FITS Formats for NRAO Phased Array Feed

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As we look ahead to tests of the L-band prototype phased array feed (PAF) on the GBT we need to plan for the transition from the free-form telescope control software and data formats of the test runs on the 20-meter telescope to the much more structured GBT system. Time allocation on the GBT is quite competitive so careful planning and rehearsal of PAF tests will be required to make use of the relatively short test runs that can be expected.

Control of the GBT and its subsystems is most efficiently done through the “ASTRID” observer interface as described in <http://www.gb.nrao.edu/gbtprops/obsman/GBTog.pdf> and the observing scripts described in chapter 5 of that document. The PAF development group will need to provide the software system to control data acquisition and agree upon a minimal interface between the GBT and PAF systems to coordinate telescope motion and data acquisition actions.

Logging of GBT actions and data products is done through a well established hierarchy of FITS files and directories that will need to be accessed to interpret the results of the PAF test measurement on the GBT. Each GBT subsystem (Antenna, Local Oscillator, Receiver, Spectrometer, etc.) has its own FITS file format, and it makes sense for the PAF to adopt a similar FITS logging and data structure. Two advantages of the GBT FITS system are that all scans are automatically self-documenting, and this documentation is clearly linked to the data. Since the GBT system is well tested for completeness, its FITS files make good templates for the PAF.

The 20-meter tests can benefit from this data logging formality and provide a debugging platform for the data acquisition and analysis software that needs to be working smoothly for the first PAF test on the GBT. It should be relatively straightforward to add FITS writing code to the current 20-meter telescope control code. The first step is to define the new FITS formats patterned after the closest existing GBT formats.

**GBT Data and Logging FITS Structure**

All of the GBT data and logging products are written to disk directories in the hierarchy shown in Figure 1. Each observing session has its own directory, e.g., AGBT03B\_023\_03, under which are separate subdirectories, one for each GBT subsystem. If a subsystem was not in use for that observing session, then it doesn’t appear in the directory tree.



Figure GBT FITS Directory Structure

In each subdirectory is a set of FITS files, one file for each observing ‘scan’. Each FITS file name is composed of the UTC date and time at the beginning of a scan. There will be files with the same name in each of the subdirectories in which the corresponding subsystems were active during a given scan. If, for any reason, the files need to be copied to another location, the directory structure must be maintained to avoid overwriting files with the same name.

The two subsystems of greatest to PAF tests are ‘GO’ and ‘Antenna’. The GO FITS files log the commanded setup information for each scan. An Antenna FITS files logs the GBT antenna configuration and the actual pointing position of the telescope at frequent intervals during the scan. Since the next generation of the PAF receiver will not do any frequency conversion at the front-end box in the GBT receiver room so we may not have need for either of the LO subsystems unless we use one of these to generate a reference tone for injection into the L-band fiber modem channels. If one of the LO’s is used, its frequency and routing information will appear in the LO1A orLO1B FITS files.

In Figure 1 the front-end setup information for the 8-10 GHz receiver is logged in the files in directory Rcvr8\_10. For the PAF receiver a new but similar FITS file format is defined in Table X of this document and its files will be written to a directory named RcvrPAF. These FITS files will log the PAF LO settings and other RF system configuration for the part of the receiver housed in the GBT control room plus the data acquisition setup parameters. The RcvrPAF FITS definition also defines table space for recording the names of the FITS files that contain the correlation coefficients from cold sky and hot load (absorber covered) calibration measurements made in the outdoor test building.

The data documentation philosophy is carried through the software correlation step with the definition of a PafCorrelator FITS file shown in Table Z. The binary table(s) in this FITS definition can accommodate the output of an FX cross-correlator with the appropriate number of polarizations, array elements, and frequency channels. The table format is essentially the same as the one defined for holding the calibration matrices from the outdoor test building measurements in the RcvrPAF FITS definition. The complete directory structure for the PAF will then look something like Figure 2.



Figure Proposed PAF FITS Directory Structure

**Example GBT FITS File – Rcvr18\_26**

Table 1 shows the structure and contents of a Rcvr18\_26 FITS file. As with all Binary Table FITS files, it is composed Header-Data Units (HDU), each with an ASCII header followed by a binary table. The one exception is the first (Primary) HDU, which has only an ASCII header. Most scientific and engineering programming languages have similar FITS access packages and commands. In Python, to see the HDU structure shown in the first box of Table 1 load the pyfits and numeric packages

>>> import pyfits as pf

>>> import numpy as np

and execute the commands

>>> hdulist = pf.open(‘Rcvr18\_26/2010\_09\_07\_23:46:32.fits’)

>>> hdulist.info()

To see the primary header contents execute

>>> print hdulist[0].header.ascardlist()

To see or access the value of one of the header keywords use

>>> print hdulist[0].header[‘TIMESYS’]

>>> time\_sys = hdulist[0].header[‘TIMESYS’]

Access to the binary data can be a little trickier because there appears to be a limit on the size of a table array, This can be circumvented by embedding large arrays in an array list so access requires an extra level of indexing. The RX\_CAL\_INFO tables are relatively small so this is not a complication, and the data can be obtained with

>>> dat = hdulist[1].data

Since there are 169 rows and 4 columns in this binary table, and each column contains one single-precision floating point number (Format = 1E), each data unit is returned in Python as a ‘tuple’ of 4 numbers.

>>> print dat[0]

(1.679e+10, 31.35, 9.61, 0.0)

From this table’s header we can see that the first column is the calibration measurement frequency (TTYPE1 = 'FREQUENCY'), with a value of 1.697e+10 Hz (TUNIT1 = 'Hz '), and the other three values are the measured receiver, low cal, and high cal temperature values in Kelvin for this frequency. Other rows are for other frequencies within the receiver passband. Once one gets the hang of it, the FITS files are generally self-documenting, which is one of their main assets. This takes some care in defining and writing the fits tables, but once this is properly coded the files are relatively easy to interpret.

**Proposed RcvrPAF FITS Format**

Table 2 is a first draft of a FITS file format for the PAF receiver, which includes all of the electronics and local oscillators between the array and the outputs to the data acquisition system. A few GBT receiver header keywords, such as ETAL, APEREFF, and BEAMEFF, have been retained, but these may be of marginal value for the PAF. The primary header contains all of the ADC setup parameter values. Since the aggregated sample file size is often nearly a gigabyte in size, only the data file name and file directory on the ‘paf0’ RAID disk are recorded in this FITS file. This goes against the GBT philosophy of keeping all data associated with a scan in one place, but only for practical reasons.

The ADC system in use as of this writing consists of ten ADLink model PCI-9812 devices, each of which has four sampler inputs as well as a common external trigger input for all four channels. Each PCI-9812 is in its own Windows PC, and its data are written to the disk on that PC’s bus. The data from these ten disks are aggregated into one data file some time after the data acquisition session. The band-limited receiver outputs from a single-polarization, 19 element array are connected to the first two inputs of each PCI-9812. The dual-polarized 19-element array requires the use of all four inputs of each PCI-9812.

As of this writing the data acquisition system consists of ten, four-channel ADC cards in ten separate Windows computers. Data acquisition is initiated by a common trigger pulse, but because the sample clock rate is one half of the external clock frequency there is an ambiguity on which external clock pulse is selected by each ADC card from the common external trigger pulse. Hence the relative timing of the data samples from different ADC boards can be offset by half of one sample interval. These change from one scan to the next. To calibrate these offsets a sine wave burst generator is connected to one channel of each of the ten ADC cards, and a short burst is imposed on the data at the beginning of each scan. The ADC channel, CW frequency, and duration of this burst is given in the values of keywords MKRCHAN, MKRFREQ, and MKYCYCLS, respectively.

The two binary tables are unique to the PAF. The first contains the mapping of array elements to aggregated ADC data channel number – one array for each polarization. This map will need to be either updated in the code that writes the RcvrPAF file or maintained as a parameter file in the receiver and ADC control system and made available to the FITS writer.

