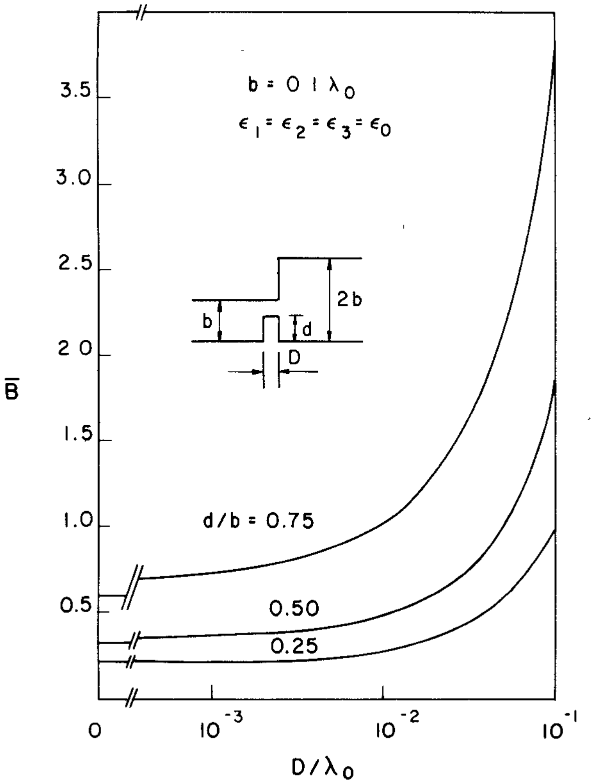

Fig. 5. Normalized junction susceptance as a function of D/λ_0 for $b = 0.10\lambda_0$ with d/b as a parameter and $\epsilon_1 = \epsilon_2 = \epsilon_3 = \epsilon_0$.

Turning now to the case of the diaphragm plus the E-plane step discontinuity we consider the special conditions of a 2:1 step and infinitesimally thin diaphragm and compare the quasi-static results [1] with those based on the conservation of complex power principle [4]. Fig. 4(a) shows that for *very small* spacings ($b_1 = b = 0.025\lambda_0$) the two methods give approximately the same solution for a wide range of dielectric constants and diaphragm heights. Fig. 4(b) considers a *small* spacing ($b_1 = b = 0.10\lambda_0$) and although the results are quite close when $\epsilon_1 = \epsilon_3$ and $\epsilon_1 = 3\epsilon_3$ there is a noticeable error in the quasi-static solution when $\epsilon_3 = 3\epsilon_1$. This discrepancy might be explained by the same reasoning as in the previous example.

Finally, we consider the case of a diaphragm whose thickness D is a small but not infinitesimal fraction of a wavelength. In Fig. 5 the normalized junction susceptance is plotted as a function of D/λ_0 with the diaphragm height ratio d/b as a parameter and for $b_3 = 2b_1 = 2b$. The dielectric constant is unity in all three regions and the width of the first guide is $0.10\lambda_0$. It is remarkable that even for diaphragm thicknesses of $0.001\lambda_0$ the susceptance is noticeably larger than for the case when the thickness vanishes completely ($D/\lambda_0 = 0$). If $d/b = 0.50$ the former susceptance is 14 percent larger, but for $d/b = 0.25$ it is only 8 percent larger. Moreover, as the thickness increases beyond $0.01\lambda_0$ the susceptance rises quite rapidly. This could be attributed to the fact that the thicker diaphragm inhibits *reactive* energy in the higher order cutoff modes ($TM_1, TM_2, \cdots$) from tunneling through to the larger guide on the right where some of it could be converted into *real* energy of the TEM mode propagating away from the diaphragm. This energy is in large part retained in the neighborhood of the left side of the diaphragm, thereby contributing to the increase in junction susceptance as shown in Fig. 5. No attempt is made to plot the susceptance for diaphragm thicknesses greater than $0.1\lambda_0$ since the simple representation of a single shunt susceptance would clearly be unrealistic.

TABLE I
NORMALIZED LOAD ADMITTANCE FOR THE E-PLANE 2:1 STEP-DIAPHRAGM DISCONTINUITY OF FIG. 5 FOR $b = 0.10\lambda_0$ AND $\epsilon_1 = \epsilon_2 = \epsilon_3 = \epsilon_0$.

D/λ_0 \ d/b	0.25	0.50	0.75
0.000	0.500 + j0.201	0.500 + j0.327	0.500 + j0.592
0.001	0.501 + j0.219	0.501 + j0.376	0.501 + j0.748
0.010	0.510 + j0.291	0.509 + j0.501	0.507 + j1.000
0.030	0.542 + j0.443	0.540 + j0.752	0.535 + j1.518
0.100	0.857 + j1.047	0.871 + j1.812	0.860 + j3.787

It is also of interest to consider the real part of the load admittance as "seen" by the smaller guide. The Ruehle and Lewin formula (see (11)) indicates that the very thin diaphragm affects only the junction susceptance and in a very simple way (compare (10) and (11)). This is confirmed by the present numerical results even for relatively large guide sizes and for thicker diaphragms. Only when the diaphragm thickness reaches $0.1\lambda_0$ does the real part of the admittance depart appreciably from 0.50 (normalized). Table I gives the load admittance information for the configuration of Fig. 5.

