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Current and Future Instrumentation on the 100m Robert C. Byrd Green Bank Telescope

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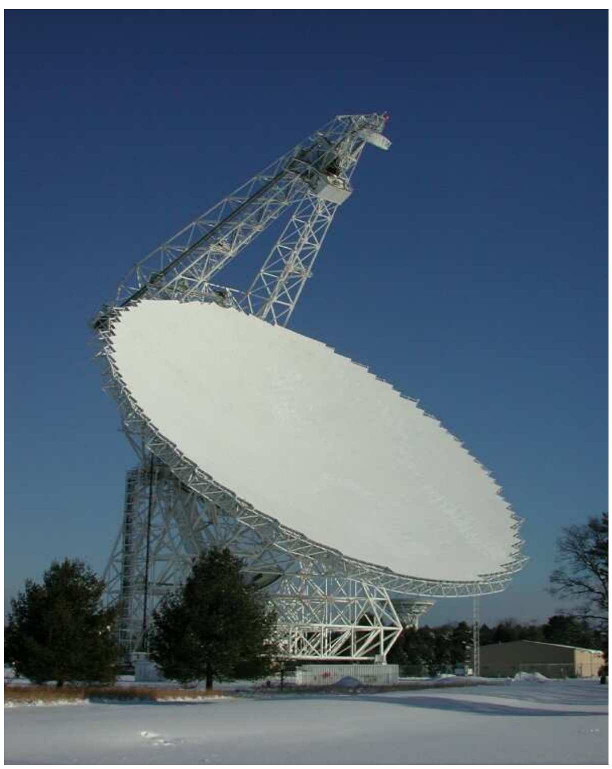
As the world's largest fully steerable single dish telescope, the Robert C. Byrd Green Bank Telescope (GBT) has exceptional sensitivity from 100MHz through 100GHz. To exploit this sensitivity and to ensure the telescope remains at the forefront of science and technology, the GBT has an ongoing development program to provide new instrumentation and infrastructure improvements for the telescope. Here I describe the current state of the GBT as well as the ongoing and future development projects and challenges for the telescope. These include focal plane arrays at 30 and 90GHz, a phased (beam-forming) array at 1GHz, affordable wide-bandwidth digital data transmission lines, state of the art FPGA-based signal processing, very low noise receivers, and image processing of TB data sets.



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Location	Green Bank, West Virginia, USA	
Coordinates	Longitude:	79: 50: 023.40600 West
	Latitude:	38: 25: 059.23600 North
	Track Elevation:	807.43 m
Optics	110 m x 100 m unblocked section of a 208 m parent paraboloid	
Available Foci (Prime and Gregorian)	f/D (prime)	0.29 (referred to 208 m parent parabola)
	f/D (prime)	0.6 (referred to 100 m effective parabola)
	f/D (Gregorian)	1.9 (referred to 100 m effective aperture)
Elevation Limits	Lower limit	5 degrees
	Upper limit	90 degrees
Slew Rates	Azimuth	35.2 degrees/min
	Elevation	17.6 degrees/min
Surface RMS	Active surface	240μm, under benign night-time conditions
Pointing accuracy	1.5$''$	
Frequency Coverage	0.2 - 50 GHz non-contiguous	
	82-98 GHz with 64-pixel bolometer array	

Table 1: Robert C. Byrd Green Bank Telescope General Characteristics

1. The Characteristics of the GBT

At 100x110m in diameter, the Robert C. Byrd Green Bank Telescope (GBT) is the largest fully steerable telescope in the world, and the largest movable structure on land. The dish itself is 2.3 acres in collecting area, and the telescope is able to track approximately 85% of the total sky area.

The off-axis design of the GBT results in a completely unblocked aperture. This greatly increases the dynamic range of the telescope, with the near side lobes on the GBT reduced by a factor of $>$10 compared with conventional antenna designs. The gain and sensitivity of the telescope are also improved for the GBT as a result of this design, with the 100m diameter GBT performing better than a 120m conventional antenna. Additionally, the unblocked aperture results in significantly reduced interference from outside sources, a result of the reduced side lobes and lack of scatter from structural components.

