# Improved "Traditional"Pointing Constants for the GBT

D. S. Balser, J. J. Condon, K. Constantikes, & R. M. Prestage

2003 Nov 26

GBT Archive: PR039
File: PROJECTS
Keys: PTCS, requirement, specification

**Abstract**

The old pointing model in use at the GBT (based on observations made in September 2002) was not accurate enough for either blind pointing at X-band or for offset pointing at 52 GHz. In order to refine the "traditional" pointing constants and reduce the blind pointing errors, we observed calibration sources covering wide ranges of azimuth and elevation at 9 GHz on 2003 October 2 and November 10. Data taken while wind speeds exceeded 2.5 m $s^{-1}$ were rejected. We estimated new pointing constants by separately minimizing the azimuth $(A)$ and elevation $(E)$ residuals on each day. The new pointing residuals are ($\sigma_{\rm A} = 3''.0$, $\sigma_{\rm E} = 5''.6$) on October 2, ($\sigma_{\rm A} = 3''.9$, $\sigma_{\rm E} = 7''.1$) on November 11, and ($\sigma_{\rm A} = 4''.2$, $\sigma_{\rm E} = 7''.9$) for the combined data and model. We also discovered the mistake afflicting the previous model. On 2003 November 20, new observations were made using our updated pointing constants but no thermal corrections. After fixed offsets $\Delta{\rm A} = +4''$, $\Delta{\rm E} = -7''$ were subtracted, the rms blind pointing errors were found to be $\sigma_{\rm A} = 2''.3$, $\sigma_{\rm E} = 4''.6$. This satisfies the scientific requirement for blind pointing that *either* $\sigma_{\rm A}$ or $\sigma_{\rm E}$ be less than $4''.3$ at 52 GHz. The remaining errors appear to be dominated by thermal distortions.

**Contents**

## History

**28.1** 2003 Nov 18. Original version (J. J. Condon).

**28.2** 2003 Nov 19. Revised version (J. J. Condon).

**28.3** 2003 Nov 26. Add November 20 data (J. J. Condon).

**28.4** 2003 Nov 26. Revise discussion of old model (R. Prestage).

### 1. Introduction

Good absolute or "blind" pointing accuracy is important for two reasons: (1) Many observations can be made without the repeated use of pointing calibrators. For "good" performance (Condon 2003a), the rms pointing error should not exceed $\sigma_2 \approx 0.14\theta$ in two dimensions, where $\theta \approx 740''/\nu(\mathrm{GHz})$ is the FWHM beam size. For example, at $\nu = 20$ GHz (K-band), we require $\sigma_2 \lesssim 5\farcs2$. Until now, the blind GBT pointing errors were much larger than this, particularly in elevation (Baler & Prestage 2003), leading to complaints by astronomers observing at X- and K-band. (2) GBT observations at higher frequencies will require accurate offset pointing and tracking for periods of 30 to 60 minutes. Gradients in the blind pointing degrade both offset pointing and tracking. Also, if the absolute pointing error is larger than $\approx 0.3\theta$ in both azimuth and elevation (Condon 2003a), it may be difficult to acquire a new pointing calibrator. Neither the gradients nor the absolute errors of the old pointing model were small enough for offset tracking at 52 GHz.

During two 24-hour periods beginning on 2003 October 2 and November 10, the PTCS group observed a number of strong pointing calibrators (Condon & Yin 2001) at 9 GHz, in order to improve the blind pointing of the GBT. The absolute positions of these calibration sources have uncertainties $\sigma_1 \approx 0\farcs5$ in one coordinate (azimuth, elevation, right ascension, or declination). Each observation was a "jack" (named after the 6-pointed metal toy) scan comprising five subscans in the following order:

1. A forward scan in azimuth, Az(F), at the nominal elevation and focus
2. A scan back in azimuth, Az(B), at the nominal elevation and focus
3. A forward scan in elevation, El(F), at the nominal azimuth and focus
4. A scan back in elevation, El(B), at the nominal azimuth and focus
5. A forward scan in axial focus, Focus(F), at the nominal azimuth and elevation

Both the left circular polarization (LCP) and right circular polarization (RCP) total-power detected outputs were recorded. On each subscan, the output of each channel was roughly a Gaussian. Least-squares fits were made to these Gaussians to determine their intensities and central positions, usually with $\sigma_1 < 1''$ position uncertainty. The "all sky" observations covered sources spanning a wide range of azimuth and elevation angles to constrain the traditional pointing constants of the GBT. This note shows how these data yield refinements for the pointing constants currently in use at the GBT, and it gives estimates of the "blind" pointing accuracy achievable under benign conditions, without the aid of real-time thermal corrections.