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Multifrequency Cryogenically Cooled Front-End Receivers for the Westerbork Synthesis Radio Telescope

J. L. CASSE, E. E. M. WOESTENBURG, AND J. J VISSER

***Abstract*—Four of the fourteen 25-m antennas of the Westerbork Synthesis Radio Telescope have been equipped with 6- and 21-cm wavelength receivers based on cryogenically cooled parametric amplifiers and up-converters. Special care has been given to the design of the input network to achieve maximum sensitivity. An integrated feed launcher and preamplifier system are housed in a dewar at cryogenic temperatures. The**

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receiver noise temperatures at 21- and 6-cm wavelength are on the average 14 K and 20 K, respectively. At 21 cm, two systems have even yielded receiver noise temperatures as low as 11 K. This paper concentrates particularly on the cooled section of the receiver system.

I. Introduction

The Westerbork Synthesis Radio Telescope (WSRT) [1], [2] consists of fourteen 25-m diameter parabolic reflectors located on a 3-km long baseline. Four of the reflectors are movable on rail tracks and are correlated with the ten fixed systems forming 40 independent two-element interferometers. The effective system temperature of one interferometer is equal to the geometrical mean of the system noise temperature of its two elements. As a result the receivers of the four movable aerials yield a relatively large weight. By means of cooling to cryogenic temperatures these receivers only, a significant improvement in the overall sensitivity is obtained while the cost and the complexity of the system are minimized. The system temperature for the ten uncooled WSRT receivers is on the average 85 K at 21-cm wavelength. After cryogenic cooling the receivers of the four movable aerials, we measured an average system temperature for these aerials of 29 K. The combination of the two systems yields an equivalent system noise temperature just below 50 K. At 6-cm wavelength, the combination of the cooled and uncooled receivers with system temperatures respectively equal to 55 K and 130 K yields an effective temperature of 85 K.

The WSRT operates presently at three wavelengths 6, 21, and 49 cm, while in the near future 18 and 90 cm are also contemplated. It is clear that for economic reasons and continuity of operation a cooled system should accommodate all frequency bands. Unfortunately, because of mechanical constraints, we had to restrict the cooled systems to the bands 21, 18, and 6 cm. The main problem encountered is related to the usable volume at the prime focus for receiver hardware and in particular to the limited space between the focus and the front plane of the front-end support structure. A consequence of this is that front-end changes have to be scheduled quite regularly to match the observing programs.

This paper describes the 6/21-cm receivers and in particular the cooled section housed in a cryostat. Great care has been taken in the design to keep the input noise contributions as low as possible. This has been achieved by reducing the input path lengths to a minimum and by cooling to 20 K part of the input transmission lines as well as the preamplifier section. Low noise preamplification is achieved using commercially available parametric amplifiers (6 cm) and parametric up-converters (21 cm) with exceptionally good performances. We measured for the best channels a system temperature at 21-cm wavelength as low as 26 K. Less than half of this noise can be attributed to the receiver.

II. Front-End Design

The prime focus of the aerial ($f/_D = 0.35$) lies 25 cm from the front of the focal box. The feed antenna, a corrugated horn with a 90° flare angle, has been designed by the Technical University of Eindhoven to fit these space requirements [3]. It consists of a circular waveguide surrounded by 7 concentric rings. It features an illumination efficiency of 69 percent for a spillover of 4 percent. The phase center of the feed is close to the aperture of the waveguide and can be made to coincide with the prime focus of the reflector.

The WSRT receiver measures the Stokes parameters of the incoming radiation. For that purpose all front-end receivers are equipped with channels matched to the two orthogonal linearly polarized components of the radiation. The direction of polarization is adjustable in steps of 0.1° over a total range of 90°.

The requirement of dual frequency and dual polarization operation led to a mechanical system designed to rotate around two axes. The front-end box main axis coincides with the reflector axis. It is around this axis that the direction of polarization can be rotated (see Fig. 1). To change frequency entails alignment of the required waveguide launcher and its feed arrangement with the reflector axis. This is achieved by rotating the dewar about its axis which is situated eccentrically with respect to the main axis as shown in Fig. 1(b). Unlike the first rotation which can be remotely controlled, the frequency change is a manual operation in which also a few waveguide and coaxial jumpers have to be changed.

The receiver is physically divided into two parts: the cryogenically cooled section and the uncooled part which is housed in two thermostatic chambers. A simplified block diagram on Fig. 2 shows the main receiver parts. Following a concept developed for the very large array [4] the front-end system configuration has a cooled 6-cm nondegenerate parametric amplifier common to the 21- and 6-cm options. For 21-cm operation a parametric up-converter is inserted in front of the paramp. The paramps are pumped at 26 GHz, the upconverters at 3.5 GHz.

The receiver is tunable from 4770 MHz to 5020 MHz and from 1360 to 1430 MHz for the 6-cm and the 21-cm bands, respectively. The central local oscillator signal is fed at 163–174 MHz and is multiplied up to the required frequency in a 9× and a 21× phase stable step recovery diode frequency multiplier. The intermediate frequency is centered around 130 MHz. The instantaneous bandwidth is 100 MHz.

The physical temperature of the uncooled section is kept constant by means of a double thermostat. The outer side of the receiver boxes is coarsely controlled (±1°C) by means of a Peltier heater/cooler system. The interior is regulated by means of a heating plate to an accuracy of about 0.1°C.

III. Cryogenically Cooled Section

The cryostat houses one-stage 6-cm parametric amplifiers manufactured by the AIL division of Cutler–Hammer. The amplifiers are fed by separate Gunn oscillators located outside the cryostat in the uncooled section. The second stage is a cooled AIL FET amplifier. In the 21-cm mode an AIL up-converter is switched in front of the paramp by means of a cooled mechanical coaxial switch manufactured by DB Products Corporation. The up-converter, the paramps, and the switches are located at the 20 K station, the FET amplifiers at the 70 K station. The 3.5-GHz pump signals for the up-converters are fed from a transistor oscillator located outside the cryostat.

