Celestial Gain Calibrations for the Q and U Imaging ExperimenT Polarimeter Array

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CMB Polarization

- Q and U polarization on the sky from the early universe.
- High sensitivity experiments, WMAP, Boomerang, DASI, CAPMAP, CBI
  - E-mode fluctuations, Constraints on the cosmological constants, slope of the primordial spectrum.
  - B-mode fluctuations, Gravity waves in the early universe. Sub μK resolution.

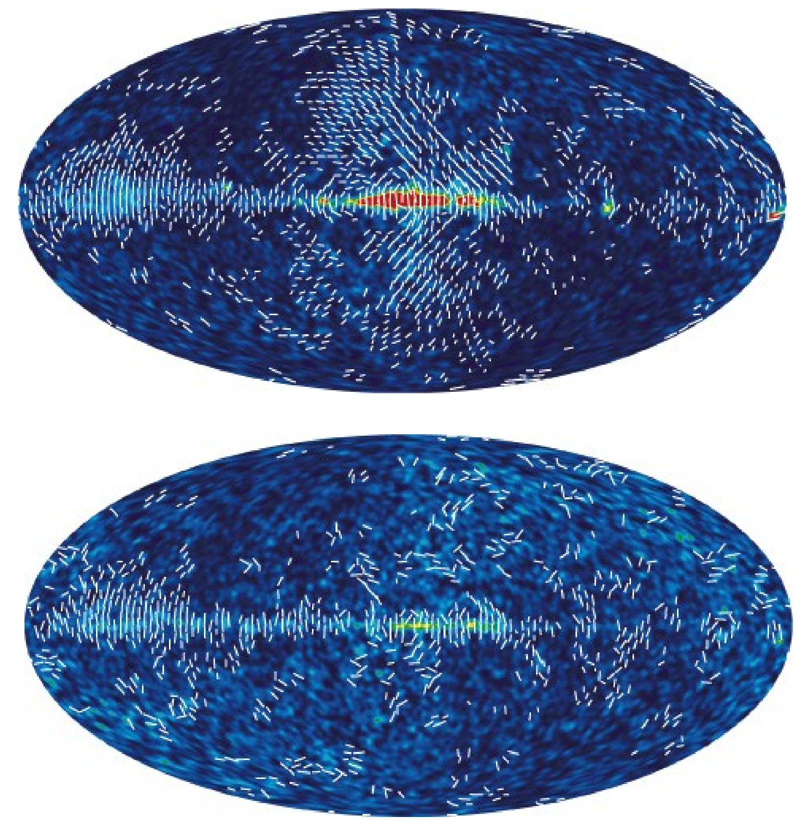
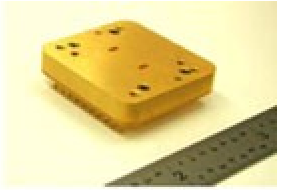


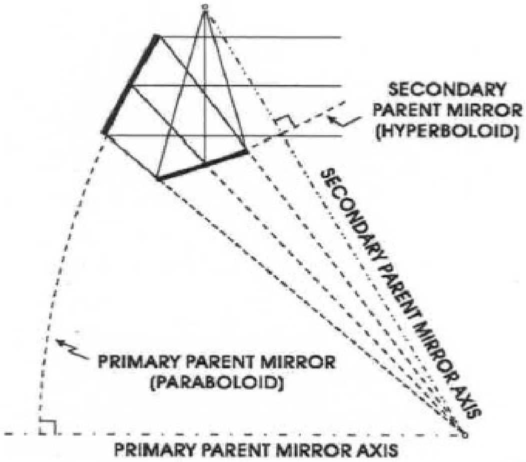
Fig. 1 Wilkinson Microwave Anisotropy Probe polarization maps.

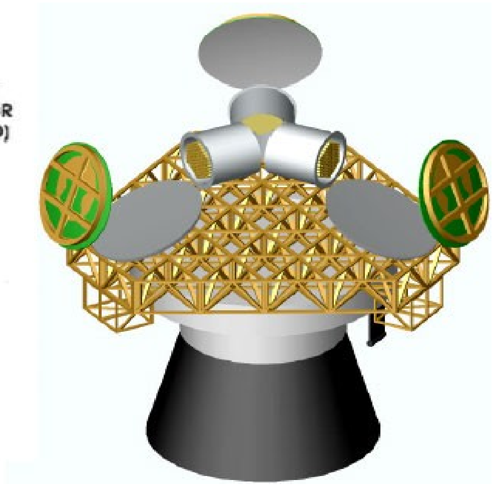
Top: Q-Band (40GHz)
Bottom: W-Band (90GHz)

QUIET Apparatus

- 91 modules at 90GHz and 19 modules at 40GHz
- Calibration occurs both in the lab and in the field.
  - Lab: Sky signals are mimicked by reflective plates.
  - Field: Observation of known celestial sources







QUIET Polarimeters

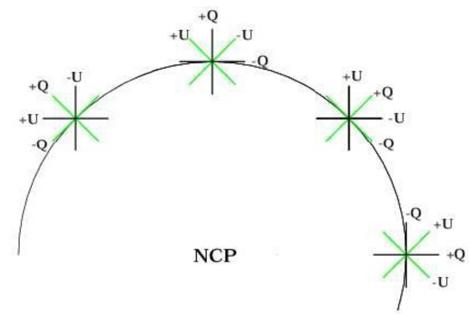
- Four diodes per module detect polarization on two axes simultaneously.