The data were analyzed independently by Dana Balser, Jim Condon, and Kim Constantikes. Their three sets of pointing constants are in good agreement, require no nonphysical terms, and significantly reduce the pointing residuals. Furthermore, Dana and Richard Prestage discovered the mistake that caused the the large errors of the old pointing model. It had perviously been speculated that these were the result of errors in the so-called "focus-tracking" model, and the proposed solution had been the introduction of nonphysical "empirical" terms. This is no longer required. We tested the new pointing constants by observing a set of calibration sources on November 20 using Kim's "isothermal" values for the traditional pointing constants and no thermal corrections. After subtracting a single pointing offset for the entire night, we found blind pointing errors $\sigma_{\rm A} = 2''.3$, $\sigma_{\rm E} = 4''.6$. These meet the scientific requirements for "good" blind pointing at 20 GHz and for offset pointing at 52 GHz.

## 2. Measured Offsets

For each position coordinate, azimuth or elevation, there are four measurements per jack scan (two polarizations $\times$ two directions). By averaging the results over both directions $[(F + B)/2]$ and polarizations $[(LCP + RCP)/2]$, we obtained the results shown in Figures 1 (based on 2003 October 2 data) and 2 (based on 2003 November 10 data) for offsets from the "empirical" pointing model in use at the GBT. Data taken while the wind speed was $s > 2.5$ m s$^{-1}$ were excluded. The azimuth offsets (upper panels) are much smaller than the elevation offsets (lower panels), which clearly have large systematic errors. The uncorrected rms offsets were $\sigma_{\rm A} = 4''.2$, $\sigma_{\rm E} = 12''.8$ on October 2 and $\sigma_{\rm A} = 8''.0$, $\sigma_{\rm E} = 20''.0$ on November 11.

