Beam-Forming Array (L-Band Prototype)

Objective:

Design and construction of an astronomically useful array feed for the GBT as the first full-scale prototype of the full-sampling array feed concept. This is an R&D project but must have a reasonable chance of satisfying the scientific requirements.

Preliminary Goals:

Bandwidth:	100 MHz
Tuning Range:	1.35 - 1.7 GHz
Number of Beams:	20
System Temp.:	25 K

Project Management:

The goals for bandwidth, frequency coverage, number of beams, and other observational parameters will be determined by a project science committee chaired by Ingrid Stairs. Committee members are Bania, Condon, Cordes, Heiles, Lazio, Lockman, Murphy, Nice, and. Turner.

The project technical committee is co-chaired by Richard Bradley and Rick Fisher. Committee members are Ford, Jewell, Lacasse, McKinnon, Prestage, Watts, Webber, and White.

Time Scale:

Four years

Funding and Personnel Requirements:

	2001	2002	2003	2004
	$60K	$100k	$100k	$50K
Project Mgmt	0.1	0.1	0.1	0.1
Elec. Engineer	1.5	2.5	2.5	2.0
Elec. Technician	1.5	2.5	2.5	2.0
Mech. Engineer	0.1	0.2	0.2	0.0
Machine Shop	0.3	1.0	2.0	1.0
Software Eng.	0.3	0.5	1.0	1.0
Staff Scientist	0.6	0.6	0.6	0.6
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Totals	4.4	6.4	8.9	6.7

April 2001

Beam-Forming Array Project Task Outline
April 2001

The beam-forming array project is an R&D effort with the goal of constructing a prototype array receiver for the GBT in the 1.3-1.7 GHz range that has sufficient sensitivity, bandwidth, and field of view to do competitive science. This document outlines the major development areas and indicates the questions that need to be answered and the risks involved.

Antenna-element/LNA module

The key to producing a sensitive receiver is the development of a dual polarized array antenna element that is well matched to a low noise HEMT amplifier over the required tuning range of the receiver. We are presently working on an accurate characterization of the impedance properties of the sinuous antenna that we think is the best candidate for covering the relatively broad bandwidth requirement of the receiver. This is a fairly new antenna so there isn't much design guidance in the literature. We presently have a design with about a 12 dB return loss over the full band, but we want to improve this to about 20 dB to ease the matching requirements of the HEMT amplifier. The placement of this antenna over a ground plane adds an extra frequency dependence to the impedance of this antenna, and we need to determine whether the spacing must be made mechanically variable to tune to different parts of the band.

The HEMT amplifiers will be in a balanced/balanced configuration. The signal from each of the four sinuous antenna arms will be amplified by a low noise balanced amplifier followed by a single stage MMIC amplifier. One linear polarization output is the anti-phase combination of two amplifier outputs from opposite arms of the antenna. A number of uncooled balanced amplifier prototypes have been built and tested, and the gain and phase balance and noise performance look good using a matched input. Design work remains to adapt the noise-optimized amplifier input impedance to the somewhat frequency-dependent real impedance and residual reactance of the antenna. Our first antenna/LNA element prototype used a short length of transmission line to allow the LNA to be mounted behind the ground plane, which adds some complexity to the impedance matching problem. We will be looking at the feasibility of mounting the LNA directly on the antenna terminals.

At the beginning of the project we will purchase an electromagnetic simulation software package to speed up the design iteration process. Our current EM package, "HFSS," cannot model this antenna with enough resolution to produce reliable results, and it certainly cannot handle the antenna in an array. We are talking to Bruce Veidt, at DRAO, for advice on the antenna simulation software selection.

Testing an antenna/LNA module is not an completely straightforward task because the success of matching the antenna and amplifier impedances is not apparent until the two are connected together over the ground plane. At that point the only input to the unit is through free space. A sufficiently well match absorbing enclosure with low leakage needs to be devised to confirm the final noise temperature of the module. The only available cold load may be the sky so ground plane spillover will need to be carefully controlled.

Other antenna types, such as fat dipoles, bow-ties, or tapered slots, will be considered if the sinuous antenna turns out to be unusable. But our current thinking is that the sinuous antenna will work.

