A 15 Element Focal Plane Array For 100 GHz

Neal R. Erickson, *Member, IEEE,* Paul F. Goldsmith, *Fellow, IEEE,* G. Novak, Ronald M. Grosslein,
P. J. Viscuso, Ronna B. Erickson, and C. Read Predmore, *Member, IEEE*

Abstract—**A focal plane imaging array receiver is described which covers the 86–115 GHz frequency range for radio astronomical observations. The 3 × 5 element array uses cryogenic Schottky diode mixers with integrated HEMT IF amplifiers. A cold quasi-optical filter selects the desired sideband, and terminates the image at 20 K. Polarization interleaving is used to minimize the array size on the sky. LO power is provided by a frequency tripled YIG tuned oscillator. The average receiver noise temperature of the array pixels varies from 250–350 K SSB depending on the frequency. Only three mechanical tuners are used in the system and all functions are under computer control.**

INTRODUCTION

AS ASTRONOMICAL millimeter-wave receiver systems improve in performance, their overall system noise temperature becomes increasingly dominated by atmospheric emission and absorption. At the important radio astronomy frequency of 115.3 GHz ($J = 1 - 0$ transition of CO), for the best receivers presently available ($T_r \sim 75$ K SSB) [1], even under ideal weather conditions the atmospheric contribution more than triples the effective receiver noise. The only practical method of increasing the data rate for spatially extended sources is to construct imaging arrays. However, for spectral line observations, the cost of the required back end spectrometers (filter banks, correlators, or acousto-optic spectrometers) is high enough to severely limit the number of pixels. Hence it is most effective to build a front end with the highest practical sensitivity, rather than building a large array with relatively poor receivers.

A second, purely practical, advantage to an array is in the reduction of unavoidable overhead time involved in any observations. This is the time required to repoint the telescope for each new map location, and also the time to move to a reference position on the sky in the typical mode of position switching. Each of these times is at least two seconds for most telescopes. While short, this time is actually comparable to the required integration time for many astronomical sources when observed with a very low noise receiver. This time is reduced by a factor of the array size.

Here we describe a 15 element imaging array receiver constructed at the Five College Radio Astronomy Observatory (FCRAO). This system is designed for astronomical spectral line observations with the 14 m radio telescope over the frequency range 86 to 115 GHz. The array operates single sideband, with fixed tuned mixers. The receiver makes extensive use of cooled optics and is the largest multi-pixel system for mm-wave observations presently in operation.

MIXERS AND IF AMPLIFIERS

Schottky diode mixers operated at a temperature of 20 K have been chosen over SIS mixers for this project because they offer a number of operational advantages, even though their noise temperature is higher:

1) They may be operated fixed tuned over a very wide band with little performance penalty. SIS mixers can now operate fixed tuned over comparable bandwidth with lower noise [2], but this is quite a recent development. When this system was planned, their sensitivity was significantly superior to Schottky mixers only when optimized for each frequency, and even now the best results are with one or more tuners.

2) Schottky mixers are insensitive to the amount of LO power over a range of nearly a factor of two, greatly simplifying the LO distribution system. SIS mixers are several times more sensitive to the amount of LO [3], which would require individual adjustment of the LO power delivered to each mixer.

3) Schottky mixers operate well at 20 K, which may be achieved with commercial refrigerators having high reliability and high cooling capacity. They are insensitive to their exact temperature. SIS mixers require cooling to ~4 K which also may be achieved with refrigerators, but these are quite expensive, with limited cooling capacity, which complicates the cryogenic design.

4) Schottky mixers are very well understood, due to their long use, and can be expected to be much more reproducible than SIS mixers, which are much newer. The situation with SIS mixers now appears to be improving in this regard.

5) Schottky mixers operate at room temperature, which is quite useful for debugging. SIS mixers must be cooled to show any operation.

Manuscript received February 25, 1991; revised July 1, 1991. The Five College Radio Astronomy Observatory is operated with support from the National Science Foundation under grant AST-8815406 and with permission of the Metropolitan District Commission of Massachusetts. This work is contribution No. 762 of the Five College Astronomy Department.

N. R. Erickson, P. F. Goldsmith, G. Novak, R. M. Grosslein, R. B. Erickson, and C. Predmore are with the Five College Radio Astronomy Observatory, Department of Physics and Astronomy, University of Massachusetts, Amherst, MA, 01003.

P. J. Viscuso is with the Cornell National Supercomputer Facility, Ithaca, NY 14853-3801.

IEEE Log Number 9102809.

Each mixer uses a fairly conventional reduced height waveguide mount similar to an earlier FCRAO design [4], but with a fixed tuned backshort since individual tuning is impractical for an array. The internal waveguide has a cross section of 0.25 × 2.3 mm and is converted to full height with a two step transformer. A contacting backshort with springy fingers is used since wear is not a concern with fixed tuning. The mixer and IF amplifier are integrated into the same block for greatest stability. A cross section of the mixer and amplifier is shown in Fig. 1. The mixer and amplifier together have a cross section of 2.0 cm square so that they may be packed closely together. The mixer block is made from OFHC copper for lowest loss. The IF filter choke is coaxial with air dielectric and is supported with a machinable ceramic (Macor [5]) ring. The contact whiskers are NiAu wire 15 μm in diameter and 250 μm long. Mixer diodes are from the University of Virginia (batch 2I1-150) and have a capacitance of 4.5 fF, a series resistance of 15 Ω, and doping optimized for cryogenic operation. The low capacitance permits a large bandwidth to be covered with a fixed backshort, and also reduces the LO power required. Diodes from this batch are somewhat variable in terms of their low temperature performance which leads to the greatest variable in the mixer behavior. The measured optimum LO power for the better mixers operating at 20 K is 20 μW but is as much as 40 μW for some elements. The mixer noise temperature varies from 50 to 90 K DSB over the range of mixers and the operating band. All mixers were tested for DSB noise in a fixture (using a ring filter for LO injection, without any optics) both with and without the integrated IF amplifiers.

