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THE 1420 MC/S RADIO TELESCOPE OF THE DOMINION RADIO ASTROPHYSICAL OBSERVATORY

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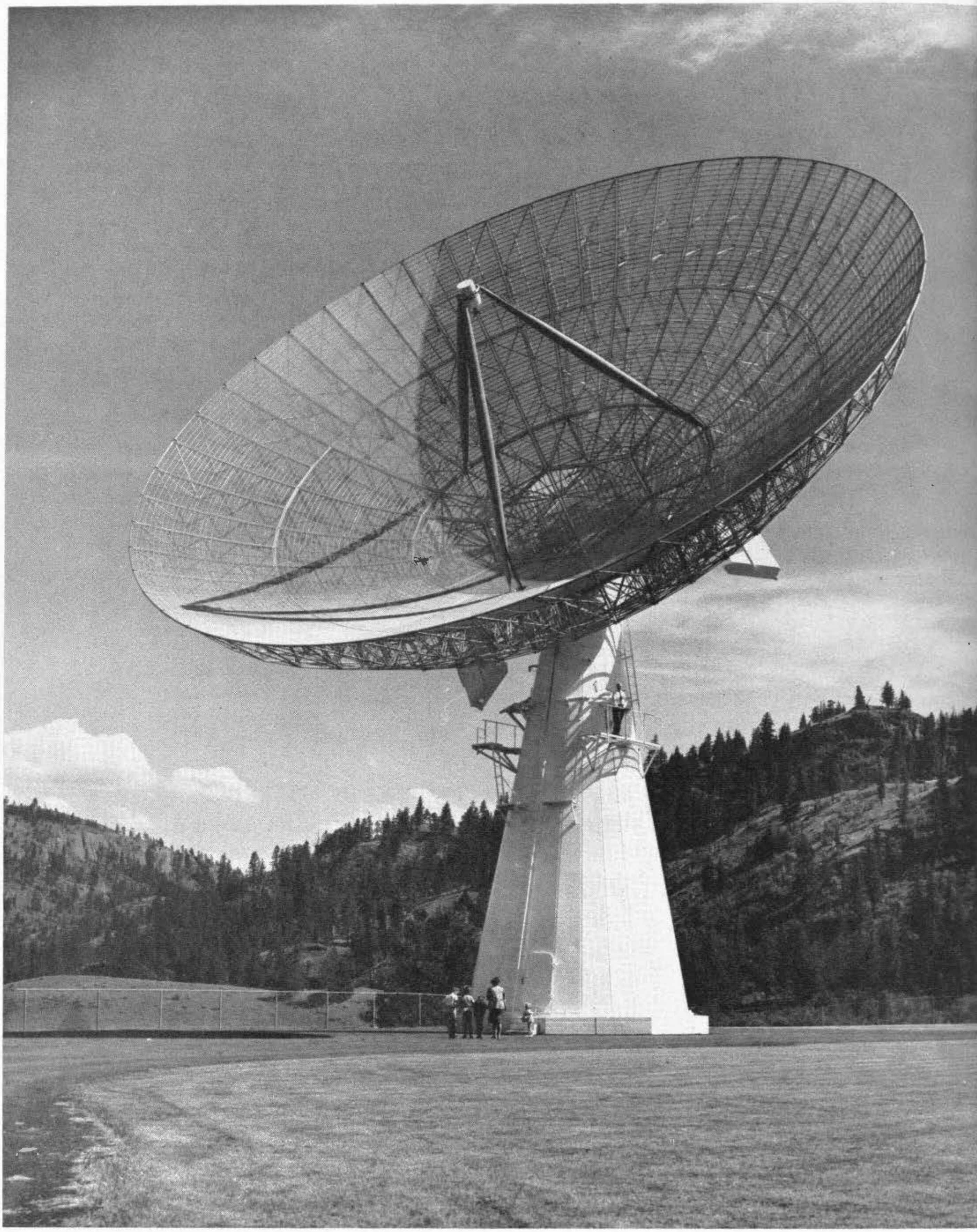

FIGURE 1. The 25.6-m radio telescope of the Dominion Radio Astrophysical Observatory.

