GBT Memo #306

Change Record

Revision	Date	Author	Sections/Pages Affected
	Remarks		
1.0	2021-Sept-27	P. Fallon	All
	Initial version.		
2.0	2022-March-30	P. Fallon	All
	Updates to describe amended code, in particular the mueller_align program.		
2.1	2022-April-12	P. Fallon	All
	Amendments based on sugesstions from Pedro Salas.		
2.2	2022-May-17	P. Fallon	Section 10
	Addition of example output.		

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Frequency-switching and position-switching GBTIDL analysis code used for determining Stokes and polarisation parameters

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Abstract

This memo describes GBTIDL code developed to calibrate XX, YY, XY and YX frequency-switched or position-switched spectra. The standard GBTIDL **getfs** and **getps** commands could be used for XX and YY calibration but not for the cross-polarisation XY and YX spectra which require calibration using polar coordinates. Stokes parameters and polarisations are determined after the calibration process and due to various polarisation conventions applied in practice, attention has been paid to ensure correct Stokes definitions are used and described in the memo. Further code has been created so that spectra taken at different telescope rotations can be Mueller matrix corrected and rotated to a zero parallactic angle before averaging.

The code can be used as indicated or amended for other observations or calculations if required. Note some observation specific parameters are hard coded and will need to be amended for each observation data set.

1. INTRODUCTION

Determining polarisation and Stokes parameters necessitates measurement of the XX, YY, XY and YX polarisation and cross-polarisation spectra.[1] Once XX, YY, XY and YX are calibrated the Stokes parameters and polarisation values can be determined. Calibration of XX and YY is straightforward and can be accomplished using the standard **getfs** or **getps** commands in GBTIDL (Braatz & Garwood 2012). However, the cross-polarisation XY and YX spectra require polar coordinates to derive the relative dispersive phase that the calibration signal is accumulating. The noise diode (ND) is a single noise source which is divided and injected into the two signal paths for the C-band Receiver, in other words a "correlated-calibration". The XY and YX spectra should be considered as a complex value which could have zero crossing at some frequencies and thus a polar coordinate calibration must be used. Polar calibration is not part of the standard GBTIDL commands and thus code has been developed and is presented here for this purpose.

GBT spectrum data is stored at regular, integration time or 'tint', intervals. Each integration has a specific number or 'intnum' and averaging all 'intnums' provides the entire spectrum data. If required, noisy 'intnums' can be excluded to ensure only clean data in the final spectrum. The standard **getfs** or **getps** commands calibrate spectra per 'intnum' then average the individual calibrated 'intnums'. For XY and YX, parts of the spectra can be close to zero resulting in noise levels being relatively large compared to the data or calibration values. Hence data is less noisy if the spectra are averaged across all 'intnums' prior to the calibration process. This sequence is followed for code presented here as opposed to the **getfs** and **getps** calibration per integration prior to averaging.

[1] Uppercase letters are used in this memo for the GBT spectra which are aligned with the telescope and thus rotate as the telescope rotates. This uppercase notation is also used in the GBT manuals, the GBTIDL User's Guide and spectrum plots. GBTIDL code uses a polarisation index with `plnum=0` for YX, `plnum=1` for XY, `plnum=2` for YY and `plnum=3` for XX. Note lowercase `xx`, `yy`, `xy` and `yx` used in the program code, i.e. not aligned to this convention.

Stokes parameters are calculated by averaging over the spectral line peak for frequency-switched spectra or across most of the frequency range for position-switched continuum spectra. For continuum spectra the middle third of the 32768 channels is specified in the code and used – this can be amended if needed, for example to exclude the top and bottom 10% of channels, as is done by **getps**. For frequency-switched observations the integration velocity range is read from the text file '**velocity_ranges.list**'.

Definition of Stokes parameters is in accordance with the IAU Commissions 24 and 40 resolution to align the horizontal and vertical axes of the Stokes parameter reference frame along the Declination and Right Ascension axes (Robishaw & Heiles 2019). The GBT polarisation was specified by Steven White, head of GBO's electronics division, as "The YY polarization is aligned perpendicular to the elevation axis, this is also the vertical polarization. XX is aligned along the elevation axis or horizontal." Thus, at zenith XX should be aligned N-S (Declination) and YY with Right Ascension as per the IAU Commission resolution. The polarisation angle is measured anticlockwise from the XX axis. As the GBT uses an alt-azimuth mount and rotates as it tracks the source object, spectra and polarisation angles need to be corrected (i.e. rotated) by the parallactic angle which can be determined from antenna azimuth, latitude and source declination.