The IF is centered at 1450 MHz with a required bandwidth of 320 MHz, set by the bandwidth of the filter spectrometer needed for extragalactic observations. The amplifier uses a HEMT input stage followed by two conventional FET stages and is integrated into the mixer block with noise and impedance matching directly to the mixer IF impedance. In this way it is not necessary to individually match the amplifier and mixer to 50 Ω, and much flatter and more stable noise and gain may be achieved. The IF amplifier housing also includes a bias port for providing dc bias to the mixer diode. The mixer IF impedance is 600 Ω at the diode. This high impedance is due to the low capacitance of the mixer diodes, and the resulting high RF impedance. The effect of the filter choke and the Macor support in the IF line is to shunt this resistance with a capacitance of 1.2 pf. The amplifiers are tuned up using a fixture which converts a 50 Ω load into this same impedance across the IF band. This fixture is simply a two quarter-wave step impedance transformer with a Macor ring at the end, with all properties computer optimized, and subsequently measured, to match the mixer IF impedance. Thus all the amplifier testing can be done using standard equipment, with some correction required for the fixture loss. Due to the small space available for the amplifier, all matching is done with lumped inductors. The circuit diagram is shown in Fig. 2. The input match and gain flatness are improved by the use of source inductance on all stages. Typically this results in a maximum input VSWR of 2:1 but for some amplifiers the VSWR is as high as 3:1. This is lower than the total VSWR that is normally achieved with a mixer and amplifier matched separately to 50 Ω, and no connecting cable length is added to cause ripples in the response. The amplifier is built to minimize thermal stress and circuit parasitics. In particular, no large substrates are used, and chip capacitors, which are known to be thermally fragile, are mounted on end, with the other end having a flexible connection. As is typical with these amplifiers, particularly when using packaged FET's, oscillation at out-of-band frequencies at low temperature is one of the most difficult problems. In this design, oscillation is suppressed using ferrite beads between stages, a lossy bypass capacitor in parallel with the source inductor, and loss added to the bias coils. The lossy capacitor is produced by extending one of the source leads over a 1 mm thick piece of ferrite loaded resin [6].

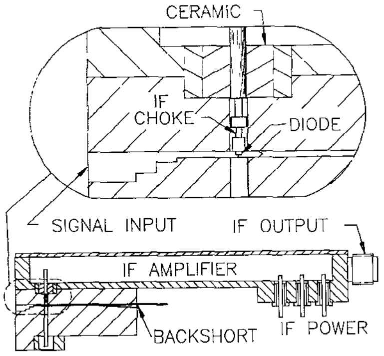

Fig. 1. Cross section of the mixer and IF amplifier.

The typical amplifier noise temperature is 4 K at 20 K physical temperature, while the worst amplifiers have a noise temperature of 9 K. The gain is greater than 30 dB including the loss of a 10 dB output attenuator. This attenuator ensures that the output match is good and that no oscillation will be experienced with any load impedance. Bias is via an internal resistor network so that all amplifiers can operate from a common power supply of +3.5 and −4 V. The bias network provides some negative feedback to the bias point to stabilize it against component aging. All amplifiers have been tested with and without LED illumination when cold, and show little or no improvement with light, so the LED's have been eliminated from the design. The behavior of the total noise over the IF band for the mixer-amplifier pair closely follows that which is predicted from the tests on the amplifier alone. However as the mixer is tuned over the RF band the IF band shows a systematic shift in the band shape due apparently to a reactive mixer IF impedance induced by the input RF mismatch. Typical results are shown in Fig. 3. It is interesting to note that this effect disappears if the mixer backshort is optimized at a given frequency, since this eliminates any RF port reactive mismatch.

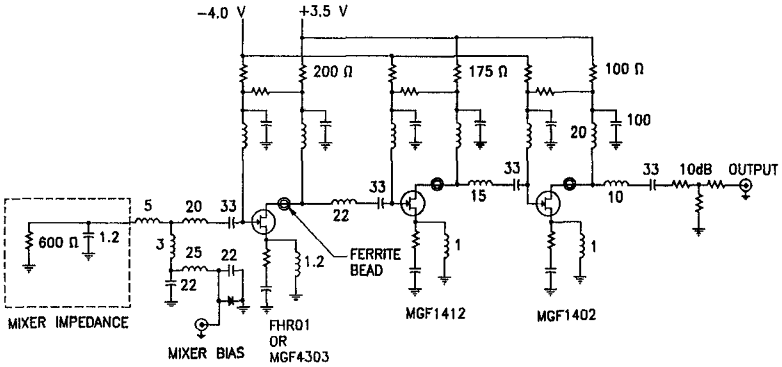

Fig. 2. Schematic diagram of the IF amplifier, with the effective mixer source impedance represented by the RC combination in the box. Inductor values in nH, capacitors in pF. All bias inductors are 20 nH and bypass capacitors are 100 pF. The source inductance bypass *RC* network is actually a lossy capacitor (see text). Unmarked bias resistors are selected to set the correct gate bias. Typical values are ~50 KΩ.

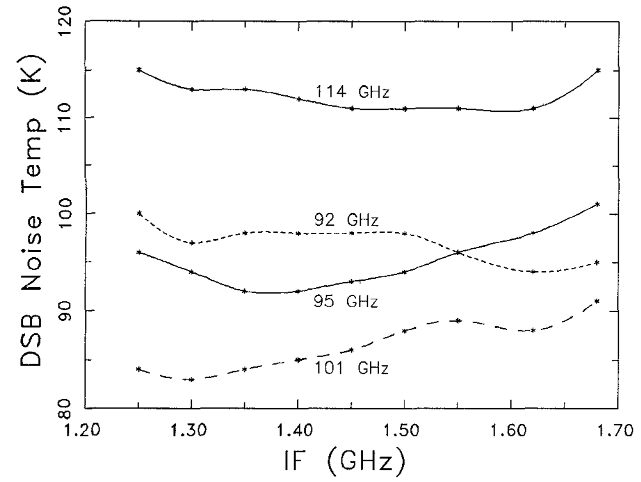

Fig. 3. Receiver IF passband for one mixer/amplifier, at various LO frequencies, measured DSB in a test fixture. Mixer is fixed tuned.

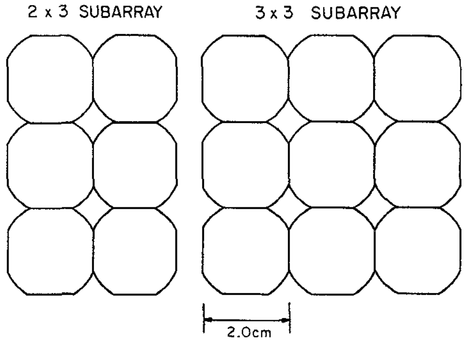

Fig. 4. Feed horn layout in the array. The gap between horns allows for polarization interleaving (see text).