$$S_1 = \frac{1}{2} g_A g_B Q$$

$$S_2 = -\frac{1}{2} g_A g_B U$$

$$S_3 = \frac{1}{2} g_A g_B U$$

$$S_4 = -\frac{1}{2} g_A g_B Q$$



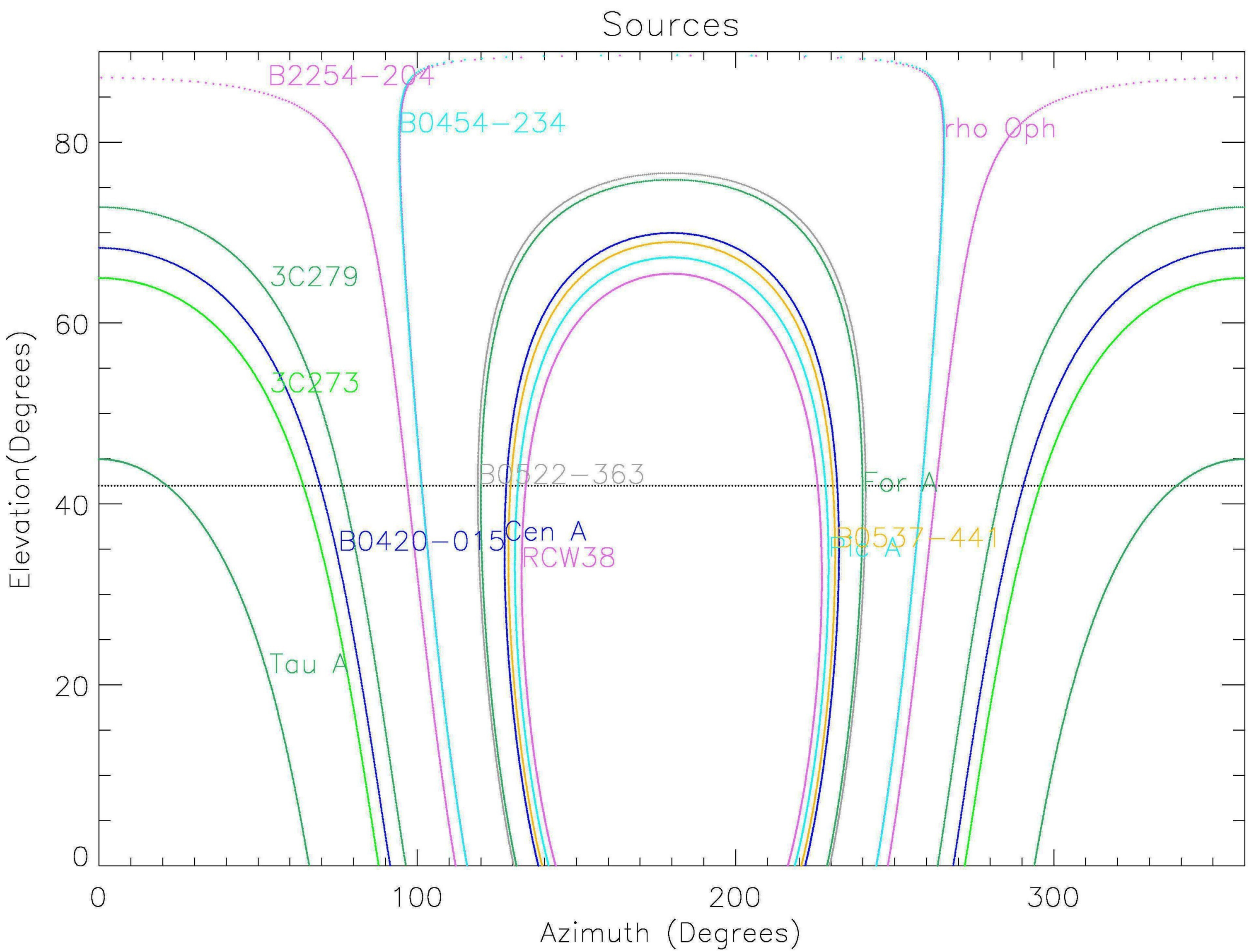
- Integrate the beam signal over a point source.

$$g_i = g_A g_B$$

$$\begin{aligned}
S_{\pm Q, \mp U}(\theta, \phi) &= \frac{g_i}{2} A_i \delta\nu [F_{\pm Q, \mp U} I(\theta, \phi) \otimes B(\theta, \phi) \\
S_{\pm Q, \mp U}(\theta, \phi) &= \frac{g_i}{2} A_i \delta\nu [F_s \delta(\theta, \phi) \otimes B(\theta, \phi) \\
S_{\pm Q, \mp U}(\theta, \phi) &= \frac{g_i}{2} A \delta\nu F_{\pm Q, \mp U} B(\theta, \phi)
\end{aligned}$$

Types of Potential Calibrators

- AGNs
- Blazars
- Planets



Parallactic Angle

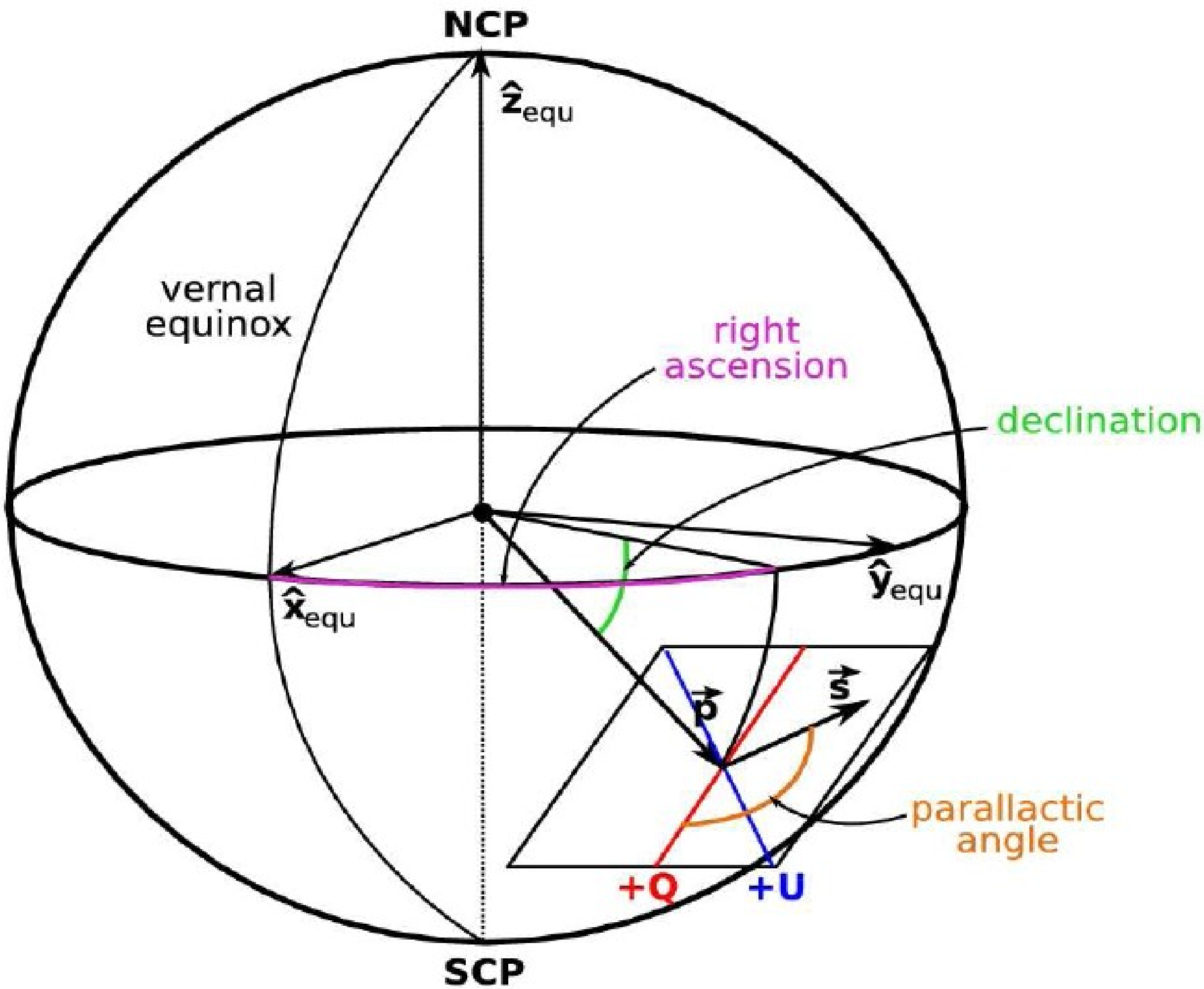
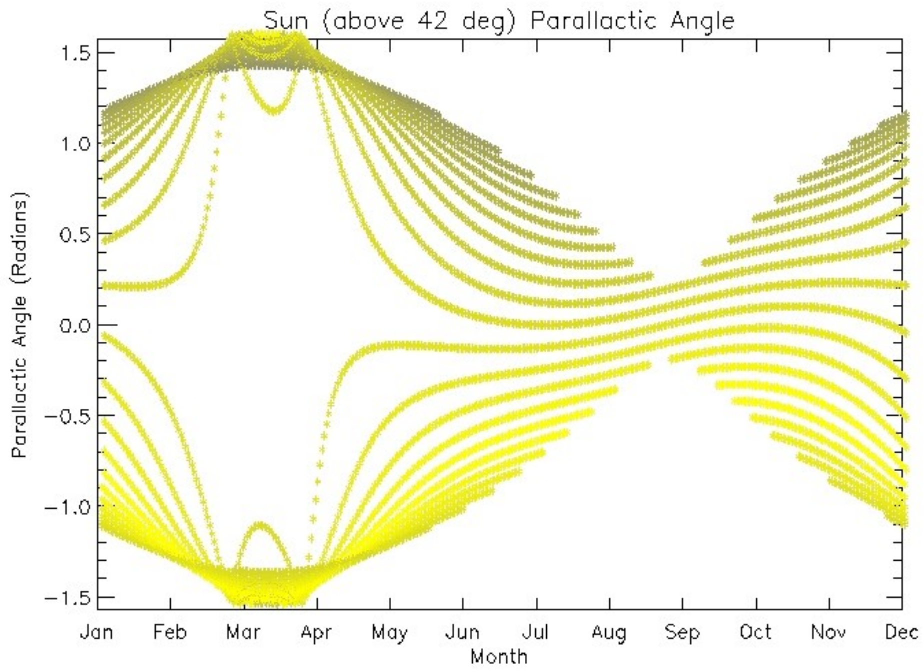