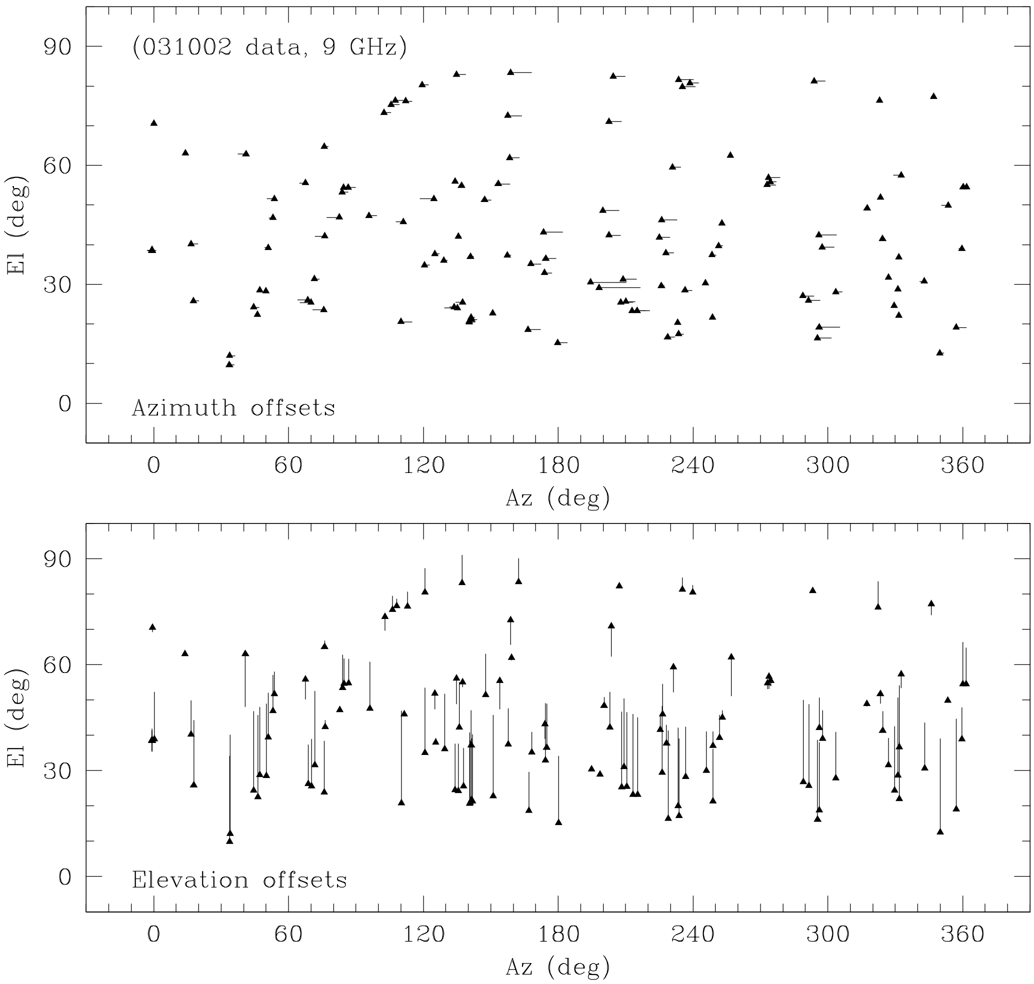


Fig. 1.— The azimuths and elevations in degrees at which the 2003 October 2 observations were made are indicated by triangles. The observed offsets in azimuth (upper panel) and elevation (lower panel) are shown as lines extending from these triangles. The lengths of these lines were multiplied by 3600 so the scales on both axes indicate the offsets in arc seconds.