The second binary table in RcvrPAF lists the file names of the FITS files that contain the correlation matrices for the data acquired with hot and cold load measurements the array in the outdoor test building. There is one hot/cold pair of files in this table for each frequency at which the measurements were taken. The format of the correlation data FITS files is shown in Table 3.

**Proposed FXcorPAF FITS File Format**

The first step in PAF calibration and beamforming is to generate complex cross-products of the ADC samples from the array elements. Table 4 shows the first draft of a FITS format for storing these cross products. The correlator is assumed to be of the “FX” type where the signal from each element is Fourier transformed into complex spectra with a given number of frequency channels, typically a power of two between 27 and 213. The ‘DC’ frequency channel is omitted, and the baseband channel center frequencies run from BANDWIDTH / num\_chan to BANDWIDTH. The same frequency channels from each pair of array elements of the same polarization are multiplied together to produce a complex cross product, and these cross products are accumulated for the duration of the ADC data scan. A PAF with *N* elements in one polarization will have *N2* cross products, but some of these are redundant. The product of element *m* times element *n* is the complex conjugate of *n* times *m* so only one of the two need to be stored. Hence there are *N(N+1)/2* unique complex cross products accumulations to be stored for each frequency channel of each polarization.

To avoid a large number of FITS table rows and columns the cross products are stored in one-dimensional arrays with one array (table column) for each polarization. The actual dimension of these arrays is given by the MTXSHAPE keyword value, where the fastest changing index is the real-imaginary index. The second fastest is the frequency channel, and the slowest is the correlation product index. The product index sequence is element 1 times elements 1 through N, 2 x (2….N), 3 x (3….N), …. N x N.

If and when the PAF system incorporates a real-time beamformer, a new FITS format will be needed that is similar to the current GBT Spectrometer format where the outputs of the formed beams are treated the same way as the data from independent feed horns in the focal plane.

**GO FITS File Format**

The GO (for “GBT Observe”) FITS file records all of the setup commands for a scan. Aside from a few basic parameters in the primary header keywords, all of the setup information is recorded as HISTORY cards in a “parameter = value” format. The purpose of this file is to record the intended actions in a scan in addition to what actually happened as recorded in the other FITS files. The parameters relevant to the 20-meter remain to be defined as FITS writing code is added to the 20-meter control software. Table 5 shows a typical GBT GO FITS file after which the 20-meter GO format will be patterned.

**Proposed Antenna FITS File Format (20-Meter)**

The purpose of the Antenna FITS files is to log the state of the antenna subsystems in the keyword parameters and to record the dynamic track of the antenna during the scan as recorded by the axis encoders and possibly other monitor points. Table 5 shows a preliminary FITS format for the 20-meter composed of a subset of GBT parameters and binary tables that appear to be relevant to the 20-meter. The details of this format will be fleshed out as FITS writing code is added to the 20-meter control software, and later versions of this document will reflect those additions and possible modifications. Table 6 shows the full GBT Antenna FITS format that will apply when the PAF goes on the GBT.

**LO1A FITS File Format**

The LO FITS file is relevant only to the GBT. It records the state of the primary first local oscillator used with GBT receivers. LO has the responsibility for time dependent frequency control such as Doppler tracking and frequency switching. The FITS format for this subsystem is include here in Table 7 since LO1A or LO1B may be used when the PAF is installed on the GBT for the injection of phase monitor signals into the PAF front-end, and the state of these signals will need to be retrieved from the FITS files.

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| **Table 1. Rcvr18\_26 FITS File Format** |
| Rcvr18\_26 HDU structure:Filename: ………/Rcvr18\_26/2010\_09\_09\_00:00:00.fitsNo. Name Type Cards Dimensions Format0 PRIMARY PrimaryHDU 27 () uint81 RX\_CAL\_INFO BinTableHDU 30 169R x 4C [1E, 1E, 1E, 1E]2 RX\_CAL\_INFO BinTableHDU 30 169R x 4C [1E, 1E, 1E, 1E]3 RX\_CAL\_INFO BinTableHDU 30 169R x 4C [1E, 1E, 1E, 1E]4 RX\_CAL\_INFO BinTableHDU 30 169R x 4C [1E, 1E, 1E, 1E]5 RX\_CAL\_INFO BinTableHDU 30 139R x 4C [1E, 1E, 1E, 1E]6 RX\_CAL\_INFO BinTableHDU 30 139R x 4C [1E, 1E, 1E, 1E]7 RX\_CAL\_INFO BinTableHDU 30 139R x 4C [1E, 1E, 1E, 1E]8 RX\_CAL\_INFO BinTableHDU 30 139R x 4C [1E, 1E, 1E, 1E] |
| name:PRIMARYheader:SIMPLE = T / file does conform to FITS standard BITPIX = 8 / number of bits per data pixel NAXIS = 0 / number of data axes EXTEND = T / FITS dataset may contain extensions COMMENT FITS (Flexible Image Transport System) format is defined in 'AstronomyCOMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H ORIGIN = 'NRAO Green Bank' / INSTRUME= 'Measurements' / device or program of origin GBTMCVER= '10.4 ' / telescope control software release FITSVER = '2.2 ' / FITS definition version for this device DATEBLD = '2010-07-22T15:29:03' / time program was linked SIMULATE= 0 / Is the instrument in simulate mode? DATE-OBS= '2010-09-09T00:00:00' / Manager parameter startTime TIMESYS = 'UTC ' / time scale specification for DATE-OBS TELESCOP= 'NRAO\_GBT' / Green Bank Telescope (Robert C. Byrd 100m) OBJECT = 'noise\_diode' / Manager parameter source PROJID = 'AGBT10C\_012\_09' / Manager parameter projectId OBSID = 'calibration' / Manager parameter scanId SCAN = 0 / Manager parameter scanNumber RECEIVER= 'Rcvr18\_26' / receiver name MIN\_FREQ= 1.80E+10 / lowest sky frequency (Hz) cutoff MAX\_FREQ= 2.65E+10 / highest sky frequency (Hz) cutoff NBEAM = 4 / number of beams ETAL = 9.900E-01 / rear spillover and scattering efficiency APEREFF = 5.800E-01 / aperture efficiency BEAMEFF = 8.100E-01 / main beam efficiency TAUZENIT= 7.000E-02 / opacity per unit air mass  |
| name:RX\_CAL\_INFOheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 16 / width of table in bytes NAXIS2 = 169 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 4 / number of fields in each row TTYPE1 = 'FREQUENCY' / label for field 1 TFORM1 = '1E ' / data format of field: 4-byte REAL TUNIT1 = 'Hz ' / physical unit of field TTYPE2 = 'RX\_TEMP ' / label for field 2 TFORM2 = '1E ' / data format of field: 4-byte REAL TUNIT2 = 'K ' / physical unit of field TTYPE3 = 'LOW\_CAL\_TEMP' / label for field 3 TFORM3 = '1E ' / data format of field: 4-byte REAL TUNIT3 = 'K ' / physical unit of field TTYPE4 = 'HIGH\_CAL\_TEMP' / label for field 4 TFORM4 = '1E ' / data format of field: 4-byte REAL TUNIT4 = 'K ' / physical unit of field EXTNAME = 'RX\_CAL\_INFO' / name of this binary table extension EXTVER = 1 / extension version TESTDATE= '2010-09-09' / date test data acquired RECEPTOR= 'R1 ' / source of IF signal FEED = 1 / feed identifier POLARIZE= 'R ' / channel's polarization BANDWDTH= 3.00E+06 / frequency width in which test was taken (Hz) ENGINEER= 'M. Stennes' / receiver engineer TECH = 'D. Woody' / responsible technician COMMENT low\_cal and high\_cal indicate selectable calibration levels data shape: (169,)data[0]: (1.76e+10, 37.09, 9.96, 0.0)data[1]: (1.7629999e+10, 33.040001, 9.5299997, 0.0)data[2]: (1.766e+10, 31.690001, 9.5299997, 0.0)data[3]: (1.7690001e+10, 31.35, 9.6099997, 0.0) |
| name:RX\_CAL\_INFO (for RECEPTOR= ‘L1’ |
| name:RX\_CAL\_INFO (for RECEPTOR= ‘R2’ |
| name:RX\_CAL\_INFO (for RECEPTOR= ‘L2’ |
| name:RX\_CAL\_INFO (for RECEPTOR= ‘R3’ |
| name:RX\_CAL\_INFO (for RECEPTOR= ‘L3’ |
| name:RX\_CAL\_INFO (for RECEPTOR= ‘R4’ |
| name:RX\_CAL\_INFO (for RECEPTOR= ‘L4’ |

