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A RADIOMETER FOR THE HYDROGEN LINE

BY

B. HÖGLUND AND V. RADHAKRISHNAN

REPORTS FROM
THE RESEARCH LABORATORY OF ELECTRONICS
No 48

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Introduction

The prediction by van de Hulst in 1944 (1) of the existence of a weak but observable radio frequency spectral line in the emission from the hydrogen gas in the galaxy and its subsequent discovery in 1951 (2) provided a more direct method for the study of the detailed structure of our galaxy than was possible with optical astronomy. Radio waves coming from distant parts of our galaxy suffer little absorption in their passage through the intervening dust and gas clouds that lie in their path. Visible light, on the other hand, is scattered so strongly by the clouds as to make optical investigations of the regions around the centre for instance, impossible.

The line radiation from galactic hydrogen is the result of a transition between two hyperfine-structure levels in the ground state of the hydrogen atoms found in interstellar space. The distribution of the hydrogen atoms roughly follows the same contours as the distribution of stars in the galaxy and it is found that the hydrogen exists in the form of clouds concentrated mainly along the galactic equator, i. e. the plane of the milky way. The studies that have already been made, notably in Holland (3), of the radiation emanating from the hydrogen clouds reveal that these clouds take on the form of spiral arms similar to those seen in pictures of some of the extra-galactic nebulae that have been observed with large optical telescopes. Lesser amounts of hydrogen do exist in directions away from the galactic equator but as a rule the strength of the radiation decreases with increasing galactic latitude. A detailed investigation of this broad belt of radiation represents years of observing time and is an undertaking that many observatories can participate in to advantage.

The Chalmers Wave Propagation Observatory at Onsala, near Gothenburg in Sweden, first became interested in hydrogen line observation in 1953 and work was started on building a receiver. The receiver was completed in 1955 and a preliminary study of certain regions in the galactic plane were made that year (4). It was soon found that the receiver, although successful as an experiment, fell short of the standards required of a reliable research instrument which was to be used for making surveys. A new receiver was therefore planned drawing on the experience of the previous one. A description of the new receiver, which has been in operation since 1957, is given in the following pages. There are some problems which have yet to be solved but the operation of the receiver has been satisfactory enough to permit regular observation programs. The programs themselves will not be discussed in this account as they will form the subject of separate reports.

The hydrogen line

In determining the distribution of hydrogen in the galaxy, we want to know the amount of gas that is present in any given direction and its distance from the earth. Furthermore if the line of sight happens to pass through a number of gas clouds at different distances, we wish to know the concentration in each cloud and the respective distances of the clouds. The method adopted is to measure the intensity and the frequency distribution of the radiation from any given direction and to deduce from these quantities the information required. Adopting the principle of differential galactic rotation it is possible to associate a given velocity component towards or away from us with any given region in the galaxy. If there existed a mass of hydrogen in this region, the frequency of the received radiation would suffer a Doppler shift proportional to the velocity component. Conversely, if the Doppler shift in frequency of the radiation reaching us from a specified direction were known, it would then be possible to compute the distance of the gas concentration. Since the exact laboratory frequency of the radiation is known to be $f_0 = 1420.4056$ Mc/s (5), the Doppler shift, Δf, is given straight away by the difference of this frequency from that of the measured radiation. A source extended along the line of sight would give rise to a broad spectrum, Fig. 1, having one or more peaks depending on the distribution of hydrogen. If one neglects the influence of the random motions of the hydrogen gas clouds — which in reality is not possible — the intensity versus frequency profile can, with a suitable change of scale, be interpreted directly as a curve giving the distribution of hydrogen concentration versus distance in the line of sight. It has been assumed in the above simplified explanation that the extension of the source in the plane perpendicular to the line of sight is larger than the beam width of the antenna used.