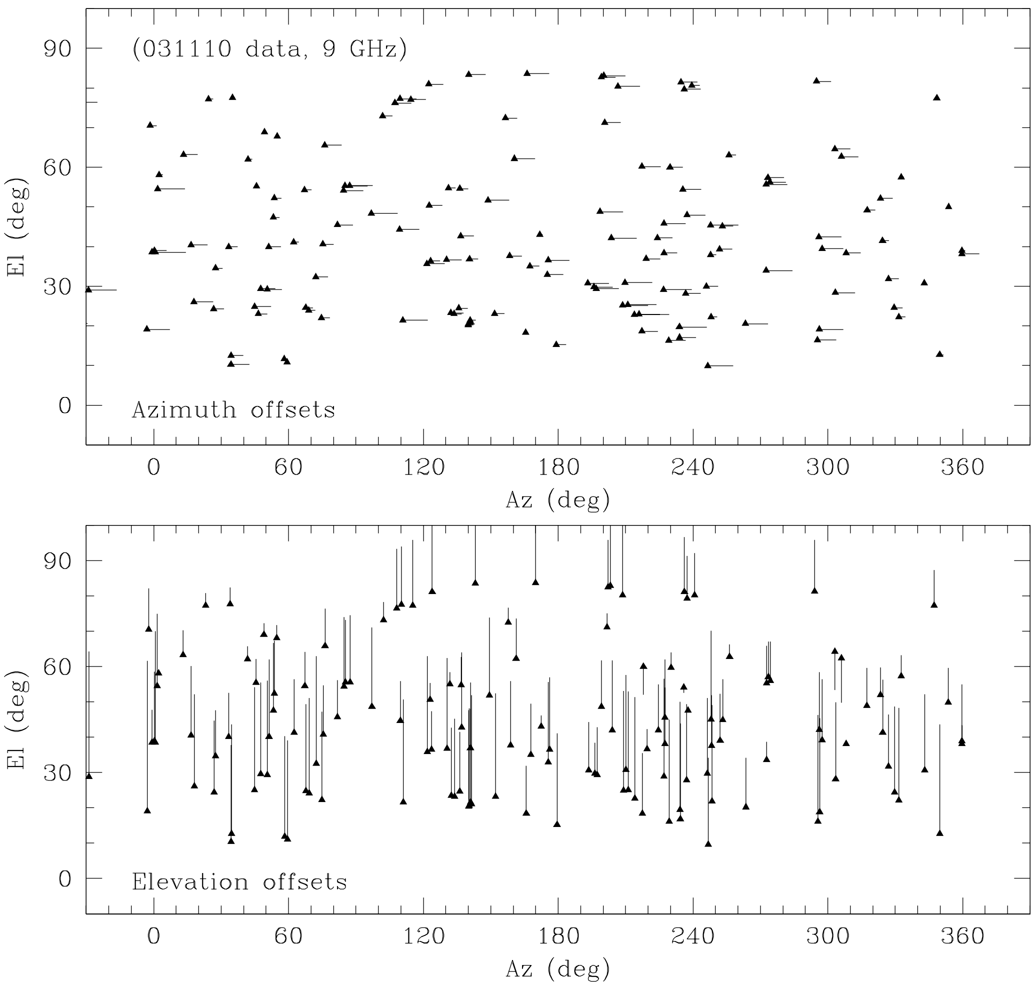


Fig. 2.— Similar to Figure 1 but based on 2003 November 10 data.

## 3. Traditional All-sky Pointing Analysis

The traditional pointing model in use at the GBT (Condon 1992; Balser et al. 2002) includes azimuth [actually $(A\cos E)$] terms

$$d_{0,0} + b_{0,1}\sin E + d_{0,1}\cos E + b_{1,1}\cos A\sin E + a_{1,1}\sin A\sin E \tag{1}$$

and elevation terms

$$d_{0,0} + c_{1,0}\sin A + d_{1,0}\cos A + b_{0,1}\sin E + d_{0,1}\cos E\ . \tag{2}$$

The azimuth and elevation offsets measured during the 2003 October 2 and November 10 pointing runs were used to update the input coefficients of Equations 1 and 2. The new coefficients which minimize the residual offsets are listed in Table 1.

Table 1. Corrections to GBT pointing constants

| Coefficient | Coordinate | October 2 (arcsec) | November 11 (arcsec) | Combined (arcsec) |
|---|---|---|---|---|
| $d_{0,0}$ | Azimuth | $+13$ | $+12$ | $+16$ |
| $b_{0,1}$ | Azimuth | $-8$ | $-5$ | $-9$ |
| $d_{0,1}$ | Azimuth | $-8$ | $-3$ | $-8$ |
| $b_{1,1}$ | Azimuth | $-4$ | $-1$ | $-3$ |
| $a_{1,1}$ | Azimuth | $-3$ | $-3$ | $-3$ |
| $d_{0,0}$ | Elevation | $+73$ | $+74$ | $+74$ |
| $c_{1,0}$ | Elevation | $+1$ | $+1$ | $+1$ |
| $d_{1,0}$ | Elevation | $+0$ | $+0$ | $+0$ |
| $b_{0,1}$ | Elevation | $-68$ | $-57$ | $-61$ |
| $d_{0,1}$ | Elevation | $-31$ | $-30$ | $-31$ |

Figures 3 and 4 show the residual offsets after we subtracted the values obtained by inserting the constants for October 2 and November 10, respectively, from Table 1 into Equations 1 and 2. The rms absolute pointing errors were reduced to ($\sigma_{\rm A} = 3\farcs0$, $\sigma_{\rm E} = 5\farcs6$) on October 2 and ($\sigma_{\rm A} = 3\farcs9$, $\sigma_{\rm E} = 7\farcs1$) on November 10. If the data from both days are combined and the "combined" model in Table 1 is used, the residuals are ($\sigma_{\rm A} = 4\farcs2$, $\sigma_{\rm E} = 7\farcs9$). The scientific requirement for blind pointing is that *either* $\sigma_{\rm A}$ or $\sigma_{\rm E} < 0.30\theta$, where $\theta$ is the FWHM beam size (Condon 2003a). At 52 GHz, this is $\approx 4\farcs3$, which we met in azimuth but not elevation. By starting our offset-pointing "jack" scans with an elevation scan instead of an azimuth scan, it appears that we can now satisfy the blind pointing requirement at 52 GHz in "benign" weather (wind speed $< 2.5$ m s$^{-1}$) without making corrections for thermal distortions (except possibly at sunrise and sunset).

