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A Cryogenically Cooled Two-Channel Paramp Radiometer for 47 GHz

JOCHEN EDRICH, SENIOR MEMBER, IEEE

***Abstract*—A field operational radiometer for 47 GHz with 18 K cooled degenerate paramps is described which has parallel channels for two ortholinear or circular polarizations. It exhibits an instantaneous RF bandwidth of 300 MHz and a tuning range up to 2 GHz. Its double-sideband system noise temperature of 100 K at midband and its minimum rms noise fluctuation of 0.16 K are several times lower than those of existing millimeter wave receivers.**

I. Introduction

During the last decade uncooled parametric amplifiers have been developed for millimeter waves and found some applications in radiometry, radar, communications, and radio astronomy up to about 38 GHz [1]–[3]. Above this frequency a few laboratory experiments at room temperature have been reported at 46 GHz [4], 60 GHz [5], [6], and 94 GHz [7]. Paramps with even lower noise which are cryogenically cooled have been reported up to 24 GHz [2], [8]. This report describes the first field operational and cryogenically cooled millimeter-wave paramp system for 47 GHz.

II. Design Considerations

A. System Layout

The main aim of this program was to develop a broadband radiometer with two channels for two linear or circular polarization. In order to obtain a small rms noise fluctuation, a low ratio $T_{op}/\sqrt{B}$ of system noise temperature T_{op} and RF bandwidth B is required [9]. A secondary goal was to tune this system for spectral line observations over a band of several gigahertz around 47 GHz. This made a low value of T_{op} even more important. A system with two cooled and synchronously pumped degenerate paramps can best meet these requirements [10]. Such a system was therefore chosen and is shown schematically in Fig. 1.

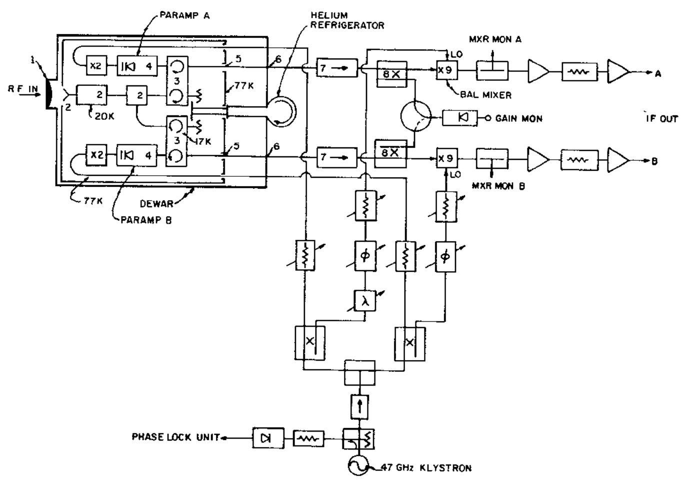

Fig. 1. Block diagram of the cooled 47-GHz receiver (numbers refer to Table I).

It requires only one source at a relatively low frequency, i.e., a klystron at 47 GHz, because it can simultaneously drive two paramps via doublers and also supply the phased LO signal to the following mixers. Another advantage of

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The author is with the Denver Research Institute, University of Denver, Denver, CO 80210.

this layout is that only one phase-lock loop is required and only one source frequency has to be changed in order to tune the entire receiver system.

B. Optimum T_{op} and $T_{op}/\sqrt{B}$ Values

Different design criteria have to be applied in the system design depending on the application of the receiver. For the radiometric mode of broad-banded continuum measurements one has to minimize the aforementioned ratio $T_{op}/\sqrt{B}$ of the double-sideband system noise temperature and the square root of the bandwidth. One can express the system noise temperature T_{op} in the following form:

$$T_{op} = T_{e1} + T_{e2}/(2G_1) \quad (1)$$

where T_{e1} represents the double-sideband noise temperature of the degenerate paramp including the noise contributions of all preceding components such as the lens, horn, and circulator (component nos. 1–3 in Fig. 1). G_1 is the power gain of the paramp as measured with a crystal detector minus the loss of the preceding components. T_{e2} represents the double-sideband noise temperature of the following mixer preamplifier including the contributions of components ahead of it (component nos. 5–8 in Fig. 1).

