GBT Pointing, Focus, and Tracking Performance

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Abstract
The GBT pointing, focus, and tracking performance has been evaluated and compared to previous results in 2003. Overall the performance has not significantly changed. We evaluate the GBT performance under benign conditions: during the nighttime when the thermal gradients are small and during periods when the winds speeds are less than 3 m/s. We determine a blind pointing and focus rms of \( \sigma_{\text{pointing}} = 4.8 \) arcsec and \( \sigma_{\text{focus}} = 2.1 \) mm, respectively; an offset pointing and focus rms of \( \sigma_{2\text{pointing}} = 2.7 \) arcsec and \( \sigma_{\text{focus}} = 1.2 \) mm, respectively, over a duration of 2 hours; and a tracking rms of \( \sigma_{\text{tracking}} = 1.2 \) arcsec over a duration of 20 minutes. There are some trends in the all sky pointing residuals which may be related to track irregularities.

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History

49.0 Original Draft (Dana S. Balser).
49.1 Slight Modifications from RMP (Dana S. Balser).
Table 1: Observational Summary

<table>
<thead>
<tr>
<th>Project</th>
<th>Receiver</th>
<th>Type</th>
<th>Scans</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPTCSPNT_060817</td>
<td>X-band</td>
<td>All Sky Pointing</td>
<td>251–275, 278–626</td>
<td>$T \sim 12$° C; mostly clear</td>
</tr>
<tr>
<td>TPTCSPNT_060818</td>
<td>X-band</td>
<td>Offset Pointing</td>
<td>19–425</td>
<td>$T = 12 – 25$° C; partly cloudy</td>
</tr>
<tr>
<td>TPTCSOOF_60330</td>
<td>Q-band</td>
<td>Tracking</td>
<td>116; 122</td>
<td>$T = 0$° C; clear</td>
</tr>
</tbody>
</table>

† Part of the dataset is located in TPTCSPNT_60817.

# Introduction

The last careful GBT pointing analysis was performed over three years ago (Condon 2003; Balser et al. 2003). The GBT performance was characterized with a two dimensional rms blind pointing of 5 arcsec and a rms blind focus of 2.5 mm. The two dimensional rms offset pointing was 2.8 arcsec and the rms offset focus was 1.5 mm. The tracking performance was an rms of 1 – 2 arcsec over approximately 1/2 hour duration. Over the last three years the telescope azimuth track has continuously been altered as old wear plates are replaced with new plates. Also, there may be other components of the telescope structure that have changed during this period.

The pointing has been periodically checked by commissioning and science observations over the last three years. Also, there were a series of pointing runs made during the summer and fall of 2005 to evaluate the pointing performance. Analysis of these data indicated no major changes in the pointing.

Between 28 June 2004 – 09 March 2006 there was an indexing error introduced in the Antenna Manager FITS file. The only parameters affected by this error were the observed commanded (Az, El) positions (OBSC\_AZ, OBSC\_EL). These columns of the Antenna Manager FITS file are typically only used during a Peak observation, where the offset coordinate mode is set to “Encoder”. In this case the (OBSC\_AZ, OBSC\_EL) columns correspond to the (Az, El) coordinates of the J2000 pointing calibrator with time. The error appears as an error in hour angle. The magnitude of the indexing error was 3 samples, or at a sampling rate of 10 Hz a timing error of 300 milliseconds. At the sidereal rate of 15 arcsec per second this corresponds to 4.5 arcsec in hour angle. The direction of the timing error is such that the incorrectly recorded source position leads the true source position (e.g., in the southern sky the determined Az will be larger than the true Az as the sources moves from East to West with time or increasing azimuth). The result of this error is that the telescope would track as expected, but the local pointing corrections (LPCs) derived from Peak observations would be systematically incorrect, by typically a few arcsecs, due to the error in the recorded pointing calibrator tracking center positions. The functional form of the total error is simply $4.5 \cos(\delta)$ arcsec.† Observations consisting of all sky pointing, offset pointing, and tracking have been performed after 09 March 2006 when the indexing error was fixed.

# Observations

Table 1 summarizes the observations. The pointing observations consisted of jackscan measurements: forward and backward scans in Az; forward and backward scans in El; and an axial (Y) focus scan in only the forward direction (see Condon 2003). These were performed using the procedure AutoPeakFocus2. The pointing calibrators were selected from PCALS3.3 (Condon & Yin 2004). The offset pointing observations consisted of jackscan observations between either two or three nearby (within 10°) calibrators over a period of several hours to access the local pointing accuracy. Finally a bright calibrator was observed at the half-power point to measure pointing fluctuations over shorter time scales for a duration of tens of minutes (e.g., Balser & Prestage 2003). During all observations the pointing model was Model4C. This model incorporates a thermally neutral traditional pointing model and dynamically applies thermal corrections to both pointing and focus (Constantikes 2003a). Also included in Model4C are corrections from a lookup table based on a model of irregularities in the azimuth track.

