Calibration of the Atacama Large Millimeter Array

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

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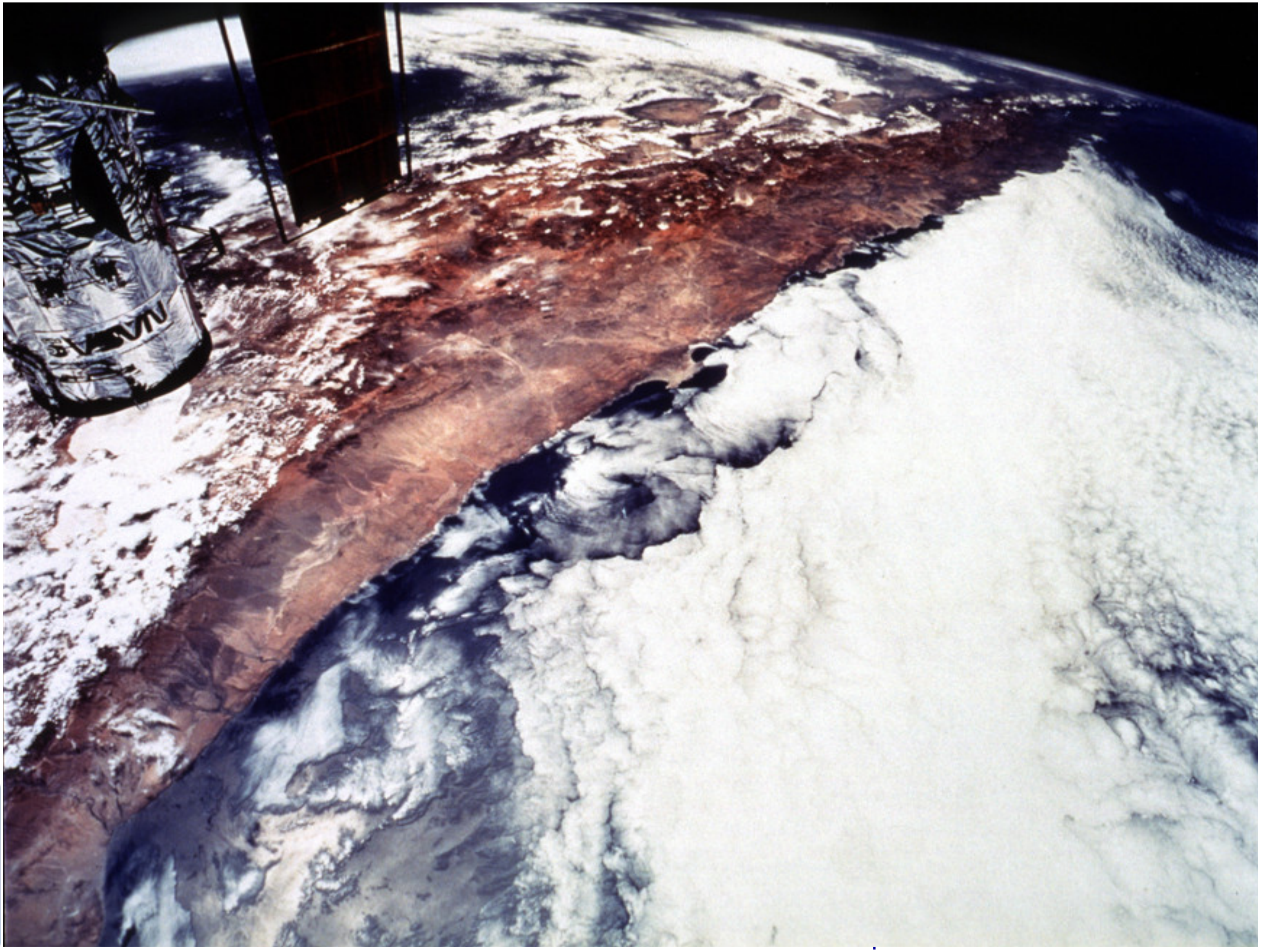
ALMA Key Science Goals

- Detect CO or CII in a normal galaxy like the Milky Way at a redshift of 3 in less than 24 hours
- Image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars in the nearest (d = 150 pc) molecular clouds
- Provide precise high-dynamic range images at an angular resolution of 0.1 arcsec

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

Atacama Desert as Seen from Shuttle/HST



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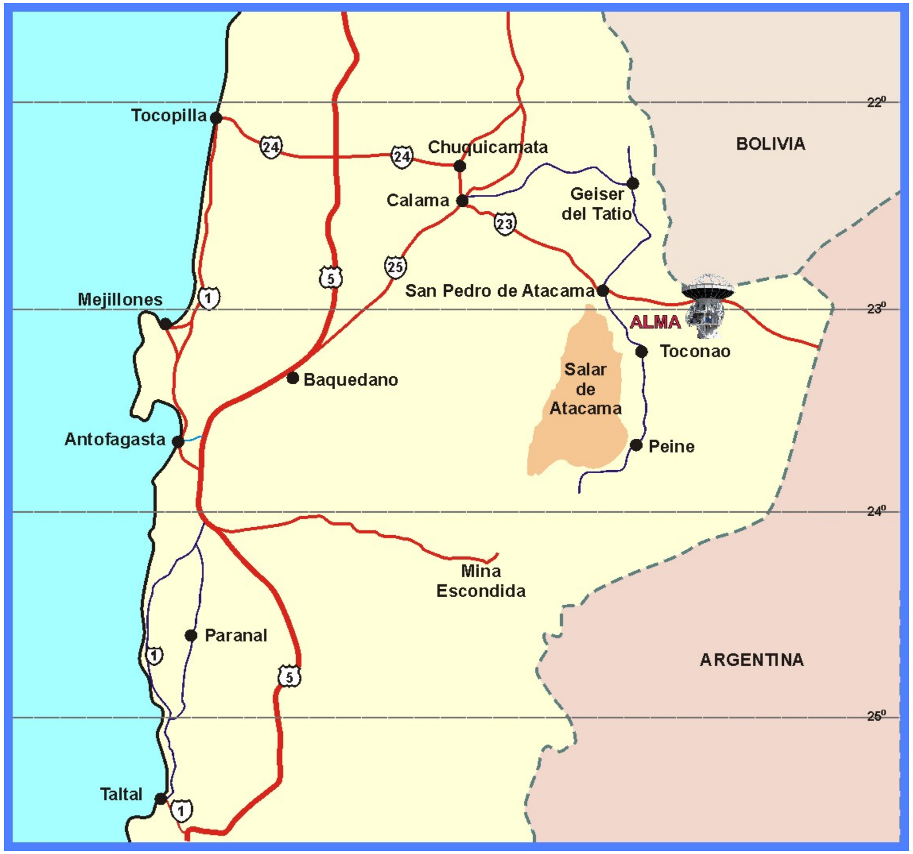
ALMA Site Location



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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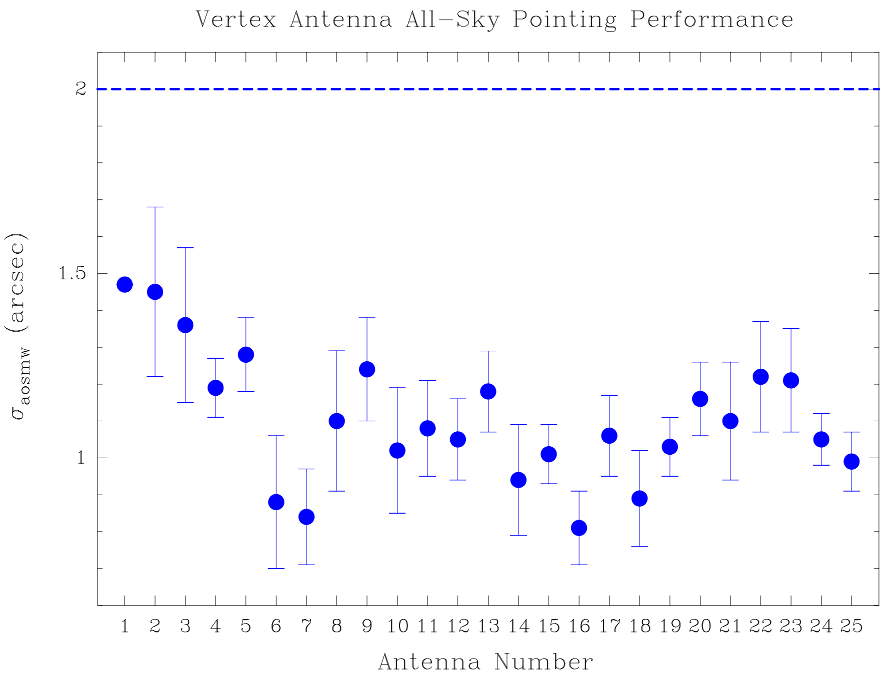
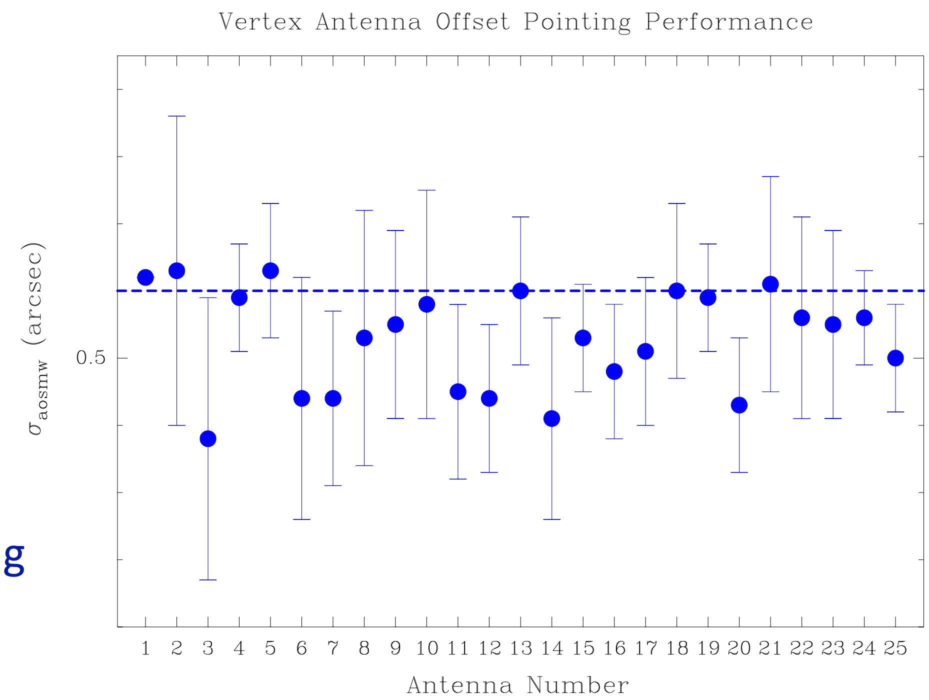
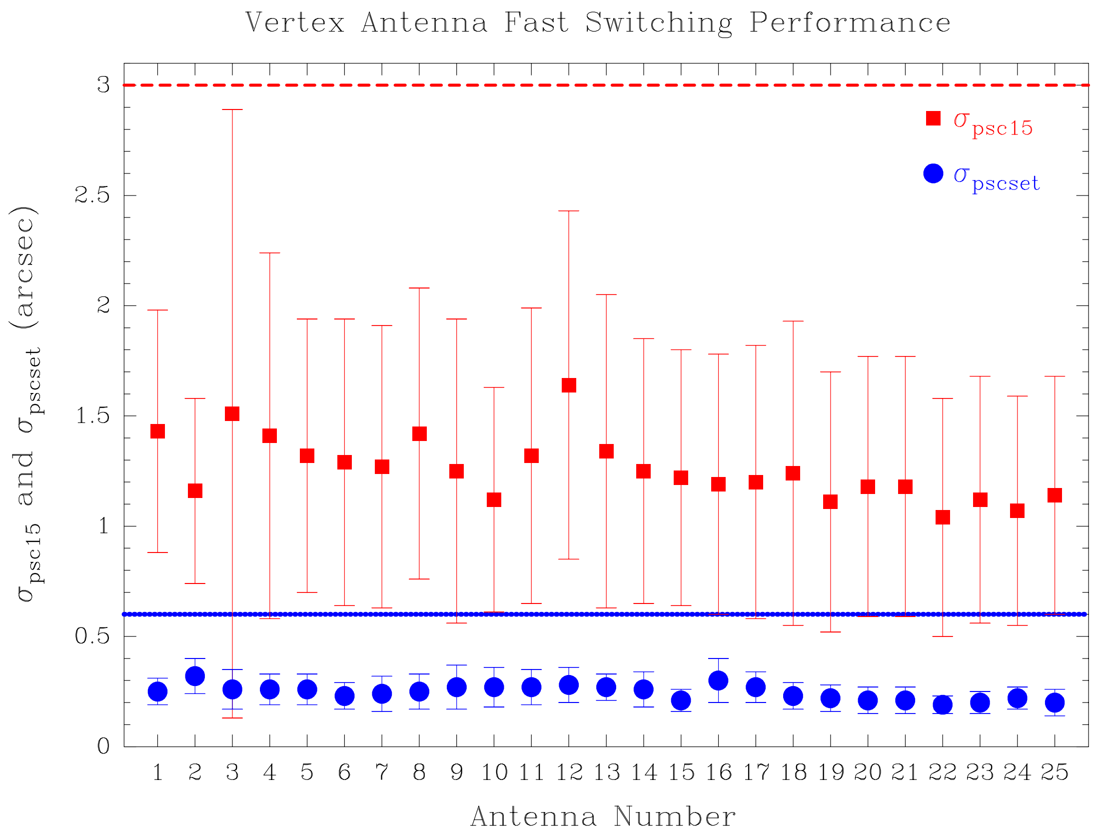
ALMA NA Antennas: Pointing Performance





