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CRYOGENIC, HEMT, LOW-NOISE RECEIVERS FOR 1.3 TO 43 GHz RANGE

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ABSTRACT

This paper describes the construction and performance of a number of receivers built for radio astronomy applications using very low-noise, high-electron-mobility transistor (HEMT) amplifiers and small, closed-cycle 13 K refrigerators. The noise temperatures of receivers, measured at the room temperature circular waveguide input, are the best ever reported for receivers built with semiconductor devices (for example, 10.5 K at 8.4 GHz) and are only slightly inferior to that of solid-state maser receivers.

I. INTRODUCTION

A series of front-ends utilizing small, closed-cycle refrigerators and very low-noise, high-electron-mobility transistor (HEMT) amplifiers have been developed for use in a new radio astronomy system [1]. This new system is called the Very Long Baseline Array (VLBA) and is comprised of ten 25-meter diameter paraboloidal reflectors, each located in a different site within the United States. Construction of the array was started in 1984 with completion expected in 1992 at a cost of approximately $80M. The VLBA complements the Very Large Array (VLA) which was completed in 1981 and comprises twenty-seven 25-meter paraboloids within a 42 km diameter site in central New Mexico; some of the front-ends and amplifiers described here have also been installed in the VLA.

The VLBA requires dual-polarization receivers at 11 frequencies, ranging from 327 MHz to 43 GHz. The two lowest frequencies utilize room temperature FET low-noise amplifiers with prime-focus feeds. All other frequencies utilize HEMT amplifiers cooled to 13 K in separate dewars at the Cassegrain focus. A possible exception is at 43 GHz where a superconductor-insulator-superconductor SIS mixer is being concurrently developed along with the HEMT amplifier.

The VLBA has furnished a mechanism for development of a integrated state-of-the-art system that makes use of the latest solid-state devices and the experience of operating 135 cryogenic receivers on the VLA.

First, a review of recent progress in cryogenically-cooled HEMT devices and amplifiers is given. Then a design and construction of a complete front-end is described, and finally front-end to antenna integration is briefly discussed.

II. CRYOGENICALLY-COOLED HEMT'S AND HEMT AMPLIFIERS

Many types of HEMT's have been evaluated for low-noise cryogenic use [2], [3] and the lowest transistor noise temperature yet reported (1.5 K at 1.5 GHz and 5.3 K at 8.5 GHz) have been measured [4]. An interesting and important aspect of the HEMT operation at cryogenic temperatures is the light sensitivity; usually HEMT's require illumination with an LED to achieve time-stable, low-noise performance [2], [3]. A comparison of noise temperatures of FET's and HEMT's cooled to 15 K with that of other low-noise devices and also other limits to noise in a receiving system is shown in Figure 1. All data for cryogenic FET's and HEMT's are NRAO measured results and referred to cold input of a device, while maser data are for JPL and NRAO masers [5]-[7]. Masers still have the lowest noise performance, but their high cost of construction and maintenance and small instantaneous bandwidth (< 100 MHz at X-band) make them impractical in many applications. A summary of the noise performance of all cryogenic front-ends constructed or planned for the VLBA is shown in Table I while detailed descriptions of some of the front-ends are given in VLBA technical reports [8]-[10]. In this table amplifier noise is referred to the cold input connector of the multi-stage amplifier, receiver noise refers to a 300 K waveguide flange connecting to the antenna feed, and system noise includes noise from the earth, atmosphere, and cosmic background. Examples of the frequency response of the gain, amplifier noise, and receiver noise (dashed line) for 8.4 GHz and 14.9 GHz receivers are shown in Figure 2. The difference between amplifier noise and receiver noise (4 K at 8.4 GHz and 7 K at 15 GHz) is due to small losses in the 300 K mylar vacuum window, losses of a polarizer, coupler, and isolator (~ 0.8 dB of loss at 15 K), and post amplifier noise.

