Abstract

This memo presents measurements of the GBT telescope gain and efficiency by K-band (18 to 27.5 GHz) Focal Plane Array (KFPA) for observations of the Moon. These calibration observations are intended to be applied to other KFPA observations to improve absolute calibration by correcting for errors in the reported noise diode measurements. The goal of this calibration effort is to achieve a few percent accuracy (±10%) in total intensity calibration. These observations are intended to correct the calibration values included with the GBT observations in the period September 2010 through January 2011. We applied these calibration values to the Moon observations to check the KFPA pipeline. These gain factors were checked by application to mapping observations of point sources 3C48 and 3C123, using two types of imaging convolving functions.

For observations of point sources, the mapping methods can reduce the peak intensities of point sources, by the gridding convolution process. If the image resolution is properly determined, the integrated intensities of the mapping observations are accurately measured. We find that the Moon referenced gain values yield integrated flux densities consistent with published values for 3C48 and 3C123.

Finally we comment on the accuracy of the calibration using Lunar observations, and point out priorities for improving the calibration gridding accuracy.
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1. Introduction

This memo presents measurements of the GBT telescope gain and efficiency by K-band (18 to 27.5 GHz) Focal Plane Array (KFPA) for observations of the Moon. These calibration observations are intended to be applied to other KFPA observations to improve absolute calibration by correcting for errors in the reported noise diode measurements. The goal of this calibration effort is to achieve a few percent accuracy (±10%) in total intensity calibration. These observations are intended to correct the calibration values included with the GBT observations in the period September 2010 through January 2011. We applied these calibration values to the Moon observations to check the KFPA pipeline. These gain factors were checked by application to mapping observations of point sources 3C48 and 3C123, using two types of imaging convolving functions.

The receiver noise diode values are measured in the laboratory and provided as a table of numbers by the observing system. For all observations from September 2010 through January 2011, the noise diode values measured in 2010 August 18 were provided. Later observations suggested that these values were too low, and the observations presented here are used to compute correction factors for absolute calibration.

Several authors have reported on the use of the Moon as a calibration target for large telescopes (Baars 1973; Mangum 1993; Greve et al. 1998). Observations of the Moon have a number of advantages, including large angular size, so that pointing is not an issue, and relatively high brightness temperature, so that measurement uncertainty is relatively small. The Moon has been previously observed at radio wavelengths for many years, e.g. Piddington & Minnett (1949), Salomonovich (1962a), Linsky (1973), and results are in good agreement.

The major disadvantage of the Moon as a calibration source are 1) the monthly variation in average temperature and 2) the variation in temperature with lunar latitude, as shown by Salomonovich (1962b). Radio wavelength emission from the Moon originates a few wavelengths within the surface, so shows smaller monthly variations at longer wavelengths. The lunar temperature is nearly constant at wavelengths longer than 10cm (Salomonovich 1962b).

Astronomical measurements of the brightness of radio sources can not separate two effects, 1) uncertainty in the measurements of the Noise Diodes and 2) overall gain of the telescope and receiver system. Fortunately, for the purposes of accurate calibration only the combination of these two factors is required.

We summarize the observations in §2 and discuss measurement of the lunar temperature in §3. In §4 we apply the deduced gain calibration values to the observations of the Moon and also to observations of bright radio source 3C48. In §5 we discuss the measured values, after calibration, from the images of the reference radio sources. In §6 the results are summarized.

For more information on the KFPA development project, see links from the page:

https://safe.nrao.edu/wiki/bin/view/Kbandfpa/WebHome
2. Observations

Observations were carried out with the GBT on 2010 December 15, as a part of KFPA commissioning tests. On this date we measured the system response to observations of the Moon and Reference Radio source 3C48. The KFPA was used for these observations, with the IF configured in the standard manner (Langston & White 2011) and the spectrometer configured for 50MHz bandwidth centered on 23706. MHz. After pointing and focus in the standard manner, all measurements were made with the spectrometer.

The observations consisted of several components and were carried out using two astrid Scripts, petal3C48 and petalMoon:

- **On-Off 3C48**
  Two spectral line scans; one On-target 3C48 and the other offset from 3C48 by 20'' in Right Ascension. The integration time was 1 second and the total observing time was 30 seconds.

