A Modular K-Band Focal Plane Array
for the Green Bank Telescope

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9/20//2007

1. EXECUTIVE SUMMARY

We propose to develop a K-Band Focal Plane Array (KFPA) receiver optimized for spectroscopic observation and mapping on the Robert C. Byrd Green Bank Radio Telescope. While no such receiver currently exists, the technology is well-established, making it feasible to put the instrument into active use relatively quickly for immediate benefit to the astronomical community. The prototype instrument will consist of 7 pixels in a hexagonal arrangement, but the design will be inherently modular – it would be easy and cost-effective to expand it to as many as 61 independent pixels with good performance.

The instrument proposed here will provide 1.8 GHz of instantaneous bandwidth for 7 dual-polarized beams. Initially, we will use the KFPA with the existing GBT IF optical transmission system and backend spectrometer. A crucial advantage to commissioning the KFPA with the existing IF and Spectrometer is that these systems are by now fully commissioned and well understood, so that we will not be faced with the difficulties of commissioning a new frontend and backend simultaneously. Use of the GBT spectrometer, however, will limit the bandwidth that can be processed simultaneously from this array to 800 MHz for 4 dual-polarized beams, or 50 MHz for all 7 dual-polarized beams. This will still provide the key capability of mapping the NH_3 (1,1) and (2,2) lines simultaneously, but it is clear that a more powerful spectrometer will ultimately be required for optimal use of this and other GBT focal plane arrays. Parallel efforts to develop this new backend capability are described in Section 8.

Table I below summarizes the heterodyne focal plane arrays currently used for astronomical observations. It is evident from this list that there is a large gap in frequency between the cm-arrays and the millimeter/sub-millimeter arrays. A K-band focal plane array on the GBT would thus provide a truly unique capability. The full 61-pixel KFPA would be the largest heterodyne focal plane array at any frequency.

TABLE I: Existing Heterodyne Focal Plane Arrays

FPA	Frequency	# of Beams	Beam Spacing (HPBWs)	T_{sys}
Parkes Multibeam (Parkes 64m)	1.23-1.53 GHz	13	2.1	21 K
ALFA (Arecibo)	1.225-1.525 GHz	7	2.0	27 K
Parkes Multibeam (Parkes 64m)	6.0-6.7 GHZ	7	2.0	25 K
SEQUOIA (FCRAO)	85-115 GHz	16	2.0	55-90 K (T_{rx})
BEARS (Nobeyama 45m)	82-116 GHz	25	2.7	75 K ($T_{rx, DSB}$)
HERA (IRAM 30m)	210-240 GHz	9	2.2	120 K (T_{rx})
HARP (JCMT)	325-375 GHz	16	2.0	130 K (T_{rx})
SMART (KOSMA 3m)	460-492GHz	4	2.0	150 K ($T_{rx, DSB}$)
SMART (KOSMA 3m)	800-880 GHz	4	2.0	400-600 K ($T_{rx, DSB}$)

The deliverables from the work described in this proposal will be as follows:

- a 7-element, dual-polarization, 18-26.5 GHz receiver with 1.8 GHz instantaneous analog bandwidth, integrated with the existing IF transmission system and GBT spectrometer
- a documented design and budget for expansion to a full 61-pixel array.

2. SCIENCE CASE

The Green Bank Telescope is a premier instrument for K band spectroscopy, with its large collecting area and sensitivity to extended, low surface-brightness emission. A seven-pixel spectroscopic array covering K band will open up areas of Galactic and extragalactic research to experiments that currently take prohibitively long to perform. A comprehensive discussion of the science case is presented in an accompanying document. Here we highlight just a few areas of research enabled by the array.

The 18-26 GHz range contains many astrophysically interesting molecular transitions. The planned design for this array will allow the mapping of the (1,1) and (2,2) rotational inversion lines of ammonia simultaneously with all pixels. Individually, these lines will yield insights into star-formation that have only recently begun to be exploited. The hyperfine structure of the ammonia inversion lines allows an excellent determination of the optical depth of dense molecular regions, such as those found in pre- and proto-stellar clouds (these clouds are typically several arcminutes in extent, well matched to the size of the array). Together, the two lines give a very good estimation of the rotational temperature within the clouds. Recent studies have begun to interpret the asymmetries found in the hyperfine lines of ammonia, which indicate the presence of a number of physical effects within molecular clouds. Non-LTE effects, and turbulent bulk motions as well as systematic motions such as infall and outflow, all may be traced and even differentiated by careful analysis of the single (1,1) ammonia transition. Important problems that may be addressed by the aforementioned analyses include the shape of the initial stellar mass function, the role of turbulence within star-formation, the contributions of the fragmentation and collapse scenarios to the overall star-formation rate and mass-function, and more accurate measurements of the contributions of thermal and turbulent motions to observed line-widths.

On a larger scale, ammonia is a valuable probe of molecular gas in extragalactic star-forming regions. This array will allow us to map the ammonia over the entire disk of nearby galaxies, not just in the central regions, yielding estimates of the temperature and density of dense gas across a range of physical environments.

In addition to ammonia, the array will be ideally suited to mapping distributions of the CCS molecule. Because of the ease with which CCS is dissociated and depleted it serves as a chemical “clock” which can be compared to the “old” molecule of ammonia, and can be a very effective probe of the age and conditions within young stellar objects. When both molecules are detected within the same region, they can be used to analyze the dynamics of a region, e.g., tracing differential rotation within molecular cores.

In addition to CCS and ammonia, the 18-26 GHz range is host to a large number of molecular emission lines which are only now beginning to be identified and understood. These lines are extremely sensitive to external conditions and so may be missed in single pointing observations. The proposed array will be able to map large areas of nearby molecular clouds, such as TMC-1, searching for chemical reservoirs that can serve as standards for understanding interstellar chemistry. Maps of clouds in specific molecular transitions and general explorations of chemistry are now especially relevant as large regions of the Galaxy are being studied in the near- to far-infrared regime by the Spitzer Infrared telescope. The GLIMPSE field contains a wealth of information on previously unidentified embedded young stellar sources. In addition, the near-infrared capabilities of the Spitzer telescope have identified many new photon dominated regions, the chemistry of which is a rich and as-yet poorly understood aspect of studies of the interstellar medium.

Finally, this array can be used to study highly-redshifted molecular lines (CO, HCN, etc.) in clusters of sub-mm galaxies at $z=3.4-5.4$. These observations will examine the role of galactic environment on the molecular properties of these galaxies and probe the physical conditions of molecular gas in clusters during the epoch of galaxy formation.