The factor 2 in (1) is due to the coherent folding of the mixer and paramp bands for the synchronously pumped case [10].

Assuming that the gain bandwidth product is determined by the paramp and can be represented by a constant K,

$$\sqrt{G_1} \cdot B = K \quad (2)$$

one can find the optimum gain $G_{1\,opt}$ for minimum $T_{op}/\sqrt{B}$ by multiplying (1) with $1/\sqrt{B}$, inserting (2) and differentiating this expression in regard to B. The result is

$$G_{1\,opt} = 1.5T_{e2}/T_{e1}. \quad (3)$$

This expression for broad-band applications shows that the optimum gain is strongly dependent on the ratio of the noise temperatures of the paramp and the mixer preamplifier.

For narrow-band applications, like spectral line work, one is solely interested in a small value of T_{op}. One will, therefore, try to minimize the second stage contribution, i.e., the second term on the right-hand side of (1), by increasing the gain G_1 as much as feasible in the view of the conflicting requirement for a good gain stability. A reasonable compromise can be given by

$$G_{1m} = 6T_{e2}/T_{e1}. \quad (4)$$

A discussion of the numerical consequences of (3) and (4) for our system will be found in Section IV-B.

III. Critical System Components

A. Cooled Circulator

One of the components most critical for the input VSWR, the noise temperature, and the bandwidth of the system was its cooled circulator, which was not available for millimeter frequencies, and, therefore, had to be developed specifically for this system. The first prototype circulator, an H-plane device, was developed for an experimental laboratory receiver [11]; it was later modified into a four-port device with improved cooling performance and reproducibility. As in the earlier model triangular ferrite pucks with triangular symmetric $\lambda/4$ transformers were used. However, a relatively wide air gap was incorporated on one side which reduced the effect of shrinkage during cooldown. The ferrite was operated near a mode similar to the $HE_{1,1,3}$ hybrid mode, excited by the field in the coupling gap. This mode of operation which approaches the ideal compact-turnstile mode [12] resulted in an isolation bandwidth of about 8 percent for the 20-dB points and an insertion loss of 0.9 dB per junction at 18 K. It therefore degraded the isolation bandwidth by about 3 percent and the insertion loss by 0.2 dB as compared to the earlier version which was designed to operate close to a mode similar to the $TM_{1,1,0}$ cylindrical-cavity resonance-counter-rotating mode [13], [14].

B. 47–94-GHz Doubler

Varactor doublers are used to provide the pump power for the paramp. A scheme involving pairs of Schottky-barrier varactors in modified Sharpless wafers was used which helped to increase the efficiency to 30 percent at room temperature [15]. During the course of this receiver development it was found that the relatively large doubler output power of more than 35 mW was not sufficient as drive for the paramp although they required less than 20 mW at the midband frequency. The loss and the reflections on the 30-cm-long stainless-steel waveguides connecting the two devices made it impossible to provide enough pump power over a band of several gigahertz without tuners which were considered impractical for the remotely controlled field operation.

Therefore, cooled versions of these doublers were developed which could directly be connected with the cooled paramp as shown in Fig. 1. Results with these cooled doublers [16], which, to the author's knowledge, represent the first successful attempts in this area, indicate that the overall efficiency increases when cooling to 33 percent. There are three main changes occurring in this cooling process.

1) The varactor series resistance increases while the capacitance stays about constant [2], [17]; therefore, the efficiency decreases.

2) The varistor effect of the diode is reduced because of the well-known changes of the forward I–V curves with temperature [18], [2]; this effect increases the efficiency.

3) Conductor losses including those of the reduced-height waveguides ($b = 0.25$ mm), the input, and the output filters are substantially reduced.

The improvements listed under 2) and 3) which lie in the order of decibels, are apparently overcoming the increased loss due to the series resistance.