- **Petal 3C48**
  A set of three Daisy (Petal) scans of 3C48, with map radius of 2.5' and radial oscillation period of 40s. The total scan duration was 80 seconds. The three Daisy scans were offset in rotation phase 30° in starting angle, to fill in the mapped region.

- **On-Off 3C48**
  Second pair of observations of 3C48, performed in the manner identical to those of the first pair.

- **On-Off Moon**
  Before observations of the Moon, the IFRack input target level was set to 6. Volts, higher than the usual value of 2.5 Volts. This was intended to avoid saturation of power levels in the IF amplifier and fiber modem components. After balancing the input levels to the IFRack and spectrometer, no further gain/attenuator changes were made during this observation. The off position was located 1 degree in Azimuth relative to the Moon center position.

- **Petal Moon**
  Three Daisy scans with radius of 17' and radial oscillation period of 120 seconds and a duration of 240 seconds. As for 3C48, the three Daisy scans were offset in rotation phase 30° in starting angle, to fill in the mapped region.

- **On-Off Moon**
  A pair of scans, On and offset of the Moon center location, as was done for the first pair of On-Off Moon scans.

We use the pairs of On-Off scan measurements to determine the gain calibration factors. factors that must be included to fully account for the measurements.

On the following date, 2010 December 16, we also observed bright radio source 3C123. Source 3C123 was mapped in the same manner as was done for 3C48; three Daisy scans bracketed by On/Off source observations. The gain values are applied these observations as well.
3. Measurements

Accurate calibration of radio wavelength observations is complicated by the number of different contributions to the observed system temperature. The calibration process is the technique by which these contributions are estimated. The measured $T_A$ values are scaled by a variety of factors, based on a model for the telescope performance and atmospheric opacity. Typically the observer will schedule an observation of empty sky, and measure the reference temperature, $T_{\text{ref}}(\nu)$, of that location. The measured values are modeled as the sum of several components, listed in equations (1) and (2), which are based on equation 8.2 of *Tools of Radio Astronomy*, by Rohls and Wilson (2005).

\[ T_{\text{sig}}(\nu, e_1) = T_{\text{rx}}(\nu) + (T_{\text{moon}} \eta_{mb}(e_1) + T_{\text{atm}}(\nu)) \eta_l \left(1 - e^{-\tau(\nu,e_1)}\right) + T_{\text{amb}} (1 - \eta_l) \]  
\[ T_{\text{ref}}(\nu, e_2) = T_{\text{rx}}(\nu) + (\eta_{mb}(e_2) T_{\text{cmb}} + T_{\text{atm}}(\nu)) \eta_l \left(1 - e^{-\tau(\nu,e_2)}\right) + T_{\text{amb}} (1 - \eta_l) \]  
\[ T_{\text{moon,obs}}(\nu, e_1, e_2) = T_{\text{sig}}(\nu, e_1) - T_{\text{ref}}(\nu, e_2) \]

The cosmic background temperature, $T_{\text{cmb}}$, is \( \sim 2.725 \) K, and the average atmospheric temperature, $T_{\text{atm}}(\nu)$, depends on the weather. The contribution to the system temperature depends on the opacity, which is strongly dependent on elevation. The receiver temperature, $T_{\text{rx}}(\nu)$, is measured in the laboratory and is independent of weather and elevation. The ambient temperature, $T_{\text{amb}}$, is measured by the weather station. The $\eta_l$ term is the correction for rear spillover, ohmic loss, and blockage efficiency.

These items are presented below as factors that reduce the true moon brightness temperature to the expected brightness temperature. We express the gains factors as the ratio of the expected brightness temperature to the measured temperature. These factors are listed below:

**Main Beam Gain**

The main beam efficiency, $\eta_{mb}$, must be included to determine the expected signal strength. This value is modeled, not measured. Recently Maddelena (2010)

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1The equations are from the KFPA Position Switched Calibration Plan, by Langston (2011) https://safe.nrao.edu/wiki/bin/view/Kbandfpa/PsCalibrationPlan
reviewed the estimates for this value, and pointed out that this factor depends on the design of the telescope optics. This parameter is particularly sensitive to the “taper” of the feed horns. This parameter is also dependent on the frequency of the observation. We estimate the uncertainty of this parameter at ±3%. A detailed study of the uncertainty of this parameter is needed.

