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

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## 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 required is well-established, making it feasible to put the instrument into active use relatively quickly for immediate benefit to the astronomical community. The initial design conservatively calls for a modest number of pixels (approximately 10), but the design will be inherently modular, facilitating easy and cost-effective expansion to as many as 61 independent elements.

Table I below summarizes heterodyne focal plane arrays currently used for astronomical observations. It is evident from this list that there is a large gap in frequency coverage between the 21cm multibeam 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 also be the largest heterodyne focal plane array in terms of number of beams 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 |
| 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 ($T_{rx}$) |

While the instrument as currently proposed is compatible with existing GBT spectrometers, it will be severely limited in the number of beams that can be processed simultaneously. At most 8 IF channels (8 beams in one polarization or 4 dual-polarized beams) can be processed with the current spectrometer and IF data transport system. It is clear that a more powerful spectrometer (in terms of the number of channels, or total processed bandwidth) is critically important for this and other focal plane arrays. We believe such a spectrometer to be a beneficial and important development in its own right, independent of this array, and thus a parallel effort for its development will be proposed separately.

Finally, it is recognized that the design concepts proposed and eventually demonstrated here will be easily adaptable to other frequency bands. A very similar array could ultimately be constructed in the 3 mm band, consisting of hundreds of elements and thereby establishing a previously unheard-of capability in radio astronomy for low-surface-brightness, high-resolution imaging (and further underscoring the importance of a more capable spectrometer). See also [RD1].

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

- a 10-element, dual-polarization, 18-26 GHz front-end receiver with up to 1 GHz instantaneous bandwidth (the baseline instrument).
- a documented design ready for duplication, with budgetary pricing (at a reduced per-element cost) for up to a 61-pixel mapping imager.

The choice of 1 GHz bandwidth was driven by limitations of the backend and data processing. It is perfectly feasible to design analog hardware that can provide all 8 GHz of bandwidth (18-26 GHz) in one chunk, and this will be shown as an easy upgrade path should the backend ever develop the capacity to handle it.

## 2. SCIENCE CASE

The immediate impact a K-Band focal plane array would have on GBT science capabilities is both unique and compelling. A more comprehensive discussion of the science that could be accomplished with this array is included in the overall Green Bank/CDL Development Plan enclosed with this proposal.

## 3. BASELINE TECHNICAL PLAN

The baseline instrument shall consist of five key subsystems: the feedhorn array, the cryogenic dewar, the cooled electronics, the Integrated Downconverter Module (IDM), and the Local Oscillator Distribution and Monitor and Control Module (LODM&C). A straw man layout of the baseline instrument comprised of these components is shown in Figure 1. The digitizer/spectrometer could be an existing backend or a newly developed, more capable piece of hardware as previously described. A preliminary block diagram of the array element (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 GHz (nearly complete K-Band coverage) |
| $T_{RX}$ (each beam, not including sky) | <25K (75% of band)<br><36K (entire band) |
| Number of beams | 10 |
| Polarization | dual, circular |
| Sideband (image) rejection | >30 dB |
| Instantaneous bandwidth | 1 GHz |
| Mass | <100 kg |
| Headroom | >30 dB (to 1 dB compression point) |