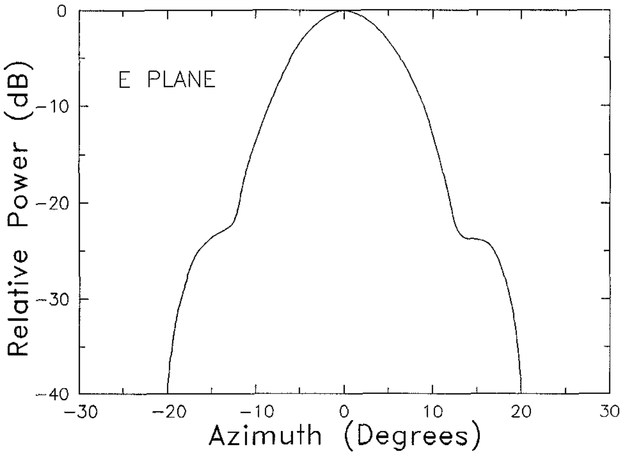

Fig. 5. *E*-plane beam pattern of the cutoff feed horn at 100 GHz. *H*-plane is similar.

FEED HORNS

A great deal of study has been directed toward the selection of optimum feed horns for array systems [7]–[9]. Fundamental relationships prevent the spacing of feed horns at intervals closer than ~1.5 beamwidths without a serious loss of coupling efficiency, but within this constraint there are many choices. Corrugated feed horns have excellent beam efficiency, and are the first choice for all low noise receivers, since there is little loss of power to sidelobes. They are problematic for an array because they are round and require a fairly thick wall (for the grooves), so that they do not pack together closely. However we have determined that the packing in a rectangular array can be significantly improved by cutting away a portion of the aperture, without a corresponding penalty in increased beamwidth or sidelobes. In an iterative process we cut away flat sections from the sides of the horns, ultimately reducing the size to 88% of the initial diameter. These flat sides are left open, exposing a rather fragile array of partial rings. This cutaway makes possible the arrangement shown in Fig. 4, and produces only a small increase in beam size. The horn size chosen, with a taper length of 8.9 cm and an outer diameter of 2.3 cm, was measured after cutting its aperture down to 2.0 cm across the flats. Initially the waist radius of the best fit Gaussian beam was 0.66 cm at 85 GHz, decreasing to 0.60 cm at 115 GHz. After cutting, the waist radius was a constant 0.60 cm over the band. The quality of the beam pattern is essentially unchanged, and a typical pattern is shown in Fig. 5. The final feedhorn size corresponds to a spacing of 2.0 HPBW at 105 GHz (midband). We found that a further reduction of size was not possible without a corresponding increase in beamwidth. The horn length scales as the square of the aperture for the same phase error, so the aperture was chosen as small as practical to minimize the feedhorn size and mass. There is no requirement that the horn size directly match to the telescope since the reimaging optics introduce a scale factor. The actual size limitation is the cross section of the mixer itself, which can be no bigger than the horn. The circular waveguide in the horn is converted to rectangular using a two step mode transition.

OPTICS

The optical system performs three critical functions: sideband filtering, polarization interleaving on the sky and reduction of the feed horn cluster size. Together these produce a rather complex appearing design. It is also essential that the optics be designed to have the minimum size, since the entire system must fit within the vacuum dewar. The overall dewar optics layout is shown in Fig. 6.

A single-sideband filter is required to eliminate the image response for well calibrated spectroscopy, and to terminate this image at a low temperature to achieve the minimum receiver noise temperature. The sideband filter in this system uses a new type of polarizing interferometer [10] developed specifically for this application, and shown schematically in Fig. 7. It consists of a pair of fused silica ($\epsilon = 3.85$) wedges ~1.2 cm thick (in total) and 10 cm square which are metallized on the back and have a wire grid on the front at 45° to the incident field. The device behaves as a very thick wave plate in reflection, and can be tuned so that the signal frequency is reflected in one linear polarization and the image in the other. Tuning this filter is accomplished by sliding the wedges over each other, thus changing the effective thickness. A somewhat complex mechanical drive is required to do this with the precision required, while operating at low temperature. It is particularly important to avoid small tilts or translations of this assembly. The dielectric filling within the sideband filter greatly reduces the tuning effects due to the range of incidence angles. In this system the incidence angles vary from 1.8 to 11.8°, causing the tuning to shift by about 600 MHz at the highest frequency of 115 GHz. Given the 2.90 GHz signal to image spacing, this results in a usable bandwidth of 300 MHz with > 10 dB image rejection for the most extreme elements. The function of this device has been verified with a swept signal source, and the response and angle tuning are nearly exactly that predicted by theory, except that the minima are down only 20 dB from the peak response. The cluster of feed horns forms a rectangle with the filter optical axis at the center of one edge to minimize the range of incidence angles. (The optimum array configuration would be a semicircle filled with mixers, with the other half circle filled with image terminations). It is important for lowest noise and most stable operation not to have any power in the image beams reflected back to the feed horns on the mixers.

For the most compact optics, a three lens system is used, which is shown unfolded in Fig. 8. It is most convenient for the feed horns to point parallel to each other, to simplify the mechanical interface. To minimize the size of the sideband filter, the axial ray from each horn is directed toward the center of the filter by means of a lens covering the entire horn cluster, directly in front of the horns. This lens has a focal length equal to the distance to the filter (318 mm), and has only a weak effect on the effective beam waist radius at the horn. A second lens (with a focal length of 360 mm) is glued to the front surface of the filter. This lens causes the diverging beams from either side to be collimated inside the filter, as is required to minimize the angle tuning effects. This lens is actually used twice, both entering and leaving the filter, so its effective focal length is 180 mm. The outgoing beams from the sideband filter are refocused to waists near the third lens which is 430 mm to the other side. This third lens with a focal length of 430 mm (serving as the dewar window) causes the axes of the beams leaving the filter to be parallel on the outside of the dewar, so that they all couple well to the telescope optics.

As a net result of the three lenses, the internal array size is magnified by a factor of 1.35, (the ratio of the focal lengths of the third and first lenses) and the effective focal plane is displaced to a point 5 cm inside the dewar window. This magnification significantly reduces the size of the cold feed horn cluster, and thus the size of the dewar. According to diffraction theory, the telescope primary is reimaged at the focal point of the window lens (assuming that this lens is large enough). By placing the sideband filter at this point, the size of the filter is determined by the angular size of the primary mirror and not by diffraction. Thus the receiver produces an illumination which falls off rapidly outside the edge of the primary, leading to reduced spillover.

