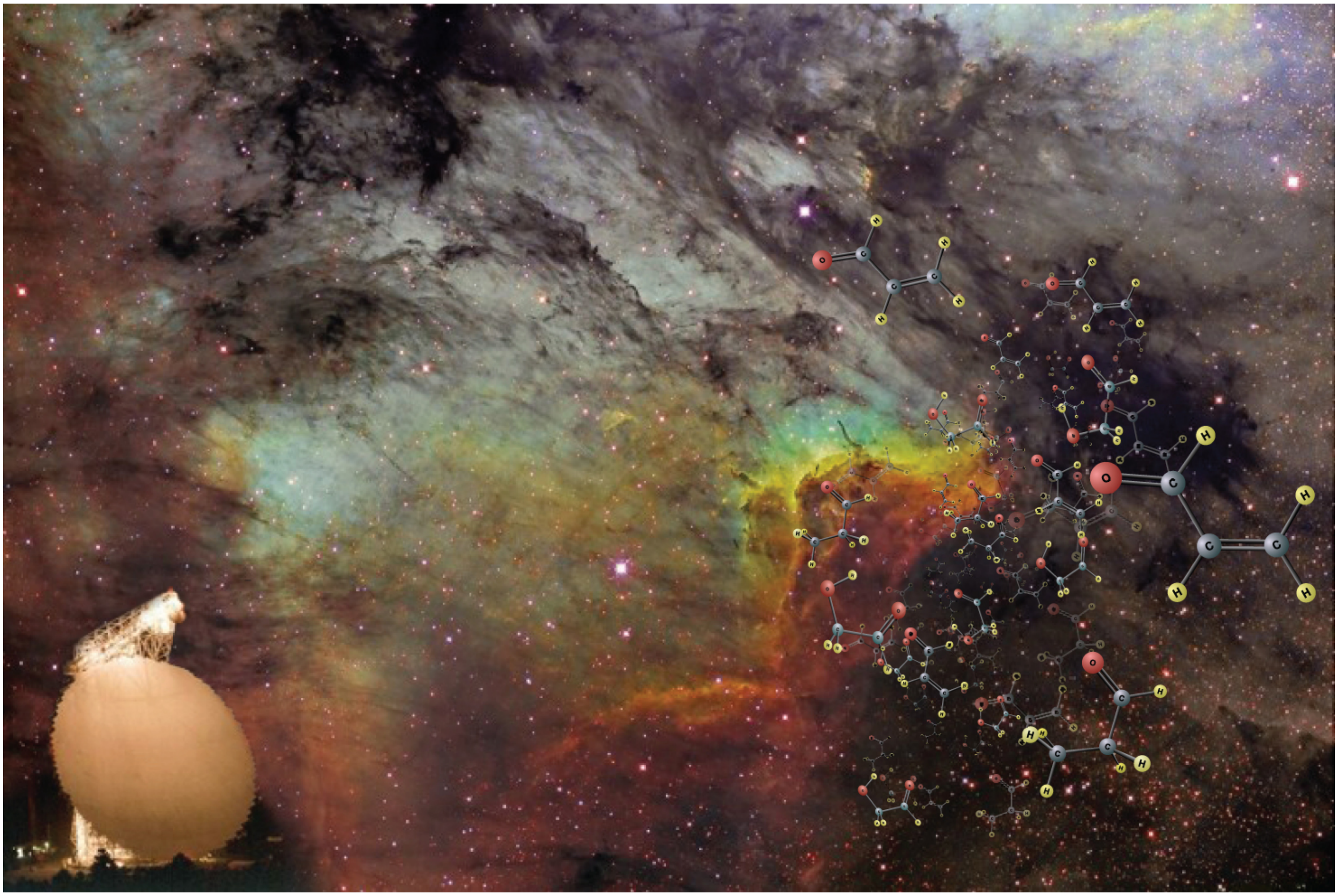
Comets to Clusters:
Wide-field Multi-pixel Camera Development for the GBT



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Summary

The NRAO has established a clear strategic plan (Lo et al., 2009, Astro2010 position paper, *The Impact of the National Radio Astronomy Observatory*) for scientific discovery and technical development in the next decade which leads naturally to a long range vision for radio astronomy. This is one of five papers outlining these activities for the Program Prioritization Panel. Here we describe in further detail one component of the NRAO's vision − achieving a quantum leap in science capability with next-generation camera systems on the Green Bank Telescope (GBT).

The camera systems described here are of three types: conventional feed horn arrays, phased array receivers, and bolometer arrays. Conventional feed horn arrays are built by packing traditional feeds tightly to maximize the number of pixels on the sky per unit area. A typical feed-horn array can achieve a pixel spacing of ~2.5×beamwidth in the focal plane, so multiple pointings of the array are needed to cover an area on the sky completely. In contrast, phased array receivers are composed of a number of small elements whose output is added digitally to yield complete sampling over some area of the focal plane. While both conventional feed horn arrays and phased array receivers can be used for spectroscopy, bolometer arrays have no spectral resolution. A bolometer consists of an "absorber" connected to a heat sink through an insulating link. Any radiation received by the absorber raises its temperature above that of the sink. Like phased array receivers, bolometer arrays can be built to provide complete sampling of the focal plane over a given sky area with a large instantaneous bandwidth.

The science achievable with these three instruments on the GBT is extraordinary and extremely varied. Five key science areas are described within this paper - comets, gas in galaxy clusters, chemistry in interstellar space, star formation under a wide variety of conditions, and the molecular and gas content in nearby galaxies. The power and flexibility of these instruments, though, ensures that a far wider variety of science will be achieved throughout their lifetimes.

There are many technological challenges to developing the next-generation of cameras at radio wavelengths, are many, yet much of the development necessary for the GBT camera systems is also needed for the realization of the Square Kilometer Array (SKA). The low cost, wide bandwidth digitized data transmission system, low noise amplification and integration techniques, and the variety of camera technologies are all applicable the SKA at frequencies above 0.3 GHz. These technologies could also be applied to existing radio telescopes, providing a rapid increase in scientific output well before the SKA vision is achieved. In addition, the data algorithms, processing, displaying, and archiving technologies developed for this program will be of direct use to the SKA while providing efficient solutions for existing telescope systems.

Some research and development for the three different camera technologies described in this paper is already underway, but there is still much to be learned. We plan a phased approach, coupling continued development with scientific results from prototype instruments. The result is unique scientific output achieved as rapidly as possible without compromising the technology needed not only for the GBT but for future radio observatories. Ultimately the technology will provide a quantum leap in scientific capability, not only for the GBT but for the SKA and many other telescopes.