Figure 17: The definition of the basis vectors in the equatorial coordinate system. Image courtesy of Colin Bischoff. [2]

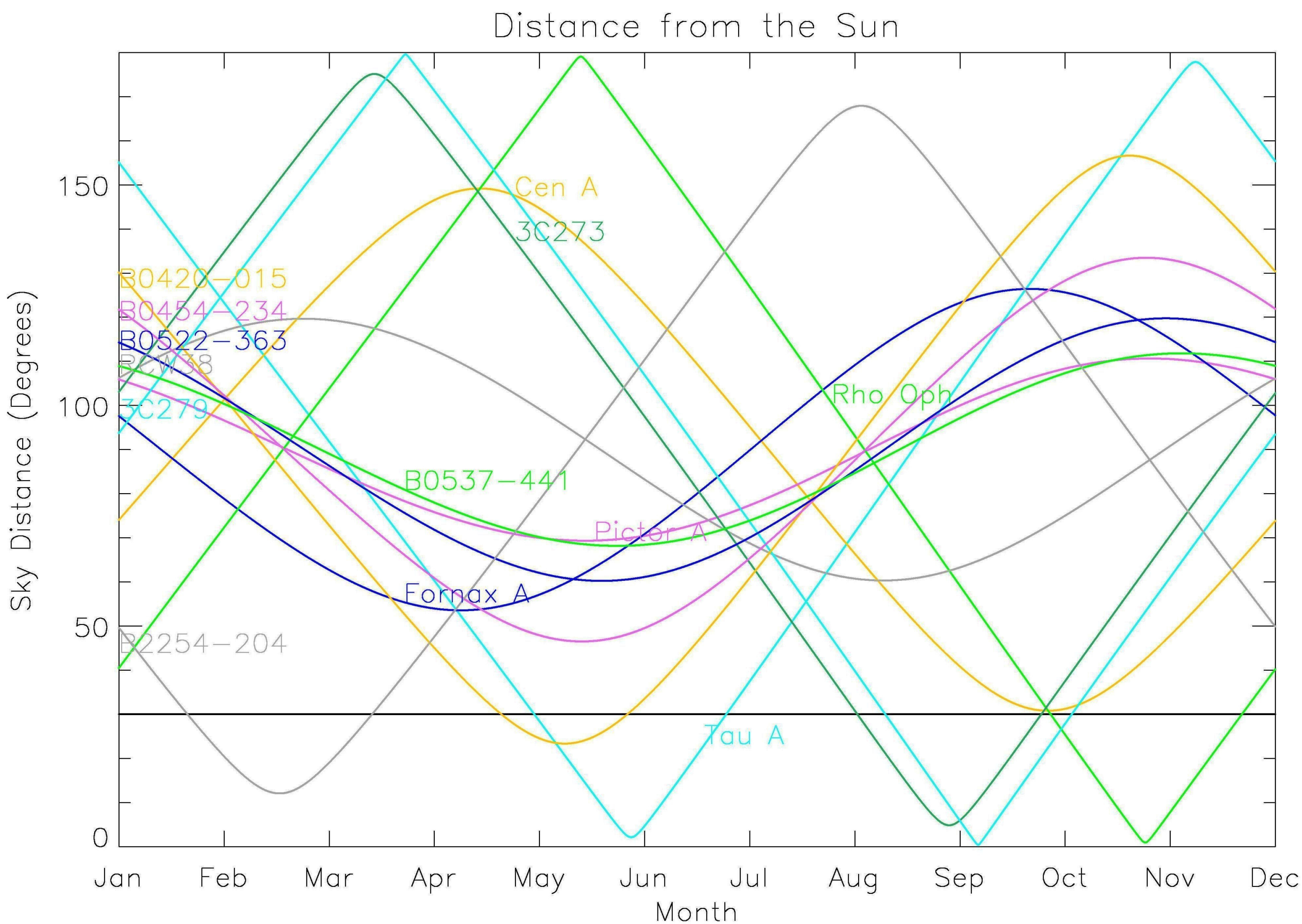
Parallactic Angle Considerations

- For successful calibration, the source should be accessible to the telescope at a broad range of parallactic angles.



$$
\begin{aligned}
g_i &= \frac{2S_{+Q}}{\cos\left(\frac{\chi_i-(\Phi_d-\Phi_p)}{2}\right)P} \\
g_i &= \frac{2S_{-U}}{\sin\left(\frac{\chi_i-(\Phi_d-\Phi_p)}{2}\right)P} \\
g_i &= -\frac{2S_{+U}}{\sin\left(\frac{\chi_i-(\Phi_d-\Phi_p)}{2}\right)P} \\
g_i &= -\frac{2S_{-Q}}{\cos\left(\frac{\chi_i-(\Phi_d-\Phi_p)}{2}\right)P}
\end{aligned}
$$