Risks: 1. Can we achieve a sufficiently low return loss with the sinuous antenna? 2. A variable spacing ground plane will add complexity to the design so we hope that it is not required, but the question remains to be answered.

Focal plane vector field calculation

The proof-of-concept receiver showed that a 19-element array could form more than 10 reasonably efficient beams on the 140-ft telescope. The GBT prime focus edge illumination angle is 45 degrees as compared to 60 degrees on the 140-ft. This difference along with the offset geometry of the GBT will require more array elements to form one beam, but the exact number still needs to be calculated. The number of elements will also depend on the number of beams required for useful science. Our estimate is that a 37-element array will suffice for the prototype.

We wrote software for a scalar calculation of the 140-ft focal plane fields. This needs to be modified to produce vector field results and to accommodate the GBT's offset geometry. These calculations will probably tax our computing resources fairly heavily, but our 140-ft calculations indicate that the task is not overwhelming. Before modifying our own software we will check with Srikanth to see whether any of his antenna packages can be adapted to the job. Most antenna design software is designed for the reverse problem of computing far field reflector patterns from a given feed pattern.

This is a high priority task and will be executed early in the project.

Risk: The array size could be bigger and more expensive than anticipated.

Effects of the mutual coupling on element impedance

An added complication to the antenna-amplifier match problem comes from the fact that the impedance of the antenna is affected by its proximity to other elements in the array. For element spacings greater than a half wavelength, which we will be using, the effect will be modest but still important. Part of the antenna element/LNA matching task will be to model and measure the sinuous antenna in the presence of other antennas in the array. The initial prototype of an antenna element/LNA module will be done on the basis of an isolated antenna, but then the second step of module design will use the embedded antenna impedances. A seven-element array will be analyzed and tested for impedance effects before expanding to an array of at least 19 elements. The impedances will be somewhat different for elements at the edge of the array from the ones at the center so the amplifier matching circuits may need to be slightly different.
Risk: We don't think that converging on an optimum match between the amplifiers and

embedded antenna will take too long with the right design and measurement tools, but this is new ground for us.

Effects of correlated noise due to mutual coupling

At some level there will be receiver noise which is correlated between the array elements due to leakage of amplifier or circulator load noise into adjacent antennas. Correlator offsets due to this noise can be easily removed, but we have not yet investigated the full ramifications of mutual coupling in this regard. Initial measurements of mutual coupling of the sinuous antennas showed it to be no worse than -15 dB so the coupling-induced correlation of internal noise should be manageable. Our amplifier design will take the coupling issue into consideration. Clearly, many arrays with mutual coupling comparable to what we will encounter have been successfully designed and built. Where we are breaking new ground is in the second-order effects of correlated noise at low levels.

Risks: 1. The correlated noise could be higher than we anticipate, which would require at least one more iteration in the antenna-element/LNA module design. 2. Correlated noise could complicate the array calibration process.

Effects of mutual coupling on the reflector illumination pattern

Another manifestation of coupling between array antenna elements is that the effective far field pattern of each element is different from its pattern measured in isolation. This is due to the coherent addition of direct radiation to an element and a bit of radiation scattered from adjacent elements. Elements at the edge of the array will have a noticeably asymmetric pattern. At the very least the weights used to form beams for combinations of elements will need to account for the different illuminations of the reflector from different elements. We don't think that this is a major problem, but the measurements and calculations remain to be done.

Risk: Beams near the edge of the array's field of view could be less efficient than expected.

Array measurements on the antenna range.

A close and continuous cross check between antenna simulation and measured element patterns must be maintained throughout the development process. The present antenna range receiver is entirely inadequate for array characterization because it would take days, if not weeks of manual operation to cover the frequency range of the array and to measure all elements in both polarizations. A narrow-band signal processor must be designed and built to make simultaneous amplitude and relative phase measurements of all elements in the array. This will be a very minor version of the the beam-forming processor required by the finished receiver so the design experience will be a useful warm-up. We should also automate more of the antenna range operation to reduce the time and effort required for each measurement so that we don't have to cut corners in the design and testing cycle.

