Multiband Low-Noise Receivers for a Very Large Array

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Invited Paper

***Abstract*—The very large array (VLA), presently under construction by the National Radio Astronomy Observatory, is an array of 27 25-m-diam antennas. This paper describes the feed and low-noise front-end systems used on the antennas. The receiving system allows operation at any one of the four frequency bands: 1.35–1.73 GHz, 4.5–5.0 GHz, 14.4–15.4 GHz, 22–24 GHz. The feed system uses an offset Cassegrain geometry so that the feeds for all four frequency bands can be in position on the antenna simultaneously. The front end comprises a cryogenically cooled parametric amplifier for the 4.5–5.0-GHz range. This paramp is preceded by cooled upconverters or cooled mixers for the other frequency ranges. Measured system performance is presented and some construction details are given.**

Introduction

One of the most challenging instrumental problems in astronomy has been the development of an instrument to map the spatial distribution of radio waves emitted by distant astronomical objects. This instrument needs to operate in the 1–25-cm wavelength range, have a resolution of 1 arc-s or less, a field of view greater than a few minutes of arc, and sensitivity sufficient to detect a flux of 10^{-27} W/m^2/Hz upon the surface of the earth.

An instrument to meet these requirements is now under construction in central New Mexico; it is being built by the National Radio Astronomy Observatory[1] and is called the very large array (VLA). The array consists of 27 25-m-diam paraboloids arranged along the arms of a Y with 21-km arms. Construction started in 1973 and should be complete by 1981. An artist's concept of the central part of the array is shown in Fig. 1. The aperture-synthesis technique of radio astronomy arrays is discussed by Ryle [1] and Chow [2], and a further introduction to the VLA is given by Heeschen [3].

The VLA has required application of the latest technology in antennas, cryogenically cooled low-noise receivers, high-speed digital processing equipment, and wide-band transmission systems. The low-noise receiver aspects of the system will be discussed in this paper.

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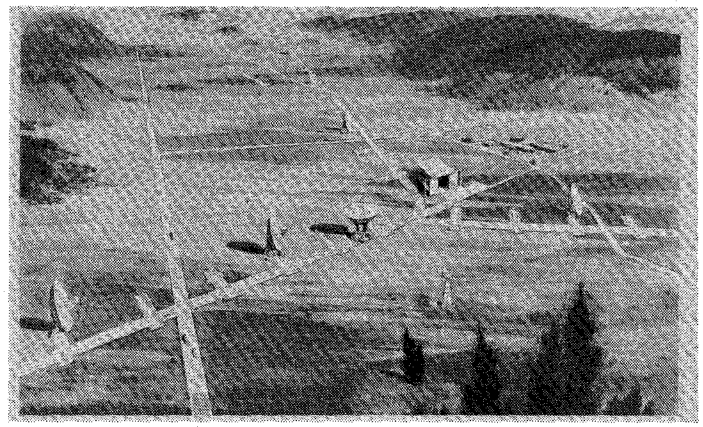

Fig. 1. Artist's conception of the VLA.

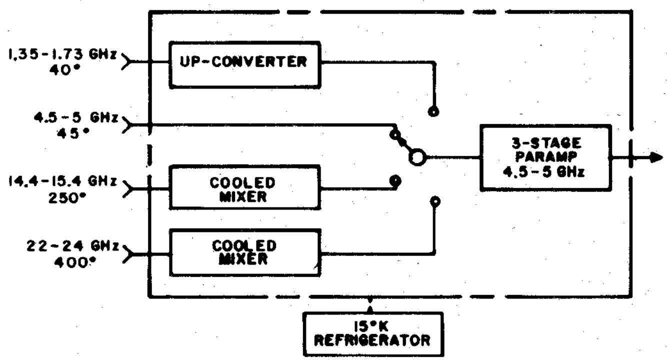

Fig. 2. VLA front-end system configuration.

Front-End System Design and Performance

The VLA requires 27 dual-polarized front ends providing ≥ 100-MHz instantaneous bandwidth in the tuning ranges 1.35–1.73 GHz, 4.5–5 GHz, 14.4–15.4 GHz, and 22–24 GHz. Noise temperature was to be as low as possible within a budget of ~ $130 K per front end including cryogenics, assembly labor, but not feeds. The complete feed and subreflector system costs ~ $40 K.