Key Science Goals

Introduction

In the next decade, to fulfill its mission, the National Radio Astronomy Observatory (NRAO) will operate a suite of forefront telescopes: Atacama Large Millimeter Array (ALMA), Expanded Very Large Array (EVLA), Robert C. Byrd Green Bank Telescope (GBT) and Very Long Baseline Array (VLBA), which provide at least an order of magnitude improvement in resolution, sensitivity, frequency coverage, spectral line capabilities, and field of view, over existing instruments from meter to sub-mm wavelengths. These telescopes will provide data that are a necessary compliment to data from observatories at other wavelengths. The details of the NRAO plan are carefully described within the AST2010 State of the Profession white paper *The Impact of the National Radio Astronomy Observatory* (http://www.nrao.edu/A2010. Here we describe in further detail one component of the NRAO's vision − achieving a quantum leap in GBT science capability with next-generation camera systems.

The GBT is a 100 meter diameter radio telescope that works between 75 MHz and 115 GHz. It is operated as a user facility by the NRAO. It is the largest fully-steerable single dish radio telescope in the world, and is being used for unique experiments over a broad range of science. Its unblocked aperture gives it the sensitivity of a much larger antenna, a high dynamic range, and excellent spectral baselines. It has very high sensitivity to low surface brightness emission. The GBT is also unique among 100-meter class radio telescopes in that it operates efficiently at wavelengths as short as 3mm.

The Instrument and Site

The GBT is a dual-offset parabolic reflector radio telescope with an active surface and unblocked aperture. The active surface is used for real-time compensation of distortions from gravity and thermal gradients. At present the telescope has an aperture efficiency of about 70% at low frequencies and about 20% at 90 GHz. There is a program underway to improve the surface figure and telescope pointing with the goal of achieving an aperture efficiency of 40% at 90 GHz. With this efficiency the GBT will have an enormous collecting area (3142 m^2), and in combination with its angular resolution (8″) it will be one of the most capable millimeter-wave telescopes in existence. The surface brightness sensitivity and high imaging speed of the GBT with large focal plane arrays will make it a direct and powerful complement to ALMA at 3mm, and the EVLA at longer wavelengths, as well as facilities at other wavelengths.

The GBT is currently equipped with a suite of heterodyne receivers covering most frequencies below 50 GHz, and a new 64-pixel bolometer array covering 81-99 GHz (MUSTANG). There are numerous detectors for spectral line, continuum, and pulsar experiments. Most receivers are located in the focal plane on a rotating turret, so that it is quick and easy to change between observing programs at different frequencies.

The GBT is located at an elevation of 860m in the National Radio Quiet Zone, an area of some 13,000 sq-miles within which there is legal protection against new fixed radio transmitters.

There is no other area with comparable protection anywhere in the US, or indeed, anywhere in the northern hemisphere. The GBT is used for astronomical observations about 6,400 hours a year. About 3,000 hours each year have atmospheric transparency suitable for work in the 3mm band. There is typically some usable 3mm weather every month of the year. Observing at 3mm is currently restricted during periods of moderate wind, but work is underway to improve the GBT's pointing and surface to allow use of more time at the highest frequencies. The flexibility of the optics allows programs to be switched rapidly to match the current weather.

The Impact of the GBT: Sample Scientific Results

Pulsars: The first publication from the GBT reported discovery of a new pulsar in a SNR, and pulsar research has continued to thrive. Detection of the fastest known pulsar has put limits on the equation of state of matter at the highest densities, and precise timing of a pulsar-pulsar binary has produced the most stringent test to date of General Relativity in strong fields. One of the current GBT key science projects is attempting to directly detect gravitational waves over the next decade using millisecond pulsars (Cordes, et al. 2009; Demorest, et al. 2009).

Chemistry: With its superb sensitivity to low surface brightness emission, the GBT has revolutionized the study of astrochemistry. It has discovered 13 new organic molecules including $CH6^-$, the first interstellar anion. Contrary to prior expectations many of these species are not concentrated in compact hot cores, but are found in extended cool clouds. These discoveries have caused chemists to re-evaluate chemical pathways and reaction rates in interstellar gas (e.g. Quan & Herbst 2007).

Highly redshifted atoms and molecules: With its sensitivity and broad frequency coverage, the GBT has been used to detect highly redshifted HI and several molecular species from objects in the early Universe. These observations have measured abundances in a damped Lyman-α system at z=2.35, have detected the reservoir of cool molecular gas around a young galaxy at z=4.7 and have measured the Zeeman effect and thus the magnetic field in a galaxy at z=0.69.

Neutral Hydrogen around galaxies: One of the early results from GBT spectroscopy was the discovery of a system of faint extended HI clouds around the Andromeda galaxy. The high dynamic range of the unblocked GBT allowed the clouds to be detected near the very bright HI disk of that galaxy. Since then, previously-unknown low surface-brightness, extended HI has been detected in Hickson compact groups and in the tidal streams of the M81/M82 system. Observations of high-velocity HI clouds around the Milky Way show that some are being captured by the disk (Figure 1).

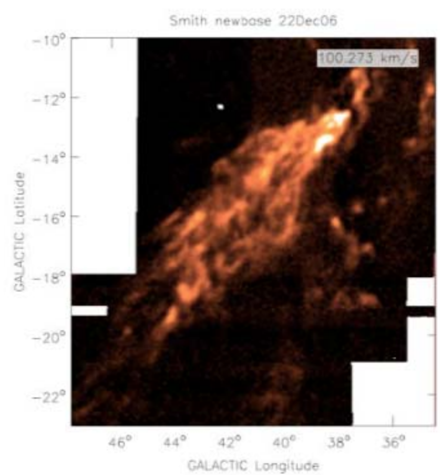

Figure 1. GBT image of HI emission from a high velocity cloud. The cloud is plunging into the Milky Way disk and bringing more than 10^6 solar mass of gas into the star-forming regions of the Galaxy. This 21cm image was assembled from about 40,000 individual pointings with the GBT, each of just a few seconds duration. (Lockman et al 2008).

The Case for Wide-Field Cameras

The results in the previous section were obtained with single or dual-pixel receivers on the GBT, and mapping extended regions is a lengthy task. Indeed, there are many interesting objects - comets, molecular clouds, nearby galaxies- that are so large in relation to the GBT resolution that they are extremely difficult to study with single-pixel receivers as mapping takes a prohibitively large amount of time. Infrared dark clouds, for example, are likely the location of the formation of stellar clusters, so it is critical to have high spatial dynamic range images of temperature and density in these objects. A typical infrared dark cloud subtends 5', and would require about five hundred pointings to be fully sampled in the 22 GHz lines of NH_3. To cover the same area in the many molecular species at 3mm wavelength would take about 8,000 pointings. The HI image of the Smith Cloud (Figure 1) took about 40,000 pointings, and was feasible to map only because each pointing was limited to a few seconds integration.