To determine accurate source Stokes parameters, a Mueller matrix correction must be applied to the measured Stokes values. The Mueller matrix correction adjusts for instrument modifications of the polarisation state (Heiles 2002; Robishaw & Heiles 2006, 2019). C-Band Mueller matrices have been determined and can be requested from the author (paper in preparation). Note, the Mueller matrix changes with frequency and differs for either the lo-cal or hi-cal ND.

2. USING THE GBTIDL CODE

The GBTIDL routines have been written for and tested on C-Band spectra collected using the VEGAS backend. It is presumed that this code can be used for spectra collected with other configurations, but specifications will need to be checked, tested and the code amended, if required. The calculated Stokes and linear-polarisation parameters are printed by the programs and can be copied for use elsewhere or the code could be amended for alternate use of the output data. A copy of the code has been stored in the GBTIDL contributed scripts directory (`/home/astro-util/gbtidl/contrib/polarization/`) at the GBO.

3. SPECTRUM CALIBRATION

The standard process to calibrate spectra using the calibration noise-diode (ND) reference signal is:

$$\text{Spectrum}_{\text{data}} = \text{Spectrum}_{\text{on-source}} - \text{Spectrum}_{\text{background}} \text{ (or baseline)}, \quad (1)$$

$$\text{Spectrum}_{\text{cal}} = \text{Spectrum}(\text{ND}_{\text{ON}}) - \text{Spectrum}(\text{ND}_{\text{OFF}}), \quad (2)$$

$$\text{Spectrum}_{\text{calibrated}} = \text{Spectrum}_{\text{data}} \,/\, \text{Spectrum}_{\text{cal}} \times \text{cal-constant}. \quad (3)$$

For GBT antenna temperature

$$\text{cal-constant} = \text{tcal} \times \exp(\text{tau} \,/\, \sin(\text{elevation})) \,/\, 0.99, \quad (4)$$

or for calibration in Jy

$$\text{cal-constant} = \text{tcal} \times \exp(\text{tau} \,/\, \sin(\text{elevation}))\,/\,0.99\,/\,(2.85 \times \text{apeff}). \tag{5}$$

Where:

$$\begin{aligned}\text{tcal} &= \text{ND calibration temperature},\\ \text{tau} &= \text{zenith opacity (frequency dependent)},\\ \text{apeff} &= \text{aperature efficiency (frequency dependent)}.\end{aligned}$$

The polar coordinate calibration for XY and YX spectra is:[2]

$$r_{\text{data}} = \sqrt{XY^2_{\text{data}} + YX^2_{\text{data}}}, \tag{6}$$

$$\theta_{\text{data}} = \arctan(YX_{\text{data}}, XY_{\text{data}}), \tag{7}$$

$$r_{\text{cal}} = \sqrt{XY^2_{\text{cal}} + YX^2_{\text{cal}}}, \tag{8}$$

$$\theta_{\text{cal}} = \arctan(YX_{\text{cal}}, XY_{\text{cal}}), \tag{9}$$

where

$$\begin{aligned}XY_{\text{cal}} &= XY(\text{ND}_{\text{ON}}) - XY(\text{ND}_{\text{OFF}}),\\ YX_{\text{cal}} &= YX(\text{ND}_{\text{ON}}) - YX(\text{ND}_{\text{OFF}}),\end{aligned}$$

and the calibrated outcome is:

$$r_{\text{calibrated}} = r_{\text{data}} \,/\, r_{\text{cal}}, \tag{10}$$

$$\theta_{\text{calibrated}} = \theta_{\text{data}} - \theta_{\text{cal}}, \tag{11}$$

$$XY_{\text{calibrated}} = r_{\text{calibrated}} \times \cos(\theta_{\text{calibrated}}), \tag{12}$$

$$YX_{\text{calibrated}} = r_{\text{calibrated}} \times \sin(\theta_{\text{calibrated}}). \tag{13}$$