The system configuration shown in Fig. 2 was selected to meet these requirements. Two sets of all components within the diagram of Fig. 2 are cooled to 15 K by a 10-W capacity refrigerator manufactured by Air Products, Inc. A cooled parametric amplifier is utilized for operation at frequencies of 4.5–5 GHz. This is an optimum frequency range for cooled paramps, and small high-performance units are available. The paramp input is connected to a

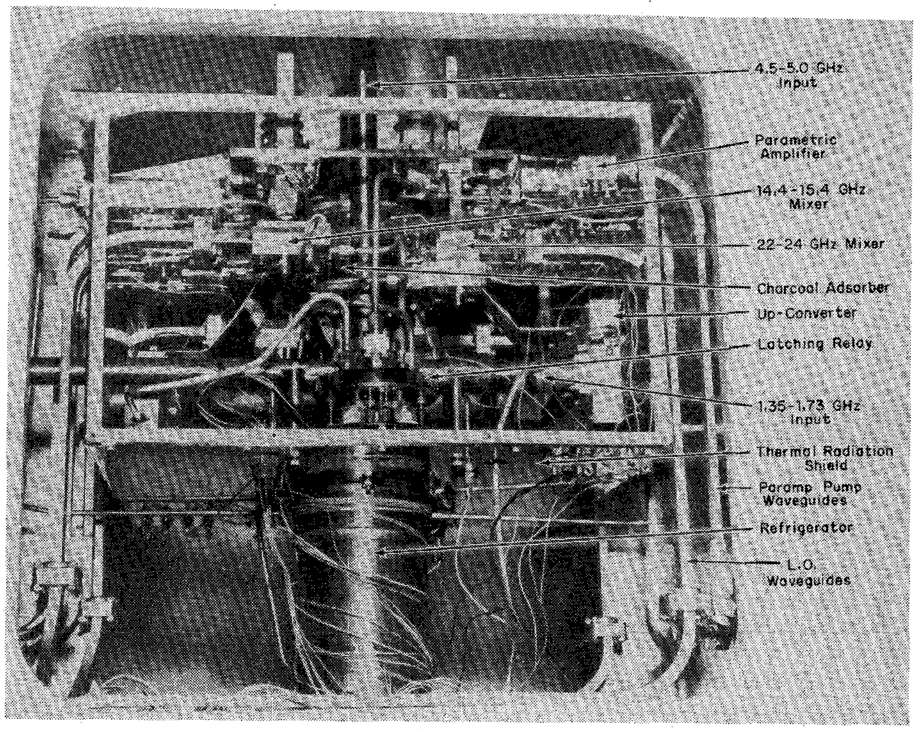

Fig. 3. Dewar interior. The sides of the radiation shield and the aluminized Mylar have been removed.

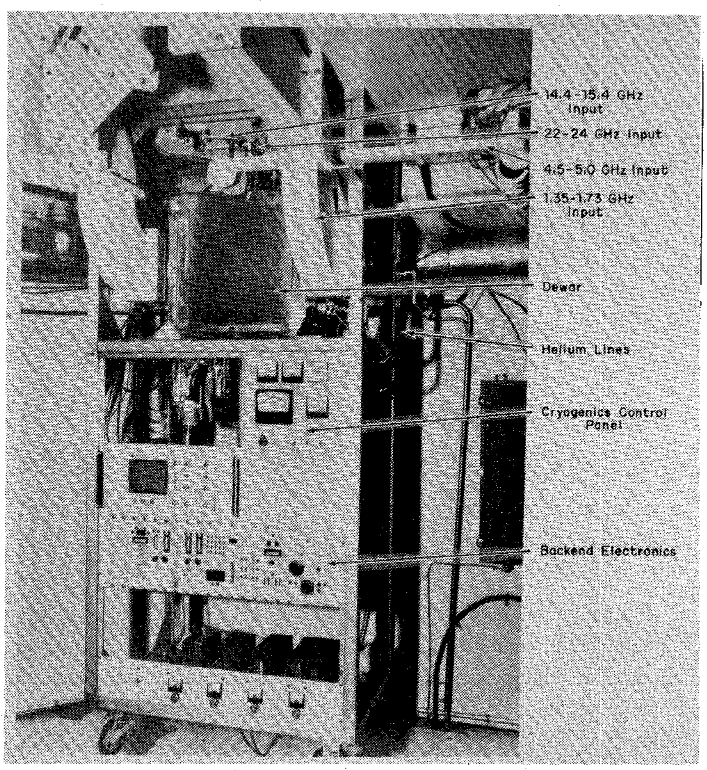

Fig. 4. Front-end rack mounted in antenna vertex room.