Another obstacle in the system use of these doublers was the relatively stringent requirement on the harmonic content of odd harmonics. This can best be understood by

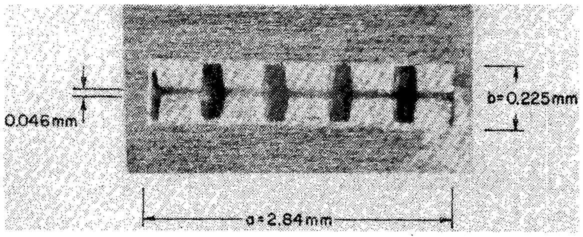

Fig. 2. Waffle-iron-type filter integrated into the 47/94-GHz cryogenically cooled varactor doubler.

looking at the first-order mixing actions of these odd harmonics mf_{LO} with the even harmonics nf_{LO} in the paramp varactor: They can yield unwanted base frequencies f_{LO} for

$$m - n = \pm 1. \tag{5}$$

The components with the largest powers which meet this condition are $m = 3$ (unwanted third harmonic) and $n = 2$ (wanted second harmonic = pump frequency). The noise sidebands of this "secondary" LO are many times wider than the one of the "primary" LO supplied directly by the drive klystron. The original design of the doubler was optimized for the wanted second harmonic and provided little filtering for the unwanted third harmonic; it therefore allowed this frequency to pass into the paramp and mix there to produce the unwanted secondary LO which lies in the passband of the paramp; it, consequently, passed unattenuated into the mixer and caused substantial LO noise because of the low IF frequency used in this system (20–500 MHz). It should be noted that medium power klystrons which can tune over such a wide frequency range necessarily exhibit a relatively wide noise spectrum. The alternative to use a tunable LO noise reduction filter was considered impractical; it would have also degraded the overall system stability and reduced the available drive power. A "waffle-iron" low-pass filter [19] was therefore incorporated into the output circuit of the doubler which provided more than 25-dB attenuation for unwanted higher order harmonics. The loss of this filter reduced the efficiency at 300 K by about 25 percent; this is primarily due to the high loss of its low impedance sections in between the gold-plated teeth which have a minimum spacing of 0.075 mm as shown in Fig. 2. Cooling increased the efficiency again to about 33 percent, suggesting 1) that most of this loss was conductor loss and 2) that some of the power previously lost in unwanted harmonics now went into the wanted second harmonic.

C. 18 K Cooled Parametric Amplifier Design

The basic design of the paramp mounts which uses 3.5 μm-diam Pt-GaAs Schottky-barrier junctions[1] packaged in modified Sharpless wafers has previously been described [20]. In the meantime several improvements were incorporated.

[1] Developed by Dr. R. Mattauch, University of Virginia, Charlottesville.

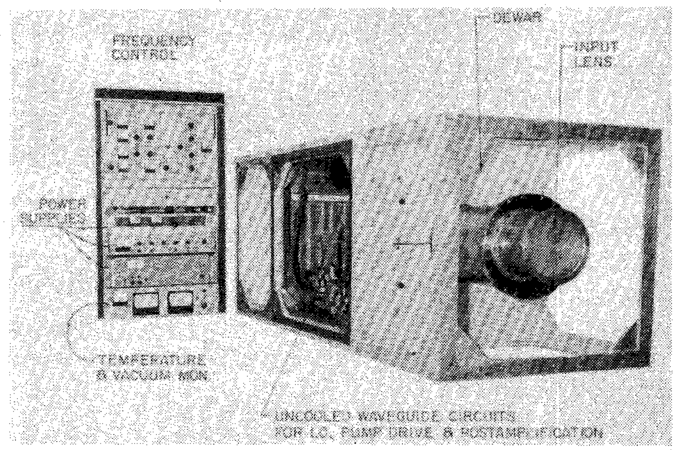

Fig. 3. Front-end and control rack of 17 K cooled paramp receiver for 47 GHz.