Risk: We have yet to make an accurate estimate of the effort required to design and built an array signal processor for the antenna range.

LNA cryogenics

It seems unlikely that we can cool the L-band array amplifiers in a single dewar with one or two cryostats. We have several ideas, including distributed cooling by piping closed cycle liquid nitrogen to the array elements or cooling the elements in groups of three or more in a common dewar and small cryostat. We'd like to try a few unconventional ideas in an attempt to simplify the cryogenics system considerably before adopting some modification of a more conventional dewar approach. We will also look at new technology, such as pulse tube coolers being studied by the ATA project. Since the cryogenics will have a substantial affect on the mechanical design of the antenna element/LNA module we will need to decide on a cryogenics method fairly early in the receiver development process.

For the moment we are assuming that a good receiver noise temperature can be achieved with cooling to the boiling point of liquid nitrogen (77K). This could simplify the cryogenics design considerably, but we need to do a detailed cost/performance study to determine whether the added expense of cooling to 20K is warranted. This will be closely tied to the antenna element/LNA module development task.

Risk: Cryogenics design and cost unknown at this point.

Optimization of beam-forming weights

We will be able to make a good estimate of the beam-forming complex weights from the simulations and receiver and antenna range measurements, but an accurate calibration method on the telescope using celestial sources must be devised for verification and final optimization. This requirement will affect the signal processor design and a stable, correlated, secondary noise source must be incorporated into the LNA. To avoid complicating the antenna-LNA match problem even further the calibration signal will probably be injected behind the first amplifier stage. HEMT amplifiers have proved to be sufficiently stable in gain and phase over many hours to allow the first stage to be outside the short-term calibration loop. Full calibration of the array and receiver will require a short and, hopefully, infrequent look at a moderately strong point source.
Optimization of beam-forming weights is a multidimensional search problem that may be best tackled with something like a genetic algorithm. Our focal plane field calculations and mutual coupling simulations and measurements will tell us how complex the search space is.

Risk: Development time for calibration and optimization procedures unknown.

I.F. module miniaturization

Each array antenna element requires its own receiver circuit, including RF and IF amplifiers, mixer(s), filters, and digital baseband sampler. The IF modules that we built for the proof-of-concept receiver are much too big for a fully functional receiver so a new design is required. Reliability of individual array elements is of paramount importance because the loss of one element disables all of the beams in which its signal participates. Replacement of a failed module must be fairly easy and straightforward. This points us in the direction of an integrated unit from the antenna to the sampler that includes a minimum of mechanical connectors. We also need to avoid bulky analog RF and IF filters. This suggests the use of simple analog filters followed by moderately high digital sample rates and digital filters. A complete analysis of receiver dynamic range and RFI filtering capabilities needs to be performed in connection with the IF module design.

We'd like to incorporate the new IF module into the antenna range test configuration of the array so this design will best be done early in the project.

Risk: None expected, but the approach will be a significant departure from current receiver designs.

Beam-forming scheme

There are two basic schemes for processing the array signals to form beams or to make a map of the array's field of view. One scheme is to add the complex voltage samples from a group of array elements with the proper weights to form a beam in a chosen direction. Each beam requires a different set of weights and its own summing process. For a given bandwidth this is probably the least expensive of the two schemes, but it does require that the beam-forming weights be known a priori. The output is a stream of voltage samples from each beam much the same as would come from a digital sampler tied to a horn feed. This is probably the most useful output for pulsar observing.
The other scheme is to compute, integrate, and store the cross products off all useful array element pairs, as is done with an aperture synthesis array, and compute the field-of-view map with appropriately weighted sums of the cross products. This has the advantage that the weights can be optimized off line after the data are stored on disk. The array may be calibrated with cross product data on a moderately strong point source.

Our current thinking is to design a hybrid processor that computes cross products in a relatively narrowband of, say, a few MHz for array calibration and some spectral line observations. For wider bandwidths the diect beam-forming scheme will be used.
Risks: 1. The hybrid architecture may prove to be too complex. 2. The affordable processing bandwidth remains to be determined.