The coefficients in Table 1 are partially correlated (Condon 1992) for observations made over the "limited" elevation range $0^\circ < E < 90^\circ$ (rather than the 'full" range $0^\circ < E < 360^\circ$, which is not accessible from the ground). Consequently, the differences between the best-fit coefficients from independent observations may appear to overstate the range of pointing corrections consistent with the data. Figure 5 shows that the errors of the combined data do not have significant residual dependences on azimuth or elevation. These residuals are dominated by thermal deformations because (1) remaining gravitational errors should depend systematically on elevation and (2) wind errors estimated from short-term pointing jitter are much smaller ($\lesssim 1''$ for wind speeds $< 2.5$ m s$^{-1}$).

## 4. Testing the New Pointing Constants

To test our new pointing models, we observed a set of pointing calibrators for about 8 hours during the night of November 20 using Kim's "isothermal" constants to control the GBT. No thermal corrections were applied, so there were small but constant pointing offsets $\Delta{\rm A} = +4''$, $\Delta{\rm E} = -7''$. After subtracting these, we found the all-sky pointing residuals plotted in Figure 6 whose rms values are $\sigma_{\rm A} = 2\farcs3$, $\sigma_{\rm E} = 4\farcs6$. The two-dimensional error$\sigma_2 = 5\farcs1$ is good enough for blind pointing at 20 GHz. The azimuth error satisfies the scientific requirement for calibrator acquisition that *either* $\sigma_{\rm A}$ or $\sigma_{\rm E}$ be less than $4\farcs3$ at 52 GHz.