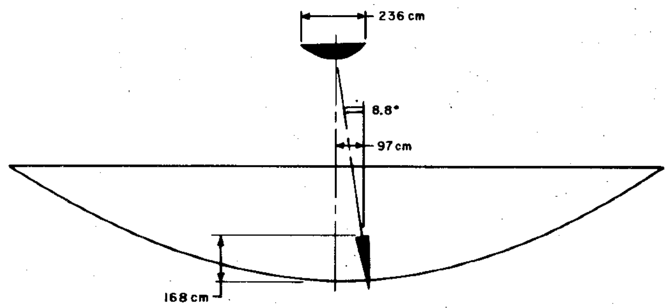

Fig. 5. VLA offset Cassegrain geometry.

TABLE I
MEASURED RECEIVER AND SYSTEM TEMPERATURES

f	T_{rx}	$T_{sys.}$
1.35 - 1.73	18°K	47°K
4.5 - 5.0	25	49
14.4 - 15.4	200	240
22 - 24	240	290

Note: These temperatures were measured in the middle of the band. In general, they increase by up to 20 percent at the band edges, except for the 22–24-GHz system where the increase is 40 percent.

solenoid-operated coaxial switch which allows either straight-through connection to a feed or connection to one of three frequency converters for the other desired frequencies. A parametric upconverter is used for the lower frequency range, and two cooled Schottky-diode mixers are utilized for the higher frequency bands. These components will be described in more detail in following sections.

The measured receiver noise temperatures and system temperatures are given in Table I. Photographs of the front-end dewar interior and of the front-end rack mounted in an antenna vertex room are shown in Figs. 3 and 4.

FEED SYSTEM

An offset shaped-reflector Cassegrain geometry as shown in Fig. 5 is utilized. The main reflector, manufactured by E-Systems Inc., is a surface of revolution with a modified

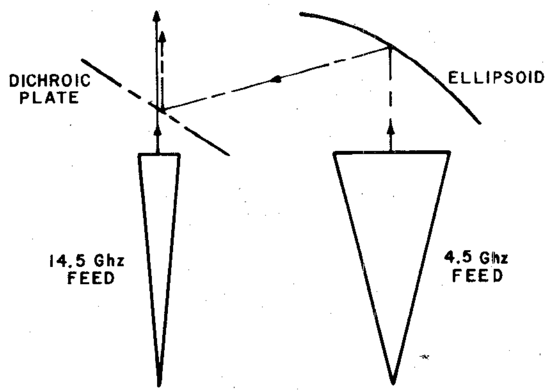

Fig. 6. Dual frequency reflector system.

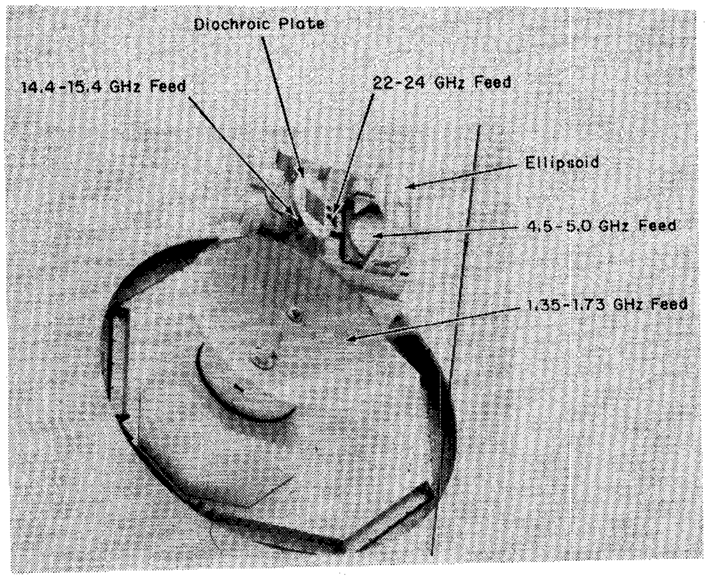

Fig. 7. Feed system on antenna.