1) The loss, inductance, and mechanical stability of the whisker assembly was improved by using more elastic phosphor bronze whiskers (0.025 mm thick) with a smaller step height on the whisker post and a gold-plated coat over the entire assembly.

2) An additional $\lambda/4$-type rejection filter helped to reduce unwanted third harmonics of the doubler.

In order to achieve a wide electronic tuning range (up to 2 GHz), the pump-modulations factor γ was reduced to about 0.08 at the midband frequency f_s. This results in a theoretical double-sideband noise temperature [10]

$$T_{DSB} = T_A\{(f_s/\gamma f_c) + (f_s/\gamma f_c)^2 + 0.5(f_s/\gamma f_c)^3\} \tag{6}$$

of 25.5 K for the varactor only which is cooled to a temperature $T_A = 20$ K and has a cutoff frequency $f_c = 850$ GHz [20].

The voltage-gain bandwidth product of a degenerate parametric amplifier can be approximated by [10]

$$\sqrt{G} \cdot B = \gamma f_s. \tag{7}$$

This equation considers the bandlimiting effects of the varactor only and neglects the influence of the input circuit and the two rejection filters which are small in this design. Using the aforementioned γ value of 0.08, a signal frequency of 47 GHz and a crystal detector measured gain of 22 dB results in an upper limit of the RF bandwidth $B = 300$ MHz. This value is within about 10 percent of the measured bandwidth of channel A.

IV. System Parameters and Comparison with Theory

A. General

The completed 47-GHz receiver system is shown in Fig. 3. The front-end part, which includes all of the RF components of the schematic Fig. 1, has an open compartment exposing the dewar and the grooved dielectric input lens. The following compartment contains the uncooled waveguide circuits for the LO, pump drive, and the mixer preamplifiers. This compartment is normally closed and foam padded for better insulation. Thermoelectric heaters and coolers are keeping it at a temperature of 30 ± 0.5 C

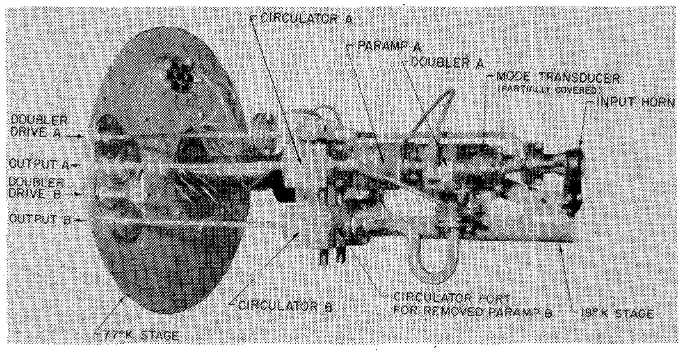

Fig. 4. Exposed view of the 18 K cooled paramp receiver for 47 GHz. Dewar and radiation shield as well as paramp and doubler mounts of the orthogonal channel B have been removed for viewing purposes.

for a change of the outside temperature between −10 and +50 C.

The receiver has been designed for, and was recently successfully used on, the Cassegrain focus of the National Radio Astronomy Observatory's (NRAO's) 36-ft telescope on Kitt Peak near Tucson, AZ. It is remotely operated, frequency tuned, and phase locked from the 19-in control rack shown on the left-hand side of Fig. 3.

Frequency tuning involves resetting the bias voltages of the doublers and paramp, the currents of the pump attenuators, and the klystron servo tuner and reflector voltage. A reproducible adjustment of the servo-controlled mechanical klystron tuner is facilitated by a servo-controlled cavity meter together with the phase-lock system. Calibration curves of these dial settings and no sweeper sources are needed for this retuning which can be performed within a few minutes.