Source Distance From the Sun



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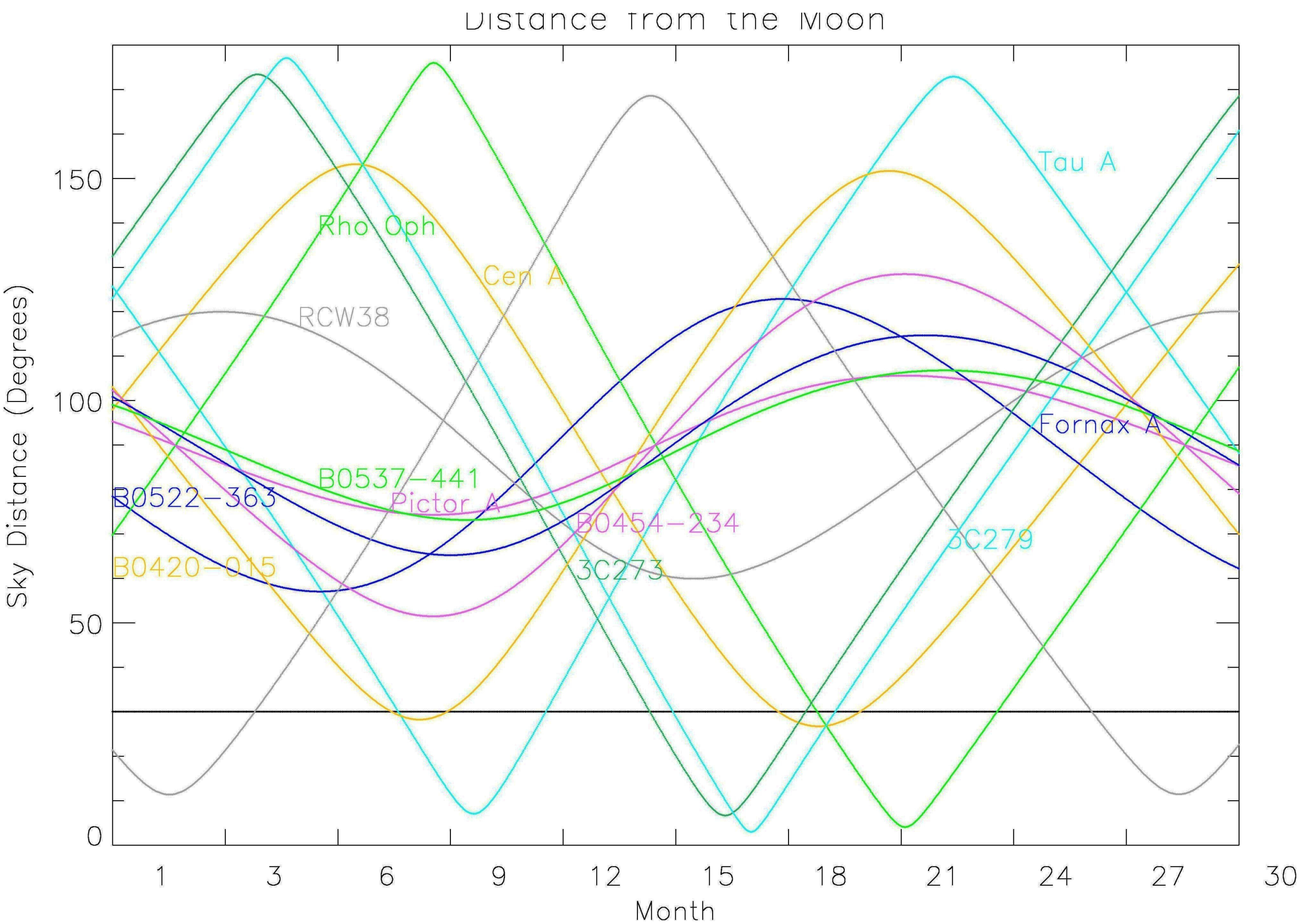
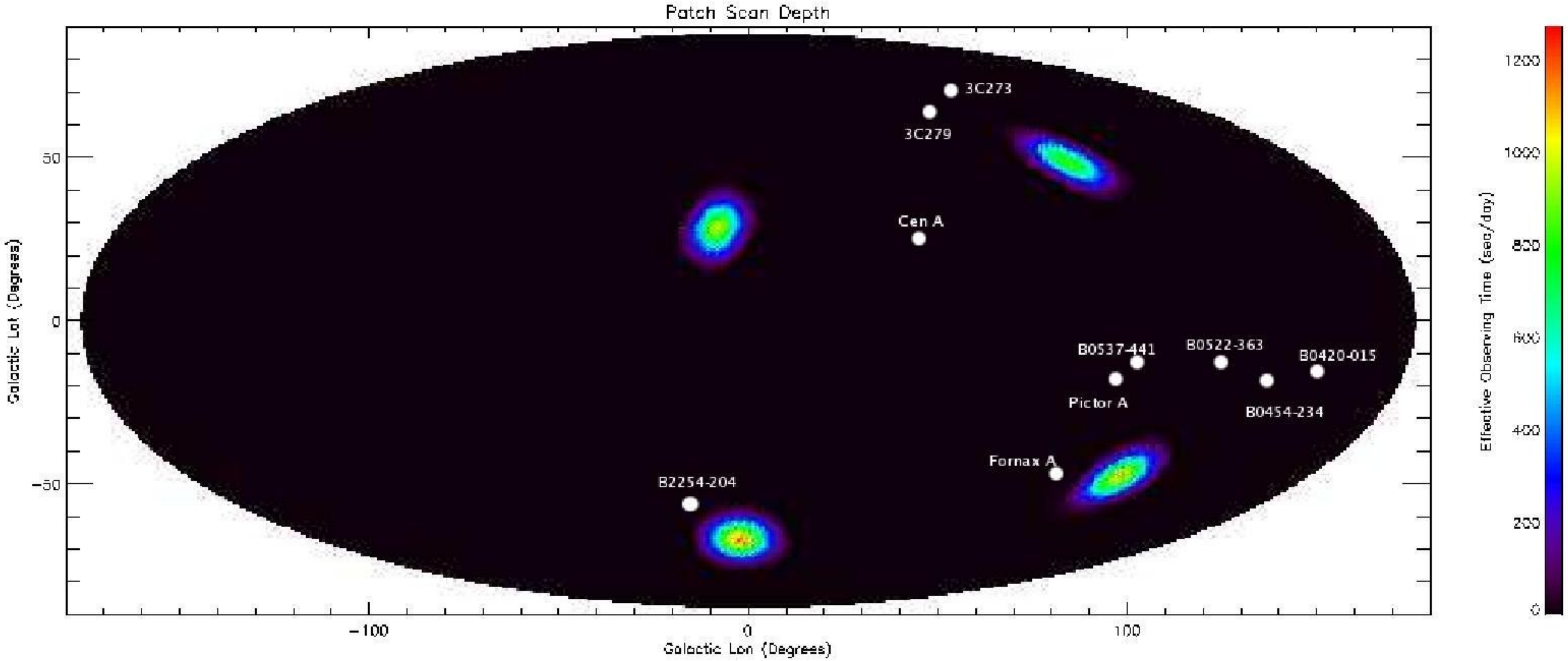
Source Distance From the Moon



Sources Near Scan Patches



Calibration Methods In Similar Experiments

DASI used **RCW38** which is unpolarized in conjunction with an external **polarizing telescope attachment**. With this they reached **<2%** uncertainty for each observing day.

CBI used 3C279, 3C273, Taurus A, Centaurus A, Saturn and Mars. Primary polarization calibrations were done with **5 minute nightly** observations of **3C279** and supplemental observations of **TauA.** These observations had a total **9%** uncertainty.

QUaD rastered across **RCW38** for unpolarized gain calibrations, and for polarized gain used near field observations of a contructed polarized source on a nearby tower.

Brightness Temperature

- Brighter sources (polarized flux/area) will give a greater signal to noise ratio, so we consider the brightness of the source. These are often reported in terms of F= Flux in Janskys, $10^{-26}W/m^2/Hz$ but QUIET is interested in a thermal unit of Kelvin/detector beam.

$$F_s = \int_{source} I(\theta,\phi)dA$$

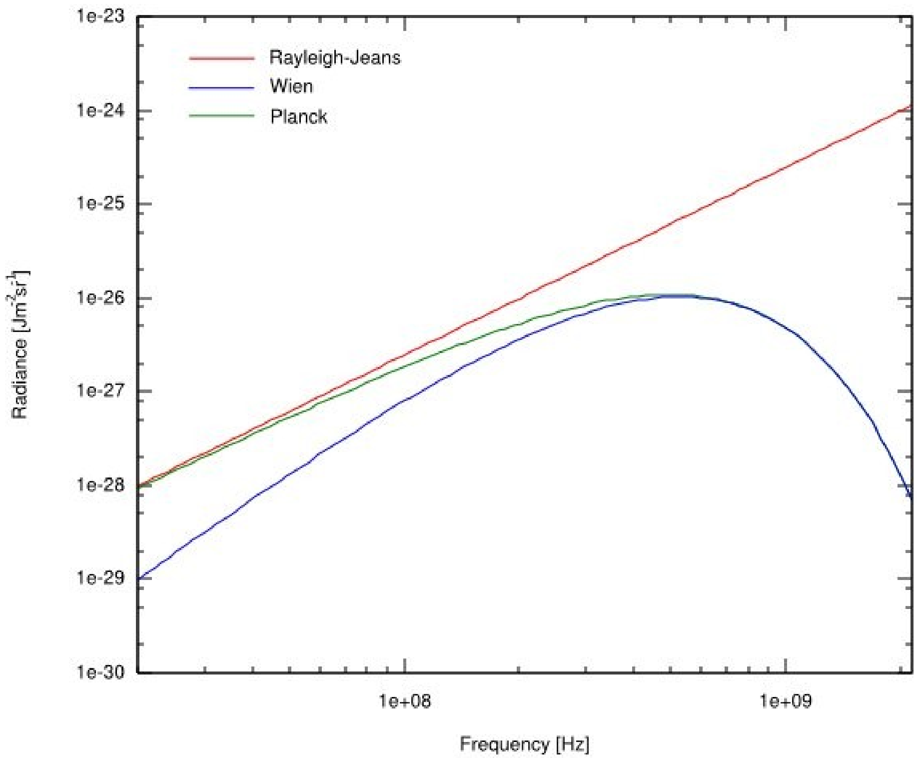
$$T = \frac{10^{-26}c^2}{2k_B\nu^2\Omega_B}F = \frac{F}{g_{RJ}\Omega_B}$$