The 1420 MC/S Radio Telescope of the Dominion Radio Astrophysical Observatory

J. L. LOCKE, J. A. GALT AND C. H. COSTAIN

ABSTRACT:—The radio telescope of the Dominion Radio Astrophysical Observatory, used both for studies of the hydrogen line and the continuum, is described. The antenna, a 25.6-metre-diameter paraboloid of focal ratio 0.34, is mounted equatorially. The radiometer is a Dicke type instrument with a comparison resistor at liquid oxygen temperature. An over-all noise temperature of 160°K is attained using an electron beam parametric amplifier.

RÉSUMÉ:—Les auteurs décrivent le radio-télescope de l'Observatoire de radio-astrophysique du Canada que l'on emploie à la fois à l'étude des raies de l'hydrogène et du spectre continu. L'antenne parabolique de 25.6 mètres de diamètre et de 0.34 d'ouverture est montée en équatorial. Le radiomètre est un instrument du type Dicke muni d'une résistance de comparaison à la température de l'oxygène liquide. On obtient une température de bruit totale de 160° K en utilisant un amplificateur paramétrique à faisceau d'électrons.

Introduction

The Dominion Radio Astrophysical Observatory was established in 1960 to pursue studies of interstellar matter, a subject that has for many years been investigated by the observatories at Ottawa and Victoria. Radio waves from neutral hydrogen at a wavelength of 21 cm provide accurate radial-velocity information and can penetrate the dust clouds in the galactic plane that are opaque to light waves. Studies of the radiation from hydrogen can be used to investigate the size, shape, mass and rotational properties of our galaxy. Radio methods are also of great value in studies of extragalactic nebulae, the sun, the moon and some of the planets.

The observatory is located about 20 km south of Penticton, B.C., in a large uninhabited valley surrounded by mountains. The site was chosen after an extensive survey and is remarkably free of electrical interference. At 119°37′W, 49°19′N, it is far enough south that observations down to declination −30° are possible. The area surrounding the observatory, being flat and devoid of trees, is well suited to the installation of interferometers or large aerial arrays.

Antenna

The antenna, shown in Figure 1, is an equatorially mounted parabolic reflector 25.6 metres in diameter with a focal length of 7.6 metres. The aluminum mesh surface conforms to a true paraboloid to within ± 1 cm. Any part of the sky may be observed directly, and the telescope position is indicated by synchronous repeaters reading declination, right ascension and hour angle. The telescope can track in hour angle at the sidereal rate, scan at speeds from 0° to 1° per minute or, for setting, can be rotated at 15° per minute. For movement in declination, similar scan and rapid motions are available; in addition there is a synchronous drive in declination of 1/4° per sidereal minute. The reflector is supported by a steel tower which is bolted to a massive reinforced concrete foundation. The polar axis was aligned by tilting the tower through an angle determined from sky photographs taken with a camera temporarily mounted on the declination axis. Errors in pointing are less than 1/10 of a beamwidth at the operating frequency.

A 25.4-cm cassegranian optical telescope is permanently mounted parallel to the axis of the antenna. This has been used to check the accuracy of the tracking motion and the perpendicularity of the polar and declination axes; it can also aid in locating a comet or other transient object whose coordinates are not well known. The optical telescope is mounted in the wall of the large cylindrical tube which forms the declination axis and supports the antenna. A system of prisms and lenses brings the light out along the axis of declination. An observer's chair rolls around the inside of the tube and remains upright as the telescope moves in declination.

Three fibreglass spars support the electronic apparatus at the focus. This is housed in a weatherproof, thermally insulated box whose temperature is maintained at 22° ± .5°C by circulating water in coils around the outside of the box. A refrigerator in the top of the tower and a heater adjust the temperature of the water in response to changes of the temperature inside the box.

Radiation from a celestial source is collected at the focus with a stepped-waveguide horn, which can be adjusted for a VSWR of less than 1.02 from 1370 Mc/s to 1450 Mc/s (Millar, 1960). The horn is flared in the E-plane to obtain nearly equal response in the E and H planes. It provides a smoothly tapered aperture illumination which falls by 14 db at the edge of the reflector. This produces a nearly circular beam with a half width of 36′ and a very low side-lobe level at 1420 Mc/s. The E-plane of the horn is parallel to the axis of declination. The horn is matched to a 50-ohm coaxial line by means of a waveguide plunger and a reactance stub. This stub, which is only needed for small impedance corrections, is an open-circuited coaxial line about $\lambda/2$ long whose electrical length can be adjusted slightly by moving a polystyrene tube in the line. This type of tuning stub avoids the problem of intermittent contact fingers which are troublesome with the more conventional $\lambda/4$ shorting stub.