- Optical Pointing Telescope results
- Radiometric all-sky results consistent
- Radiometric offset measurements pending

ALMA NA Antennas: Fast Switching Performance



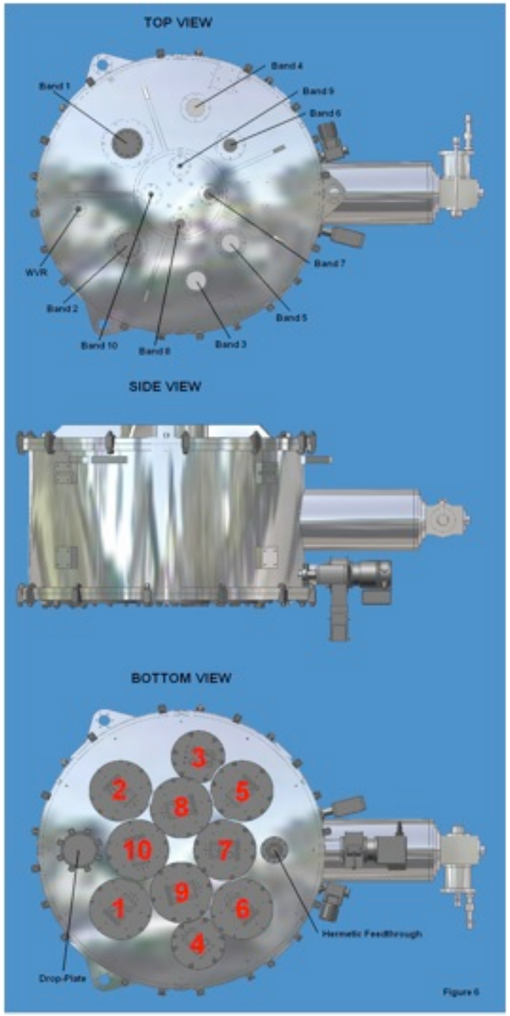
- Optical Pointing Telescope results
- Radiometric measurements pending

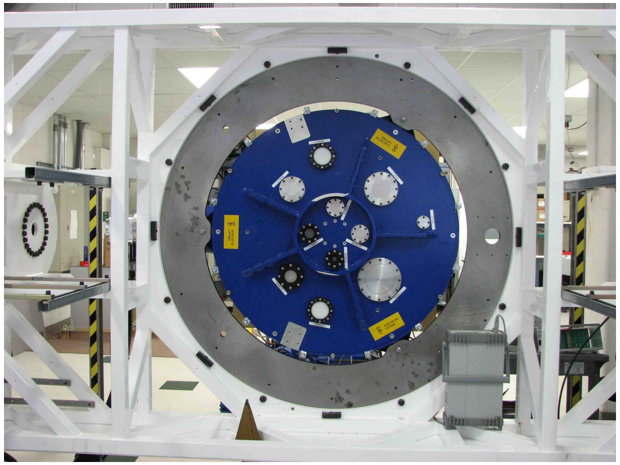
ALMA Antennas Delivery Status

- 58 antennas delivered and integrated
  - North American (Vertex): 25 of 25
  - European (AEM): 17 of 25
  - East Asian (Melco): 4 of 4 (12m) and 12 of 12 (7m)
- 58 antennas in use at the AOS (late-March 2013)
- Performance based on contractor acceptance testing meets specifications