†See http://wiki.gb.nrao.edu/bin/view/PTCS/PointingFocusSysError for details.
3 Results

3.1 All Sky Pointing and Focus

An all sky pointing run was made in August 2006 using the scheduling block PointingRunV2.sb listed in Appendix A. The sky coverage is shown in Figure 1 for project TPTCSPNT_060817. The sky coverage was excellent and data were collected during benign conditions (low wind speeds and at nighttime when the thermal gradients are small). For all analyses the data quality was filtered by only accepting scans for (1) wind speeds less than 3 m/s; (2) errors in the Gaussian centroids less than 0.5 arcsec for pointing data; and (3) errors in the Gaussian centroids less than 0.5 mm for focus data.

The results are shown in Figures 2–8. The data quality can be evaluated by comparing the difference between the polarization channels \( (LCP - RCP) \) and the difference between the forward and backward directions \( (F - B) \). As discussed by Condon (2003) only receiver noise and 1/f noise should cause fluctuations in the difference \( (LCP - RCP) \), while the difference \( (F - B) \) is affected by receiver fluctuations plus real pointing and focus shifts due to the atmosphere and telescope, but not errors in the calibrator position.

Overall the data quality here is similar to earlier measurements. The beam squint is small for the X-band receiver \( (< 0.1 \text{ arcsec}) \), 1/f noise can be detected causing errors in the pointing that are twice the theoretical values, and the measured hysteresis is small but significant for high frequency observations \( (~ -1 \text{ arcsec in Az and ~ -2 arcsec in El}) \). A software error in the data analysis that caused a large hysteresis at lower frequencies (e.g., L-band) when the telescope scanning rates were large was fixed in 2004 (see Balser & Prestage 2004). Therefore, the hysteresis measured here is not identical to measurements discussed in Condon (2003).

The local pointing corrections (LPCs) and the local focus corrections (LFCs) are plotted as a function of azimuth and elevation to measure any pointing or focus trends and to measure the blind pointing and focus accuracy of the GBT. The blind pointing is determined by using the maximum one-dimensional rms error since the source only has to be detected in a given cross scan for this requirement. The one-dimensional rms blind pointing is \( \sigma_{\text{pointing}} = 4.8 \text{ arcsec} \). The rms axial focus error is \( \sigma_{\text{focus}} = 2.1 \text{ mm} \). N.B., we have assumed that a single jackscan observations has been made at the beginning of the observing session to remove any pointing or focus offset. Figure 8 shows the dynamic and local pointing and focus corrections versus time.

Small scale structure can be detected in the LPCs versus azimuth, especially for the cross-elevation residuals (see Figure 4 and 5). Recall that small scale structure versus azimuth was modeled and incorporated as a lookup table in Model4C. The current results may indicate that the azimuth track irregularities are not well modeled or have changed due to the continuous replacement of track plates. Also, there may be a slight linear trend in the elevation residuals versus elevation (see Figure 5). Model4C was determined using only data between elevations 20-80 degree which may account for some of the trend.
Figure 1: Sky coverage of all sky pointing run TPTCSPNT_060817.

Azimuth centered on 180°
Figure 2: Polarization difference in the LPCs as a function of azimuth (top panel) and elevation (bottom panel). Plotted are the polarization differences for cross-elevation LPCs in the forward (solid red circles) and backward (open red circles) directions and for elevation LPCs in the forward (solid blue triangles) and backward (open blue triangles) directions.
Figure 3: Direction difference in the LPCs as a function of azimuth (top panel) and elevation (bottom panel). Plotted are the direction differences for cross-elevation LPCs in LCP (solid red circles) and RCP (open red circles) polarizations and for elevation LPCs in the LCP (solid blue triangles) and RCP (open blue triangles) polarizations.
Figure 4: Cross-elevation local pointing corrections as a function of azimuth (top panel) and elevation (bottom panel). Plotted are the forward direction LCP channel (solid red circles), the backward direction LCP channel (open red circles), the forward direction RCP channel (solid blue triangles), and the backward direction RCP channel (open blue triangles).
Figure 5: Elevation local pointing corrections as a function of azimuth (top panel) and elevation (bottom panel). Plotted are the forward direction LCP channel (solid red circles), the backward direction LCP channel (open red circles), the forward direction RCP channel (solid blue triangles), and the backward direction RCP channel (open blue triangles).
Figure 6: Polarization difference LFCs in the forward direction as a function of azimuth (top panel) and elevation (bottom panel).
Figure 7: Local focus corrections as a function of azimuth (top panel) and elevation (bottom panel). Plotted are the LFCs for the LCP (open red circles) and the RCP (open blue triangles) channels.
Figure 8: Top panel: local and dynamic pointing corrections versus universal time. Plotted are the cross-elevation LPCs (solid red circles), the elevation LPCs (solid orange triangles), the cross-elevation dynamic corrections (open blue circles) and the elevation dynamic corrections (open cyan triangles). Bottom panel: local and dynamic focus corrections versus universal time. Plotted are the LFCs (solid red circles) and the dynamic corrections (open blue circles).
3.2 Offset Pointing and Focus