3. BASELINE TECHNICAL PLAN

The baseline instrument shall consist of six key subsystems: the feedhorn array, the cryogenic dewar, the cooled electronics, the Integrated Downconverter Modules (IDMs), the Local Oscillator Distribution and Monitor and Control Module (LODM&C), and the IF Transmission System. A conceptual layout of the baseline instrument is shown in Figure 1. Note that in order to process 7 dual-polarized beams without installing a new IF transmission system and spectrometer, the outputs from two pixels are multiplexed onto a single fiber channel. Thus, there will be two different kinds of IDMs in the array with different IF output frequencies, and an array of IF multiplexers which feed directly into the existing GBT IF Transmission System. A preliminary block diagram of the array elements (consisting of a feedhorn, cold electronics, and an IDM, hereafter referred to as a "pixel") is shown in Figure 2.

TABLE II: Baseline Instrument Specifications

Specification	Requirement
Frequency band	18-26.5 GHz (complete K-Band coverage)
T_{RX} (each beam, not including sky)	<25K (75% of band) <36K (entire band)
Number of beams	7
Polarization	dual, circular (axial ratio <= 1dB)
Sideband (image) rejection	>30 dB
Instantaneous RF bandwidth	1.8 GHz
Mass	<100 kg
Headroom	>30 dB (to 1 dB compression point)

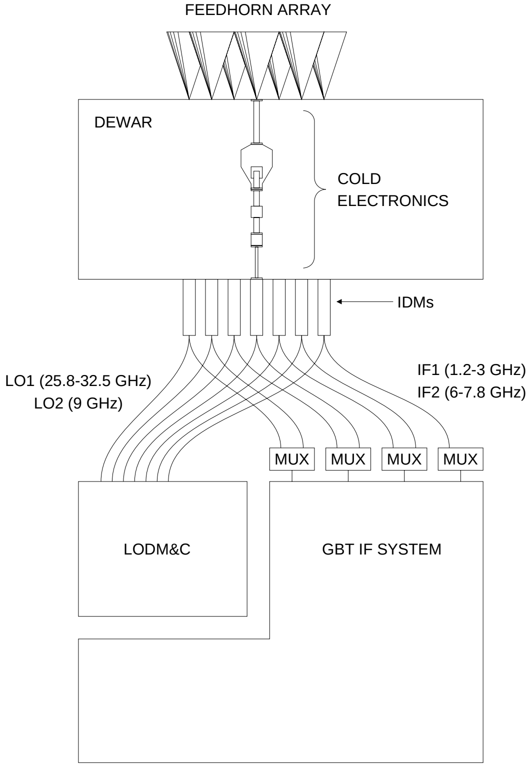


Figure 1. Conceptual configuration of the baseline K-Band focal-plane array receiver.

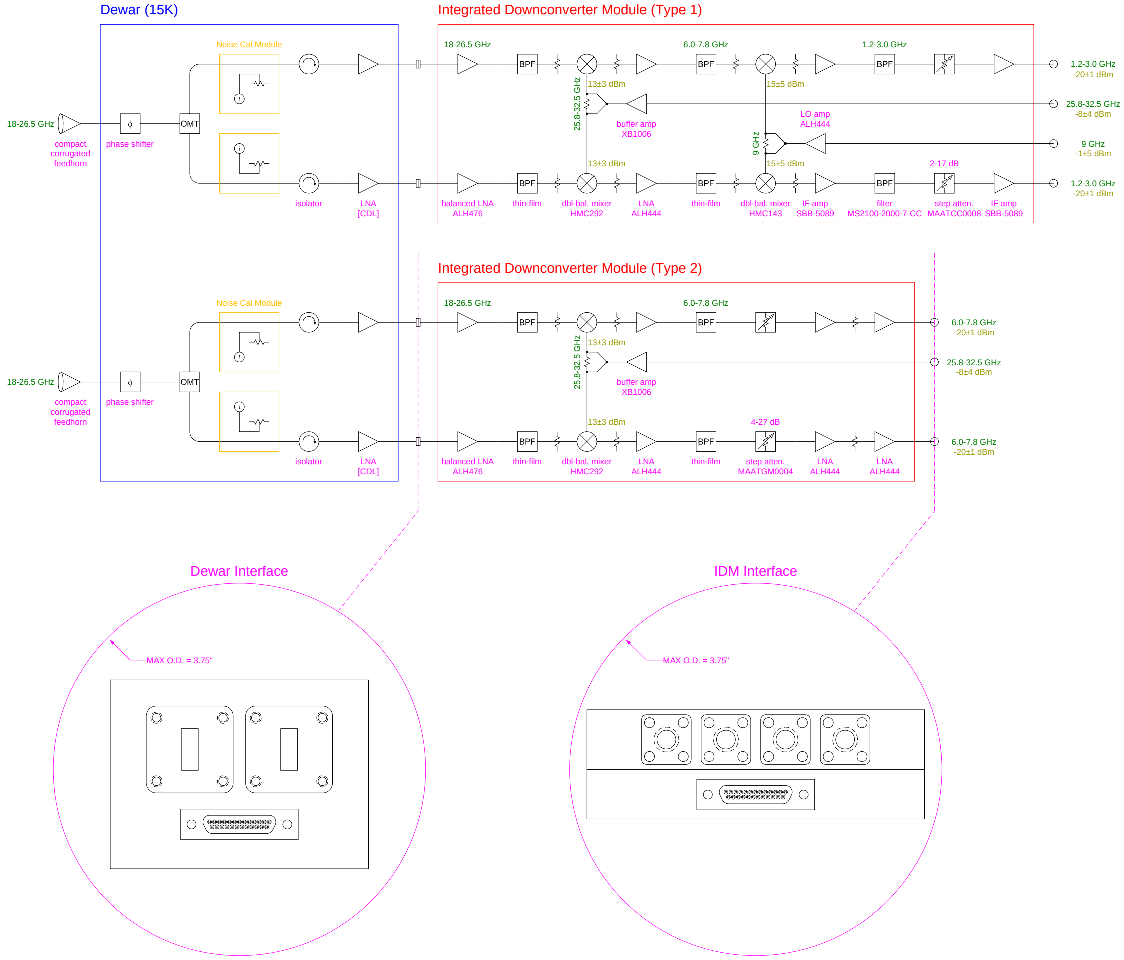
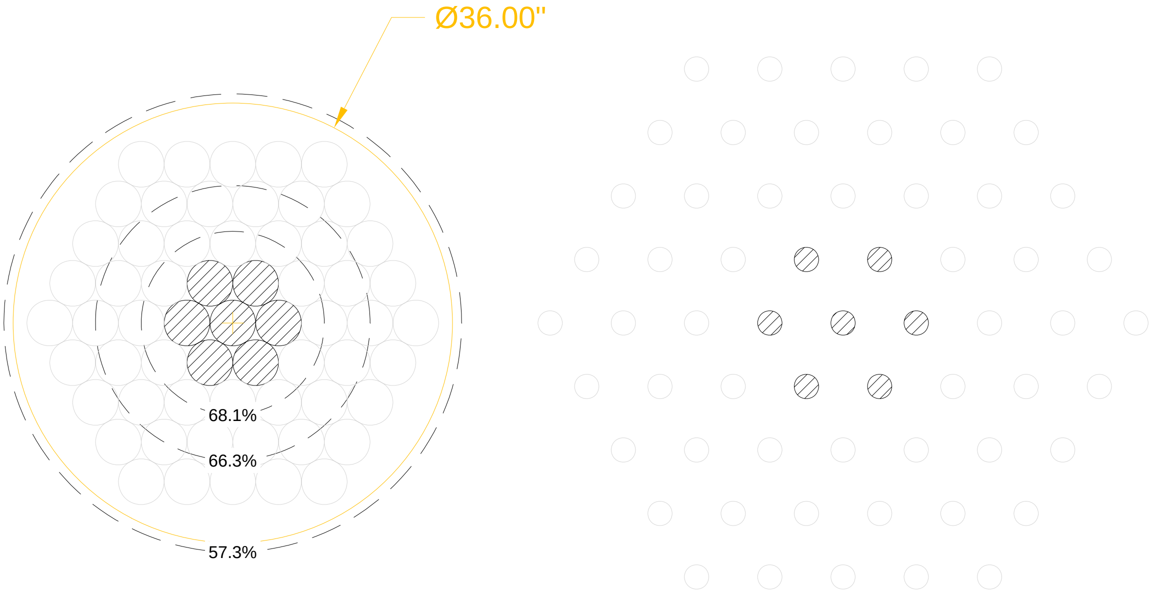