Signal processing

We are fairly certain that a fully digital beam-forming approach is best. There is little doubt that hundreds of MHz can be processed digitally. The cost per dollar drops considerably with each new generation of digital technology. The main question that needs to be answered is how much bandwidth can we afford within the time frame of this project. A parallel effort to develop an analog beam former that might provide wider bandwidths for continuum applications appears to us to be unwarranted since it would be a temporary solution that will be abandoned as the digital solution gets cheaper.

There is a lot to be said in favor of using frequency-dependent element signal weights in the beam-forming process regardless of whether we adopt a cross-correlation or a direct beam-forming scheme. This suggests that an FFT engine will be attached directly to each element sampler. There appears to be no significant processing power penalty to this approach. One question to be answered is whether to use modest frequency resolution in this early FFT and subdivide the spectrum for higher spectral resolution in later stages or do the full spectral processing in one step. In any case, one of the first tasks that can proceed early in the project is the design of an FFT engine, very likely using field programmable gate array technology. We are in the process of acquiring FPGA development tools and expertise in Green Bank.

Because of the large number of array elements and beams on the sky the data rate and the number of independent signals from the beam-forming array will be quite high. The current GBT configuration of eight analog IF fibers is not well suited to transmitting array signals to the GBT control room. At least some of the array signal processing is best done in the GBT receiver room, but the exact configuration will be determined after a full system analysis. The possibility of avoiding the stability and dynamic range limitations of the analog IF fiber system is particularly attractive, but we need to come up with a scheme for transmitting substantial bandwidth in at least several tens of signals from the array receiver to the GBT control room.

Risk: The cost of signal transmission to the GBT control room remains to be determined.

Student involvement

We'd like to involve students interested in radio astronomy instrumentation, and we are actively seeking interest from the UVA astronomy and engineering departments. For the array project to proceed with some certainty we don't think that any of the student tasks can be in the critical path, but we can identify parallel research projects that could enhance the array R&D without affecting the development schedule. During the initial system design we will try to identify independent research projects that can be adopted by students over the next few years.

Task Schedule

Year 1 major tasks:

Development of antenna element/LNA module
Modeling of antenna element in the array
MDS modeling of array elements in circuit
Focal plane field calculations
Antenna range signal processor design and construction

Year 2 major tasks:

- Uncooled 7-element array measurement and evaluation
- Uncooled 19-element array measurement and evaluation
- Development of cooled antenna element/LNA module
- Design beam-forming electronics
- Design full element module, antenna through sampler

Year 3 and ½ of year 4 major tasks:

- Final design and construction of prototype receiver
  - Element modules
  - Beam-forming processor

Second ½ of year 4 major tasks:

- Prototype receiver tests

Personnel requirements (FTE persons):

	Year 1	Year 2	Year 3	Year 4
Project Management	0.1	0.1	0.1	0.1
Electronics Engineer	1.5	2.5	2.5	2.0
Electronics Technician	1.5	1.5	2.5	2.0
Mechanical Engineer	0.1	0.2	0.2	0.0
Machine Shop	0.3	1.0	2.0	1.0
Software Engineer	0.3	0.5	1.0	1.0
Staff Scientist(1)	0.6	0.6	0.6	0.6
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Totals	4.4	6.4	8.9	6.7

(1) Bradley 0.3, Fisher 0.3

Non-Personnel Spending Profile:

CY2001	CY2002	CY2003	CY2004
$ 60K	$100K	$100K(2)	$50K(2)

(2) Final cost of beam-forming processor depends on yet-to-be-determined cost of processing bandwidth in $/MHz and required bandwidth for useful science.