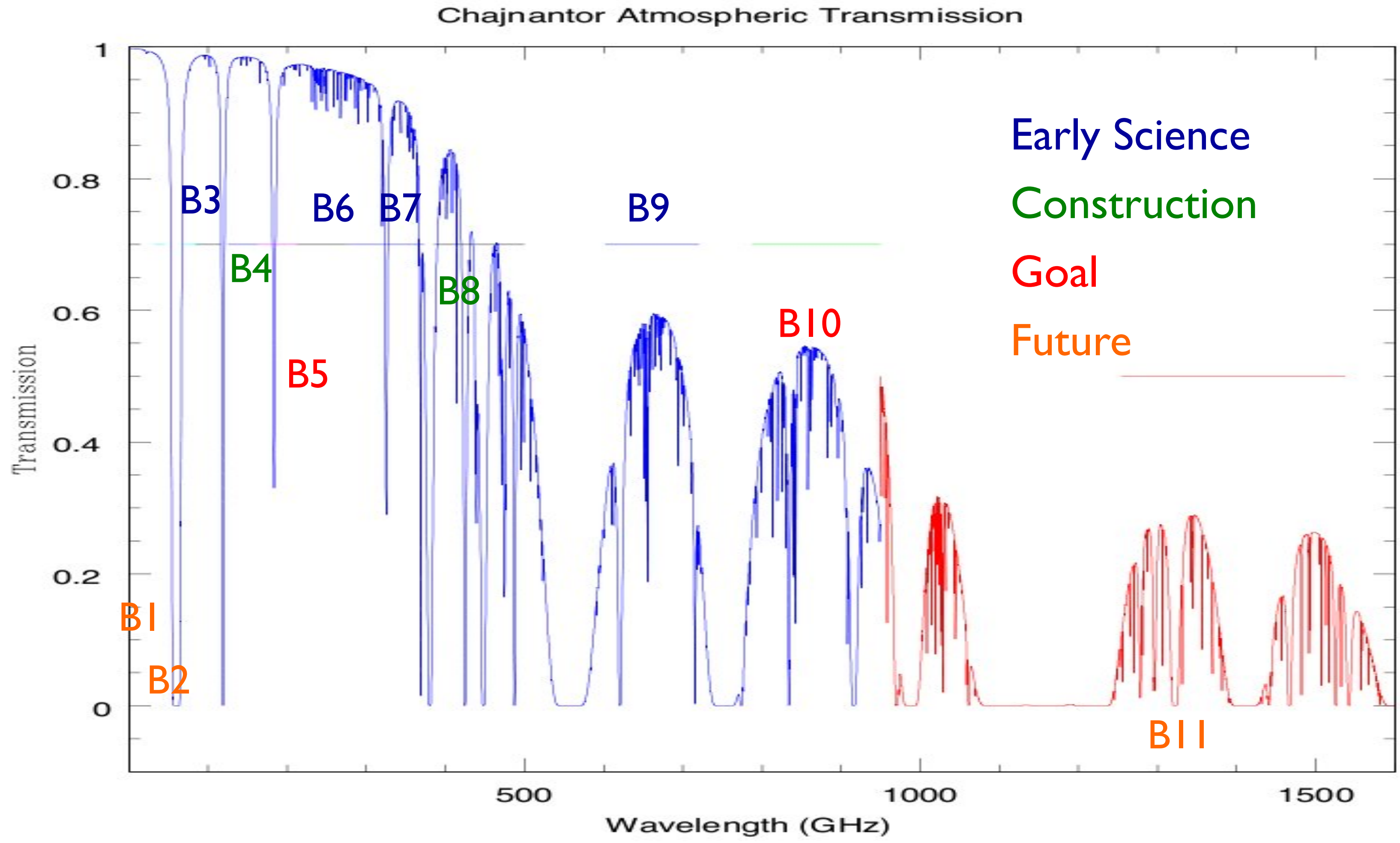
ALMA Receivers

- 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

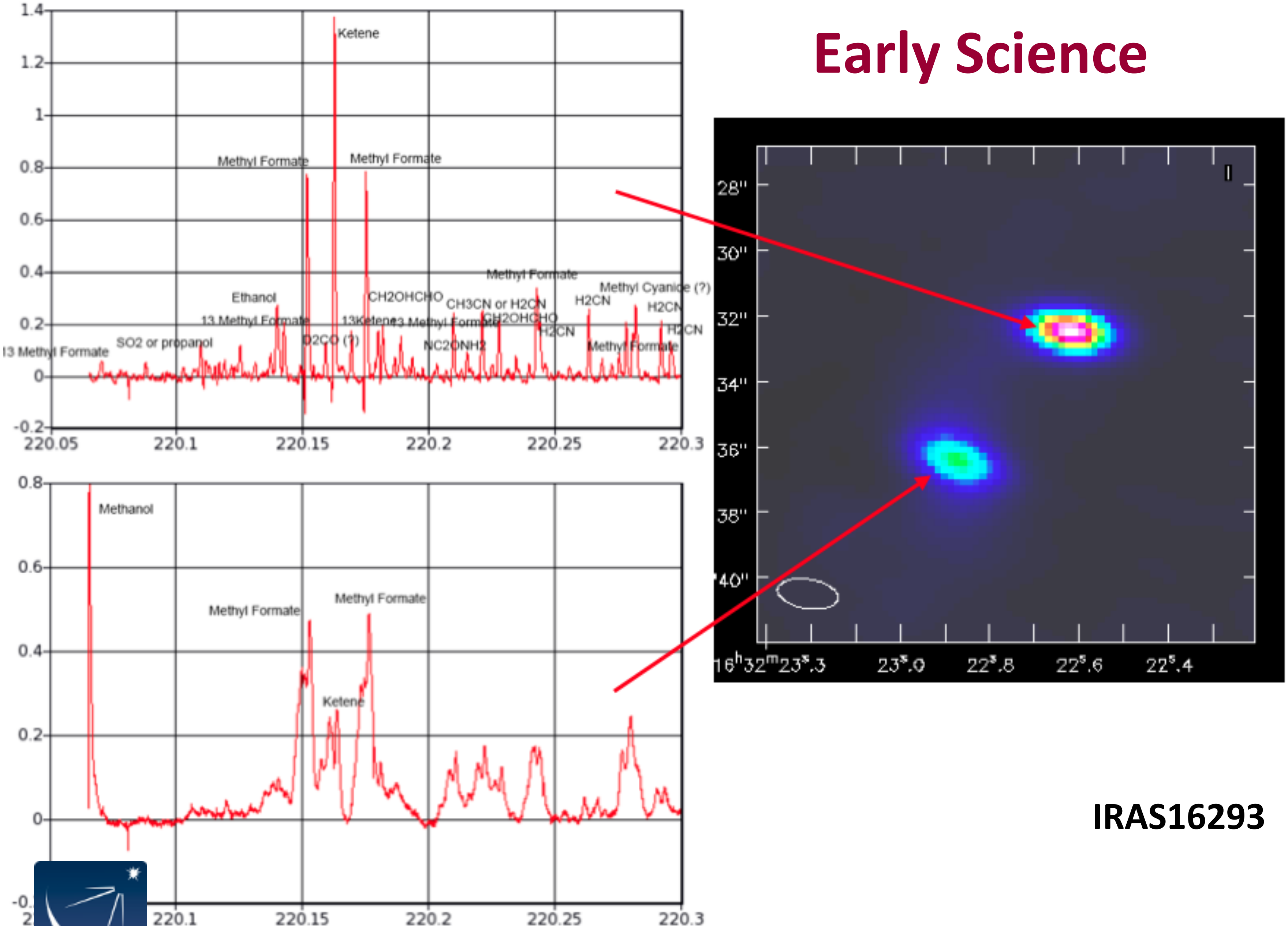


Early Science

The Antennae Galaxies

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

Early Science

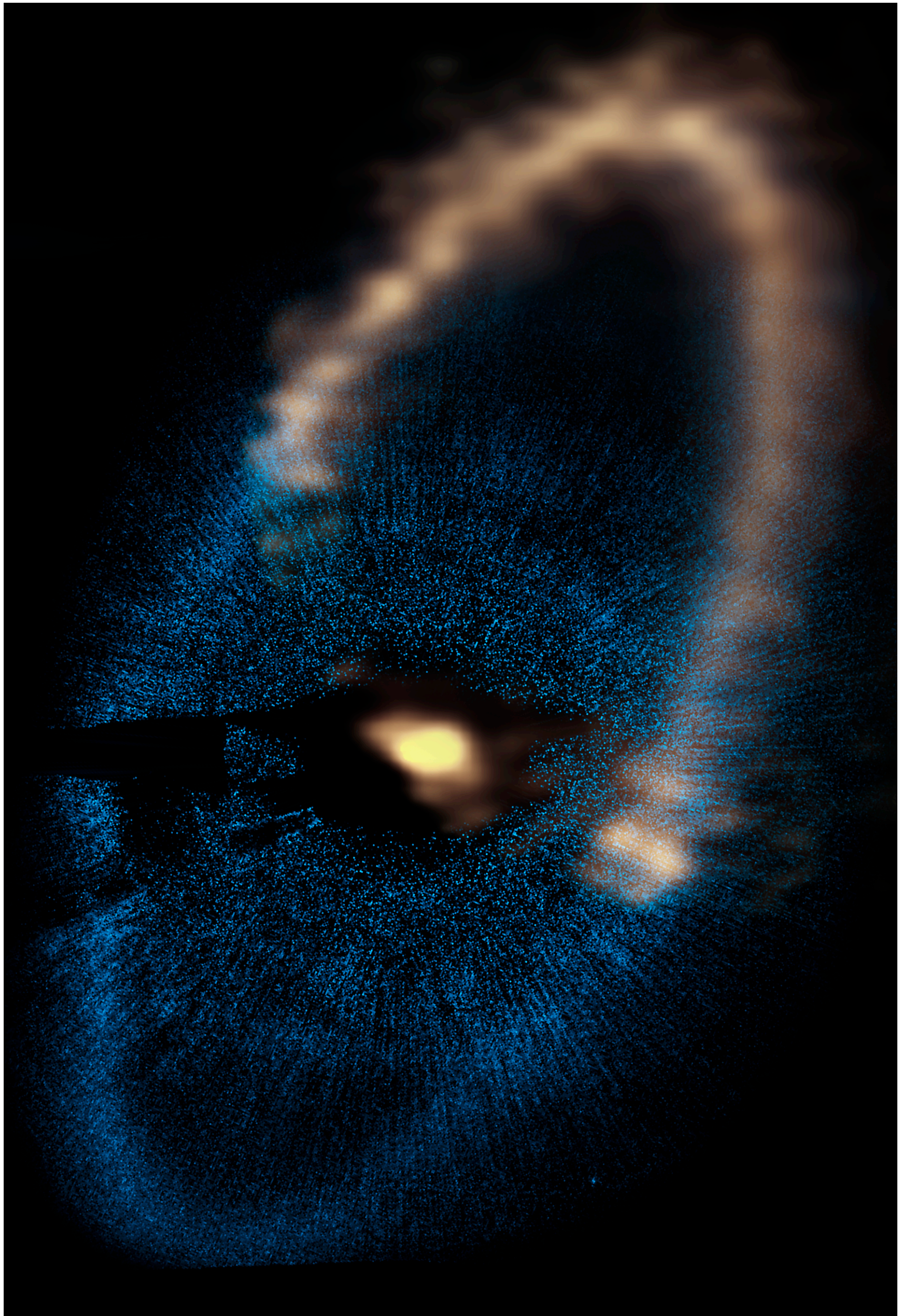


IRAS16293

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



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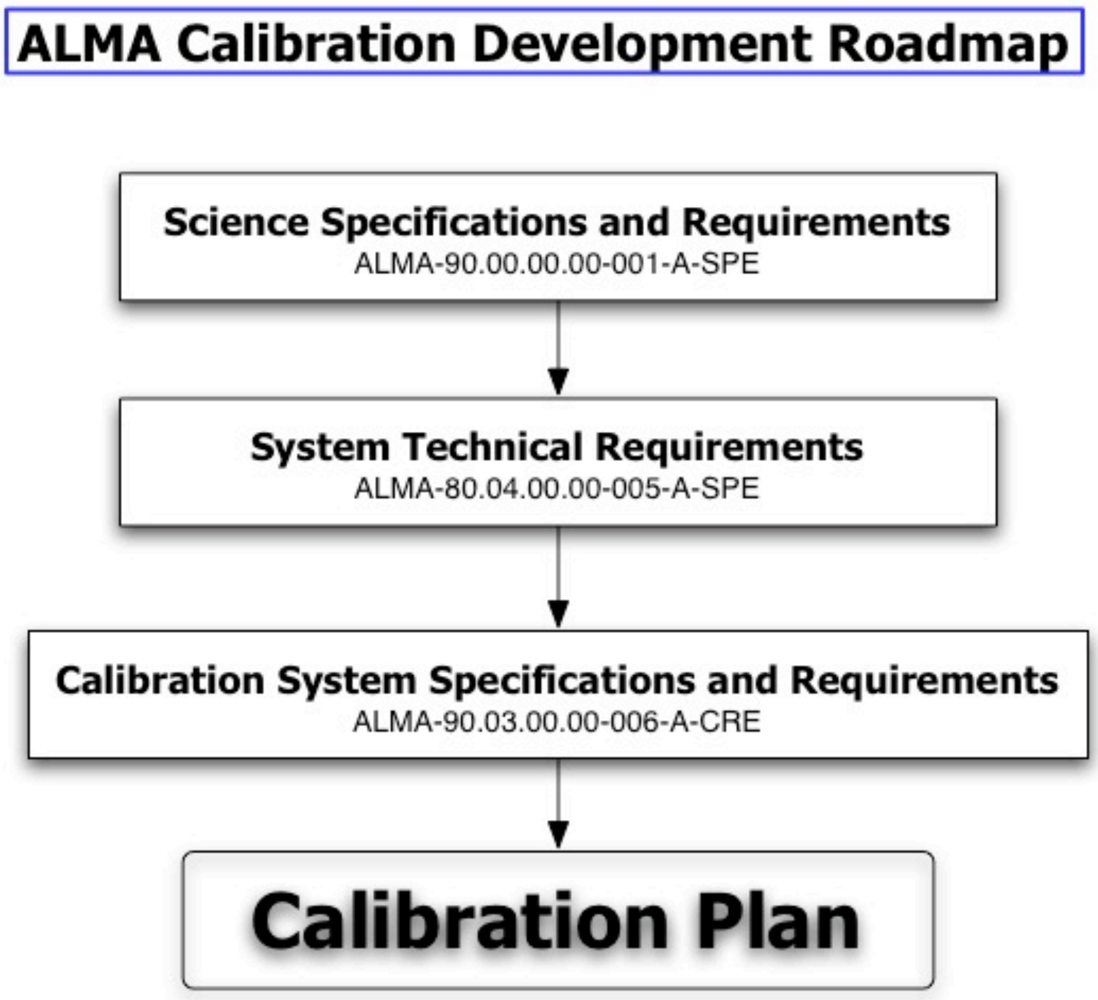
ALMA Operations Timeline 2012-2013