Figure 2. Block diagram of the two pixel types which constitute the focal plane array, showing the analog/RF signal processing components.

A short description of each of these subsystems follows.

a. FEEDHORN ARRAY

The feed horn array covering the 18-26.5 GHz band shall be located outside the dewar and thus will be at ambient temperature. Each of the elements shall be a compact corrugated horn having a profile taper from the throat to the aperture of the horn. Each horn will be followed by a phase shifter and an OMT located inside the dewar, giving dual-circular polarization capability. The array can be laid out in several ways, but the current plan is to arrange the elements in a closely packed hexagonal pattern (alternately staggered linear rows of pixels) for the most dense sampling of the focal plane. This is illustrated in Figure 3. The array elements covered by this proposal are shown by the dark, filled circles. The open circles represent future expansion. The spacing between elements is dictated by the outside diameter of the feed horn, which is 3.5" and results in a beam spacing of about three half-power beamwidths. A maximum efficiency (illumination and spillover) of 68% is predicted for the on-axis feed and the efficiency is nearly the same for the next two rings consisting of 19 elements. For the feeds at the edge of the mounting ring the aperture efficiency would drop to about 57%.



a) feed geometry **b) beam pattern on sky**

Figure 3. Feedhorn array geometry and resulting beam pattern. Aperature Efficiency as a function of offset from center is indicated by the dashed contours on the left. The first 7 elements comprising the prototype instrument covered by this proposal are shaded.

b. CRYOGENICS DEWAR

Preliminary studies seem to indicate that it is neither cost-effective nor efficient to cluster sub-arrays of pixels into smaller dewars and to then duplicate them. The baseline dewar shall therefore be built at full size, with room for expansion to a fully-populated focal plane (36" maximum diameter). The top and bottom of the dewar shall be sealed with cover plates having access holes in only those locations where the 7 pixels are initially populated. The top interface shall include a thermal gap and quarter-wave choke ring around each feed flange. See Figure 2 for a diagram of the pixel interface at the bottom bulkhead, which consists of a pair of WR-42 waveguides and a DC multi-pin connector for monitoring and bias lines. Expansion to the fully populated array may be achieved simply by making new holes for the additional pixels, or manufacturing new cover plates as required.

c. COLD ELECTRONICS

The dewar shall house, on its 15 K stage, a K-Band phase shifter and an OMT. Each output of the OMT shall be routed to an isolator, followed by a Noise Calibration Module (NCM) and the CDL K-Band LNA based on the WMAP design and using a CRYO3 wafer first-stage HFET. All of these components shall be co-located on the 15 K stage in the dewar. Stainless steel waveguide shall form a thermal transition for the connection to the dewar/IDM interface. The noise temperature of the LNA as a function of frequency is shown in Figure 4. The NCM will be a new integrated block consisting of a 30 dB directional coupler and a noise source. The noise source could be either a diode or a MMIC amplifier with calibrated ENR versus bias current.