The two cold lenses are made of boron nitride [11], a low loss machinable ceramic with $\epsilon \approx 4.3$. This material is made from a pressed powder and is quite soft. Late in this project, this material was found to be quite variable both in its dielectric constant and its loss. BN in crystalline form is strongly birefringent, and some of this characteristic persists in the pressed powder form, apparently due to partial alignment of the microcrystals during pressing. This effect is variable with some samples showing $\epsilon_{xx} = 4.16$ and $\epsilon_{yy} = 4.62$, while others are nearly isotropic. This latter effect is a nuisance but has little effect if the optical axis is aligned along the polarization of the signal. The loss varies from 0.4 dB/cm to 1.5 dB/cm at 100 GHz for the four samples measured. This loss decreases by a factor of ~4 at 77 K. The surfaces of these lenses are impedance matched with $\lambda/4$ layers of teflon fabric [12] laminated with epoxy resin. Using vacuum lamination, the dielectric constant is only increased slightly above that of the teflon by the epoxy filler. This combination was used primarily because it survives thermal cycling well, and it also produces an excellent match. Coatings of solid teflon or polyethylene produce severe thermal

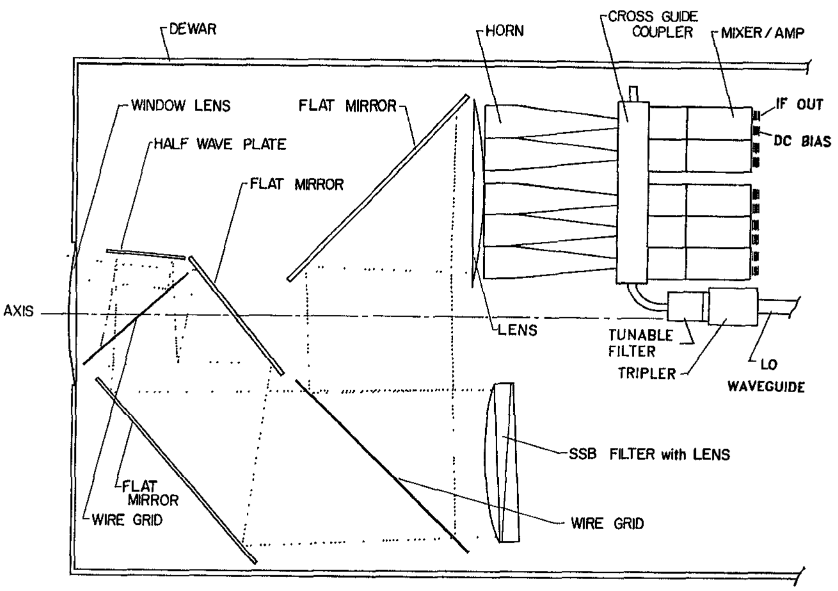

Fig. 6. Optics layout in the dewar. Cold image terminations are below the feed horns. Beam profile is shown as a dotted line. Wire grids are arrays of wires perpendicular to the plane of the drawing.

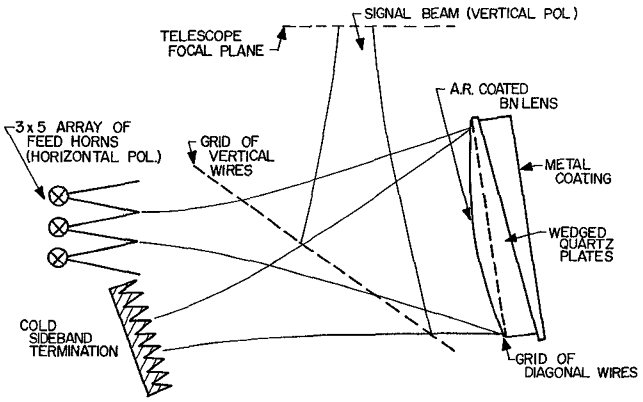

Fig. 7. Reflective polarizing interferometer used as a sideband filter. Optics shown are similar to the array optics but are simplified for clarity.

stress at low temperatures and generally crack the lenses to which they are bonded. The dewar window lens is made of fused silica, with matching coatings of polyethylene fused onto the surface. This method of AR coating works well at room temperature.

Wire grids are free standing arrays of gold plated tungsten wires, 25 μm in diameter spaced on 120 μm centers. These wires are soldered to frames made of Ni42, (42% Ni, 58% Fe) with a thermal expansion coefficient which matches tungsten satisfactorily over the required range. Three such grids are used, and all have survived many thermal cycles.

The image termination consists of a simple V-shaped cavity with a 6.4 × 10.8 cm opening, lined with absorber. This absorber is made from epoxy heavily loaded with carbon black which is cast in place to a thickness of 2.5 mm. The opening angle of 27° ensures that any beam makes several bounces before exiting. A single load serves for all beams. The mixers and feed horns are mounted directly above this load, which extends up to the edge of the feeds.

The sideband filter and the image band termination operate at a temperature of 20 K. The other system optical elements are cooled to 80 K since their loss is quite small and they contribute little to the system noise. By cooling these elements we provide a shield against room temperature radiation from the dewar window which would otherwise warm the more critical elements. To reduce the radiation load on the sideband filter from the window, all 80 K surfaces with a view of the window are painted with a carbon loaded paint [13] which is absorbing at 10 μm. Even mirrors reflecting the beam are so painted, since a thin layer of this paint has unmeasurably low loss at 3 mm.

To produce a more compact array on the sky, and to reduce the dewar window size, polarization diplexing is used to interleave six of the beams between positions of the other nine at a location just inside the dewar window. This is most easily visualized if the beams are regarded as traveling outward from the mixers. The 2 × 3 group is well separated from the 3 × 3 group at this point because all beam locations, including the gap between groups of feed horns, are reimaged at this point, as may be seen in Fig. 6 by the splitting of the beam envelope lines. Here the 3 × 3 group is reflected by ~90° by a mirror and then passes through a wire grid. The 2 × 3 group, initially in the same polarization, misses this mirror and passes through the same grid. It then reflects at nearly normal incidence off a wire grid-mirror combination which is equivalent to a half wave plate in reflection. This plate rotates the polarization of these beams by 90°, and causes them to now reflect off the same grid. At this point they rejoin the 3 × 3 group, in positions between the beams in this group. The optical alignment has been measured to produce nearly exactly the predicted beam