GBT Project Planning Meeting

Project	Project Management			Electronics & System Eng.			Electronic Technician			Mechanical Engineering			Machine Shop			Software Engineering			Staff Scientist			Totals			
	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003	All
Receiver/RFI Related Projects																									
3mm Rx modules 1 & 2	0.1	0.1	0.1	0.1	0.2	0.2		1	1					0.3	0.2		0.2	0.2				0.2	1.8	1.7	3.7
3CAM bolometer array																	0.2	0.2				0	0.2	0.2	0.4
External/User Built Projects:																						0	0	0	0
Caltech Ka-band Receiver				0.1	0.3			0.3								0.2	0.2					0.3	0.8	0	1.1
Bolomat (Upenn)																						0	0	0	0
EOR Rx (MIT)																						0	0	0	0
CH Rx (Uva/NRAO)																						0	0	0	0
K-band array (Australia)																									
RFI Excision Research (MRI)	0.1	0.1	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0.2	0.2	0.2	0.5	0.5	0.3	1.8	1.8	1.6	5.2
Local RFI Mitigation	0.1	0.1	0.1	0.5	0.5	0.5	1	1	1	0.1	0.1	0.1	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	2.3	2.3	2.3	6.9
Beam Forming Array (L-band prototype)	0.1	0.1	0.1	1.5	2.5	2.5	1.5	1.5	2.5	0.1	0.2	0.2	0.3	1	2	0.3	0.5	1	0.6	0.6	0.6	4.4	6.4	8.9	19.7
Rx Upgrades and Additions											0.1	0.4		0.2	0.4							0	0.3	0.8	1.1
Q-band Tertiary Mirror				0.3				0.2		0.2	0.3		0.2	0.4			0.2			0.05		0.7	1.15	0	1.85
Gregorian Feed Rotator					0.1			0.05		0.1	0.1			0.2			0.3					0.1	0.75	0	0.85
GBT Operations/Development																									
GBT Operations/Commissioning Support				6	5	5	2			0.1	0.1	0.1	0.2	0.1	0.1	4	2	2				12.3	7.2	7.2	26.7
Outfitting							7			0.1			0.4									7.5	0	0	7.5
Az track/LM Support										0.1			0.2									0.3	0	0	0.3
Pulsar Support				0.2			0.1				0.1			0.2		0.2	0.5					0.5	0.8	0	1.3
VLBI Support										0.1	0.1			0.2	0.1		0.2					0.1	0.5	0.1	0.7
Pointing/Focus Project (phase II/III)				0.1	0.5	0.5		0.4	0.4	0.4	0.3		0.7	0.8	0.2	1	1.2	1.2				2.2	3.2	2.3	7.7
Active Surface Project (phase II/III)				0.2	0.1	0.1	0.1	0.1	0.1	0.3			0.1	0.2	0.1	0.1	0.5	0.5				0.8	0.9	0.8	2.5
Electronics Projects:																						0	0	0	0
GBT servo system test set phase I	0.02			0.1			0.04															0.16	0	0	0.16
GBT servo system test set phase II	0.02			0.1			0.04						0.04	0.04								0.2			
NG Tracking station design																									
Replace site timing system clocks	0.01			0.04			0.02															0.07	0	0	0.07
Vibration monitoring of GBT wheels	0.02			0.1			0.1															0.22	0	0	0.22
Servo system Improvements				0.2	0.2	0.2	0.3	0.04	0.04													0.5	0.24	0.24	0.98
Indoor Antenna Range Outfitting	0.1			0.1			0.1				0.1			0.2								0.3	0.3	0	0.6
Software Projects:																						0	0	0	0
Proposal and Observation Mngmt.																0.2	0.5	0.5				0.2	0.5	0.5	1.2
Data Reduction Pipeline																		0.5				0	0	0.5	0.5
Remote Observing																		0.5				0	0	0.5	0.5
Data Archiving																	0.2	0.2				0	0.2	0.2	0.4
Other GB Telescopes																						0	0	0	0
85-3 Operations				0.04	0.04	0.04																0.04	0.04	0.04	0.12
OVLBI Operations				0.5	0.2		0.5	0.1														1	0.3	0	1.3
Tracking Station																						0	0	0	0
External NRAO support																						0	0	0	0
CDL / ALMA shop support										0.2	0.3	0.3	1	0.6	0.7							1.2	0.9	1	3.1
Totals:	0.57	0.4	0.4	10.7	10.1	9.54	13.3	5.19	5.54	1.8	1.8	1.1	3.44	4.74	4.1	6.4	7.1	7.2	1.2	1.25	1	37.4	30.6	28.9	96.7