An exposed view of the cooled portion of the receiver with its dewar and the radiation shield removed is shown in Fig. 4. Its 18 K cooled scalar horn produces, together with an uncooled dielectric lens, a half-power beamwidth of 4° which is optimized for the Cassegrain arrangement on the 36-ft telescope. The straight-through arm of the following mode transducer feeds the vertical-polarized component with minimum attenuation and mismatch into the upper paramp A. The mode transducer produces an isolation of 25 dB for the two orthogonal polarizations. Its horizontally polarized component is fed via the three-quarter S-shaped and twisted waveguide into the circulator B and paramp B (Fig. 4). A quarter-wave plate section can be inserted in between the horn and the transducer; this produces left-hand or right-hand circular polarization with an axial ratio of 1.2. Six cobalt–nickel permanent magnets are biasing the two four-port circulators; they produce an elliptically shaped magnetic field through all four functions, thus maximizing the fields while keeping the weights and stray fields to a minimum.

The system is normally started on the ground by evacuating it with a mechanical roughing pump to a pressure of 10^{-2} torr which requires a few minutes.

Cooling of the refrigerated part of the receiver to 18 K requires about 7 h, which can also be performed on the ground, since mounting of the cooled front-end box on the

TABLE I
SIGNIFICANT NOISE CONTRIBUTIONS IN CRYOGENIC PARAMP SYSTEM FOR 47 GHz

No[a)]	Component Description	Phys. Temp. K	LOSS L_R Refl. db	L_D Diss. db	L_T Tot. db	DSB[d)] Noise Contrib. K
1	Lens (2.8 cm polystyrene)	293	0.33	0.2	0.53	13.8
2	Scalar horn with mode splitter and transition to rectangular guide[b)]	17	0.3	0.4	0.7	1.8
3	Circulator, two junctions	17	0.2	1.6	1.8	10.1
4	Paramp[c)]	17	--		-22	51.2[c)]
5	Output waveguide between 77K stage and 300K stage, stainless steel goldplated	200	0.05	0.2	0.25	(0.1)
6	Output waveguide windows, two 0.05 mm thick cellophane films	293	0.1	0.05	0.15	(0.1)
7	Isolator incl. 24 cm lg. connecting waveguide sections	293	0.1	1.0	1.1	0.4
8	Monitor coupler , 10 db	293	0.1	0.5	0.6	0.3
9	Balanced mixer preamplifier T_{IF} = 300°K; L_C = 7.5 db; t = 1.2	293	--	--	--	14.5
	Theoretically expected DSB system noise temperature				92.1 ± 10 K	
	Measured DSB system temperature of Channel A at 47.3 GHz and Channel B at 46.5 GHz				100 ± 10 K	

NOTES
a) Component numbers refer to block diagram Fig. 1, Channel A.
b) Spillover contributions are not included.
c) Cutoff frequency f_c=850 GHz at the bias voltage V_B= -.7V. Capacitance modulation factor γ = 0.08. Gain measured with crystal detector: G=22 db. Theoretical noise temperature of the paramp only, T_{ep}=25.5 K (DSB).
d) Defined as noise temperature of individual components times the loss of preceding elements.

36-ft telescope is typically accomplished in about 25 min; the system is therefore again cooled down to 18 K and ready for use within another 20 min. The down time for the telescope due to this receiver change is therefore kept to less than 45 min.

B. System Noise Performance and Comparison with Theory

The noise budget presented in Table I shows that the theoretically expected system noise temperature of 92 K agrees reasonably well with the measured double-sideband noise temperature of 100 K at the midband frequencies 47.3 and 46.5 GHz of channels A and B, respectively. From this it is also apparent that the paramp contribution $\Delta T = L \cdot T_{ep} = 51.2$ K is quite significant. One part of this contribution is given by the loss, $L = 3$ dB, of input components and another part is due to the noise temperature, $T_{ep} = 25.5$ K, of the paramp itself. The varactors are capable of T_{ep} values as low as 7 K [20]. However, their capacitance modulation was intentionally kept small ($\gamma \simeq 0.08$). This step was taken in order to increase the electronic tuning range to more than 1 GHz. It also made it possible to cover the entire frequency range without mechanical tuners between the paramps and the doublers. Tuners would have otherwise been required because of the limited power available from the doublers and the narrow bandwidth of the pump circuits.