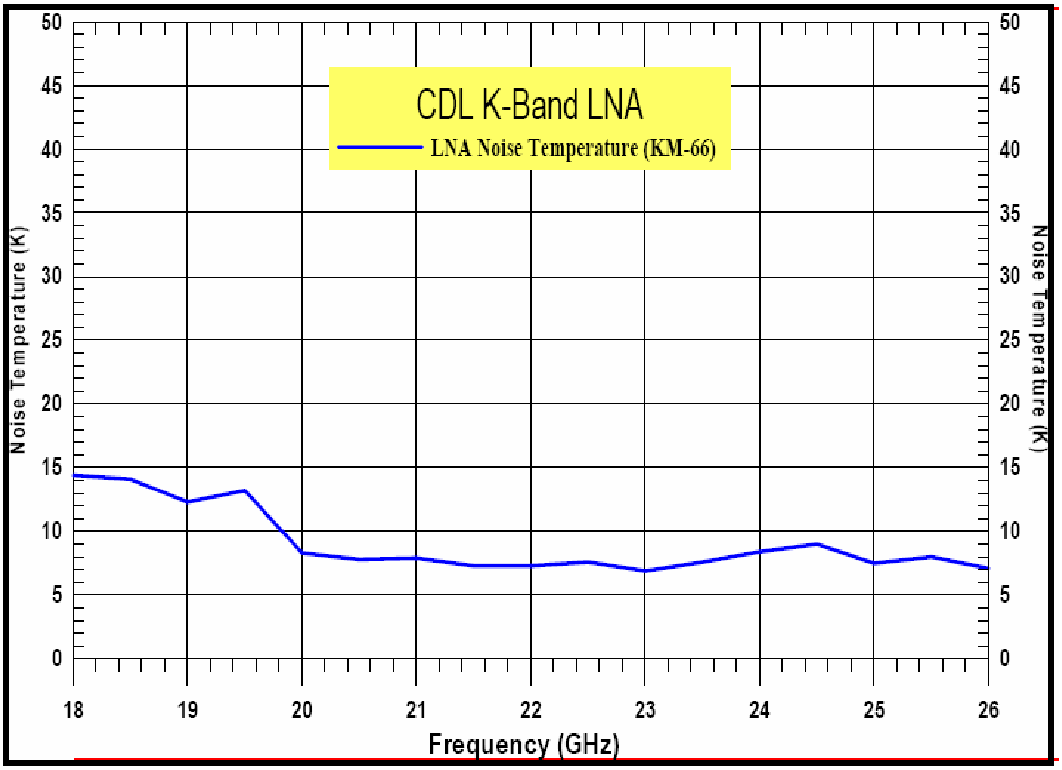


Figure 4. Measured noise temperature of the CDL K-Band LNA.

d. INTEGRATED DOWNCONVERTER MODULE (IDM)

The IDMs, which will operate at room temperature, shall be multi-chip split-block assemblies consisting of off-the-shelf MMICs identified in Figure 2. Since all of the required components are commercially available, these modules can be rapidly prototyped at low cost in the project development phase. For higher frequency bands some MMICs would need to be developed, and while this MMIC development is a valuable and ongoing CDL research project, it is not strictly required for the K-Band array.

The input stage of the IDMs shall be a room temperature low-noise amplifier. By selecting a balanced amplifier for this component, we hope to avoid the need for isolators between the room temperature and cooled parts of the receiver, but isolators could easily be added to the design at a later stage if found necessary.

There will be two types of IDMs, having two different IF output frequencies. This allows the IFs from two pixels to be combined onto a single fiber optic channel for transmission back to the spectrometer. The Type 1 IDM shall employ a super-heterodyne mixing scheme with the first IF at 6-7.8 GHz, and the final IF output at 1.2-3 GHz. The Type 2 IDM consists of only the first stage of mixing, with its final IF at 6-7.8 GHz. After downconversion, these channels are combined in a multiplexer and then fed to the existing GBT IF Transmission System. This will require only two LOs to implement, the first at 25.8-32.5 GHz, and the second at 9 GHz. Both LOs shall be provided in a coherent fashion to all of the array elements by the LODM&C. The mixing scheme described here has been designed to be as simple as possible, to use existing MMIC components, and to avoid any possible spurious tones from appearing in the observation band.

It should be noted that nothing in the cold electronics limits the instantaneous bandwidth to less than the full 18-26.5 GHz. The 1.8 GHz IF bandwidth is instead a fundamental limitation of the current GBT IF transmission system. When the IF transmission system and spectrometer are upgraded to process larger bandwidths (necessary if we wish to expand beyond the proposed 7 elements), it will be a simple matter to replace the current channelizing IDMs with the appropriate block-conversion IDMs. This was considered a more efficient solution than performing the block-conversion up-front followed by second narrower-bandwidth downconversion.

e. LOCAL OSCILLATOR DISTRIBUTION AND MONITOR AND CONTROL MODULE (LODM&C)

The LODM&C requires two inputs from the LO rack in the center of the receiver turret on the GBT. Two Agilent 83620A synthesizers are available to provide these inputs (one variable, the other fixed). A block diagram of the LODM&C is shown in Figure 5. Like the IDMs, this subsystem shall be constructed using commercial off-the-shelf parts, and is modular in design for later expansion.

