Performance of a Highly Sensitive, 19-element, Dual-polarization, Cryogenic L-band Phased-array Feed on the Green Bank Telescope

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Abstract

A new 1.4 GHz, 19-element, dual-polarization, cryogenic phased-array feed (PAF) radio astronomy receiver has been developed for the Robert C. Byrd Green Bank Telescope (GBT) as part of the Focal L-band Array for the GBT (FLAG) project. Commissioning observations of calibrator radio sources show that this receiver has the lowest reported beam-formed system temperature ($T_{\text{sys}}$) normalized by aperture efficiency ($\eta$) of any phased-array receiver to date. The measured $T_{\text{sys}}/\eta$ is 25.4 ± 2.5 K near 1350 MHz for the boresight beam, which is comparable to the performance of the current 1.4 GHz cryogenic single-feed receiver on the GBT. The degradation in $T_{\text{sys}}/\eta$ at ∼4$^\circ$ (required for Nyquist sampling) and ∼8$^\circ$ offsets from the boresight is, respectively, ∼1% and ∼20% of the boresight value. The survey speed of the PAF with seven formed beams is larger by a factor between 2.1 and 7 compared to a single-beam system, depending on the observing application. The measured performance, both in frequency and offset from the boresight, qualitatively agrees with predictions from a rigorous electromagnetic model of the PAF. The astronomical utility of the receiver is demonstrated by observations of the pulsar B0329+54 and an extended H II region, the Rosette Nebula. The enhanced survey speed with the new PAF receiver will enable the GBT to carry out exciting new science, such as more efficient observations of diffuse, extended neutral hydrogen emission from galactic inflows and searches for fast radio bursts.

Key words: instrumentation: miscellaneous – intergalactic medium – ISM: individual objects (Rosette Nebula) – large-scale structure of universe – pulsars: individual (B0329+54) – techniques: imaging spectroscopy

1. Introduction

Radio astronomy is primarily an observational science, in which high-sensitivity, large-scale surveys are an essential tool for new discoveries (Condon et al. 1998; Barnes et al. 2001; Manchester 2001; DeZotti et al. 2010; Bekhti et al. 2016). While large apertures enhance sensitivity, they have a more limited field of view (FoV) when equipped with a single feed. The survey speed of a telescope is proportional to its FoV and the square of the signal-to-noise ratio (S/N) required for the survey. In this paper, we describe a new 1.4 GHz (L-band) phased-array feed (PAF) system, built for the Robert C. Byrd Green Bank Telescope (GBT) as part of the Focal L-band Array for the GBT (FLAG) project, which can enhance the FoV of the telescope by a factor of 7 and has sensitivity comparable to the existing single-feed 1.4 GHz receiver.

There are wide-ranging scientific interests to increase the FoV of the GBT near the L band. Here we focus on two scientific motivations. It is now known that galaxies must be accreting gas to sustain their star formation. With the current known gas content of galaxies, current star formation rates can be sustained only for a few billion yr. However, there is evidence that the gas content of galaxies has remained roughly constant for the past 10 billion yr, implying that galaxies must be accreting gas from the intergalactic medium (Prochaska et al. 2005). Current theories suggest that this accretion occurs in one of two modes: a hot mode, where the gas is heated to $10^6$ K, or a cold mode, where the gas remains below $10^5$ K (Kereš et al. 2005, 2009; Sancisi et al. 2008). The cold mode, in particular, should be the dominant form of accretion for low-mass galaxies in low-density environments. Such accretion should be detectable via observations of neutral hydrogen at 21 cm (H I) at column densities of N(HI) $\lesssim 10^{18}$ cm$^{-2}$ (Popping et al. 2009). To detect H I emission from the cold accretion flows from nearby galaxies, sensitive single-dish observations are essential (Chynoweth et al. 2008; Mihos et al. 2012; Wolfe et al. 2013; de Blok et al. 2014; Pisano 2014; Wolfe et al. 2016). Since the expected line strengths are weak, such surveys require enormous amounts of observing time. To reduce the observing time, it is essential to increase the FoV of the telescope with high-sensitivity multibeam systems.
The discovery of fast radio bursts (FRBs) has generated renewed interest in exploring the transient radio sky (Lorimer et al. 2007; Katz 2016). FRBs are bright, approximately millisecond-duration individual pulses from compact sources exhibiting pulse-dispersive delays over a wide bandwidth. The dispersive delays far exceed the values expected from the interstellar medium of our Galaxy, indicating that they are extragalactic in origin. This has been confirmed by the localization and optical counterpart identification for FRB 121103, the only known repeating burst source (Chatterjee et al. 2017). So far, about 24 FRBs have been detected (Petroff et al. 2016), with most of the detections made near 1.4 GHz. The physical nature of and mechanism producing the burst are not known. Studies of such short-duration radio transients are poised for a revolution with large FoV telescopes and flexible, high-throughput back ends (see, for example, Bannister et al. 2017).

The FoV of a radio telescope when equipped with a single feed is limited to the full width at half maximum (FWHM) of the primary beam, which is \( \lambda/D \), where \( \lambda \) is the observing wavelength and \( D \) is the aperture diameter of the reflector. The feeds are usually optimized to maximally receive radiation from the reflector while attenuating the ground spillover. The physical size of the feed is determined by this optimization process. Traditionally, the FoV of telescopes is increased by placing multiple such optimized feeds in the focal plane—referred to as a focal plane array (FPA). The physical separation between feeds in an FPA is determined by the size of the feeds. The large physical separation of the feeds results in nonoverlapping beams on the sky. Further, the off-axis beams suffer efficiency degradation, since the feed optimization is usually done for the central beam. Both of these effects result in a relatively poor mapping efficiency improvement.

In the last decade, the use of phased arrays employing a set of smaller focal plane radiating elements—referred to as PAFs—has gained wide interest among the radio astronomy community (Fisher & Bradely 2000; Hay & Bird 2015; Warnick et al. 2016). In such PAF receivers, each element is electrically small and thus does not optimally illuminate the reflector. However, an optimal illumination with low spillover is obtained by the weighted sum of the amplified signal voltages from multiple elements. Multiple beams can be formed by adding signals with different sets of complex weights. The beams formed in this manner can be made to overlap, thus increasing the mapping efficiency. The design and optimization of PAFs are complicated by mutual coupling effects between elements (see, for example, Diao & Warnick 2017). The mutual coupling distorts the element beam pattern and introduces channel-to-channel noise coupling between neighboring low-noise amplifiers (LNAs) that follow these elements. Thus, accurate methods for electromagnetic modeling and beam forming are needed in order to achieve efficient performance.

Currently, PAFs are being developed for both single-dish radio telescopes and radio interferometers. Designing efficient PAFs requires proper accounting of electromagnetic coupling and beam forming, which has led to new theories and techniques in PAF modeling (Woestenburg 2005; Warnick & Jensen 2007; Hay 2010). Further, several leading radio astronomy institutions have made significant progress on developing PAF receivers and systems. The Westerbork Synthesis Radio Telescope (WSRT; Oosterloo et al. 2010) and the Australian Square Kilometer Array Prototype (ASKAP; Hay & O’Sullivan 2008; Chippendale et al. 2015) have both built uncooled, broadband (>800 MHz) PAFs near 1.4 GHz. The elements used by the WSRT for their PAF, called the APERture Tile In Focus (APERTIF), are Vivaldi antennas. The ASKAP Chequerboard PAF is made of a self-complementary connected element array (Hay & O’Sullivan 2008). A phased-array feed demonstrator (PHAD) has been developed by the Dominion Radio Astrophysical Observatory (DRAO) using Vivaldi elements (Veidt et al. 2011). Cryogenic PAF development is being pursued for the Arecibo telescope by Cornell University (Cortes-Medellin et al. 2015) and for the Five hundred meter Aperture Spherical Telescope (FAST; Wu et al. 2016); both have operating frequencies near 1.4 GHz. A higher-frequency (70–95 GHz) PAF is also being developed by the University of Massachusetts ( Erickson et al. 2015).