The GBT lies within two radio frequency interference protection zones – the National Radio Quiet Zone and the West Virginia Radio Astronomy Zone. The National Radio Quiet Zone, or NRQZ, was established by the United State's Federal Communications Commission in 1958 to minimize possible harmful interference to the National Radio Astronomy Observatory (NRAO) in Green Bank, WV and the radio receiving facilities for the United States Navy in Sugar Grove, WV. The NRQZ encloses a land area of approximately 13,000 square miles and provides protection against all fixed radio transmitters within the protected zone. The West Virginia Radio Astronomy Zone (WVRAZ) was established by the state of West Virginia in 1957 and provides protection in a 10mile radius center on the GBT against any electrical equipment which may provide interference the reception of the GBT. of radio waves emanating from any non-terrestrial source. The combination of these two protection zones provides an excellent safeguard for the telescope. Further

Science	Backend	Max. Bandwidth	Min. frequency res.	Min. time res.	Notes
Spectral Line	Spectrometer	4x800 MHz	0.2 kHz	2s	3 dB dynamic range
	Spectral Processor	4x40 MHz	0.08 kHz	1s	Full Stokes available High dynamic range
	Zpectrometer	14 GHz	18 MHz	1s	Usage in collaboration with A. Harris, UMd
Pulsar	GUPPI	800 MHz	200 kHz	20μs	Full Stokes and on-line folding modes available
Continuum	DCR	1280 MHz	N/A	0.2s	
	CCB	14 GHz	N/A	5ms	For 26-40GHz receiver only
	MUSTANG	16 GHz	N/A	0.1ms	64-pixel, 82-98 GHz array
VLBI	Mark 5	Upgrade to 4 Gps underway			

Table 2: A complete listing of all backend available for common usage with the GBT.

information on the NRQZ and WVRAZ can be found at `http://www.gb.nrao.edu/IPG/`.

The GBT currently has receivers which cover from 0.2 through 48 GHz (non-contiguously) with a 64-pixel transition-edge sensor type bolometer array which covers from 82-98 GHz. The system temperature for these receivers varies from 8K - 30K. At the lower frequency ranges the receivers are typically native linear polarization with a hybrid available to synthesize circular polarization. Starting at 12GHz and higher, the receiver are native circular polarization only, and have two feeds to allow for continuous observation of the source of interest.

A wide variety of signal processing options are also available for the GBT, ranging from high spectral resolution through high time resolution back ends, and including excellent VLBI and continuum back ends as well as significant flexibility for use supplied instruments to be put on the telescope. A complete list of all available backends is given in Table 2, and a complete listing of all GBT instrumentation is given in the GBT proposal guide (`http://science.nrao.edu/gbt`).

The aperture efficiency of the GBT is currently 35% at 90GHz, resulting from a $\sim$240μ surface r.m.s across the dish in benign, nighttime conditions. The telescope pointing is also excellent, with a 1.5$''$ offset pointing accuracy. Full details of the GBT's performance can be found at `https://safe.nrao.edu/wiki/bin/view/GB/PTCS/WebHome`.

While not located at an ideal location for 100 GHz observations, the GBT nonetheless has a significant amount of good high frequency weather. A minimum of 2800 hours per year of good weather at 90 GHz is expected ($\tau \leq 0.2$), and a minimum of 1400 hours per year of excellent 90 GHz weather is available ($\tau \leq 0.1$). As the GBT is dynamically scheduled, observers are able to take maximum advantage of the good weather conditions. The sum result of these factors is that the GBT is a superb telescope through for science ranging as high as 115 GHz.

2. GBT Development Program

The NRAO has an ongoing development program to maximize the scientific output of the