parabolic profile typical of reflectors shaped for high efficiency [4]. The shaping is small enough to allow prime focus operation at frequencies below 1.3 GHz. The subreflector, which is not a surface of revolution, is shaped to give high efficiency by generating almost uniform illumination in the aperture of the main dish. The profile of the subreflector is also shaped to give uniform phase in the aperture of the main reflector and an on-axis beam with a secondary focal point 97 cm from the axis of the main reflector. The feeds are arranged on a circle of radius 97 cm around the main reflector axis, and the frequency is changed by rotating the subreflector around the reflector axis until the secondary focus lies on the required feed. The offset Cassegrain reflector geometry has been pioneered by the Jet Propulsion Laboratory in the Goldstone 64-m paraboloid [5]. The theory for shaping the offset geometry is given by Potter [6]. The VLA geometry was calculated by the Rantec Division of the Emerson Electric Company.

Simultaneous operation at 4.5–5.0 GHz and 14.43–14.53 GHz is made possible by placing a dichroic (frequency sensitive) reflector over the 14.4–15.4-GHz feed and an ellipsoidal reflector over the 4.5–5.0-GHz feed as shown in Fig. 6. This dual frequency system was designed by Rantec and is based on the system developed by the Jet Propulsion Laboratory [7]. The use of the dual frequency system increases the system temperature by 3.7 and 3.2 K at 4.75 and 14.48 GHz, respectively, and the antenna efficiency is reduced by a factor of 0.97 in both frequency bands.

TABLE II
MEASURED ANTENNA EFFICIENCIES

f	Total Antenna Efficiency
1.35 - 1.73	41%
4.5 - 5.0	65
14.4 - 15.4	53
22 - 24	44

Note: These efficiencies are measured on antenna #1 for which the measured rms surface deviation of the main reflector and subreflector combined is 0.58 mm at an elevation angle of 50°. The rms surface deviation can increase to 0.79 mm depending on elevation angle and wind velocity.

A photograph of the feed system is given in Fig. 7, and the measured system performance is given in Table II. Antenna efficiencies were measured using astronomical radio sources [8]. To give uniform illumination in the aperture of the main dish, the VLA antenna geometry requires a feed pattern taper of 11.5 dB at the edge of the subreflector, which subtends a total angle of 18° at the feed. The subreflector edge illumination, which is higher than usual for shaped systems, was chosen to prevent the aperture of the 1.35–1.73-GHz feed from becoming too large. An important consideration in the design, because of the large number of feeds needed, is that the feeds should have as low a cost as possible. Since all feed outputs enter the same cryogenic dewar, and waveguide losses must be minimized, another important design constraint is that all feeds should be approximately the same length. The nominal feed length used is 178 cm and results in a 23-GHz feed which is four times longer than it needs to be and a 1.35–1.73-GHz feed which is only a quarter of the length of the appropriate optimum horn.

The 22–24-GHz and the 14.4–15.4-GHz feeds are square cross-sectional multiflare horns [9] designed by Rantec. These horns combine reasonable fabrication cost with good pattern circularity and sidelobe performance. The cost of long corrugated horns for these frequencies would have been significantly more. The 4.5–5.0-GHz feed is a lens-corrected corrugated horn designed by J. J. Gustincic.