III. CRYOGENIC FRONT-END

A block diagram and photograph of a typical VLBA front-end are shown in Figures 3 and 4, respectively. A critical area of a very low-noise design is a low-loss transition from an ambient temperature feed horn to a cryogenic amplifier. The VLBA front-ends utilize a gapped circular waveguide transition from the feed to a cooled polarizer located within the vacuum dewar. Noise calibration signals are injected through cooled directional couplers. A careful thermal design allows all of these components to be cooled by a small closed-cycle refrigerator to about 13 K. Photographs showing interior views of the cryogenics dewar are shown in Figures 5 and 6. The refrigerator is a CTI Model 22 and has cold stations at 13 K and 50 K; the latter is used to cool radiation shields for the 13 K components. Some important features of the cryogenic design are:

(1) Use of charcoal pellets on the 13 K and 50 K stations to cryo-absorb residual gases in the dewar.

(2) Flexible copper strap thermal connections to accommodate thermal contractions and isolate refrigerator vibration.

(3) Use of a choked-gap in the input circular waveguide to provide thermal isolation (300 K to 13 K) with extremely low signal loss. The gap is supported by fiber-glass cylinders which are gold metallized to reduce thermal radiation.

IV. FRONT-END TO ANTENNA INTEGRATION

Close integration of receivers, feeds, and the parabolic reflector is vital to the achievement of low system noise temperature, ease of maintenance, and quick change of receiving frequency. The VLBA system utilizes shaped-reflector Cassegrain optics to bring the received signal to a 2.7 meter diameter by 7 meter high feed room located at the vertex of the paraboloid. The subreflector is slightly asymmetric so that the received beam can be focused to any point on a 1.7 meter diameter circle by rotation of the subreflector. The feed horns for 1.5 GHz through 43 GHz are then positioned at different angles along this circle so that a frequency change is performed under remote control in a few minutes by subreflector rotation.

Each cryogenic receiver is mounted in the vertex room at the end of a corrugated feed horn. The receivers typically weigh 55 pounds and can be changed by two people in less than 30 minutes. The cool-down time is of the order of several hours and the MTBF is expected to be of the order of a year. Two helium compressors are mounted on the antenna and provide the refrigerant for the cryogenic refrigerators. Extensive monitoring and remote control of cool-down and vacuum-pumping are provided so that in normal operation the system will be operated through a telephone link to a control room which may be thousands of miles away.

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TABLE I. VLBA Cryogenic Receivers

Frequency Range GHz	Amplifier Noise K	Receiver Noise K	System Noise K	Input WG Diameter cm
1.35-1.75	1.5*	6†	20†	16.33
2.15-2.35	4	10	25	9.75
4.6-5.1	6.3†	11	26	4.490
8.0-8.8	6.5*	10.5*	29*	2.602
10.2-11.2	13.7†	19	32	2.045
14.4-15.4	18.5†	26†	40	1.487
22.2-24.6	41*	50*	77	0.931
42.3-43.5	70	85	105	0.526

*Measured results - GE HEMT.

†Measured results - Fujitsu HEMT.

All other figures are expectations.