The main characteristics of the cooled devices are given in Table I.

The cryostat (shown in Figs. 3 and 4) has a diameter of 40 cm and a length of 50 cm. It consists of a circular aluminium base plate supporting the cooling unit and some of the transmission lines and a stainless-steel bell shaped cover sealed to the base plate by means of an O-ring.

Cooling is based on a Cryogenic Technology Inc. model 1020 refrigerator. The refrigerator provides two stations at nominal temperatures of 20 K and 70 K, respectively. The main compressor which feeds the helium gas under pressure is installed at the base of the telescope. Stainless-steel lines (rigid and flexible) are used to bring the gas to the focal box.

The two cooled stations house the devices mentioned above. The 20 K plateau (on top) is surrounded by a copper radiation

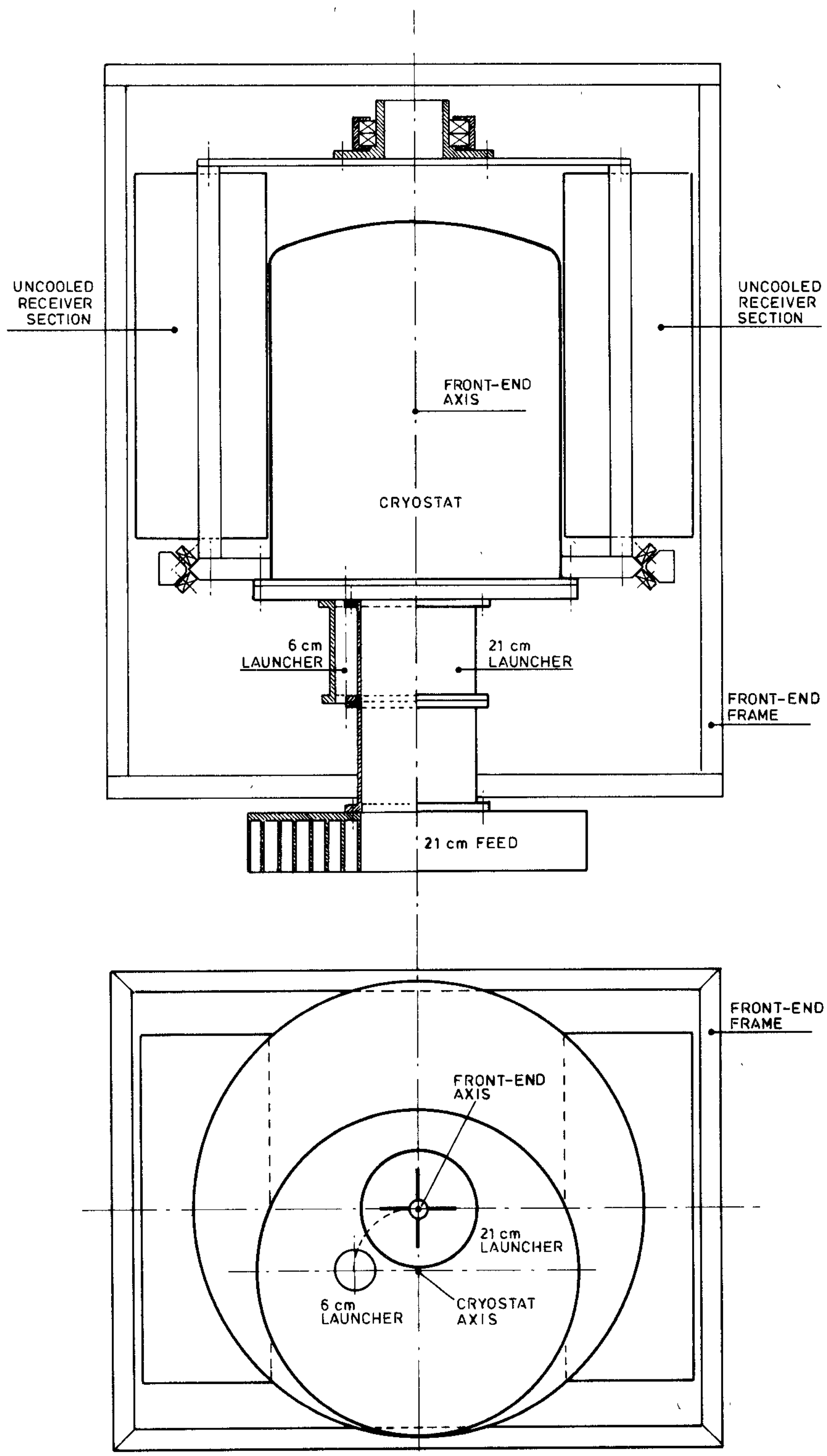

Fig. 1. Mechanical layout of the multifrequency front-end receiver. (a) Scalar feed and the 21-cm launcher entering the cryostat. Flanking the cryostat are the two thermostats. The entire receiver rotates inside the front-end frame around the main axis. (b) 21-cm feed has been removed so that the apertures of both the 6-cm and the 21-cm launchers are visible As can be seen, the cryostat is placed eccentrically with respect to the front-end main axis. The receiver fills a volume of about 1 m^3; it weighs 250 kg.

shield attached to the 70 K station. The shield is wrapped in several layers of aluminized Mylar foil in order to reflect a maximum amount of radiation from the 300 K bell. For the same reason, the underside of the 70 K plateau has been gold-plated.