FLAG is a collaborative project between the National Radio Astronomy Observatory (NRAO), the Green Bank Observatory (GBO), Brigham Young University (BYU), and West Virginia University (WVU). During the first phase of the project, a prototype cryogenic “kite dipole array” was built and tested successfully on the GBT (Roshi et al. 2015). In this paper, we present the construction of the next-generation cryogenic PAF and describe the measurement of its performance and comparison with a PAF model. The new PAF is optimized for the GBT optics to provide the required FoV with a diameter of ~20′. Additionally, all of the instrumentation from the LNA to the back end was upgraded. A brief description of the new system is given in Section 2. For testing and commissioning of the system on the GBT, Nyquist-sampled voltage data were recorded in an instantaneous bandwidth of 300 kHz, and all signal processing was done off-line. The data-processing method is described in Section 3. Before the system was installed on the GBT, the receiver temperature of the PAF was measured at the outdoor test facility at the GBO, as described in Section 4. The test observations made with the GBT are summarized in Section 5, and the results are given in Section 6. We have also observed a pulsar and an extended continuum source using the PAF system on the GBT. The results of these observations are presented in Section 7. The main results are summarized in Section 8. A GPU-based digital signal-processing back-end instrument has been realized for real-time calibration and beam forming by the FLAG collaboration. This system will form the back end for the PAF for science observations with the GBT. The details of the real-time beam former will be published elsewhere.

2. Instrumentation

The PAF consists of a hexagonal array of 19 dual-polarization dipole elements at ambient temperature connected to 19 pairs of cryogenic LNAs located in a vacuum dewar. Optimization of the design for maximum sensitivity over the antenna FoV of angular diameter ~20′ and across a bandwidth of 150 MHz required adjusting the geometric parameters of the dipoles, which had been developed in prior work (Warnick et al. 2011). The optimal design is dependent upon the noise parameters of the LNA and uses maximum S/N beam forming as a parameter. The dipole array is shown in Figure 1(a). The dipoles were fabricated using brass and subsequently plated with copper (with thickness \( \approx 6.35 \mu m \)) followed by 1 \( \mu m \) of gold to reduce ohmic loss. An air-filled coaxial conductor
transmission line was used to minimize dielectric loss. These vertical transmission lines function as a balun and a means of fixing the correct separation between the radiating elements and the ground plane. Two teflon beads located at either end of the transmission line center the inner conductor. Between the dipoles and the LNAs, which are located in the cryostat, there is a custom low-loss coaxial assembly that also serves as a thermal transition and a vacuum barrier, as shown in Figure 1(b). The LNAs use SiGe transistors selected for their low-noise performance at cryogenic temperatures (Weinreb et al. 2009). The measured average gain of the LNAs is 38 dB over their 1.2–1.7 GHz frequency range, and the median noise temperature is 4.85 K (the peak-to-peak variation in the measured values is 1.5 K) when operated at a physical temperature of 15 K (Groves III & Morgan 2017). A highly integrated, 40-channel electronics assembly encompasses all of

Figure 1. (a) The 19-element dual-polarized dipole array. (b) Dipole and custom low-loss, low thermal conductivity transition to the LNA.

Figure 2. Block diagram showing the design of the phased-array receiver system.
of the receiver: calibration signal injection, warm post-amplification, power leveling, local oscillator (LO) distribution, down conversion, analog-to-digital conversion, and serial data transmission through optical fiber, as shown in Figure 2. This post-amplification electronics assembly is the first deployment of a novel integrated unformatted digital link developed at NRAO (Morgan et al. 2013), which allowed the entire analog signal path and digitizers to be located directly behind the phased array. This reduced the power dissipation and minimized the physical footprint. We have confirmed many aspects of this new design, including the methodology for recovering bit and word boundaries in the unformatted received data streams (Morgan & Fisher 2014). The digital link can be scaled in bit rate, bandwidth, and channel count for future PAF applications. The fiber-optic link transports the samples over approximately 2 km to the Jansky Laboratory to terminate in equipment racks containing five ROACH2 FPGA boards,9 which perform bit and byte alignment, 512 channel polyphase filter bank, and sideband separation operations. The data from the spectral channels are requantized to 8 bits, packetized, and sent to an Ethernet switch through 10 GbE links. Only 500 spectral channels, selected by removing channels from the band edge, are sent to the switch. The data acquisition system developed for commissioning and testing consists of a Linux computer equipped with a high-speed disk and connected to the switch through a 10 GbE link. The complex voltage samples from one of the spectral channels are recorded to the disk for off-line processing.

The PAF and the associated receiver box are placed at the prime focus of the GBT. The GBT LO system is used for the first down conversion. The digital down converters and the back-end system are synchronized through a 10 MHz observatory-wide frequency reference, which is also used to lock the GBT LO system. The LO frequencies were set to 1550, 1450, 1350, or 1250 MHz for most observations, since the sideband separation coefficients were previously calibrated for these LO values. For each LO setting, data were collected from a subset of 300 kHz PFB channels. The observing frequency corresponding to this subset of PFB channels was located within the 150 MHz bandwidth centered at the LO value.

For future science observations, a complete GPU-based digital signal-processing back-end instrument has been realized to process all 500 channels from the FPGA boards, covering 150 MHz bandwidth (see Figure 2). It performs phased-array calibration, beam forming, correlation, and pulsar and transient searches. It has several unique capabilities not found on other PAF-equipped telescopes. Array covariance matrices are saved continuously from the correlator as the primary data product. This enables post-correlation beam forming (Hay & Bird 2015) after the fact for spectral-line or continuum observations, so that different beam-forming weights can be applied to improve beam patterns or to compute any desired number of overlapping beams on the sky (within the limits of the FoV accessible to the finite number of PAF elements). Also, we are in the process of developing software for two new operational modes: (a) a commensal mode, where a quick-dump real-time beam-formed spectrometer runs concurrently with the correlator to permit opportunistic transient searches during observations of neutral hydrogen, and (b) a radio frequency interference (RFI) mitigation mode, where the correlator and real-time beam former can be linked to form a tracking RFI-nulling adaptive beam former. This instrument was commissioned separately on the GBT in summer 2017, and the results will be presented elsewhere.

3. Data Processing and Performance Metric

The off-line processing of the recorded data proceeded with first taking a 64-point Fourier transform of the complex voltage time series, which provided a spectral resolution of ∼300/64 = 4.7 kHz. The cross-correlations between signals from all 38 dipole outputs for each spectral channel were then computed, and the correlation matrix $R$ was obtained as

$$R = \frac{1}{N} \sum_{i=0}^{N-1} V[i] V[i]^H.$$ (1)

Here $V[i]$ is the time series of the complex voltage vector formed from the 38 dipole outputs from a spectral channel. The number of samples $N$ used for the computation typically corresponds to an integration time of 5 s. The high spectral resolution is very useful to excise narrowband RFI. After RFI editing, the cross-correlations were averaged over 300 kHz bandwidth.

An off-line post-correlation beam former is implemented in a MATLAB10 program (Jeffs et al. 2008; Hay & Bird 2015). For typical observations, the cross-correlations on the source and at a nearby off-source position were measured. In this case,

$$S/N = \frac{w^H R_{on} w}{w^H R_{off} w} - 1,$$ (2)

where $R_{on}$ and $R_{off}$ represent the on-source and off-source correlation matrices, respectively, and $w$ is the beam-former weight. The beam-former weights are obtained by maximizing the $S/N$, which will be the eigenvector corresponding to the maximum Rayleigh quotient. For forming beams at different positions in the FoV of the PAF system, the above procedure is repeated by moving the telescope and positioning the source appropriately.