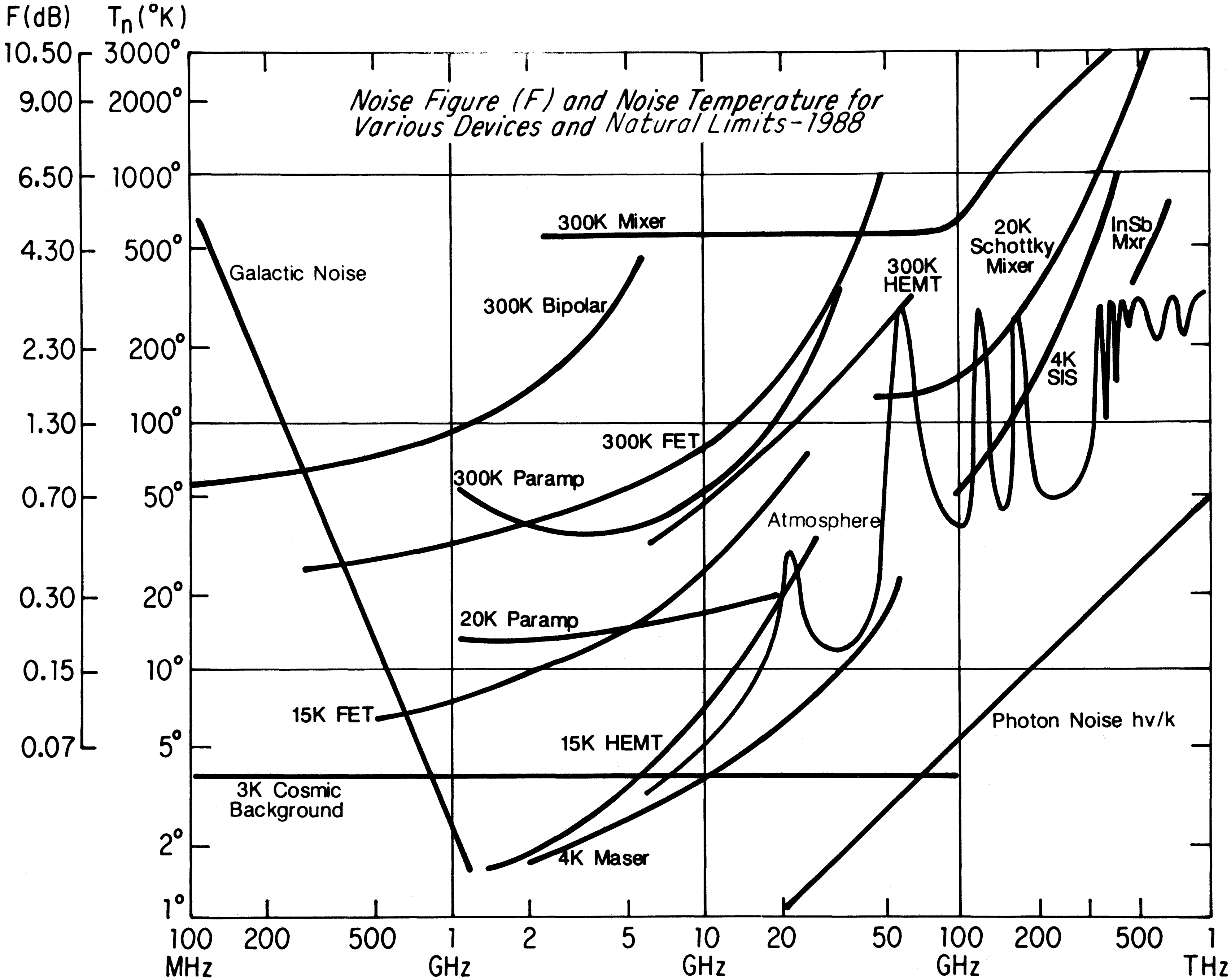

Fig. 1. State-of-the-art of low-noise cryogenic devices for frequencies below 50 GHz referred to the cold input terminal of a device. All data for cryogenic FET's and HEMT's are NRAO measured results. Maser data are for JPL and NRAO masers [5]-[7]. It should be noted that masers are inherently matched at the input and have sufficient gain to make contribution of subsequent stages insignificant. This gives them a greater advantage than presented in the figure for frequencies above X-band.