An offset pointing run was made in August 2006 using the scheduling block OffsetPointingRun.sb in Appendix A. Two pairs of calibrators were tracked. The sky coverage is shown in Figures 9 and 13 for source pair 1 (0119 + 3210, 0126 + 3313) and for source pair 2 (1130 − 1449, 1139 − 1350), respectively. Source pair 1 was observed while the Sun was rising and the target sources setting. The local time was early morning when the thermal gradients are still small but growing. Source pair 2 was observed during the day from late morning to early afternoon when the thermal gradients are significant.

The results are shown in Figures 10-12 for source pair 1 and Figures 14-16 for source pair 2. The data were analyzed in two ways: (1) we compared the LPCs and LFCs of consecutive pairs of observations with one source acting as the offset pointing calibrator while the other source acting as the target; and (2) we compared the LPCs and LFCs in time with one source providing an initial local correction compared to the other source over a period of several hours. The first analysis provides a measure of the offset pointing locally in position and in time, while the second explores how the offset corrections varies over larger timescales. Some data were edited due to high winds (> 3 m/s) or errors in Gaussian centroids (> 0.5 arcsec in pointing and > 0.5 mm for focus).

Using source pair 1 as an example of the offset pointing performance under benign conditions we achieve a two-dimensional rms pointing error of $\sigma_2(\text{pointing}) = 2.7$ arcsec and a rms focus error of $\sigma(\text{focus}) = 1.2$ mm over a period of about 2 hours. The actual pointing and focus errors are slightly larger, however, since the mean values are significantly larger than zero (see Figure 12). We may be detecting the beginning of thermal effects from the Sun as it rises and heats the antenna.

Source pair 2 data measure the offset pointing performance during daytime conditions when the thermal gradients are significant. The axial focus can change by 10 mm in two hours (see Figure 16). The thermal model is applied dynamically every 10 seconds and performs quite well during the nighttime. During the daytime, however, the model sometimes degrades the performance. Therefore, the measured performance during the daytime, illustrated in Figures 14-16 for source pair 2, may be worse than it would otherwise be without the dynamic corrections. In particular, the dynamic focus corrections are usually better than the dynamic pointing corrections. Therefore, it is probably best to apply the dynamic focus corrections but not the dynamic pointing corrections during daytime periods for the current model (Model4C).
Figure 9: Sky coverage for offset pointing run TPTCSPNT_060818 for source pair 1 (0126+3313, 0119+3210).
Figure 10: Offset pointing corrections versus azimuth (top panel) and elevation (bottom panel). Plotted are the offset LPC difference between a target source (0126+3313) and the nearest reference source (0119+3210) for cross-elevation (open red circles) and elevation (open blue triangles).
Figure 11: Offset focus corrections versus azimuth (top panel) and elevation (bottom panel). Plotted are the offset LFC difference between a target source (0126+3313) and the nearest reference source (0119+3210).
Figure 12: Top panel: Offset pointing corrections versus time. Plotted are the offset LPC difference between a target source (0126+3313) and a reference source (0119+3210) over time for cross-elevation (open red circles) and elevation (open blue triangles). Bottom panel: offset focus corrections versus time.
Figure 13: Sky coverage for offset pointing run TPTCSPNT_060818 for source pair 2 (1139-1350, 1130-1449).
Figure 14: Offset pointing corrections versus azimuth (top panel) and elevation (bottom panel). Plotted are the offset LPC difference between a target source (1139-1350) and the nearest reference source (1130-1449) for cross-elevation (open red circles) and elevation (open blue triangles).
Figure 15: Offset focus corrections versus azimuth (top panel) and elevation (bottom panel). Plotted are the offset LFC difference between a target source (1139-1350) and the nearest reference source (1130-1449).
Figure 16: Top panel: Offset pointing corrections versus time. Plotted are the offset LPC difference between a target source (1139-1350) and a reference source (1130-1449) over time for cross-elevation (open red circles) and elevation (open blue triangles). Bottom panel: offset focus corrections versus time.
### Table 2: Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sigma_1$ (Pointing) [arcsec]</th>
<th>$\sigma_1$ (Focus) [mm]</th>
<th>$\sigma_2$ (Pointing) [arcsec]</th>
<th>$\sigma_2$ (Focus) [mm]</th>
<th>$\sigma_2$ (tracking) [arcsec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>5.0</td>
<td>2.5</td>
<td>2.8</td>
<td>1.5</td>
<td>1-2</td>
</tr>
<tr>
<td>2006</td>
<td>4.8</td>
<td>2.1</td>
<td>2.7</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