**Gain versus Elevation** In addition to the main be efficiency, there is also a weak dependence of gain on elevation, $Gain(el)$. The $Gain(el)$ factor is near unity for higher elevations. The uncertainty appears to be better than ±1%. The GBT Pipeline position-switched reference Langston (2011) lists the parameters used in the calibration. To reduce the number of factors in equations 1-6, above, we define $\eta_{mb}(el) \equiv \eta_{mb} \times Gain(el)$.

**Rear Spillover** The Ohmoic loss and rear spillover factor $\eta_l$ also reduces the expected signal strength. This parameter has never been measured for the GBT, but is expected to be accurate to better than ±1%.

**Number of atmospheres** The number of atmospheres, $X_{atm}(el)$, of opacity is calculated from the standard model. This parameter is well determined for $el > 10^\circ$.

**Atmospheric Opacity** The zenith opacity is read from a weather database and using the source elevation at the time of the observation, the opacity factor is calculated. $\tau(\nu, el) = \tau_0(\nu) \times X_{atm}(el)$. The variation in opacity from the model probably dominates the error in measured temperature. Over short intervals the sky temperature variation is ±.5 K, in typical weather and greater in adverse weather. For good weather observations the time variation is small and the factor may be estimated to better than ±0.5%.

**Off Temperature** The location of the off source position is assumed to have no radio sources and the only astronomical contribution assumed to the Off-source intensity is the cosmic background temperature, $T_{cmb}$. Assuming no pathological case of a very bright radio source in the Off position, the off temperature is accurate to the confusion limit, approximately ~0.2 K, at 24 GHz. This parameter can dominate the uncertainty for observations of weak sources. By mapping the region around a source, the uncertainty in this parameter can be reduced. The 3C48 and 3C123 observations, presented here, reduce this uncertainty by fitting a model to the background brightness variation.

**Ambient Temperature** The contribution of Rear Spillover to the measured temperatures is the factor of Ambient Temperature, $T_{amb}$ times the factor $(1 - \eta_l)$. The ambient temperature is measured with relatively high accuracy, typically ±5 K for ambient temperatures in the range of 270 to 300 K. Also, as equation 6 shows, only the variation in ambient temperature adversely effects calibration.

The lunar brightness temperatures are measured twice at each epoch. The measured values for each of the beams is listed in Table 2.
3.1. Gain Compression

During data reduction of the Towards and Offset Moon observations we found that the measured noise diode Cal On - Cal Off values were reduced by a small factor when observing the Moon. This calibration scale difference results in the Offset Moon noise diode calibration yielding a strong measured temperature that found if using the Towards Moon noise diode differences. This effect is shown in Figures 1 and 2, for beam 1, Left and Right circular polarizations. The noise diode values are larger for scans 26 and 31, Offset Moon position, light and dark blue curves, respectively, compared to the Toward Moon scans 25 and 30, red and orange respectively. The scale factor difference is small, 4%, but significant. The calculations of gain factors described next, use the appropriate scaling factors, so that application to weaker source observations should yield correct results.

This noise diode compression effect was first noticed as a difference in the measured temperature of the moon when comparing the results of a difference in measuring the system temperature in two offset positions, compared with the results of $T_{\text{ref}}(\text{sig} - \text{ref})/\text{ref}$ calibration. In the later calibration technique, the noise diode values measured in the Toward-Moon position are not used.

The measured noise diode differences are consistent with position on the sky, suggesting the gain differences are not due to time variation. For measurement of the brightness temperature of the Moon, we use the Toward-Moon measured counts of noise diode intensity. For the Off-Moon measurements, we use the Off-Moon measurements, to compensate for gain compression.

4. Gain Calibration

The gain calibration process has two major parts, 1) estimating the Moon brightness temperature, and 2) computing the antenna gain factors.

4.1. Moon Brightness Temperature

Linsky (1973) proposed use of the Moon as a Radiometric standard for microwave calibration of large radio telescopes. They proposed that the average of all measurements of one lunar month, 29.53 days, be used the standard. They made a complete set of observations at many wavelengths, from 12µm to 1m. We adopt the lunar center brightness temperature average value of 239±10 K from Linsky (1973) for 1.25 cm (24.0 GHz).