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| **Table 2. RcvrPAF FITS File Format (proposed)** |
| RcvrPAF HDU structure:Filename: ………/RcvrPAF/2010\_11\_07\_00h39m08.fitsNo. Name Type Cards Dimensions Format0 PRIMARY PrimaryHDU 27 () uint81 ELEM\_MAP BinTableHDU 18 1R x 2C [20I, 20I]2 CAL\_MTRX BinTableHDU 27 1R x 4C [107520E, 107520E, 107520E, 107520E]3 CAL\_MTRX BinTableHDU 27 1R x 4C [107520E, 107520E, 107520E, 107520E] |
| name:PRIMARYheader:SIMPLE = T / conforms to FITS standard BITPIX = 8 / array data type NAXIS = 0 / number of array dimensions EXTEND = T ORIGIN = 'NRAO Green Bank' INSTRUME= 'Measurements' / device or program of origin GBTMCVER= '00.0 ' / telescope control software release FITSVER = '0.0 ' / FITS definition version for this device DATEBLD = '0000-00-00T00:00:00' / time program was released SIMULATE= 0 / Is the instrument in simulate mode DATE-OBS= '2011-07-29T20:49:33' / Manager parameter startTime TIMESYS = 'UTC ' / time scale specification for DATE-OBS TELESCOP= 'NRAO\_20M' / Green Bank 20-meter OBJECT = 'none ' / Manager parameter source PROJID = 'A20Mxxxx' / Manager parameter projectId OBSID = 'calibration' / Manager parameter scanId SCAN = 0 / integer scan identifier RECEIVER= 'RcvrPAF ' / receiver name MIN\_FREQ= 1300000000.0 MAX\_FREQ= 1750000000.0 NELEM = 19 / number of elements LO1FREQ = 2150000000.0 / LO1 frequency in Hz IF1FREQ = 400000000.0 / IF1 center frequency in Hz IF1BW = 5000000.0 / IF1 bandwidth in Hz LO2FREQ = 396000000.0 / LO2 frequency in Hz IF2FREQ = 2810000.0 / IF2 center frequency in Hz IF2BW = 402000.0 / IF2 bandwidth in Hz VRANGE = 1.0 / voltage range in Volts SAMPRATE= 1250000.0 / sample rate in Hz SCANLEN = 10.0 / scan length in seconds SAMPCLKF= 2500000.0 / sample clock freq Hz (2x samp rate MKRPFREQ= 200000.0 / marker burst frequency in Hz MKRVPP = 5.0 / marker burst maximum in volts MKRCYCLS= 200 / number of marker pulse cycles MKRCHAN = 1 / ADC channel with marker tone, base 0 NUMBITS = 12 / no. ADC bits (8|12) in agg file NUMBYTES= 2 / number of bytes (1|2) in agg file NUMCOMP = 10 / number of active DAQ computers ADCPBRD = 2 / number recorded channels per ADC board ADCAGG = 20 / number of channels in aggregate file DATETIME= '2011-07-22\_22:11:00' / date and time of PAF DAQ setup TRIGMODE= 'post ' / PAF DAQ trigger mode TRIGSRC = 'ext ' / PAF DAQ trigger source TRIGPOL = 'pos ' / PAF DAQ trigger polarity TRIGLVL = '0x80 ' / PAF DAQ trigger level CLKSEL = 'lt ' / PAF DAQ ADC clock selection CLKSRC = 'ext ' / PAF DAQ ADC clock source DBLBUF = 'True ' / PAF DAQ double buffer flag COMMENT FITS (Flexible Image Transport System) format is defined in Astronomy COMMENT and Astrophysics, volume 376, page 359; bibcode: 2001A&A...376..359H  |
| name:ELEM\_MAPheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / array data type NAXIS = 2 / number of array dimensions NAXIS1 = 80 / length of dimension 1 NAXIS2 = 1 / length of dimension 2 PCOUNT = 0 / number of group parameters GCOUNT = 1 / number of groups TFIELDS = 2 / number of table fields TTYPE1 = 'XELEMMAP' TFORM1 = '20I ' TUNIT1 = 'none ' TTYPE2 = 'YELEMMAP' TFORM2 = '20I ' TUNIT2 = 'none ' EXTNAME = 'ELEM\_MAP' / extension name COMMENT maps element numbers to aggregated data ADC channels COMMENT array index = element number, COMMENT value = ADC channel number, base 1 data shape: (1,)data[0]: (array([ 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20], dtype=int16), array([0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], dtype=int16)) |
| name:CAL\_CORRELheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / array data type NAXIS = 2 / number of array dimensions NAXIS1 = 72 / length of dimension 1NAXIS2 = 7 / length of dimension 2PCOUNT = 0 / number of group parametersGCOUNT = 1 / number of groupsTFIELDS = 4 / number of table fields TTYPE1 = 'CENTER\_FREQ' TFORM1 = 'D 'TUNIT1 = 'Hz 'TTYPE2 = 'HOT\_COR\_FILE'TFORM2 = '32A 'TTYPE3 = 'COLD\_COR\_FILE’TFORM3 = '32A 'EXTNAME = 'CAL\_CORREL' / name of this binary table extension TESTDATE= '2011-07-01' / date test data acquired BANDWDTH= 10000000.0 / bandwidth of correlated spectra, Hz ENGINEER= 'Bob Simon' / receiver engineer TECH = 'Ken Ward ' / receiver technician  [(1410000000.0, '2012\_01\_16\_12h34m22s', '2012\_01\_16\_12h55m01s') (1412000000.0, '2012\_01\_16\_12h36m26s', '2012\_01\_16\_12h57m05s') (1414000000.0, '2012\_01\_16\_12h38m30s', '2012\_01\_16\_12h59m09s') (1416000000.0, '2012\_01\_16\_12h40m34s', '2012\_01\_16\_13h01m13s') (1418000000.0, '2012\_01\_16\_12h42m38s', '2012\_01\_16\_13h03m17s') (1420000000.0, '2012\_01\_16\_12h44m42s', '2012\_01\_16\_13h05m21s') (1422000000.0, '2012\_01\_16\_12h46m46s', '2012\_01\_16\_13h07m25s')] |