The most difficult feed to design is the 1.35–1.73-GHz feed. The length constraint has been mentioned previously. The very wide bandwidth (25 percent) is needed so that observations of both hydrogen gas and the hydroxyl radical can be made using a single feed. The subreflector is not in the far field of the feed, so the far-field pattern must be focused into the near field to prevent loss of efficiency due to phase errors [10]. The straightforward design solution of a short horn with a large correcting lens in its aperture proved to be too expensive. The results

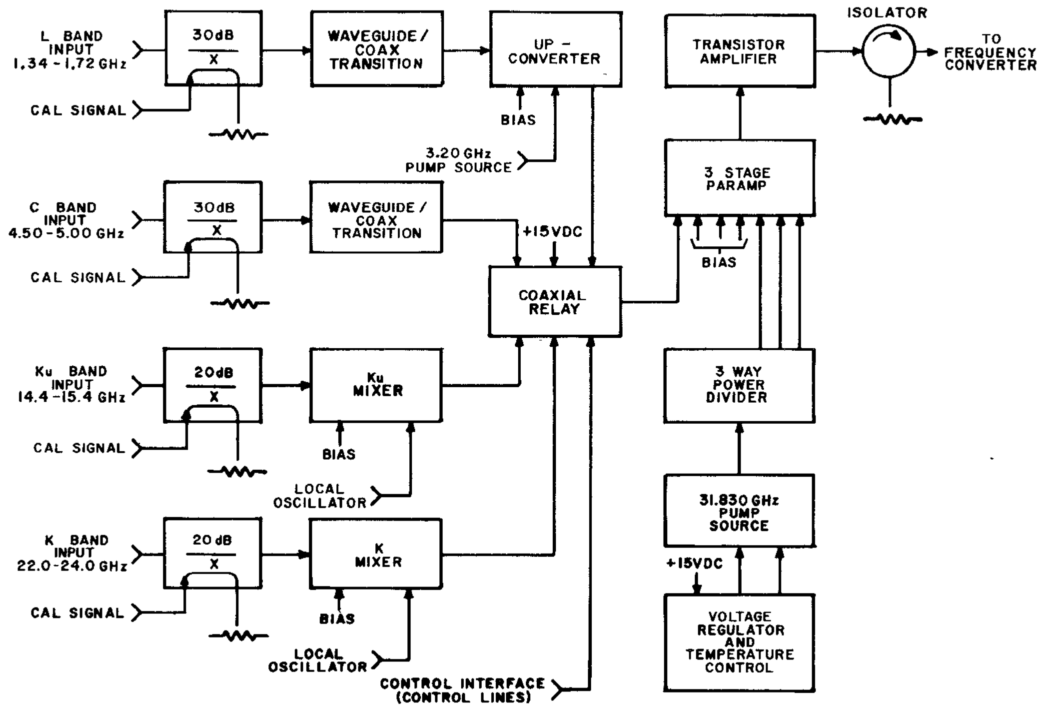

Fig. 8. Front-end block diagram.

shown in Table II were obtained using a center-fed 213-cm-diam elliptical reflector as the feed. This feed can be seen in Fig. 7. The reflector profile was elliptical rather than parabolic to correct for the subreflector being in the near field of the feed. The relatively low efficiencies obtained with this feed result from the difficulty of obtaining a high spillover efficiency with a feed of this type [11]. A new type of feed for the 1.35–1.73-GHz band is presently under development by J. J. Gustincic. This feed consists of a small horn illuminating a large lens constructed partially from solid dielectric and partially from waveguide elements. This new feed, which is expected to combine improved performance with low cost, will be described separately [12].

For all four frequency bands it is possible to have either dual linear polarization or dual circular polarization by manually changing the polarization transducer at the feed output. For linear polarization orthomode junctions are used which have VSWR's better than 1.10 and isolations better than 45 dB across the band for the 4.5–5.0, 14.4–15.4, and 22–24-GHz bands. For these bands circular polarization is achieved using sloping-septum polarizers [13], which have axial ratios better than 0.4 dB and isolations better than 30 dB across the band. The sloping-septum polarizer is suitable for low-cost quantity productions because it can be cast in a single piece and requires a minimum of fine tuning. In the 1.35–1.73-GHz band linear polarization is achieved using an orthomode junction that has a VSWR better than 1.17 and an isolation better than 45 dB. Circular polarization will be formed using a 3-dB hybrid after the orthomode junction. All orthomode junctions and polarizers are supplied by Atlantic Microwave.