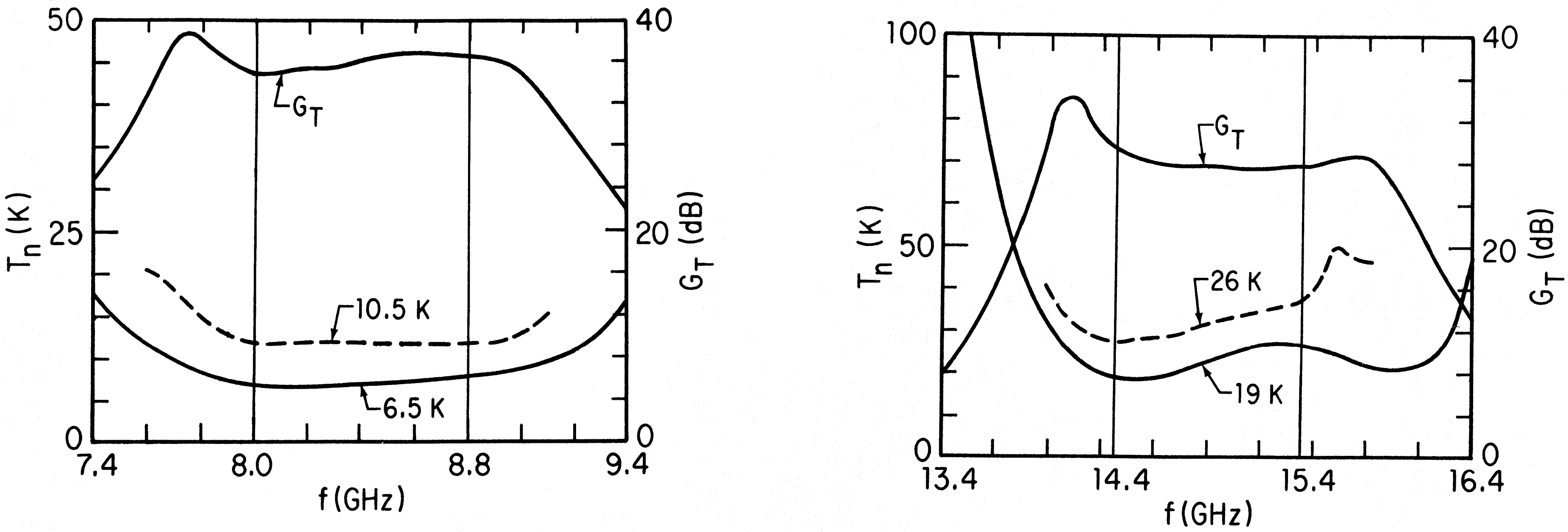

Fig. 2. Gain and noise temperature of HEMT amplifiers cooled to 15 K (solid lines) and total receiver noise (dashed lines) for both 8.4 GHz (left) and 14.9 GHz (right) receivers. The amplifier noise is referred to the cooled amplifier input connector while the receiver noise is referred to a 300 K waveguide flange.