Radiometer

A block diagram of the radiometer is shown in Figure 2 and a list of the principal components and their manufacturers is given in Table 1. Power from the horn is fed to a ferrite circulator switch that alternately connects the aerial or a matched resistive termination to the following amplifier. After amplification and detection the signal is applied to a demodulator operating in synchronism with the input switch. The demodulator output is proportional to the difference in power received from the aerial and the comparison resistor.

It has been shown by Orhaug and Waltman (1962) that a Dicke radiometer of this type has maximum stability when the aerial temperature is equal to the temperature of the comparison resistor. Under usual operating conditions at high frequencies the aerial temperature is lower than the temperature of the comparison termination. To make the two temperatures equal, noise power from a discharge tube is introduced into the aerial side of the switch through a directional coupler and a motor-driven variable attenuator. To keep to a minimum the noise power that must be injected to balance the system, the comparison resistor is immersed in liquid oxygen at 90°K. A calibration signal can be inserted through a second directional coupler. The ferrite circulator switch operates at 97.7 cps and is similar to the one described by Lax and Button (1962). Besides acting as a SPDT coaxial switch it also functions as an isolator preventing small changes in antenna or comparison resistor impedance from degrading the performance of the following amplifier. Switching is accomplished by

TABLE I. EQUIPMENT SUPPLIERS

Block No.	Manufacturer	Block No.	Manufacturer
(1)	D.S. Kennedy Co.	(25)	Microlab, CA4IN
(2)	National Research Council, Ottawa.	(26)	Arra π Line, Model 3414-30
(3)	Hewlett-Packard Co.	(27)	Airborne Instruments Laboratory, Type 7010
(4)	Melabs, Model X-124A	(28)	Narda Microwave Corp., 3003-10
(5)	Zenith Radio Corp., Model LB (Power Supplies, D.R.A.O.)	(29)	Alfred Electronics, Model 703
		(30)	Gombos Microwave Inc., Model 2S12
(6)	Applied Research Inc., Model HFF-T-ZX	(31)	Alfred Electronics Inc., Model 502A—(Higgins HA-2E)
(7)	Microlab, Series CJ-N		
(8)	Ewen-Dae Corp.	(32)	Gombos Microwave Inc., Model 3S12
(9)	D.R.A.O.	(33)	Fideltone Mcrowave Inc., (JVM), Modified by D.R.A.O.
(10)	Ewen-Dae Corp.		
(11)	Ewen-Dae Corp.	(34)	D.R.A.O.
(12)	Ewen-Dae Corp.	(35)	D.R.A.O.
(13)	Bulova Watch Co. and Daven Co.	(36)	D.R.A.O.
(14)	Ewen-Dae Corp.	(37)	Fieldtone Microwave Inc., (JVM)
(15)	R.C.A. 2N384 Transistor	(38)	D.R.A.O.
(16)	Ewen-Dae Corp.	(39)	Ewen-Dae Corp., Modified by D.R.A.O (see Figure 2)
(17)	Stevens Arnold Corp. Model A32-94		
(18)	Texas Instrument Inc., Servo Riter Model PSD	(40)	Melabs Model RL-3
		(41)	Ewen-Dae Corp.
(19)	D.R.A.O.	(42)	D.R.A.O.
(20)	Hewlett-Packard Co., Model 405 CR	(43)	D.R.A.O.
(21)	D.R.A.O.	(44)	D.R.A.O.
(22)	I.B.M. Type 024	(45)	D.R.A.O.
(23)	Stoddart Aircraft Radio Co., Inc., 92234-58	(46)	D.R.A.O.
(24)	Sulfrian Cryogenics, Inc.	(47)	Phelps Dodge Electronics Products Corp., Styroflex.

D.R.A.O.—Dominion Radio Astrophysical Observatory.