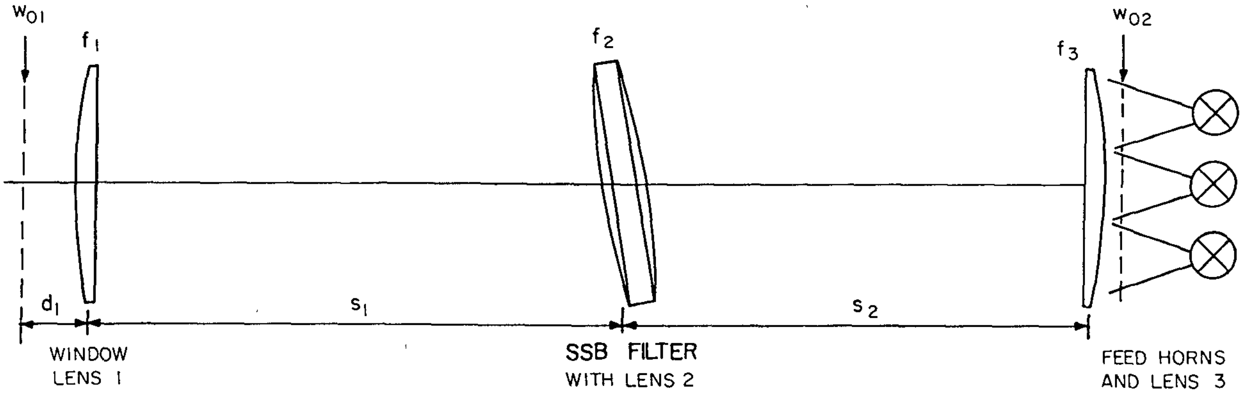

Fig. 8. Unfolded optical path, with the reflective sideband filter shown as a biconvex lens rather than as a lens covered mirror. The actual focal plane is to the right of the window lens (d_1 is negative). $f_1 = s_1, f_3 = s_2$.

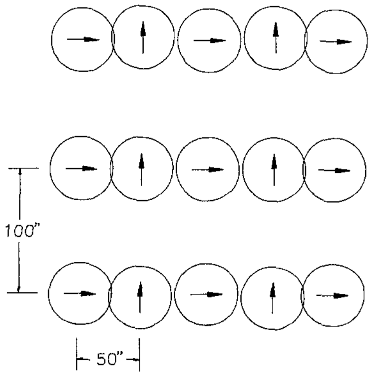

Fig. 9. Array beams on the sky, with half power beam width at 105 GHz. Polarizations are shown by arrows.

spacing. However, this interleaving cannot be done without a small difference in the optical path for the two polarizations. Thus there is a small shift in focus and also scale size between the two groups. The focus shift is ~3 cm which is small compared to the depth of field of the $f/D = 4.15$ telescope, while the scale factors differ by only 5%.

The beam spacing on the sky is measured to be 50 arcsec between pixels in the 3 × 3 group, and 53 arcsec in the 2 × 3 group. Their ideal positions are shown in Fig. 9. The FCRAO 14 m telescope has a FWHM beam width at 105 GHz of 50 arc sec. Achieving exactly the correct interleaving is difficult, because the positions of the two subarrays move in opposite directions at the focal plane under motions of most of the optical components. Thus even when the alignment is correct at one dewar orientation, small gravitational shifts as the dewar is rotated or tilted cause the interleaved spacing to change by ~0.1 beamwidth. These effects are reproducible and can be measured and corrected in the reduction of astronomical data.

LOCAL OSCILLATOR

The local oscillator system is designed to be entirely computer controlled, with a minimum number of mechanical adjustments and highly reliable frequency setting. To inject the LO into the mixers without any tuning, a multiport crossguide coupler is used. This consists of a single main line for the LO and a series of 15 coupled cross guides, each designed for 22–24 dB LO coupling across the band. While such a coupler is inefficient for a single mixer, for the array 6–9% of the input power is actually delivered to the mixers. The coupler uses full height waveguide for the cross guides for the signal and 1/2 height guide for the long LO line. Coupling is via one or three round holes depending on the coupling needed. The reduced height in one waveguide helps maintain a much flatter and stronger coupling than could be achieved otherwise. Each coupling hole produces a VSWR of ≈1.2, which if allowed to cascade over 15 holes could result in a net VSWR at some frequencies of 15! This is reduced to a more acceptable value by introducing a tuning rod near each junction. The VSWR of each is then reduced to a value of 1.05–1.1 depending on frequency. The effect of this residual VSWR is to produce a coupling ripple on a fine scale in frequency which is different for each coupled port. This ripple is about ±1 dB about the mean. The required LO power at each mixer may be met by an input power of 4 mW to the coupler assembly. The insertion loss of the coupler between the first and fifteenth port for the LO path is about 4.5 dB, requiring a continuous increase in coupling with length along the coupler. The insertion loss for the short cross guides is <0.2 dB.

The LO is a phase locked YIG tuned FET oscillator in the 29–38 GHz range driving a 90–120 mW power amplifier. This is followed by a fixed tuned frequency tripler at a temperature of 20 K mounted close to the LO coupler. The tripler uses a varactor diode with $C_j(0) = 29$ fF, $R_s = 10\ \Omega$ and $V_b = 21$ V (University of Virginia type 8P3). This tripler is designed to permit a good input and output match over the full band of operation with no mechanical tuning. A cross section is shown in Fig. 10. Input matching is aided by an inductive stub in series with the contact whisker, which is $\lambda/2$ long at the output frequency. Broadbanding of the input match is accomplished by the coaxial input filter, which is computer designed to produce a flat input response from 29.5–38 GHz. This filter structure uses five sections (impedances 12 and 66 Ω) and is designed to simultaneously produce a short circuit at

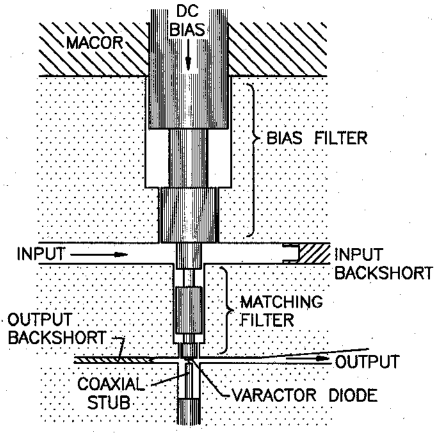

Fig. 10. Cross section of the fixed tuned tripler for 88–114 GHz.

the top wall of the output waveguide in the second and third harmonic bands. The input waveguide is reduced to 1/4 height to match to the input impedance of the filter. The output waveguide is also reduced to 1/5 height for a better impedance match, and a short section of reduced width guide is included in the output to eliminate any second harmonic leakage. The tripler backshorts are set using a swept source and a broadband flat detector to achieve ±1 dB flatness across the band. The bandwidth of this tripler is about as wide as can be made in a single diode configuration without severe spurious harmonic problems. At the lowest input frequency of 29.5 GHz, the fourth harmonic falls at 118 GHz, while at the highest frequency of 38 GHz, the second harmonic lies at 76. While the fourth harmonic is inherently much weaker than the third, the second harmonic output must be very strongly suppressed by the cutoff filter, and impedance matching is difficult if the output frequency approaches the filter cutoff.