As the system temperature can be significantly impaired by the input losses, waveguides were chosen to connect the feed to the pre-amplifiers as shown on Fig. 3. The waveguide cutoff has been chosen so that only the $TE_{1,1}$ mode can propagate. The waveguides, made of aluminium, are split into two parts connected to the 20 K and the 300 K stations. A gap of 0.8 mm for 21 cm and

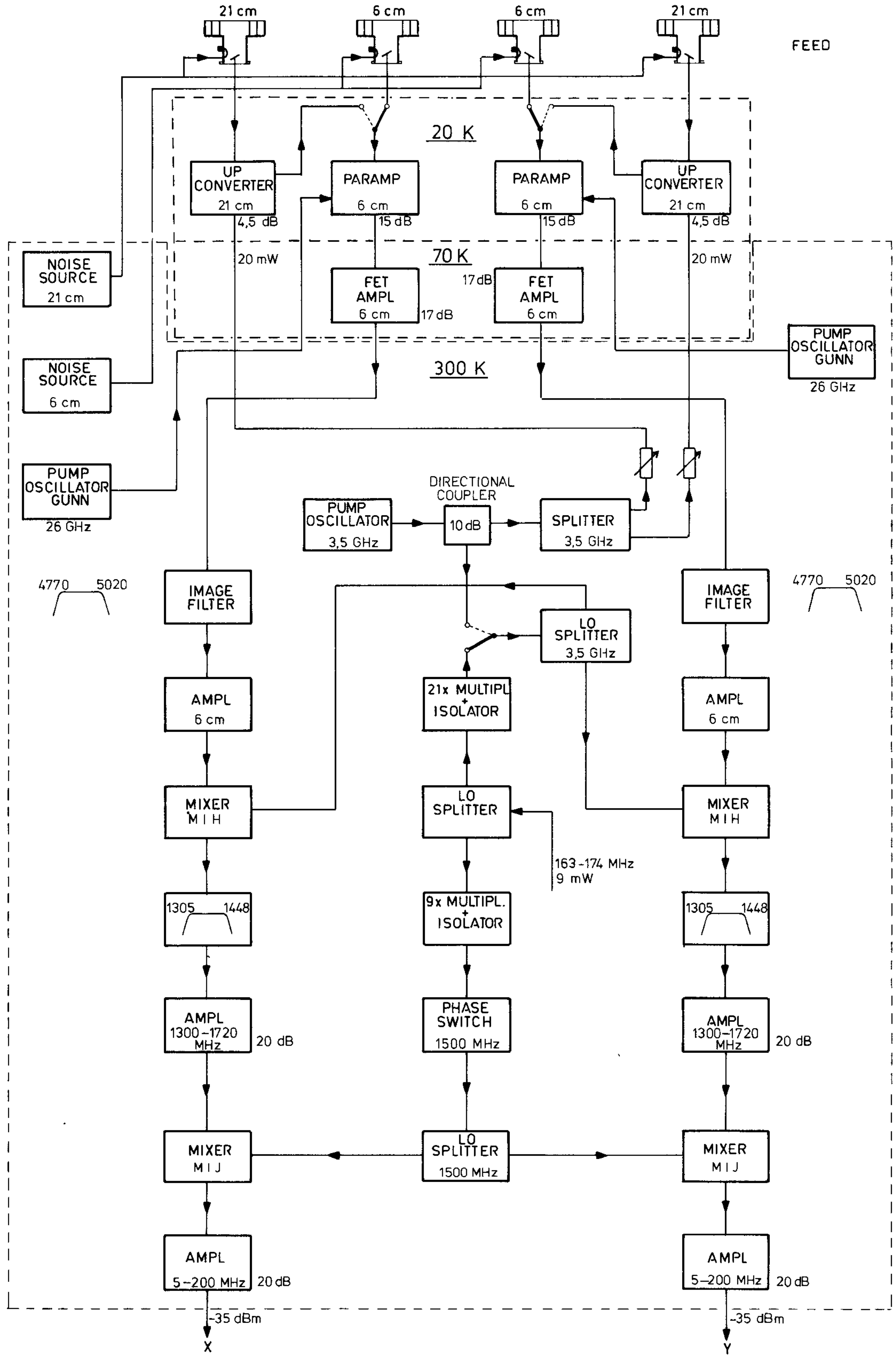

Fig. 2 Block diagram of the 6/21-cm front-end receiver. The cooled section is shown on top within the dashed lines. The salient features, like gain and frequency range of the various parts, are indicated.

0.4 mm for 6 cm ensures that no thermal losses (which would be prohibitive) can take place through conductivity along the waveguide walls. In order to reduce the thermal load by radiation through the aperture of the waveguides the inner walls have been gold-plated. By inserting infrared absorbers into the 70 K waveguides we hope to reduce further radiation leakage through the waveguides. At the base plate the waveguides are vacuum sealed by means of 10-mm thick rexolite windows. The discontinuity