We define the performance metric as the inverse of the maximum $S/N$ when observing a compact astronomical source (Warnick & Jeffs 2008). As shown below, this inverse $S/N$ can be expressed in terms of $T_{sys}/\eta$, if the flux density of the source is known, and it can be directly obtained from the observations of a compact source without making any assumptions. This metric is useful to compare the performance of different PAFs. A nearby off-source position needs to be observed to derive $T_{sys}/\eta$, and hence its value will depend on the diffuse foreground emission temperature at the off-source position. The measured value of $S/N = \frac{T_{sys}}{T_{off}}$ for the off-course system temperature $T_{sys}$ and the excess antenna temperature

$$T_a = \frac{SA\eta}{2k}.$$ (3)

Here $S$ is the flux density of the source, $A$ is the physical area of the telescope aperture, $k$ is Boltzmann’s constant, and $\eta$ is the product of the aperture efficiency of the telescope and radiation

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9 https://casper.berkeley.edu/wiki/ROACH-2_Revision_2

10 https://www.mathworks.com/products/matlab.html
efficiency of the PAF. Substituting in Equation (3), we get
\[
T_{\text{sys}} = \frac{SA}{2kS/N_{\text{max}}},
\]
where \(S/N_{\text{max}}\) is the maximum S/N. We use the flux densities of calibrator sources provided by Perley & Butler (2017). These flux densities are accurate to 3%–5%.

4. Receiver Temperature

The receiver temperature of the PAF was measured at the outdoor test facility at the GBO. This facility is a small outdoor structure with a retractable roof facilitating hot- and cold-load measurements with the PAF receiver to obtain the receiver noise temperature by the \(Y\)-factor method (Warnick et al. 2010). The receiver is mounted with the dipoles facing up toward either an ambient temperature load (hot load) or the cold sky. A large aluminum cone, flaring upward from the edge of the dipole array, is attached to the receiver and functions to shield the dipoles from wide-angle ground radiation. To derive the \(Y\) factor, the array output voltage correlation \(R_{\text{hot}}^W\) was measured with an absorber placed in front of the array, which forms an isotropic hot load at ambient temperature. A second correlation measurement, \(R_{\text{cold}}^W\), was made by pointing the array to a region of sky away from the galactic plane, and this formed the cold load. In this case, the factor
\[
Y = \frac{w^H R_{\text{hot}}^W w^H R_{\text{cold}}^W}{w^H w},
\]
and the receiver temperature
\[
T_{\text{rec}} = \frac{T_{\text{hot}} - YT_{\text{cold}}}{Y - 1},
\]
where \(T_{\text{hot}}\) and \(T_{\text{cold}}\) are the temperatures of the hot load and cold sky, respectively, and \(w\) are the weights. The derived value of the receiver temperature depends on the weights, as seen from Equation (5). The cold-sky temperature is estimated from the sky brightness temperature distribution and typically has a value of \(\sim 8\) K (Delahaye et al. 2002). The hot-load temperature is 296.5 K. Despite the use of the conical ground shield, the cold-sky correlations were not devoid of contribution from ground-scattered radiation. From single-feed measurements using the outdoor test facility, it is estimated that a residual of \(\sim 4\) K can be present in the receiver temperature values due to this scattered radiation.

Figure 3(a) shows the measured receiver temperature \(T_{\text{dipole}}\) for each dipole. These temperatures are obtained using the \(Y\) factor derived from the output power of each dipole in the array. Thus, for example, \(T_{\text{dipole}}\) for dipole 1 is equivalent to using \(w^H = [1, 0, 0, ..., 0]\) (i.e., weight 1 for dipole one and 0 for all other dipoles) in Equation (5) and then estimating the temperature using Equation (6). This weighting scheme is applied for each dipole to get 38 \(T_{\text{dipole}}\) values (see Figure 3(a)). The \(T_{\text{dipole}}\) values range between 12 and 18 K near 1336 MHz. The missing value at dipole 13 in the \(Y\) polarization is due to a bad LNA on that channel. The median value of \(T_{\text{dipole}}\) versus frequency is shown in Figure 3(b). The minimum \(T_{\text{dipole}}\) is about 13.3 K near 1336 MHz.

The measured \(T_{\text{dipole}}\) has contributions from ground scattering and mutual coupling between array elements. Since both of these contributions produce noise correlations at the output of the array, they can be canceled out to a large extent. This cancellation corresponds to the maximum Rayleigh quotient of \(Y\), which will provide a minimum receiver temperature, \(T_{\text{rec,min}}\). The weight vector that needs to be applied in Equation (5) to get the maximum \(Y\) is the eigenvector corresponding to the maximum eigenvalue of the matrix \(R_{\text{cold}}^\dagger R_{\text{hot}}\). Figure 3(b) shows the \(T_{\text{rec,min}}\) obtained from \(X\) and \(Y\)-polarization data separately. The measured LNA noise temperature, \(T_{\text{LNA}}\), versus frequency is

![Figure 3](image-url)
also shown in Figure 3(b). The minimum difference between the measured LNA noise temperature and $T_{\text{rec,min}}$ is $\sim 2.5$ K near 1350 MHz. We attribute this excess noise temperature to any residual correlated noise and to losses ahead of the LNA, which include (a) loss in the dipoles and balun, (b) loss in the thermal transition, and (c) connection losses. Thus, the measured excess noise temperature provides an upper limit to the losses ahead of the LNA (i.e., the loss in temperature should $\leq 2.5$ K). In this paper, we assume that the losses ahead of the LNA are independent of the beam-former weights.

5. Observations

In 2017 March, the phased-array receiver was installed on the GBT. Extensive observations were made on a set of seven calibrator sources to measure the system performance. A list of observed calibrator sources, their J2000 coordinates, and the flux density at 1350 MHz are given in Table 1. A log summarizing the observations is given in Table 2. The observations can broadly be classified into two categories: (a) to measure the performance over the FoV and (b) to measure the boresight performance. The performance over the FoV was measured by observing on a grid of positions (“grid” observations) centered on the strong radio source Virgo A. The grid observation was made at 1336 MHz (bandwidth $\sim 300$ kHz). The grid positions were separated by $3^\circ$ in both the elevation and cross-elevation directions. On- and off-source measurements were made toward all calibrators in Table 1 to derive the boresight performance. The observed off-source positions have $+1^\circ$ offset in R.A. and $0^\circ$ offset in decl. from the J2000 source positions. The measurements were made over a set of frequencies ranging from 1200 to 1500 MHz, each with a bandwidth of 300 kHz.

6. Results

The grid observations are used to check the responses of individual dipoles. Figures 4 and 5 show the distribution of the S/N (as defined in Equation (2)) but for a single dipole obtained on Virgo A from each of the 19 $\times$ 2 dipoles (i.e., without forming beams). The peak S/N for the central dipole was about 2.6. As noted earlier, dipole number 13 in the $X$ polarization was not functional. Dipole 14 in the $Y$ polarization had a lower peak S/N compared to the central dipole by a factor of 2. This lower S/N is attributed to a faulty digital link. As discussed below, the two faulty dipoles have affected the results obtained from the $Y$-polarization data set.

6.1. $T_{\text{sys}}/\eta$ over the FoV

A map of the $T_{\text{sys}}/\eta$ is obtained from the grid observation data set by maximizing the S/N at each offset position. Figures 6(a) and (b) show the distribution of $T_{\text{sys}}/\eta$ as a function of elevation and cross-elevation offsets. The distribution is fairly symmetric about the center for the $X$ polarization. The asymmetry seen in the $Y$ polarization toward the southwest side is due to faulty dipoles 13 and 14. The radial distributions (i.e., offset from the boresight) of the normalized $T_{\text{sys}}/\eta$ for the $X$ and $Y$ polarizations are shown in Figures 7(a) and (b). Only data points for elevations $\geq 3^\circ$ from those shown in Figure 7(b) are used for making the radial distribution of the $Y$ polarization. The half power beamwidth at 1336 MHz is $\sim 10^\circ$. The beam separation required for Nyquist sampling (i.e., $\lambda/(2D)$, where $\lambda$ is the wavelength of observation and $D = 100$ m is the diameter of the GBT aperture plane; Padman 1995) is $\sim 4^\circ$. The degradation in $T_{\text{sys}}/\eta$ at this offset is $\sim 1\%$.