In recent years, focal-plane arrays on single dishes have been a powerful tool for discovery. The list of these instruments includes SCUBA on the JCMT, the Parkes multi-beam, SEQUOIA on the FCRAO 14m, ALFA at Arecibo, MAMBO and HERA on the IRAM 30m, BOLOCAM on the CSO, and so on. NRAO is currently building a 7-pixel focal plane array to operate in the 18-26 GHz band that will be the first of a suite of focal plane cameras on the GBT.

Key Science for Focal-plane Cameras on the GBT

The wide bandwidth camera program for the GBT will eventually cover all frequencies at which the GBT operates, but for the purpose of this brief document we will concentrate on the science that will be possible with the four instruments proposed for the next decade. The first instrument is a 100 pixel ≤70 – 115 GHz heterodyne receiver that has an angular resolution of 8" at 90 GHz and a pixel spacing of 2.5 beamwidths. The 3'x3' footprint of the camera can be completely sampled in 25 pointings. At lower frequencies we plan a 64 pixel heterodyne focal plane array at 18-30 GHz and a phased array at 1GHz. In the continuum, we plan a 1,000 pixel bolometer array fully sampling the focal plane at 90 GHz with 8" resolution over a field of view of about 2'x2'. Below we illustrate the potential of the 3mm systems. The science case for the phased array feeds is more fully laid out in the AST2010 technology white paper (Fisher, et al. 2009)

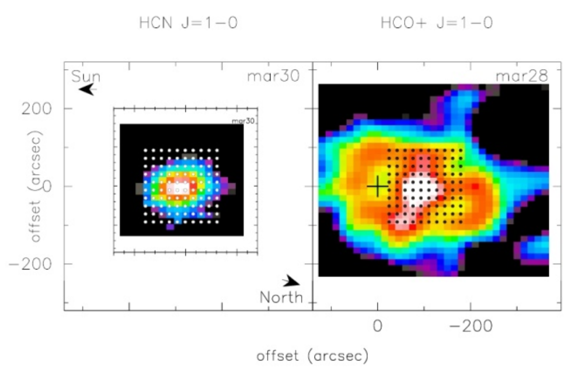

Figure 2 Molecular emission maps of comet Hale-Bopp made in HCN (left) and HCO^+ (right) with the 14m telescope of the FCRAO whose angular resolution is about the size of the cross in the right panel. Overlaid dots show the footprint of a 100-pixel GBT array in these lines. Figures courtesy A.J. Lovell.

Comets: Relics of Solar System Formation

Comets contain primitive material from the formation of the solar system, and as such, their study is critical to our understanding of problems from the formation of the solar system to the origin of life on earth. By their nature comets are transitory: an HCN molecule ejected from the nucleus travels at ~1 km/s for about $6\text{-}8\times10^4$ seconds until it is photo-discociated by solar UV, producing a coma with a size ~100,000 km. At a distance of 0.5 AU it subtends about 5' and its structure can change in a few hours. Study of comets requires an instrument that can make rapid measurements with high angular resolution over a wide field of view and have high sensitivity to low surface-brightness lines (Figure 2). Focal plane arrays on the GBT will be a unique tool that will transform cometary research.

Researchers now depend on the occasional spectacular comet like Hale-Bopp to produce enough signal to be detected in more than a few molecular species, but with 3mm cameras on the GBT it is likely that there will be several comets every year, each detectable over 3-4 weeks, that can be studied.

The Chemical Bond in Interstellar Space

The chemical processes in the ISM produce a rich set of organic molecules, exotic species, and "pre-biotic" molecules that may be relevant to the origin of life on earth. For several decades molecules have been used as probes of interstellar processes, transforming our understanding of star formation and evolution, and the physical conditions in molecular clouds. There is now a new paradigm arising from the chemistry community that inverts this process to use the unique conditions afforded by interstellar clouds in the study of chemistry itself. Terrestrial laboratories are largely limited to reactions in liquids or high-density gases. A question such as: *"How does non-equilibrium chemistry proceed in a weakly ionized gas in the presence of magnetic fields?"* crosses traditional disciplinary boundaries as it can be answered only by astronomical observations in conjunction with theoretical and laboratory studies. The newly-established Center for Chemistry in the Universe (http://www.virginia.edu/ccu) has been formed to use astronomical techniques to understand fundamentals of chemistry, and radio astronomy, and in particular, the GBT, is central to these efforts.

Molecular lines are weak and often from extended sources, so progress thus far has been limited to study of only a handful of molecular clouds, almost entirely in the Milky Way. In coming years, however, studies will be extended throughout the Milky Way and to nearby galaxies as specific chemistry questions arise that require observations of a molecular cloud with specific physical conditions for their answer. The 3mm focal plane camera on the GBT will give an instantaneous high-sensitivity snapshot of the chemistry in a molecular cloud at 100 locations with a resolution of 0.03 pc in a cloud 1 kpc distant. It will determine if a cloud is chemically interesting or peculiar, and will allow surveys of many hundreds of objects to discern the pattern of chemical evolution around the galaxy.

The Context of Star Formation

Stars form on the scale of a solar system, but their formation can be triggered by events on much larger scales, up to the size of a galaxy: density waves, tidal encounters, AGN activity, feedback from previous star formation, cloud collisions, and so on. Although there have been recent impressive advances in our understanding of the formation of isolated stars, our understanding of the process of clustered star formation is still primitive. Advances will require observations on all angular scales to understand the factors that make up the context of star formation. Study of infrared dark clouds is particularly promising. These objects are ubiquitous in the Galaxy, have low temperatures and high densities, and may be the progenitors of star clusters (Figure 3). At this time, many of their physical properties are poorly known. It is not even known whether they are transient or long lived (Bally, et al. 2009; Feigelson, et al. 2009).

Figure 3 shows an IRDC with the footprint of the GBT 3mm focal plane array superimposed. With the angular resolution, planned bandwidth, and sensitivity of the GBT a complete array of molecular species can be studied. Deuterated molecules will trace very cold material, not accessible in the more common molecules. HCN can trace the disposition of dense gas. There are molecules whose presence is indicative of shocks or ionization fronts. Numerous molecules have their ground state lines in the 3mm band (e.g. HCN, HCO^+, CN, CO) and provide different physical tracers of the gas. The kinematic structure of the cloud will show the influence of turbulence and outflows. Focal plane cameras on the GBT will provide the context of star formation on scales complimentary to that studied by ALMA and the EVLA.

