A Proposal for Improving Astronomical Pointing Measurements

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2007 Aug 8

GBT Archive: PR070
File: PROJECTS
Keys: PTCS, pointing, calibration

Abstract

GBT instrumentation and pointing analyses have improved so much that errors in past X-band ($\nu \approx 9\,\mathrm{GHz}$) astronomical measurements of calibration-source positions (two-dimensional rms $\sigma_2 \approx 0\farcs7$) may impede future progress. This Project Note proposes new Ka-band ($\nu \approx 31\,\mathrm{GHz}$) pointing observations that should reduce the two-dimensional rms of astronomical position errors from $\sigma_2 \approx 0\farcs7$ to $\sigma_2 \leq 0\farcs3$. It also presents the catalog of "gold standard" calibration sources needed to attain this accuracy.

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58.0 2007 Aug 8. Original version (J. J. Condon).

1. Introduction

GBT instrumentation, pointing performance, and analysis (Constantikes 2006) have reached the level of accuracy that errors associated with past astronomical observations of calibration sources are large enough (two-dimensional rms $\sigma_2 \approx 0\rlap{.}''7$) to impede future progress. Most PTCS pointing data were taken at X band ($\nu \approx 9\,\mathrm{GHz}$), include calibration sources whose centroids may be shifted by asymmetric extended emission, and are based on relatively inaccurate NVSS (Condon et al. 1998) positions. The astronomical uncertainties can be reduced to $\sigma_2 \leq 0\rlap{.}''3$ by (1) making future PTCS pointing observations at Ka band ($\nu \approx 31\,\mathrm{GHz}$) and (2) observing only strong, compact calibrators with accurately known positions. These advantages of observing at $\nu \approx 31\,\mathrm{GHz}$ are given in Section 2, and the new catalog of "gold standard" pointing calibrators is presented in Section 3.

2. Reasons for Observing at Ka Band ($\nu \approx 31\,\mathrm{GHz}$)

There are three benefits of increasing the observing frequency for PTCS pointing observations from $\nu \approx 9\,\mathrm{GHz}$ (X band) to $\nu \approx 31\,\mathrm{GHz}$ (Ka band):

- The position fitting error at a given signal-to-noise ratio (SNR) is lowered by reducing the half-power beam width (HPBW) of the GBT from $\theta \approx 82''$ to $\theta \approx 24''$. The rms two-dimensional pointing error caused by noise alone when fitting Gaussians to two perpendicular scans is (Condon 2003a)

  $$\sigma_2 = \left[\frac{2}{\pi \ln(2)}\right]^{1/4} \theta \left(\frac{\sigma_{\rm n}}{S}\right) \approx \theta \left(\frac{\sigma_{\rm n}}{S}\right) , \qquad (1)$$

  where S is the peak flux density of the calibrator and $\sigma_{\rm n}$ is the noise smoothed over the time τ equal it takes to scan between the beam half-power points. (Note that τ is not the *sample* integration period, which is usually much shorter than the time used to scan between half-power points. The fitting uncertainty σ_2 is independent of the sample integration period.)

- The Ka-band pseudocorrelation beamswitching receiver has much lower $1/f$ noise and wider bandwidth than the total-power X-band receiver, so the SNR at a given source flux density will be much higher except during bad observing weather. For a scan rate of 1 arcmin per second of time, $\tau \approx 0.4\,\mathrm{s}$ at $\nu \approx 31\,\mathrm{GHz}$. The system equivalent flux density at $\nu \approx 31\,\mathrm{GHz}$ is $S_{\rm sys} \approx 25\,\mathrm{Jy}$ and the bandwidth is $\Delta\nu \approx 3.5\,\mathrm{GHz}$, so

  $$\sigma_{\rm n} \approx \frac{2^{1/2} S_{\rm sys}}{(\Delta\nu\,\tau)^{1/2}} \approx 1.0\,\mathrm{mJy} \qquad (2)$$

  when $1/f$ noise is small.