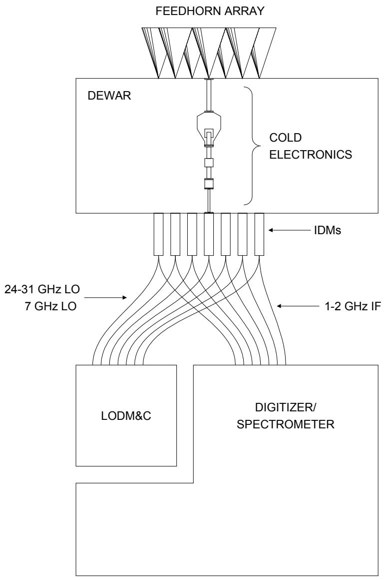


**Figure 1. Straw man configuration of the baseline K-Band focal-plane array receiver.**

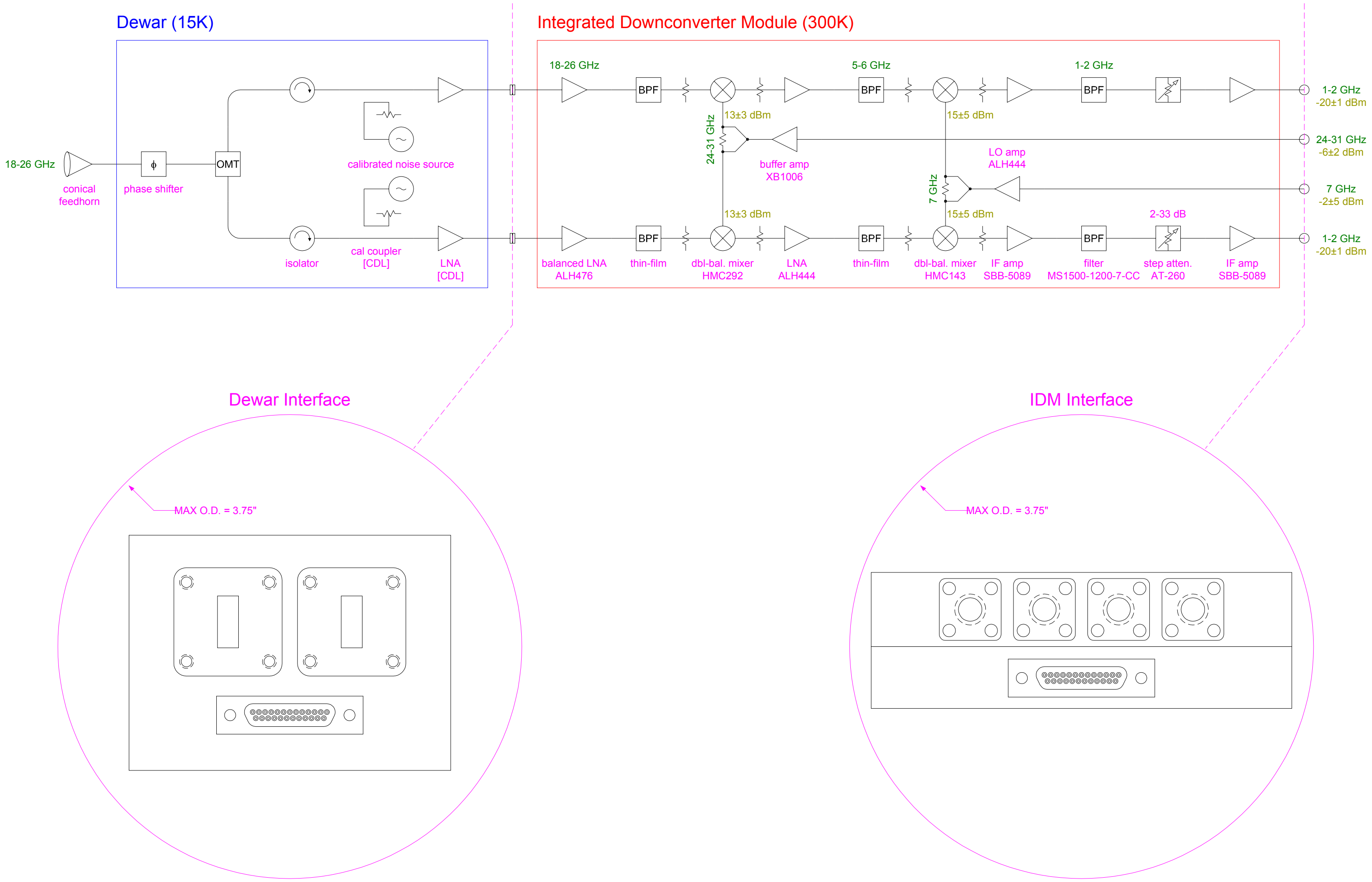
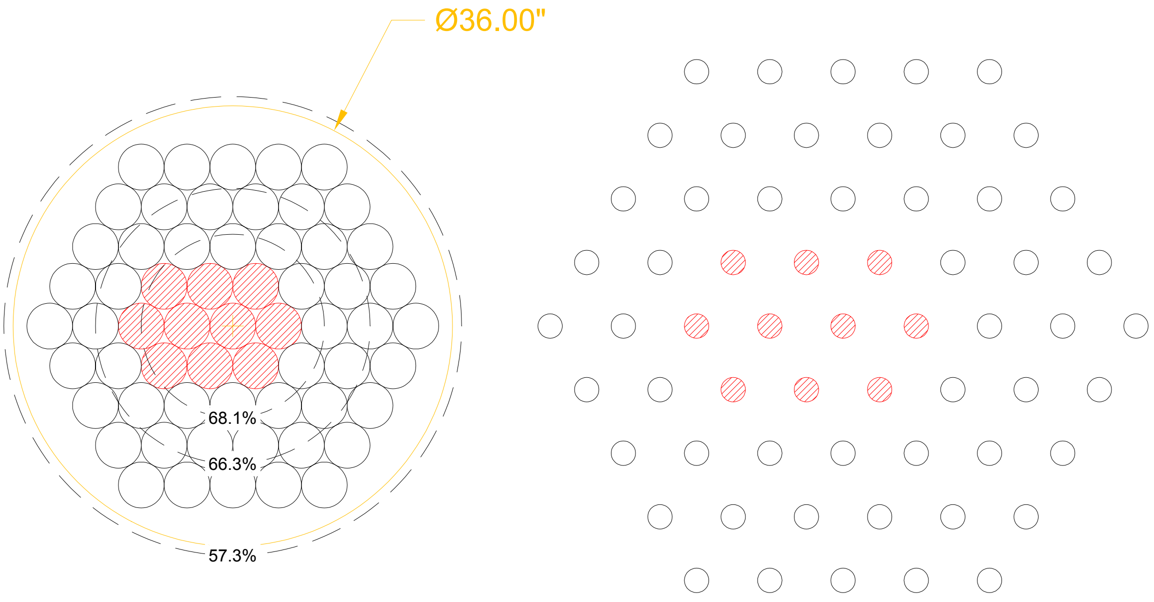


**Figure 2. Block diagram of one pixel of the focal plane array, showing the analog/RF signal processing components.**

A short description of each of these subsystems follows.