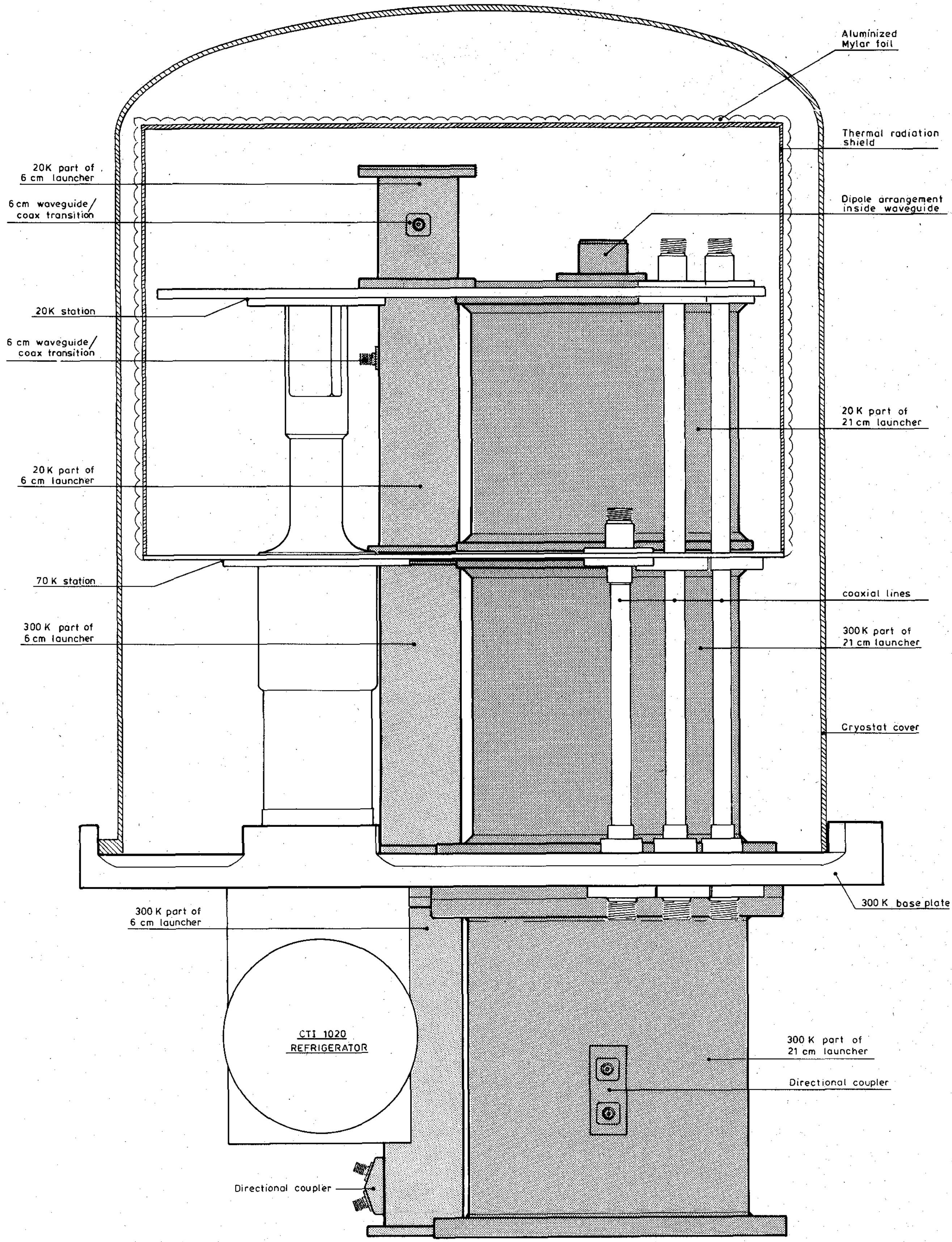

Fig. 3 Schematic of the cryostat. The CTI model 1020 refrigerator attached to the base plate provides the two cold stations at physical temperatures of 70 K and 20 K in the form of two aluminium circular plates. The waveguide launchers are in two parts: one at 300 K and one at 20 K. The waveguides are vacuum sealed by a rexolite window tuned by irises (not shown). The thermal shield is at 70 K, the cryostat cover at 300 K. The directional couplers shown on the 300 K launcher sections are used for noise injection.

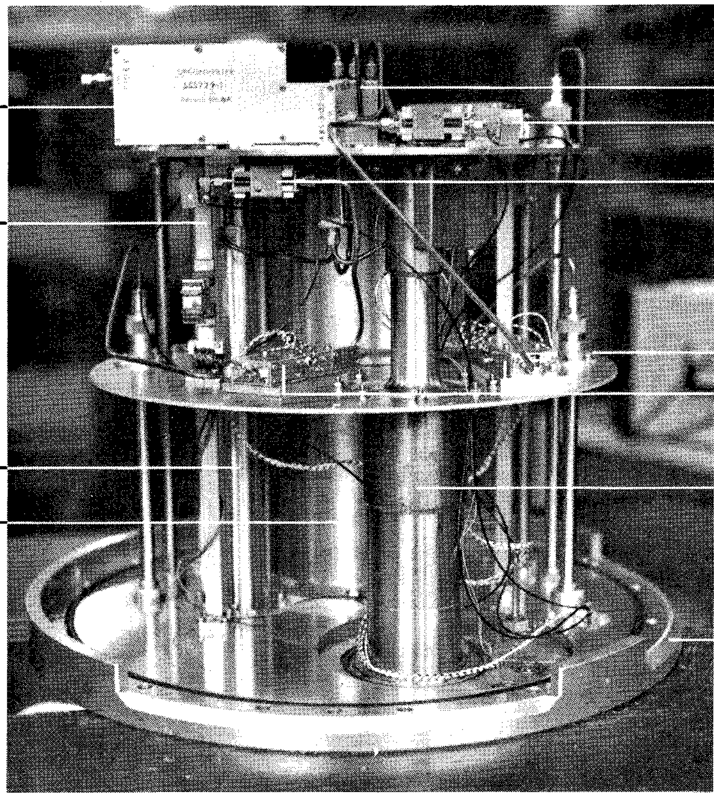

Fig. 4. Interior of the cryostat with the 70 K thermal shield removed. The coaxial connections between the receiver parts are made of semirigid cables. The connectors are of the SMA type. On the paramp pump waveguide is a flexible connection meant to absorb some of the mechanical stresses.