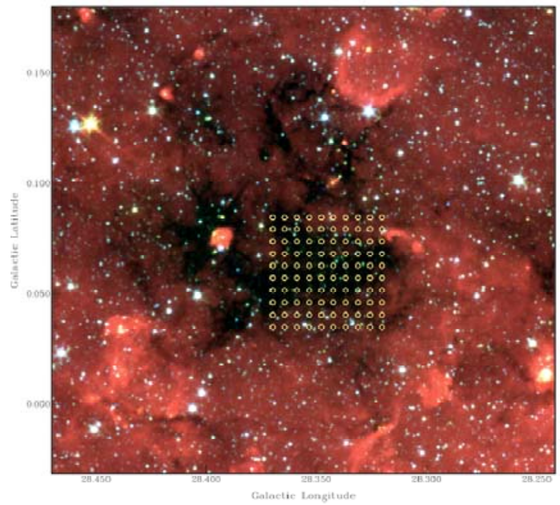

Figure 3. An infrared dark cloud with the footprint of the 3mm GBT focal plane array. These clouds are likely the progenitors of star clusters. Many thousand have recently been discovered, but their internal constitution is largely unknown. They are ideal targets for the high sensitivity and wide-field coverage of the GBT with focal plane arrays.

The Molecular Content and Chemistry of Nearby Galaxies

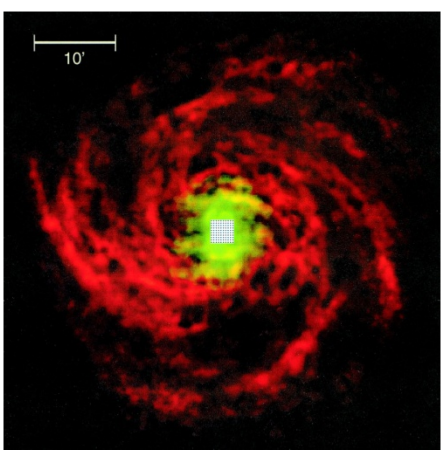

Figure 4. An image of the nearby galaxy IC342 in ^{12}CO (green) and HI (red) with the footprint of the GBT 3mm focal plane array in the center. In one minute the array will be able to detect lines from a dozen molecular species at S/N>10, and in less than one hour can completely map the area within the array footprint.

The evolution of a galaxy is driven by its gas. There are good measurements of the HI in many nearby galaxies, but properties of the molecular gas, the material most closely linked to star formation, are still largely unknown. The rich variety of molecular tracers provides probes of specific physical conditions such as shocks (SiO), quiescent gas (N_2H^+), dense gas (HCN), and warm and cold temperature gas (NH_3). The goal of this research is to determine the global chemical structure of galaxies and the chemistry that relates to a galaxy's dynamical history, abundance gradient, or feedback mechanism (Meier, et al. 2009) Only with knowledge of the chemical evolution of nearby galaxies can we make sense of observations of proto-galaxies at high-z.

A 100 pixel FPA working in the 3mm band on the GBT will transform our understanding of molecular clouds and chemistry across galactic disks. For an object at 1 Mpc distance it will have a footprint about 900 pc on a side and a resolution of 40 pc. In less than one hour (spending 1 minute at each position) it could map this area completely to a noise level $\Delta I = 0.025$ K-km/s. In the ^{12}CO line this corresponds to a surface density uncertainty of 5×10^{18} cm^{-2} in H_2 or 0.08 M_{sun} pc^{-2}. Integrated over a beam the mass uncertainty (1σ) would be equivalent to 100 M_{sun}. For a molecular cloud like those studied recently in IC342 (Meier & Turner 2005), in one hour the array will also detect a stunning variety of molecular species such as $C^{34}S$, a tracer of photo dissociation, CH_3OH, which traces shocks, N_2H^+, and HCN at a signal-to-noise ratio between 10 and 60 (Figure 4). Not only the chemical structure, but the physical conditions and kinematics of the gas will be determined.

Gas in Galaxy Clusters

Measurements of the Sunyaev-Zel'dovich Effect (SZE) have long been sought as a probe of cosmology, and these measurements have matured to the point where images of the SZE in large samples of galaxies have been obtained (e.g., Reese et al. 2002, Udomprasert et al. 2004). High-angular resolution X-ray data from Chandra have revealed embedded cold blobs of gas which may be remnants of past merger activity (Markevitch et al. 2000) and enabled detailed study of ongoing subcluster mergers (Kempner et al. 2002). SZE observations are currently limited to a comparatively low-resolution view of the Intra-Cluster Medium (ICM).

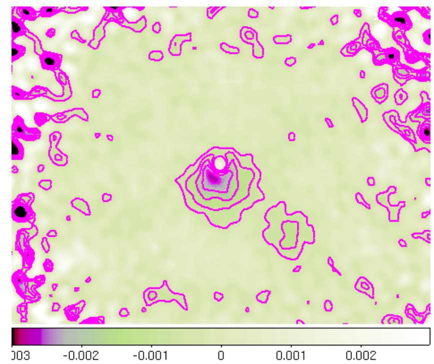

Figure 5. MUSTANG+GBT map of the Sunyaev-Zel'dovich Effect (SZE) in the rich, x-ray luminous galaxy cluster RXJ1347-1145. The image and the magenta contours show the SZE decrement; (GBT Integration time: 3.3 hours)

A large focal plane bolometer array on the GBT would have exceptional properties and stand out among instruments at SZ frequencies in combining excellent surface brightness sensitivity with high resolution. The 8" beam of GBT at 90 GHz will provide a detailed view which, when compared with Chandra and XMM data, will help to understand the physical processes in the ICM. This will be essential to determine the systematics inherent in interpreting the cluster counts from ongoing SZ surveys such as SZA (Muchovej et al. 2007), ACT (Swetz et al. 2008) and SPT (Staniszewski et al. 2008). Previous 20" resolution SZ observations with the Nobeyama 45-m telescope (Kitayama et al. 2004) suggest that our understanding of the ICM even in nearby, well-studied x-ray clusters may be dramatically incomplete due to the presence of hot shocks which largely fall out of the band of imaging x-ray telescopes.

Preliminary work with the 64-pixel bolometer array MUSTANG on the GBT (Figure 5), completed in less than a quarter of the time required for the Nobeyama observations, support this scenario. With a 1000-pixel, background limited 90 GHz detector array on the GBT it will be possible to image large samples of SZ clusters at high resolution to study the prevalence and impact of these hidden shocks. A 5'x5' map to 10 microKelvin RMS will be possible in under an hour with such an instrument, making possible systematic studies of large samples of clusters. These data would also probe the mechanisms by which AGN inject entropy into the ICM (Pfrommer, Ensslin & Sarazin 2005) and reduce the scatter in distance measurements by better determining the geometry of the cluster gas pressure profiles.