The cross-polarization properties of the offset shaped-reflector geometry are unusual and deserve mention. In circular polarization the offset Cassegrain geometry gives rise to a cross-polarization distribution in the aperture of the main dish that causes a separation of 0.06 beamwidths between the left- and right-handed circularly polarized beams. This effect is also seen in asymmetric prime focus reflectors [14], [15]. The effect is important to the VLA when a map of circular polarization is synthesized out to the 3-dB points of the beam. Several techniques that show promise of reducing the beam separation include generating higher order modes in the feed horns [16], placing a polarization-sensitive lens in front of the feed horn, or reshaping the subreflector to give an off-axis beam. A more complete description of the circularly polarized beam separation problem will be given separately [17].

Front-End Component Description

A detailed block diagram of the front end is given in Fig. 8. The 4.5–5-GHz channels of the receiver utilize a three-stage parametric amplifier [18]. The stages are of identical design, and each is capable of 10-dB gain. The resulting 30-dB gain is flat within 1.0 dB across the 4.5–5.0-GHz band. The noise temperature of the amplifier is 17 K, but the input waveguide-to-coaxial transition, bandswitch, coaxial cables, and transistor postamplifier add approximately 8 K to the receiver noise temperature. Pump power (40 mW/stage) at 31.83 GHz is derived from a Gunn-effect oscillator. The oscillator's temperature and bias voltage are stabilized within 0.1°C and 2 mV, respectively, to insure good stability of the amplifier gain and phase shift. The parametric amplifier is manufactured by Comtech Laboratories, Inc. The transistor postamplifier, made by Locus, Inc., has a 7-dB noise figure and adds 35 dB gain. It and the subsequent stages contribute less than 1.3 K to the 5-GHz receiver noise temperature.

Future receivers will use a two-stage 25-dB-gain parametric amplifier followed by a room-temperature gallium arsenide FET amplifier of 40-dB gain and 3-dB noise figure. This change will be made to reduce cost and complexity of the receiver with no sacrifice of performance. The present paramps will be reduced to two stages, retuned for 25-dB gain, and refitted with gallium arsenide FET amplifiers. The two-stage parametric amplifier will be manufactured by the AIL Division of Cutler–Hammer, and the FET amplifier by Avantek.

A waveguide-to-coaxial transition is used at 4.5–5 GHz. To minimize the receiver noise temperature, the transition probe and center conductor of the necessarily long coaxial line are cooled to the same temperature as the parametric amplifier. The outer conductor, a thin-wall stainless-steel thermal insulating component, is silver plated and has a longitudinal temperature gradient between the cryogenic stage temperature and room temperature. A waveguide-mounted quartz dome surrounds the probe to provide the necessary vacuum seal [19].

The bandswitch is a four-position coaxial latching relay cooled to the cryogenic stage temperature to reduce its noise temperature. This switch is manufactured by DB Products Corporation.

A parametric upconverter with a 3.20-GHz pump frequency converts the 1.35–1.73-GHz band to 4.55–4.93 GHz. The upconverter is fabricated in microstrip on an alumina substrate. It is a two-diode balanced design to reduce input circuit currents at the lower sideband frequency, which is within the input frequency range. Conversion gain is approximately 3.5 dB and the instantaneous bandwidth (1 dB) is approximately 200 MHz. Varactor bias and pump power level are varied to tune different band segments. The upconverter is manufactured by the AIL Division of Cutler–Hammer.

Cooled resistive mixers are used for the 14.4–15.4-GHz and 22–24-GHz bands [20]. The structure of both mixers is similar; each uses a single gallium arsenide Schottky diode in an image-enhancement design. The local oscillator (LO) frequency is below the signal frequency for the 22–24-GHz mixer; above for the 14.4–15.4-GHz mixer. Consequently the LO bands are contiguous, and a single 17–20-GHz YIG-tuned Gunn-effect oscillator can be used for both mixers. The diodes, which are supplied by the University of Virginia solid-state device laboratory, have a diameter of 5 μm, a zero-voltage junction capacitance of 0.03 pF, and a series resistance of 5 Ω.