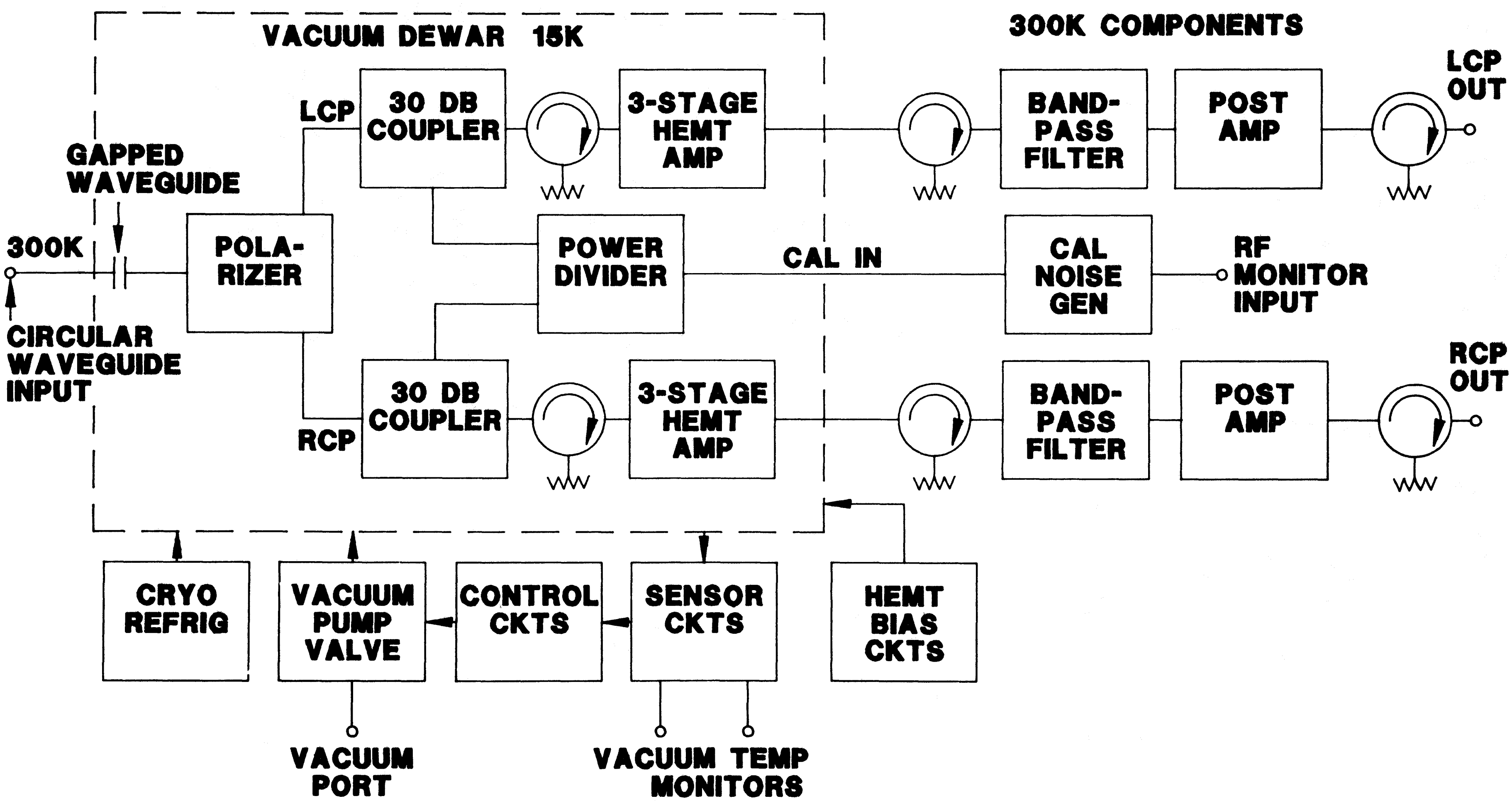

Fig. 3. Block diagram of typical VLBA front-end. For 8.4 GHz and above, the polarizer is cooled to 15 K rather than 50 K. Also, for frequencies above 4.6 GHz, isolators are placed at amplifier inputs. Approximately 30 dB gain at 15 K and 20 dB gain at 297 K is provided.