It was discussed in Section II that there are two distinct sets of gain and bandwidth combinations depending on the system applications. The broad-band radiometric case is given by (3) and yields a gain $G_C = 18.2$ dB for the paramp

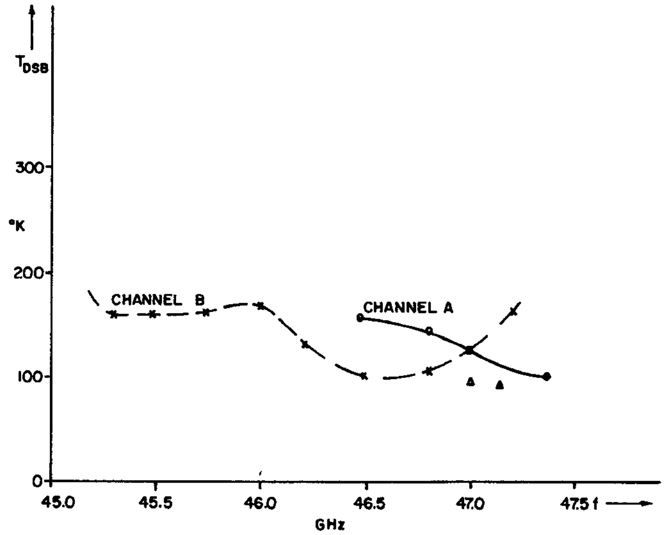

Fig. 5. Measured system noise temperatures of the 18 K cooled 47-GHz paramp receiver as a function of signal frequency. Measurement points marked with triangles were taken while the receiver was in use on the Cassegrain focus of the NRAO 36-ft telescope in October 1975.

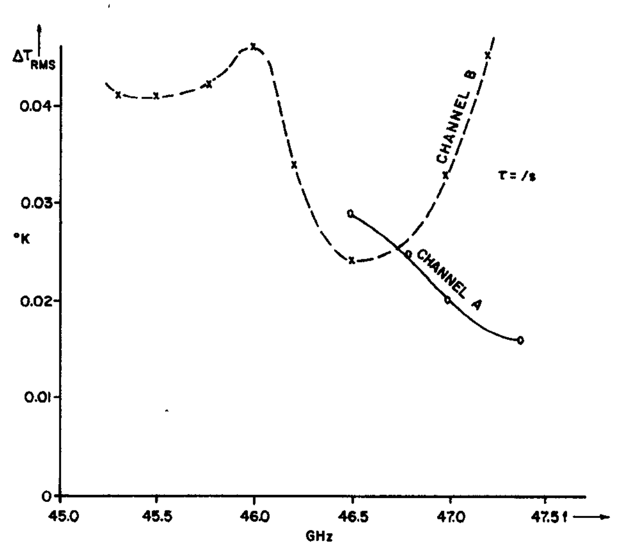

Fig. 6. RMS noise fluctuation of the 18 K cooled paramp receiver as a function of signal frequency. These curves are calculated using (8) with the measured bandwidth, noise temperature (Fig. 5), and an integration time of $\tau = 1$ s.

only, whereas the narrow-band case yields a theoretical gain value $G_S = 21$ dB for the paramp only, which is close to the one actually used (22 dB). Knowing these gains and their associated bandwidths one can calculate the rms noise fluctuation [9]

$$\Delta T_{\text{rms}} = T_{\text{op}} \cdot \sqrt{2} \cdot \sqrt{2}/\sqrt{B\tau} \tag{8}$$