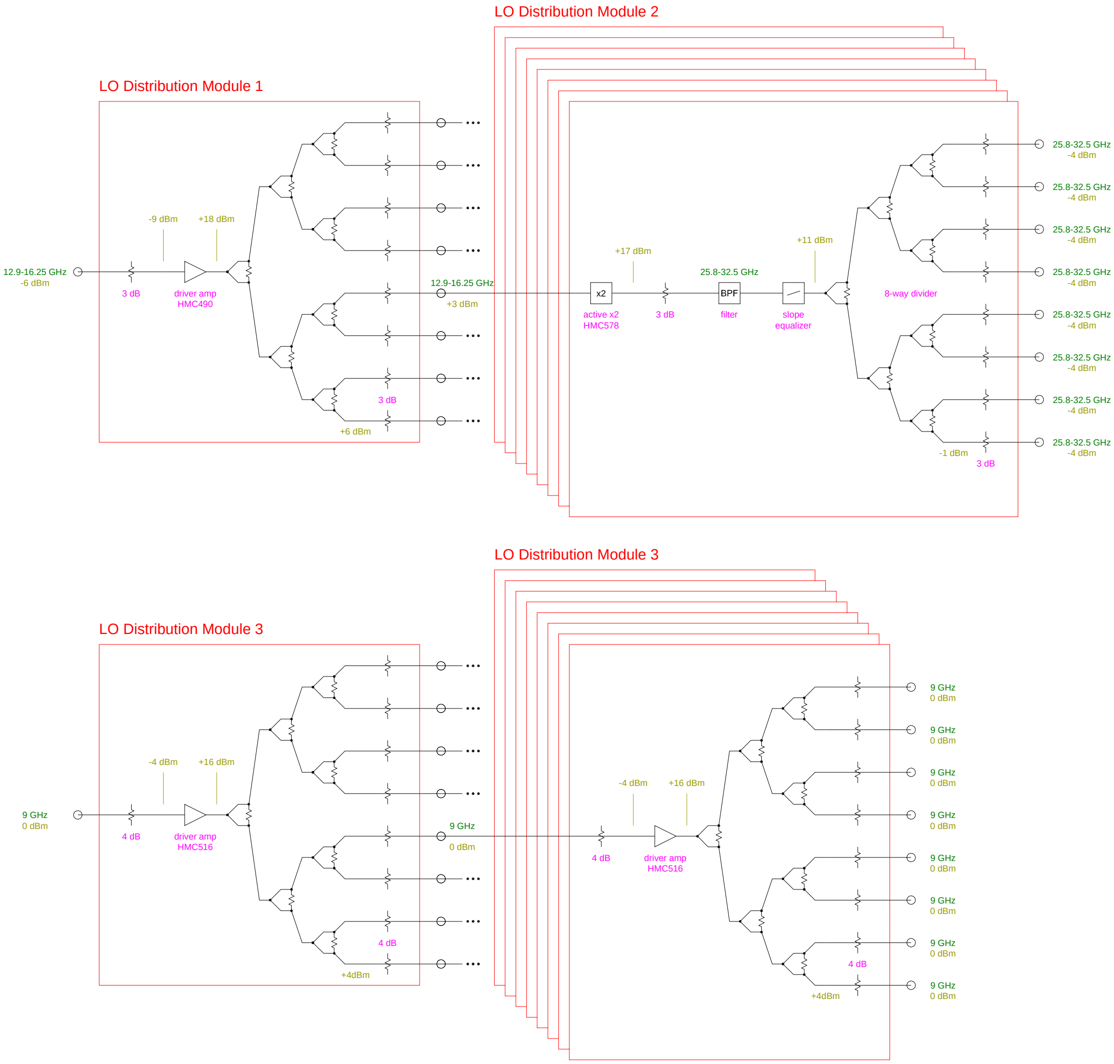


Figure 5. Block diagram of the LO Distribution Modules.

The Monitor and Control system shall be responsible for providing regulated bias voltages to the elements in the array, monitoring the health of key components such as the LNAs, and coordinating time-sensitive events such as noise-cal switching and LO sweep.

f. IF TRANSMISSION SYSTEM

The existing GBT IF Transmission system will be used unaltered for this instrument. In order to make 7 beams fit, the outputs of the pixels will have to be multiplexed. As the two IF output ranges of the IDMs are well-spaced in frequency, the requirements on the multiplexers are very light. Only 3 multiplexers are needed for the current proposed instrument containing 7 pixels.

4. BASELINE BUDGET

The following cost estimate is given in Y2007 dollars. The FTEs in the first four labor columns will be charged to the LM funds allocation. These represent a mix of existing NRAO staff (primarily at CDL) or, in the case of software and astronomy, potential new hires since existing staff in these disciplines are overstretched. The fifth column indicates existing GB staff whose efforts will be funded from the ongoing Green Bank Operations budget.

TABLE III: Labor Estimates for Year 1

Item	**Machinist [FTEs]**	**Technician [FTEs]**	**Astronomer [FTEs]**	**Engineer [FTEs]**	**Eng&Tech GB ops [FTEs]**
Compact Feedhorn	0.2	0.0	0.0	0.2	0.0
Noise Calibration Module (NCM)	0.25	0.25	0.0	0.25	
Integrated Downconverter Module (IDM)	0.1	0.25	0.0	0.5	0.0
LO Distribution	0.1	0.0	0.0	0.0	1.0
M&C, biasing, PCB design and layout	0.0	0.0	0.0	0.0	1.0
Mechanical design (overall receiver, cryostat)	0.25	0.0	0.0	0.0	0.75
Parallactic Angle Rotator	0.25	0.0	0.0	0.0	0.5
Project management	0.0	0.0	0.0	0.0	0.25
Systems engineering	0.0	0.0	0.0	0.25	0.0
Project scientist	0.0	0.0	0.5	0.0	0.0
Software Development	0.0	0.0	0.0	0.5	0.0
Total FTEs:	1.15	0.5	0.5	1.7	3.5
Funded Total = $368k **Total GB Ops = $302k**					

TABLE IV: Labor Estimates for Year 2

Item	**Machinist [FTEs]**	**Technician [FTEs]**	**Astronomer [FTEs]**	**Engineer [FTEs]**	**Eng&Tech GB ops [FTEs]**
NCM housing and assembly	0.1	0.1	0.0	0.1	0.0
IDM housing and assembly	0.0	0.25	0.0	0.25	0.0
Project management	0.0	0.25	0.0	0.0	0.125
Systems engineering	0.0	0.0	0.0	0.25	0.0
Receiver assembly and cabling	0.25	0.0	0.0	0.0	1.0
Project scientist	0.0	0.0	1.0	0.0	0.0
Software Development	0.0	0.0	0.0	0.5	0.0
Total FTEs:	0.35	0.6	1.0	1.1	1.125
Funded Total = $295k **Total GB Ops = $133k**					

TABLE V: Labor Estimates for Year 3

Item	**Machinist [FTEs]**	**Technician [FTEs]**	**Astronomer [FTEs]**	**Engineer [FTEs]**	**Eng&Tech GB ops [FTEs]**
Receiver Engineer	0.0	0.0	0.0	0.0	0.25
Project scientist	0.0	0.0	1.0	0.0	0.0
Software Development	0.0	0.0	0.0	0.5	0.0
Total FTEs:	0.0	0.0	1.0	0.5	0.25
Funded Total = $160k **Total GB Ops = $ 34k**					

TABLE VI: Parts Cost

Part	**Qty.**	**Unit cost**	**Extended cost**
Feedhorns	7	$ 2.0k	$ 14.0k
Phase shifters and transitions	7	$ 7.0k	$ 49.0k
OMTs	7	$ 2.0k	$ 14.0k
Isolators	14	$ 0.5k	$ 7.0k
NCM parts	14	$ 0.8k	$ 11.2k
LNAs	14	$ 3.0k	$ 42.0k
IDM parts	7	$ 2.9k	$ 20.3k
LODM&C parts	1	$ 5.0k	$ 5.0k
Refrigerator	1	$ 8.0k	$ 8.0k
Parallactic Angle Rotator	1	$19.5k	$ 19.5k
Funded Total = $190k			

NOTE: These labor and parts costs are based on extensive experience with similar components, such as the EVLA cooled amplifiers and the ALMA Active Multiplier Chains.

TABLE VII: Final Cost Summary

Item	**LM Budget**	**Total Cost**
Total Funded Labor	$ 824k	$ 824k
Total GB Operations Labor	$ 0	$ 468k
Total Parts Cost	$ 190k	$ 190k
Contingency	$ 202k	$ 202k
Total	$1216k	$1684k

The final cost of this project thus comes in at about $1.684M. Note that the cost per pixel in production quantities is about $88k (Y2007 dollars), so a rough cost for adding the future 54 pixels is $4.75M (conservatively, since some of these modules do not scale with array size, like the LODM&C, and the parts cost would be reduced in large quantity). This estimate assumes that most of the production efforts are from year two. This would, of course, also require a new spectrometer.