Table 1
GBT Development Project Spend Profiles

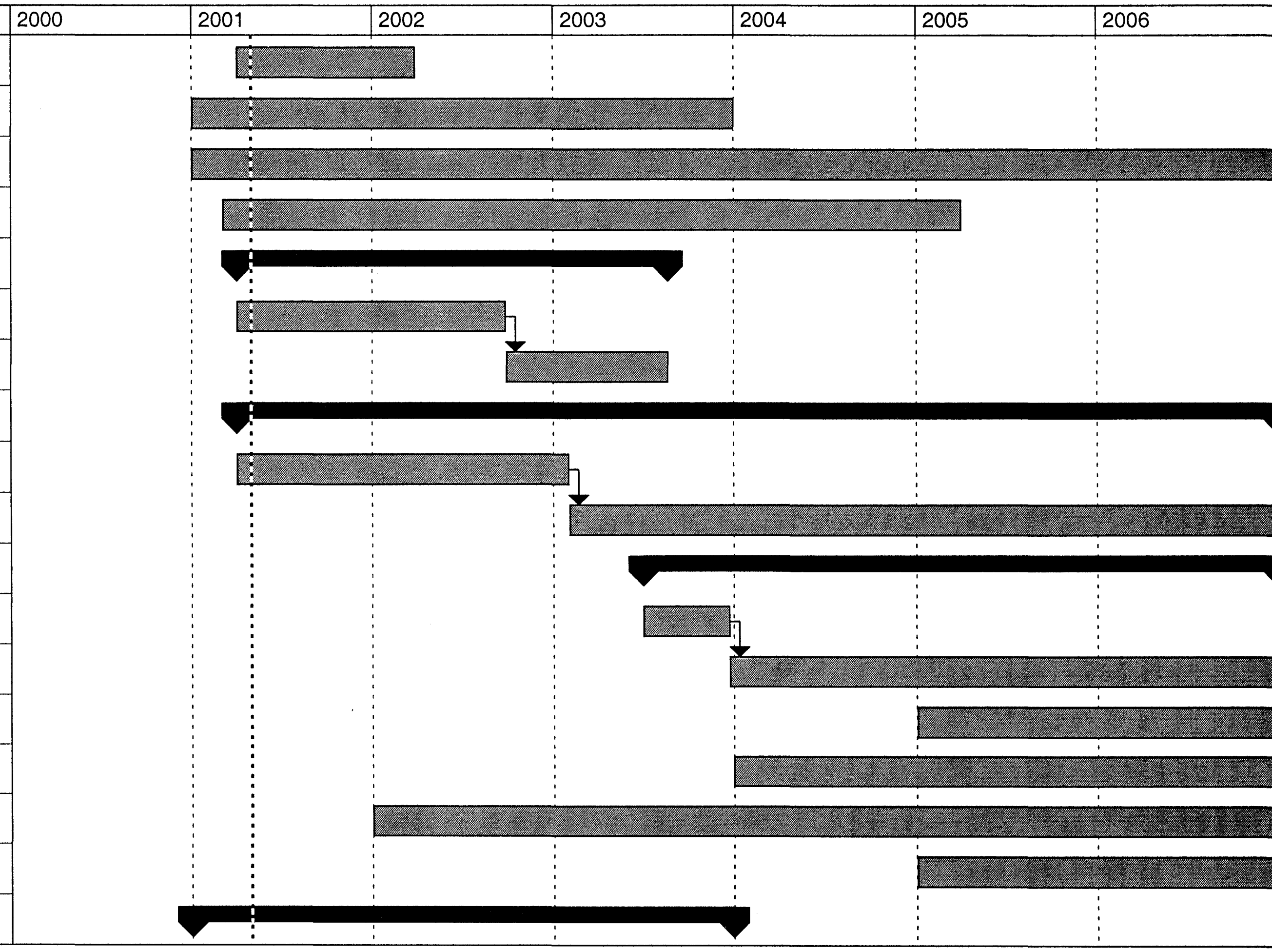
		Calendar Years					Total Cost	Total Cost
Project	**CY2000**	**CY2002**	**CY2003**	**CY2004**	**CY2005**	**CY2006**	**2002-06 (LRP)**	**2001-06**
Q-Band Tertiary Mirror	30	10					10	40
RFI Excision MRI Project							0	0
RFI Mitigation	60	30	25	25	25	25	130	190
Beam-Forming Array (L Band Prototype)	50	200	30	20			250	300
3 mm Rx	130	60					60	190
3CAM Bolometer Array	100	200	800	1000	1000	350	3350	3450
3 mm Focal Plane Array			50	400	100	50	600	600
Spectrometer / IF Upgrades					250	250	500	500
Wideband, multi-input spectrometer				250	100	50	400	400
Rx Upgrades & Additions	230	100	50	25	25	25	225	455
K-Band, Beam-Forming Array					150	250	400	400
External / User-built Projects	300	200	200				400	700
								0
Totals:	900	800	1155	1720	1650	1000	6325	7225