The zenith opacity was low on this day, 0.030±0.003 at 23.7 GHz, based on the archived measurements. For a more detailed description of the method for recording weather information see Lockman & Maddelena (2010) and references therein. The intensity scale factor for atmospheric opacity was 1.052±0.005.
Salomonovich (1962a) tabulated a large number of Moon temperature measurements at different wavelengths. These observations show a phase offset between lunar phase and peak brightness temperature. Figure 3 shows their observations at 0.88 cm for 4 different lunar phases.

Assuming a sinusoidal variation of temperature as a function of lunar phase, with a phase offset, we model the physical temperature as a function of date. New Moon corresponds to a phase of 0° and full Moon phase is 180°. The phase offset is 40±5 deg and amplitude is 35±5 K. We apply this model to estimate the lunar brightness temperature at the time of the observations, listed in Table 1. For this date the lunar phase was 115.1° and the lunar temperature was 230.0±10.1 K. The relative temperature uncertainty was 4.4%. After computation of all gain factors for all beams and polarizations, these values are tabulated and input to the KFPA pipeline for use in all subsequent calibrations of KFPA data.

Results of the pipeline calibration and imaging are shown in Figure 4-a and 4-b. Figure 4-a shows the observations in the RA-Dec frame. During the observations, the Moon is steadily moving. Bob Garwood provided some GBTIDL scripts which take as arguments the calibrated spectra files, the raw observation spectra and two scan numbers. The scan numbers correspond to two observations when tracking the center of the Moon. The procedures interpolate in time the coordinate offsets and apply these offsets to the image spectra. These scripts work with any GBT observations made toward moving bodies (Moon, planets or comets). The result of this computation is shown in Figure 4-b.

Mapping observations consisted of 3 Daisy scans with radius of 17' and scan period of 120 seconds. The 3 scans have starting orientations offset by 30° to provide more uniform coverage of the object in a short duration. These Moon map scans required 12 minutes observation. A full Daisy pattern would require 23 motions of 120s duration, or 46 minutes.

Figure 4-b shows that the temperature variation in the center of the Moon is small, while the lunar poles show significantly lower temperature. The sub-solar point on the Moon shows a significantly higher temperature. This effect is included in the temperature model.

### 4.2. Application to 3C48 and 3C123

After computing the gain factors, these factors they were applied to observations of source 3C48. The pipeline was run with the '-allmaps' argument, which creates images of all images in an observing session. The pipeline also provides the spectra calibrated in a variety of ways, for the 3C48 observation the calibration was in Janskys (pipeline argument '-u Jy'). The 3C48 observations were carried out using the pipeline without tuning any special parameters for calibration and imaging. The default image gridding method for the pipeline is using a Gaussian convolution function. This method produces a smoother output image, with fewer extrema than the alternate sync-Bessel convolution function.
As noted, the 3C48 image was produced from 3 Daisy scans of the region which were position-switch calibrated in the standard manner. The resulting image is shown in Figure 5. The pipeline input file is shown in Figure 6.

4.3. Convolving Functions

After calibration, the KFPA pipeline performs imaging using AIPS single dish tools. These tools have a number of options, including the number of channels to average, image size, pixel size and convolving function parameters.

Since the GBT spectral integrations are made while moving the telescope at a rate of approximately 4 samples per FWHM beam width, there is a slight smearing of the source by approximately ∼8'' in the along-motion direction. Also since the pixels approximately 1/5th of the beam size, this results an image with slightly reduced angular resolution. This effect is seen in the resulting 3C48 images. Note that the total flux density is conserved, but is smeared. By accounting for the GBT angular resolution in the imaging process, a point source flux density is recovered in the measurement of the integrated intensity.

