The New Beamformer Backend for FLAG

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The purpose of this document is to briefly summarize the technical aspects of the three currently available observing modes for the Focal L-Band Array for the Green Bank Telescope (FLAG) — a cryogenically cooled phased array feed (PAF) that operates between the frequencies between 1 and 2 GHz. The frontend of FLAG consists of 19 dual polarization (XX and YY) dipoles with cryogenically cooled low noise amplifiers. The hexagonal arrangement of the dipoles is optimized for maximum sensitivity over the antenna field-of-view (FoV) of angular diameter ($\sim 20'$). A 40-channel electronics assembly handles the analog-to-digital conversion and serial data transmission along optical fiber through a novel digital downlink developed at NRAO. FLAG is currently the world's most sensitive PAF with the lowest ever published beamformed system temperature ($T_{\rm sys}$) normalized by aperture efficiency (η) of 25.4$\pm$2.5 K near 1350 MHz for the boresight beam (Roshi, D. A., Shillue, W., Simon, B., et al. 2018, AJ, 155, 202) This is effectively equivalent with the L-Band cryogenic single-pixel receiver currently in place on the Green Bank Telescope (GBT). Since that publication, a new backend has been setup to handle the signal processing. The left panel of Figure 1 shows the decrease in $T_{\rm sys}/\eta$ derived from 'frequency sweep' observations of a calibration source. There is a trend of decreasing $T_{\rm sys}/\eta$ as a function of time for both polarizations with the February 2018 calibration data showing the lowest observed $T_{\rm sys}/\eta$. A correction to increase the digital gain just prior to the re-quantization was implemented for the August 2017 and February 2018 observing runs. While this figure only shows data for the boresight beam, the trend is observed in all outer beams. Since only the ratio of T_{sys}/η is directly measurable with a PAF, it is more instructive to list sensitivity in terms of the system equivalent flux density (SEFD) that folds in this ratio. Pingel (2018, PhDT), measures the SEFD to be near 12 Jy for each formed beam at 1.420 GHz (with the potential to be as low as 9.8 Jy).

The backend for the PAF was developed in collaboration with the Brigham Young University (BYU), West Virginia University (WVU) and the Green Bank Observatory (GBO). It consists of five high performance computing nodes (HPCs), each equipped with two Nvidia GeForce Titan X Graphical Processing Units (GPUs). Each HPC is connected to the Reconfigurable Open Architecture Computing Hardware (ROACH)[1] Field Programmable Gate Arrays (FPGA) boards and received one fifth of the total bandwidth of 151.59 MHz. Each HPC can run in three basic modes: (1) the calibration correlator mode (CALCORR); (2) the polyphase filter bank (PFB) correlator mode (PFBCORR); (3) the real-time beamformer mode (RTBF). The default observing setup of these modes are summarized in Table 1. Note that beams can be spaced in any configuration that suites the scientific objectives. In most cases, beams are formed as demonstrated in the right panel of Figure with a boresight beam surrounded by six outer beams all with FWHM of about $9.1'$. The setup shown in here demonstrates the beam spacing for spectral line on-the-fly mapping, where beams will overlap at their half-power points to ensure adequate spatial Nyquist sampling. The beam spacing in the RTBF mode will be more spread out in order to maximize the FoV.

CALCORR This mode is used when observing a standard calibration point-source to derive complex beamforming weights and match flux scales. The arrangement of the beams in this mode is entirely up to the observer as a beam can be formed by placing a calibration source at the desired beam center. The total 151.59 MHz bandpass is made up of 500 'coarse' channels each with a frequency resolution of 0.30318 MHz. The minimum integration time is 1 s, but can be set to be longer. The two main observing strategies for calibration include (1) a $\sim$40 min 'calibration grid' where a 30×30 arcminute^2 area is mapped around a source with a known flux to characterize the response of the array over the entire FoV; and (2) a $\sim$10 min 'seven-point' scan where the calibrator is placed at the center of each beam to be formed through discrete pointings.

PFBCORR In this primary science mode for on-the-fly maps, a 30.318 MHz (100 coarse channels) section of the original bandpass is selected to be sent through a PFB to obtain finer channelization. A contiguous set of five coarse channels is output to 160 'fine' channels for with a frequency resolution of 9.47 kHz; the resulting bandpass is therefore made up of 3200 fine channels and has a minimum integration time of 0.5 s with an option to be increased.