The grid observations were used to examine the seven formed beam patterns. Figure 8(a) shows the boresight maximum S/N beam measured using Virgo A, and in Figure 8(b), a beam with $5^\circ$ offset from the boresight is shown. The maximum S/N beams are smooth and approximately Gaussian for levels between 0 and $-10$ dB. All of the seven formed beams show similar properties.

6.2. Boresight $T_{\text{sys}}/\eta$

Plots of the measured boresight $T_{\text{sys}}/\eta$ versus frequency for the two polarizations are shown in Figures 9(a) and (b). The data presented in these plots are from observations toward strong radio sources with flux density $< 50$ Jy. The weights for beam forming were derived by maximizing the S/N on the observed source itself. The best median $T_{\text{sys}}/\eta$ for $X$ polarization is 25.4 K at 1336 MHz, and the peak-to-peak spread in the values is $\pm 2.5$ K. The scatter in $X$-polarization values is due to a combination of (a) uncertainty in the flux densities of the
sources, (b) variation in off-source sky contribution, and (c) telescope pointing offset. The $3\sigma$ thermal noise uncertainty in all of these measurements is $\sim 0.3$ K. The median $T_{\text{sys}}/\eta$ increases by $\sim 5$ K near the edge of the 150 MHz bandwidth of interest, centered at 1350 MHz.

The median $T_{\text{sys}}/\eta$ of the $Y$ polarization near 1336 MHz is $32.3 \pm 5$ K (peak-to-peak). To investigate the origin of the higher $T_{\text{sys}}/\eta$ and the larger scatter of the $Y$-polarization measurement, we examine the observation toward 3C147 near 1336 MHz. The $T_{\text{sys}}/\eta$ values derived from this data set are 25 and 36 K for the $X$ and $Y$ polarizations, respectively. The normalized weight distributions obtained from this data set are shown in Figures 10(a) and 10(b). As seen in the figure, the weight distributions are centered near dipole 5, which is due to an uncorrected telescope pointing offset. Since dipoles 13 and 14 in the $Y$ polarization are faulty, the PAF is unable to form an optimum beam, and hence the $T_{\text{sys}}/\eta$ for the $Y$ polarization is higher. We examined the data sets from all calibrators in the frequency range 1300–1400 MHz and found that a subset of the observations have telescope pointing offsets close to zero, as inferred from the weight distribution (see Figure 11(a)). The derived $T_{\text{sys}}/\eta$ values for this subset are similar for both polarizations and are between 25 and 28 K. The weight distribution for the subset with $T_{\text{sys}}/\eta > 30$ K for the $Y$ polarization is shown in Figure 11(b). As seen in the figure, the weight distribution is centered at dipole 5 for all of the data in this subset. We conclude that the larger scatter and higher $T_{\text{sys}}/\eta$ for the $Y$ polarization compared to the $X$ polarization is due to the telescope pointing offset and the presence of the two faulty dipoles. The large telescope pointing offset is because the GBT did not have an accurate pointing model for the PAF receiver system while we were doing the measurements.

The radio source Virgo A is the strongest calibrator source observed during the commissioning. The flux density of this source is 218.8 Jy at 1350 MHz. The best $T_{\text{sys}}/\eta$ values measured on this source are 28 and 30 K for the $X$ and $Y$ polarizations, respectively. The $1\sigma$ noise is 0.3 K. These values are about 3–5 K higher than the median value obtained from sources with flux density <50 Jy. A possible cause of this higher $T_{\text{sys}}/\eta$ is the noise contribution due to the source itself (Anantharamaiah et al. 1991), which may be affecting the beam-former weight solutions.

We compare the performance of the PAF with the existing cryogenic optimized single-feed 1.4 GHz receiver on the GBT, which has a $T_{\text{sys}}/\eta \sim 25.7$ K. Our measurements show that the performance of the PAF system is comparable to this single-feed receiver. Achieving comparable performance is a major milestone in the development of the PAF. Table 4 lists

Figure 4. The S/N distributions at 1336 MHz in elevation and cross-elevation directions for each X-polarization dipole obtained from grid observations.
Figure 5. Same as Figure 4 but for $Y$ polarization. Dipole 13 has a faulty LNA, and dipole 14 has a peak S/N a factor of 2 lower than that of the central dipole due to a faulty digital link.

Figure 6. (a) Distribution of the $T_{sys}/\eta$ in the elevation and cross-elevation directions for the $X$ polarization obtained from Virgo A grid observations. (b) Same as (a) but for the $Y$ polarization. The asymmetry seen in the southwest is due to faulty dipoles 13 and 14 (see text).
Figure 7. (a) The $T_{\text{sys}}/\eta$ vs. radial offset from the boresight for the X polarization are marked by circles. The half power beamwidth of 10$'$ at 1336 MHz is marked by the vertical line. The PAF model prediction is shown by the solid green line. The system temperature in the model is increased by 2.5 K to account for the loss ahead of the LNA (see Figure 3(b)). (b) Same as (a) but for the Y polarization. Data points in Figure 6(b) with elevation offset $> -3'$ are used for making the Y-polarization plot.

Figure 8. (a) Boresight beam formed using maximum S/N weights. The $-3$, $-6$, and $-10$ dB contours are marked. (b) Offset beam at about 5$'$ south of the boresight direction. The $-3$, $-6$, and $-10$ dB contours are marked in black. The contour in white is same as the $-3$ dB contour of the boresight beam shown in (a). The dark blue regions on the left and right sides of the plots are due to the loss of data resulting from the applied cubic interpolation to make the figures.

Figure 9. The $T_{\text{sys}}/\eta$ for the boresight beam obtained from observations with the PAF on the GBT for the (a) X polarization and (b) Y polarization. The sources observed are indicated in the legend.
the $T_{\text{sys}}/\eta$ values of multibeam receivers in other telescopes for comparison.

### 6.3. Survey Speed

The intrinsic survey capability per unit bandwidth of an astronomical receiver is found by evaluating the squared sensitivity integral given in (Hay & Bird 2015, Equation (83))

$$\text{SSFoM} = \int S^2(\Omega) d\Omega,$$

where the sensitivity map $S(\Omega)$ is the receiver sensitivity as a function of sky angle $\Omega$. By dividing the survey-speed figure of merit (SSFoM) by the peak sensitivity, the survey-speed weighted field of view (SSFoV) of the instrument can be found as

$$\text{SSFoV} = \frac{1}{S_{\text{max}}^2} \int S^2(\Omega) d\Omega. \quad (8)$$

The PAF sensitivity map is measured by steering the telescope to place a bright calibrator source at each position on a grid of closely spaced points in the sky, measuring the realized sensitivity of the receiver with the source at that location, and thereby sampling the sensitivity map at many discrete points. The integrals in SSFoM and SSFoV are approximated as sums over the sample points. These figures of merit are quite general and can be used to compare single-pixel receivers, cluster feeds, PAFs, and aperture arrays on an equal footing.