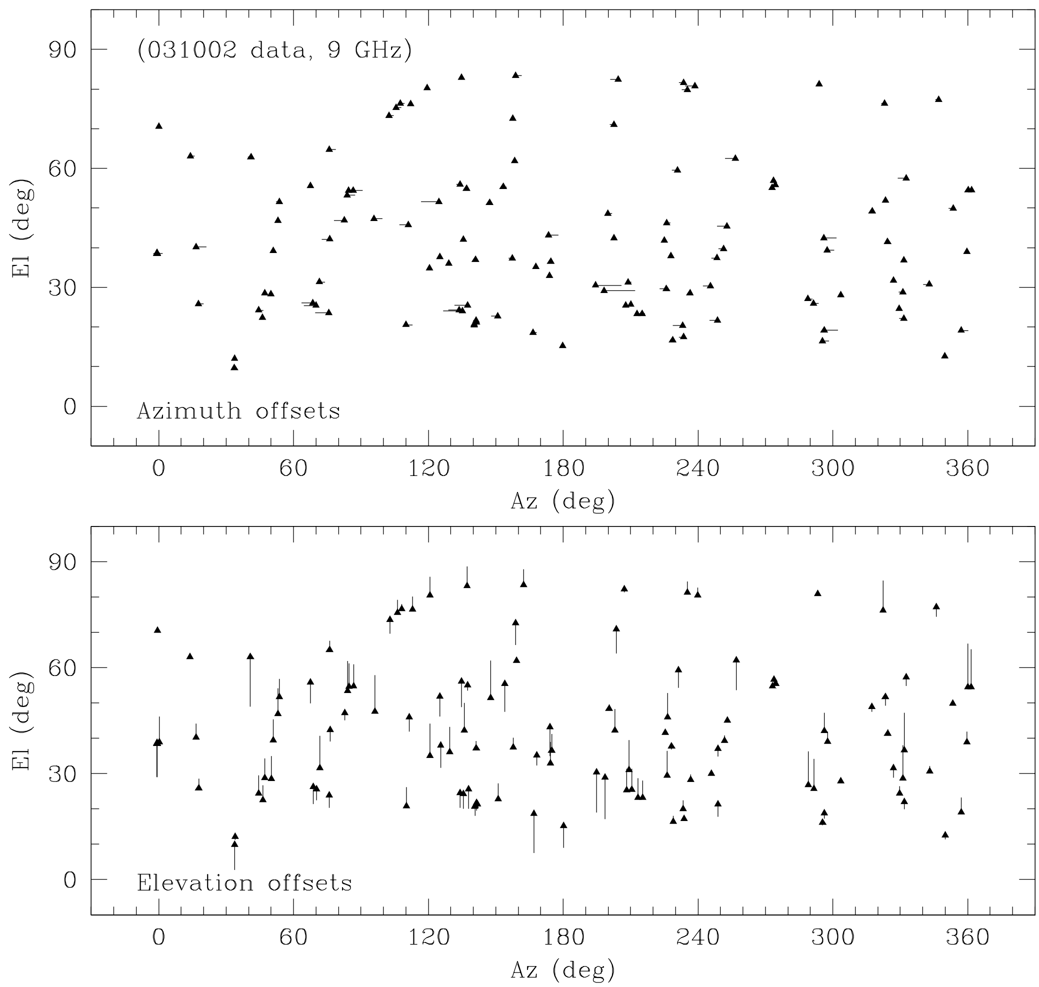


Fig. 3.— The azimuths and elevations in degrees at which the observations was made are indicated by triangles. The corrected offsets in azimuth (upper panel) and elevation (lower panel) are shown as lines extending from these triangles. The lengths of these lines were multiplied by 3600 so the scales on the axes indicate the offsets in arc seconds.

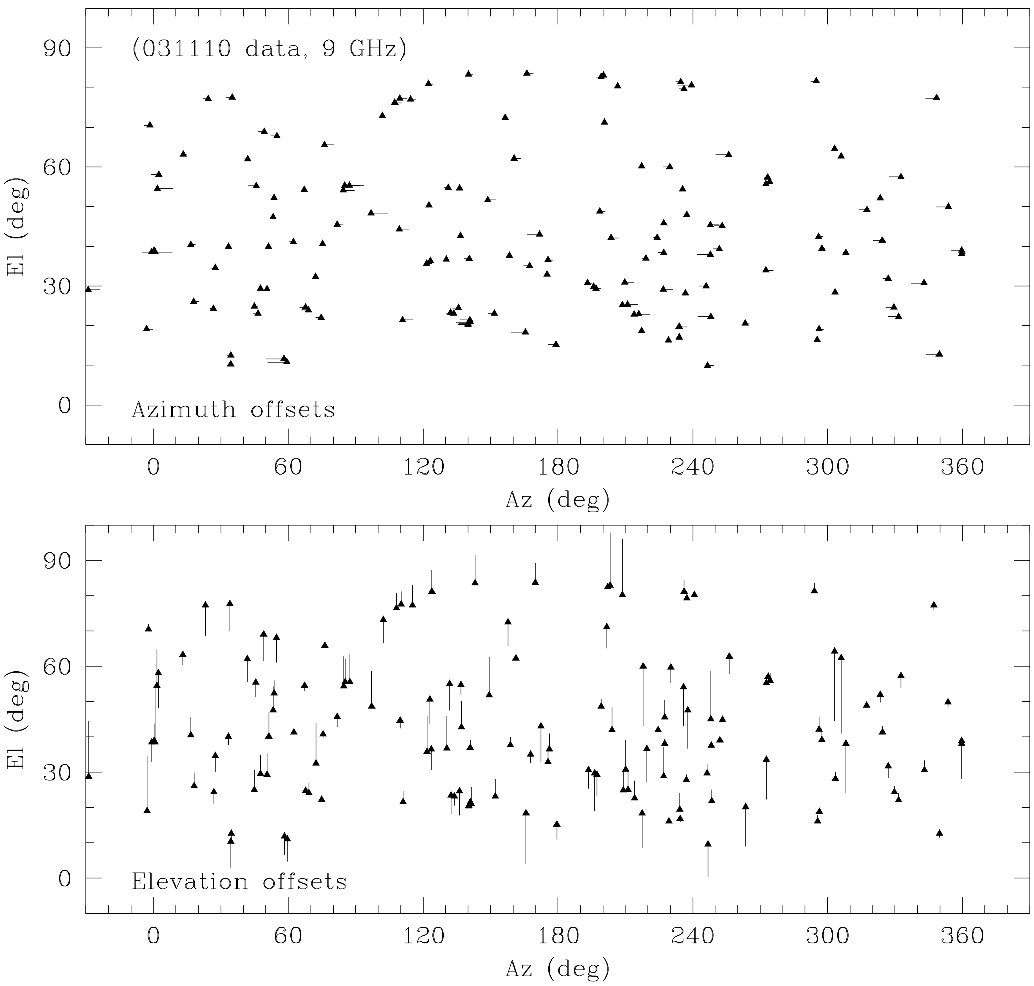


Fig. 4.— Similar to Figure 3 but based on 2003 November 10 data.