The receiver components are cooled by a two-stage closed-cycle helium refrigerator with 10-W second-stage capacity at 20 K and 30-W first-stage capacity at 77 K. All electronic components are mounted on the second stage; the first stage is used to cool a thermal radiation shield. The second stage typically operates at 15 K and is stable to ± 1.0 K over all changes in ambient temperature, antenna elevation, and a period of time of several weeks. Because of the large cooled mass, short-term temperature fluctuations (i.e., those at the cycling rate of the refrigerator) are too small to measure accurately and are on the order of 0.1 K rms. Eight hours are required to cool the receiver from 295 to 15 K.

Thermal insulation is provided by an aluminum vacuum chamber (Dewar) and conventional radiation shields. The vacuum chamber is rectangular and made of $\frac{1}{2}$-in-thick 6061-T6 aluminum plates joined by heliarc welding. No special surface treatment is used other than a thorough cleaning. Fluorocarbon rubber seals are used on most feedthroughs, with butyl rubber for the large door seals. Because of the large number of seals necessary (approximately 55 O-rings) the helium leak rate is on the order of 10^{-5} std. cm^3/s.

An adsorber containing approximately 10 g of activated charcoal is attached to the second stage of the refrigerator. This adsorber will maintain the pressure below 10^{-6} torr for more than a year of normal operation. No other vacuum pumps are used while the receiver is cold; however, a mechanical vacuum pump is turned on automatically if a power failure causes the receiver temperature to rise, releasing gas from the adsorber.

Bright nickel-plated aluminum radiation shields are used around the second stage (other cooled components are of copper or aluminum, and are also nickel plated). Because of the large number of openings, the shields are wrapped with several layers of aluminized mylar. As a result, the radiative heat load on the second stage is small compared to the conductive heat load.

Conclusion

The VLA front-end development has demonstrated that low noise can be achieved with a high degree of frequency flexibility and a reasonable system cost.

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System Implications of Large Radiometric Array Antennas

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Abstract—**Current radiometric earth and atmospheric sensing systems in the centimeter wavelength range generally employ a directive antenna connected through a single terminal pair to a Dicke receiver. It is shown that this approach does not lend itself to systems with greatly increased spatial resolution. Signal-to-noise considerations relating to antenna efficiency force the introduction of active elements at the subarray level; thus if Dicke switching is to be used, it must be distributed throughout the system. Some possible approaches are suggested. The introduction of active elements at the subarray level is found to ease the design constraints on time delay elements, necessary for bandwidth, and on multiple-beam generation, required in order to achieve sufficient integration time with high resolution.**

I. Introduction

IMAGING microwave radiometers are being used increasingly to sense remotely geophysical parameters such as sea state, sea ice distribution, cloud types and distributions, and soil moisture. Instruments of this type which have evolved over the past decade differ considerably in details of design; nevertheless two basic performance parameters, viz. their angular or spatial resolution and their temperature resolution or sensitivity, have remained relatively constant over this period. This is illustrated in Table I, which compares four such systems in the range of 15–40 GHz [1]–[4]. The angular resolutions of these systems are determined primarily by the size of their antennas, which is on the order of 1 m in linear dimension for each.

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TABLE I
RADIOMETER CHARACTERISTICS

	AN/AAR-33	Sea Sat-A	Nimbus E	Nimbus F
Date	1967	Proposed	1972	1975
Frequency (GHz)	15	18,22,36	19.35	37
Antenna	Paraboloids	Paraboloids	Array	Array
Beamwidth	2.2° x 1.7°	1.5° x 1.5° to 0.74° x 0.74°	1.4° x 1.4°	1.2° x 0.7°
ΔT(°K)	1.7	0.6 - 0.9	1.5	1

The payload capabilities of the Space Shuttle [5] have led to the proposal of antennas larger by an order of magnitude [6], [7], which should lead to a corresponding increase in angular resolution. The question addressed here is to what extent such antennas will be compatible with the remainder of radiometric imaging systems as they are now implemented on aircraft and satellites. It will be found that major changes in system design are required. These changes are dictated by considerations of integration time, bandwidth, and antenna losses. Of these, the antenna losses seem to have received the least attention so far, and yet they have the most far-reaching implications. Moreover, it turns out that proposed solutions for the antenna-loss problem also increase the degrees of freedom for solving the others.

II. Basic Considerations

A. General

Most current and proposed aircraft and satellite imaging radiometers are variations of the Dicke-switch type [8],