4. STOKES AND POLARISATION PARAMETERS

The Stokes parameter definition is in accordance with the IAU Commissions 24 and 40 resolution to align the horizontal and vertical axes of the Stokes parameter reference frame along the Declination and Right Ascension axes (Robishaw & Heiles 2019).

$$I = XX + YY, \tag{14}$$

$$Q = XX - YY, \tag{15}$$

$$U = 2 \times XY, \tag{16}$$

$$V = 2 \times YX. \tag{17}$$

[2] Note use of the $\arctan(y, x)$ or $\arctan2(y, x)$ function is crucial as this returns a value in the range $-180°$ and $180°$, versus the general arctan(*single-value*) function which only returns a value in the range $-90°$ and $90°$.

Note that there is sometimes confusion by use of various other conventions, in particular the calculation of I as the average of XX and YY, which results in Stokes values half of what is presented here.

The quantification of linear polarisation, or fractional linear polarisation is

$$p_{\rm lin} = \sqrt{Q^2 + U^2)} \,/\, I; \quad 0 \le p_{\rm lin} \le 1, \tag{18}$$

with position angle of linear polarisation[3]

$$\chi = 0.5 \times \arctan(U, Q); \quad 0^\circ \le \chi \le 180^\circ, \tag{19}$$

and fractional circular polarisation

$$p_{\rm cir} = V \,/\, I; \quad -1 \le p_{\rm cir} \le 1. \tag{20}$$

5. MUELLER MATRIX CORRECTION

The Stokes parameters are modified by the telescope observation – the feed, dish surface, coaxial cable lengths, optical fibers and electronics can introduce gain and phase differences in the X and Y channels that modify the polarisation. This modification is described by the 4×4 Mueller matrix (Heiles 2002; Robishaw & Heiles 2019). Source Stokes parameters can be determined from the observed values by application of the inverse Mueller (M_{Muller}) and rotation (M_{sky}) matrices

$$\begin{bmatrix} I_{\rm src} \\ Q_{\rm src} \\ U_{\rm src} \\ V_{\rm src} \end{bmatrix} = (\boldsymbol{M}_{\rm Mueller} \cdot \boldsymbol{M}_{\rm sky})^{-1} \begin{bmatrix} I_{\rm obs} \\ Q_{\rm obs} \\ U_{\rm obs} \\ V_{\rm obs} \end{bmatrix}. \tag{21}$$

As the GBT has an alt-azimuth mount, the spectrometer observations need to be aligned using the parallactic angle (PA) in a standard rotation matrix

$$\boldsymbol{M}_{\rm sky} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2PA) & \sin(2PA) & 0 \\ 0 & -\sin(2PA) & \cos(2PA) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{22}$$

Note, the Mueller matrix varies with frequency and different Mueller matrices apply for either the lo-cal or hi-cal ND calibration (paper in preparation). So the appropriate Mueller matrix for the observation frequency and ND configuration must be used.

[3] Note use of $\arctan(y, x)$ or $\arctan2(y, x)$ as per footnote 2.

6. USE OF DATA CONTAINERS

In order to retain the data and calibration spectra for XX, YY, XY and YX, use of the sixteen global data containers (DCs) in GBTIDL have been carefully coordinated between the programs. Specific data containers have been reserved as follows:

- 3, 4, 7 and 8 are for uncalibrated background (or baseline) subtracted YY, XX, YX and XY;
- 11, 12, 5 and 6 are used for calibration spectra of YY, XX, YX and XY; and
- 13, 14, 9 and 10 are used for calibrated spectra of YY, XX, YX and XY.

This leaves DC0, DC1, DC2 and DC15 for general use in the programs specified here. The use of these DCs is detailed in the program descriptions and by commentary in the code. In addition, DC9 and DC10 are employed for general use as they are only needed for storage after the polar coordinate calibration of XY and YX.