Table 2
GBT Long Range Facility Development Projects
Staff Effort Estimates

Project	Duration (yrs)	Capital Cost (k$)	Total Staff (FTEs)	Project Management	Electronics & System Eng.	Electronic Technician	Mechanical Engineering	Machine Shop	Software Engineering	Project Scientist
Q-Band Tertiary Mirror	0.8	40	1.0		0.3		0.3	0.3	0.2	0.05
RFI Excision MRI Project	2.0		3.4	0.2	1.5	1.5				0.2
RFI Mitigation	6.0	190	3.6	0.6	2.0	1.0				
Beam-Forming Array (L Band Prototype)	4.0	300	14.0	1.0	6.0	4.0	0.3	0.3	2.0	0.4
3 mm Rx	3.0									
Module 1	2.2	119	2.5	0.2	0.3	1.5		0.3		0.2
Module 2	0.8	71	1.1	0.1	0.2	0.5		0.2		0.1
3CAM Bolometer Array	5.0	3450	40.8	7.5	8.8	9.0	1.0	2.0	10.0	2.5
3 mm Focal Plane Array	3.0	600	9.7	0.8	2.0	3.5	0.3	1.5	1.0	0.6
Spectrometer / IF Upgrades	2.0	500	4.7	0.2	1.0	3.0		0.4		0.1
Wideband, multi-input spectrometer	3.0	400	4.9	0.3	1.5	2.5			0.5	0.1
Rx Upgrades & Additions	6.0	455	6.8	0.6	1.8	2.5	0.3	1.0		0.6
K-band Beam-forming array	2.0	400	4.4	0.2	1.5	2.0	0.2	0.3		0.2
External / User-built Projects										
Caltech/Cornell Pulsar Search Backend	0.3	15	0.5	0.0	0.2				0.2	0.05
Caltech Ka-Band Rx	1.5	300	1.1	0.1	0.3	0.3	0.2	0.3		0.05
BoloMat (UPenn)	0.5	200	1.1	0.1	0.3		0.2	0.3	0.2	0.05
UMass Redshift Machine	0.5	20	1.0	0.0	0.3		0.2	0.2	0.2	0.05
Other		165	0.5	0.5						
Totals:		7225	100.33	11.75	27.85	31.25	2.85	7.13	14.25	5.25

GBT Facility Development Projects

ID	Task Name
1	**Q Band Tertiary Chopper**
2	**RFI Excision MRI Project**
3	**RFI Mitigation**
4	**Beam-Forming Array**
5	**3 mm Rx**
6	Module 1 (68-95 GHz)
7	Module 2 (90-116 GHz)
8	**3CAM Bolometer Array**
9	Feasibility Study
10	Construction
11	**3 mm Focal Plane Array**
12	Design, planning
13	Construction
14	**GBT Spectrometer/IF Upgrades**
15	**Wideband, multi-input spectrometer**
16	**Receiver Upgrades & Additions**
17	**K-Band Beam-Forming Array**
18	**External / User-built projects**



Project: GB_Dev_Projects
Date: Sun 4/29/01

Task | Split | Progress | Milestone
Summary | Rolled Up Task | Rolled Up Split | Rolled Up Milestone
Rolled Up Progress | External Tasks | Project Summary