Technical Overview

The technological challenges in developing the next generation of cameras at radio wavelengths are many and will have a wide-ranging impact. Much of the work necessary for the GBT camera systems is also needed for the realization of the Square Kilometer Array (SKA) and is a part of the SKA technology development program. These technologies could also be installed on planned and existing radio telescopes, providing a rapid increase in scientific output well before the SKA vision is achieved.

In addition to the hardware challenges, the data output from the next-generation cameras will be higher than what is produced from any other radio telescope, either in existence or under construction. As a result, the data algorithms, processing, displaying, and archiving technologies developed for this program will be of direct use to the SKA while providing efficient solutions for existing telescope systems.

Further details regarding the technological development of the next generation camera systems can be found in a number of AST2010 technology white papers which have been submitted[1] and which can also be found online at http://www.nrao.edu/A2010. Here we provide a broad overview of the issues faced.

In considering different paths forward to develop the needed technologies, one significant feature of all the instruments described within this program plan in that they are all intended for use on an existing telescope and so do not require any additional infrastructure, construction, or resources beyond what is described below. The result is an inexpensive path to rapidly achieve exciting science and technological developments.

Conventional Feed-horn Focal Plane Arrays

To meet the scientific goals a conventional feed horn array must achieve the following: Low instrumental noise, dual polarization, wide instantaneous bandwidth (10-20 GHz or greater), closely packed feed horns ($\leq$2.5 beam width separation on the sky), stable baselines at the μJy level, and high spectral resolution ($\leq$2 km s^{-1} at 115 GHz). These requirements pose a number of significant technological challenges.

Integrating and packaging the receiver systems: Efficient integration and packaging of the feed horn array is a difficult problem. Focal plane arrays to date have evolved from single pixel receivers, and existing arrays with up to a few tens of elements have naturally been assembled from individual receivers and components, albeit efficiently packed together. This is sufficiently expensive, time consuming, and difficult to maintain that as one moves to the next level – arrays with many tens of pixels – the approach *must* be modified and multi-pixel modules employed. Additionally, in order to maximize the scientific potential of a feed horn array one must typically place the feed horns as close together as possible. This allows for a more efficient imaging of compact regions on the sky, the removal of uncertainty in the telescope pointing (e.g. due to wind) through permitting re-gridding, and permitting the use of the multiple feeds for image

[1]See ASTRO2010 technical white papers by Goldsmith, et al, Dicker et al, Fisher et al, Woody, et al, and Readhead, et al.

calibration and reduction. Further details on the issue with integration and packaging of the system can be found in the "key technologies" section of this paper.

Achieving low noise, dual polarization across a wide bandwidth: Typical scientific requirements of a receiver system include very low noise with instantaneous bandwidths of greater than 20 GHz and dual polarization with a high isolation between the polarization components. This often cannot be achieved using a single technology. As an example, Monolithic Microwave Integrated Circuits (MMICs) do not typically have the noise performance necessary for the scientific needs of the array. As a result, a hybrid system, involving a combination of MMIC and discrete Field Effect Transistors (FETs) may be the proper approach. However there is still significant research which must be done to achieve the optimum solution for a focal plane array (FPA).

Affordable data transmission systems: A large focal plane array receiver requires the transmission of the received data from the receiver to the signal processing system. In many cases this is a significant consideration, as the focal plane array may lie far from the location of the signal processing equipment, often for reasons of practicality as well as to reduce the radio frequency interference seen at the telescope from the signal processor. Conventional analog transmission suffers from instabilities which can cause serious reduction in the sensitivity of the observations. Digital data transmission systems show considerable promise in this regard, but face a number of obstacles as well. In particular the current technologies are too large, too heavy, consume too much power, and are simply too expensive for practical use in a large focal plane array. Alternative technologies such as multi-gigasample analog-to-digital converters are coming and may help, but they too require significant research and development before their use is practical. Research is also needed into integrated photonics and other techniques to shrink the size, weight, power consumption, and minimizing the radio frequency interference generated from these systems. Note that research and development in this area is directly applicable to SKA technologies.

Bolometer Arrays

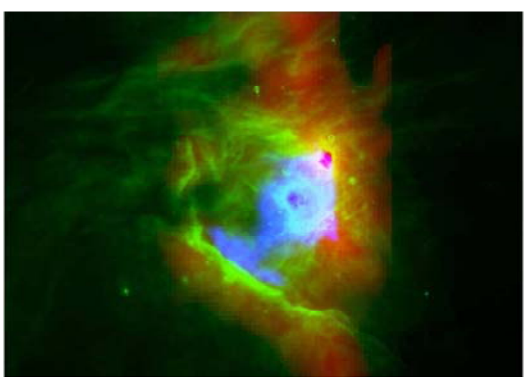

Figure 6. A false-color image of Orion with GBT+MUSTANG 90 GHz data (blue), SCUBA 850 μm (red), and Spitzer IRAC 8 μm data (green). The bar to the south-east is a classic ionization front, with MUSTANG tracing free-free emission, IRAC the PAH emission, and SCUBA the heated dust on the other side.

Large format bolometer arrays offer the prospect of revolutionary strides in sensitivity over the next decade so are the focus of extensive development activity throughout the millimeter and submillimeter instrument communities. The ability to implement background photon-noise limited, robustly operable detector arrays will be crucial to the success of future projects such as CCAT and space-borne CMB polarization experiments. Their ability to sensitively map large areas of sky will complement ALMA in defining systematic samples of objects, and extreme instances of them, for further study. The GBT development effort will occur in synergy with these enterprises, and will facilitate testing and refining design concepts on a platform which at the same time generates forefront science.

MUSTANG (Dicker et al. 2006) is a 64-pixel, SQUID-multiplexed TES bolometer array which has been developed and commissioned for general use on the GBT. The project was successful in developing solutions to the technical problems faced by TES bolometer array receivers, such as vibrations, magnetic fields, optical design, and SQUID/TES tuning and operations. We were also able to perfect the scan strategy, develop a complete data pipeline, understand the impact of the weather on our data, and characterize the high frequency performance of the GBT. In our first seasons on the telescope we have been able to make exciting observations of star formation (Figure 6) and the Sunyaev-Zel'dovich Effect (Figure 5); these observations were made in a fraction of the time that comparable, but lower resolution measurements have required previously.

In spite of these outstanding results challenges remain. Amongst these are eliminating residual microphonic susceptibility of the pixels and achieving background photon noise limited performance (in radio terms, $T_{rx} \ll T_{sky}+T_{cmb}$). In the near term we will approach these problems by assessing new pixel designs, and by cooling the detectors below their current operating temperature of 300 mK.