$$\Omega_{BQ} = 7.517 \times 10^{-5} sr$$

$$\boxed{T_Q = 259\frac{\mu K}{Jy}}$$

$$\Omega_{BW} = 1.522 \times 10^{-5} sr$$

$$\boxed{T_W = 278\frac{\mu K}{Jy}}$$



Source Brightnesses

Source	QBand (Jy)	WBand (Jy)	Pol. %	Pol. QBand (μK)	Pol. WBand (μK)
TauA	299 ± 6	229 ± 11	7.0 ± 0.3	$5,420.2 \pm 257$	4454.9 ± 287
CenA	34.8 ± 0.3	11.5 ± 0.4	13 ± 5	$1,171.6 \pm 46.2$	415.5 ± 286.7
PicA	4.4 ± 0.1	2.2 ± 0.4	29.6 ± 0.8	337.3 ± 12	181.0 ± 33
ForA	10.5 ± 2.5	0 ± 0	8.1 ± 2.2	220.3 ± 80	0.0
B0420	10.1 ± 0.2	6.4 ± 0.3	17 ± 1	444.7 ± 28	302.4 ± 23
B0454	2.6 ± 0.1	1.6 ± 0.4	27 ± 1	181.8 ± 10	120.1 ± 30
B0522	3.4 ± 0.1	2.6 ± 0.3	6.4 ± 0.5	56.4 ± 5	46.2 ± 6
B0537	5.7 ± 0.1	4.6 ± 0.4	3.4 ± 0.5	50.2 ± 7	43.5 ± 7
3C273	16.8 ± 0.1	10.5 ± 0.4	4.8 ± 0.8	208.8 ± 35	140.1 ± 24
3C279	18.2 ± 0.1	13.3 ± 0.4	3.8 ± 0.8	179.1 ± 38	140.5 ± 30
B2254	6.6 ± 0.1	5.2 ± 0.5	14.3 ± 0.63	244.4 ± 11	206.7 ± 22

Gain Uncertainty Dependence on Scan Time

$$g_i = g_A g_B = \frac{\pm 2 g_{RJ} \Omega_B S_{\pm Q, \mp U}}{\cos\left(\frac{\chi_i - (\Phi_d - \Phi_p)}{2}\right) F A_i \delta\nu [\delta(\theta,\phi) B(\theta,\phi)]}$$

$$g_i \propto \frac{S}{T} \quad \Rightarrow \frac{\Delta g_i}{g_i} = \sqrt{\left(\frac{\Delta S}{S}\right)^2 + \left(\frac{\Delta T}{T}\right)^2}$$

$$\Delta S_Q = 0.6mK\sqrt{s}$$
$$\Delta S_W = 1mK\sqrt{s}$$

Optimal calibration scanning efficiency is estimated to be ~75% for the 17 polarization modules in the Qband array.

Source Calibration Potential

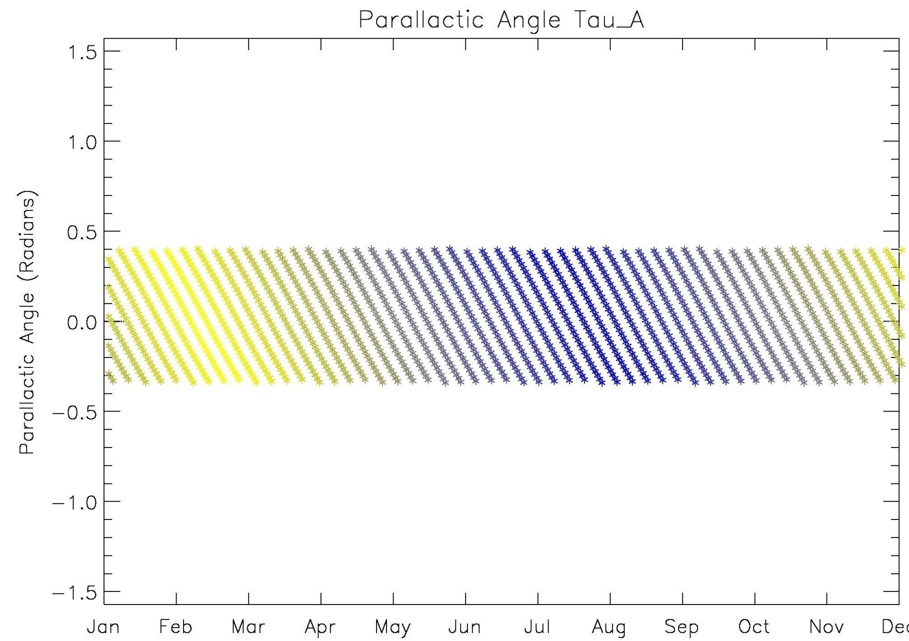
Source	Avail. hrs.	sec/day/module	Qband S/N
Tau A	2.3	365	172.7
CenA	7.1	1128	65.6
PicA	7.2	1144	19.0
ForA	7.2	1144	12.4
B0420	5.9	937	22.7
B0454	7.1	1128	10.2
B0522	7.2	1144	3.2
B0537	7.1	1128	2.8
3C273	5.6	889	10.4
3C279	6.2	985	9.4
B2254	6.9	1096	13.5

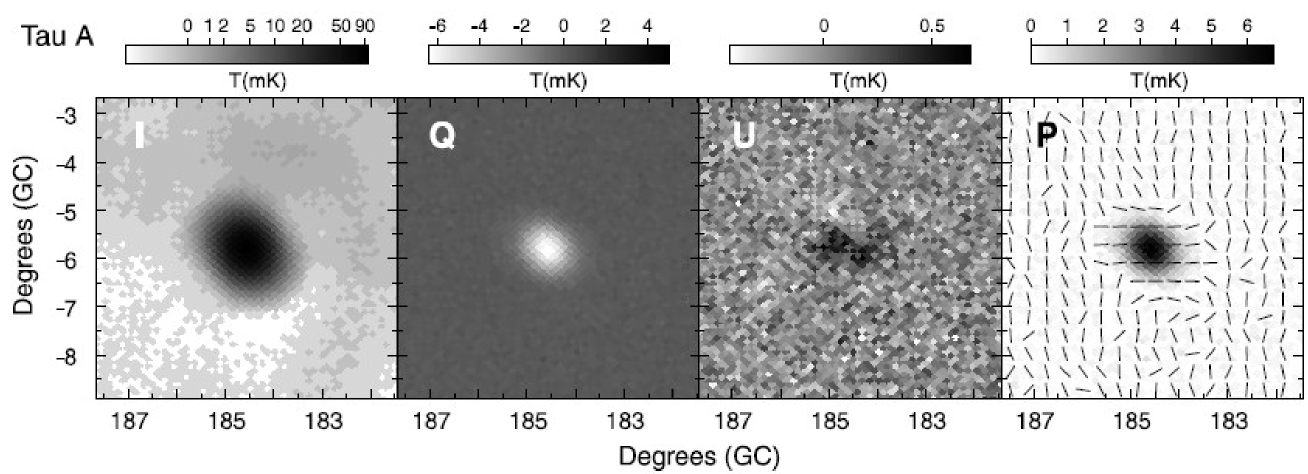
Taurus A

(S/N = 170 after 3 hours)