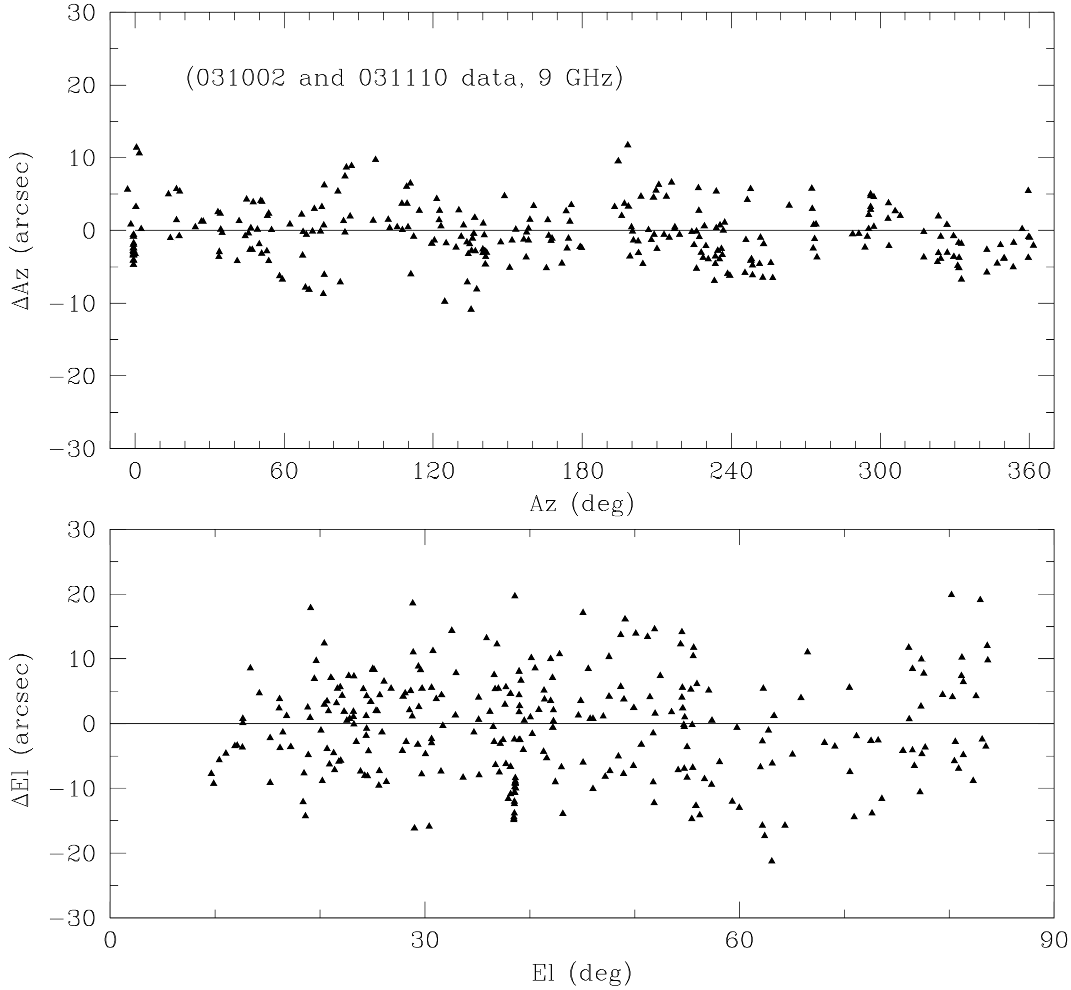


Fig. 5.— Residual pointing errors from the October 2 and November 11 combined data and pointing model.