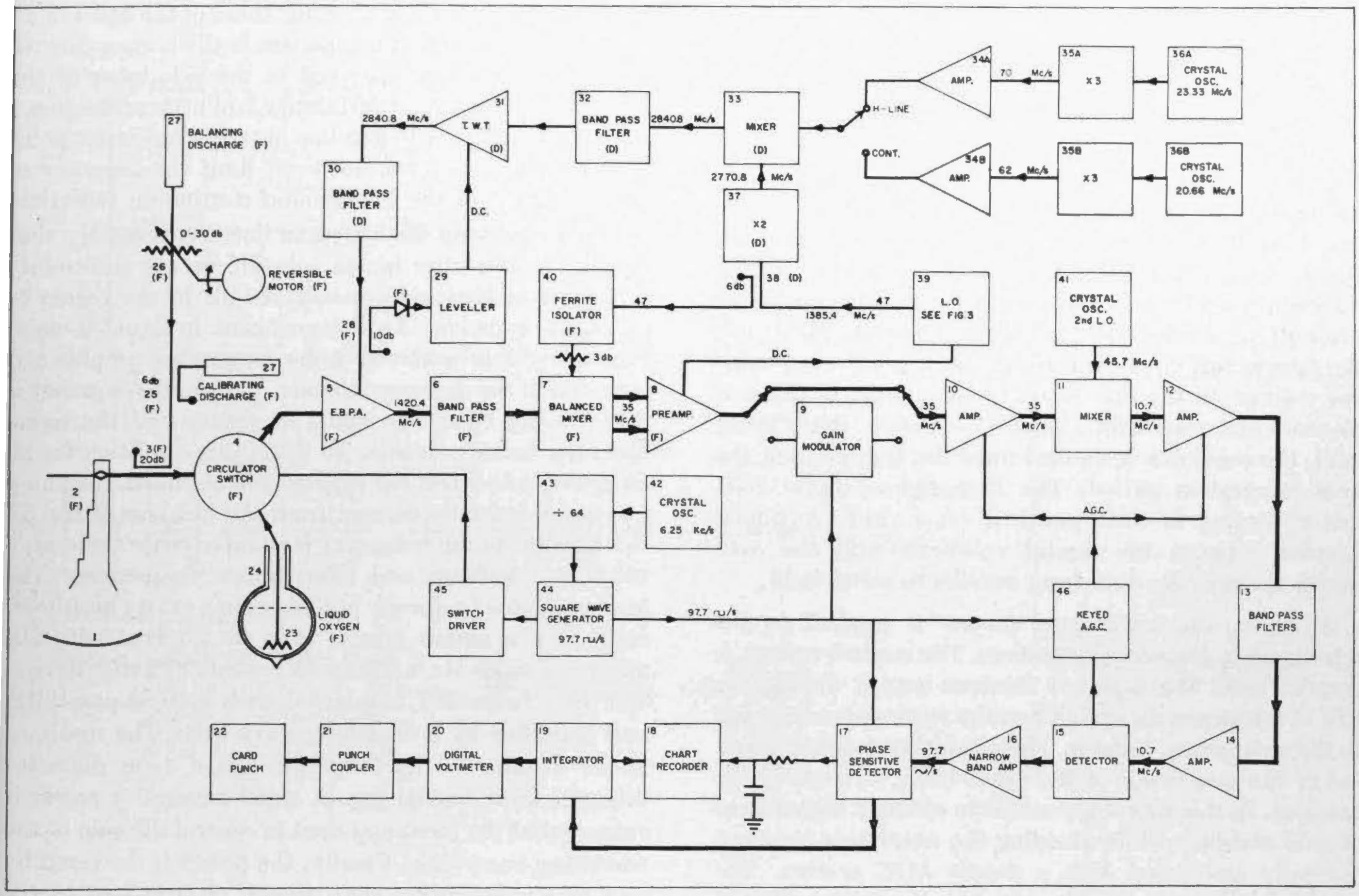

FIGURE 2. Block diagram of the radiometer. Numbers refer to Table 1. Items marked (F) are located at the focus of the radio telescope. Items marked (D) are located in the declination axis. All other apparatus is in laboratory building.

reversing the magnetic field applied to the ferrite. The loss in the switch is about 0.1 db and hence contributes only approximately 7°K to the receiver noise temperature.