5. DEVELOPMENT PLAN

a. FEEDHORN/PHASE-SHIFTER/OMT

A feedhorn covering the 18-26.5 GHz bandwidth for the GBT does not exist, so one needs to be developed. However, as it is very similar to existing feedhorns in other bands, the development is low-risk and can be completed in a relatively short time.

Fortunately, quadrature phase shifter [RD3] and OMT designs [RD4] suitable for this application already exist. The OMT is approximately 2.8" wide, and with the addition of a standard E-plane bend and a 90° twist can be made to conform to the output waveguide layout at the dewar interface shown in Figure 2.

The feedhorns will not be cooled. Although doing so would potentially improve the receiver noise temperature by 20%, this adds a number of significant technical challenges to the cryogenics system and increases the cost of the project. After careful consideration of the costs and benefits of this approach, the decision was made that leaving the feedhorns outside the dewar would prove the optimum solution for large-format focal-plane arrays.

b. INTEGRATED DOWNCONVERTER MODULES (IDMS)

Although we already possess the expertise and know-how to build all of the individual components (case in point, our state-of-the-art low-noise single-pixel receivers on the EVLA), some development effort will be needed to integrate these components in an optimal fashion for use in a multi-pixel focal plane array. The front end electronics should be compact and integrated as much as possible, to ensure not only the closest array packing but also to reduce the cost of manufacturing large numbers of pixels.

In the given block diagram, all the MMICs used in the IDMs are commercially available, so no MMIC development will be necessary. These include the second-stage RF amplifiers as well as the down conversion stages providing the 1.2-3 GHz and 6-7.8 GHz outputs, as well as level setting attenuators.

Although the IF processing given in this proposal allows use of 1.8 GHz of dual-polarization spectrum per pixel, the outputs from the cryostat contain the full 8 GHz per pixel. In the future, a more complex IF processing and digitization scheme could be used (the ultimate being a 17 Gs/sec digitizer), along with an advanced spectrometer, to observe the entire 18-26.5 GHz simultaneously with high frequency resolution. This addition would require no change to the cold electronics system.

c. NOISE CALIBRATION MODULE (NCM)

To simplify the plumbing inside the dewar, we plan to integrate the broadband noise source within the coupler housing, requiring only a DC bias line to be routed to the outside. The noise source can be either a MMIC amplifier with known and fairly constant noise temperature over the specified band, a commercial noise diode, or a simple Schottky diode. Cold tests will be required to determine the best components to use for this scenario. The coupling should be weak, say about -30 dB, and the level of injected noise should be about 10% of T_{sys}.

d. CRYOGENIC LOW-NOISE AMPLIFIERS

The baseline design shall employ the CDL K-band LNAs, based on the WMAP design, but upgraded with a CRYO3 wafer device for its first stage. These have been tested and are being integrated into the EVLA receivers. This design yields the best reported noise temperature, about 7K over most of the band. While a MMIC design would be attractive for a focal plane array, at K-band there is currently no competitive MMIC.

e. MECHANICAL DESIGN AND CRYOGENICS

In order to meet the mass budget of less than 100 kg, some effort will need to be spent on making the receiver as light as possible. The dewar would require some attention since it needs be large to accommodate future pixels, and making the dewar as short as possible should help. Mechanical design and drawings of the entire receiver assembly and interfaces will also need to be prepared. The array receiver should of course be mechanically compliant with the GBT receiver mounting ring and power systems. Further, it has been anticipated that any focal plane array on the GBT will require a parallactic angle rotator, which is included in the baseline plan.

A CTI 1020 refrigerator has been selected for the baseline plan. This is compatible with the existing refrigerator power supplies on the GBT. The NRAO has a long history of using the CTI 1020 and it has a known and very good lifetime and maintenance record. With this refrigerator and the expected heat loads from a 61 pixel array (about 17 W on the first stage), the allowable power dissipation is 180 mW/pixel if they operate at 20 K, or 120 mW/pixel if they operate at 15 K. The anticipated power dissipation is only 36 mW/pixel (18 mW per amplifier). Thus, cooling the entire array in one dewar appears feasible.

Significant thought will be given to how all the pieces of the array are assembled. Not only must all of the parts fit in a close-packed arrangement, but the necessary mounting flanges and fasteners will have to be accessible to permit careful assembly, maintenance, and repair. Many existing focal plane arrays have encountered difficulty with this too-often underestimated issue. The lessons learned from this experience in particular will be invaluable when the observatory undertakes the development of other focal plane arrays, say at 3 mm where the elements will be even more densely packed.

6. THE GBT SPECTROMETER AS A BACK END

The existing GBT spectrometer has four modes of operation which will support the proposed array. It can be configured to provide 16 spectral windows, each of 50 MHz total width and 16384 channels, giving, at 22 GHZ, a total velocity coverage of 680 km/s at a channel spacing of 0.04 km/s. This is a good match to surveys in the Galactic plane and allows in-band frequency switching as well. For observations where greater velocity resolution is desired the spectrometer will support a mode with 16 spectral windows each of 12.5 Mhz bandwidth and 16384 channels which gives, at 22 GHz, a total velocity coverage of 170 km/s at 0.01 km/s channel spacing. This is likely to be the main mode for study of individual molecular clouds.
Two broad-band modes are available with the spectrometer, though at the cost of a reduced number of spectral windows. The spectrometer can provide 8 spectral windows at either 200 MHz total bandwidth with 8k channels or 800 MHz total bandwidth with 2k channels. At 22 GHz these modes give 2700 km/s at 1.3 km/s channel spacing, and 11,000 km/s at 5.3 km/s channel spacing, respectively. The broad band modes are well matched to observations of extragalactic molecular clouds, galactic nucleii, and high-redshift molecular lines.

The compatibility of the GBT spectrometer with K-band science is no accident – it was designed nearly 15 years ago with this in mind. For a focal plane at a much higher frequency, however, it would be seriously inadequate.

7. PROJECT PLAN

This shall be a joint project between the observatory's Central Development Laboratory (CDL) and Green Bank facilities. The CDL possesses the technical expertise to develop the feed, LNAs, and downconverter electronics, while Green Bank has the first-hand knowledge of the telescope necessary to design the cryostat and instrument interfaces, as well as to perform the receiver integration and testing. Green Bank will further provide technician and shop support for the development effort.

A preliminary schedule of the major tasks for this project is shown in Table VIII. A start date of 1st October 2007 is feasible given authorization to proceed.