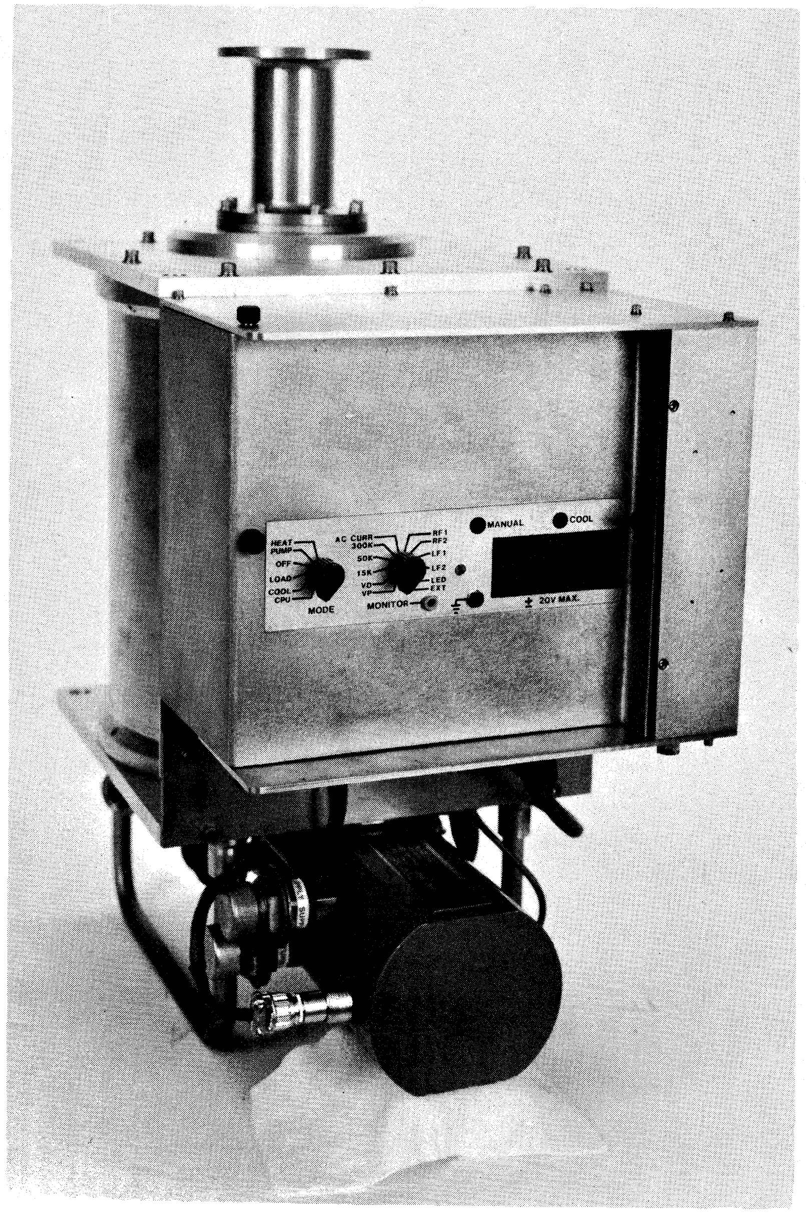

Fig. 4. Photograph of 4.8 GHz VLBA front-end. A typical front-end is ~ 30 cm wide and weighs 55 pounds. The input dual-polarization circular waveguide is shown at top. The front-end can be controlled and monitored either locally or by a remote computer.