  A reasonable goal for the noise contribution to position error is $\sigma_2/\theta < 0.005$, which corresponds to $\sigma_2 \approx 0\rlap{.}''12$ at $\nu \approx 31\,\mathrm{GHz}$. Equations (1) and (2) require $S > 200\,\mathrm{mJy}$. Allowing for some $1/f$ noise and our poor knowledge of calibrator flux densities at $\nu \approx 31\,\mathrm{GHz}$, a more conservative lower limit for the estimated flux density of a suitable pointing calibrator is $S \approx 400\,\mathrm{mJy}$.

- Observations at higher frequencies reduce the centroid position shifts caused by asymmetric steep-spectrum jets emerging from compact flat-spectrum cores.

Figure 1 shows the quasar 3C 273 at optical (gray scale) and radio (contours) wavelengths. The compact quasar "core" dominates the radio and optical fluxes, and it is the position of the core that has been measured accurately by long-baseline interferometers. Unfortunately, 3C 273 and a number of other radio sources contain short one-sided "jets" that are not well resolved by single-dish telescopes. A single-dish telescope measures the centroid position of the core plus the asymmetric jet, so the single-dish position may be slightly offset from the interferometer position of the core. In general, the cores have "flat" ($\alpha \equiv -d \ln S / d \ln \nu \sim 0$) radio spectra and the jets have "steep" ($\alpha \sim 0.8$) spectra. Thus the offsets between the interferometer and single-dish positions decline roughly as $\nu^{-0.8}$, and going from $\nu \approx 9\,\mathrm{GHz}$ to $\nu \approx 31\,\mathrm{GHz}$ should reduce such offsets by about a factor of 2.7.

Position offsets caused by extended emission can also be minimized by observing only those calibration sources that do not have detectable extended emission when observed with high-resolution interferometers.