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| **Table 3. FXcorPAF FITS File Format (proposed)** |
| FXcorPAF HDU structure:Filename: ……/FXcorPAF/2010\_11\_07\_00h39m08.fitsNo. Name Type Cards Dimensions Format0 PRIMARY PrimaryHDU 21 () uint81 CROSS\_CORREL BinTableHDU 18 1R x 2C ['53760E', '53760E'] |
| name:PRIMARYheader:SIMPLE = T / conforms to FITS standard BITPIX = 8 / array data type NAXIS = 0 / number of array dimensions EXTEND = T ORIGIN = 'NRAO Green Bank' INSTRUME= 'fx\_cor\_paf' / device or program of origin GBTMCVER= '00.0 ' / telescope control software release FITSVER = '0.0 ' / FITS definition version for this device DATEBLD = '0000-00-00T00:00:00' / time program was released SIMULATE= 0 / Is the instrument in simulate mode DATE-OBS= '2011-07-28T18:05:30' / Manager parameter startTime TIMESYS = 'UTC ' / time scale specification for DATE-OBS TELESCOP= 'NRAO\_20M' / Green Bank 20-meter OBJECT = 'none ' / Manager parameter source PROJID = 'A20Mxxxx' / Manager parameter projectId OBSID = 'xxx ' / Manager parameter scanId SCAN = 0 / integer scan identifier ADCDIR = '/export/raid2/data/04292011' ADCFILE = 'g11x11apr2902off030101' / ADC file name COMMENT FITS (Flexible Image Transport System) format is defined in Astronomy COMMENT and Astrophysics, volume 376, page 359; bibcode: 2001A&A...376..359H |
| name:CLK\_OFFSETSheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / array data type NAXIS = 2 / number of array dimensions NAXIS1 = 4 / length of dimension 1 NAXIS2 = 40 / length of dimension 2 PCOUNT = 0 / number of group parameters GCOUNT = 1 / number of groups TFIELDS = 1 / number of table fields TTYPE1 = 'DELAY ' TFORM1 = 'E ' TUNIT1 = 'sec ' EXTNAME = 'CLK\_OFFSETS' / name of this binary table extension data shape: (40,)data[]: [(0.0) (0.0) (4.0054002e-07) (4.0054002e-07) (3.9665508e-07) (3.9665508e-07) (-6.55402e-09) (-6.55402e-09) (3.9178317e-07) (3.9178317e-07) (4.6835531e-09) (4.6835531e-09) (-9.9224637e-09) (-9.9224637e-09) (3.8833716e-07) (3.8833716e-07) (-2.1664024e-09) (-2.1664024e-09) (3.8659175e-07) (3.8659175e-07) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0) (0.0)] |
| name:CROSS\_CORRELXTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / array data type NAXIS = 2 / number of array dimensions NAXIS1 = 430080 / length of dimension 1 NAXIS2 = 1 / length of dimension 2 PCOUNT = 0 / number of group parameters GCOUNT = 1 / number of groups TFIELDS = 2 / number of table fields TTYPE1 = 'XCROSCOR' TFORM1 = '53760E ' TUNIT1 = 'corcoef ' TTYPE2 = 'YCROSCOR' TFORM2 = '53760E ' TUNIT2 = 'corcoef ' EXTNAME = 'CROSS\_CORREL' / name of this binary table extension NUMADC = 20 / Number of ADC channels CTRFREQ = 1423000000.0 / center frequency in HzBANDWDTH= 625000.0 / bandwidth of correlated spectra, Hz MTXSHAPE= '[210,128,2]' / [num\_correl, num\_chan, real\_imag]  data shape: (1,)data[0]: [4.606e+08 0.000e+00 1.187e+08 0.000e+00 2.518e+08 0.000e+00 ...] |

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| **Table 4. GO FITS File Format** |
| GO HDU structure:Filename: ……/GO/2010\_11\_07\_00:39:08.fitsNo. Name Type Cards Dimensions Format0 PRIMARY PrimaryHDU 73 () uint8 |
| name:PRIMARYheader:SIMPLE = T / conforms to FITS standard BITPIX = 8 / array data type NAXIS = 0 / number of array dimensions EXTEND = T ORIGIN = 'NRAO Green Bank' TIMESYS = 'UTC ' / time scale specification for DATE-OBS OBJECT = '1845+0953' / Manager parameter source SCAN = 1 / integer scan identifier LASTON = 1 / Last On for pos switching OBSERVER= 'Paola Castangia' / Name of observer DATE-OBS= '2010-11-07T00:39:08' / Manager parameter startTime DATEBLD = '2010-07-22T18:09:36' / time program was released TELESCOP= 'NRAO\_GBT' / Green Bank Telescope (Robert C. Byrd 100m) GBTMCVER= '10.4 ' / telescope control software release INSTRUME= 'Turtle ' / device or program of origin PROJID = 'AGBT10C\_012\_09' / Manager parameter projectId SIMULATE= 0 / Is the instrument in simulate mode OBSID = 'Map ' / Manager parameter scanId LASTOFF = 0 / Last Off for pos switching FITSVER = '2.7 ' / FITS definition version for this device BLOCK = 'masersys\_check' SWSTATE = 'NONE ' COORDSYS= 'RADEC ' PROCNAME= 'Peak ' PROCTYPE= 'POINTING' PROCSIZE= 4 PROCSEQN= 1 VELOCITY= 0.0 OBSTYPE = 'CONTINUUM' SWTCHSIG= 'TPWCAL ' VELDEF = 'VRAD-TOP' RESTFRQ = 21500000000.0 RESTFRQ1= 21500000000.0 SKYFREQ = 21500000000.0 SUBMOTIN= 'SubFocus' / Subreflector control object SUBSTRTY= -80.0 / Scan start position on Y-axis in mm SUBOFFSY= 160.0 / Scan offset on Y-axis in mm REFBEAM = '2 ' RADESYS = 'FK5 ' EQUINOX = 2000.0 RA = 281.406875 DEC = 9.895666666666667 HISTORY Configuration keywords: HISTORY vdef = "Radio" HISTORY swtype = "none" HISTORY deltafreq = 0 HISTORY pol = "Circular" HISTORY nchan = "high" HISTORY swper = 0.1 HISTORY vframe = "topo" HISTORY swmode = "tp" HISTORY backend = 'DCR' HISTORY swfreq = 0,0 HISTORY tint = 0.1 HISTORY beam = 'B12' HISTORY vhigh = 0.0 HISTORY bandwidth = 320 HISTORY nwin = 1 HISTORY noisecal = "lo" HISTORY iftarget = None HISTORY receiver = 'Rcvr18\_22' HISTORY restfreq = 21500 HISTORY obstype = 'Continuum' HISTORY vlow = 0.0 HISTORY spect.levels = 3 HISTORY Catalog attributes: HISTORY coormode : J2000 HISTORY source : W49N HISTORY veldef : VOPT-LSR HISTORY location : J2000 @ (19:10:13.39, 09:06:14.00) HISTORY velocitydefinition : Optical HISTORY VEL : 8.0 HISTORY restframe : KinematicalLSR |