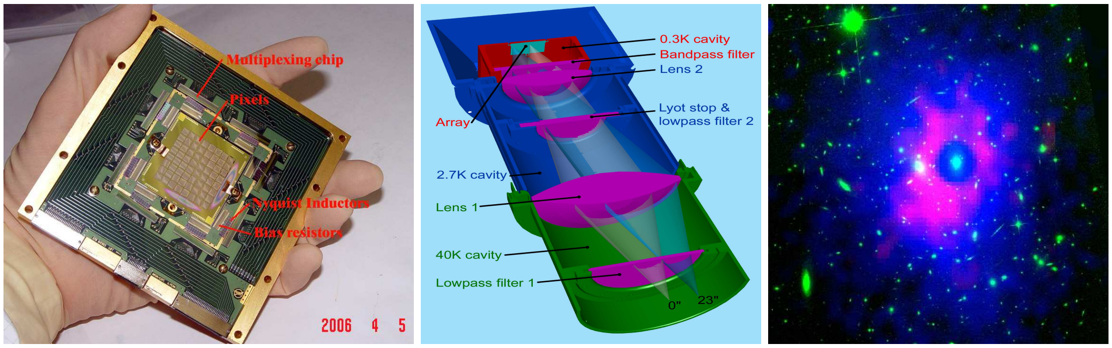

Figure 1: Left: Image of the MUSTANG array. Middle: MUSTANG optics. Right: Recent Mustang image of the Sunyaev Zeld'ovich effect in Galaxy Cluster RXJ1347-1145 (Red) superimposed on Chandra X-ray (blue) and HST optical (green). At 9", this is the highest resolution image of the SZ effect made to date. Images from [1].

GBT while developing the hardware and techniques necessary for the long term future of radio astronomy. All development is done in conjunction with college, university and other research groups around the country and the world.

NRAO's Green Bank Observatory is heavily involved in three main development areas – multi-pixel cameras, digital signal processing, and data processing of massive data sets. The details of this development work is explained in the subsequent sections.

2.1 Multi-pixel cameras

Camera development work on the GBT is broken into three main development areas - bolometer arrays at frequencies around 90 GHz, traditional feed horn arrays at frequencies above18 GHz, and phased array feeds ar frequencies near 1 GHz. Each of these technologies is extremely complementary and the development of the three technologies simultaneously allows the GBT to provide the optimum instrumentation for the science needs of its observers.

2.1.1 Bolometer Arrays

The GBT currently has available to observers an 8 by 8 pixel planar array of transition edge sensor (TES) bolometers known as MUSTANG (Multiplexed SQUID TES Array at Ninety GHz). Currently the array does not use feed horns - instead high density polyethylene lenses and capacitive mesh filters capture the light and focus it on the detectors. The filters also define the 81-99GHz bandpass of the array. The lenses of the instrument also control the illumination of the telescope. The array is read out with time-based SQUID multiplexing electronics. Images of the MUSTANG array can be seen in 1, and details on the array can be found in [2].

The next step in the bolometer development program is a significantly more sensitive, larger field of view detector array using a feed-horn plus micro-strip coupled TES detectors design. This array will have twice the instantaneous field of view of MUSTANG and background photon-noise limited performance (T_{sys} ~30K). The instrument is currently unfunded, but should be developed within 3 years of receiving funding.

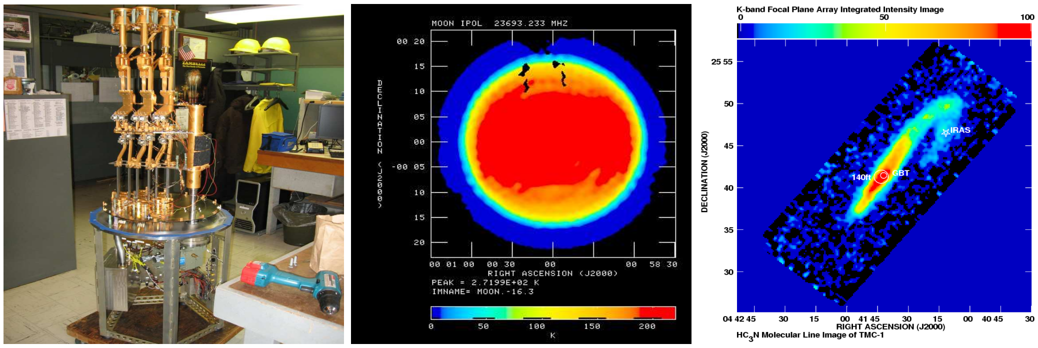

Figure 2: Left: Image of the 7-pixel 18-26 GHz (K-band) focal plane array for the GBT before installation into the cryogenic system. Middle: Image taken of the moon at 24.138 GHz, smoothed. The dark patches to the north are where no data were obtained. Left: Image of the HC_3N 18.196 GHz line within TMC-1. Images from [3].

The ultimate goal of this development work is a 1,000-pixel, photon noise-limited array for the GBT. NRAO's bolometer array development work is being done through collaboration with the University of Pennsylvania, the National Institute of Standards, Cardiff University, and others.