The current MUSTANG detectors consist of a 1μm thick, 2.88mm square membrane of bismuth-coated silicon suspended by four 10μm wide legs from a frame 0.25mm wide. This design has proved serviceable for several seasons of initial observations but is limited by both intrinsic noise and vibrational susceptibility. A number of potential improvements have been identified, including reducing the overall pixel size, alternate pixel geometries, and using alternate refrigerators technology (Normal-insulator-Superconductor (NIS) refrigerators and Adiabatic Dilution Refrigerator are both promising options.)

The work described above will make use of the existing MUSTANG cryostat and warm readout electronics, allowing a rapid turnaround between implementing new designs and using them to do science. In its current form MUSTANG can accommodate up to 256 detectors. Should a sufficiently sensitive instrument – at or near the BLIP noise limit – result from these efforts, the path would be clear for a kilo-pixel class bolometer array on the GBT. Such an instrument would have a long-mm wave sensitivity and mapping speed that will be unsurpassed for the foreseeable future, enabling sensitive large area surveys at 3mm, rapid (under an hour) high-resolution imaging of the Sunyaev-Zel'dovich Effect in galaxy clusters, and deep surveys for the highest redshift galaxies.

On the decadal horizon other technologies may prove important in realizing the full potential of large format bolometer arrays. Two options of note are the use of microstrip antennas to couple the detectors to free space radiation, in place of the variants of bare-absorber or feedhorn coupling which currently dominate camera designs, and Microwave Kinetic Inductance Detectors (MKIDS). Microstrip techniques (e.g., Nahum & Richards 1991) offer the prospect of efficiently coupling to the telescope without feed horns, whose bulk and cost are undesirable for large-format cameras. They also offer the prospects of very low NEP's, low vibrational susceptibility, clean polarimetry, and the use of a variety of microstrip techniques such as integrated bandpass frequency filters (e.g., Myers et al. 2005). MKIDS (Day et al. 2003) are a potential long-term replacement for TES detectors. While not yet technically mature for use at millimeter wavelengths, they have the advantages of being more easily fabricated and robust than TES detectors, and can be massively frequency multiplexed using fairly simple commercial technology. Due to the relative simplicity they are an attractive long-term prospect for use in a large format camera.

Phased Array Feeds

A number of talented groups around the world, notably in Australia, The Netherlands, and Canada, are actively working on instruments, variously referred to as active, phased, beam-forming, or smart arrays to distinguish them from the more conventional independent-pixel feed-horn arrays which sample less than 1/16th of the available sky area within the array's field-of-view. A focal plane phased array feed (PAF) can electronically synthesize multiple, simultaneous beams on the sky for complete coverage of the field of view without loss of sensitivity in each beam. However, a substantial amount of signal processing is required to form each PAF beam and phased arrays need considerably more development work to achieve system temperatures comparable to the best single-beam and conventional horn arrays. For survey and mapping applications the higher system temperature penalty of a non-cryogenically cooled PAF can be compensated by forming more beams and trading off the required increase in integration time for greater sky coverage per pointing, but this makes sense only when post-beam-forming signal processing requirements are relatively light, such as modest bandwidth spectral line observations. In applications where single-beam or horn array systems are already starved for signal processing power and data storage capacity, such as pulsar and transient searches and high-redshift HI surveys, the trade-off of more beams at higher system temperature does not make economic sense.

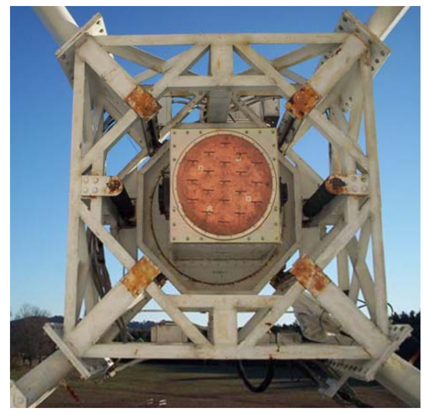

Figure 7. 19-element phased array feed mounted on Green Bank 20-Meter Telescope (Jeffs, et. al 2008)

The fundamental challenge to low-noise performance in phased array feeds is to achieve a good impedance match between the array elements and the low noise amplifiers (LNAs). This is severely complicated by mutual coupling between elements in the compact array. A well matched element-LNA unit in isolation is no longer matched when imbedded in the array. An inherently broadband element, like a Vivaldi antenna will show a frequency dependence of its impedance when imbedded in an array. To add insult to injury, the best-noise impedance match between element and LNA depends on how that element's signal is combined with the signals of other elements in the array. In other words, the best noise impedance of a given element in the array varies from one formed beam to the next. Hence, the designer is presented with a complex optimization problem and an inevitable compromise. Fortunately, the noise added to T_{sys} by this compromise is proportional to the optimum noise temperature (T_{min}) of the LNA, so it is subject to improvement with physical cooling. Design tools do exist for computing the electromagnetic, impedance, and added noise effects of mutual coupling and, to some extent, optimizing array free parameters. The basic antenna element type, impedance modification structure, and connection topology are still left to the designer's experience and intuition to establish a starting point and free parameter set. The two very different wideband array types clearly illustrate different initial assumptions.

High Performance Computing –
Software and algorithm optimization

In addition to the hardware challenges, the data output from the next-generation cameras will potentially be higher than what is produced from any other radio telescope, either in existence or under construction. As a result, the data algorithms, processing, displaying, and archiving technologies developed for this program will be of direct use to the SKA while providing efficient solutions for existing telescope systems.

Accurate and efficient reduction and examination of data from these instruments is vital to achieving the instruments' scientific potential. As an example of the difficulty posed, a 100 pixel, dual polarization, focal plane array could readily output >1 GHz of spectral line data which has been sliced into >10,000 individual spectral channels at a rate of once every 0.1 seconds. Properly treating the massive amount of data coming from such a system is a difficult project in itself. To take advantage of the scientific potential of a multi- pixel camera system, significant research needs to be put into a number of issues. These include:

- Calibration algorithms which maximize the observing efficiency while minimizing any systematics which remain in the data after it has been calibrated and reduced;
- Optimizing the ability to examine the three dimensional data, both for diagnostic purposes when taking scientific data or performing systems analyses;
- Enabling the scientific users to explore their calibrated dataset in such a way as to encourage the discovery of both expected and unexpected phenomena;
- Archiving the data in the national virtual observatory.

The above list requires significant research into algorithms, parallel processing and optimization, as well as the practical aspects of storing and transporting the large dataset around the internal and external networks.