- 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

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 / $\nu \geq$ 370 GHz)
Amplitude (Absolute)	5% (all frequencies)
Corrected Visibility Phase	< 57 deg at 950 GHz for timescales < 10 seconds

ALMA Calibration Development



ALMA Calibration Types

Operations/Maintenance Calibration

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

User Calibration

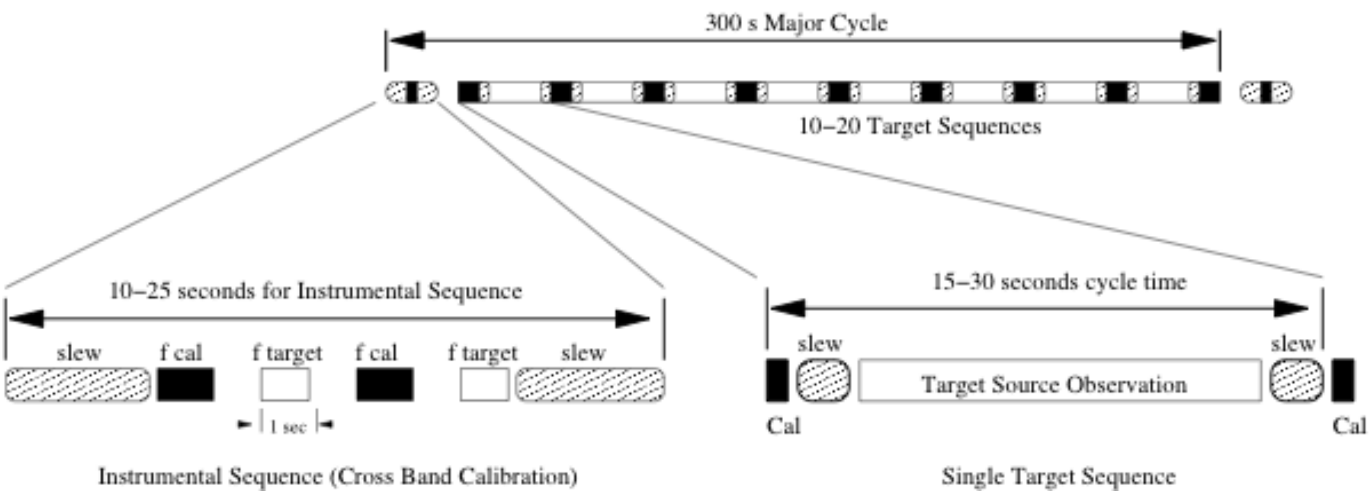
- Reference Pointing
- Amplitude
- Phase
- Bandpass
- Polarization

Phase Calibration

- *Target Sequence:* Over a period of 15 to 30 seconds the following measurement sequence is observed involving the target and phase calibration source located typically less than or equal to 2 degrees away from the target source:
    1. Tune to the calibration frequency if cross-band calibration required.
    2. Phase calibrator measurement (tint ≤ 1 second).
    3. Tune to the source frequency if cross-band calibration required.
    4. Target source measurement (tint ≤ 25 seconds).
    5. Tune to the calibration frequency if cross-band calibration required.
    6. Phase calibrator measurement (tint ≤ 1 second).
- *Instrumental Sequence:* This cycle of measurements is required for cross-band calibration of dual-frequency fast switching measurements. Over a period of 10 to 25 seconds a strong phase calibrator source which can be detected at both the target and calibration frequency is used to provide the phase scaling from the target (usually higher) frequency to the calibration (usually 90 GHz) frequency:
    1. Tune to calibration frequency.
    2. Phase calibrator measurement (tint ≤ 1 second).
    3. Tune to target frequency.
    4. Phase calibrator measurement (tint ≤ 1 second).
    5. Repeat this sequence.

Phase Calibration Sequence

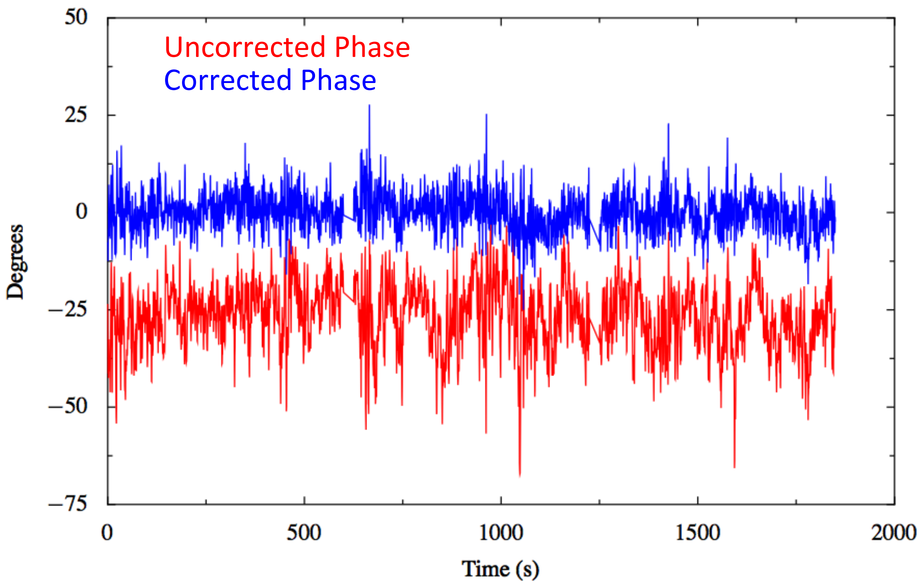
- Measure system phase by monitoring a relatively strong phase-stable signal outside the Earth's atmosphere (i.e. quasar).
- Monitor phase stability as a function of time on both short (fast switching) and long (phase monitoring) timescales.
- For higher frequency bands (> 350 GHz) calibrator availability 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



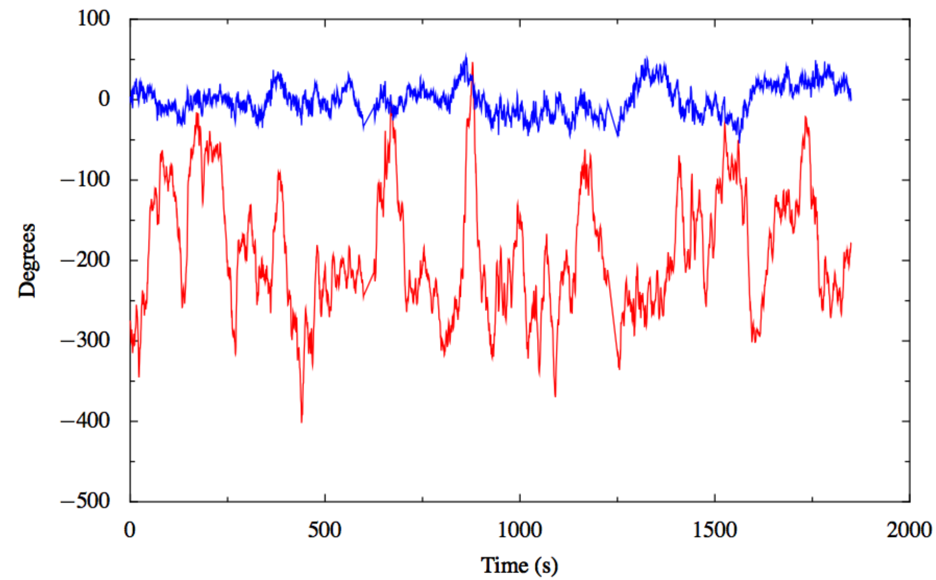
Water Vapour Radiometers (WVR)

- 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)