Varactor multipliers work well at low temperatures [14] and for this device the output at 77 K is 0.7 dB greater than that obtained at room temperature. The increased output is due to a 30% reduction in R_s for the varactor, apparently due to increased carrier mobility at low temperature. An additional benefit of the cooling is that the maximum safe input power to the tripler increases, and allows the use of the full available pump power (80–100 mW at the tripler input). At room temperature this much power would damage the varactor. The cooled system produces 4 mW minimum over 90–114 GHz, with about 2 mW at 87 GHz. Tripler bias is typically 6 V and is optimized at each frequency. Due to the uniformity of the output power over the band, and the relative insensitivity of the mixers to their LO drive, no LO level adjustment is needed.

Because the tripler output match is quite broadband, the tripler produces some fourth harmonic output near the low end of the band, which is at most 10 dB down from the tripled output. This would be acceptable except in combination with the crossguide coupler, whose coupling rises sharply above the design band, reaching a resonance with near-unity coupling in the 120–127 GHz range. These effects together would cause the coupled power for some mixers to become dominated by the fourth harmonic in this range. At higher and lower frequencies the coupled fourth harmonic is weak, at least so far as it is detected by the mixers.

To cure this problem a filter was designed to reject the 120–130 GHz band. To achieve the required very rapid crossover, a dual *E*-plane stub filter is used consisting of two *E*-plane tees separated by $3\lambda/2$. The side arm of each tee is 1/10 height waveguide $\sim\lambda/4$ long with a short circuit at the end. The use of very reduced height waveguide stubs eliminates the need for coupling irises into full height stubs as in more conventional designs [15]. This filter was machined as a single wafer ~3 mm thick with the main waveguide milled through and each stub machined as a channel in either side. The backshort wall of the stubs was machined in place, but shimming was required (using indium foil) to adjust the exact tuning. The remaining wall of each stub is formed by the mating flange. This filter has less than 0.2 dB loss in band, and 15–20 dB loss in the 120–130 GHz band. The only adverse effect is that the reactive termination in the fourth harmonic band causes a very narrow-band dip in the tripled output. Multiplier analysis [16] has shown that a particular nonoptimal value of fourth harmonic reactance will greatly suppress tripling, and this value is certain to be achieved somewhere in band, due to the spacing between the tripler and filter. This is a good reason not to use a wide-band rejection filter, since such dips would appear at several frequencies. With this filter and the tunable noise rejection filter (described below) included, the fourth harmonic power coupled to any mixer never exceeds −10 dBc at any frequency in the band and is typically much lower.

The *Ka*-band power amplifier produces substantial noise due to its 8 dB input noise figure and its net 30 dB gain. This would add about 5–20 degrees to the mixer noise temperature if unfiltered. In addition, the tripler produces some noise due to the higher temperature of the varactor and due to avalanche breakdown from the high drive level. Both noise contributions are reduced by mechanically tuned filters with periodic frequency response. These are made using quarter wave thick dielectric slabs filling the waveguides in two locations ~3 cm apart, producing an approximately periodic response with a depth determined by the dielectric constant of the slabs. The periodicity for both filters is chosen to be 2.9 GHz to ensure that the noise is a minimum at 1.45 GHz away from the carrier. The insertion loss at the peaks is ~0.5 dB for both. The filters are tuned by inserting a teflon vane into a slot in the guide to vary the phase shift between the slabs. This type of tuning with no mechanical contact is quite reproducible, and works well at ambient and at low temperatures. The *Ka*-band filter uses pairs of BN slabs $\lambda/2$ apart to achieve higher rejection than is possible with any single slab of a convenient dielectric. Its rejection is greater than 20 dB across the band. The cold tunable filter on the tri-

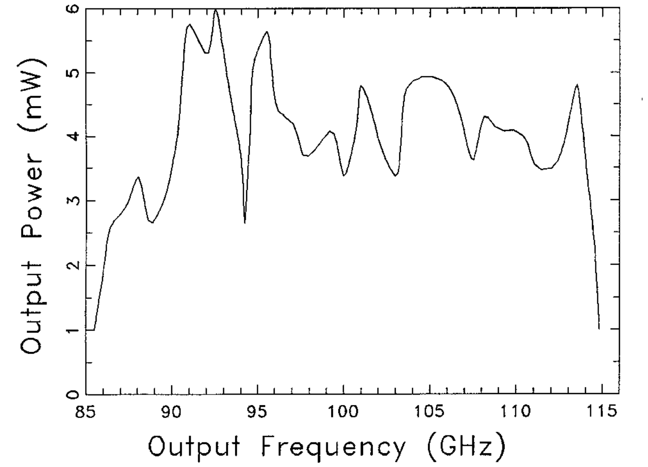

Fig. 11. Output of the complete local oscillator chain, including all filters, referenced to the LO input of the crossguide coupler. Operating temperature is 20 K. The sharp dip near 94 GHz is due to an adverse fourth harmonic termination.

pler output uses two pairs of rexolite slabs [17] achieving 10–14 dB rejection.

The input waveguide to the tripler is BeCu flexible waveguide in *Ka* band. This offers both low thermal conductivity, and enough flexibility to take up the thermal contraction of the mechanical supports upon cooling. The waveguide vacuum window is a rexolite slab drilled from both sides with round holes on axis to form $\lambda/4$ matching sections. The thickness of the center section is also $\lambda/4$ for widest bandwidth with low VSWR.

The available LO power at the input to the crossguide coupler versus frequency is shown in Fig. 11. The tripler response is relatively flat, with much of the small scale ripple added by the two following filters. The frequency slope to the crossguide coupler causes the LO power at the mixers to increase toward higher frequencies.

GENERAL OPERATION

All of the cold components are mounted on a single optics plate measuring 33 × 48 cm, which is mounted in a vacuum dewar 41 cm diameter × 59 cm long. This plate is supported with minimal thermal conduction by several fiberglass standoffs and stainless steel wires, so that the alignment is stable in any orientation. Cooling is provided by two refrigerators with 3.5 W cooling at 20 K. One refrigerator cools the mixer/amplifiers, feed cluster and cold load to 20 K, since the temperature of these components is most critical. The load on this refrigerator is fairly high since the HEMT amplifiers together dissipate 1.4 W and 30 coaxial cables and one waveguide connect directly from the mixers to room temperature. The 20 K stage of the second refrigerator is used to cool the sideband filter, while the 80 K stage cools the large optics plate. The overall cooldown time is about 12–15 h. The dewar is mounted at the Cassegrain focus of an altitude-azimuth telescope and must rotate to maintain a fixed orientation as the telescope tracks an astronomical source. The allowed rotation range is ±90°. The dewar window is on the axis of this dewar so that the pointing of the array does not depend on rotation. The rotation requires that the entire dewar be mounted on two large bearings while all cables and helium refrigerator hoses pass through a cable wrap.