TABLE I
MAIN PARAMETERS OF THE COOLED EQUIPMENT

	paramp	FET amplifier	up-converter
operating temperature	20 K	70 K	20 K
gain	15 dB	17 dB	4.5 dB
frequency band	4770-5020 MHz	4770-5020 MHz	1350-1520 MHz
noise temperature	15 K	56 K	7 K
power requirements	10 mW	30 mW	20 mW
pump frequency	26.1 GHz	-	3.5 GHz

they introduce is tuned out by compensation rings.

As a result of asymmetric thermal stresses the axes of the two sections of both waveguides are displaced with respect to each other by several millimeters after cooling. This causes the cross polarization isolation, in particular at 6 cm, to deteriorate. This problem has been solved by installing centering pins on the 70 K plateau, which keep the waveguides aligned. The thermal losses are kept low by using thin guide pieces.

Also shown in Fig. 3 and quite distinguishable in Fig. 4 are the output and up-converter pump coaxial lines and the paramp pump waveguides. Both lines have been made of stainless steel with a wall thickness of 0.2 mm.

The thermal losses of the system have been calculated as follows:

radiation transfer between 300 K and 70 K shields	1.9 W;
radiation loss in signal waveguides at 20 K	1.1 W;
conductivity losses in transmission lines	1 W;
dissipation of electronic equipment	0.2 W.

The CTI model 1020 refrigerator has a cooling capacity of 8 W at the 20 K station with a 5-W load on the 70 K station. Sensors have been installed to monitor the various temperatures in the system. The average physical temperature readings are 15 K and 50 K for the 20 K and the 70 K plateaus, respectively. The total mass to be cooled to 20 K is approximately one kilogram. In spite of the reduced specific heat at cryogenic temperatures this mass is sufficient to stabilize the temperature of the 20 K station to better than 0.1 K.

On the 20 K side of the input waveguides are the waveguide-to-coax transitions. At 21 cm they consist of a pair of crossed halfwave dipoles fed by a cooled balun. At 6 cm, two orthogonal monoprobes separated along the waveguide axis by one wavelength are used. The cross polarization isolation is better than 40 dB.

For amplitude calibration purposes the 300 K waveguide sections are also equipped with 30-dB directional couplers in the form of coupling loops [5]. These probes are fed by noise sources using avalanche diodes kept in the uncooled section. The amplitude stability of the noise step is better than 0.01 dB.

IV. PERFORMANCES

As the telescope calendar comprises regular sessions at other wavelengths besides at 6 and 21 cm, the cooled front-end receivers generally remain in continuous operation for a few months at a time. The temperature cycling which results is undesirable and has been the cause of several breakdowns, usually in the form of broken connections. Repairs are generally straightforward but very time consuming as the receivers have to be brought