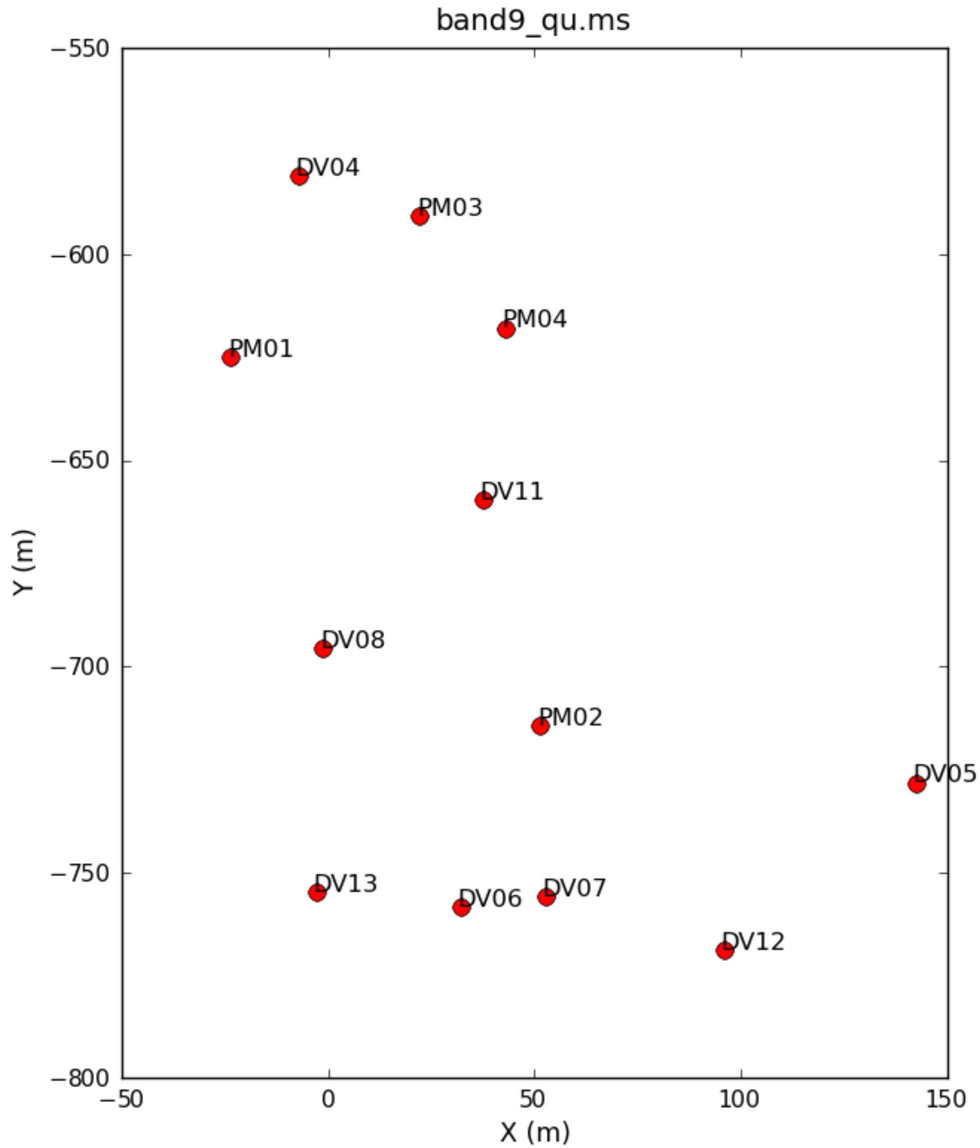
ALMA Phase Calibration at 660 GHz

- 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

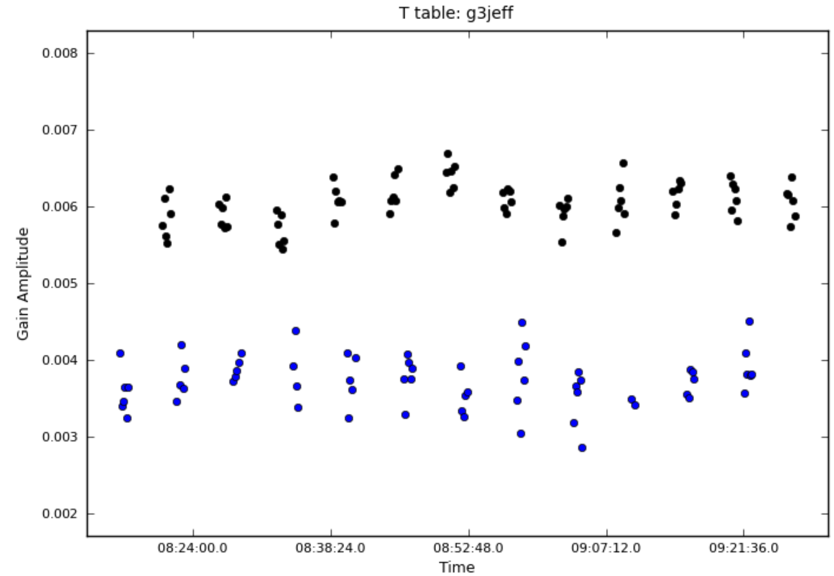


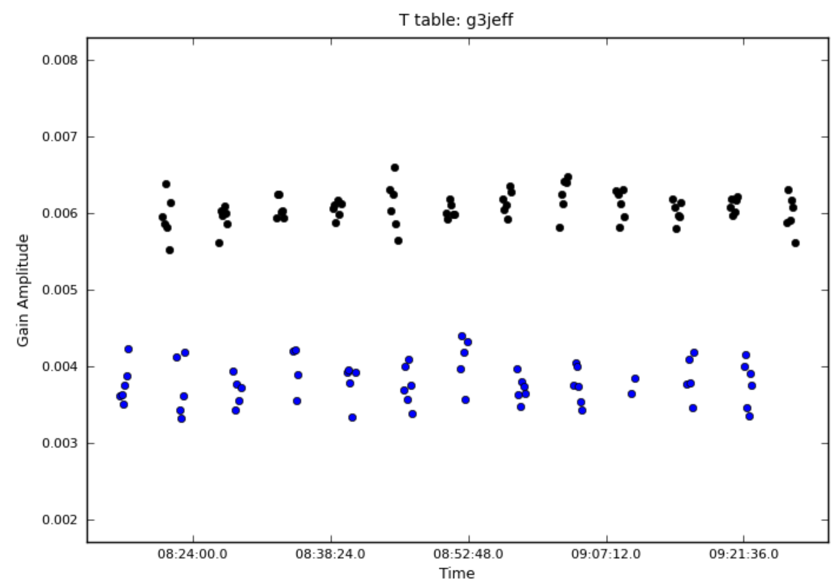
Fomalont (2012)

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.**



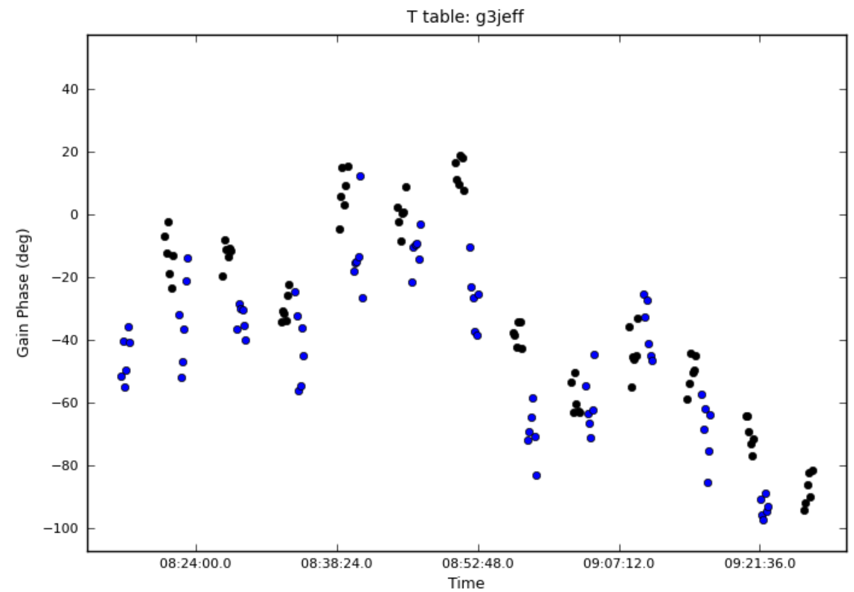


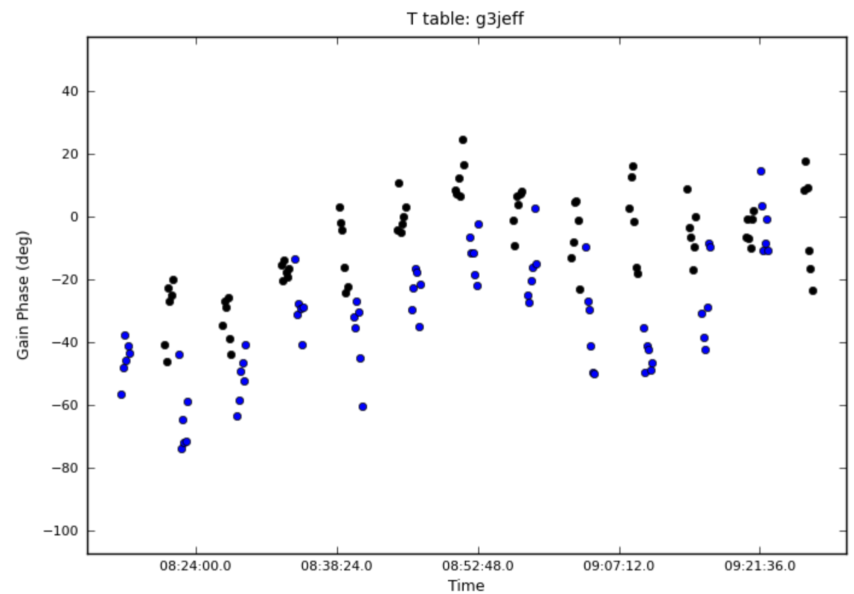
Fomalont (2012)

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.**



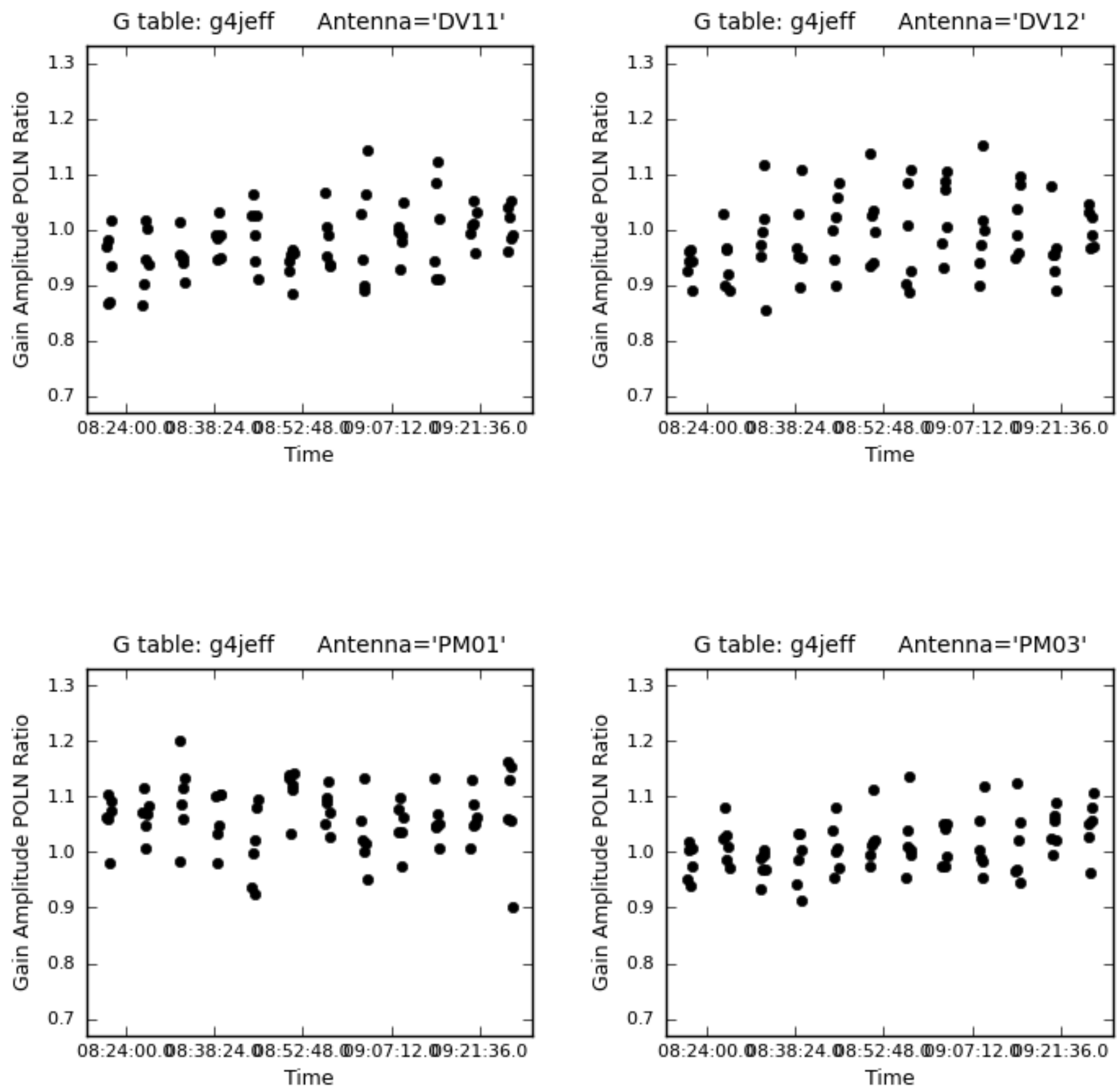


Fomalont (2012)

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.