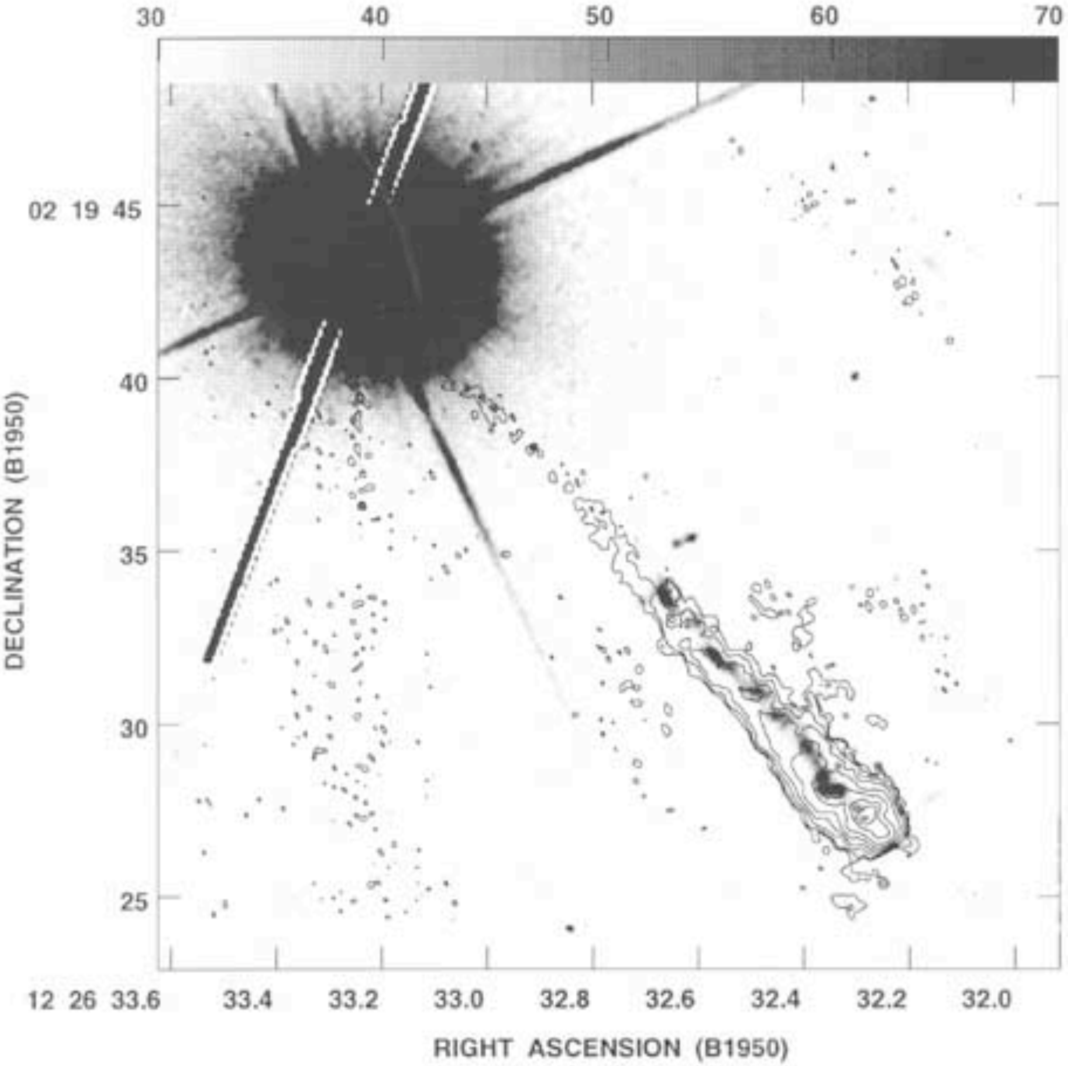

Fig. 1.— The quasar 3C 273 is dominated by a compact flat-spectrum core whose position has been measured very accurately by long-baseline interferometers. However, 3C 273 has an asymmetric steep-spectrum radio jet (contours) that shifts the centroid position observed with a single-dish telescope. This shift is smaller at higher frequencies.

3. "Gold Standard" Pointing Calibrators for the PTCS

This section presents a new GBT pointing catalog, PCALS4.1, that replaces the current GBT pointing catalog, PCALS4.0. It differs from PCALS4.0 only in having a twelfth column whose value is "P" (for PTCS "gold standard" pointing calibrators) or blank (for all other pointing calibrators).

3.1. New PTCS Requirements for Pointing Calibrators

Future PTCS pointing observations should use only those calibration sources that satisfy all three criteria below.

- They should be strong enough at $\nu = 31\,\mathrm{GHz}$ so that $\sigma_2/S < 0.005$.

  For efficient observing, the calibrator high-frequency flux densities should be known at least approximately, so we doesn't waste observing time on sources that are too weak. Most suitable high-frequency calibration sources have flat radio spectra, and their 31 GHz flux densities often vary by up to a factor of two on time scales of years. Unfortunately, few recent Ka-band flux measurements exist. Instead, 31 GHz flux densities must be estimated by interpolation or by extrapolation from measurements made at lower frequencies as far back as 20 years ago. To be conservative, I have chosen to consider only those sources for which the CALFIND algorithm (Appendix) estimates $S \geq 400\,\mathrm{mJy}$ at $\nu \approx 31\,\mathrm{GHz}$ for inclusion in the PTCS "gold standard" pointing catalog.

  As high-frequency observing increases at the GBT, it will be necessary for either PTCS or telescope operations to measure and occasionally monitor high-frequency flux densities of the stronger calibration sources.

- The calibrators should have very accurate (two-dimensional rms error $\sigma_2 < 0''.15$) core positions measured by long-baseline interferometers. The original GBT Pointing Catalog (Condon & Yin 2001) is satisfactory for normal scientific observations at wavelengths as short as $\lambda = 7\,\mathrm{mm}$ but is unsatisfactory for future PTCS use because it is uses 1.4 GHz NVSS (Condon et al. 1998) positions, which were measured with the compact VLA D-configuration and have $\sigma_2 \approx 0''.7$ errors. That catalog is available on the web:
  `ftp://ftp.cv.nrao.edu/NRAO-staff/jcondon/PCALS2.2`
  The 2005 GBT Pointing Catalog (Condon & Yin 2005(@) replaces many of the NVSS positions with more accurate core positions measured with larger VLA configurations or with the VLBA. It is also available on the web:
  `ftp://ftp.cv.nrao.edu/NRAO-staff/jcondon/PCALS4.0`

  The VLA calibrator list
  `http://www.vla.nrao.edu/astro/calib/manual/csource.html`
  gives J2000 positions and accuracy codes (A for position error $\sigma_2 < 0''.002$, B for $0''.002 < \sigma_2 < 0''.01$, C for $0''.01 < \sigma_2 < 0''.15$, and T for $\sigma_2 > 0''.15$) for almost 2000 sources. Having accuracy code A, B, or C is a necessary but not sufficient condition for inclusion in the PTCS "gold standard" catalog.