#### 3.3 Tracking

The tracking performance was evaluated by tracking the half-power point of the calibrator 2253+1608 at Q-band for a duration of 20 minutes. The results are summarized in Figures 17-18. The two-dimensional rms tracking error is $\sigma_2$ (tracking) = 1.2 arcsec over a duration of 20 minutes, consistent with previous estimates. This provides an upper limit to the tracking error since the observed fluctuations can also be caused by receiver noise and atmospheric fluctuations. The main fluctuations occur at 0.28 Hz (or a harmonic) that has been demonstrated to be associated with the servo system (Constantikes 2003b). These servo fluctuations can be detected at Q-band even when observing the center position of a calibrator and they degrade the telescope efficiency. Notice that there is also some power between 0.25 – 0.45 Hz.

#### 4 Summary

The results are summarized in Table 2 for previous results in 2003 (Condon 2003; Balser et al. 2003) and for 2006 (this memo). Overall the pointing, focus, and tracking performance has not significantly changed over a three year period.

#### 5 References


Figure 17: Half-power track on 2253+1608 offset in the azimuth direction. Top panel: position offset versus time. A linear polynomial has been subtracted from the data. The sample time is 0.1 seconds. Bottom panel: power spectrum.
Figure 18: Half-power track on 2253+1608 offset in the elevation direction. Top panel: position offset versus time. A linear polynomial has been subtracted from the data. The sample time is 0.1 seconds. Bottom panel: power spectrum.
A Observing Scripts
Table 3: PointingRun.sb

# PointingRun.sb - all sky pointing run
#
#-------------------------------------------------------------
#
# Note:
#
# 1. If nPeak is very large (> 25) it will take some time to validate.
#
#-------------------------------------------------------------
#
# History:
# 08/09/05: R. Prestage. Original based on a template by Amy Shelton
# 08/25/05: D. Balser. Add new procedure AutoPeakFocus2.
# 05/08/06: D. Balser. Add slew at the end to deal with transition.
# 05/09/06: D. Balser. Add code to keep track of Az,El direction between SB's.

# Import general modules
import os
import sys
import random

# Add ptcs directory to the path so we can reference files as modules
ptcsturtledir = "/home/groups/ptcs/obs/turtle"
sys.path.append(ptcsturtledir)

# Use grail client to get current (Az,El) position
import antenapos

# include configurations and archivist definitions
execfile(os.path.join( ptcsturtledir, "configs.py"))
execfile(os.path.join( ptcsturtledir, "archivist.py"))
execfile(os.path.join( ptcsturtledir, "LST.py"))
execfile(os.path.join( ptcsturtledir, "localToEq.py"))
execfile(os.path.join( ptcsturtledir, "ZernikeOnV2.py"))

# define the new version of AutoPeakFocus
codedir=ptcsturtledir
DefineScan("AutoPeakFocus2",
   os.path.join( codedir, "AutoPeakFocus2.py"))

# get the initial (Az,El) position
az, el = antenapos.GetAntennaPos()

# --------------------some input info ---------------------
azStart = 0.0  # starting az
azEnd   = 360.0  # ending az
azStep  = 36.0   # az step
elStart = 10.0  # starting el
elEnd   = 85.0  # ending el
elStep  = 12.0  # el step
doConfig = True  # flag for configuration
lat = 38.433121  # latitude from database
nPeak = 25       # number of peaks
fluxLimit = 1.0  # flux limit [Jy]
searchRadius = 10.0 # search radius [deg]