Table 3: Tau A

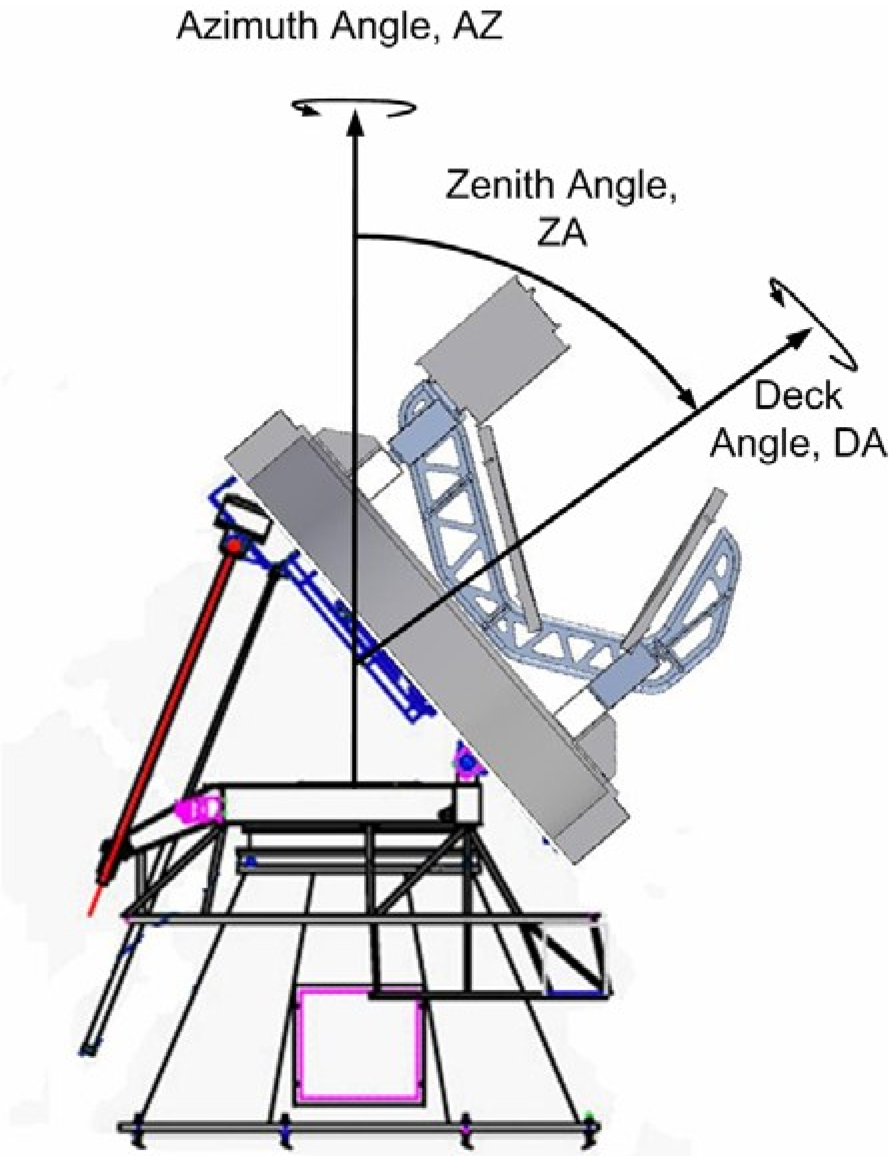
RA	$05^h34^m31.97^s$	NED[19]
DEC	$22^d00^m52.1^s$	NED[19]
Gal. Longitude	184.557	NED[19]
Galactic Latitude	-5.784	NED[19]
41 GHz Total Flux (Jy)	299 ± 6	$WMAP$[31]
94 GHz Total Flux (Jy)	229 ± 11	$WMAP$[31]
α Spectral Index	-2.3	$WMAP$[31]
% Polarization (QBand)	$7.0 \pm 0.3\%$	$WMAP$[31]
% Polarization (WBand)	$7.6 \pm 2.0\%$	$WMAP$[31]
QBand Pol. Temp. (μK)	5420.2 ± 256	per module
WBand Pol. Temp. (μK)	4836.6 ± 1284	per module
Parallactic Angle Range	$\frac{-\pi}{3} \leq \chi \leq \frac{\pi}{3}$	[9]
Time above 42°($hrs.$)	2.268	[9]
Other Names	Messier 001 J0534+2200	Crab Nebula



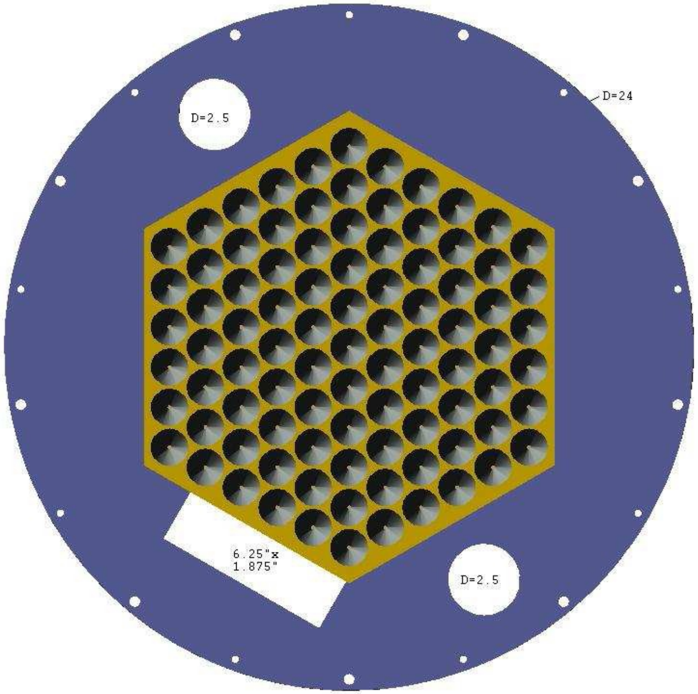


Taurus A

(Thoughts on Deck Rotation)



Full array can only see Tau A if deck is rotated. Otherwise, only half the modules will see TauA.