### a. FEEDHORN ARRAY

The feed horn array covering the 18-26 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 maximum sampling of the focal plane. This is illustrated in Figure 3. The array elements for the baseline instrument are highlighted in red. 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, as indicated by the dashed circle, efficiency drops to about 57%.



**a) feed geometry**

**b) beam pattern**

**Figure 3. Feedhorn array geometry and resulting beam pattern. The first 10 elements comprising the baseline instrument are highlighted in red.**

### 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 ten 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. Alternatively, this could be used as a multi-object spectrograph, as described in [RD4]. That is, custom cover plates could be manufactured to arrange, say, 10-15 pixels in a layout that specifically matches a particular object on the sky. The only constraint would be that the pixels must fit within the 36" diameter dewar, and could be no closer than 3 half-power beamwidths. In practice however, this could be very difficult. To change configurations, one would need to warm up the receiver, remove it from the telescope, take out the pixels, replace the standard cover plates with (pre-prepared) custom cover plates, reinsert the pixels in their new locations, close up and cool down again. Performing this operation multiple times and doing it efficiently and safely could be tricky, and careful attention to mechanical design will be necessary if this is implemented.

### 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.

Its is worth noting that while we have assumed circular polarization is desired and have designed the baseline instrument accordingly, a slight simplification would result from choosing linear polarization instead. This would allow the phase shifter to be left out, reducing the size of the dewar and perhaps improving the noise temperature by a few Kelvin.

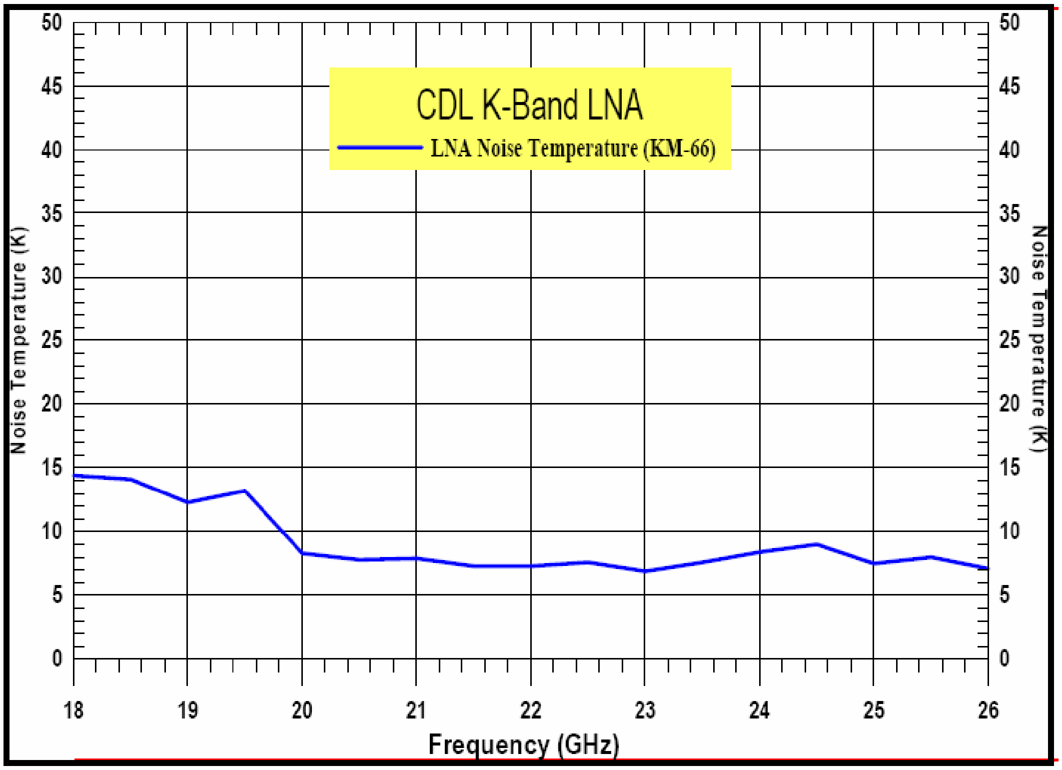


**Figure 4. Measured noise temperature of the CDL K-Band LNA.**

### d. INTEGRATED DOWNCONVERTER MODULE (IDM)

The IDM, which will operate at room temperature, shall be a single multi-chip split-block assembly consisting of off-the-shelf MMICs identified in Figure 2. Since all of the required components are commercially available, this module 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 IDM 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.

A super-heterodyne mixing scheme is employed for high image rejection (>30 dB). The first LO would be required to be tunable over a 24-31 GHz frequency range, while the second LO shall be a fixed frequency 7 GHz source. Both LOs shall be provided in a coherent fashion to all of the array elements by the LODM&C.

Step attenuators are provided at the output of the IDM to enable leveling of the signal power into the digitizers. These digital attenuators have 1 dB resolution and a range of 30 dB (50 dB versions are also available). The phase delay introduced by each core attenuator should be very stable and may be calibrated *a priori*, before deploying the array.