When maximum sensitivity rather than maximum stability is required, the balancing discharge tube is turned off and a gain modulator inserted in the intermediate frequency amplifier. This device uses attenuators and a crystal diode switch operating in synchronism with the input switch to reduce the power from the comparison resistor until it is equal to that from the antenna. Although this mode of operation has a property of a balanced Dicke system of being insensitive to gain fluctuations, it is sensitive to noise factor fluctuations. In the present case, a change in receiver noise temperature, T_N °K, will appear as an output deflection of approximately $\frac{1}{2}$ T_N °K.

The radio frequency preamplifier is an electron beam parametric amplifier (Adler tube) similar to the one described by Adler, Hrbek and Wade (1959). Its gain, when operating at minimum noise temperature of 90°K, is about 23 db. To obtain optimum performance, the electrode potentials, magnetic field and pump power are stabilized to a high degree and the input impedances must be accurately matched. The Adler tube is operated in a degenerate mode for hydrogen-line reception and the pump power required at twice the signal frequency is about 200 mw. A double-cavity band-pass filter following the Adler tube keeps stray pump power out of the crystal mixer and prevents local oscillator power from entering the parametric amplifier. The balanced crystal mixer combines the signal, whose nominal frequency is 1420.4 Mc/s, and the local oscillator power at 1385.4 Mc/s to produce an intermediate frequency of 35 Mc/s. A cascode preamplifier and three pentode stages amplify the signal before it is transmitted by cable to the laboratory building. The signal is then further amplified and converted to 10.7 Mc/s where the pass-band is limited by filters of 2, 5, 10, 50, 200 or 6000 kc/s bandwidth. The first four are crystal filters. After further amplification the signal is detected in the base-to-emitter junction of a transistor. A tuned audio amplifier follows the detector and the signal is then applied to a chopper-type demodulator driven in synchronism with the ferrite switch at the focus.

The DC output of the demodulator is applied to a simple RC low-pass filter and then to a potentiometer pen recorder. The output also feeds an integrator in which a capacitor is charged for an accurately timed interval, usually half a sidereal minute, with a current proportional to the output of the receiver. At the end of the interval an identical capacitor begins charging while the voltage on the first capacitor is applied to the pen recorder and read with a digital voltmeter. After being read, the capacitor is shorted until the beginning of the next integration period. The three-figure digital voltmeter reading is then punched on a card. A punch coupler between the digital voltmeter and the card punch changes the data from parallel to serial form.

A keyed automatic gain control is applied to the intermediate frequency amplifiers. The control voltage is derived from the detected receiver output during the half of the switching cycle when the receiver is connected to the comparison resistor. The gain is therefore independent of the magnitude of the signal being received by the antenna. In this way it is possible to obtain a high degree of gain stability while avoiding the non-linear response normally associated with a simple AGC system. The sensitivity is, however, dependant on the temperature of the comparison resistor and the receiver noise temperature. The comparison resistor is maintained at constant temperature. The effect of changes in receiver noise on the output of the system is proportional to the percentage change in the total input noise and to the size of the unbalanced switched signal. Since the receiver is normally operated in a nearly balanced condition, small changes in receiver noise are unimportant.

Because changes in temperature of the comparison resistor will normally be indistinguishable from changes in aerial temperature, the temperature of the comparison resistor must be held constant to within the desired accuracy of the measurements; for some observations this is of the order of 0.05°K. This requirement is met by immersing the resistor in liquid oxygen. Liquid oxygen is used instead of the cooler liquid nitrogen because the temperature of a liquid nitrogen bath will rise as oxygen from the atmosphere dissolves in it. The resistor is at the bottom of a 5-litre dewar flask fixed to a spar near the focus. A rigid evacuated coaxial line connects the resistance termination to a short length of thermally insulated RG9B cable.

The stability of the system for times of the order of an hour or more is limited by changes in the temperature of the ground which is observed in the side lobes of the antenna. This apparent instability is of little consequence for most galactic hydrogen-line observations or for point source studies. It does, however, limit the accuracy of measurements of the background continuum radiation.