- The calibrators must be sufficiently compact that asymmetric extended structure is not likely to displace the centroid observed with the GBT. The presence or obsence of extended structure is indicated by the resolution codes in the VLA calibrator list (X for extended, P for point source, S for nearly a point source). A necessary condition for inclusion in the PTCS "gold standard" catalog is a "P" or "S" resolution code in the VLA "D" configuration (baselines from about 40 m to 1000 m) at $\lambda = 2\,\mathrm{cm}$ or $\lambda = 1.3\,\mathrm{cm}$ or $\lambda = 0.7\,\mathrm{cm}$.

3.2. The "Gold Standard" Calibrator Catalog

The catalog "Gold Standard" catalog is the subset of 460 sources in PCALS4.0 that satisfy all three requirements listed in Subsection 3.1. For easier adoption by existing programs that read PCALS4.0 (e.g., the program CALFIND described in the Appendix), PCALS4.1 is available as the ascii table
`ftp://ftp.cv.nrao.edu/NRAO-staff/jcondon/PCALS4.1`
that differs from PCALS4.0 only by the addition of a new column, columnn 12, where "P" indicates a PTCS "gold standard" calibrator. Table 1 shows a few lines extracted from PCALS4.1 that contain "P" in column 12.

Column 1.—J2000 IAU name, format JHHMM+DDMM.

Column 2.—J2000 right ascension. The precision reflects the accuracy: $0\overset{s}{.}0001$ precision for the accurate positions measured with interferometers having sub-arcsecond resolution, $0\overset{s}{.}001$ precision for FIRST positions, and $0\overset{s}{.}01$ for NVSS positions and VLA "T" calibrators.

Column 3.—J2000 declination. The precision reflects the accuracy: $0\overset{''}{.}001$ precision for the accurate positions measured with very high resolution interferometers, $0\overset{''}{.}01$ precision for FIRST positions, and $0\overset{''}{.}1$ for NVSS positions and VLA "T" calibrators.

Column 4.—Minimum HPBW (arcsec) for which the calibrator is suitable. All sources with only NVSS positions have $\theta_{\mathrm{min}} \geq 15''$ because the the NVSS resolution ($\theta = 45''$) and position accuracy ($\sigma_2 = 0\overset{''}{.}7$) are not good enough for GBT use at $\lambda = 3\,\mathrm{mm}$. Larger minimum sizes ($\theta_{\mathrm{min}} = 20''$ or $\theta_{\mathrm{min}} = 30''$) indicate small discrepancies between NVSS positions and positions measured with higher resolution. Such sources may be extended up to $\phi \approx 20''$ and cannot be trusted for observations with smaller GBT beams.

Column 5.—Maximum HPBW (arcsec) for which the calibrator is suitable. Observations with GBT beam sizes larger than θ_{max} may be degraded by confusion.

Column 6.—L-band ($\lambda \approx 20\,\mathrm{cm}$) flux density (Jy). Nearly all of these are 1.4 GHz NVSS flux densities. Even though they were measured during the mid-1990's, they should stil be quite accurate ($< 5\%$ rms uncertainty) because extragalactic sources usually do not vary intrinsically or scintillate strongly at this frequency.

Column 7.—C-band ($\lambda \approx 6\,\mathrm{cm}$) flux density (Jy). Flux densities at 6 cm and shorter wavelengths may be fairly inaccurate (up to 50% uncertainty) because most were measured many years ago and flat-spectrum sources are often variable at all wavelengths $\lambda \lesssim 6\,\mathrm{cm}$.

Column 8.—X-band ($\lambda \approx 3.6\,\mathrm{cm}$) flux density (Jy).

Column 9.—U-band ($\lambda \approx 2\,\mathrm{cm}$) flux density (Jy) from the VLA calibration list.