The convolving function parameters determine how the irregularly sampled spectra are placed on the square grid of image pixels. The convolving function is intended to smooth data and interpolate between spectra taken at slightly offset locations. There are two types of convolving functions used with the pipeline, a Gaussian convolving function and a sync-Bessel convolving function. The Gaussian function has the advantage of smoothly interpolating between sampled spectra, with the disadvantage of a slight loss of angular resolution. The imaging parameters for the pipeline are the result of a number of experiments with different parameters. For the KFPA, we found that visually appealing images if relatively small pixel sizes were used. For observations at 23706 MHz, the average of the \( NH_3 \) 1,1 and 2,2 transitions, 6'' square pixels were a good choice for the 31.3'' GBT FWHM beam width. This pixel size results in a FWHM beam width of ∼5 pixels. The AIPS task SDGRD takes as an argument the number of pixels in the convolving function. For the Gaussian function, a 5 pixel diameter convolving function is appropriate. Since the sky is sampled roughly every 9'', this was chosen as the Gaussian FWHM. Convolving the GBT beam size with a 9'' Gaussian yields an image angular resolution of 32.6''.

If slightly higher angular resolution is required in the GBT image, the Sync-Bessel convolving function may be used. As described by Mangum et al. (2007), this yields higher angular resolution at the cost of slightly noisier image, with reduced ability to interpolate between gaps in the spectral samples. Note that the Sync-Bessel convolution function is negative at larger angular distances from the sample location. In order to avoid numerical problems, we limited the convolving function diameter to 3 pixels. Otherwise our convolving function parameters are the same as those used by Mangum et al. (2007). Since the minimum convolving function is the pixel size, 6'', the resulting angular resolution of the image was was 31.8''. Integrating the 3C48 intensity yields the expected
source brightness, within the uncertainty of the measurement. See Figure 4 and Table 4.

Note that the peak intensity of the point sources are reduced in the images, due to smearing the source by observing while moving the GBT pointing direction. Slowing the telescope motion and decreasing the angular separation of adjacent scans of the source will reduce the source smearing. The image contains all of the source emission, and by properly accounting for the image angular resolution, the total flux density is measured.

4.4. Fitting Intensity Model

After imaging the region, the spectral line cube summed to produce a continuum image. We chose to reduce the spectral resolution to 6.1 MHz and fit the source sizes using the central channel of the band. The fit to the image was accomplished with AIPS task JMFIT. The model continuum intensity image consisted of two components. Component 1 was a two dimensional gaussian of the source intensity. Component 2 was a continuum model (plane) of the background brightness variation. (The JMFIT arguments are CTYPE = 1, 3, 0 ; DOPOS=1 ; DOWID=1 ; DOMAX = 1; NITER = 1000 ; NGAUS = 2.)

Component 1 measures the source intensity and also source smoothing due to observations while moving the telescope. The resulting component fit shows the angular resolution of the observation was 37.3±2.8 × 35.1±2.7 with position angle $\theta = 120±50^\circ$.

Component 2, the background intensity measures the un-modeled sky brightness variation and any un-modeled galactic background intensity. For this observation, the background was slightly negative, with average intensity of -0.1 Jy.

Table 4 lists the flux densities available from Baars et al. (1977) and Ott et al. (1994) for 3C48 and 3C123, along with values deduced from these measurements, after application of the gain factors. Note that the measurement uncertainty is relatively large for the estimate of the total intensities of these sources. By reducing the mapping speed, the flux densities could be more accurately measured.

The difference between the sky brightness of the two offset spectral observations is a measure of uncertainty in the measurements due to weather.

5. Results

On-Off Observations of the Moon can be used to compute the beam/polarization scaling factors needed to calibrated the KFPA mapping intensity scale.

The calibration accuracy based on Moon observations is limited the following factors:
Lunar Brightness
Uncertainty is limited by methods of calibration of other radio telescope observations. For these observations the absolute uncertainty was 10.1K/230.K = 4.4%.

$\eta_{mb}(\nu, el)$ The uncertainty in the main beam efficiency is approximately 3%. Reducing this uncertainty is a priority for reducing the absolute uncertainty of lunar calibration.

Opacity
The opacity scale factor uncertainty is relatively small in good weather, approximately ±1%.

Measurement
The measurement uncertainties, based on repeated observations, suggest that the lunar brightness can be measured to ±2%.

Linearity
The Moon antenna temperature is higher than normally encountered in astronomical observations. Gain compression can compromise the measurement accuracy. Measurement accuracy of ±1% should be achievable.

Assuming all these uncertainties add in quadrature, the resulting accuracy of the calibration factors based on the Lunar Observations is ±6%. This accuracy exceeds the calibration accuracy obtainable from published flux densities of bright compact reference radio sources.