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| **Table 5. (20-Meter) Antenna FITS File Format (proposed)** |
| Antenna HDU structure:Filename: ………/Antenna/2012\_03\_05\_20:18:45.fitsNo. Name Type Cards Dimensions Format0 PRIMARY PrimaryHDU 66 () uint81 ANTPOSGR BinTableHDU 21 13R x 6C [D, D, D, D, D, D] |
| name:PRIMARYheader:SIMPLE = T / conforms to FITS standardBITPIX = 8 / array data typeNAXIS = 0 / number of array dimensionsEXTEND = TORIGIN = 'NRAO Green Bank'INSTRUME= 'Antenna20m' / device or program of originGBTMCVER= '00.0 ' / telescope control software releaseFITSVER = '0.0 ' / FITS definition version for this deviceDATEBLD = '0000-00-00T00:00:00' / time program was releasedSIMULATE= 0 / Is the instrument in simulate modeDATE-OBS= '2012-03-05T20:18:45' / Manager parameter startTimeTIMESYS = 'UTC ' / time scale specification for DATE-OBSTELESCOP= 'NRAO\_20M' / Green Bank 20-meterOBJECT = 'none ' / Manager parameter sourcePROJID = 'A20Mxxxx' / Manager parameter projectIdOBSID = 'Grid ' / Manager parameter scanIdSCAN = 0 / integer scan identifierLSTSTART= 0.0 / Start Time in seconds since local sidereal midSITELAT = 38.433 / North latitude of intersection of the az/el axeSITELONG= 798.4 / West longitude of intersection of the az/el axeSITEELEV= 850.0 / Height of the intersection of az/el axesSITESYS = 'NAD83 ' / Coordinate system datumSITETYPE= 'GEODETIC' / Type of positionINDICSYS= 'RADEC ' / Coordinate system of major/minor axesRADESYS = 'FK5 ' / Coordinate reference frame of major/minor axesEQUINOX = 2000.0 / Equinox of selected coordinate reference frameOFFSYS = 'PAF ' / Offset Coordinate system of major/minor axesDELTAUTC= 0.0 / UT1 - UTC offset for beginning of scanIERSPMX = 0.0 / X Polar motion correction for beginning of scanIERSPMY = 0.0 / Y Polar motion correction for beginning of scanREFMODEL= 'wikipedi' / Refraction algorithm in useMNTOFFAZ= 0.0 / Azimuth servo encoder offsetMNTOFFEL= 0.0 / Elevation servo encoder offsetLPC\_AZ1 = 0.0 / First azimuth local zero point correction coeffLPC\_AZ2 = 0.0 / Second azimuth local zero point correction coefLPC\_EL = 0.0 / Elevation local zero point correction coeffDIABMODE= 'OFF ' / State of diurnal aberration correctionPOLARMTN= 'OFF ' / State of polar motion correction parameterCOSVMODE= 'OFF ' / State of cosVMode parameterAMBTEMP = 0.0 / Ambient Temperature CAMBPRESS= 0.0 / Ambient Pressure in milliBarsAMBHUMID= 0.0 / Ambient Humidity fractionFOCTRMOD= 'OFF ' / Focus tracking mode selectionFOCPATM = 'OFF ' / Parallactic angle tracking selectionTRCKBEAM= 1 / The selected beam for this scanTRCKBMXE= 0.0 / XEL Offset of tracking beam wrt receiver packagTRCKBMEL= 0.0 / EL Offset of tracking beam wrt receiver packageSDMJD = 55991.84690972222 / MJD of scan midpointSOBSC\_AZ= 322.6712559897086 / Observed Az command at scan midpointSOBSC\_EL= 58.32163506693117 / Observed El command at scan midpointSOBSCREF= 0.0104241368459881 / Refraction command at scan midpointSMNTC\_AZ= 322.0889296011865 / Encoder Az command at scan midpointSMNTC\_EL= 58.20166200148314 / Encoder El command at scan midpointPNTMODEL= '20-meter' / Type of az/el pointing correction modelP1 = -0.614458 / Pointing coeff P1P3 = 0.002687 / Pointing coeff P3P4 = -0.02085 / Pointing coeff P4P5 = 0.007284 / Pointing coeff P5P6 = 0.003707 / Pointing coeff P6P7 = -0.12783 / Pointing coeff P7P8 = -0.07183199999999999 / Pointing coeff P8P9 = 0.027348 / Pointing coeff P9P15 = -0.001024 / Pointing coeff P15P16 = -0.004177 / Pointing coeff P16COMMENT FITS (Flexible Image Transport System) format is defined inCOMMENT and Astrophysics, volume 376, page 359; bibcode: 2001A&A...376..359H |
| name:ANTPOSGRheader:XTENSION= 'BINTABLE' / binary table extensionBITPIX = 8 / array data typeNAXIS = 2 / number of array dimensionsNAXIS1 = 48 / length of dimension 1NAXIS2 = 13 / length of dimension 2PCOUNT = 0 / number of group parametersGCOUNT = 1 / number of groupsTFIELDS = 6 / number of table fieldsTTYPE1 = 'DMJD 'TFORM1 = 'D 'TTYPE2 = 'RAJ2000 'TFORM2 = 'D 'TTYPE3 = 'DECJ2000'TFORM3 = 'D 'TTYPE4 = 'MNT\_AZ 'TFORM4 = 'D 'TTYPE5 = 'MNT\_EL 'TFORM5 = 'D 'TTYPE6 = 'REFRAC 'TFORM6 = 'D 'EXTNAME = 'ANTPOSGR' / name of this binary table extensiondata:[ (55991.846875000003, 23.390158693821029, 58.811512151801246, 322.09379679969101, 58.207745999613778, 0.010421662397779296) (55991.846875000003, 23.390019229618172, 58.811520816206247, 322.09299680000692, 58.206746000008657, 0.010422069089805575) (55991.846886574072, 23.390153860022888, 58.811528883565757, 322.09217440052481, 58.205718000655992, 0.010422487178121475) (55991.846886574072, 23.390014394426984, 58.81153743094778, 322.09137440084072, 58.204718001050878, 0.010422893887679526) (55991.846898148149, 23.390149023400191, 58.811545378010926, 322.09055200035277, 58.203690000440929, 0.010423311994530535) (55991.846898148149, 23.390009556413769, 58.811553808368473, 322.08975200066862, 58.202690000835808, 0.010423718721622491) (55991.846909722219, 23.390144183959123, 58.811561635113492, 322.08892960118652, 58.201662001483143, 0.010424136845988103) (55991.846909722219, 23.390004715409386, 58.811569948455663, 322.08812960049659, 58.200662000620738, 0.010424543591127508) (55991.846921296295, 23.390139062717349, 58.811577671343741, 322.0873056007415, 58.199632000926883, 0.01042496254717607) (55991.846921296295, 23.38999959295619, 58.81158586753304, 322.08650560105741,58.198632001321762, 0.010425369309359576) (55991.846932870372, 23.390134217650758, 58.811593453548738, 322.08568320056946, 58.197604000711813, 0.010425787470312899) (55991.846932870372, 23.389995936944857, 58.811572411996053, 322.08483919982757, 58.196623999784514, 0.010426186113537343) (55991.846944444442, 23.390130560352596, 58.811579877484469, 322.08401680034547, 58.195596000431848, 0.010426604291833822)] |