Column 10.—K-band ($\lambda \approx 1.3\,\mathrm{cm}$) flux density (Jy) from the VLA calibration list.

Column 11.—Q-band ($\lambda \approx 0.7\,\mathrm{cm}$) flux density (Jy) from the VLA calibration list.

Column 12.—Calibration code: "P" for PTCS "gold standard" source, blank otherwise.

Table 2 shows a small portion of the catalog. The entire catalog is available electronically as file PCALS4.1 at `ftp://ftp.cv.nrao.edu/NRAO-staff/jcondon/`.

Table 1. Examples of “Gold Standard” calibration sources selected from the GBT Pointing Calibrator Catalog PCALS4.1

IAU J2000 NAME	Right Ascension (J2000)	Declination (J2000)	$\theta_{\rm min}$ (asec)	$\theta_{\rm max}$ (asec)	S(20 cm) (Jy)	S(6 cm) (Jy)	S(3.6 cm) (Jy)	S(2 cm) (Jy)	S(1.3 cm) (Jy)	S(0.7 cm) (Jy)	Code
0005+5428	00:05:04.3635	+54:28:24.926	0	45	0.17	0.23	0.39	0.48	0.	0.46	P
0005+3820	00:05:57.1754	+38:20:15.148	0	90	0.57	0.80	1.1	0.67	0.	0.8	P
0006−0623	00:06:13.8928	−06:23:35.335	0	180	2.05	1.30	1.60	1.10	0.	1.5	P
0010+1724	00:10:33.9906	+17:24:18.761	0	180	0.92	0.98	0.95	0.70	0.	0.5	P
0011+0823	00:11:35.2696	+08:23:55.587	0	45	0.63	0.40	0.37	0.	0.	0.42	P
0012−3954	00:12:59.9080	−39:54:25.836	0	45	0.49	1.5	1.6	0.	1.2	0.	P
0017+5312	00:17:51.7598	+53:12:19.121	0	45	0.39	0.69	0.64	0.6	0.	0.4	P
0019+2021	00:19:37.8545	+20:21:45.644	0	90	0.98	0.71	1.18	1.1	0.	0.5	P
0019+7327	00:19:45.7864	+73:27:30.017	0	45	1.25	1.30	1.48	1.40	0.	0.80	P
0025+3919	00:25:26.1577	+39:19:35.439	0	180	0.71	0.81	0.54	0.60	0.	0.4	P
0025−2602	00:25:49.1683	−26:02:12.695	0	180	8.75	3.50	1.93	1.50	0.	0.36	P
0029+3456	00:29:14.2424	+34:56:32.246	0	45	1.90	1.85	0.96	0.60	0.58	0.36	P
0029+0554	00:29:45.8964	+05:54:40.695	0	45	0.29	0.33	0.38	0.	0.	0.51	P
…	…	…	…	…	…	…	…	…	…	…	…

Some of these “gold” calibrators are of special interest for PTCS pointing observations:

- Close pairs and triples of sources are useful for measuring the rate at which GBT pointing errors grow with calibrator/target separation. There are $N = 460$ “gold” calibrators in the $\Omega \approx 10.3\,\mathrm{sr}$ of sky north of $\delta = -40°$, so the mean density is $\eta \approx 45\,\mathrm{sr}$ and the mean angular distance $\langle\phi\rangle$ from one calibrator to its nearest neighbor is (Condon & Yin 2001)

  $$\langle\phi\rangle = \frac{1}{2sqrt\eta} \approx 4.3\,\mathrm{deg}\ . \tag{3}$$

  All pairs separated by $< 1°$ are listed in Table 2.

- There are three flux-density calibrators in the “gold” list: 3C 48 = 0137+3309, 3C 147 = 0542+4951, and 3C 286 = 1131+3030. The on-line VLA calibration manual at
  `http://www.vla.nrao.edu/astro/calib/manual/baars.html`
  provides the the latest (1999.2) and best analytic expressions for their flux densities in the form

  $$\log S = A + B\log\nu + C(\log\nu)^2 + D(\log\nu)^3\ , \tag{4}$$

  where S is the flux density in Jy and ν is the frequency in GHz. These expressions are valid up to $\nu = 50$ GHz. The coefficients A, B, C, and D are listed in Table 3 along with the implied $\nu = 31$ GHz flux densities.