7. FREQUENCY-SWITCHING CODE

Four programs are used to perform the frequency-switching calibration and polarisation analysis:

1) **get_freq_switch_data**
2) **baseline_calc**
3) **parangle**
4) **freq_switch_polcal**

The following operations are required in GBTIDL to locate the data and compile the code before the frequency-switching code can be used:

- `offline,'AGBT20B_424_03'`
  or
  `filein,'/home/scratch/pfallon/AGBT20B_424_03.raw.vegas'`[4]
- `.compile get_freq_switch_data`
- `.compile baseline_calc`
- `.compile parangle`
- `.compile freq_switch_polcal`

The programs are called by the main **freq_switch_polcal** routine but can be run separately if required. Note, no channels are flagged in the frequency-switching code. Data flagging was done separately for the author's observations ($AGBT20B\_424\_03$) and generally should be done prior to the data analysis.

[4] An example project number is shown here and needs to be changed to reference the data being analysed.

The GBTIDL frequency-switched programs, required parameters and descriptions are:

1) **get_freq_switch_data**, scan_file_number, frequency_number, polarisation_number

- **Example:** `get_freq_switch_data,11,0,2`
- **Objective:** Emulate GBTIDL **getfs**, for a specified polarisation and frequency, but without calibration. The data and cal spectra, i.e. average of all integrations or 'intnums', are returned as output. Note **getfs** calibrates per integration, averages over all integrations and returns a single outcome spectrum.
- **Calculation:** Each scan, per frequency and per polarisation, comprises four spectra: ND_{ON} not-frequency-switched; ND_{ON} frequency-switched; ND_{OFF} not-frequency-switched; and ND_{OFF} frequency-switched. To maximise use of all data, thus minimising signal to noise, all four spectra are frequency-aligned and accumulated (averaged) for the data spectrum – this is calculated by:
  (a) Subtract frequency-shifted from not-frequency-shifted, to create not-frequency-shifted less background.
  (b) Subtract not-frequency-shifted from frequency-shifted, to create frequency-shifted less background, and then frequency shift back to the reference frequency setting.
  (c) Average (a) and (b) for both ND_{ON} and ND_{OFF} to create the data spectrum.
- **Testing and checking:** This calculation follows the **getfs** approach as closely as possible (ref: GBTIDL 2021). Comparisons of XX and YY, after calibration in **freq_switch_polcal**, with **getfs** indicate almost identical spectra. Note minor differences result from the baseline subtraction and calibration after averaging integrations versus **getfs** calibrating per integration before averaging.
- **Output:**

  DC0 uncalibrated background-subtracted data spectrum. Average of all integrations.

  DC9 average for ND_{ON}, i.e. average of two spectra after appropriate frequency-switching.

  DC10 average for ND_{OFF}, i.e. average of two spectra after appropriate frequency-switching.

  So, calibration-spectrum = DC9 − DC10.

2) **baseline_calc**, polynomial_order_min, polynomial_order_max, baseline1_velocity_min, baseline1_velocity_max, baseline2_velocity_min, baseline2_velocity_max, quiet_mode

- **Example:** `baseline_calc,3,3,0.0,8.5,13.0,21.0,1`

- **Objective:** Determine a baseline constructed by a polynomial best fit over the specified velocity regions below and above the spectral line.
- **Input:** Spectrum in DC0.
- **Output:** Returns last fitted baseline in DC15.
- **Usage:** Can be used in a non-quiet_mode (`quiet_mode ne 1`) to step through and review baselines of different order. Used in quiet_mode when called by **freq_switch_polcal** to calculate a single baseline (`polynomial_order_min=3` and `polynomial_order_max=3`). Initial use of **baseline_calc** for the author's data indicated a third order polynomial as an optimal baseline fit but this routine allows for other polynomials to be tested and used.

3) **parangle**, azDeg, decDeg, sitelat=sitelat

- **Example:** `pr = −parangle(az,dec,sitelat=38.4314)`
- **Objective:** Code to calculate the parallactic angle. Called by programs **freq_switch_polcal**, **position_switched_polcal** or **mueller_align**.
- **Output:** Parallactic angle for specified azimuth angle, target latitude and telescope latitude.
- **Comments:**
  - The parallactic angle definition, in particular when it is positive or negative, is crucial. At the observed point in the sky the parallactic angle is the position angle of the vertical, i.e., the angle between direction to the North Celestial Pole and to the zenith. It is measured from North through East and is always negative when the source is in the East and positive when in the West (Robishaw 2006). Note the negative sign when **parangle** is called to ensure the correct definition.
  - The azimuth and declination angles are taken from the scan input data file, i.e. the scan header information. This data is retrieved by:

```
az = !g.s[0].azimuth
dec = !g.s[0].target_latitude
```

  - The GBT latitude is 38.4314°. If this parameter is not specified then **parangle** automatically defaults to this value.
  - The **parangle** routine is a function and must be called as indicated above to return the parallactic angle. Other routines described in this memo are programs which return spectra in the global data containers, save the spectrum data and print the output parameters.