To remove the dependence of the FoV on dish size and obtain a dimensionless number that allows instruments with different aperture sizes to be compared more easily, the SSFoV is commonly expressed as a number of beams. The angular FoV is divided by the area of the sky per beam when fully sampled by independent, formed beams to obtain

$$N_b = \frac{\text{SSFoV}}{\Omega_b} = \frac{\text{SSFoM} \ S_{\text{max}}^2}{\Omega_b} \quad (9)$$

Figure 10. Normalized weight distributions obtained from 3C147 observations near 1336 MHz for the (a) $X$ and (b) $Y$ polarizations. The distributions are superposed on the dipole-array geometry; the white circles show the locations of the dipoles. These plots illustrate the reason for the higher $T_{\text{sys}}/\eta$ and larger spread in the measured values for the $Y$ polarization. The $T_{\text{sys}}/\eta$ for the $Y$ polarization obtained from the 3C147 data set is 36 K, and that for the $X$ polarization is 25 K (see Figure 9). The distribution of weights is centered on dipole 5 due to the telescope pointing offset. Dipoles 13 and 14 (both are faulty) in the $Y$ polarization are needed to get the optimum $T_{\text{sys}}/\eta$. Thus, the higher $T_{\text{sys}}/\eta$ for the $Y$ polarization compared to the $X$ polarization in this measurement is due to the faulty dipoles.

Figure 11. (a) Normalized weights (blue, $X$ polarization; red, $Y$ polarization) obtained from a subset of measurements shown in Figure 9 where the weight distribution is centered at dipole 1. For this subset of measurements, the $T_{\text{sys}}/\eta$ values for both the $X$ and $Y$ polarizations are comparable. (b) Normalized weights for the subset of data with $T_{\text{sys}}/\eta > 30$ K for the $Y$ polarization in the frequency interval 1300–1400 MHz (see Figure 9(b)). The weight distribution for all of these measurements is centered near dipole 5.
The amount of beam overlap required for full sampling, which determines the value of the area $\Omega_b$ per fully sampled beam, is treated in Hay & Bird (2015). While Equation (7) is the primary definition of SSFoM, the number of beams in Equation (9) is quite convenient and widely used in comparing various types of instruments.

6.3.1. Practical Survey Speed with Real-time Beam Forming

The FoV expressed as a number of independent beams $N_b$ as in Equation (9) is generally not equal to the number of beams that are formed in signal processing. The above considerations apply to the intrinsic survey speed of the analog receiver front end. When the digital back end is included in the analysis, the survey speed of an instrument may be limited further in the signal processing when the receiver back end operates in real-time beam-forming mode. To reduce hardware costs, fewer beams than are required to fully sample the FoV may be formed. In this case, the practical survey speed of the instrument is lower than the intrinsic SSFoM in Equation (7).

In other cases, such as array receivers with signal-processing back ends that allow post-correlation beam forming, in certain observing modes, more beams may be formed than are required to fully sample the FoV. In this case, the number of formed beams is greater than $N_b$ in Equation (9). If the formed beams overlap, there is a correlation between the signal and noise from beam to beam, and the information provided by the beams may not be independent.

In view of the complex relationship between the FoV expressed as a number of beams and the number of beams that are formed in digital signal processing, there are differences in the assumptions made in the reported number of beams from one instrument to another. Despite the ambiguity, FoV as number of beams is so convenient a metric, and so generally used in the community, that we accept the disadvantages of this way of parameterizing FoV and provide comparison values, while stating as carefully as possible the assumptions made in the calculation.

To analyze the practical survey speed with a given number of formed beams, we consider three observing cases, which are typical applications of a PAF system on a telescope.

1. Survey observations that do not require averaging of data simultaneously obtained from the different beams. Examples for this observing case are searching for pulsars and HI observations of objects with angular size smaller than the FWHM beam size.
2. Imaging a region of the sky with the PAF system. HI and continuum imaging of extended sources are examples for the second case. Performing such observations with the PAF in the on-the-fly (OTF) mode has some advantages, for example, to reduce the telescope pointing overhead. Averaging data obtained from different beams in an OTF observation can optimize the survey speed. However, the sky position needs to be aligned before averaging the images from the different beams, which makes the noise in each pixel of the images uncorrelated. This is demonstrated in Figure 12 using a 1D scan toward Virgo A obtained with FLAG.
3. Some survey observations that require averaging of data simultaneously obtained from the different beams. An example of such case is imaging of HI emission from an extended source and then smoothing the image to obtain a low angular resolution (>FWHM beamwidth) spectrum. The noise correlation between beams will result in a spatial correlation of noise in the image, and hence the S/N will not improve by the square root of the number of pixels averaged. As discussed below, this class of observations will benefit by keeping the PAF beams at twice the Nyquist separation or more.

Survey-speed metrics for each of these observation cases will be given in the next section.

6.3.2. Effective Number of Beams

In a PAF system, if a large number of highly overlapping beams were formed in signal processing, the beams would be highly correlated, and little new information could be gleaned from adjacent beams. This manifests as strong signal and noise correlation between beams. Further, the sensitivity of each formed beam will differ because of the correlation of receiver noise between elements in the PAF. Closely following the intrinsic number of beams defined by Equation (9), we develop

![Figure 12](image-url)
in this section a figure of merit, in a practical sense, that measures the FoV of the PAF with a given number of formed beams: the effective number of beams.

Survey speed is determined by the time required to integrate an image such that the sensitivity in each pixel is higher than some desired sensitivity. We consider surveying a region of the sky of angular size $\Omega_s$, sampled at $\Omega_{n,}\,\text{the independently sampled beam area in Equation (9). The number of pointings that need to be made for such an observation is }\Omega_s/\Omega_{n,}\,\text{Imaging speed can be improved with a multibeam system by moving the telescope so that the region of interest is observed in each beam and then averaging the images obtained from different beams. As discussed above, for observing cases 1 and 2, the noise correlation between the beams does not affect the net sensitivity of the averaged image. However, the sensitivities of the beams are different and need to be taken into account in the survey-speed calculation. The effective number of beams for such applications is defined as

$$N_{\text{eff}} = \frac{1}{\left(\frac{A_{\theta}}{T_{\text{sys},n}}\right)_{\max}} \sum_{n=1}^{N_{\text{beam}}} \left(\frac{A_{\theta}}{T_{\text{sys},n}}\right)^2,$$

where $A_{\theta}$ is the physical area of the telescope $\frac{A_{\theta}}{T_{\text{sys},n}}$ is the ratio of the effective area of the telescope to the system temperature for beam $n$, and $(\frac{A_{\theta}}{T_{\text{sys},n}})_{\max}$ is the maximum value of $\frac{A_{\theta}}{T_{\text{sys},n}}$. The SSFom is

$$\text{SSFom} \approx N_{\text{eff}} \left(\frac{A_{\theta}}{T_{\text{sys},n}}\right)^2 (\theta_b)^2,$$

where $\theta_b$ is the square root of the independent beam area, which, from the treatment of Hay & Bird (2015), is $\lambda/(2D)$.

For observing case 3, we must first determine the beam-to-beam noise correlation, as represented in the fluctuations in the estimated power at the output of a formed PAF beam. We estimate the correlation coefficient as

$$\rho_{n,m} = \frac{\langle (P_{B_n} - \bar{P}_{B_n})(P_{B_m} - \bar{P}_{B_m}) \rangle}{\sqrt{(P_{B_n} - \bar{P}_{B_n})^2}(P_{B_m} - \bar{P}_{B_m})^2}}.$$

Here

$$P_{B_n} = P_{B_n}[f] = w_n^H R[f] w_n,$$

$$P_{B_m} = P_{B_m}[f] = w_m^H R[f] w_m,$$

are the time series of the power from beams $n$ and $m$, respectively, estimated from the time series of the correlation matrices $R[f]$ after multiplying it with the beam-former weights $w_n$ and $w_m$ for the two beams. The expectations of $P_{B_n}$ and $P_{B_m}$ are obtained as

$$\bar{P}_{B_n} = \frac{1}{M} \sum_{j=0}^{M-1} P_{B_n}[f],$$

$$\bar{P}_{B_m} = \frac{1}{M} \sum_{j=0}^{M-1} P_{B_m}[f].$$

The angle brackets in Equation (12) indicate time average over $M$ samples. A plot of the calculated noise correlation between the boresight and off-boresight beams of FLAG as a function of beam separation is shown in Figure 13. The noise correlation is obtained from the off-source data. The correlation drops by about 60% at the Nyquist beam separation ($\sim 4'$), and it drops to $\sim 15\%$ at twice the Nyquist beam separation.