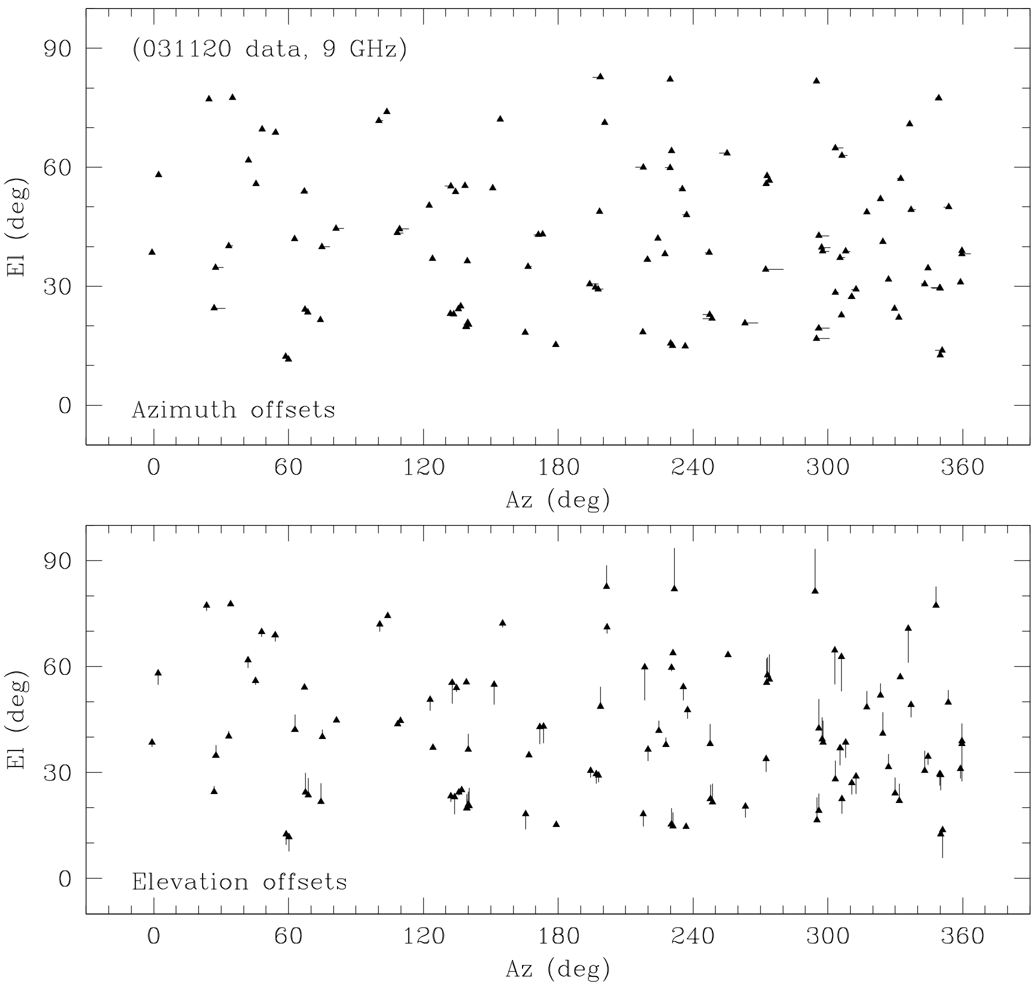


Fig. 6.— Residual pointing errors with our new pointing constants.

## REFERENCES

Balser, D. S., Maddalena, R. J., Ghigo, F., & Langston, G. I. 2002, “GBT X-band (9.6 GHz): All Sky Pointing,” GBT Commissioning Memo 17

Balser, D. S., & Prestage, R. M. 2003, “Systematic Elevation-Dependent Pointing Errors,” PTCS/PN/24

Condon, J. J. 1992, “GBT Pointing Equations,” GBT Scientific Memo 75

Condon, J. J. 2003a, “Refined PTCS Scientific Requirements,” PTCS/PN/27

Condon, J. J. 2003b, “Quick Astronomical Corrections for GBT Pointing and Focus Tracking,” GBT PTCS/PN/10.2

Condon, J. J., & Yin, Q. F. 2001, “Offset Pointing Calibrators for Large Radio Telescopes,” PASP, 113, 362

Constantikes, K. 2003, “Algorithms for Correction of Thermal Pointing and Focus Errors,” PTCS/PN/25

---