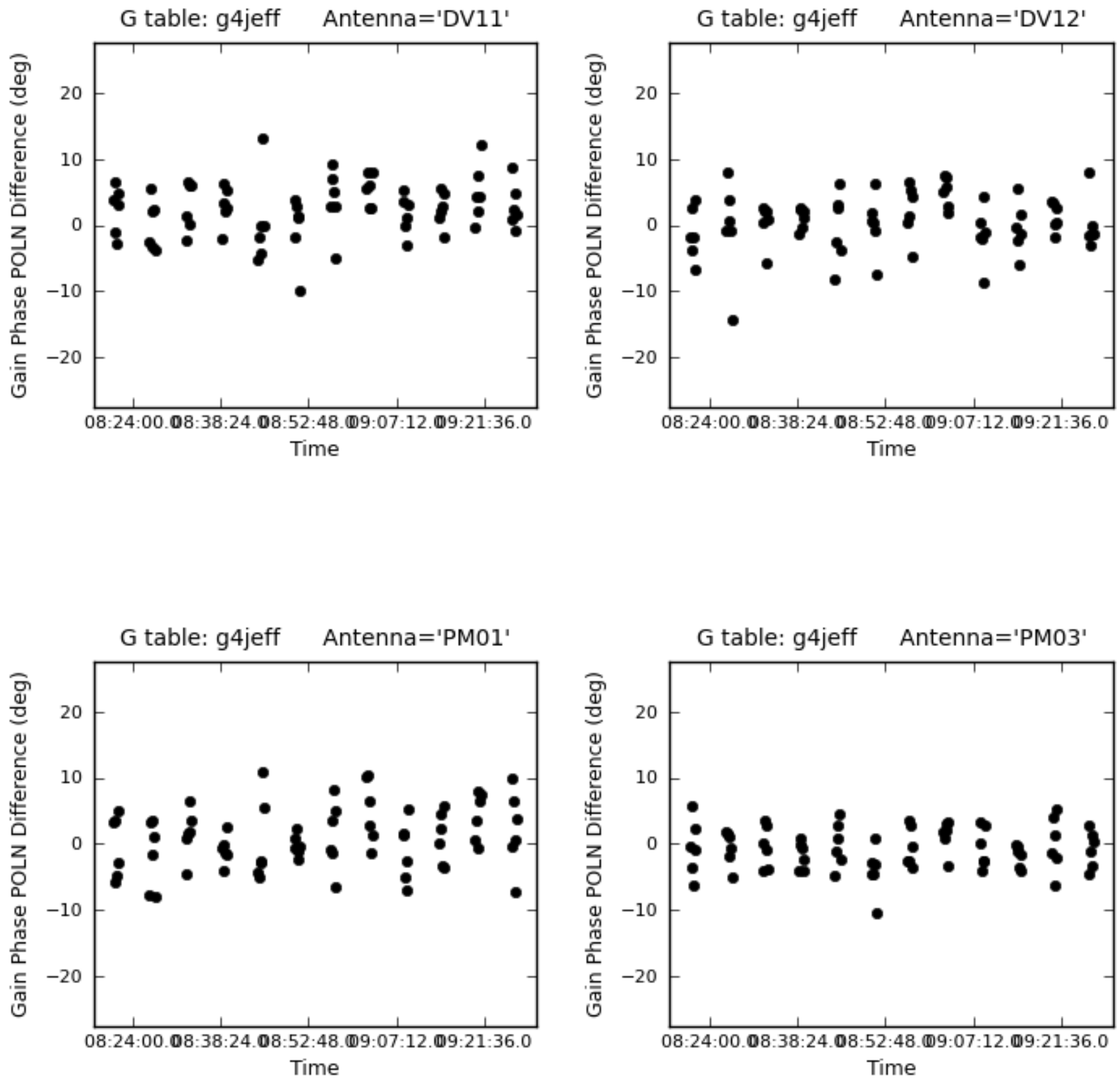


Fomalont (2012)

ALMA Phase Calibration at 660 GHz

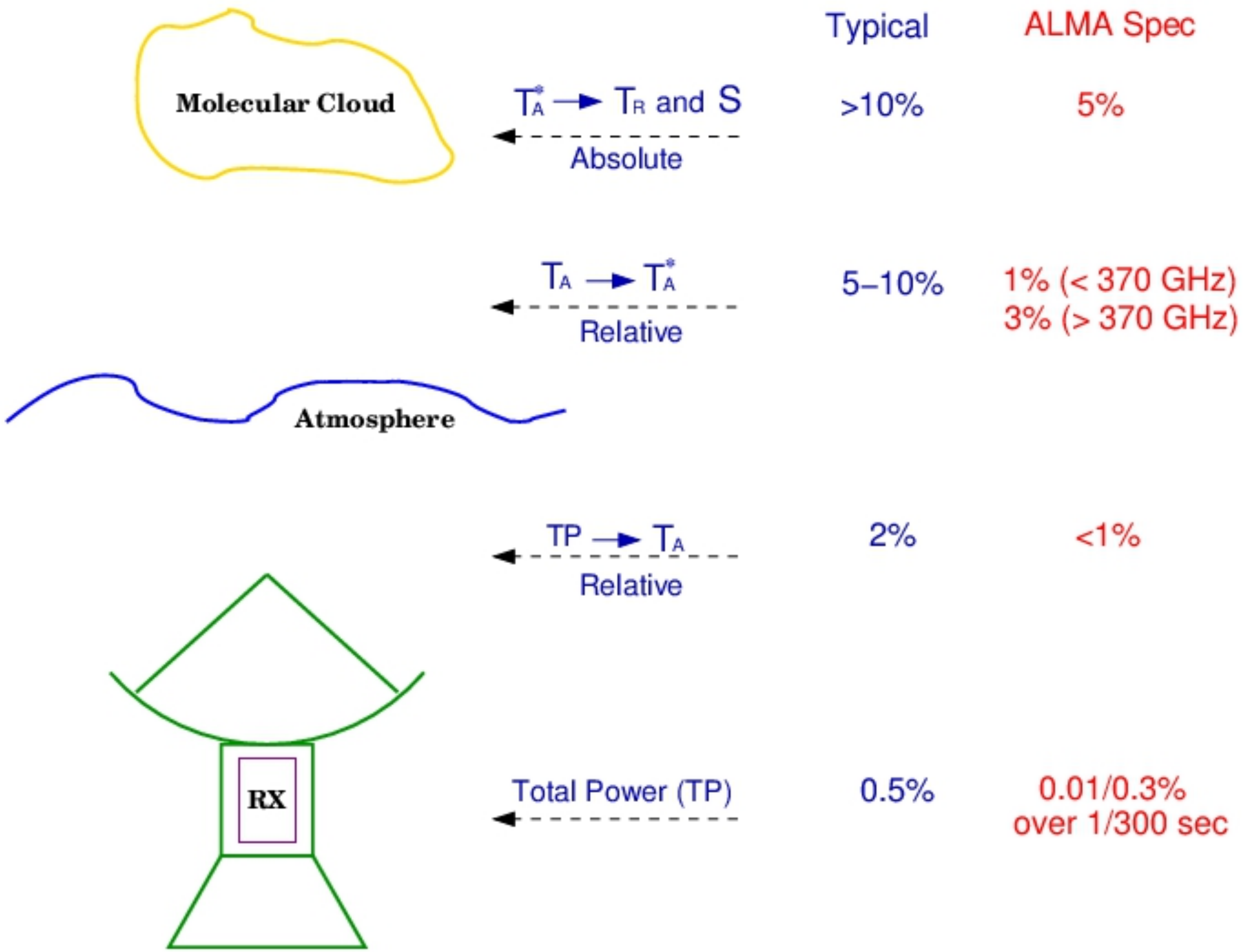
Phase Difference XX-YY

- 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



Multi-Load Amplitude Calibration Theory

Mangum (2002)

$$(T_A^*)^{two-load} = \left(\frac{V_{source} - V_{sky}}{V_{load1} - V_{load2}}\right) \left\{\frac{f_1\left[J^s_{load1} + R_i J^i_{load1}\right] + (1 - f_1)\left[J^s_{sky} + R_i J^i_{sky}\right]}{\eta_l \exp(-\tau_s)}\right\} - \left\{\frac{f_2\left[J^s_{load2} + R_i J^i_{load2}\right] + (1 - f_2)\left[J^s_{sky} + R_i J^i_{sky}\right]}{\eta_l \exp(-\tau_s)}\right\}$$

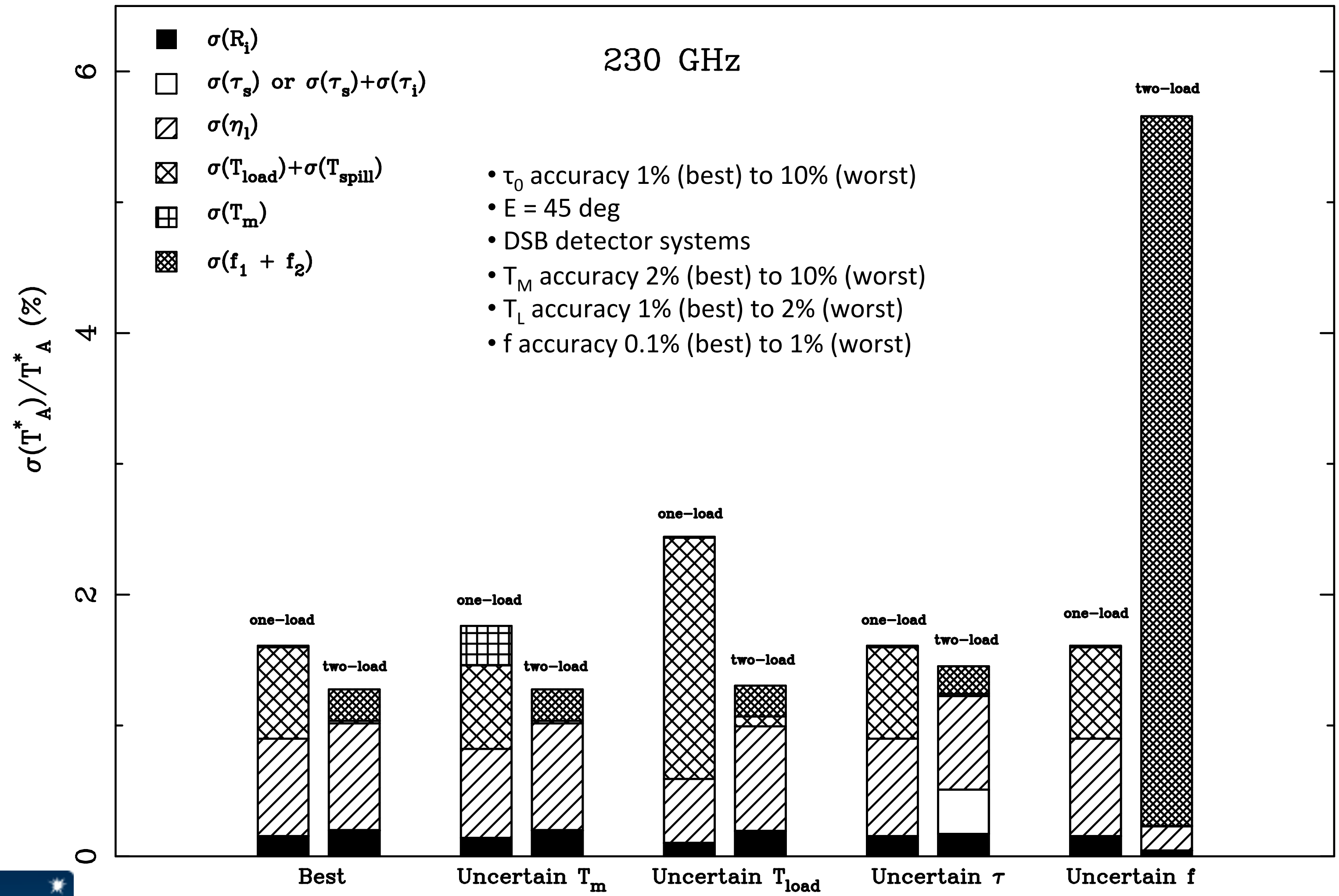
$$(T_A^*)^{one-load} = \frac{\Gamma}{\eta_l \exp(-\tau_s)}\Bigg[J^s_{load} - \eta_l J^s_m\left[1 - \exp(-\tau_s)\right] - (1 - \eta_l)\, J^s_{spill} - \eta_l J^s_{bg} \exp(-\tau_s) + R_i\Big[J^i_{load} - \eta_l J^i_m\left[1 - \exp(-\tau_i)\right] - (1 - \eta_l)\, J^i_{spill} - \eta_l J^i_{bg} \exp(-\tau_i)\Big]\Bigg]$$

