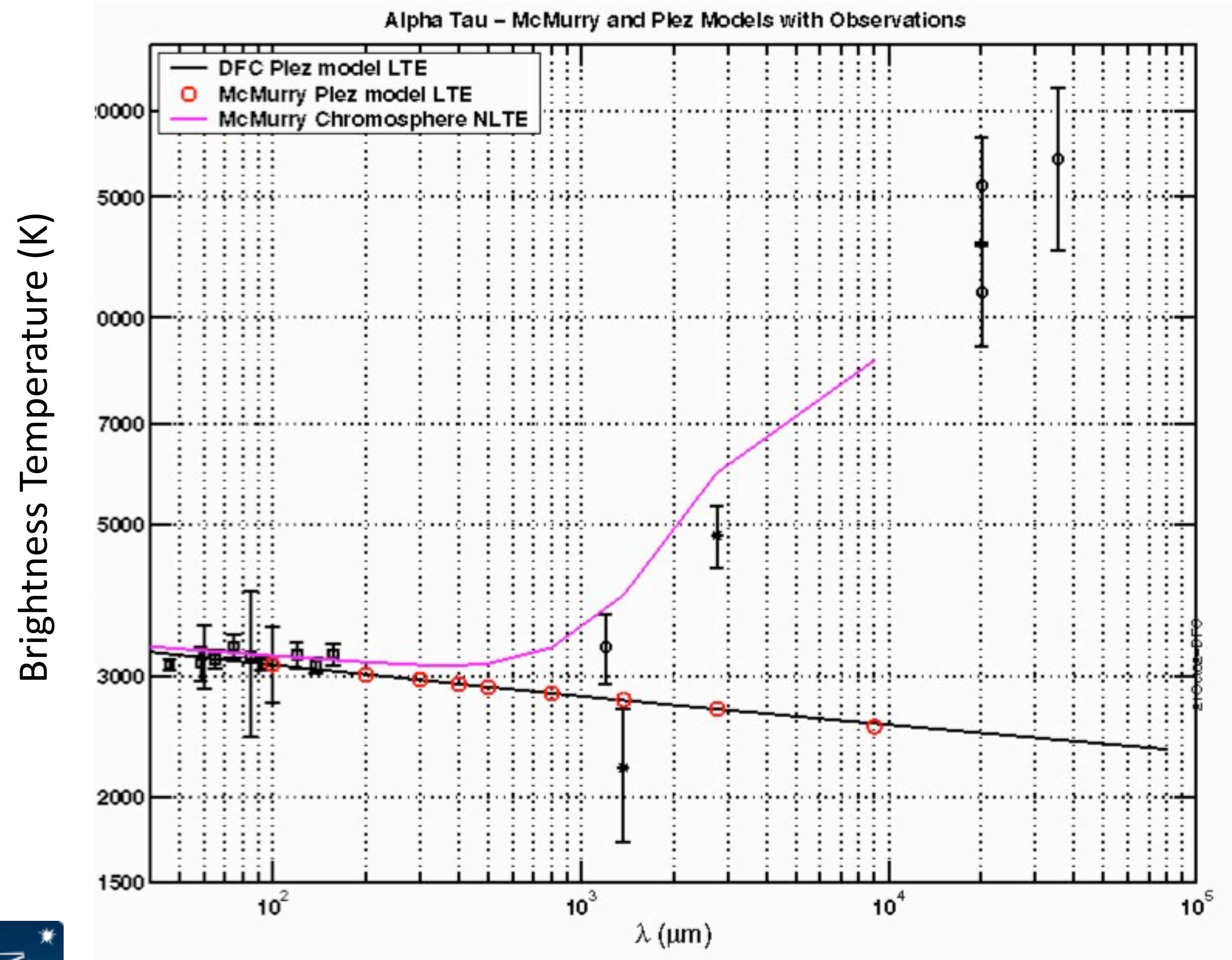
Historical and Potential Millimeter/Submillimeter Amplitude Calibrators

Source	Advantages	Disadvantages
Moon	Reasonably well modeled Bright	Too big Too much structure at nominal spatial resolution
HII Regions	Well modeled Bright	Too big (with structure)
Planets and Satellites	Well studied Bright	Best (Mars) no better than 5% (millimeter) Too big (Jupiter, Saturn, Mars, Venus) Phases (Venus) Too complicated (Mars: dust storms, polar caps) Poorly modeled (most except Mars)
Quasars	Radio flux standards well developed	Weak at millimeter/submillimeter
Asteroids	Simple (black bodies) Bright	Time variable fluxes (Ceres: ±4% interday) Poorly modeled in submillimeter Poorly known physical dimensions
Cool Giant Stars	Simple (RJ emission) Point sources Multiple sources distributed over sky	Weak(?) Active chromospheres(?)