where B represents the IF bandwidth, τ the integration time, and T_{op} the double-sideband system noise temperature. The two square root factors in (6) are due to the beam switching and the nonideal detection process in the back end of the receiver [9]. The numerical difference in the ΔT_{rms} values for the discussed broad-band and narrow-band cases amounts to only 3 percent. Because of this negligibly small difference, it was decided to optimize the system according to the narrow-band gain formula given by (4). Fig. 5 shows the variation of the system noise temperature for both channels versus frequency as measured in the laboratory. Also included as two triangles around 47 GHz are two noise measurements while the system was used on the 36-ft telescope in October 1975. A slightly lower noise temperature was achieved at that time by removing a lossy IF monitor tee and cooling the equipment to a 1 K lower temperature with a more powerful helium compressor. Channel B is pumped slightly harder and also has a higher transformation ratio in its signal input circuit. It can tune over more than 2 GHz which is twice as wide as channel A; this has the advantage of an almost two times wider instantaneous bandwidth (up to 300 MHz). This fact can also be seen from the plot of ΔT versus frequency in Fig. 6, which shows that the optimum operating point for minimum ΔT of both channels lies around 47 GHz.

The strip chart output of one channel shown in Fig. 7 indicates that the 1-Hz gain modulation caused by the

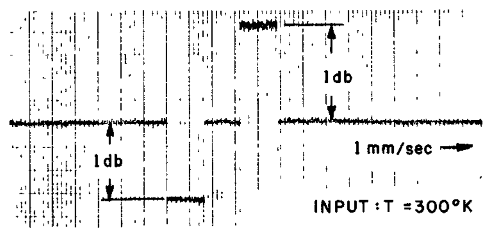

Fig. 7. Strip chart record of the detected IF output of the 18 K cooled 47-GHz paramp receiver ($\tau = 0.01$ s. $BW = 300$ MHz; $f_s = 47.2$ GHz).

TABLE II
SUMMARY OF SYSTEM PARAMETERS

Frequency tuning range	46.5 to 47.4 GHz (Ch. A) 45.3 to 47.3 GHz (Ch. B)
Instantaneous 3 db rf bandwidth for midband paramp gain G = 22 db	230 to 300 GHz (Ch. A) 110 to 160 MHz (Ch. B)
Double-sideband system noise temperature	100 to 160 K (Ch. A) 110 to 170 K (Ch. B)
R.M.S. noise fluctuation for 1 sec time constant	0.016 to 0.029 K (Ch. A) 0.024 to 0.046 K (Ch. B)
Input VSWR	<1.25 (Ch. A & B)
Gain stability for normal operational temperature control (±0.5°C), with pump leveled and phase locked	<0.1 db (Ch. A & B)
Half-power beam width for all four polarizations	4 ± 0.3°
Polarizations	Two linear or two left-or right-circular
Cooldown time	7.5 hours
Vacuum in dewar when refrigerated	$<10^{-5}$ Torr
Physical temperature of paramps	18 K

refrigerator as well as the short-term stability and drifts are less than 0.1 dB.

Table II summarizes the most important electrical, temperature, vacuum, and mechanical parameters.

V. Conclusions and Outlook

The minimum noise temperatures of 100 K achieved with this field operational system have advanced the state-of-the-art of receiver noise by a factor of 3 as compared to cooled mixer systems [21], [22] and by about an order of magnitude as compared to receivers using uncooled mixers [22], [23]. Traveling-wave maser systems such as the one presently being completed [24] might be able to achieve a 50-percent lower system noise temperature because of their lower input loss contributions; however they have to be cooled to 4 K, are more complex, often require more than one pump source, and do not have the "gigahertz bandwidth" potential of paramp systems. Josephson devices have recently shown promising millimeter-wave mixing characteristics [25] and might eventually lead to practical systems with lower noise, broader bandwidths, and many times wider tuning ranges extending up to at least 300 GHz [26].

Future cooled paramp systems for the 40–60-GHz range could readily be improved to yield noise temperatures of less than 50 K and instantaneous RF bandwidths of at least 1.5 GHz [20]. This could be achieved by using separate 47-GHz sources for each channel consisting of a two-stage cooled paramp and followed by an uncooled mixer. Klystrons would presently be the only choice that can supply the required power of more than 0.5 W per channel.

Based on the experience gained from this development it is apparent that future 100-GHz paramp systems for radiometry, communications, or radar can achieve single-sideband noise temperatures of less than 250 K when 20 K cooled or 700 K when uncooled with bandwidths of at least 1.5 GHz.

Acknowledgment

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