Key Technology Driver #1
System Integration for Conventional Feed Horn Arrays

Integration and packaging of the feed horn array is a difficult problem. Yet it is a problem which must be overcome for any large focal plane array system, and it is a problem which has been habitually underestimated. Focal plane arrays to date have evolved from single pixel receivers, and existing arrays with up to a few tens of elements have naturally been assembled from individual receivers and components, albeit packed together. This is sufficiently expensive, time consuming, and inefficient for maintenance that as one moves to the next level – arrays with many tens of pixels – this approach *must* be modified and multi-pixel modules employed. A few clever approaches to date such as the SEQUOIA and QUIET arrays have made pioneering progress, but more work remains.

The problem of integrating and packaging the focal plane array is not "merely" a problem of making everything small enough to fit behind the feed horn, but it must also deal with heat-strapping, thermal expansion, weight limitations, vacuum integrity, power and signal distribution, and cryogenic loading. Additionally, all components must be packaged in such a way that testing, maintenance, and replacing any one component in the array can be done with minimal impact on the system and carried out fairly rapidly.

Independent of the array's electrical performance, a good integrated system must meet the following criteria:

1. Optimize the packing density and performance to minimize observing time for a given sky coverage;
2. Allow for adequate thermal expansion of the components;
3. Isolate the receiver from microphonic effects ;
4. Minimize heat loading on the cryogenics;
5. Minimize weight, as most telescopes have finite weight limits at the location of the receivers;
6. Minimize the wiring and vacuum feed throughs within the system, for simplicity and reliability;
7. Allow efficient maintenance and repair of individual (or small clusters of) pixels.

Integration and miniaturization are key to meeting these requirements. At the very least, the orthomode transducer (OMT), noise source, noise coupler, and cryogenic amplifiers should be integrated into a single block. Investigation of receiver configurations and calibration strategies which minimize the number of needed components is also very important.

Key Technology Driver #2
High Speed Analog to Digital Conversion and Data Transmission

The scientific output of the planned cameras for the GBT can be greatly enhanced by increasing the instantaneous bandwidth which is available to the instruments' users. While current low noise frontend amplifiers and heterodyne receivers have ten GHz or more of available bandwidth, the conversion of the analog signal into bits for digital processing is a severe bottleneck in the signal and data path. The result is either a loss of scientific information during observations (if the observer chooses to concentrate on a portion of the available frequency band), a significant increase in the telescope time to obtain the desired science (if the entire band is needed, the observer will have to step through the band in frequency increments), or a loss of sensitivity, in the case of continuum observations. The initial development of a 5-10 GHz bandwidth sampler will improve the productivity of many radio astronomy facilities and enable new observations that are not currently feasible. Subsequent development of even wider bandwidth samplers would match the projected increase in frontend bandwidth and digital signal processing over the next decade.

Analog to Digital Conversion: The advance of high speed analog to digital conversion is being pushed by companies that design and manufacture instruments such as oscilloscopes, as well as by research in military applications. On the test equipment front, specifications for the digitizers focus on accuracy and speed, with density and power consumption a secondary focus. The major problem for the GBT is the need to sample, digitize, and transmit via optical fiber, with high density, and low power consumption. These requirements are orthogonal to the goals of the test equipment manufacturers, and so we cannot wait and hope the problem will be solved for us. As a result, while work has been done on optical analog to digital converter techniques that may have promise in radio astronomy applications, significant research is needed to turn existing systems into the technology necessary for radio astronomy. (See Valley 2007 for a review of optical analog to digital converter techniques.)

Data Transmission: On the other hand, the communications industry is marching forward with very high speed data transmission technology. As an example, the communications industry is bringing 40 and 100 Gb/second Ethernet to market, and a 100 Gb Ethernet transceiver was demonstrated at the recent Optical Fiber Communication Conference and Exposition. Current options are, though, far from sufficient as the aforementioned system would require about 40 watts of power, not including the digitizers. There is, however, considerable promise for improvement beyond the current state of data transmission.

A more detailed study of the technological advancements necessary for high speed analog to digital conversion and data transmission can be found in the technology white paper by Woody, et al. (2009)

Key Technology Driver #3
Phased Array Feeds

One key technology which must be developed to meet the scientific potential of phased array feeds is successfully cryogenic cooling. Phased array feeds need more development work to achieve system temperatures comparable to the best single-beam and conventional horn arrays. For survey and mapping applications the penalty in increased noise inherent in a non-cryogenic phased array feed can be compensated by forming more beams and trading off the required increase in integration time for greater sky coverage per pointing. However, this makes sense only when post-beam-forming signal processing requirements are relatively light, such as modest bandwidth spectral line observations. In applications where single-beam or horn array systems are already starved for signal processing power and data storage capacity, such as pulsar and transient searches and high-redshift HI surveys, the trade-off of more beams at higher noise levels does not make economic sense.

A first step in this development starts with a non-cryogenic array with modest signal processing bandwidth, and progressing steadily toward a cryogenic science array. This will offer early benefits of phased array feed technology to spectral line observers with an uncooled array. At this stage, an important aspect of system temperature reduction will be addressed as comprehensive beam noise optimization of the array receiver, including mutual noise coupling effects and LNA integration. Great progress in understanding the technology of close-packed arrays and sensitivity optimization algorithms has been made in the last five years, but, as with any new technology, there are many subtleties to be discovered and understood before the full potential of phased array feeds can be realized.

Once this step is achieved the program can move forward on developing a cryogenically cooled system. To achieve this step, the array elements, LNAs, and cryogenics must be designed as a unit because some antenna element types may be difficult to cool or have too much loss even at low temperatures. Similarly, the thermal isolation from the surroundings must not interfere with the electromagnetic properties of the array. This is a more difficult challenge than with a horn feed because the entire hemisphere above the ground plane, rather than just the horn aperture, must be free of obstruction.

The normal engineering strategy of designing and testing individual components separately, with the confidence that they will then work well in unison, no longer holds. An array must be tested as a unit, including its beam-former. To this end the array development teams have built setups that allow running "hot-cold" noise measurements with absorber over the entire array for the "hot" value and cold sky as the "cold"' environment. Since the array has a broad reception pattern care must be taken to account for all sources of thermal noise in the surroundings, including elevation dependence of atmospheric noise and time dependence of the galactic background.

Activity Organization, Partnerships, and Current Status

Activity Organization: All of the camera development projects are collaborations between University research groups and the National Radio Astronomy Observatory (NRAO). These projects represent an opportunity to broaden community participation in technology development not only for the GBT but also for the SKA and other telescopes such as CCAT, CARMA, etc. The distribution of work is varied, depending on the details and needs of the various subprojects, but in all cases the NRAO has a staff scientist and engineer involved with the subproject to ensure both integration into the GBT system once the subproject is complete and expertise on site once the instrument is a fully integrated into the GBT instrument suite. Overall management of the project also lies with the NRAO and is under the control of a staff project manager.