# ----------------------------------------------
# read direction and set
infile = open(os.path.join( codedir , "azElDirection.txt"), 'r')
foo = infile.readlines()[0].split(' ')
azStep = abs(azStep) * float(foo[0])
elStep = abs(elStep) * float(foo[1])
infile.close()

if doConfig:
    # configure
    ifdoConfig:
    Comment("Configuring the system for selected band")
    Configure(xband)

    # Define the archivist setup we use and send it
    Comment("Adding and configuring the Archivist.")
    SetValues("ScanCoordinator", {'subsystemSelect,Archivist': 1})
    SetValues("Archivist", archivistParameters)

while nPeak > 0:
    # get the time [hr]
    lst = LST()
    # convert AzEl into J2000
    rawJ2000 = localToEq(az, el, lat, lst)
    Comment("Current antenna location is az: %g , el : %g " % (az, el) )
    Comment("Current antenna location is ra: %g , de : %g " % (rawJ2000[0], rawJ2000[1]))

    # perform peak/focus
    AutoPeakFocus2(loc=locationJ2000, flux=fluxLimit,
        radius=searchRadius, balance=True,
        configure=False, abort=False,
        doZernModel="2005WinterV2")

    # increment elevation
    el = el + elStep
    # change direction if we reach the limits
    if el < elStart or el > elEnd:
        elStep = -elStep
        el = el + (1+random.random()) *elStep
        # increment azimuth
        az = az + azStep
        # change direction if we reach the limits
        if az < azStart or az > azEnd:
            azStep = -azStep
            az = az + (1+random.random())*azStep
    # decrement the counter
    nPeak = nPeak - 1

    # determine Az,El direction and write to file
    azDir = int(azStep/abs(azStep))
elDir = int(elStep/abs(elStep))
    foo = str(azDir) + " " + str(elDir)
    outfile = open(os.path.join( codedir , "azElDirection.txt"), "w")
    outfile.write(foo)
    outfile.close()

    # Slew to last location
    locationAzEl = Location("AzEl", az, el)
    Slew(locationAzEl)
# OffsetPointingRun.sb - Offset pointing
#
# History:
# 09/01/05: D. Balser. Original
#
# Import general modules
import os
import sys
import random
#
# Add ptcs directory to the path so we can reference files as modules
ptcsturtledir = "/home/groups/ptcs/obs/turtle"
sys.path.append(ptcsturtledir)
#
# And try this out:
import antenapos
#
# include configurations and archivist definitions
execfile(os.path.join( ptcsturtledir , "configs.py"))
execfile(os.path.join( ptcsturtledir , "archivist.py"))
execfile(os.path.join( ptcsturtledir , "LST.py"))
execfile(os.path.join( ptcsturtledir , "localToEq.py"))
execfile(os.path.join( ptcsturtledir , "ZernikeOnV2.py"))
#
# define the new version of AutoPeakFocus
codedir=ptcsturtledir
DefineScan("AutoPeakFocus2",
          os.path.join( codedir , "AutoPeakFocus2.py"))

# ------------some input info ---------------------
doConfig = True  # flag for configuration
nSrc = 2  # number of sources in sequence
nPeak = 25  # number of peaks
#
# Condon list of Triple sources
srcList = ['0119+3210', '0126+3313', '0137+3309']
#srcList = ['0827-2026', '0836-2016', '0837-1951']
#srcList = ['1635+3808', '1642+3948', '1653+3945']
# Condon list of Double sources
#srcList = ['2023+3153', '2020+2942']
#srcList = ['1911-2006', '1923-2104']
#srcList = ['2158-1501', '2206-1835']
#srcList = ['0541+4729', '0542+4951']
#srcList = ['0813+4813', '0808+4950']
#srcList = ['1326+3154', '1331+3030']
#srcList = ['1130-1449', '1139-1350']
#  
#  
#
if doConfig:
    # configure
    Comment("Configuring the system for selected band")
    Configure(xband)

    # Define the archivist setup we use and send it
    Comment("Adding and configuring the Archivist.")
    SetValues("ScanCoordinator", {'subsystemSelect,Archivist': 1})
    SetValues("Archivist", archivistParameters)

# perform nPeak offset measurements
while nPeak > 0:

    # Loop through nSrc offset sources
    for i in range(nSrc):
        Comment("Offset source %d of %d (%d observations remain)" % (i+1, nSrc, nPeak))

        # perform peak/focus
        AutoPeakFocus2(source=srcList[i], balance=True, configure=False, abort=False)

    # decrement the counter
    nPeak = nPeak - 1