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| **Table 6. (GBT) Antenna FITS File Format** |
| Antenna HDU structure:Filename: ………/Antenna/2010\_11\_07\_00:39:08.fitsNo. Name Type Cards Dimensions Format0 PRIMARY PrimaryHDU 117 () uint81 BEAM\_OFFSETS BinTableHDU 24 4R x 5C [32A, 1D, 1D, 1J, 1J]2 ANTPOSGR BinTableHDU 57 301R x 16C [1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D, 1D]3 DYN\_POINT BinTableHDU 21 4R x 4C [1D, 1D, 1D, 1D]4 DYN\_FOCUS BinTableHDU 15 4R x 2C [1D, 1D] |
| name:PRIMARYheader:SIMPLE = T / file does conform to FITS standard BITPIX = 8 / number of bits per data pixel NAXIS = 0 / number of data axes EXTEND = T / FITS dataset may contain extensions COMMENT FITS (Flexible Image Transport System) format is defined in 'AstronomyCOMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H ORIGIN = 'NRAO Green Bank' / INSTRUME= 'Antenna ' / device or program of origin GBTMCVER= '10.4 ' / telescope control software release FITSVER = '2.14 ' / FITS definition version for this device DATEBLD = '2010-07-22T15:28:04' / time program was linked SIMULATE= 0 / Is the instrument in simulate mode? DATE-OBS= '2010-11-07T00:39:08' / Manager parameter startTime TIMESYS = 'UTC ' / time scale specification for DATE-OBS TELESCOP= 'NRAO\_GBT' / Green Bank Telescope (Robert C. Byrd 100m) OBJECT = '1845+0953' / Manager parameter source PROJID = 'AGBT10C\_012\_09' / Manager parameter projectId OBSID = 'Map ' / Manager parameter scanId SCAN = 1 / Manager parameter scanNumber LSTSTART= 8.065490547828468E+04 / Start Time in seconds since local sidereal midSITELAT = 3.8433119E+01 / North latitude of the az/el axis intersection SITELONG= 7.9839833E+01 / West longitude of the az/el axis intersection SITEELEV= 8.24595E+02 / Height of the intersection of az/el axes SITESYS = 'NAD83 ' / Coordinate system datum SITETYPE= 'GEODETIC' / Type of position INDICSYS= 'RADEC ' / Coordinate system of major/minor axes RADESYS = 'FK5 ' / Coordinate reference frame of major/minor axes EQUINOX = 2.00000E+03 / Equinox of selected coordinate reference frame OFFSYS = 'AZEL\_ENCODER' / Offset Coordinate system of major/minor axes DELTAUTC= -1.00182284E-01 / UT1 - UTC offset for beginning of scan IERSPMX = 6.07709838E-05 / X Polar motion correction for beginning of scanIERSPMY = 7.93467683E-05 / Y Polar motion correction for beginning of scanPFM\_CONF= 'Model5e ' / Name of pointing/focus configuration entry PFM\_VERS= '1 ' / Version of pointing/focus configuration REFMODEL= 'PTCSPN35.2' / Refraction algorithm in use MNTOFFAZ= -1.12395400E+01 / Azimuth servo encoder offset in degrees MNTOFFEL= 8.50000000E-02 / Elevation servo encoder offset in degrees COMMENT AZ LPC is defined as LPC\_AZ1 + LPC\_AZ2 DIV COS(EL) LPC\_AZ1 = 0.00000000E+00 / First azimuth local zero point correction coeffLPC\_AZ2 = 0.00000000E+00 / Second azimuth local zero point correction coefLPC\_EL = 0.00000000E+00 / Elevation local zero point correction coefficiePNTMODEL= 'GBT MEMO 173' / Type of az/el pointing correction model COMMENT PNTAZXXX and PNTELXXX coefficients are defined in GBT Memo 173, COMMENT and PTCS Project Note-53. COMMENT PNTAZXXX and PNTELXXX units are RADIANS unless otherwise noted. PNTAZD00= -1.72064157E-04 / Horizontal collimation coefficient PNTAZB01= 2.86082735E-05 / Elevation Axis collimation coefficient PNTAZD01= 4.20484723E-05 / Azimuth zero PNTAZA11= -1.78265021E-05 / Zenith E tilt PNTAZB11= -1.35263017E-05 / Zenith N tilt PNTAZC21= 0.00000000E+00 / Azimuth track PNTAZD21= 0.00000000E+00 / Azimuth track PNTAZB02= 0.00000000E+00 / Az Asymmetric Alidade Twist PNTAZD02= 0.00000000E+00 / Az Symmetric Alidade Twist PNTAZH00= -2.66104533E-06 / Az hysteresis maximum correction amplitude PNTAZH01= 2.50000000E+04 / Az hysteresis coefficient (in sec/rad) PNTAZR00= 0.00000000E+00 / Az hysteresis rate coeff. (in rad/rad/sec) PNTELD00= -3.33500568E-03 / Elevation zero PNTELC10= 1.12439928E-05 / Zenith E tilt PNTELD10= -2.84477033E-05 / Zenith N tilt PNTELB01= 3.07936701E-03 / Asymmetric gravity PNTELD01= 3.73402896E-03 / Symmetric gravity PNTELH00= -4.80925475E-06 / El hysteresis maximum correction amplitude PNTELH01= 2.50000000E+04 / El hysteresis coefficient (in sec/rad) PNTELR00= 0.00000000E+00 / El hysteresis rate coeff. (in rad/rad/sec) PNTLAMB1= 3.33226712E-04 / Avg Lambda1 Track correction in degrees PNTLAMB2= 3.18878008E-04 / Avg Lambda2 Track correction in degrees PNTLAMB3= -1.06093631E-04 / Avg Lambda3 Track correction in degrees FTRKXDA = 2.12547000E+02 / X position focus tracking constant coeff. (mm) FTRKXDB = -3.01981000E+02 / X position focus tracking cos() coeff. (mm) FTRKXDC = -2.55524000E+01 / X position focus tracking sin() coeff. (mm) FTRKYDA = -1.68143561E+02 / Y position focus tracking constant coeff. (mm) FTRKYDB = 1.91115422E+02 / Y position focus tracking cos() coeff. (mm) FTRKYDC = 6.23700430E+01 / Y position focus tracking sin() coeff. (mm) FTRKZDA = 9.55800000E+00 / Z position focus tracking constant coeff. (mm) FTRKZDB = 1.11823000E+01 / Z position focus tracking cos() coeff. (mm) FTRKZDC = -2.18582000E+01 / Z position focus tracking sin() coeff. (mm) FTRKXTA = -1.40000000E-01 / X tilt focus tracking constant coeff. (deg) FTRKXTB = 0.00000000E+00 / X tilt focus tracking cos() coeff. (deg) FTRKXTC = 0.00000000E+00 / X tilt focus tracking sin() coeff. (deg) FTRKYTA = 0.00000000E+00 / Y tilt focus tracking constant coeff. (deg) FTRKYTB = 0.00000000E+00 / Y tilt focus tracking cos() coeff. (deg) FTRKYTC = 0.00000000E+00 / Y tilt focus tracking sin() coeff. (deg) FTRKZTA = -6.00000000E-02 / Z tilt focus tracking constant coeff. (deg) FTRKZTB = 0.00000000E+00 / Z tilt focus tracking cos() coeff. (deg) FTRKZTC = 0.00000000E+00 / Z tilt focus tracking sin() coeff. (deg) LFC\_X = 0.00000000E+00 / X axis local focus offset (mm) LFC\_Y = 0.00000000E+00 / Y axis local focus offset (mm) LFC\_Z = 0.00000000E+00 / Z axis local focus offset (mm) LFC\_XT = 0.00000000E+00 / X tilt local focus offset (deg) LFC\_YT = 0.00000000E+00 / Y tilt local focus offset (deg) LFC\_ZT = 0.00000000E+00 / Z tilt local focus offset (deg) DIABMODE= 'ON ' / State of diurnal aberration correction POLARMTN= 'ON ' / State of polar motion correction parameter COSVMODE= 'ON ' / State of cosVMode parameter AMBTEMP = -7.60E-01 / Ambient Temperature C AMBPRESS= 9.32E+02 / Ambient Pressure in milliBars AMBHUMID= 6.43E-01 / Ambient Humidity fraction WEATHSTA= 'Weather\_Station\_2' / Source of Weather Information OPTICSMD= 'GREGORIAN OPTICS' / Optical path configuration FOCTRMOD= 'ON ' / Focus tracking mode selection FOCPATM = 'OFF ' / Parallactic angle tracking selection TRCKBEAM= '1 ' / The selected beam for this scan TRCKBMXE= -2.483333333E-02 / XEL Offset of tracking beam wrt receiver packagTRCKBMEL= -2.483333333E-02 / EL Offset of tracking beam wrt receiver packageSDMJD = 55507.027349537 / MJD of scan midpoint SOBSC\_AZ= 254.676368062017 / Observed Az command at scan midpoint SOBSC\_EL= 33.6732387971487 / Observed El command at scan midpoint SOBSCREF= 0.0243893987759611 / Refraction command at scan midpoint SMNTC\_AZ= 254.638145821139 / Encoder Az command at scan midpoint SMNTC\_EL= 33.7330889798402 / Encoder El command at scan midpoint DYN\_ENA = 'ON ' / State of dynamic pointing corrections DYNFENA = 'ON ' / State of dynamic focus corrections SDYN\_AZ1= 0. / az1 dynamic correction (deg) at scan midpoint SDYN\_AZ2= -0.000271287783793 / az2 dynamic correction (deg)/cos(el) at scan miSDYN\_EL = 0.000107765216667 / el dynamic correction (deg) at scan midpoint SDYN\_Y = -8.10625998 / Y axis dynamic focus correction (mm) at scan mi |