8. Backend Development and Upgrade Path

As described, the project proposed here will provide 7 dual-polarized pixels with 1.8 GHz instantaneous bandwidth, which can be used with the existing GBT IF system and Spectrometer. This will provide powerful new capabilities on a rapid timescale, and is an exciting new development in its own right. However, to harness the ultimate potential of the GBT at K-band additional developments should be considered. These are outside the scope of the existing proposal, but included in the GBT Long Range Plan.

A new Spectrometer based on the CICADA development program: The CICADA (Configurable Instrument Collaboration for Agile Data Acquisition) development program is an NRAO-GB led collaboration between NRAO, the UC Berkeley CASPER group and others to develop next generation digital backends using FPGAs and the agile approach developed by the CASPER group. The project currently underway is a new pulsar backend (colloquially known as "Scott's Dream Machine"). However, another deliverable of the first year of CICADA development will be the design of a Spectrometer which could cover the full 1.8GHz bandwidth for each of the seven dual-polarization K-band feeds. The approximate cost of the full system would be in the range of $500-800k. Construction of this could commence in FY2009 were funds available. We are actively seeking potential partners, including the U. Maryland Electrical Engineering department, to collaborate on this project. However, to the extent that any contingency funds are not required for the frontend development, we would use these to purchase hardware for the initial stages of the new spectrometer; even one pixel's worth would provide significant new capacity over the existing GBT Spectrometer.

New data (IF) transmission system: The seven-pixel K-band array will use the existing GBT analog fiber to transmit the IF signal from the receiver cabin to the GBT Spectrometer in the control room. However, this will represent the limits of the capacity of that system. To expand to additional pixels will require a new approach to digitizing, transmitting and processing the data from a larger array (at K-band or any other wavelength). Digital signal processing developments relevant to radio astronomy instrumentation are moving at a breakneck pace, driven by SKA demonstrators and similar projects. We would intend to take advantage of those developments, with significant local efforts starting in FY2010.

Expansion of the K-band array to 61 pixels. This would be a straightforward extension of the current 7-pixel project, essentially replicating the production pixels unchanged. The precise cost will depend upon results from the seven pixel version, but as indicated is likely to be in the range of $4.75M. This work could commence in FY2011.

~ 100 pixel W-band (68-92GHz) array receiver. A W-band receiver on the GBT, with 8" angular resolution and 2000m^2 effective collecting area would be extremely powerful; the recently developed science case for such a receiver is absolutely compelling. This instrument would be built in collaboration with a consortium of university groups; preliminary discussions are underway.

9. COLLABORATIONS AND APPLICATION TO OTHER WORK.

Although this frontend project will be self-contained within the observatory, we are actively pursuing collaborators for the wider focal plane array program. We have already mentioned interest from the U. Maryland EE department on potential backend collaborations. The University of Calgary Radio Astronomy Lab (UCRAL) have explicitly expressed interest in collaborating in the area of pipeline processing (the NRAO e2e division is involved in these discussions). A group lead by Tony Readhead (Caltech) and Todd Gaier (JPL) are planning to develop a W-band FPA for the GBT, and we will work closely with them to ensure our development work is well coordinated. Thus the K-band array proposed here will be not only an powerful instrument in its own right, but also a necessary first step in the development of larger and more capable instruments.

All of the technology developed under this program will also be directly relevant to future NRAO projects, and specifically the SKA. A key enabler for the SKA will be effective component packaging, and control of unit costs. Experience developed during the execution of this project will be directly applicable. Advanced Digital Signal Processing is also a key area where NRAO must catch up with, if not advance the state of the art. Finally, all of NRAO's new instruments require advances in data pipelining and image processing, and the development of such techniques in the context of the KFPA, including both internal NRAO and external collaborations, will also be of benefit in other areas.

10. ACKNOWLEDGMENTS

This proposal has benefited from extensive discussions with many NRAO scientific and technical staff. The primary contributors to this proposal are: Matt Morgan, Eric Byerton, Karnaljeet Saini, Sri Srikanth, Roger Norrod, John Ford, Richard Prestage, Jay Lockman, Larry Morgan, D.J. Pisano, and Steve White.

11. REFERENCES

[RD1] "A 3 mm Receiver for the GBT," GBT 3 mm Receiver Working Group, 06-March-2000. http://www.gb.nrao.edu/electronics/projects/3mmRx/3mmrx_proposal.pdf

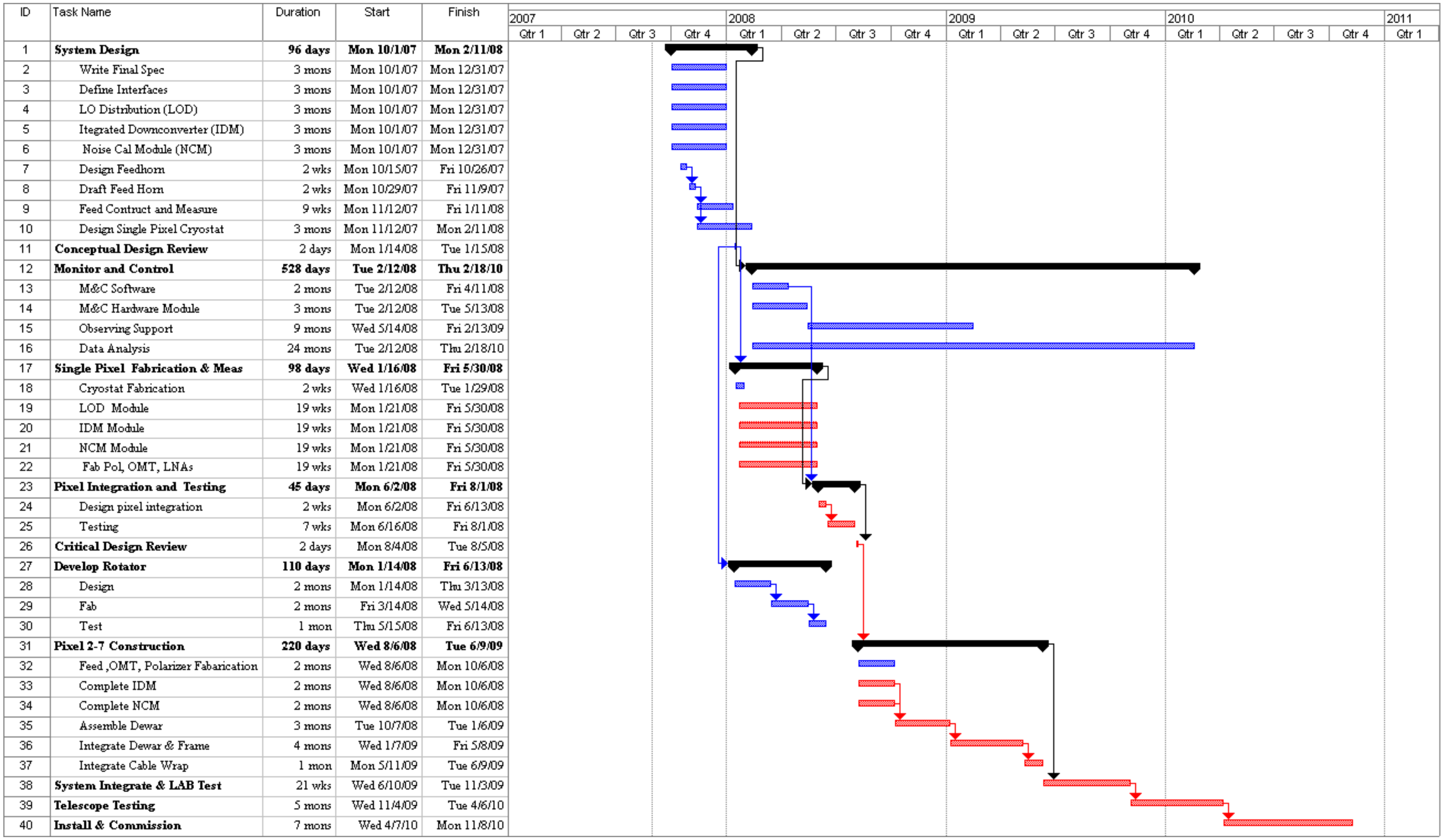
[RD2] "A Survey of OMTs," Anthony R. Kerr, 08-December-2006 revised 06-March-2007. http://www.cv.nrao.edu/~akerr/OMTsurvey2006-exp.ppt