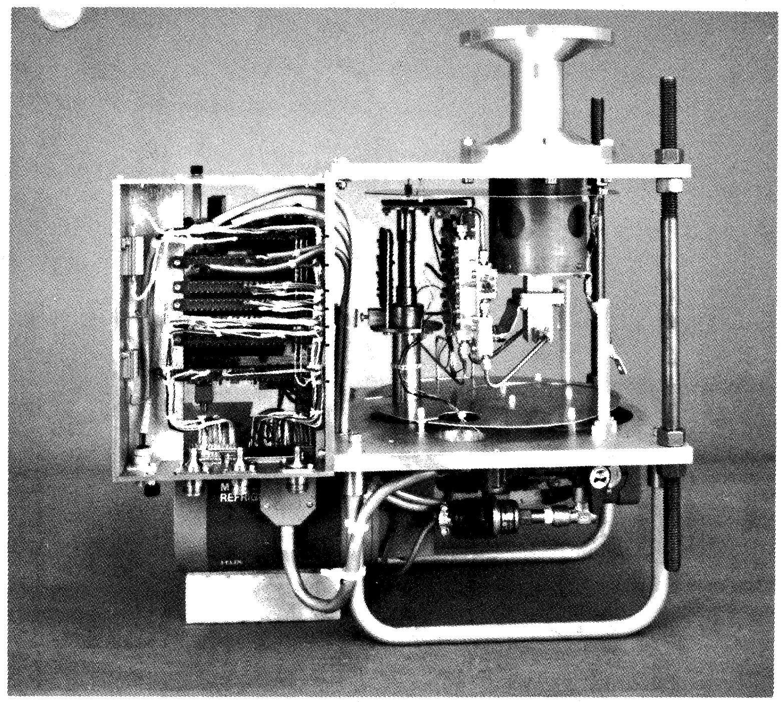

Fig. 5. Interior view of 8.4 GHz receiver. The vacuum cylindrical jacket and a radiation shield have been removed. From left to right the major components are a 300 K card cage for bias, control, monitor, and post amplifiers, the refrigerator cooling-head, amplifier mounting plate, and polarizer for both senses of circular polarization.

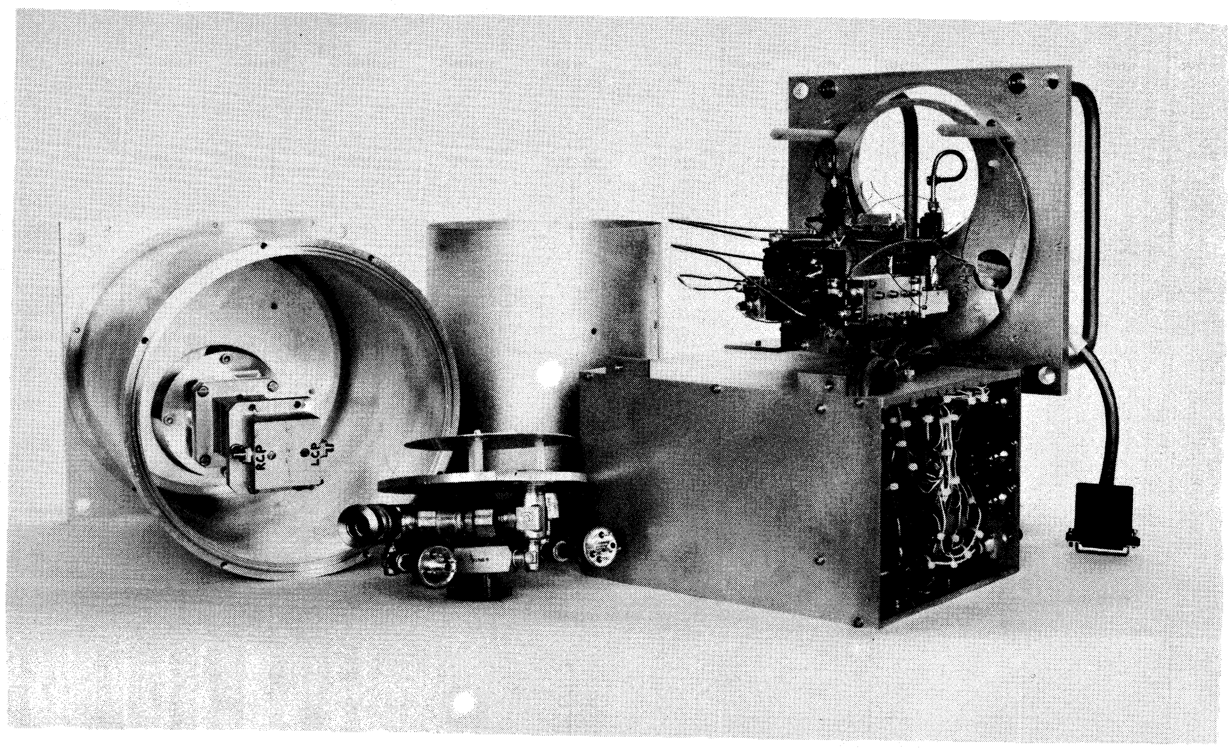

Fig. 6. A partially disassembled view of the 8.4 GHz receiver. From left to right the components are the cylindrical vacuum jacket with polarizer mounted to top plate, (foreground) an access cover with vacuum valves and gauge, (background) a 50 K radiation shield, and the card cage with amplifier mounting plate (refrigerator removed).