The beam-to-beam noise correlation will result in a spatial correlation of noise in the image made with a PAF. For a given beam spacing, the spatial correlation coefficient of the noise in the image will be same as that given by Equation (12), even though the correlation coefficient is obtained by time average (the underlying stochastic process is ergodic in nature). A lower angular resolution image needs to be made for the third class of applications, but the $S/N$ of the image will not improve by the square root of the number of pixels averaged during smoothing. The improvement in $S/N$ depends on the angular resolution to which the image is smoothed. For the specific case when the image is smoothed to an angular resolution approximately equal to SSFom (see Equation (8)), the final noise variance is

$$\sigma^2 = \frac{1}{N_{\text{beam}} \sum_{n,m=1}^{N_{\text{beam}}} \sigma_m \sigma_n \rho_{n,m}}.$$

where $\sigma_m$ and $\sigma_n$ are the rms noise fluctuations in beams $m$ and $n$, respectively, and $\rho_{n,m}$ is the correlation coefficient of the noise in beams $m$ and $n$ (see Equation (12)) for the beam spacing used for the survey. The survey speed is inversely proportional to this noise variance. Approximating the sensitivity of the beams as equal and factoring the resulting survey speed as in Equation (9) leads to the effective number of beams,

$$N_{\text{eff}} = N_{\text{beam}} \left(\frac{1}{N_{\text{beam}} \sum_{n,m=1}^{N_{\text{beam}}} \rho_{n,m}}\right)^{-1}.$$

If the correlation $\rho_{n,m}$ vanishes for $n \neq m$ (i.e., the noise is uncorrelated between beams), the number of effective beams is equal to the number of formed beams, as expected. Thus, the third class of observing application will benefit by keeping the beams at twice the Nyquist separation or more, since $\rho_{n,m}$ is smaller for larger beam spacing (see Figure 13).
6.3.3. Survey-speed Comparisons

The SSFoMs of FLAG, obtained using Equation (11), with seven beams spaced at Nyquist separation (~4') and twice Nyquist separation (~8'), are listed in Table 3. A major use of the new PAF system on the GBT will be to observe extended HI emission from nearby galaxies. These observations will be typically done in the OTF mode and fall into the first and second category of observations mentioned above. The $T_{\text{sys}}/\eta$ of FLAG is optimum near 1350 MHz, and it degrades by a factor of ~1.1 near 1.42 GHz. Thus, the SSFoMs for HI observations are 2184 and 1640 deg$^2$ m$^{-2}$ K$^{-2}$ for the two beam separations (see Table 3), which are a factor of 5.3 and 4 higher than those of the GBT single-feed receiver. A comparison of the SSFoM of FLAG, the existing GBT single-feed receiver, and our estimated values for multibeam receivers at other telescopes is given in Table 4. We computed the intrinsic SSFoM (see Equation (7)) of FLAG using the data shown in Figure 6(a). The SSFoV = 0.11 deg$^2$; $N_{\text{eff}} \sim \frac{\text{SSFoV}}{\eta^2} = 25$.

The derived SSFoM at 1.31 GHz is obtained as SSFoV × $S_{\text{max}}^2$, where SSFoV = 1.4 deg$^2$ and $S_{\text{max}} = 3217/60 = 53.6$ m$^2$ K$^{-1}$. Here $N_{\text{eff}} \sim \frac{\text{SSFoV}}{\eta^2} = 144$. The real-time processing bandwidth is assumed to be the same as the front-end bandwidth of ~700 MHz.

Table 3
Survey Speed of FLAG

| Receiver System | $\theta_b$ (arcmin) | $T_{\text{sys}}/\eta$ (K) | $N_{\text{eff}}$ (deg$^2$ m$^{-2}$ K$^{-2}$) | SSFoM (deg$^2$ m$^{-2}$ K$^{-2}$) |
|-----------------|---------------------|--------------------------|-----------------------------------------------|----------------------------------|
| FLAG (Nyquist)  | 4                   | 25.4, 25.7               | 6.9                                           | 2924                            |
| FLAG (2 × Nyquist) | 4                  | 25.4, 30.5               | 5.2                                           | 2195                            |
| FLAG (H, Nyquist) | 3.8                | 28.0, 28.3               | 6.9                                           | 2184                            |
| FLAG (H, 2 × Nyquist) | 3.8           | 28.0, 33.5               | 5.2                                           | 1640                            |

Notes.

1. The physical area of the GBT aperture is taken as 7854 m$^2$ for the calculation of SSFoM using Equation (11).
2. $\theta_b = \frac{\lambda}{2D}$ is taken as the Nyquist beam separation.
3. $T_{\text{sys}}/\eta$ values are provided for the central beam and all outer beams for cases where two values are listed.
4. Survey metric for spectroscopic observations.
5. Intrinsic SSFoM.
6. Real-time signal-processing bandwidth.
7. FLAG with seven formed beams placed at Nyquist (~4') beam separation.
8. Here 1.1 Jy K$^{-1}$ is used for the calculation of SSFoM.
9. The region illuminated by ALFA is taken as ~213 m in diameter. Here 11 K Jy$^{-1}$ for the central beam and 8.5 K Jy$^{-1}$ for the outer beams are used for the calculation of SSFoM.
10. Aperture efficiency of 48% used for the calculation of SSFoM.
11. The SSFoM at 1.31 GHz is obtained as SSFoV × $S_{\text{max}}^2$, where SSFoV = 1.4 deg$^2$ and $S_{\text{max}} = 3217/60 = 53.6$ m$^2$ K$^{-1}$. Here $N_{\text{eff}} \sim \frac{\text{SSFoV}}{\eta^2} = 144$. The real-time processing bandwidth is assumed to be the same as the front-end bandwidth of ~700 MHz.

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Table 4
Survey-speed Comparison

| Receiver System | $A$ (m$^2$) | Freq. (GHz) | $\theta_b$ (arcmin) | $T_{\text{sys}}/\eta$ (K) | $N_{\text{eff}}$ (deg$^2$ m$^{-2}$ K$^{-2}$) | SSFoM (deg$^2$ m$^{-2}$ K$^{-2}$) | BW (MHz) | SSFoM × BW (deg$^2$ m$^{-2}$ K$^{-2}$ MHz) |
|-----------------|-------------|-------------|---------------------|--------------------------|-----------------------------------------------|----------------------------------|----------|------------------------------------------|
| FLAG (Nyquist)  | 7854        | 1.35        | 4                   | 25.4, 25.7               | 6.9                                           | 2924                            | 150      | 3.6 × 10$^5$                             |
| FLAG            | 7854        | 1.35        | 4                   | 25.4                     | ~25                                           | 10690                           | 150      | 1.6 × 10$^6$                             |
| GBT L-band      | 7854        | 1.35        | 4                   | 25.7                     | 1.0                                           | 415                             | 400      | 1.7 × 10$^5$                             |
| Parkes multibeam| 3217        | 1.37        | 5.9                 | 41.9                     | 13                                            | 1010                            | 300      | 3.0 × 10$^5$                             |
| Arecibo ALFA    | 35633       | 1.37        | 1.8                 | 35.2, 45.5               | 4.6                                           | 4228                            | 300      | 1.3 × 10$^6$                             |
| Effelsberg 7beam| 7854        | 1.41        | 3.7                 | 45.8                     | 7                                             | 782                             | 300      | 2.3 × 10$^5$                             |
| Parkes with PAF | 3217        | 1.31        | 5.9                 | 60.0                     | ~144                                          | 4025                            | 700      | 2.8 × 10$^6$                             |
There is a constant $T_{sys}/\eta$ over the 400 MHz bandwidth of the GBT, the survey speed of the single-feed system is $1.7 \times 10^5$ deg$^2$ m$^4$ K$^{-2}$ MHz. The SSfoM bandwidth product of FLAG is about 2.1 times larger than that of the GBT single-feed system for pulsars or other broadband applications.