$$\Gamma \equiv \frac{V_{source} - V_{sky}}{V_{load1} - V_{load2}}$$

$$V_{load1} = V_{load}$$

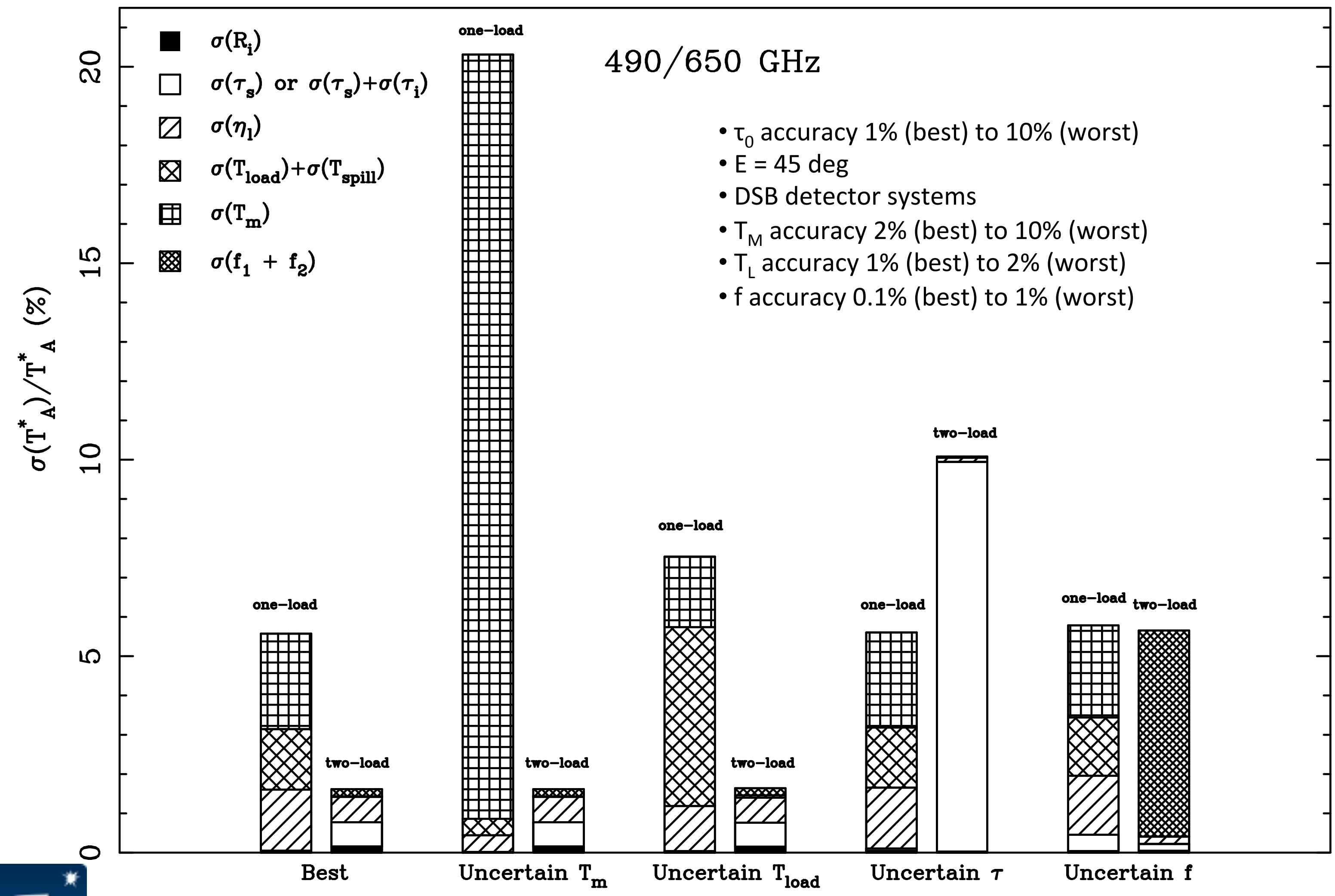
$$V_{load2} = V_{sky}$$

Multi-Load Amplitude Calibration Analysis



Mangum (2002)

Multi-Load Amplitude Calibration Analysis

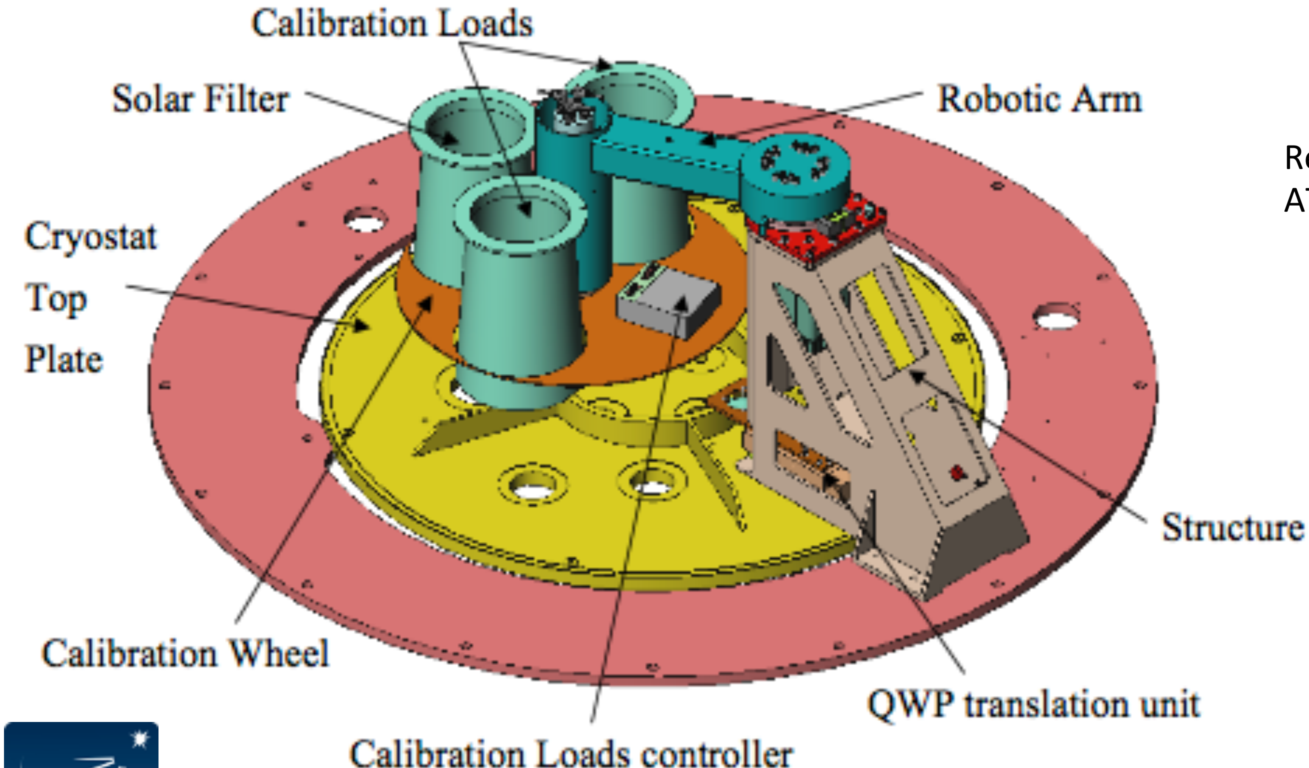


Mangum (2002)