In both correlator modes, each GPU runs two correlator threads making use of the xGPU library[2], which is optimized to work on FLAG system parameters. All of the backend's observing modes are considered to be 'total power', so no signal injection from a noise diode or frequency-switching is possible. Depending on the

[1] https://casper.berkeley.edu/wiki/ROACH-2_Revision_2
[2] https://github.com/GPU-correlators/xGPU/tree/master/src

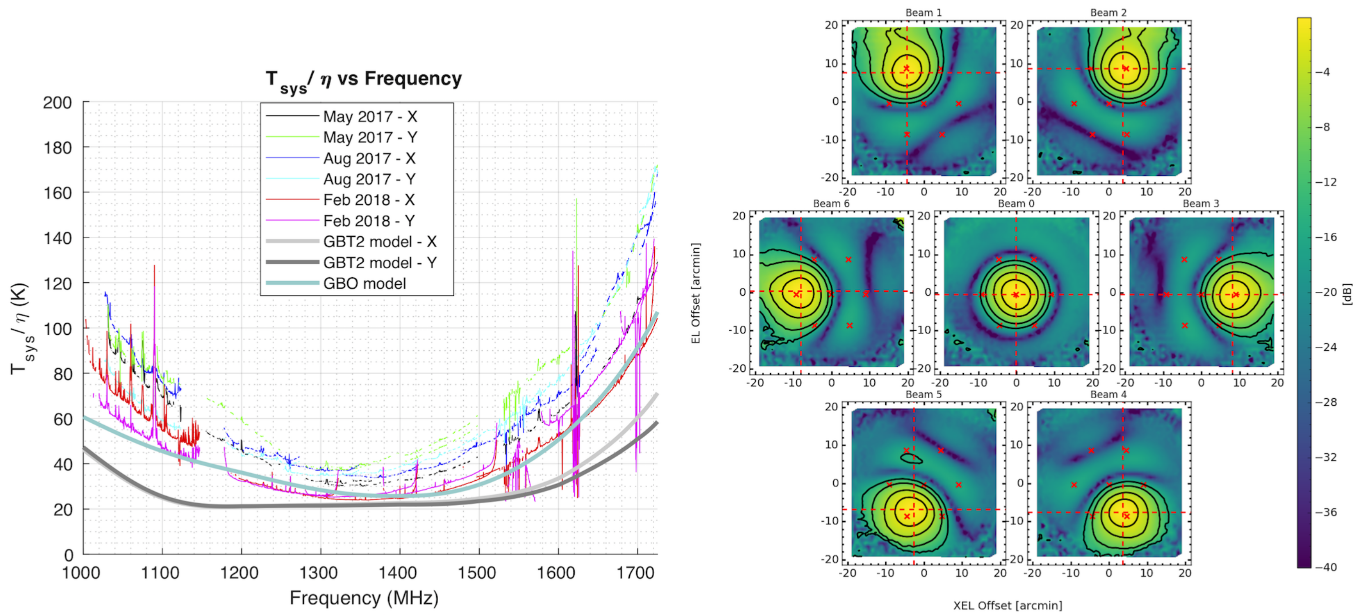

Figure 1: *left*: T_{sys}/η as a function of frequency for multiple observing runs. *right*: A typical formed beam pattern (taken from GBT16B_400_12), The red crosses denote the beam pointing centers, while the vertical dashed red lines show the location of the peak response of the formed beam. The spacing here is typical for spectra line mapping. The spacing for transient science will be more spread out to maximize the FoV.

correlator mode, each correlator thread handles one-twentieth of the total bandwidth made up of either 25 *non-contiguous* coarse frequency channels or 160 contiguous fine channels. The raw output from each correlator thread is a distinct FITS file containing the correlations between each dipole, which requires the beamforming in these modes to be done off-line.

RTBF The final available observing mode is designed for the detection of pulsar and transient sources such as fast radio bursts (FRBs). In this mode, the integration time increases by three orders of magnitude to minimum value of 130μs to resolve the rotation period of millisecond pulsars and the most short-lived of transient sources (though, as with the correlator modes, can be increased). In order to maximize flux sensitivity, the entire 151.59 MHz bandwidth is utilized. As the beamforming is done within the backend GPUs, the 20 output FITS files contain raw beamformed spectra in units of counts in for 25 non-contiguous coarse channels. This mode is specifically setup for handling the beamforming of seven total beams that whose locations are set at the time of the observation.

Data Reduction The software used to perform the 'post-correlation' beamforming of the spectral line data, where weights are applied to saved covariance matrices, is a custom `SpectralFiller` Python package[3]. The primary purpose of this software suite is to act as an FLAG specific version of the GBO program `sdfits`. It generates an SDFITS file containing raw beamformed spectra in the units of counts for each formed beam that can be manipulated within the GBTIDL environment exactly in the same manner as data from the VEGAS backend. The RTBF output data are converted into filterbank format and reduced in standard software package available to the pulsar community.

[3]https://github.com/nipingel/SpectralFiller

Mode	BW[a] [MHz]	Number of Channels	$\Delta\nu$[b] [MHz]	t_{int}[c]	FoV[d] [arcminutes]
CALCORR	151.69	500	0.3018	1.0	Variable
PFBCORR	30.18	3200	0.00947	0.5	18
RTBF	151.59	500	0.30318	1.3×10^{-4}	27

[a] The total available bandwidth [b] Frequency resolution
[c] minimum integration time [d] Typical field-of-view of beam arrangement (assuming seven total beams)

Table 1: Summary of Mode Properties