It should be noted that the 1 GHz bandwidth may ultimately be considered a limitation of this instrument. While it is perfectly feasible to design a downconversion scheme that provides the full 8 GHz of bandwidth in K-Band (indeed, such a design was created on paper in the course of writing this proposal), the decision was eventually made to use a 1 GHz bandwidth to better match the capabilities of potential digitizers and data processing for a 61-element array. Clearly, nothing inside the dewar limits this bandwidth. Should it ever become feasible for the backend to process all 8 GHz of bandwidth over a large number of channels, it will be a simple matter to replace the current channelizing IDMs with block-conversion IDMs. This was considered a more efficient solution than performing the block-conversion up-front followed by 1 GHz channelizers.

### 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 IDM, this subsystem shall be constructed using commercial off-the-shelf parts, and is modular in design for later expansion.

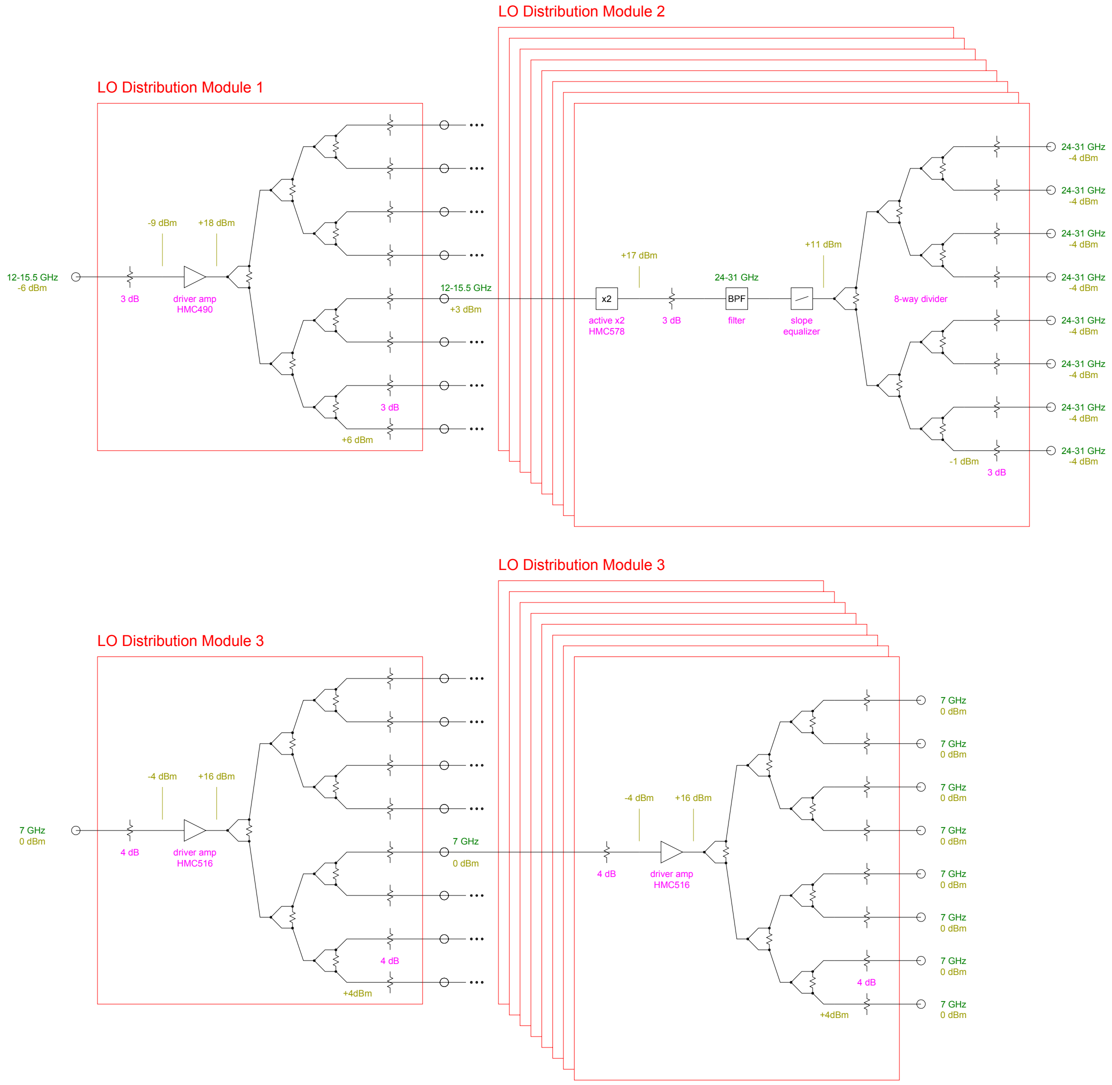


**Figure 5. Block diagram of the LO Distribution Modules.**

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.

## 4. BASELINE BUDGET

The following cost estimate is given in Y2007 dollars.