All function are computer controlled by a local PC including the three mechanical tuners needed. Mixer bias is set by 15 current sources which the computer can individually adjust for best operation, given the fixed LO power. All filter and bias settings are stored in the PC, and adjustments are iterated automatically to compensate for drifts. The system is designed for remote observing and should make possible a number of new observing strategies due to its high data rate and frequency agility.

The large dewar window (10 cm square) has the potential to introduce RFI into the components inside the dewar at frequencies within or near the IF band, as can be demonstrated with a laboratory source. In all other respects the dewar is quite RF tight, with even the second stage IF amplifiers inside to minimize pickup. RF pickup from UHF TV stations and aircraft radar has been found to be a significant problem at the FCRAO. Rather than resorting to extensive shielding of all parts within the dewar, an RF shield was devised to cover the window. This is a very open wire mesh, made using 25 μm diameter wire spaced by 2.4 mm, with two sets of wires at right angles. This mesh reduces the window leakage by 20–25 dB near 1.4 GHz, bringing this source of pickup down near the level due to other sources. This mesh has low loss in the signal band, varying from 0.2 dB at 90 GHz to <0.1 dB at 115 GHz. It is important to avoid a wire spacing near λ since this is found to cause a loss of $\approx$0.6 dB near the threshold for scattering. This mesh was not used for the data presented here, since it will only be installed in the event that RFI is found to be a significant problem.

PERFORMANCE

Noise performance data for the system is shown in Fig. 12. Due to the number of mixers, only the average noise is shown, along with the highest and lowest noise of the individual pixels at each frequency. Most frequencies have been measured in both sidebands, and while the average performance shows little variation with sideband, individual mixers can show a sideband ratio up to 1.3/1. Over much of the band, the variations in the system noise between pixels are consistent with what would be expected, based on data measured on the mixers in a test fixture. An approximate breakdown of the input losses at midband (100 GHz), and their effective temperatures, is as follows:

Input lens	3% at 295 K
Input optics (interleaving)	5% at 80 K
Sideband filter and lens	5% at 30 K
Image termination	20 K
Lens at feed horns	3% at 80 K
Feed horn/coupler	5% at 20 K

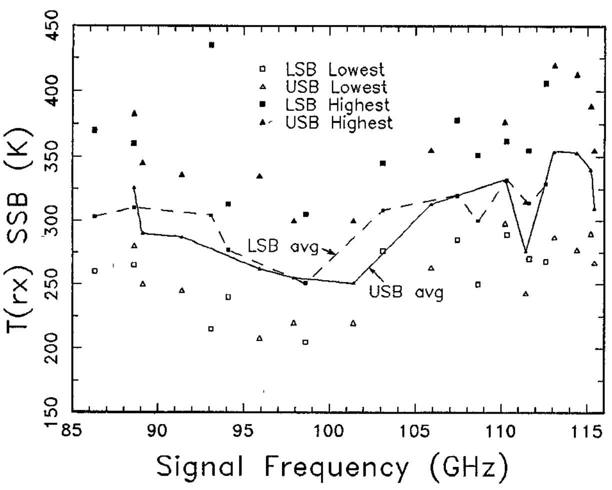

Fig. 12. Array SSB system noise temperature vs frequency. Noise temperatures averaged for all pixels are connected by lines. Data points show the highest and lowest noise for individual pixels at the same frequencies. All data are measured near the center of the IF band.

These losses would result in an array system temperature of 248 K SSB for a mixer/amplifier with a DSB noise temperature of 81 K at the waveguide flange, and these numbers are consistent with measurements. All losses have been measured at room temperature, but their cold behavior can only be estimated. Losses are believed to be slightly higher at 115 GHz than at midband, since matching coatings are at the edge of their band, and material losses increase. However, only in the best pixels is the noise at 115 GHz consistent with data on individual mixers, and the dispersion is much greater; while the individual mixers are within ±6% of the mean, in the full system the spread is ±17%. While it might be expected that the optical path contributes comparable loss to all elements, the excess variation in noise implies that some properties of the array depend on location. The coupler ports and feed horns losses have all been measured at room temperature and are quite similar. There are insufficient data on other elements at present to determine the source of these variations. Possible sources include the following:

1) Poor mounting of the mixer to the coupler. Since all heat sinking of the mixer is across the waveguide flange, and the thermal load includes the IF amplifier power, poor contact here can lead to an elevated operating temperature. It may also lead to high RF losses if the gap is large enough. It is nearly impossible in the array to inspect the flange contact, but this effect should affect all frequencies comparably.

2) Beam truncation within the optics depending on location. In principal, all optics are sufficiently oversize to reduce this to a level of only a few percent at most, but misalignment may bring some beams closer to an edge than planned. However at 115 GHz, the beam is at least as small as at other frequencies, and at some points smaller.

3) High mismatch of the matching coatings on the lens immediately in front of the mixers. This lens is close enough to the horns to interact strongly with the mixers if it reflects a significant amount of power. It has been tested near the center where it reflects less than 2% of the power even at the band edges, but it has not been tested over the full surface, and the coating may be nonuniform. This effect should be largest at the highest frequencies.

4) Insufficient LO power to certain mixers. The coupler shows a total spread of 3 dB in coupling between ports and this may lead to some mixers having too little LO. Test fixture data were taken at an LO level typical of that available in the system, but this typical level is not achieved on all ports.

It seems likely that these sources taken together can account for the observed variations. When the source of this discrepancy is found, it should be possible to bring the average noise at 115 GHz down to about 310 K. Further improvements in the overall system should permit a small additional reduction in average noise at all frequencies.

Noise across the IF band was measured for all elements only at 115.3 GHz (the most important operating frequency), and is similar to the DSB response measured in the test fixture as shown in Fig. 3. The IF bandwidth for most pixels exceeds the requirement of 320 MHz, and is quite flat.

This system is now installed on the FCRAO 14 m telescope with all elements operational. At the time of writing, the system has operated for over four months without a failure of any front end component. Over 250 000 individual pixel spectra have been obtained in this time, more than the total for the previous ten years at this facility using single pixel receivers.