Partnerships: Current partners are: NRAO, U. Pennsylvania, NIST, U. Virginia, U. Calgary, West Virginia U., U. California (Berkeley), U. Maryland, U. Cincinnati, Brigham Young U and Xilinx Corp. The 3mm conventional array project is still gathering momentum and organization, and a large number of additional groups have expressed interest in participating in the development of the receiver and its components. These include faculty and researchers at: U. Massachusetts, CalTech, Stanford U., JPL, and Agnes Scott College.

Current Status: A 7-pixel K-band conventional focal plane array is being developed at the NRAO and is scheduled to be commissioned on the telescope in fall, 2009. This is a prototype instrument which will provide the NRAO with the necessary background to understand the issues and complexities of building a focal plane array system. The NRAO and its collaborators are also in the process of building an FPGA-based signal processing system which is due for release in June, 2009. This instrument is the first GBT instrument to use FPGA technologies and is allowing the NRAO to gain expertise in this field. Organization for building the 100-pixel 3mm focal plane array and the infrastructure components necessary for the focal plane array program is just beginning. A meeting is being arranged for early summer 2009 to bring the various interested parties together and plan for the stages of research, development, and funding.

The GBT currently has a 64-pixel 90-GHz TES bolometer on the telescope which is fully commissioned and will be released for general science use on October 1, 2009. A proposal to develop and install a 256 pixel bolometer array has been submitted to the NSF for the 2009 MRI proposal call. A proposal for the 1000 pixel system (MASTERCAM) has been developed but funding not yet been identified.

The NRAO and BYU have developed an uncooled 19-element phased array feed at 1.4 GHz with a 68K system temperature which has been tested on Green Bank 20 meter telescope (Jeffs, et al. 2008). To further this work, and MRI grant has been submitted to build and test a beam system for installation on the GBT in three years.

Work is in progress with the University of Virginia to identify areas where computer parallelization may benefit the camera development program. This is a part of a larger project to identify high performance computing needs within the radio astronomy community. The NRAO has also received funding to work on integrating radio astronomy data into the national virtual observatory, a necessary step in developing the archive plans for this project.

Activity Schedule

The goal for the next generation camera program is to develop technologies which will benefit far more than the just the telescope for which they are being designed. Thus significant focus is on the research and development phase. To maximize the scientific output of the program while ensuring the accuracy of the new concepts and instrumentation, all of the projects outlined in this paper will build, test, and release prototype instruments during their research and development phase. After testing the prototype instruments, there is time built into each instrumental schedule to make changes and modifications before a final production instrument is built. However, major modifications in the concept behind the prototypes may cause a delay in the instrument's release beyond the schedule laid out below. The end of the development stage and start of the production stage is clearly demarcated below and in the timeline (Table 1).

Research, development, and construction of the projects and subprojects within this program will take place in parallel.

Conventional Feed-horn Focal Plane Arrays

The first two phases of the conventional feed-horn focal plane array program are the research and development components. *Phase I* of the project is to design and build the prototype system for testing in the laboratory. *Phase II* then develops the first 7 feeds of the 100 pixel 3mm focal plane array along with a 14 channel digitized data transmission system and associated spectrometer. This will allow for full testing of the receiver while also allowing for existing instruments on the GBT to take advantage of the new hardware which will provide wider bandwidths and more stable baselines than is currently available for any instrument.

Once the proto-type instruments are fully tested and the lessons learnt from those tests are incorporated into the final design, production of the final instrument can commence. *Phase III* of this project will see the construction of the remaining 93 pixels for the 3mm system, the remaining data transmission lines, spectrometer, and data analysis software.

Once the 100-pixel 3mm receiver is complete, work will begin on the next conventional FPA for the GBT (*Phase IV*). (This is currently envisioned as a 64-pixel K-band array, but that decision will be reassessed based on scientific interest once the production time is near.) The timeline and cost of this instrument is significantly less than that of the 3mm system, as it will take direct advantage of the research and development work done for the modularization and other components of the 3mm receiver system, digitized data transmission system, spectrometer, and software.

Table 1. Timeline for GBT Multi-Pixel Camera Development and Release (Decade View)

	Year:	1	2	3	4	5	6	7	8	9	10
Traditional Feed Horn Arrays	*Phase I: Prototype W-band built, tested, and plans finalized*										
	Phase II: 7-pixel W-band FPA built, tested, and released										
	Phase III: 100-pixel W-band FPA built, tested, and released										
	Phase IV: Second GBT FPA built, tested, and released										
Digitized data transmission system	*Phase I: Prototype built, tested, and plans finalized*										
	Phase II: 14-line prototype										
	Phase III: 200-line system built, tested, and released										
200 IF wideband spectrometer	*Phase I: Prototype built, tested, and finalized*										
	Phase II: 14-line FPA Spectrometer built, tested, released										
	Phase III: 200-line FPA Spectrometer built, tested, released										
Data reduction, visualization, archiving	*Phase I: Prototype built, tested, and finalized*										
	Phase II: End-to-end system for 7 pixel FPA										
	Phase III:End-to-end system for ≤100-pixel FPA										
Bolometer Array	*Phase I: 1k pixel SQUID TES bolometer array*										
	Phase II: 5k-10k pixel array with MKID or other technology										
Phased Array Feeds	*Phase I: Dual-polarized cryogenic antenna with digital output*										
	Phase II: Develop FPGA-based beam former										
	Phase III: Build 37 element systems for GBT, Arecibo, etc										
	Phase IV: Extend technolgies to ≥5GHz, with ≥1 GHz BW										

Bolometer Array

The goal with the bolometer array project is a flexible development program which can maximally take advantage of the best bolometer technologies available at any given time and work to provide practical applications and uses of these technologies. Currently, SQUID-multiplexed TES bolometers are the most reliable options for building a low noise bolometer system. As a result, the current plan is to use this technology to build a 1,000 pixel TES SQUID bolometer array within the next four years. However, as new technologies improve, the project would take advantage of those technologies to rapidly develop the instrumentation necessary to place the technologies on the GBT. Were the MKID technology to improve at a pace more rapid than anticipated, for example, the TES SQUID array phase could be bypassed if a larger, MKID array with equal or greater sensitivity could be developed quickly.

The research and development being done by other groups to improve the underlying technologies makes the timeline for the project necessarily increasingly approximate. However, the group's past experience and expertise with MUSTANG results in a fairly accurate idea for the timeline necessary to design and fabricate an instrument once the underlying technology is well developed.

Phased Array Feeds

The phased array feed project is inherently a research and development project. As a result, although a clear development path is in place, an accurate timeline for the individual components is difficult to produce. Nonetheless, describing the path forward for this project is straightforward, and that path is outlined in Table 1.

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