TABLE III: Labor Estimates for Development

| **Item** | **Machinist [FTEs]** | **Technician [FTEs]** | **Astronomer [FTEs]** | **Engineer [FTEs]** |
|---|---|---|---|---|
| Compact Feedhorn | 0.2 | 0.0 | 0.0 | 0.2 |
| Noise Calibration Module (NCM) | 0.1 | 0.1 | 0.0 | 0.25 |
| Integrated Downconverter Module (IDM) | 0.1 | 0.25 | 0.0 | 0.5 |
| LO Distribution | 0.1 | 0.5 | 0.0 | 0.25 |

| | | | | |
|---|---|---|---|---|
| M&C, biasing, PCB design and layout | 0.0 | 0.5 | 0.0 | 0.5 |
| Mechanical design (overall receiver, cryostat) | 0.25 | 0.5 | 0.0 | 0.5 |
| Parallactic Angle Rotator | 0.25 | 0.25 | 0.0 | 0.25 |
| Project management | 0.0 | 0.0 | 0.0 | 0.5 |
| Systems engineering | 0.0 | 0.0 | 0.0 | 0.5 |
| Project scientist | 0.0 | 0.0 | 0.5 | 0.0 |
| Software Development | 0.0 | 0.0 | 0.0 | 0.4 |
| | | | | |
| Total FTEs: | 1 | 2.1 | 0.5 | 3.85 |
| | | | | |
| **TOTAL $ = $696k** | | | | |

TABLE IV: Labor Estimates for Production (10-element array)

| Item | Machinist [FTEs] | Technician [FTEs] | Astronomer [FTEs] | Engineer [FTEs] |
|---|---|---|---|---|
| NCM housing and assembly | 0.25 | 0.25 | 0.0 | 0.1 |
| IDM housing and assembly | 0.0 | 0.25 | 0.0 | 0.25 |
| LODM&C housing and assembly | 0.0 | 0.25 | 0.0 | 0.25 |
| Receiver rack assembly and cabling | 0.25 | 0.5 | 0.0 | 0.25 |
| Project management/systems engineering | 0.0 | 0.0 | 0.0 | 0.5 |
| Project scientist | 0.0 | 0.0 | 0.25 | 0.0 |
| Receiver engineer | 0.0 | 0.0 | 0.0 | 0.5 |
| Mechanical design | 0.0 | 0.0 | 0.0 | 0.5 |
| | | | | |
| Total FTEs: | 0.5 | 1.25 | 0.25 | 2.35 |
| | | | | |
| **TOTAL $ = $408k** | | | | |

TABLE V: Parts Cost (10-element array)

| Part | Qty. | Unit cost | Extended cost |
|---|---|---|---|
| Feedhorns | 10 | $2k | $20k |
| Phase shifters and transitions | 10 | $7k | $70k |
| OMTs | 10 | $2k | $20k |
| Isolators | 20 | $0.5k | $10k |
| NCM parts | 20 | $0.5k | $10k |
| LNAs | 20 | $3k | $60k |
| IDM parts | 10 | $2k | $20k |
| LODM&C parts | 1 | $5k | $5k |
| Refrigerator | 1 | $8k | $8k |
| Compressor | 1 | $8k | $8k |
| Parallactic Angle Rotator | 1 | $20k | $20k |
| | | | |
| **TOTAL $ = $251k** | | | |

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.

The final cost of this project thus comes in at about $1.4M. No contingency has yet been added to these figures. Note that the cost per pixel in production quantities is about $66k (Y2007 dollars), so a rough cost for adding the future 51 pixels is $3.4M (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 would, of course, also require a new spectrometer.

## 5. DEVELOPMENT PLAN

### a. FEEDHORN/PHASE-SHIFTER/OMT

We do not currently have a compact feedhorn design covering the 18-26 GHz bandwidth for the GBT, so one will need 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 and OMT designs [RD3] 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.

One of the more difficult design decisions is whether or not to cool the feedhorns. The estimated benefit in receiver noise that results from cooling the feedhorn is shown in Figure 6, where the entire RF/IF chain is taken into account and different assumptions are made about the ambient temperature and loss of the horn. However, moving the feedhorns inside the dewar raises a number of complex issues. For one, the optical window is 150 times larger, adding significantly to the heat load on the refrigerator due to thermal radiation. IR filters would undoubtedly be required, but even with them it is unlikely that a single refrigerator would be feasible; the array would have to be divided into sub-arrays in separate dewars. This raises issues of refrigerator reliability, power requirements, and the capacity of the compressors. Further, Green Bank engineers have learned from painful experience that cooling the feedhorn can create subtle baseline problems resulting from weak coupling with cavity modes inside the dewar.

The question naturally becomes whether or not the potential benefit of cooling the feedhorn balances out the added complexity of its implementation – and the cost of the inevitable extra development time and troubleshooting that comes with that complexity. The authors' opinion is that not cooling the feedhorn is the wiser choice, as indicated in the baseline plan, but this question warrants further study.