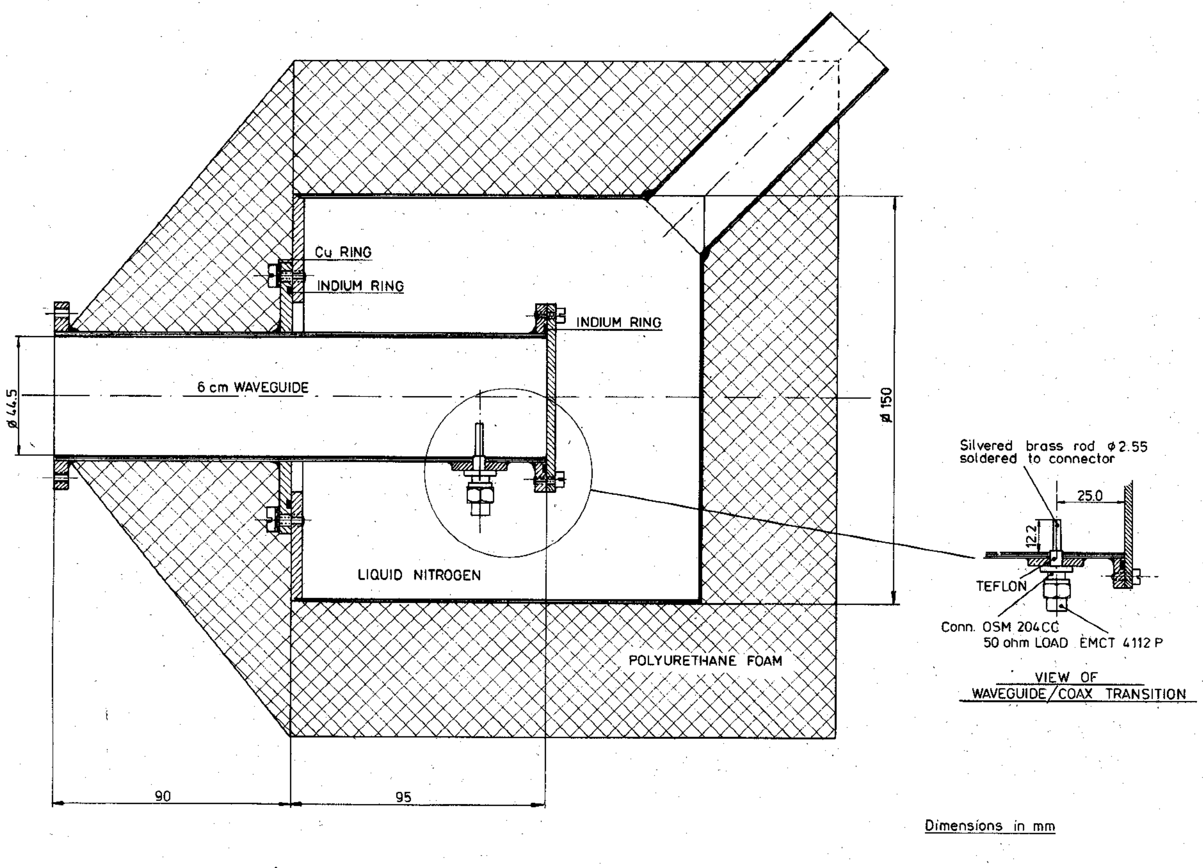

Fig. 5. Schematic of a cooled waveguide load for 6-cm wavelength. A 50-Ω coaxial load coupled into the waveguide by means of a probe is immersed in liquid nitrogen. The nitrogen vessel is insulated with a thick layer of polyurethane foam.

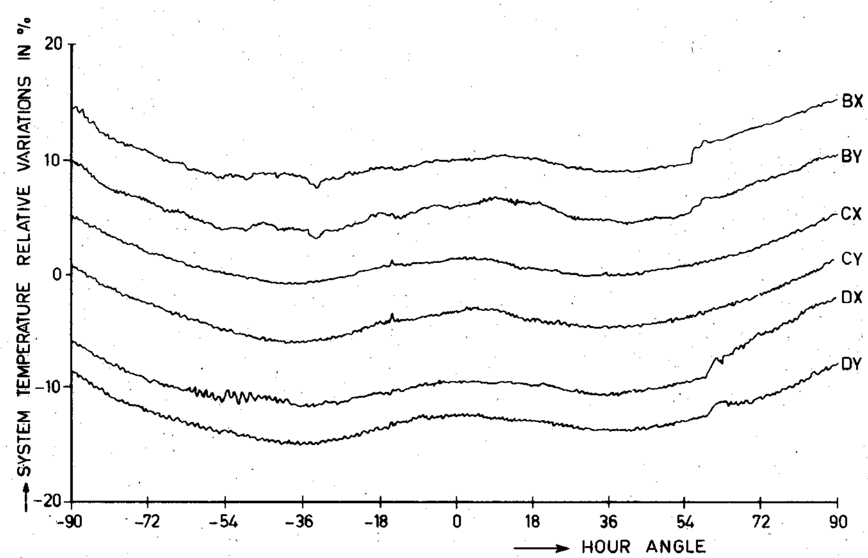

Fig. 6. Plot of the percentage relative variation of the system temperature at 21-cm wavelength as a function of hour angle for several antennas pointed at a source at 50° declination. The X and Y symbols indicate the sense of polarization; the letters $A-D$ refer to a given telescope. The gain variations have been calibrated out by means of the noise source.

back gently to ambient temperature in order to reduce the thermal shock.

A total of 9–10 h is required to evacuate the system and to cool it from 300 K to 20 K. It begins with vacuum pumping the cryostat with a mechanical pump for a few hours until a vacuum of 10^{-1} torr is reached. After an hour of pumping with the diffusion pump down to a vacuum of 10^{-3} torr the refrigerator can be switched on. After 6 h of cooling the operating temperature is reached and the vacuum pump can be dispensed with since the vacuum, provided the leaks are negligible, will be maintained at 10^{-5}–10^{-6} torr by cryopumping. In practice the refrigerator can be switched off for several hours before the vacuum has