The comparison of receiver sensitivities with those at other facilities is complicated by the contribution of atmospheric opacity, which varies with site, and with the properties of each telescope. An additional complication is introduced because few receivers, if any, deliver the same noise performance on the telescope that they do in the laboratory. The best reported operational SIS receiver [1], in use at the National Radio Astronomy Observatory 12 m telescope, yields a system temperature on the sky (referenced to the top of the atmosphere) of $T_s = 380$ K [18] due to the large oxygen opacity ($\tau \sim 0.4$) and various telescope related losses. For the array, the pixel averaged noise measured on the sky under good conditions is 740 K SSB. This latter noise also includes the loss ($\sim 6\%$) due to the radome enclosure at the FCRAO. The data rate enhancement of the array over a single such SIS receiver is a factor of 3.9, while as the opacity becomes higher this factor increases. At 100 GHz, where atmospheric opacity is much lower ($\tau \sim 0.2$), the same SIS receiver yields a noise temperature of 220 K on the sky while this array gives 350 K. In this case the data rate of the array is 5.9 times faster. Note that two receivers are actually used at the National Radio Astronomy Observatory in a dual polarization mode, requiring half as much time to obtain a given noise level, and thus their system compares more favorably to the array.

Conclusion

A fifteen element array has been built which achieves the goal of a greatly increased data rate over that of single element receivers. The array offers relatively close packing of beams on the sky, full remote observing capability, and frequency agility over the 86–115 GHz range. This system has proven to be reliable and very easy to use, with fully automated operation. Development of the array has required advances in mm-wave optics and LO systems as well as in the mixers themselves. Further system improvements seem practical to lower the array averaged noise, and to make the array even more powerful as an astronomical tool.

Acknowledgment

A project of this size requires the contributions of many individuals, and thanks are due to the entire staff of the FCRAO for their long and dedicated work on this array. We also thank A. R. Kerr for useful comments on the manuscript.

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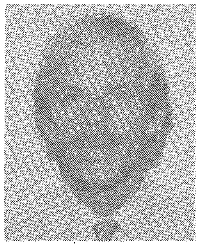


Neal R. Erickson (M'85) received the B.S. degree from the California Institute of Technology, Pasadena, in 1970 and the Ph.D. degree in physics from the University of California at Berkeley in 1979.

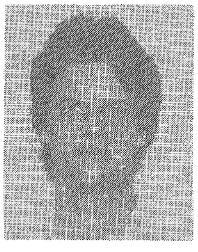
Since that time he has worked for the Five College Radio Astronomy Observatory at the University of Massachusetts in the area of receiver instrumentation for millimeter and submillimeter radio astronomy. This work has involved receivers from 80 to 700 GHz and includes the lowest noise Schottky diode mixers reported for both 100 and 230 GHz. He has been a leader in the area of high efficiency frequency multipliers, which he has now constructed up to 600 GHz. He has also designed novel optical systems for a number of these receiver systems. He led a successful effort to measure and reset the surface panels of the FCRAO 14 m telescope using holographic mapping at 38 GHz. In 1982 he was one of the founders of Millitech Corporation, and since that time he has worked there primarily in the areas of frequency multipliers and low noise mixers for near millimeter and submillimeter frequencies. His design for a 500 GHz harmonic mixer has become the basis for the receiver system on the Submillimeter Wave Astronomy Satellite, on which he is one of the co-investigators.

Paul F. Goldsmith (M'75–SM'85–F'91) carried out the Ph.D. research at the University of California at Berkeley, developing a sensitive heterodyne receiver for the 1.3 mm wavelength range and using it to carry out some of the earliest observations of the $J = 2$-1 transition of carbon monoxide and its isotopic variants. This research into the structure of molecular clouds continued at Bell Laboratories, where he was also involved in designing the quasioptical millimeter wave feed system for the 7-m offset Cassegrain antenna.

In 1975 he moved to the University of Massachusetts, where he studied the thermal balance of interstellar clouds and their physical conditions. He also initiated development of cryogenic mixer receivers at the Five College Radio Astronomy Observatory, developing a system which had very low noise as well as exceptional calibration accuracy as a result of the extensive use of quasioptical technology for single sideband filtering and input switching. In 1981 he led a team which carried out the first submillimeter astronomical observations with a laser local oscillator heterodyne system. At the University of Massachusetts, his astronomical research has addressed questions of the relationship of molecular clouds to young stars and detailed studies of molecular material near the center of the Milky Way. A Professor at the University of Massachusetts since 1986, Dr. Goldsmith is one of the co-investigators for the Submillimeter Wave Astronomy Satellite (SWAS). His research in technology has focused on Gaussian optics, quasioptical system design, and imaging systems. In 1982 he was one of the founders of Millitech Corporation, where he is Vice President for Research and Development, and works primarily in the area of millimeter wavelength imaging, and quasioptical component and system design.

Dr. Goldsmith is a member of the American Astronomical Society, Sigma Xi, and URSI.

G. Novak, photograph and biography not available at the time of publication.



Ronald M. Grosslein received the B.A. degree with honors in physics from Amherst College, Amherst, MA, in 1978.

He joined the staff of the Five College Radio Astronomy Observatory, Amherst, in 1979, assisting with cooled microwave receiver construction, testing, and maintenance. In 1985 he began work on cooled FET LNA's. More recently he built, tuned, and tested most of the cooled HEMT IF amplifiers for the FCRAO array receiver.

P. J. Viscuso, photograph and biography not available at the time of publication.

Ronna B. Erickson received the B.S. degree in physics and astronomy from the University of Massachusetts, Amherst, MA, in 1980.

She then worked on cryogenic receivers for radio astronomy at the Five College Radio Astronomy Observatory, Amherst. From 1982 to 1988 she was with Millitech Corp., where she worked on millimeter and submillimeter components and systems, and was also a Program Manager for large systems. After working on laser optical systems for Amherst Process Instruments, she returned to the Five College Radio Astronomy Observatory to work on the Quabbin Array (QUARRY) project.

She is a member of the American Astronomical Society and the American Institute of Physics.

C. Read Predmore (M'73) received the B.S. degree in physics from the Virginia Polytechnic Institute, Blacksburg, in 1967 and the Ph.D. degree in physics from Rice University, Houston, TX in 1971.

From 1971 to 1972 he was an Assistant Professor in the Department of Space Physics and Astronomy at Rice University. In 1972, he joined the National Radio Astronomy Observatory where he worked on the development and design of the TE_{01} transmission system for the Very-Large-Array radio telescope. Since 1975, he has been at the University of Massachusetts, Amherst, where he is an Associate Professor in the Department of Physics and Astronomy and is doing research and development for the 14m millimeter wavelength telescope of the Five College Radio Astronomy Observatory. In addition to millimeter receivers, his research interests include digital spectrometers, polarization measurements of astronomical sources and millimeter wavelength Very Long Baseline Interferometry (VLBI).

Dr. Predmore is a member of the American Astronomical Society and URSI.