4) **freq_switch_polcal**, scan_file_number, frequency_number, quiet_mode

- **Example:** `freq_switch_polcal,11,0,0`
- **Objective:** Obtains and calibrates XX, YY, XY and YX spectra for the specified scan and frequency. Then determines and prints the Stokes and polarisation parameters.
- **Calculation:** Uses **get_freq_switch_data** to obtain spectra for each of XX, YY, XY and YX. For each data spectrum a baseline using **baseline_calc** is calculated then subtracted. Spectra are then calibrated: XX and YY by the standard $\text{spectrum}_{\text{data}}/\text{spectrum}_{\text{cal}}$; and XY and YX using polar coordinates. Spectra are scaled to Jy. Finally, mean spectrum intensities over the spectral line are determined and used for calculating the Stokes parameters.
- **Comments:**
  - Velocity ranges for baseline subtraction and for the Stoke parameter integration are read from the text file '**velocity_ranges.list**'. Amending these velocity ranges is required for different baseline fitting ranges and for different Stokes integration ranges. The values specified in each line of the '**velocity_ranges.list**' file are:
    - Frequency number (if_num);
    - Minimum and maximum Stokes velocities for range over which Stokes values are integrated;
    - Baseline velocity minimum and maximum for baseline fitting range below the spectral line;
    - Baseline velocity minimum and maximum for baseline fitting range above the spectral line; and
    - The velocity offset – set to zero if the spectral line is at the center of spectrum, or non-zero if the spectral line is not at the spectrum's specified radial velocity.
  - The baseline polynomial order is set to 3 (in the code) and should be amended as needed.
  - Note, Jy scaling is done in this code, as spectra received from **get_freq_switch_data** are calibrated in counts.
  - Non-quiet_mode `(quiet_mode ne 1)` plots each step of the analytic process and requires the user to click on the graph to progress to the next step.

8. ADDITIONAL CODE FOR MUELLER-MATRIX-CORRECTION, ROTATION AND AVERAGING SPECTRA

Spectra taken sequentially or over a period of time, will each have different rotation of the alt-azimuth GBT telescope, i.e. different parallactic angles, as the telescope rotates while it tracks the source. These observed spectra need to be corrected by the Mueller matrix and rotated to result in accurate source spectra as per equation 21. Note, the Mueller matrix correction needs to occur before the rotation as $(\boldsymbol{M}_{\text{Mueller}} \cdot \boldsymbol{M}_{\text{sky}})^{-1}$ in equation 21 is equivalent to $(\boldsymbol{M}_{\text{sky}})^{-1} \cdot (\boldsymbol{M}_{\text{Muller}})^{-1}$.

In order to average spectra, each spectrum must be Mueller matrix corrected and rotated (or aligned N-S) and this is accomplished by **mueller_align**. The program **multi_scan_align** averages the corrected and aligned scans, then calculates and prints Stokes and polarisation parameters. The code is written for frequency-switched scans obtained by **freq_switch_polcal** but can be amended to analyse position-switched or other spectra.

Two programs perform the Mueller-correction with rotation and then averaging:

5) **mueller_align**

6) **multi_scan_align**

Standard operations in GBTIDL are required to compile this code before use. In addition the frequency-switched analysis programs must be compiled as these routines are utilised.