| name:BEAM\_OFFSETSheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 56 / width of table in bytes NAXIS2 = 4 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 5 / number of fields in each row TTYPE1 = 'NAME ' / label for field 1 TFORM1 = '32A ' / data format of field: ASCII Character TUNIT1 = 'none ' / physical unit of field TTYPE2 = 'BEAMXELOFFSET' / label for field 2 TFORM2 = '1D ' / data format of field: 8-byte DOUBLE TUNIT2 = 'deg ' / physical unit of field TTYPE3 = 'BEAMELOFFSET' / label for field 3 TFORM3 = '1D ' / data format of field: 8-byte DOUBLE TUNIT3 = 'deg ' / physical unit of field TTYPE4 = 'SRFEED1 ' / label for field 4 TFORM4 = '1J ' / data format of field: 4-byte INTEGER TUNIT4 = 'none ' / physical unit of field TTYPE5 = 'SRFEED2 ' / label for field 5 TFORM5 = '1J ' / data format of field: 4-byte INTEGER TUNIT5 = 'none ' / physical unit of field EXTNAME = 'BEAM\_OFFSETS' / name of this binary table extension data size: 4data[0]: ('1', 0.0, 0.0, 1, 2)data[1]: ('2', 0.049666666666666671, 0.0, 1, 2)data[2]: ('C', 0.024833333333333336, 0.024833333333333336, 0, 0)data[3]: ('MR12', 0.024833333333333336, 0.0, 0, 0) |
| name:ANTPOSGRheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 128 / width of table in bytes NAXIS2 = 301 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 16 / number of fields in each row TTYPE1 = 'DMJD ' / label for field 1 TFORM1 = '1D ' / data format of field: 8-byte DOUBLE TUNIT1 = 'd ' / physical unit of field TTYPE2 = 'RAJ2000 ' / label for field 2 TFORM2 = '1D ' / data format of field: 8-byte DOUBLE TUNIT2 = 'deg ' / physical unit of field TTYPE3 = 'DECJ2000' / label for field 3 TFORM3 = '1D ' / data format of field: 8-byte DOUBLE TUNIT3 = 'deg ' / physical unit of field TTYPE4 = 'MNT\_AZ ' / label for field 4 TFORM4 = '1D ' / data format of field: 8-byte DOUBLE TUNIT4 = 'deg ' / physical unit of field TTYPE5 = 'MNT\_EL ' / label for field 5 TFORM5 = '1D ' / data format of field: 8-byte DOUBLE TUNIT5 = 'deg ' / physical unit of field TTYPE6 = 'REFRACT ' / label for field 6 TFORM6 = '1D ' / data format of field: 8-byte DOUBLE TUNIT6 = 'deg ' / physical unit of field TTYPE7 = 'MAJOR ' / label for field 7 TFORM7 = '1D ' / data format of field: 8-byte DOUBLE TUNIT7 = 'deg ' / physical unit of field TTYPE8 = 'MINOR ' / label for field 8 TFORM8 = '1D ' / data format of field: 8-byte DOUBLE TUNIT8 = 'deg ' / physical unit of field TTYPE9 = 'OBSC\_AZ ' / label for field 9 TFORM9 = '1D ' / data format of field: 8-byte DOUBLE TUNIT9 = 'deg ' / physical unit of field TTYPE10 = 'OBSC\_EL ' / label for field 10 TFORM10 = '1D ' / data format of field: 8-byte DOUBLE TUNIT10 = 'deg ' / physical unit of field TTYPE11 = 'SR\_XP ' / label for field 11 TFORM11 = '1D ' / data format of field: 8-byte DOUBLE TUNIT11 = 'mm ' / physical unit of field TTYPE12 = 'SR\_YP ' / label for field 12 TFORM12 = '1D ' / data format of field: 8-byte DOUBLE TUNIT12 = 'mm ' / physical unit of field TTYPE13 = 'SR\_ZP ' / label for field 13 TFORM13 = '1D ' / data format of field: 8-byte DOUBLE TUNIT13 = 'mm ' / physical unit of field TTYPE14 = 'SR\_XT ' / label for field 14 TFORM14 = '1D ' / data format of field: 8-byte DOUBLE TUNIT14 = 'deg ' / physical unit of field TTYPE15 = 'SR\_YT ' / label for field 15 TFORM15 = '1D ' / data format of field: 8-byte DOUBLE TUNIT15 = 'deg ' / physical unit of field TTYPE16 = 'SR\_ZT ' / label for field 16 TFORM16 = '1D ' / data format of field: 8-byte DOUBLE TUNIT16 = 'deg ' / physical unit of field EXTNAME = 'ANTPOSGR' / name of this binary table extension data size: 301data[0]: (55507.027175925927, 281.47590258353233, 9.8135042559794368, 254.46231661315917, 33.779896697998048, 0.024346506442299676, 281.47590258353233, 9.8135042559794368, 254.62875502561815, 33.720537994820241, -52.883733034133911, 17.367509734630584, 6.731169956922531, -0.13945446908473969, 0.00024432133068330586, -0.060513909906148911)data[1]: (55507.027177083335, 281.47488919786207, 9.8146514560771809, 254.46446238037109, 33.779553375244141, 0.024346821934978637, 281.47488919786207, 9.8146514560771809, 254.62907258403922, 33.720222708018682, -52.867412567138672, 17.363721811771391, 6.7251042842864983, -0.13963094353675842, 0.00047658185940235853, -0.05986008420586586)data[2]: (55507.027178240744, 281.47382622689491, 9.8161299717551795, 254.46695147033691, 33.779381713867188, 0.024346977084032637, 281.47382622689491, 9.8161299717551795, 254.62939014060373, 33.719907420741492, -52.869017362594604, 17.367705035209656, 6.7199189782142632, -0.139356330037117, 0.00058272457681596279, -0.060023520141839981)data[3]: (55507.027179398145, 281.47263744524838, 9.8177840765920443, 254.46969805236816, 33.779210052490235, 0.024347116118526458, 281.47263744524838, 9.8177840765920443, 254.62970769531177, 33.719592132988616, -52.879094266891478, 17.355031692981719, 6.7325680971145623, -0.13972793519496918, 0.000138391915243119, -0.060022883117198944) |
| name:DYN\_POINTheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 32 / width of table in bytes NAXIS2 = 4 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 4 / number of fields in each row TTYPE1 = 'DMJD ' / label for field 1 TFORM1 = '1D ' / data format of field: 8-byte DOUBLE TUNIT1 = 'd ' / physical unit of field TTYPE2 = 'DYN\_AZ1 ' / label for field 2 TFORM2 = '1D ' / data format of field: 8-byte DOUBLE TUNIT2 = 'deg ' / physical unit of field TTYPE3 = 'DYN\_AZ2 ' / label for field 3 TFORM3 = '1D ' / data format of field: 8-byte DOUBLE TUNIT3 = 'deg ' / physical unit of field TTYPE4 = 'DYN\_EL ' / label for field 4 TFORM4 = '1D ' / data format of field: 8-byte DOUBLE TUNIT4 = 'deg ' / physical unit of field EXTNAME = 'DYN\_POINT' / name of this binary table extension data size: 4data[0]: (55507.027096064812, 0.0, -0.00028102395594399999, 0.000144041219444)data[1]: (55507.027223379628, 0.0, -0.00027128778379300001, 0.000107765216667)data[2]: (55507.027350694443, 0.0, -0.000272059930795, 0.000102382251389)data[3]: (55507.027478009259, 0.0, -0.000280012907054, 0.000130063568056) |
| name:DYN\_FOCUSheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 16 / width of table in bytes NAXIS2 = 4 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 2 / number of fields in each row TTYPE1 = 'DMJD ' / label for field 1 TFORM1 = '1D ' / data format of field: 8-byte DOUBLE TUNIT1 = 'd ' / physical unit of field TTYPE2 = 'DYN\_Y ' / label for field 2 TFORM2 = '1D ' / data format of field: 8-byte DOUBLE TUNIT2 = 'mm ' / physical unit of field EXTNAME = 'DYN\_FOCUS' / name of this binary table extension data size: 4data[0]: (55507.027084150846, -8.1188800220000008)data[1]: (55507.027211235982, -8.0701392700000003)data[2]: (55507.027338593914, -8.1062599800000008)data[3]: (55507.027465973151, -8.1139253399999998) |