[RD3] "A Wideband Corrugated Rectangular Waveguide Phase Shifter for Cryogenically Cooled Receivers," Sri Srikanth, IEEE Microwave and Guided Wave Letters, vol. 7, pp. 150-152, June 1997.

[RD4] "A Full Waveguide Band Orthomode Junction," Ed Wollack, Electronics Division Internal Reports #303, 16-May-1996. http://www.gb.nrao.edu/electronics/edir/edir303.pdf

[RD5] "A Radio Multi-Object Spectrograph," C. Carilli, G. Watts, and R. Fisher, internal memo

TABLE VIII: Program Schedule



ID	Task Name	Duration	Start	Finish
1	**System Design**	**96 days**	**Mon 10/1/07**	**Mon 2/11/08**
2	Write Final Spec	3 mons	Mon 10/1/07	Mon 12/31/07
3	Define Interfaces	3 mons	Mon 10/1/07	Mon 12/31/07
4	LO Distribution (LOD)	3 mons	Mon 10/1/07	Mon 12/31/07
5	Itegrated Downconverter (IDM)	3 mons	Mon 10/1/07	Mon 12/31/07
6	Noise Cal Module (NCM)	3 mons	Mon 10/1/07	Mon 12/31/07
7	Design Feedhorn	2 wks	Mon 10/15/07	Fri 10/26/07
8	Draft Feed Horn	2 wks	Mon 10/29/07	Fri 11/9/07
9	Feed Contruct and Measure	9 wks	Mon 11/12/07	Fri 1/11/08
10	Design Single Pixel Cryostat	3 mons	Mon 11/12/07	Mon 2/11/08
11	**Conceptual Design Review**	2 days	Mon 1/14/08	Tue 1/15/08
12	**Monitor and Control**	**528 days**	**Tue 2/12/08**	**Thu 2/18/10**
13	M&C Software	2 mons	Tue 2/12/08	Fri 4/11/08
14	M&C Hardware Module	3 mons	Tue 2/12/08	Tue 5/13/08
15	Observing Support	9 mons	Wed 5/14/08	Fri 2/13/09
16	Data Analysis	24 mons	Tue 2/12/08	Thu 2/18/10
17	**Single Pixel Fabrication & Meas**	**98 days**	**Wed 1/16/08**	**Fri 5/30/08**
18	Cryostat Fabrication	2 wks	Wed 1/16/08	Tue 1/29/08
19	LOD Module	19 wks	Mon 1/21/08	Fri 5/30/08
20	IDM Module	19 wks	Mon 1/21/08	Fri 5/30/08
21	NCM Module	19 wks	Mon 1/21/08	Fri 5/30/08
22	Fab Pol, OMT, LNAs	19 wks	Mon 1/21/08	Fri 5/30/08
23	**Pixel Integration and Testing**	**45 days**	**Mon 6/2/08**	**Fri 8/1/08**
24	Design pixel integration	2 wks	Mon 6/2/08	Fri 6/13/08
25	Testing	7 wks	Mon 6/16/08	Fri 8/1/08
26	**Critical Design Review**	2 days	Mon 8/4/08	Tue 8/5/08
27	**Develop Rotator**	**110 days**	**Mon 1/14/08**	**Fri 6/13/08**
28	Design	2 mons	Mon 1/14/08	Thu 3/13/08
29	Fab	2 mons	Fri 3/14/08	Wed 5/14/08
30	Test	1 mon	Thu 5/15/08	Fri 6/13/08
31	**Pixel 2-7 Construction**	**220 days**	**Wed 8/6/08**	**Tue 6/9/09**
32	Feed ,OMT, Polarizer Fabarication	2 mons	Wed 8/6/08	Mon 10/6/08
33	Complete IDM	2 mons	Wed 8/6/08	Mon 10/6/08
34	Complete NCM	2 mons	Wed 8/6/08	Mon 10/6/08
35	Assemble Dewar	3 mons	Tue 10/7/08	Tue 1/6/09
36	Integrate Dewar & Frame	4 mons	Wed 1/7/09	Fri 5/8/09
37	Integrate Cable Wrap	1 mon	Mon 5/11/09	Tue 6/9/09
38	**System Integrate & LAB Test**	21 wks	Wed 6/10/09	Tue 11/3/09
39	**Telescope Testing**	5 mons	Wed 11/4/09	Tue 4/6/10
40	**Install & Commission**	7 mons	Wed 4/7/10	Mon 11/8/10