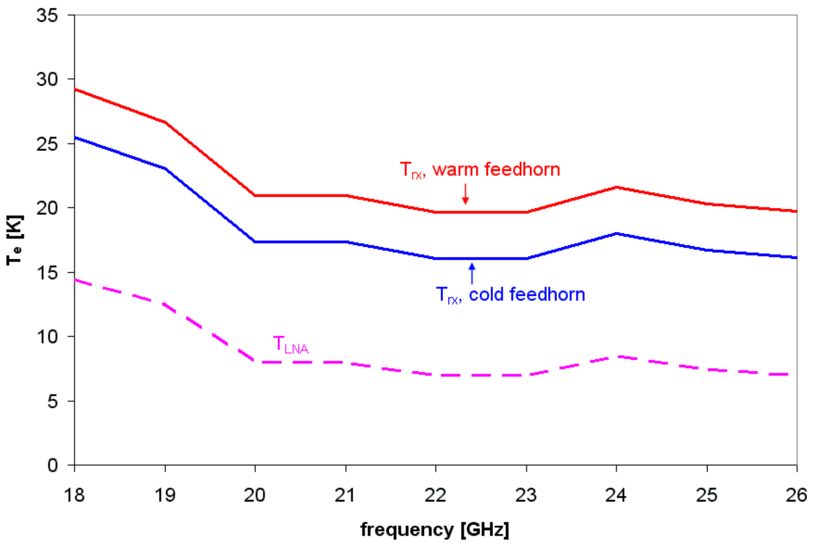


**Figure 6. Comparison of receiver noise temperature with warm and cold feedhorns.**

### b. INTEGRATED DOWNCONVERTER MODULE (IDM)

Although we already possess the expertise and know-how to build all of the individual components (case and point, our state-of-the-art low-noise single-pixel receivers on the EVLA), some development effort shall be needed to integrate these components in an optimal fashion for use in a multi-pixel focal plane array. The design of each pixel needs to be re-evaluated to minimize the cost of duplication and integration. 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 baseline block diagram, all the MMICs used in the IDM are commercially available, so no MMIC development will be necessary. However, the IDM does need to be prototyped to ensure that the performance of all these MMICs is adequate. Concurrent with this project are individual research projects on MMIC development for integrated downconverter modules for this and for other bands.

The possibility of integrating the downconverter inside the dewar on the first stage at about 50K can be investigated, although it is not believed at this time that this arrangement offers any particular advantage in terms of performance and/or cost. It would also preclude future simultaneous observation of the entire 18-26 GHz spectrum (see below).

The baseline design is to place the integrated module just outside the cryostat. It shall consist of the second RF amplifier as well as the down conversion stages providing the 1-2 GHz outputs and the level setting attenuators, which provide the processed IF signal for the digitizers. A double conversion scheme is needed to achieve sufficient image rejection. An alternate option would be to use a wideband IF block downconverter stage so that a simpler bandpass filter and a fixed frequency LO (~14 GHz) may be used for image rejection. This would necessitate further IF processing to break down the wideband IF (~4-12 GHz) signal into manageable bandwidths for the digitizers (similar to the ALMA scheme). An image-rejecting mixer has been ruled out, since about 20 dB image rejection is probably near the limit of what is practically achievable and is not believed to be sufficient for spectroscopy.

Although the IF processing given in this proposal allows use of 1 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 16 Gs/sec digitizer), along with an advanced spectrometer, to observe the entire 18-26 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 $T_{sys}$.

Although shown in the diagram immediately before the amplifiers, it is possible the NCM could be designed to precede the phase shifter where the waveguide is dual-polarization. This has the advantage of reducing the number of components and incorporating more of the front-end in the calibration, but the performance of a wideband dual-mode coupler will have to be studied.

### 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. One future option may involve the NGST 35 nm InP HEMT process. This is very recent development and none of the devices have been evaluated at cryogenic temperatures, but they hold the promise of K-band noise temperatures that are perhaps as low as 4 K. A 35 nm LNA MMIC would be a very attractive development. It will not be supported by this effort, but independent CDL research projects shall be investigating this possibility. Later substitution of even better amplifiers would be a straightforward task. For a W-band focal plane array a MMIC first stage would probably be chosen, since existing chips have noise performance competitive with the hybrid design.

### 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.

### f. SPECTROMETER

The receiver proposed here can be used in conjunction with the existing GBT Spectrometer, though it will be severely limited in the number of channels. Up to 8 IF channels could be sent to the spectrometer via the existing IF system. These could feed eight of the 200/800 MHz BW samplers or sixteen of the 50/12.5 MHz samplers (*e.g.* two 50MHz bands per IF tuned anywhere in the 1 GHz BW). Additional funds would be needed for data transport of a larger number of channels.

However, a new spectrometer that takes better advantage of high-throughput instruments like this array is being proposed under separate cover. An attractive possibility is to locate this new spectrometer in the receiver room, and possibly in the same rack as the KFPA receiver. To do so would require resolving a number of issues related to mass, volume, power, heat dissipation, and RFI.

## 6. 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 VI. Although it arbitrarily starts in June of 2007, it has not yet been possible to determine in detail how the actual availability of personnel will impact the schedule.

## 7. COLLABORATIONS

The University of Calgary Radio Astronomy Lab (UCRAL) and Herzberg Institute of Astrophysics (HIA) have expressed some interest in collaborating on this project. Specifically, they believe they can make useful contributions to a data processing pipeline (described in more detail in the backend proposal), to the design and fabrication of the cold-stage and low-noise amplifiers, and to the manufacture of the Integrated Downconverter Module. However, the actual breakdown of tasks between UCRAL, HIA, and NRAO has yet to be determined.