6.4. Comparison with the PAF Model, System Parameters, and FoV

For high-sensitivity receivers, further reductions in system noise become increasingly challenging as system performance improves. This is especially true for phased-array receivers, for which mutual coupling effects require a holistic approach to the design optimization of the array elements and front-end electronics. Extensive modeling efforts were critical to the PAF design optimization and understanding the system performance (Warnick et al. 2011, 2009; Roshi & Fisher 2016). The steps involved in the modeling are the following (Roshi & Fisher 2016). The dipole array was first modeled using a full-wave finite-element solver in the CST microwave studio$^{12}$ to obtain the element beam patterns and impedance matrix. The embedded beam patterns are then obtained from the element patterns. The secondary radiation patterns for the GBT optical geometry were obtained using a physical optics approximation. The embedded patterns, along with the GBT geometry, were used to compute the noise covariance matrices due to ground spillover. The secondary patterns were used to compute the signal response due to the source and noise covariances due to the sky background radiation. The impedance matrix of the array combined with a noise model for the cryogenic LNAs (Pospieszalski 2010) provided the receiver noise covariance. The amplifier noise parameters used for the modeling are minimum receiver temperature $T_{min} = 4.2$ K, optimum impedance $Z_{opt} = 28.9 – j3.5$ Ω, and Lange parameter $N = 0.007$. The noise parameters are considered to be approximately constant over the frequency range 1200–1550 MHz. This LNA noise model is obtained from the amplifier modeling and reproduces the measured LNA noise temperature; however, we note that these parameters cannot be uniquely constrained from noise temperature measurements alone. Accurate noise modeling of the LNA and the measurement of noise parameters are underway; the PAF model results with these new values will be presented elsewhere. The signal response and noise covariances were used to compute the expected S/N. The maximum S/N beam-former algorithm was then used to find beam-former coefficients for each desired beam steering direction. The model was run repeatedly for a set of frequencies ranging from 1200 to 1550 MHz. With the accurate representation of the PAF by input parameters, the model can predict the receiver temperature, antenna temperature, spillover temperature, and full polarization electromagnetic fields in the antenna aperture. Below, we compare the measured system performance with PAF model predictions.

The PAF model prediction for the boresight direction is shown in Figure 14, along with the measured median $T_{sys}/\eta$ as a function of frequency.$^{13}$ The median values were computed from the measured data points shown in Figure 9 over a frequency interval of ~1.5 MHz. The median values for the $Y$ polarization were computed from the subset of measured values that is not severely affected by the pointing offset and faulty dipoles (see Section 6.2). The model results are plotted with an additional noise contribution to $T_{sys}$ to account for the losses ahead of the LNA. For the LNA noise parameters used here, model results with an additional noise of 2.5 K (see Figure 3(b)) are in qualitative agreement with the measurements at frequencies below 1.45 GHz. The discrepancy between model and measurement at frequencies above 1.45 GHz may be due to a combination of the following factors: inaccuracy in the amplifier noise parameters, error in the electromagnetic simulation, unmodeled ground scattering due to the feed support structure, or manufacturing errors in the dipoles. Ground scattering from the feed support may have additional contributions at higher frequencies where the increase in system temperature is dominated by the presence of array grating lobes. These possibilities are the subject of an ongoing investigation.

The model prediction for $T_{sys}/\eta$ versus offset from the boresight is shown in Figure 7. The model results, obtained with the 2.5 K excess noise due to the losses upstream of the LNA (see Figure 3(b)), tracks closely with the measured variation of $T_{sys}/\eta$ as a function of the radial offset very well. The increase in $T_{sys}/\eta$

Figure 14. The PAF model prediction (solid line) along with the median measured $T_{sys}/\eta$ with their peak-to-peak variations for the X (left) and Y (right) polarizations. The data points shown in Figure 9 are used to compute the median $T_{sys}/\eta$. The median is computed from the set of measurements in a frequency interval of ~1.5 MHz. The model assumes lossless PAF; hence, the system temperature in the model is increased by 2.5 K to take into account the losses ahead of the LNA (see Figure 3(b)).

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$^{12}$ Commercial 3D electromagnetic simulation software; https://www.cst.com/.

$^{13}$ The model curve is not a least-squares fit to the data. Currently, the major contribution to the uncertainty in the modeled value is the inaccuracies in one of the input parameters to the model, the amplifier noise parameters and their frequency dependence. We are in the process of accurately modeling the amplifier noise parameters and measuring them. The PAF model results based on these new measurements will be presented elsewhere.
for offsets larger than $5'$ is due to the finite size of the dipole array. This is evident from Figure 15, where we plot the normalized beam-former weight distribution over the dipole-array geometry for the boresight beam and a beam $\sim 5'$ offset from the boresight direction. These weight distributions are obtained from grid observation data toward Virgo A. As seen in the figure, significant amplitudes for the weights are clustered around seven dipole elements, roughly following the Airy pattern due to the compact source. At offsets $\gtrsim 5'$, the cluster of seven elements is located at the edge of the array centered on dipole 5 (see Figure 16(b)). Thus, at offsets more than $5'$ from the boresight, the dipole array does not have enough elements to sample the Airy pattern well. Thus, the FoV limitation of the array indicated by the upward slope of $T_{\text{sys}}/\eta$ in Figure 7 is caused only by the limited extent of the array, and thus could be extended by the addition of more elements.

On-telescope measurements do not provide $T_{\text{sys}}$ and $\eta$ separately, and so we infer these values and other system parameters from the PAF model. The inferred system parameters are summarized in Table 5. The system temperature after forming the beams is about 16 K, with contributions from receiver noise of 7.5 K, spillover of 3.5 K, and sky background plus atmosphere of 5.5 K. The median increase in formed beam S/N on a compact source is about a factor of eight compared to a single dipole near 1336 MHz. This increase in S/N implies a $T_{\text{sys}}/\eta$ of $\sim 216$ K for the single-dipole case, based on scaling the measured $T_{\text{sys}}/\eta$ for the formed beam (see Table 5). This high $T_{\text{sys}}/\eta$ is due to the large spillover contribution when observing with a single dipole. The inferred spillover temperature from the model is $\sim 100$ K for the single-dipole case. The spillover efficiency is increased to about 98% in the process of beam forming, thus reducing the modeled $T_{\text{sys}}/\eta$ to about 27 K for the formed beam. The high ground suppression achieved for the formed beam results in a somewhat lower aperture efficiency (about 60%) compared to the GBT single-feed system, an inevitable trade-off for the 19-element prime-focus PAF.

The uncertainties in the model predictions have several contributions, which include (a) amplifier noise parameters and their frequency dependence, (b) accuracy of the CST simulation results, and (c) the model not accounting for the scattering due to feed support structures. The estimated values of $T_{\text{sys}}/\eta$ at frequencies below $\sim 1300$ MHz sensitively depend on the

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Figure 15. (a) Normalized amplitude distribution of the weights obtained for the boresight direction superposed on the dipole-array geometry. The white circles indicate the location of the dipoles in the array, along with the dipole number. (b) Same as (a) but for $5'$ offset from the boresight direction.