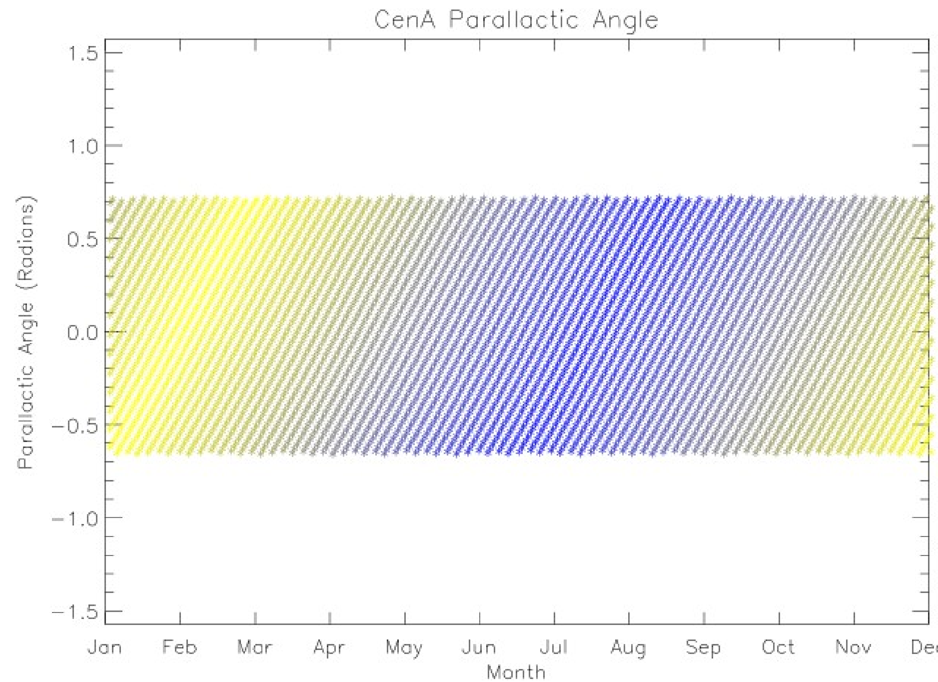


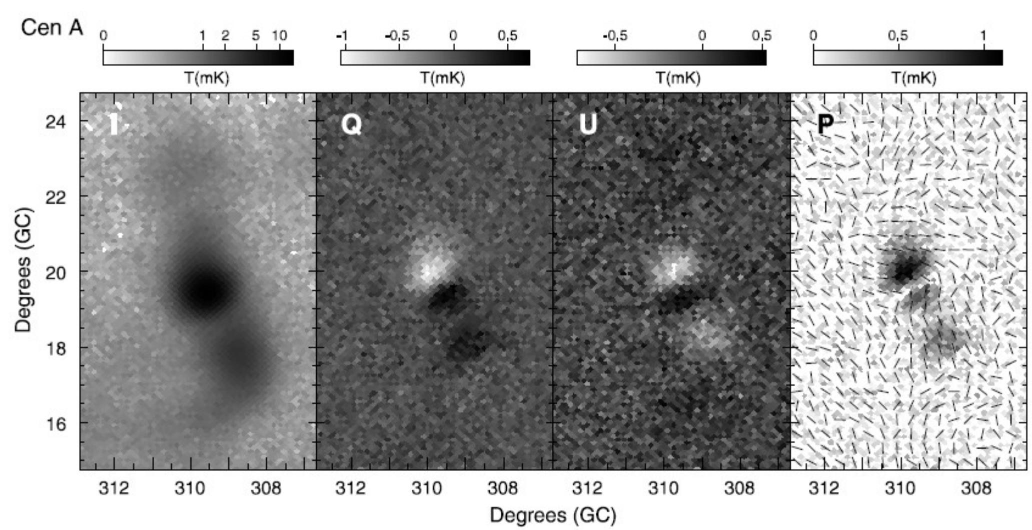
Centaurus A

(S/N = 65 after 7 hours)

Table 4: Cen A

RA	$13^h25^m27.62^s$	NED[19]
DEC	$-43^d01^m8.8^s$	NED[19]
Galactic Longitude	309.516	NED
Galactic Latitude	+19.417	NED
41 GHz Total Flux (Jy)	34.8 ± 0.3	[17]
94 GHz Total Flux (Jy)	11.5 ± 0.4	[17]
α Spectral Index		WMAP[31]
% Polarization	$13 \pm 0.5\%$	Junkes [11]
QBand Pol. Temp. (μK)	$1,171.6 \pm 46.2$	per module
WBand Pol. Temp. (μK)	415.5 ± 286.7	per module
Parallactic Angle Range	$\frac{-4\pi}{3} \leq \chi \leq \frac{4\pi}{3}$	[9]
Time above 42°($hrs.$)	7.08	[9]
Other Names		NGC5128
		B1322-428
		J1325-4257



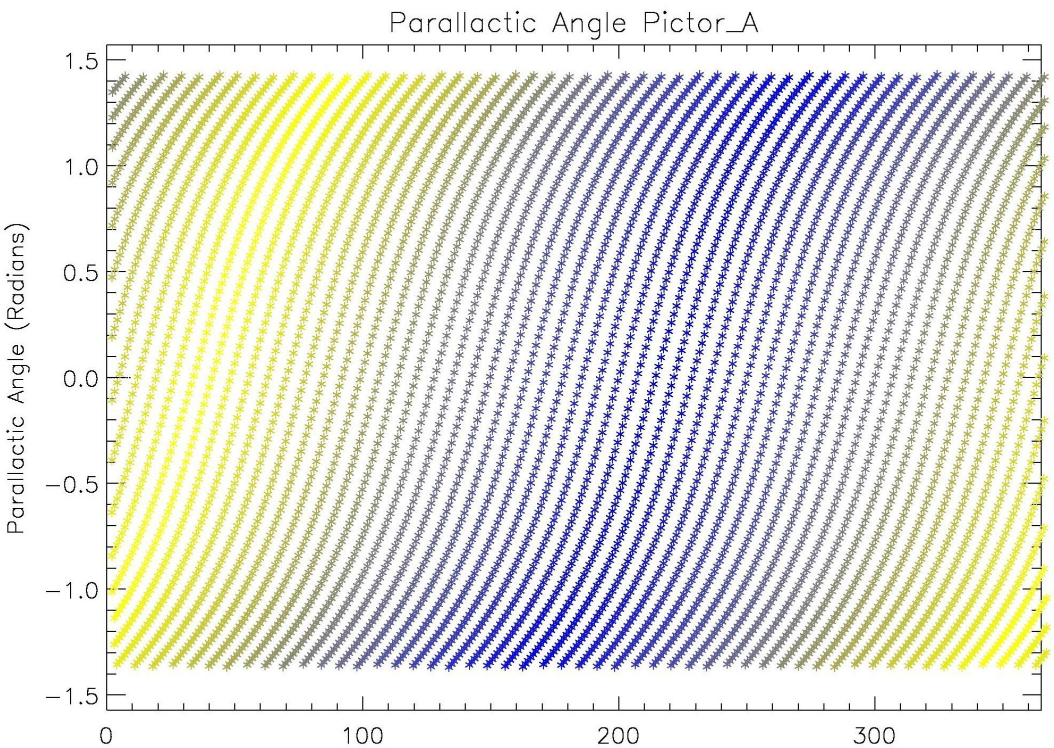


Pictor A

(S/N = 19 after 7 hours)

Table 5: Pictor A

RA	$5^h19^m49.7^s$	NED[19]
DEC	$-45^d46^m44.5^s$	NED[19]
Gal. Longitude	251.597	NED[19]
Galactic Latitude	−34.6344	NED[19]
41 GHz Total Flux (Jy)	4.4 ± 0.1	$WMAP$[31]
94 GHz Total Flux (Jy)	2.2 ± 0.4	$WMAP$[31]
α Spectral Index	−0.7	$WMAP$[31]
% Polarization	$\geq 29.6 \pm 0.8\%$	VLA[22]
QBand Pol. Temp. (μK)	337.283 ± 11.9	per module
WBand Pol. Temp. (μK)	180.97 ± 33.3	per module
Size (arcmin)	$0.912' \times 0.724'$	NED[19]
Parallactic Angle Range	$\frac{-4\pi}{3} \leq \chi \leq \frac{4\pi}{3}$	[9]
Time above 42°($hrs.$)	7.08	[9]
Other Names	B0518-4549 WMAP J0519-4546 WMAP 150	