## 8. EXTENSION TO A 3 MM HETERODYNE FOCAL PLANE ARRAY

Many have wondered about the feasibility of implementing a similar array at W-Band. By providing wide-area coverage with good resolution and high surface brightness sensitivity, a 3 mm array would be very complementary to the capabilities of ALMA. Many of the concepts described in this proposal and developed during the course of this project would be applicable to the 3 mm band as well. Integrated noise calibration, modular pixel design, and innovation with respect to the close-packed mechanical assembly would be common themes in the two arrays. On other hand, a 3 mm array presents a number of additional challenges, as outlined below.

First and most obvious is that the feedhorn would be significantly smaller, less than 1" in diameter. Assuming that we would want the pixels packed as tightly as possible for maximum coverage of the focal plane, everything else in the front end would have to fit behind this ~1" diameter cross-section. This is certainly feasible, but will require integration to be taken a step further. There is clearly not sufficient room for two standard WR-10 waveguide flanges side-by-side, so it would make sense for all components in the pixel, including the front-end LNAs, to be integrated into dual-channel blocks with dual-waveguide flanges. Monitor and control lines would also be limited, as there would not be room for a very large multi-pin connector. Further, the OMT would have to be very carefully designed so that the output guides are aligned and parallel as standard external bends and twists are far too bulky.

Second, commercial off-the-shelf components are far more difficult to find at W-Band than they are at K-Band. Where W-Band components are available, they rarely have the bandwidth required for radio astronomy. Fortunately, the observatory and its peers (such as Caltech/JPL and other universities) have developed some MMIC chips for these types of applications. In point of fact, unlike K-Band there does exist a W-Band MMIC LNA with better cryogenic noise performance than any MIC yet produced. The designs are proven, but the chips are not regularly stocked so at the very least a shared wafer run or two would be required to obtain them.

Finally, a W-Band array that takes advantage of even a fourth of the available focal plane would consist of over 250 elements. This places even greater constraints on the power dissipation per pixel and the cryogenics design. Were the pixels to be divided into separately-cooled sub-arrays, it is doubtful that the vacuum vessels and appended refrigerators could be crowded close enough together to avoid large gaps in the beam pattern. Further, the demands on the backend and data processing become proportionately worse. No spectrometer currently existing or yet proposed has the capacity to handle the torrent of data produced by such an instrument.

Nonetheless, the equally impressive scientific potential of a 3 mm array of this type makes it difficult to ignore [RD1]. It would clearly be a more long-term development than the KFPA described in this proposal, with a higher degree of technical risk, but should additional funding become available it could very quickly become a high-priority research topic at the observatory.

## 9. REFERENCES

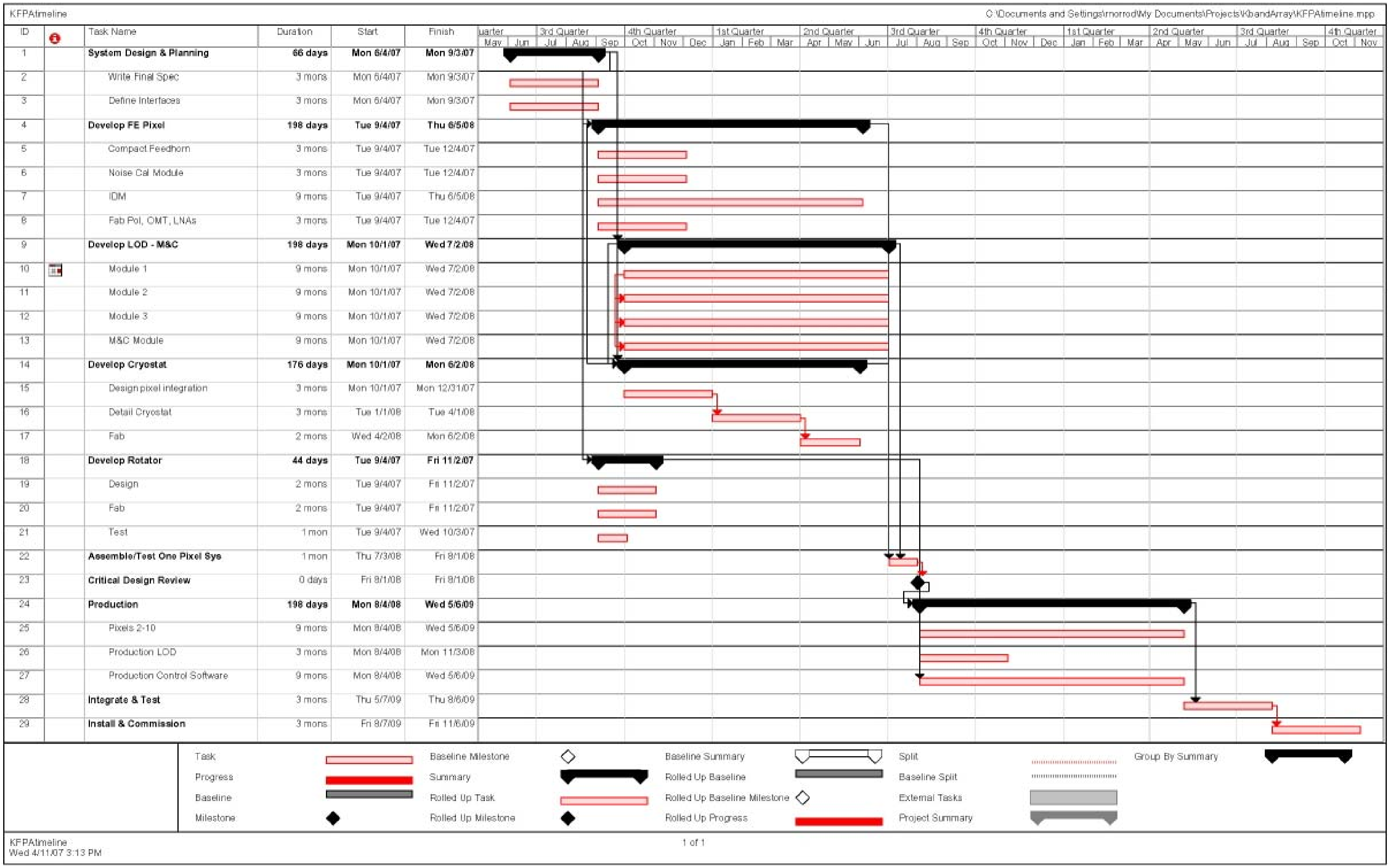
[RD1] "A 3 mm Receiver for the GBT," GBT 3 mm Receiver Working Group, 06-March-2000. http://www.gb.nrao.edu/electronics/projects/3mmRx/3mmrx_proposal.pdf