Cool Giant Stars as Absolute Amplitude Calibrators

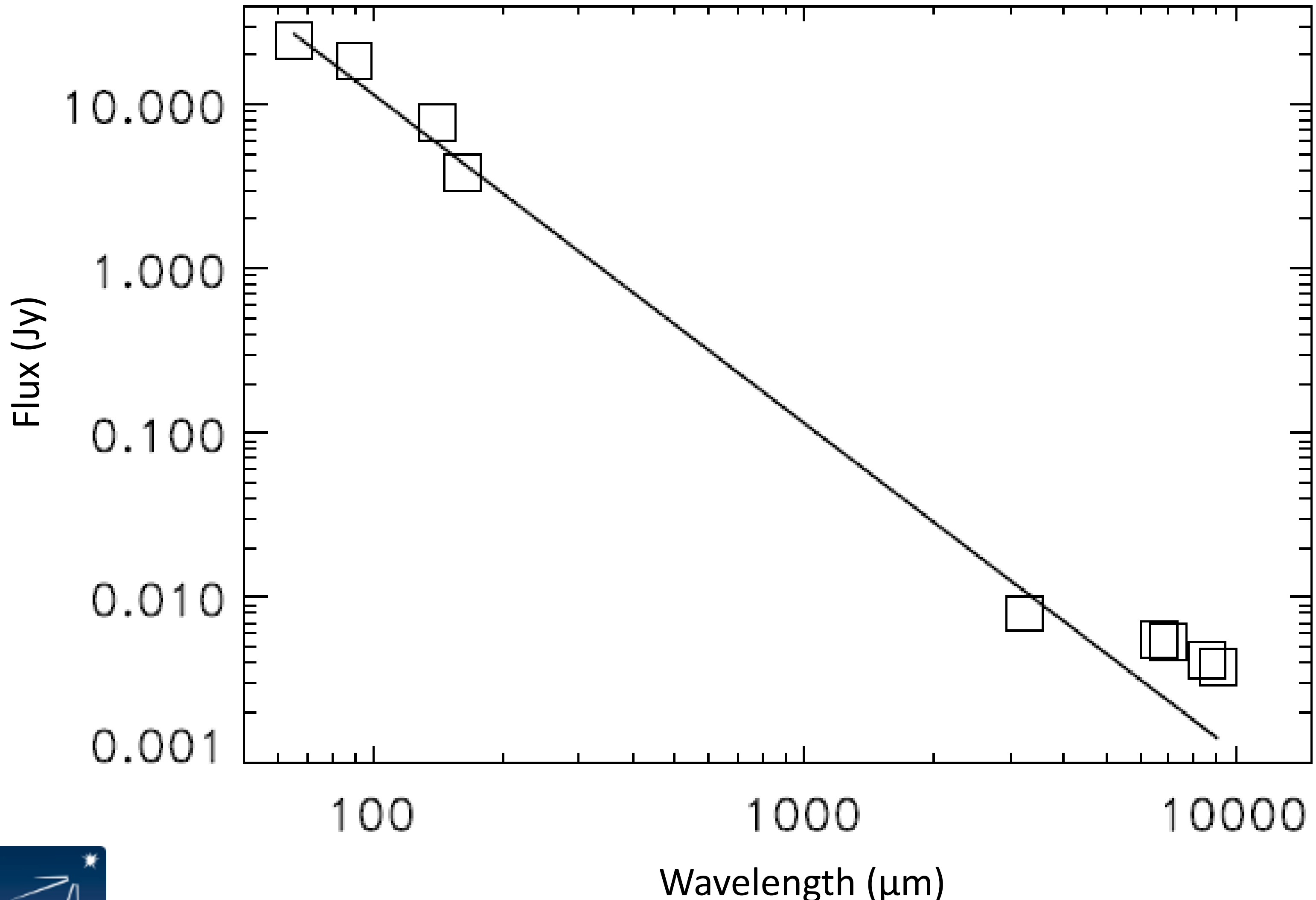
- Well established MIR and FIR absolute calibrators (ISO, MSX, AKARI, FIS)
- Absolute NIST-based calibration to 1.1% (MSX radiometric sphere measurements) at 8-21 μm
- Radiative photosphere extrapolation to 240 μm for ISO ISOPHOT calibration found to mesh well with planetary flux standard (Schultz etal. 2002)
- FIS (65 – 160 μm) absolute calibration using extrapolated RJ fluxes (Shirahata etal. 2009)
- Millimeter/Submillimeter properties a "mixed bag"
    - Altenhoff etal. (1994) surveyed 270 stars at 1.2 mm which included 37 cool giants (15 detected).
    - Most of these 15 stars present 1.2 mm emission which is larger than predicted (active chromosphere)
    - αTau and αBoo measured at 1.4 and 2.8 mm (Cohen etal. 2005) suggests active chromospheric emission at $\lambda > 100$ μm
    - γCru (closest M giant) appears to be a simple RJ radiator out to $\lambda \approx 5$ mm
    - Ultraviolet/optical studies suggest that chromospheric activity declines for later spectral types (i.e. M)

αTau



Cohen etal. (2005)

γ Cru



Cohen etal. (2012)

Summary

- The ALMA calibration specifications present a major challenge to many aspects of radio astronomical instrumentation development and measurement techniques.
- Good progress has been made toward verifying the ALMA calibration specifications.
- A remaining challenge is the absolute amplitude calibration specification, which is in many ways a research project requiring input from ALMA measurements.