- `.compile mueller_align`
- `.compile multi_scan_align`
  or
  `.compile multi_scan_align_session_5`

5) **mueller_align**, stokes_velocity_min, stokes_velocity_max, quiet_mode

- **Example:** `mueller_align,10.8,11.0,1`
- **Objective:** Starts with calibrated **freq_switch_polcal** spectra. Determines Stokes spectra as per equations 14 to 17 and applies the inverse Mueller matrix. The 4 × 4 Mueller matrix is read from a file '**mueller_matrix.txt**' and then inverted before amending the Stokes spectra. $(\boldsymbol{M}_{\text{sky}})^{-1}$ is applied to rotate the spectra to align N-S, i.e. polarisation angle zero at north, as per definition in Robishaw & Heiles (2019). Stokes spectra are returned in DC12, DC11, DC8 and DC7. The Stokes values and polarisation for the specified velocity range are calculated and printed.
- **Input:** Assumes XX, YY, XY and YX spectra in DC14, DC13, DC10 and DC9 as per output from **freq_switch_polcal** or **position_switched_polcal**.
- **Output:** Stokes I, Q, U and V spectra returned in DC12, DC11, DC8 and DC7, along with printed source Stokes and polarisation parameters. Note use of data containers to ensue no spectrum data is overwritten before it is used.
- **Note:** The values in '**mueller_matrix.txt**' must be correct for the spectrum frequency and ND configuration, i.e. '**mueller_matrix.txt**' must contain the appropriate frequency and ND Mueller matrix. Other matrix values can be stored in this text file but need to be commented out by ';' at the beginning of the line.

6) **multi_scan_align**, frequency_number
or
multi_scan_align_session_5, frequency_number

- **Example:** `multi_scan_align,0`
- **Note:** Two examples are provided as the program averages several scans and the scan numbers are included as part of the code. The two examples **multi_scan_align**, and **multi_scan_align_session_5** are for different sets of scans. Use of this program will require amending the code to use appropriate scan numbers. Alternatively the code could be amended to read the scan numbers from a text file.
- **Objective:** Averages Mueller-matrix-corrected and rotated frequency-switched spectra to produce source Stokes I, Q, U and V spectra and polarisation parameters. Calls **freq_switch_polcal** to obtain calibrated observed spectra then **mueller_align** to do the Mueller matrix correction and rotation. The velocity range for the Stoke parameter integration is read from the text file '**velocity_ranges.list**'. Amending these velocity ranges is required to calculate Stokes values over different spectrum velocities.
- **Output:** Plots averaged and aligned Stokes I, Q, U and V spectra and saves output in .fits file for later use. Prints Stokes and linear polarisation parameters.
- **Comments:** Scan numbers are set for the author's '$AGBT20B\_424$' observations so the scan numbers and .fits file names will need to be amended for different data sets.

9. POSITION-SWITCHING CODE

Two programs are used to obtain and analyse the position-switched spectra:

7) **get_position_switched_data**

8) **position_switched_polcal**

Standard GBTIDL data identification and compile operations are required for these programs and **parangle** before use:

- `offline,'AGBT20B_424_03'`
  or
  `filein,'/home/scratch/pfallon/AGBT20B_424_03.raw.vegas'`[5]
- `.compile get_position_switched_data`

[5] As per footnote 4, an example project number is shown.

- `.compile position_switched_polcal`
- `.compile parangle`

get_position_switched_data is called by **position_switched_polcal** but it can be run separately if required. Note, no channels are flagged in the position-switching code. Data flagging was done separately for the author's observations ($AGBT20B\_424\_03$) and generally should be done prior to the data analysis.

7) **get_position_switched_data**, scan_on_file_number, frequency_number, polarisation_number, quiet_mode

- **Example:** `get_position_switched_data,6,0,2,0`
- **Objective:** Code to emulate GBTIDL's **getps** command. To avoid division by small values with high signal-to-noise in the XY and YX calibration, this code averages all integrations before calibration whereas **getps** calibrates per integration then averages.
- **Testing and checking:** The calculation follows the **getps** approach as closely as possible (ref: GBTIDL 2021) and comparisons per integration ('tint') with **getps** for XX and YY spectra show identical results. There are minor differences when comparing the outcome of all integrations as **getps** calibrates per integration then averages – this can create differences of the order of 0.1% in spectrum values. Differences may also be caused by exposure and 'tint' times resulting in a partial final integration as **getps** only uses complete integrations.
- **Output:** DC2=calibrated-spectrum (in Jy), DC1=data, DC15=cal-data. Note:
  - DC2=calibrated-spectrum only used for XX and YY
  - DC1=data and DC15=cal-data are used by **position_switched_polcal** for polar calibration of XY and YX
  - Output spectra produced for a single polarisation and a single frequency.
- **Comments:**
  - If in quiet_mode (`q_mode eq 1`) no detail is shown. Non-quiet_mode (`q_mode ne 1`) shows all spectra and then a comparison and difference with **getps**.
  - The `scan_on_file_number` is the file number for the on-source position-switched scan, the off-source position-switched scan is: `scan_off=scan_on+1`, i.e. this code is for OnOff position-switching and will need to be amended for OffOn position-switching observations.
  - General commentary and detail on use of data containers is included in the code.