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

[RD4] "A Radio Multi-Object Spectrograph," C. Carilli, G. Watts, and R. Fisher, internal memo.

TABLE VI: Program Schedule



KFPAtimeline

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| ID | | Task Name | Duration | Start | Finish |
|---|---|---|---|---|---|
| 1 | | **System Design & Planning** | **66 days** | **Mon 6/4/07** | **Mon 9/3/07** |
| 2 | | Write Final Spec | 3 mons | Mon 6/4/07 | Mon 9/3/07 |
| 3 | | Define Interfaces | 3 mons | Mon 6/4/07 | Mon 9/3/07 |
| 4 | | **Develop FE Pixel** | **198 days** | **Tue 9/4/07** | **Thu 6/5/08** |
| 5 | | Compact Feedhorn | 3 mons | Tue 9/4/07 | Tue 12/4/07 |
| 6 | | Noise Cal Module | 3 mons | Tue 9/4/07 | Tue 12/4/07 |
| 7 | | IDM | 9 mons | Tue 9/4/07 | Thu 6/5/08 |
| 8 | | Fab Pol, OMT, LNAs | 3 mons | Tue 9/4/07 | Tue 12/4/07 |
| 9 | | **Develop LOD - M&C** | **198 days** | **Mon 10/1/07** | **Wed 7/2/08** |
| 10 | | Module 1 | 9 mons | Mon 10/1/07 | Wed 7/2/08 |
| 11 | | Module 2 | 9 mons | Mon 10/1/07 | Wed 7/2/08 |
| 12 | | Module 3 | 9 mons | Mon 10/1/07 | Wed 7/2/08 |
| 13 | | M&C Module | 9 mons | Mon 10/1/07 | Wed 7/2/08 |
| 14 | | **Develop Cryostat** | **176 days** | **Mon 10/1/07** | **Mon 6/2/08** |
| 15 | | Design pixel integration | 3 mons | Mon 10/1/07 | Mon 12/31/07 |
| 16 | | Detail Cryostat | 3 mons | Tue 1/1/08 | Tue 4/1/08 |
| 17 | | Fab | 2 mons | Wed 4/2/08 | Mon 6/2/08 |
| 18 | | **Develop Rotator** | **44 days** | **Tue 9/4/07** | **Fri 11/2/07** |
| 19 | | Design | 2 mons | Tue 9/4/07 | Fri 11/2/07 |
| 20 | | Fab | 2 mons | Tue 9/4/07 | Fri 11/2/07 |
| 21 | | Test | 1 mon | Tue 9/4/07 | Wed 10/3/07 |
| 22 | | **Assemble/Test One Pixel Sys** | 1 mon | Thu 7/3/08 | Fri 8/1/08 |
| 23 | | **Critical Design Review** | 0 days | Fri 8/1/08 | Fri 8/1/08 |
| 24 | | **Production** | **198 days** | **Mon 8/4/08** | **Wed 5/6/09** |
| 25 | | Pixels 2-10 | 9 mons | Mon 8/4/08 | Wed 5/6/09 |
| 26 | | Production LOD | 3 mons | Mon 8/4/08 | Mon 11/3/08 |
| 27 | | Production Control Software | 9 mons | Mon 8/4/08 | Wed 5/6/09 |
| 28 | | **Integrate & Test** | 3 mons | Thu 5/7/09 | Thu 8/6/09 |
| 29 | | **Install & Commission** | 3 mons | Fri 8/7/09 | Fri 11/6/09 |

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Wed 4/11/07 3:13 PM

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