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

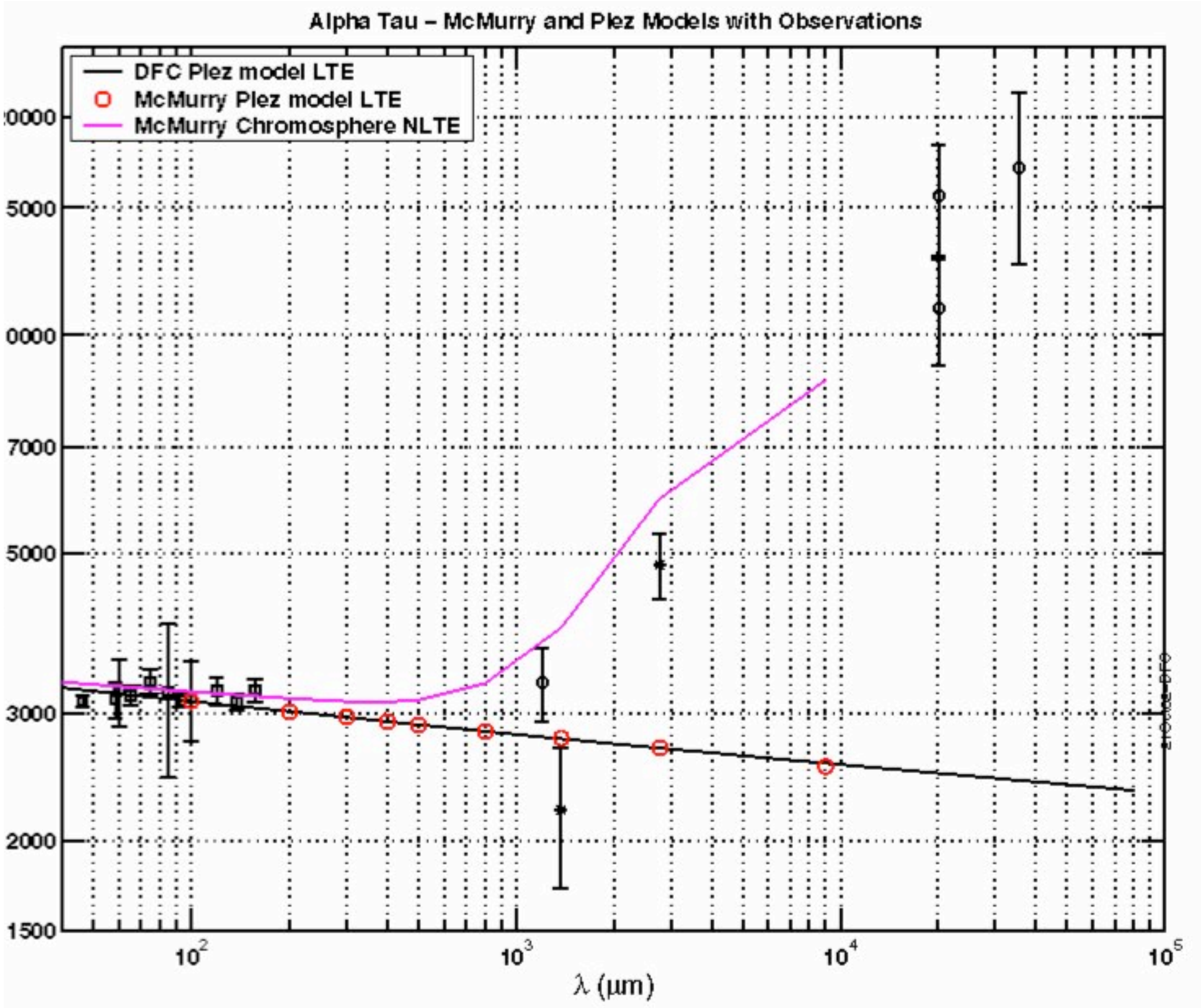
Source	Advantages	Disadvantages
Moon	Reasonably well modeled Bright	Too big Too much structure at nominal spatial resolution
HII Regions	Well modeled Bright	Too big (with structure)
Planets and Satellites	Well studied Bright	Best (Mars) no better than 5% (millimeter) Too big (Jupiter, Saturn, Mars, Venus) Phases (Venus) Too complicated (Mars: dust storms, polar caps) Poorly modeled (most except Mars and Uranus)
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)

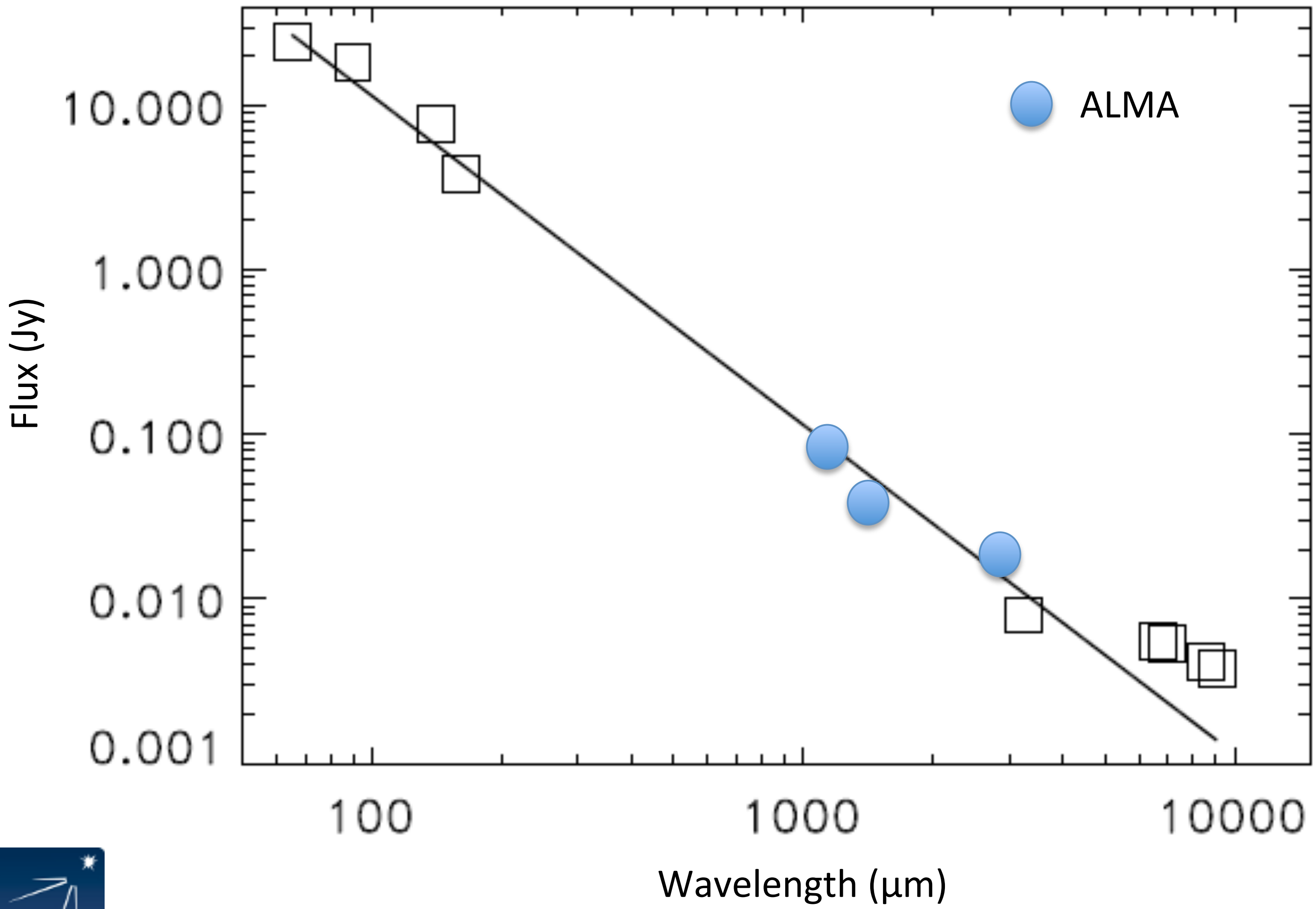
αTau

Brightness Temperature (K)



Cohen etal. (2005)

γ Cru



Cohen etal. (2013)

ALMA Amplitude Calibration Studies

- Most extensive measurements of potential flux density calibrators done during a single 24 hour long calibration run observed in October 2012.
- Includes measurements of cool giants Gamma Crux and HD71229.
- CASA (Common Astronomy Software Applications) 4.0 included (vastly) improved flux density models for solar system bodies (ALMA Memo 594 by Bryan Butler).
  - Galilean satellites.
  - Asteroids still poorly modeled.
  - Does not include a good model of the galactic background (should be able to derive this from Planck all-sky measurements).
- Relative calibration of Neptune and Uranus good to approximately 3-5%.
- No measurements of potential asteroid flux calibrators.
- May be able to use selected quasars as relative amplitude calibrators over less than 2 week timescales.

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ALMA Amplitude Calibration Studies

RATIO OF CALIBRATED/MODEL FLUX DENSITIES OF SS-OBJECTS

	spw 0	spw 1	spw 2	spw 3		
Band 3 frequencies:	97.5,	98.5,	109.0,	110.5	GHz	
Band 6	214.0,	212.6,	229.5,	228.0	GHz	
Band 7	350.0,	348.5,	336.5,	338.0	GHz	sidebands switched in this band

Solar system obj	Band 3		Band 6		Band 7		Comments
	Flux	DATA/MODEL	FLUX	DATA/MODEL	Flux	DATA/MODEL	
Uranus	11.0	1.00(----)	36.0	1.00(----)	66.0	1.00(----)	Amplitude reference
Neptune	3.6	1.04(0.04)	12.6	1.01(0.02)	27.0	1.08(0.02)	LSB
	4.4	1.01(0.04)	14.3	1.07(0.02)	28.0	1.10(0.03)	USB
Mars	32.0	1.07(0.03)	130.0	1.02(0.02)	300.0	0.98(0.04)	
Ganymede	1.6	1.04(0.03)	7.0	1.03(0.03)	17.0	0.99(0.04)	Jupiter Interference?
Callisto	1.6	1.09(0.04)	7.4	1.03(0.03)	18.0	1.01(0.04)	Jupiter Interference?
Ceres	0.35	0.94(0.02)	1.5	0.94(0.02)	3.7	0.94(0.02)	
Pallas	0.19	1.02(0.04)	0.8	0.98(0.02)	1.8	0.99(0.02)	
Vesta	0.13	0.75(0.06)	0.4	0.74(0.02)	1.1	0.73(0.02)	
Titan	0.30	--	0.8	0.98(0.03)	1.6	1.06(0.02)	Saturn Interference
Mercury	50.0	--	250.0	--	650.0		No Model
Venus	550.	1.05(0.02)	1500.	0.85(0.08)	<2000.0	0.80(0.20)	Very resolved, bright
Juno	<0.01	--	0.03	1.3 (0.2)	0.07	1.4 (0.3)	
BEST FIVE		1.04(0.03)		1.02(0.02)		1.00(0.02)	

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, though amplitude calibration characterization just beginning.
- A remaining challenge is the absolute amplitude calibration specification, which is in many ways a research project requiring input from ALMA and Herschel measurements.

Publications of the Astronomical Society of the Pacific (PASP)

- Welcomes articles which describe calibration strategies and measurements at all wavelengths
- Fast submission-to-publication (average 60 days)
- Published continuously since 1889
- Revenue generated from journal subscriptions and page charges supports ASP education and public outreach efforts (see http://astrosociety.org)

Definitions

- ***Accuracy:*** How close a measured value is to the true value. For example, how close a measured flux is to the true source flux.
- ***Precision:*** The statistical error on a measurement. Synonymous with "repeatability".
- ***Repeatability:*** Agreement of the fluxes for a non-variable point source observed at a specific frequency at different times.
- ***Cross-Band Accuracy:*** Accuracy of flux ratios from measurements made in different frequency bands.
- ***Relative Calibration Accuracy:*** Calibration with respect to T_A^* (multi-load calibration system) scale.
- ***Absolute Calibration Accuracy:*** Calibration with respect to a specific calibration standard source (the T_R or S scale).

ALMA Calibration Plan