Table 2. Close Pairs of Calibrators

Source 1	Source 2	Separation (deg)	Notes
1310+3220	1310+3233	0.2	
1848+3219	1848+3244	0.4	
0217+0144	0219+0120	0.5	
1640+3946	1642+3948	0.5	Both sources $S > 1$ Jy
1657+4808	1658+4737	0.5	
1044+8054	1058+8114	0.6	Circumpolar pair
0424−3756	0428−3756	0.8	
1326+3154	1329+3154	0.8	Near 1331+3030 = 3C 286
2151+0709	2148+0657	0.9	

Table 3. Flux-density Calibrators

Source	A	B	C	D	$S_{31\,\mathrm{GHz}}$ (Jy)
3C 48	1.31752	−0.74090	−0.16708	+0.01525	0.78
3C 147	1.44856	−0.67252	−0.21124	+0.04077	1.29
3C 286	1.23734	−0.43276	−0.14223	+0.00345	1.94

A. The Calibrator Finding Program CALFIND

The FORTRAN subroutine CALFIND finds suitable calibrators in file PCALS4.1 satisfying user-specified constraints on search center position, search angular radius, observing frequency, minimum flux density, and "gold" status. It is available as
`ftp://ftp.cv.nrao.edu/NRAO-staff/jcondon/calfind2.f`.

Given the observing frequency ν, CALFIND calculates the GBT beamwidth θ. CALFIND returns only those calibrators with $\theta_{\rm min} < \theta < \theta_{\rm max}$ unless $\theta > 540''$, in which case it shows all sources with $\theta_{\rm max} \geq 540''$ and prints a warning about possible confusion.

CALFIND estimates the flux density at the observing frequency ν as follows. The appropriate frequency band is assigned by:

$$\begin{aligned} 0 < \nu({\rm GHz}) &\leq 3 && \rightarrow {\rm L}\ (\lambda \approx 20\,{\rm cm}) \\ 3 < \nu({\rm GHz}) &\leq 7 && \rightarrow {\rm C}\ (\lambda \approx 6\,{\rm cm}) \\ 7 < \nu({\rm GHz}) &\leq 12 && \rightarrow {\rm X}\ (\lambda \approx 3.6\,{\rm cm}) \\ 12 < \nu({\rm GHz}) &\leq 18 && \rightarrow {\rm U}\ (\lambda \approx 2\,{\rm cm}) \\ 18 < \nu({\rm GHz}) &\leq 30 && \rightarrow {\rm K}\ (\lambda \approx 1.3\,{\rm cm}) \\ 30 < \nu({\rm GHz}) & && \rightarrow {\rm Q}\ (\lambda \approx 0.7\,{\rm cm} \end{aligned}$$

If a measured flux density is available in the assigned band, CALFIND accepts the source if and only if that flux exceeds the specified minimum. If there is no measured flux density in the assigned band, CALFIND accepts the source if (1) the measured flux density in the band immediately higher in frequency exceeds the specified minimum or (2) if the measured flux density in the band immediately lower in frequency exceeds twice the specified minimum or (3) if the flux density estimated by extrapolating the L-band flux density with a spectral index $\alpha = +0.8$:

$$S_{\rm est} = S_{\rm L} \left(\frac{\nu}{1.4\,{\rm GHz}} \right)^{-0.8} \tag{A1}$$

exceeds the specified minimum.

CALFIND determines whether a calibrator at α, δ lies within the search circle of angular radius ρ centered on (α_0, δ_0) by converting all positions to Cartesian coordinates on a unit sphere; e.g.,

$$x = \cos\alpha\,\cos\delta \tag{A2}$$

$$y = \sin\alpha\,\cos\delta \tag{A3}$$

$$z = \sin\delta \tag{A4}$$

This avoids the poles and wraparound ambiguities of the (α, δ) coordinate system and allows searches to cover the whole sky ($\rho > 180°$). The calibrator is kept if

$$\rho > 2\,{\rm arcsin} \left\{ \frac{[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2]^{1/2}}{2} \right\} \tag{A5}$$

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This preprint was prepared with the AAS LaTeX macros v5.2.