2.1.2 Traditional Feed Horn Arrays

The first traditional feed horn array for the GBT has just been commissioned for general use. The K-band Focal Plane Array (KFPA) is a 7-pixel array at 18-26.5 GHz. T_{sys} for the pixels range from 16-34K across the band for all seven receivers , although those ranges may lower slightly during work done on the array in summer, 2010. The first call for science proposals on the KFPA has been announced, and observers will begin using the instrument in the fall of 2010. A full data reduction pipeline is also in development for this instrument, and will be released for general use in 2011.

The next traditional focal plane array to be built for the GBT is an 8-pixel prototype array from approximately 88-116 GHz (the final frequency range is still under investigation). Unlike the KFPA, this array will be using a fully integrated design for all array components. Additionally, the array will be taking advantage of newly designed, wide bandwidth, low noise amplifiers to produce an extremely low noise receiver system.

The goal of the current traditional feed horn array development program is a 100+ pixel focal plane array at W-band, which would be a direct replica of the prototype 8-pixel array.

Work on the traditional feed horn arrays is being undertaken with collaboration with Stanford University, the California Institute of Technology, and the University of Maryland.

2.1.3 Phased Array Feeds

To complement the work being done on traditional feed horn arrays, the NRAO has also undertaken an ambitious program to develop a cryogenic, 1.4 GHz, phased array feed (PAF, also commonly called beam-forming arrays) for the GBT. The design for the first PAF is $\geq$300 MHz bandwidth within the 1.35 - 1.72 GHz frequency range. The receiver temperature goal is 16K, leading to a system temperature for all beams of 25k. The system will be designed to have 100 or more beams and will employ the real-time RFI mitigation techniques developed by Warnick, et al. at Brigham Young University [5].

Prototype work is currently underway on the new array receiver with wider channel bandwidth (5 MHz vs 0.5 MHz), dual-polarization dipoles, a dewar to cool the LNAs, and an FPGA beam former. All tests to date have streamed raw samples directly to disk and formed beams in post-processing.

Further information on the phased array program can be found at [4].

2.2 Digital Signal Processing

The NRAO has a significant digital signal processing group primarily centered at the Green Bank site. The group is working primarily with the CASPER groups at the University of California, Berkeley and also with West Virginia University and the Lincoln Laboratories at the Massachusetts Institute of Technology. The main area of interest is currently Field Programmable Gate Array (FPGA) technologies for backends, although the group is also looking into low cost A/D converters and other concepts.

2.2.1 FPGA-based Backends

The first FPGA-based back end for the GBT is now in general use. This is a high time resolution backend used primarily for observation of pulsars. GUPPI, the Green Bank Ultimate Pulsar Processing Instrument, is a backend built with off-the-shelf hardware designs and custom FPGA "Gateware". This gateware is compiled and loaded into the 7 Xilinx FPGA's used for GUPPI's implementation. GUPPI has two different modes - incoherent filter bank (search) and coherent de-dispersion (timing) The instrument provides full Stokes information, a minimum time resolution of 20.48 μs, and 800 MHz in bandwidth. New modes are added to the instrument as needed.

The next instrument to be built by the NRAO/CASPER team is FPGA-based Spectrometer to replace the existing GBT spectrometer and spectral processor. The instrument is planned to have a 1 GHz instantaneous bandwidth, Sub-banding possible across the entire 8GHz IF of the GBT, and 16 channel inputs with 12-bit sampling. The instrument will be a vast improvement over the current GBT capabilities, and will also pave the way for implementation of RFI mitigation

Figure 3: Left: Image of the uncooled 19-element phased array feed installed on the 20m telescope in Green Bank, WV. Middle: Image of the latest single-polarization array that is designed for wider bandwidth and better noise match with mutual coupling taken into account. Right: A wide-field map of the Cygnus continuum emission complex, obtained in 2008 with the test feed installed on the 20m telescope. The PAF data is is shown in the color image, and a gray-scale composite of the same region assembled from the Canadian Galactic Plane Survey digital continuum images is shown for comparison. Images from [4].