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| **Table 7. LO1A FITS File Format** |
| LO1A HDU structure:Filename: ……/LO1A/2010\_11\_07\_00:39:08.fitsNo. Name Type Cards Dimensions Format0 PRIMARY PrimaryHDU 38 () uint81 STATE BinTableHDU 27 2R x 5C [1D, 1D, 1J, 1J, 1D]2 SOUVEL BinTableHDU 22 1R x 4C [1D, 1D, 1D, 1D]3 LO1TBL BinTableHDU 27 1R x 6C [1D, 1D, 1D, 1D, 1D, 1D] |
| name:PRIMARYheader:SIMPLE = T / file does conform to FITS standard BITPIX = 8 / number of bits per data pixel NAXIS = 0 / number of data axes EXTEND = T / FITS dataset may contain extensions COMMENT FITS (Flexible Image Transport System) format is defined in 'AstronomyCOMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H ORIGIN = 'NRAO Green Bank' / INSTRUME= 'LO1A ' / device or program of origin GBTMCVER= '10.4 ' / telescope control software release FITSVER = '2.3 ' / FITS definition version for this device DATEBLD = '2010-07-22T15:21:30' / time program was linked SIMULATE= 0 / Is the instrument in simulate mode? DATE-OBS= '2010-11-07T00:39:08' / Manager parameter startTime TIMESYS = 'UTC ' / time scale specification for DATE-OBS TELESCOP= 'NRAO\_GBT' / Green Bank Telescope (Robert C. Byrd 100m) OBJECT = '1845+0953' / Manager parameter source PROJID = 'AGBT10C\_012\_09' / Manager parameter projectId OBSID = 'Map ' / Manager parameter scanId SCAN = 1 / Manager parameter scanNumber LSTSTART= 8.06549050782047E+04 / Start Time in seconds since local sidereal midnSITELAT = 3.843312100000000E+01 / North latitude of intersection of the az/el axSITELONG= 7.983983499999999E+01 / West longitude of intersection of the az/el axSITEELEV= 8.24551E+02 / Height of the intersection of az/el axes SITESYS = 'NAD83 ' / Coordinate system datum SITETYPE= 'GEODETIC' / Type of position RADESYS = 'FK5 ' / Coordinate reference frame of major/minor axes EQUINOX = 2.00000E+03 / Equinox of selected coordinate reference frame DELTAUTC= -1.0018E-01 / UT1 - UTC offset for beginning of scan IERSPMX = 6.0771E-05 / X Polar motion correction for beginning of scanIERSPMY = 7.9347E-05 / Y Polar motion correction for beginning of scanCOSVMODE= 'OFF ' / State of cosVMode parameter RESTFRQ = 2.15000000000000E+10 / Rest Frequency of source in Hz IFFREQ = 6.00000000000000E+09 / Specified IF center Frequency in Hz LOOFFSET= 0.00000000000000E+00 / Additional Frequency offset due to Rcvr internaLOMULT = 1.0000E+00 / Frequency Multiplier due to Rcvr internal multiREQDPTOL= 1.0000E+01 / Requested Doppler tracking tolerance in Hz POWERLVL= 4.650E+00 / Requested LO Power Level in dBm SIDEBAND= 'UPPER ' / i.e. LOFREQ=ABS(SKY-IFFREQ)/LOMULTI-LOOFFSET  |
| name:STATEheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 32 / width of table in bytes NAXIS2 = 2 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 5 / number of fields in each row TTYPE1 = 'BLANKTIM' / label for field 1 TFORM1 = '1D ' / data format of field: 8-byte DOUBLE TUNIT1 = 'SECONDS ' / physical unit of field TTYPE2 = 'PHSESTRT' / label for field 2 TFORM2 = '1D ' / data format of field: 8-byte DOUBLE TUNIT2 = 'NONE ' / physical unit of field TTYPE3 = 'SIGREF ' / label for field 3 TFORM3 = '1J ' / data format of field: 4-byte INTEGER TUNIT3 = 'T/F ' / physical unit of field TTYPE4 = 'CAL ' / label for field 4 TFORM4 = '1J ' / data format of field: 4-byte INTEGER TUNIT4 = 'T/F ' / physical unit of field TTYPE5 = 'FREQOFF ' / label for field 5 TFORM5 = '1D ' / data format of field: 8-byte DOUBLE TUNIT5 = 'Hz ' / physical unit of field EXTNAME = 'STATE ' / name of this binary table extension NUMPHASE= 2 / Number of Phases if only Internal Switching SigSWPERIOD= 1.000E-01 / Switching period MASTER = 'DCR ' / Switching Signals Master data shape: (2,)data[0]: (0.002, 0.0, 0, 0, 0.0)data[1]: (0.002, 0.5, 0, 1, 0.0) |
| name:SOUVELheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 32 / width of table in bytes NAXIS2 = 1 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 4 / number of fields in each row TTYPE1 = 'DMJD ' / label for field 1 TFORM1 = '1D ' / data format of field: 8-byte DOUBLE TUNIT1 = 'd ' / physical unit of field TTYPE2 = 'VELOCITY' / label for field 2 TFORM2 = '1D ' / data format of field: 8-byte DOUBLE TUNIT2 = 'm/s ' / physical unit of field TTYPE3 = 'VDOT ' / label for field 3 TFORM3 = '1D ' / data format of field: 8-byte DOUBLE TUNIT3 = 'm/s/s ' / physical unit of field TTYPE4 = 'VDOTDOT ' / label for field 4 TFORM4 = '1D ' / data format of field: 8-byte DOUBLE TUNIT4 = 'm/s/s/s ' / physical unit of field EXTNAME = 'SOUVEL ' / name of this binary table extension VELDEF = 'VRAD-TOP' / Radio definition, Observatory or Topocentric data shape: (1,)data[0]: (55506.552083333336, 0.0, 0.0, 0.0) |
| name:LO1TBLheader:XTENSION= 'BINTABLE' / binary table extension BITPIX = 8 / 8-bit bytes NAXIS = 2 / 2-dimensional binary table NAXIS1 = 48 / width of table in bytes NAXIS2 = 1 / number of rows in table PCOUNT = 0 / size of special data area GCOUNT = 1 / one data group (required keyword) TFIELDS = 6 / number of fields in each row TTYPE1 = 'DMJD ' / label for field 1 TFORM1 = '1D ' / data format of field: 8-byte DOUBLE TUNIT1 = 'd ' / physical unit of field TTYPE2 = 'RA ' / label for field 2 TFORM2 = '1D ' / data format of field: 8-byte DOUBLE TUNIT2 = 'deg ' / physical unit of field TTYPE3 = 'DEC ' / label for field 3 TFORM3 = '1D ' / data format of field: 8-byte DOUBLE TUNIT3 = 'deg ' / physical unit of field TTYPE4 = 'LO1FREQ ' / label for field 4 TFORM4 = '1D ' / data format of field: 8-byte DOUBLE TUNIT4 = 'Hz ' / physical unit of field TTYPE5 = 'VFRAME ' / label for field 5 TFORM5 = '1D ' / data format of field: 8-byte DOUBLE TUNIT5 = 'm/s ' / physical unit of field TTYPE6 = 'RVSYS ' / label for field 6 TFORM6 = '1D ' / data format of field: 8-byte DOUBLE TUNIT6 = 'm/s ' / physical unit of field EXTNAME = 'LO1TBL ' / name of this binary table extension data shape: (1,)data[0]: (55507.027175925927, 281.40687500004009, 9.895666666679503, 15500000000.0, 0.0, 0.0) |