8) **position_switched_polcal**, scan_on_file_number, frequency_number

- **Example:** `position_switched_polcal,6,0`
- **Objective:** Calls **get_position_switched_data** to obtain each of the *XX*, *YY*, *XY* and *YX* polarisation spectra. Then *XY* and *YX* polar coordinate calibration, followed by calculating and printing Stokes and linear polarisation parameters.
- **Comments:**
  - Note specific use of data containers to ensure stored data for each polarisation.
  - The spectra are in calibrated in Jy, as per calibration in **get_position_switched_data**.
  - The range over which the spectra are integrated to determine the mean *XX*, *YY*, *XY*, *YX* and Stokes parameters is currently set to the middle 80% of the channels in the spectrum. This is the same range used by **getps** which removes the upper 10% and lower 10% of channels to avoid the edge effects of the spectra. The number of channels is determined from the spectrum and, if required, the percent of ignored edge channels can be amended by changing the 10% value specified in the code. Note, the channel integration range specifies the bandwidth over which the average parameter values are determined.
  - In order to run the code for a range of frequencies or scan numbers, the command

    ```
    for  i=0,7  do  position_switched_polcal,6,i
    ```

    could be used. Note that only *scan_on* numbers are required for this program and that scans for OnOff position-switching follow a sequence *scan_on*, *scan_off*, *scan_on*, ...

10. EXAMPLE OUTPUT

The following is a GBTIDL session shows all the commands required to run the `multi_scan_align` program and the program's output. This detail should enable a user to test the program and ensure the correct output is obtained. Note, the program output in GBTIDL is spaced so it is easy to read and copy to a text file, however this spacing is not correctly shown in the text below.

```
[pfallon@euclid ~/AGBT20B_424]$ gbtidl
/home/apps/itt/idl71/bin/bin.linux.x86_64/idl:  /opt/local/lib/libuuid.so.1:  no
version information available (required by /lib64/libSM.so.6)
IDL Version 7.1.1 (linux x86_64 m64).  (c) 2009, ITT Visual Information Solutions
Installation number:  15269-3.
Licensed for use by:  National Radio Astronomy Observatory

Starting GBTIDL
```

```
Display Device :  X
Visual Class :  TrueColor
Visual Depth :  24-Bit
Color Table Size:  256
Number of Colors:  16777216
Decomposed Color:  0

-------------------------------------------------------------------
Welcome to GBTIDL v2.10.1

For news, documentation, enhancement requests, bug tracking,
discussion, and contributions, visit:

http://gbtidl.nrao.edu

For help with a GBTIDL routine from the command line, use
the procedure 'usage'.  For example:

usage,'show' ; gives the syntax of the procedure 'show'
usage,'show',/verbose ; gives more information on 'show'
-------------------------------------------------------------------

GBTIDL -> filein,'/home/scratch/pfallon/AGBT20B_424_03.raw.vegas'
GBTIDL -> .compile get_freq_switch_data
% Compiled module:  GET_FREQ_SWITCH_DATA.
GBTIDL -> .compile baseline_calc
% Compiled module:  BASELINE_CALC.
GBTIDL -> .compile parangle
% Compiled module:  PARANGLE.
GBTIDL -> .compile freq_switch_polcal
% Compiled module:  FREQ_SWITCH_POLCAL.
GBTIDL -> .compile mueller_align
% Compiled module:  MUELLER_ALIGN.
GBTIDL -> .compile multi_scan_align
% Compiled module:  MULTI_SCAN_ALIGN.
GBTIDL -> multi_scan_align,0
% Compiled module:  READCOL.
% Compiled module:  STRNUMBER.
Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg)
Sky, theta_data,theta_cal
11 4.765E+00 5.3 132.9 32.8 -35.30 0.6667 -0.0536 -0.0115 0.0503 8.2 -84.0 -119.3
-15.2 -128.9
11 4.765E+00 5.3 132.9 32.8 -35.30 0.6744 0.0447 -0.0939 0.0516 15.4 -32.3 -32.3
```

Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg) Sky, theta_data,theta_cal
12 4.765E+00 5.3 134.4 33.7 -34.24 0.5959 -0.0437 0.0034 0.0755 7.4 87.8 53.5 -52.8 -128.6
12 4.765E+00 5.3 134.4 33.7 -34.24 0.6024 0.0262 -0.0847 0.0752 14.7 -36.4 -36.4

Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg) Sky, theta_data,theta_cal
14 4.765E+00 5.3 136.4 34.8 -32.95 0.6046 0.0299 -0.0231 -0.0194 6.2 -18.9 -51.8 11.8 -128.6
14 4.765E+00 5.3 136.4 34.8 -32.95 0.6058 0.0320 -0.0015 -0.0161 5.3 -1.3 -1.3

Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg) Sky, theta_data,theta_cal
15 4.765E+00 5.3 138.0 35.7 -31.80 0.6192 0.0377 -0.0177 0.1011 6.7 -12.6 -44.4 -24.4 -128.8
15 4.765E+00 5.3 138.0 35.7 -31.80 0.6200 0.0146 -0.0023 0.1034 2.4 -4.5 -4.5

Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg) Sky, theta_data,theta_cal
17 4.765E+00 5.3 140.1 36.6 -30.39 0.6780 0.0067 0.0080 -0.0230 1.5 25.1 -5.3 -2.6 -128.5
17 4.765E+00 5.3 140.1 36.6 -30.39 0.6811 0.0197 -0.0384 -0.0227 6.3 -31.4 -31.4

Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg) Sky, theta_data,theta_cal
18 4.765E+00 5.3 141.8 37.5 -29.15 0.6357 -0.0217 -0.0509 -0.0465 8.7 -56.5 -85.7 70.1 -128.4
18 4.765E+00 5.3 141.8 37.5 -29.15 0.6410 0.0862 -0.0272 -0.0409 14.1 -8.7 -8.7

Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg) Sky, theta_data,theta_cal
20 4.765E+00 5.3 144.0 38.4 -27.62 0.7130 0.0422 -0.0166 0.0741 6.4 -10.7 -38.3 -9.9 -128.5
20 4.765E+00 5.3 144.0 38.4 -27.62 0.7139 0.0176 -0.0008 0.0765 2.5 -1.3 -1.3

Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg) Sky, theta_data,theta_cal
21 4.765E+00 5.3 145.8 39.1 -26.28 0.6379 0.0677 0.0262 0.0041 11.4 10.6 -15.7 -12.4 -128.6
21 4.765E+00 5.3 145.8 39.1 -26.28 0.6363 -0.0307 0.0030 0.0029 4.8 87.2 87.2

```
Scan, freq, Tcal, Az, El, Par-angle, I, Q, U, V, Pol (%), Pol(deg) Tele, Pol(deg)
Sky, theta_data,theta_cal
23 4.765E+00 5.3 148.1 39.9 -24.65 0.6433 0.0652 0.0270 -0.0145 11.0 11.2 -13.4 5.1
-128.4
23 4.765E+00 5.3 148.1 39.9 -24.65 0.6418 -0.0282 -0.0002 -0.0157 4.4 -89.8 -89.8

AVERAGED AND ALIGNED DATA
I, Q, U, V, Pol (%), Pol(deg) Sky
0.6463 0.0202 -0.0273 0.0238 5.3 -26.7 -26.7
Showing calibrated (Jy), Mueller corrected, rotation-aligned and averaged.  Red=I.
White=Q. Blue=U. Yellow=V
GBTIDL ->
```

11. FEEDBACK

Please contact the author if there are any queries or suggestion for modification of the programs. Should you identify bugs or issues with the code or calculations your feedback would be appreciated.

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