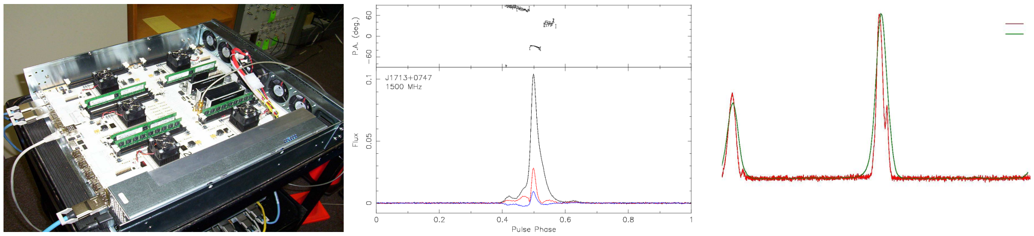

Figure 4: Left: Images of the BEE2 core of the GUPPI instrument. The instrument provides full Stokes information, a minimum time resolution GUPPI is based on the open-source and FPGA-based CASPER infrastructure (http://casper.berkeley.edu) and uses two iBOBs with high speed ADC cards to feed a BEE2 board where most of the signal processing is performed. Data flows over 10GigE to a large server with 15TB of RAID and is recorded at up to 200 MB/s in PSRFITS format. Middle: Full Stokes pulse profiles from a 30-min, 800-MHz bandwidth observation of the 4.57-ms pulsar J1713+0747 centered at 1500 MHz with 2048 channels (Red is linear polarization, blue is circular polarization). Right: Plot showing the improved time resolution provided by coherent de-dispersion (using GASP, in green) compared to one of GUPPI's incoherent mode (in red), while observing near 1400 MHz. Images from [6] and [7].

techniques. Additionally, the instrument is a prototype for the instrument necessary for a 100+ pixel focal plane array at W-band. The instrument is estimated to be complete within 3 years.

2.2.2 Data Transmission

One of the major hardware components necessary for any large telescope array, and also vital to achieving the long term vision for the GBT is an affordable, relatively small,energy efficient data transmission system. Existing data transmission systems are too large, too heavy, consume too much power, and are too expensive to deploy on a 100+pixel instrument on the GBT, and are not yet a realistic solution for any large telescope array. NRAO has recently undertaken a project to solve this issue using FPGA-based technologies in the belief this path will provide not only an affordable system but also will provide improve band pass shapes over the available analog technologies. This research has only just begun.

3. Data Processing of Massive Data Sets

The new instruments planned for the GBT as well as the variety of telescopes coming on-line and planned for the future will have data rates which are vastly larger than any rates we have experienced to date (Table 3). In addition to concerns regarding archiving and accessing these massive datasets, algorithms and technologies must be capable of handling the high data rates expected from these instruments. Additionally, as the data is being taken, observers need the ability to determine the data quality in real time, without the ability to scroll through even a fraction of the total data being written to disk. The reduction of the data is also not a simple task, as merely creating the code to be parallelized reducing the pixels individually is the equivalent to throwing out significant amounts of data on both atmospheric conditions and RFI which could result in vastly improved data quality. Finally, the act of finding the signal within these data sets should not be ignored. This is not a problem unique to radio astronomy, or even to astronomy, as many different fields of science are, or will soon be, facing a similar issue.

ALMA/EVLA	GBT now	GBT 100 pixel FPA	SKA
65 MB/s 5 TB/day	1-200 MB/s 3 GB - 2x0 TB/day	1 GB/s i80 TB/day	>>1 GB/s >>80 TB/day

Table 3: Peak Data Rates

Significant work is currently underway within a number of radio astronomy groups to develop algorithms to efficiently discover signals which follow a predetermined shape or pattern, but it often the unique signals which give rise to the most exciting discoveries, and determining the method to find these signals within the data sets is a challenge which must be undertaken. The NRAO is only beginning this research, and is actively looking for partners to work with us on these exciting and varied issues.

4. Conclusion

In conclusion, the GBT is an absolutely amazing scientific telescope. The 105m dish has excellent sensitivity, pointing accuracy, and ease of use. The GBT has a 90GHz aperture efficiency of 35% and a pointing accuracy of 1.5 $''$, values which will continue to improve in the future. Frequency coverage for the GBT currently ranges from 200 MHz through 48 GHz (non contiguously), with a 64-pixel bolometer array from 82-98 GHz and a new two-pixel receiver from 68-92 GHz expected by the end of 2011. A variety of signal processing backends are available for spectral line, continuum, pulsar, and VLBI work. Additionally, and perhaps most excitingly, major new instruments coming on-line – multi-pixel cameras, high time and frequency resolution backends, an improved data transmission system, improved signal processing routines, and a program to fill in the gaps in frequency coverage at high frequencies.

Further information on the GBT is available at `http://science.nrao.edu`.

References

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