Figure 16. (a) Observation of the pulsar B0329+54 with a single dipole (top) and with a maximum S/N boresight beam. The increase in S/N is about a factor of 8. (b) Image of the Rosette Nebula made with the PAF near 1.336 GHz.
Table 5

| System Parameters       | Value      |
|-------------------------|------------|
| $T_{sys}/\eta$ near 1350 MHz | 25.4 ± 2.5 K |
| LNA noise temperature   | 5 K        |
| Inferred loss ahead of LNA$^a$ | 2.5 K     |
| Cosmic microwave background temperature | 2.7 K |
| Galactic background temperature$^c$ | 0.8 K |
| Beam-formed receiver temperature | 7.5 K |
| Spillover temperature   | 3.5 K      |
| Total system temperature | 16.5 K    |
| Estimated spillover efficiency | 98.8% |
| Estimated aperture efficiency | 60%     |
| Model $T_{sys}/\eta$ near 1350 MHz | 27.5 K$^d$ |

Notes.

$^a$ Model results with an additional noise of 2.5 K to account for losses ahead of the LNA (see Figure 3(b)) are in qualitative agreement with the measurements for the amplifier noise parameters used here.

$^b$ Median of the off-source sky temperature estimated from the 1.4 GHz survey data of Reich & Reich (1986).

$^c$ Delabaye et al. (2002).

$^d$ The uncertainty in the model value is up to 20% (see text).  

amplifier noise parameters due to a higher level of mutual coupling in the array. At frequencies above ~1450 MHz, the grating lobes become significant; hence, the scattering due to the feed support structure could limit the accuracy of the computation. In the frequency range near 1350 MHz, we estimate that the model predictions are accurate to within 20%. This estimation of accuracy is obtained by considering different amplifier noise parameters that are consistent with the LNA noise temperature measurements and examining the variation of the computed $T_{sys}/\eta$ near 1350 MHz.

7. Observations of Astronomical Sources

We have observed the pulsar B0329+54 and the Rosette Nebula with the PAF system on the GBT. The data taken toward these sources were obtained using the experimental setup described in Section 2 and processed as described in Section 3.

7.1. PSR B0329+54

The pulsar B0329+54 was observed with the PAF receiver on 2017 March 16. The observed frequency was 1336.0275 MHz with a bandwidth of 300 kHz. The pulse width of B0329+54 at 10% of the peak average pulsar amplitude is 31.4 ms (Manchester et al. 2005). Therefore, the cross-correlations were integrated for about 10 ms. An on-off observation on the calibrator 3C123 was performed before taking the pulsar data in the same observing setup. The data set on the calibrator was used to obtain the beam-former weights. A time series from the pulsar data was then obtained by estimating the power using the beam-former weights for every 10 ms. This power was converted into flux density units using the calibration factor derived from the 3C123 observations. The calibrated, beam-formed time series from the X-polarization data is shown in Figure 16(a) (bottom line). For comparison, the time series obtained from the central dipole is also shown in Figure 16(a) (top line). The improvement in S/N in the formed beam output is about a factor of 8, similar to what is measured from observations of calibrator sources. This indicates that the transfer of beam-former weights from calibrator observations gives the expected improvement in S/N on the target source.

7.2. Rosette Nebula

The continuum emission from the Rosette Nebula was observed at a frequency of 1336.0275 MHz with a bandwidth of ~300 kHz. The telescope was moved in a raster scan mode along R.A. and decl. while recording the voltages. The data from each row of the raster scan were recorded to a file and processed off-line as described in Section 3. The integration time for the cross-correlations was set to ~170 ms. The telescope speed for the raster scan was such that it moved by about 1' (1/10 of the beamwidth) in the sky during this integration time. The time stamps on the data and telescope position were used to obtain the sky position corresponding to each integration time.

The synchronization between the data acquisition system and the telescope for the raster scan mode of observing was not robust. This synchronization issue had two effects: (a) the sky position derived had to be corrected manually to get the true equatorial coordinates of the observed positions, and (b) we lost data for a few R.A. scans, which corresponded to a gap of about 28' in decl. in the image. As described below, this gap is filled with data obtained from different beams of the PAF.

We observed the calibrator 3C123 along with Rosette observations in order to derive the beam-former weights. However, this data set could be used only to obtain the weights for the boresight beam and another off-boresight beam (5' in elevation toward north) due to a telescope pointing offset. The images made from these two beams had the expected sensitivity. But, due to the loss of data, the image had gaps and could not be filled with the data from two beams alone. We therefore derived the beam-former weights from grid observations toward Virgo A taken 2 days before the Rosette observations. These beam-former weights did not provide the optimum S/N due to the temporal change in instrumental gain and phase between the Virgo A and Rosette observations. The degradation in S/N was about 20%. The Virgo A data set was used to form images from different beams and calibrate the estimated power in Jy. The PAF system did not have a calibrated noise source ahead of the LNA; hence, converting the flux density scale to brightness temperature scale had some uncertainty. Further, the data from beams outside the nominal FoV of the PAF (~20') were used to fill the gaps in the image (see above). The calibration factor to convert Jy to brightness temperature in K had to be increased by 33% for these beams. Thus, the overall accuracy of the brightness temperature scale of the image is estimated to be about 30%. Determining the Jy-to-K conversion and its stability for the PAF system is part of ongoing research work.

After calibration, a linear baseline, estimated using the data points away from the Rosette Nebula, was subtracted from each R.A. scan. The variation of the mean value of the baseline from scan to scan was ~10%, which may be due to system gain.
variation. The image obtained from the baseline-subtracted data and after combining the data from three beams (central beam, a beam 9′ north in elevation, and a beam 9′ south in elevation) is shown in Figure 16(b). The combined image is smoothed with a box function of ∼8′ × 8′ in size.

The features of the Rosette Nebula seen in Figure 16(b) compare well with those observed earlier by Celnik (1985) at 1410 MHz. The manual adjustment of the sky position needed due to the loss of synchronization mentioned above resulted in a residual artifact at about the 2 K level in the image. This artifact is entirely due to the synchronization between data acquisition and telescope control systems and is not due to the PAF.

8. Summary and Conclusion

We presented the measured performance of the FLAG front end, a new 1.4 GHz, 19-element, dual-polarization, cryogenic PAF radio astronomy receiver built for the GBT. A brief description of the instrumentation was given, which included a novel method of implementing an unformatted digital link. The performance of the system was measured by placing the PAF at the prime focus of the GBT and observing a set of astronomical calibrators. The performance metric, $T_{\text{sys}}/\eta$, had a median value of 25.4 ± 2.5 K near 1350 MHz. This value is comparable to the performance of the single-feed system of the GBT at 1.4 GHz. The median $T_{\text{sys}}/\eta$ was higher by about 5 K near the edge of the 150 MHz bandwidth of interest, centered at 1350 MHz. The increase in $T_{\text{sys}}/\eta$ at 1336 MHz at ∼4′ offset, required for Nyquist sampling, was ∼1%, and at ∼8′ offset, it was ∼20%. The distribution of $T_{\text{sys}}/\eta$ in the elevation and cross-elevation directions was radially symmetric. This symmetry enables the PAF to form seven high-sensitivity beams within the FoV, resulting in an increase in survey speed by a factor between 2.1 and 7, depending on the observing application. The FoV of the PAF system is limited by the size of the array, as there are not enough elements to form a high-sensitivity beam for offset angles ≥5′. The PAF model predictions qualitatively agree with the measured variation of $T_{\text{sys}}/\eta$ with frequency as well as offset from boresight. The results from the observations of a pulsar and an extended source with the PAF system on the GBT are also presented.

The results presented here were processed by a narrowband off-line processing system. Future observations will use a new real-time 150 MHz bandwidth digital signal-processing system developed by the FLAG collaboration. The PAF and the broadband beam former comprise the complete FLAG instrumentation, which will enable efficient searches for pulsars and FRBs and observations of diffuse extended neutral hydrogen emission in the circumgalactic medium of nearby galaxies.

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