The application of these factors in the KFPA pipeline results in measured values of the intensities of bright reference radio sources 3C48 and 3C123 that are consistent with published values to within 10%.

These calibration factors, given in Table 3, should be applied to all KFPA commissioning and shared risk observations from the interval September 2010 to January 2011.

Additional observations should be made towards more reference radio sources, mapping at a slower angular rate, to reduce the measurement uncertainty. After each major change to the KFPA, the Moon calibration observations should be repeated to confirm the noise diode calibration values.

REFERENCES
Langston, G. I. 2011, GBT Memo Series, 274
Lockman, F. J., & Maddalena, R. J. 2010, GBT Memo Series, 267
Maddalena, R. J. 2010, GBT Memo Series
Salomonovich, A. E. 1962a, Soviet Ast., 6, 55

Table 1: Lunar Equatorial Temperatures at the time of observations on 2011 December 15

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Table 2. Measured Lunar Temperatures

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Table 3. Scale Factors deduced from Lunar Temperatures

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Table 4: Flux Density Measurements compared with published values

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<tr>
<td>3C48</td>
<td>1.034±0.085</td>
<td>1.130±0.093</td>
<td>0.874±0.066</td>
<td>1.125±0.136</td>
<td>0.850±0.069</td>
<td>1.111±0.143</td>
</tr>
<tr>
<td>3C123</td>
<td>-</td>
<td>2.925±0.293</td>
<td>2.001±0.062</td>
<td>2.931±0.140</td>
<td>1.957±0.065</td>
<td>2.862±0.146</td>
</tr>
</tbody>
</table>

Fig. 1.— Comparison of RR polarization measured values of Cal On-Cal Off data for scans towards the Moon and offset from the Moon. Scan 25, toward Moon is red and scan 26, offset from Moon is light blue. Scan 30, toward Moon is orange and scan 31, offset from the Moon is dark blue. Notice the Cal On-Cal Off values are consistent with target location, but do not appear to be varying with time. The data are hanning smoothed and decimated to increase the SNR.
Fig. 2.— Comparison of LL polarization measured values of Cal On-Cal Off data for scans towards the Moon and offset from the Moon. This plot is zoomed in on the central range of the values, compared to the full range shown in the previous figure. The color coding is the same as in the previous figure.
Fig. 3.— Images of the Moon taken at 8mm (37.5 GHz) at different lunar phases by Salomonovich (1962b).
Fig. 4.— KFPA observations of the Moon at 23.8 GHz (left), after processing by the KFPA pipeline. On the right are the same data, after translation of coordinates to a moon centered frame.
Fig. 5.— KFPA image of 3C48 after calibration and convolving samples with a Sync-Bessel function (left). The convolving function diameter is 3 pixels. The color scale range is -0.3 to 0.9 Jy/Beam. KFPA image of 3C48 after convolving with a Gaussian function (right). The convolving function FWHM is 9″ and the function diameter is 5 pixels.
Fig. 6.— KFPA image of 3C123 after calibration and convolving samples with a Sync-Bessel function (left). The convolving function diameter is 3 pixels. The color scale range is -0.3 to 1.7 Jy/Beam. KFPA image of 3C123 after convolving with a Gaussian function (right). The convolving function FWHM is 9" and the function diameter is 5 pixels.
#KFPA pipeline arguments for point source 3c123
--clobber
-v 4
--refscan1 22
--refscan2 27
#potentially turn off automatic mapping
--imaging-off
#--allmaps
-m 23:25
#Limit noise range to 4 K RMS
-n 4.0
#The following allows selecting all beams, but 4
#-f 1,2,3,5,6,7
#-f -4
#Potentially select only RR or LL polarization
 #-p RR
#Select the maximum number of processors
#--max-processors 14
--gain-factors-left 1.815,1.756,1.958,1.882,2.209,2.151,2.524
--gain-factors-right 2.008,1.842,1.947,1.900,2.167,2.145,2.446
-i /home/sdfits/TKFPA_41/TKFPA_41.raw.acs.fits
 #-u Tmb
 -u Jy

Fig. 7.— KFPA Pipeline arguments to calibrate observations of 3C123