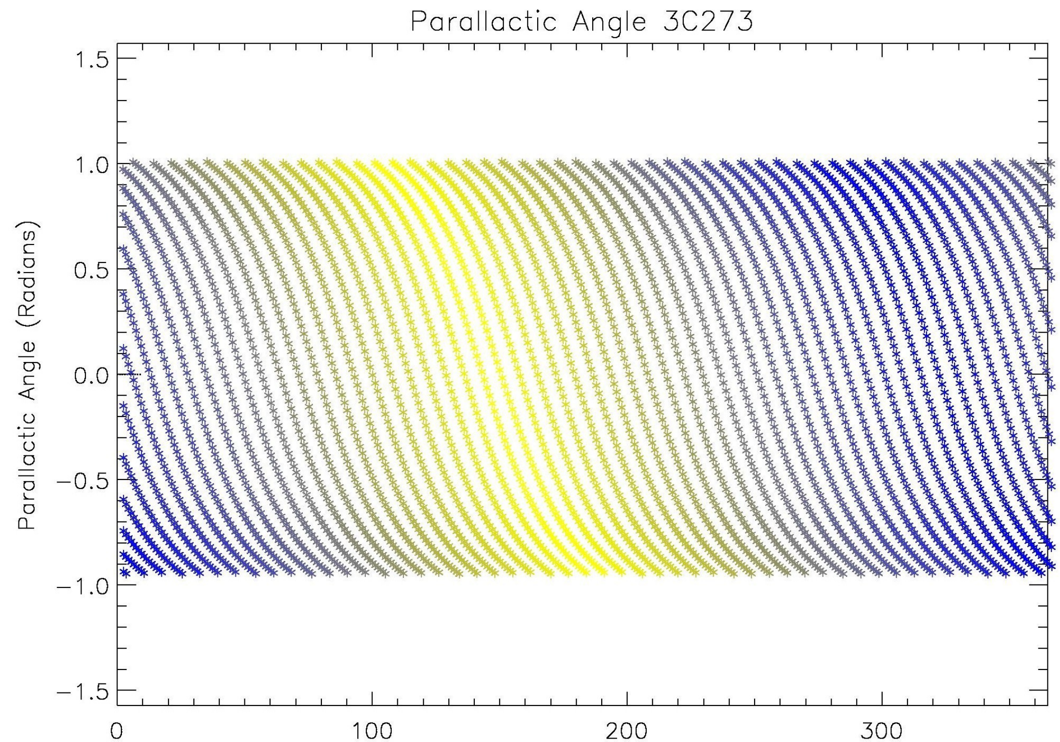


3C273

(S/N = 10.4 after 5.6 hours)

Table 7: 3C273

RA	$12^h29^m06.7^s$	NED[19]
DEC	$+02^d03^m09^s$	NED[19]
Galactic Longitude	289.951	NED
Galactic Latitude	64.359NED	
41 GHz Total Flux (Jy)	16.8 ± 0.1	$WMAP$[31]
94 GHz Total Flux (Jy)	10.5 ± 0.4	$WMAP$[31]
α Spectral Index	-0.3	$WMAP$[31]
% Polarization	$4.8 \pm 0.8\%$	$WMAP$[31]
QBand Pol. Temp. (μK)	208.83 ± 34.8	per module
WBand Pol. Temp. (μK)	140.06 ± 24.0	per module
Parallactic Angle Range	$-\pi \leq \chi \leq \pi$	
Size (arcmin)	$0.12' x 0.08'$	NED
Time above $42°(hrs.)$	5.6	[9]
Other Names		
	WMAP J1229+0203	[31]
	WMAP 170	[31]
	B1226+023	$PKSBlazar$

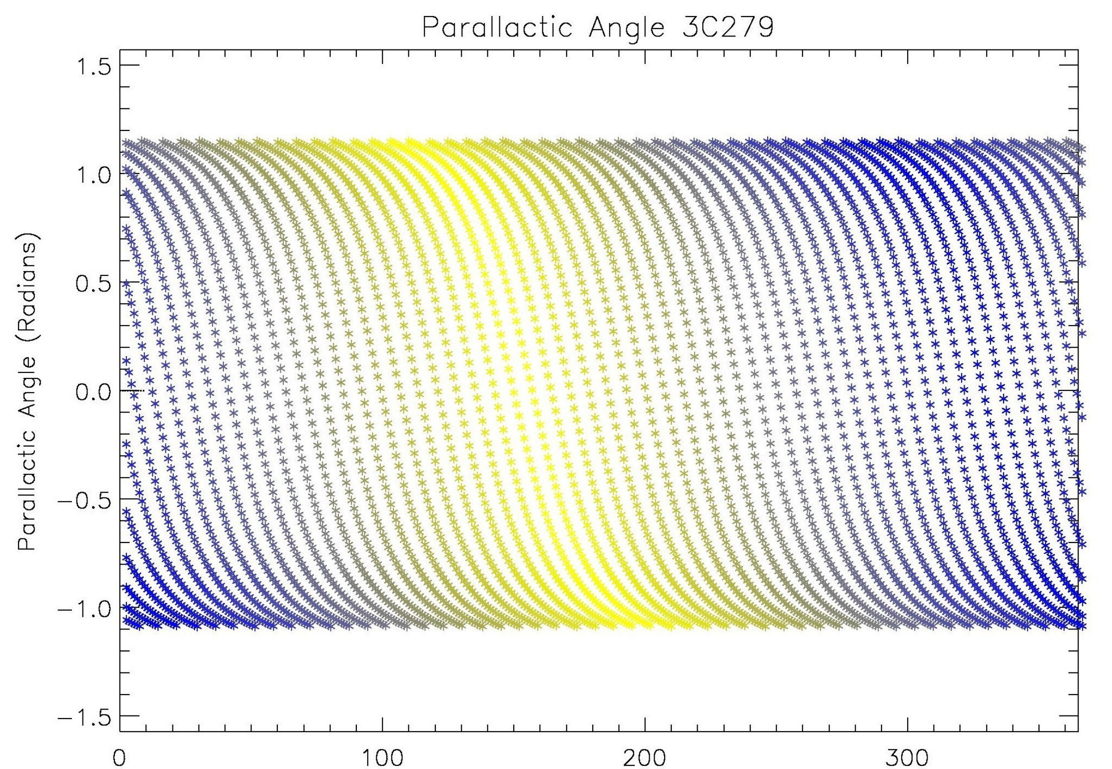


3C279

(S/N = 9.4 after 6.2 hours)

Table 8: 3C279

RA	$12^h56^m11.17^s$	NED[19]
DEC	$-05^d47^m21.5^s$	NED[19]
Galactic Longitude	305.104	NED[19]
Galactic Latitude	57.062	NED[19]
41 GHz Total Flux (Jy)	18.2 ± 0.1	$WMAP$[31]
94 GHz Total Flux (Jy)	13.3 ± 0.4	$WMAP$[31]
α Spectral Index	0.1	$WMAP$[31]
% Polarization	$3.8 \pm 0.8\%$	$WMAP$[31]
QBand Pol. Temp. (μK)	179.1 ± 37.7	per module
WBand Pol. Temp. (μK)	140.5 ± 29.9	per module
Parallactic Angle Range	$-\pi \leq \chi \leq \pi$	[9]
Time above $42°(hrs.)$	6.21	[9]
Other Names		
	B1253-055	
	J1256-0547	



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