When observing the hydrogen line it is necessary that the signal and idler bands coincide or are sufficiently separated so that only one band falls in the region of hydrogen emission. An improvement in signal-to-noise ratio of $\sqrt{2}$ is achieved if the parametric amplifier is operated in the degenerate mode. The pump frequency is then exactly twice the signal frequency and the signal and idler bands coincide. To fulfill this condition for all frequencies to which the receiver can be tuned, the pump frequency must be derived from the local oscillator. In this case the pump frequency is equal to twice the sum of the local oscillator and intermediate frequencies. The local oscillator frequency is doubled in a cavity multiplier employing a planar triode. It is then mixed with the output of a 70-Mc/s source in a similar cavity device. The sum frequency is selected with a band-pass filter and amplified by a travelling wave tube. The resultant power is sent to the focus through a 4-cm diameter nitrogen filled coaxial line. A small amount of power is extracted at the focus and used to control the gain of the travelling wave tube. Finally, the power is delivered by way of a balun and a short length of twin lead to the quadrupole structure inside the Adler tube. When observations of the continuum rather than the hydrogen-line are to be made, the receiver is tuned to 1424 Mc/s and the pump frequency returned to 2840 Mc/s; the signal and idler bands are then spaced on either side of the hydrogen frequency. This doubles the effective bandwidth of the receiver.

Local Oscillator

A block diagram of the local oscillator is shown in Figure 3. For observing galactic hydrogen, its frequency is approximately 1385.4 Mc/s. The local oscillator must be frequency stable to a small fraction of the receiver bandwidth and must be continuously tunable over a range of several megacycles.

To satisfy both requirements, the local oscillator frequency is synthesized by adding a high frequency (1235 Mc/s) derived from a very stable crystal oscillator to a lower variable frequency (≈ 150.4 Mc/s). To obtain the 1235 Mc/s power an oscillator is phase-locked to the 247th harmonic ($4 \times 62 - 1 = 247$) of a stable 1 Mc/s