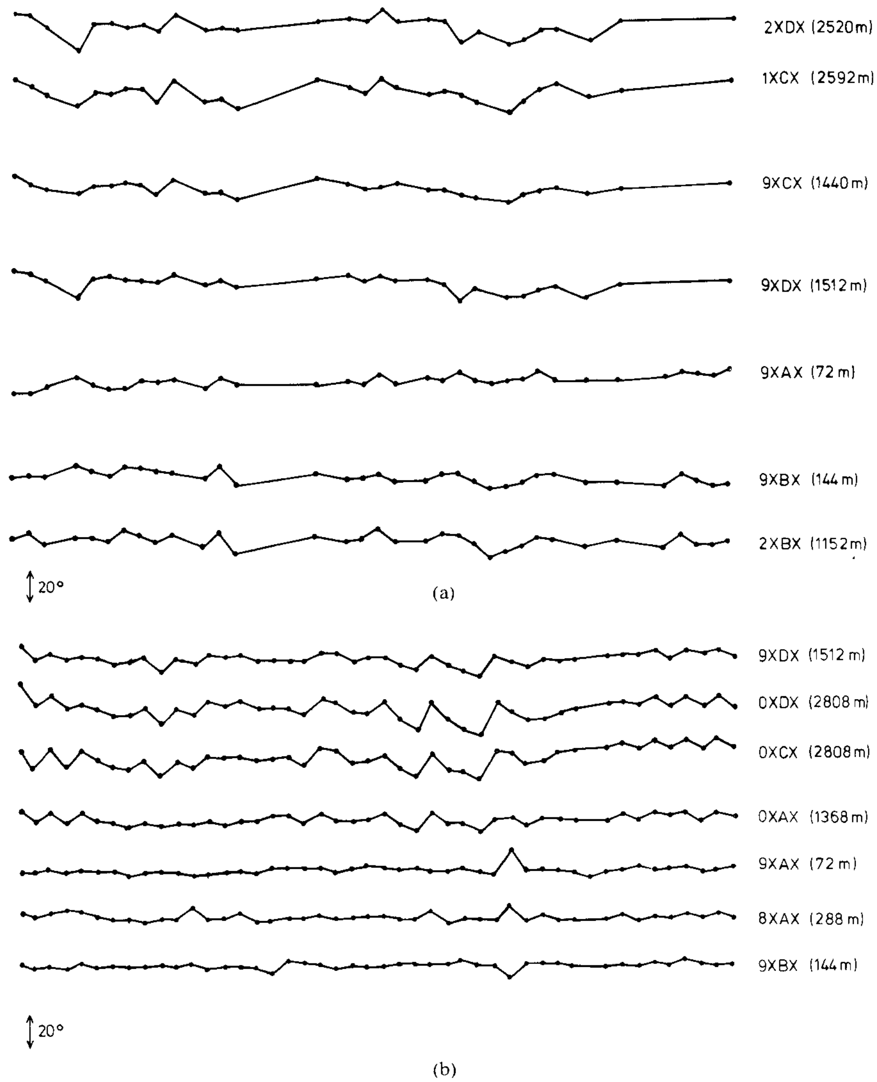

Fig 7 Phase behavior in electrical degrees for a number of interferometers as a function of time during a 24-h run at 6-cm wavelength (a) and 21-cm wavelength (b). The length of the various baselines is given between parentheses. The X symbol indicates one direction of polarization. In these plots, the tropospheric or ionospheric instabilities have not been removed. These instabilities increase with the length of the baseline

TABLE II
SYSTEM TEMPERATURE NOISE CONTRIBUTION

	21 cm	6 cm
receiver	14 K	20 K
spillover	10 K	10 K
mesh transmission	1 K	20 K
sky	4 K	5 K
	29 K	55 K

deteriorated to the extent that the system cannot be restarted without restoring first the vacuum. It is quite normal to have these receivers transported cooled from Westerbork to the laboratory in Dwingeloo (25 km) for repairs or testing purposes.

Noise temperature measurements on the front-ends are performed in the laboratory using home made waveguide loads at ambient and 70 K temperatures. A load for 6-cm wavelength is shown in Fig 5 For the cooled load the coaxial termination is immersed in liquid nitrogen. The loads have been adjusted to a VSWR of 1.10 over the band 4770–5020 MHz.

The lowest noise temperature measured at 21 cm on the telescope was 26 K. In this case the measured receiver temperature was 11 K, a number which can be further split up into up-converter and paramp contributions of 5 K and 4 K, respectively. The input loss contribution is estimated to be 2 K. This excellent performance is partly a result of the particularly successful AIL up-converter whose gain approaches the maximum available value of 5.5 dB. The system temperatures at 6 and 21 cm have been measured to be 55 K and 29 K, respectively, on the average. Estimates of the various noise contributions for the average system temperatures are indicated in Table II.

The spillover for both feeds has been computed from their radiation patterns to be about 4 percent. Transmission through the mesh of the reflector at 6-cm wavelength is about 8 percent. Two of the movable telescopes have a finer mesh which yields at 6 cm a loss of only 4 percent in which case the system noise temperature (at 6 cm) is reduced to about 45 K.

The WSRT measures the phase difference and the amplitude of the signals received by the 40 interferometers. Because the receiver noise temperature has become comparable to the antenna contribution, the system temperature fluctuates with time as, for instance, the antenna spillover response sweeps over different parts of ground and sky. This effect can be separated from gain fluctuations by means of noise source calibration. In Fig. 6 the percentage noise temperature variations have been plotted for several channels as a function of hour angle for a source at 50° declination. In these graphs the system temperature varies by as much as 7 percent, i.e. about 2 K. The amplitude accuracy after calibration is of the order of 1 percent.

The phase stability of some of the 6- and 21-cm interferometers is depicted in Fig. 7 for a 24-h run in which the aerials have been pointed at known calibrators at various hour angles and declinations. These results have been obtained after corrections had been applied for the atmospheric refraction suffered by the various calibrators. The graphs include the effects of the troposphere and the ionosphere which can be noticed on the long baselines, particularly at 21 cm. The short baseline plots indicate that even with cooled systems, an rms phase stability of 1 to 2 electrical degrees over long periods is achievable.

V. Conclusions and Future Developments

It will be difficult to improve on the system temperatures obtained with the receivers described. At 21-cm wavelength, using a maser receiver, one could probably reduce the lowest system temperature achieved (26 K) by not more than 5 K. The spillover contribution to the system temperature can in principle be reduced from 10 K to 5 K by using an improved feed antenna. The mechanical constraints, however, complicate the problem tremendously.

The average effective system temperatures of the WSRT at 6- and 21-cm are presently 85 K and 50 K, respectively. Another significant sensitivity improvement could be made by cooling all receivers. This step is being contemplated for 21-cm wavelength together with a simpler configuration wherein cooled FET amplifiers replace the up-converters. A prototype 21-cm front-end equipped with a FET amplifier based on a design developed at the University of California, Berkeley [6] has been completed. Noise temperature measurements indicate similar performances to those obtained with the up-converters.

The multifrequency front-ends described in this paper have also been designed to accommodate a third frequency around 1660 MHz, the OH molecule band. As the 21-cm waveguide is unsuited to propagate this frequency it will enter the cryostat via a pair of coaxial lines. A prototype 18-cm system using cooled FET amplifiers is now nearing completion.

Acknowledgment

Many colleagues from the Foundation Central Technical Service Division have been involved in the construction and testing of the new front-ends. In particular, the authors wish to thank I. Starre for working out the mechanical aspects of the cooled receivers. A. van Ardenne's contributions, particularly in solving a resonance problem in the 21-cm launcher system, are greatly appreciated.

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