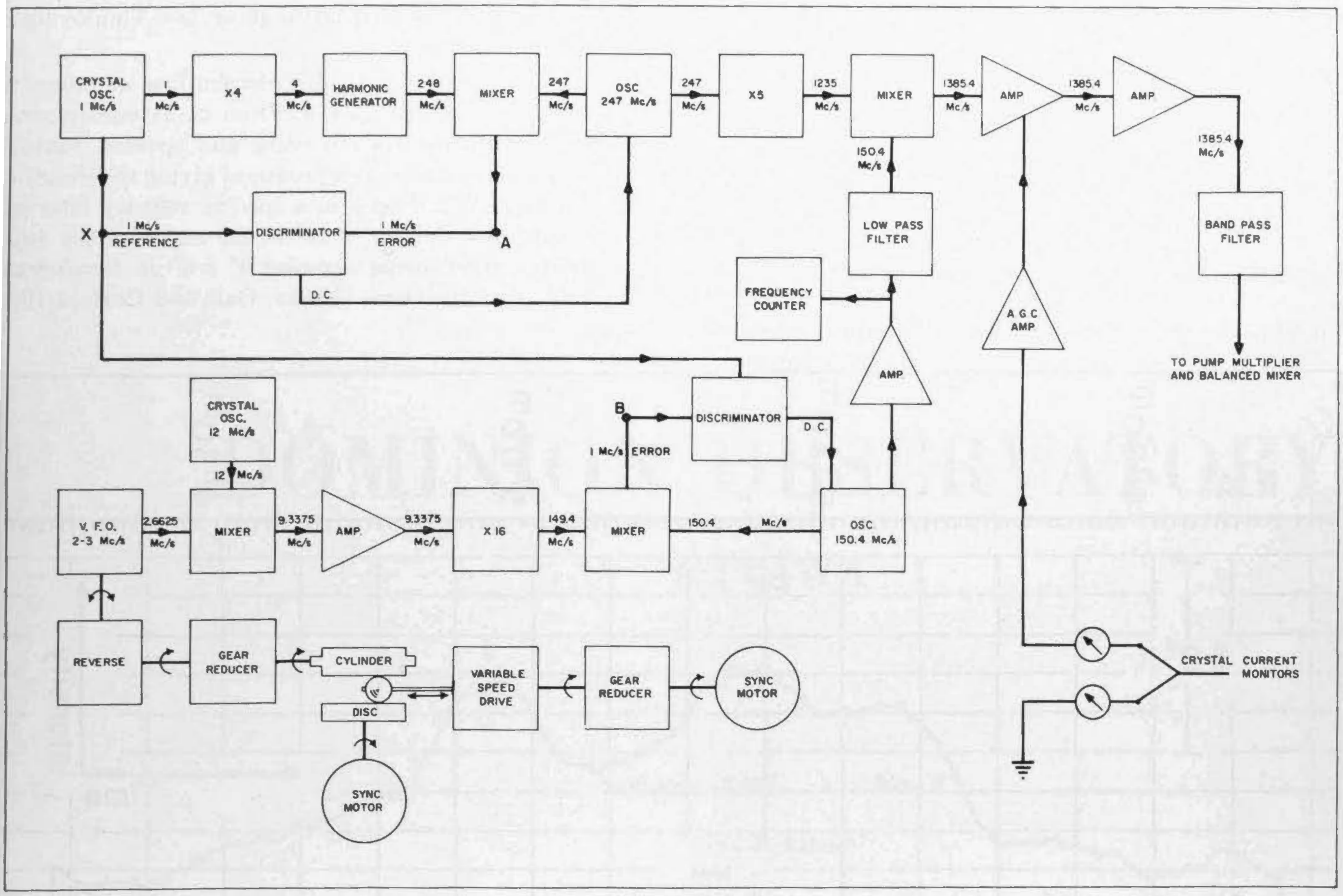

FIGURE 3. Block diagram of first local oscillator. (Shown as number 39 in Figure 2.)

crystal oscillator. This frequency is then multiplied by 5 to give 1235 Mc/s. The variable frequency is derived from an inductively tuned oscillator operating at a nominal frequency of 2.6625 Mc/s. This frequency is subtracted from a crystal-controlled frequency of 12 Mc/s and the difference multiplied by 16 to obtain a frequency of 149.4 Mc/s. A free-running oscillator is then phase-locked 1 Mc/s higher to produce 150.4 Mc/s. This frequency is added to 1235 Mc/s to obtain the 1385.4 Mc/s local oscillator frequency. The power is then amplified by two triode stages and delivered to a 4-cm-diameter coaxial cable which conducts it to the mixer at the focus and the pump-frequency multiplier in the declination axis. An automatic gain control voltage derived from the mixer crystal current is applied to the penultimate amplifier. The operation of the two phase-locked systems is continuously monitored by observing lissajous figures between point X and the points A and B in Figure 3.

Since the local oscillator determines the frequency of reception, it is important for hydrogen-line observations that its frequency be accurately known. The 1 Mc/s crystal is checked periodically against the standard frequency transmissions of WWV. The variable frequency oscillator is monitored continuously by means of a frequency counter and markers at selected frequency intervals are placed on the pen recorder.

When drift scans are used to observe hydrogen moving at a *particular velocity* with respect to the local standard of rest, the receiving frequency must be altered continuously to compensate for doppler shifts caused by the changing components of the sun's and earth's motion in the direction of observation. The frequencies, f, corresponding to the desired velocity, are therefore calculated using the tables of MacRae and Westerhout (1956) for each half hour of right ascension. Values of $\frac{df}{d\alpha}$ and $\frac{d^2f}{d\alpha^2}$ are calculated or obtained from a plot of frequency *vs* right ascension. At the start of an observation the local oscillator is set to the appropriate frequency. The scan rate, $\frac{df}{d\alpha}$, is set to the calculated value by positioning the ball of a ball-disc variable drive which connects a synchronous motor to the oscillator turning adjustment. A second motor and speed reducer changes the scan rate by moving the ball along the radius of the disc at a speed proportional to $\frac{d^2f}{d\alpha^2}$. The quadratic approximation to the variation of frequency with time is usually adequate for observations lasting an hour or two employing a 10-kc/s bandwidth.

A sample drift record of hydrogen-line emission in *Auriga* is shown in Figure 4. From many such records combined with declination scans and spectra, contour maps of the sky have been produced giving the distribution of neutral hydrogen in a specific velocity interval. Five maps covering 30° x 20° in the region of the anticentre and three maps covering 6° x 8° in *Geminorum* are presented elsewhere (Locke, Galt and Costain 1964 a,b).

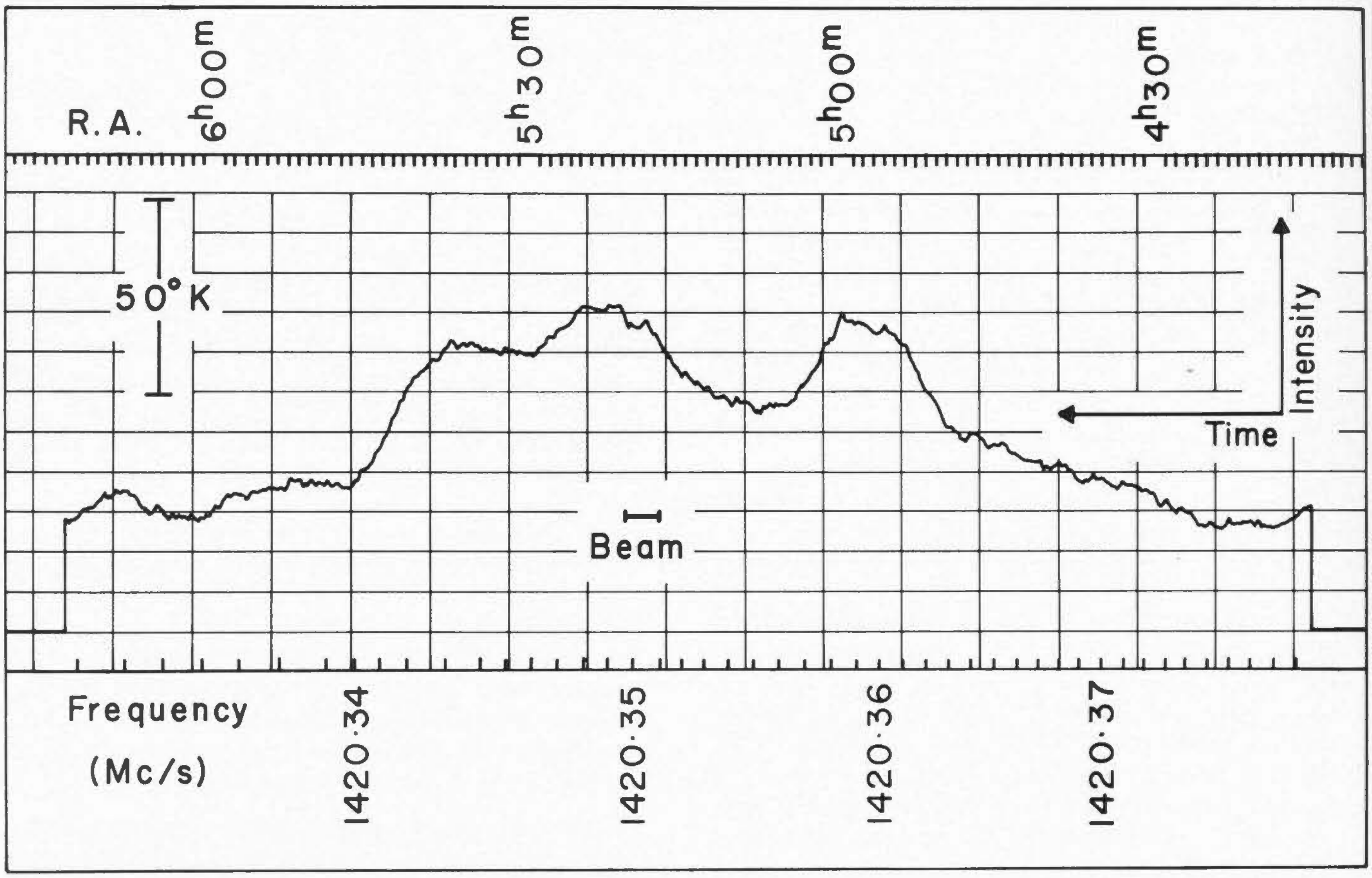

FIGURE 4. Sample drift record at declination 39°30′ and radial velocity V = −15.7 km/s. Observed April 26, 1962, beginning at 1519 P.S.T.

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