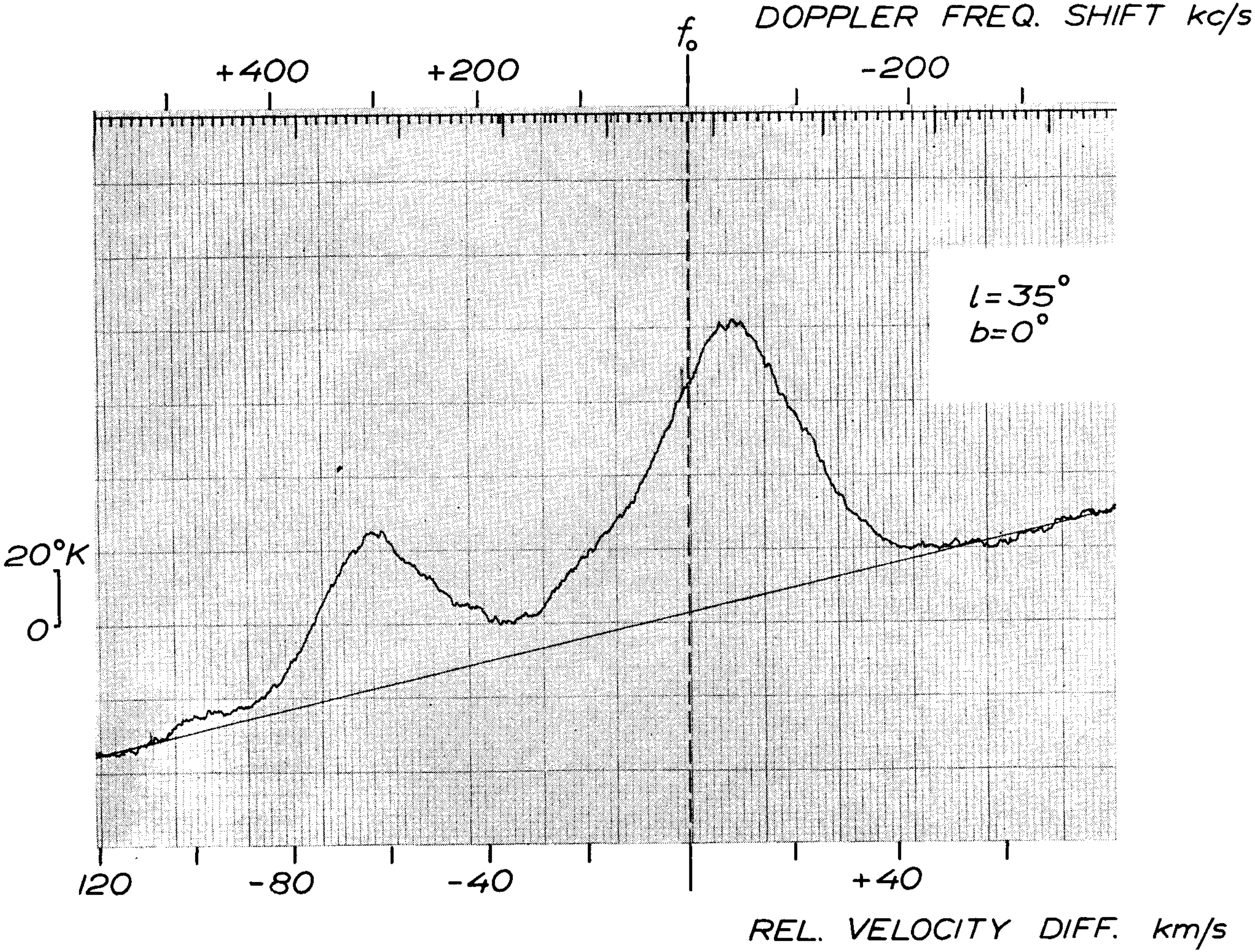

Fig. 1. An intensity recording of the radiation from the cold galactic hydrogen in the direction of the constellation of Cygnus — galactic coordinates $1 = 35^\circ$, $b = 0^\circ$. The horizontal axis is calibrated in Doppler frequency shift, $\Delta f = f - f_0$, and in the corresponding relative velocity difference, Δv. On the vertical axis is indicated the approximate antenna temperature scale. Frequency calibration marks can be seen along the top edge of the records.

If this is so, the radiation fills the antenna beam and the antenna temperature becomes the same as the temperature of the source. The actual temperatures encountered are of the order of 100° K in the region of the galactic plane decreasing to a few degrees absolute at high latitudes.

The antenna

The reflector

The antenna, with which the receiver is used, is a parabolic reflector 7.5 meters in diameter of the Würzburg type having at its focus a dipole. The original altazimuth mounting with attached cabin has been dispensed with and replaced by an equatorial mount, Fig. 2.

Fig. 2. A photograph of the antenna and receiver cabin. The antenna is equatorially mounted.

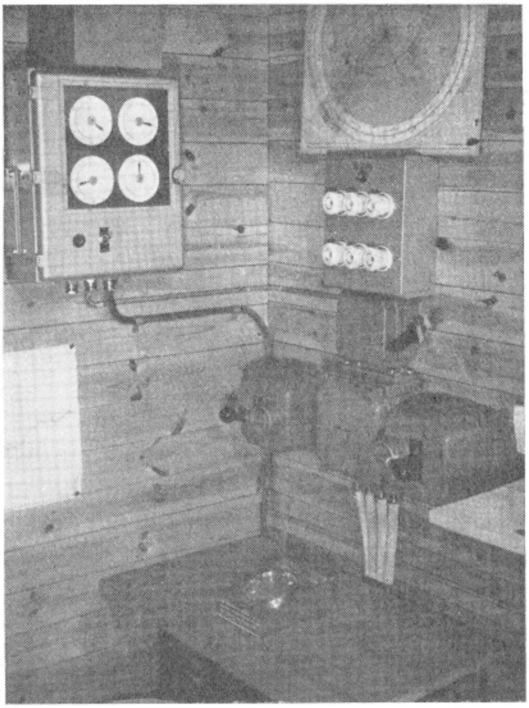

Fig. 3. The selsyn repeater and the controls for the antenna drive. The clock seen in the foreground shows siderial time.

It is equipped with motor drive and has a choice of speeds for either tracking or quick positioning. Selsyn repeaters inside the cabin, Fig. 3, indicate the pointing of the antenna and supplement the original scales on the framework of the reflector. Checks made on the pointing of the antenna by taking drift curves of the sun passing across the stationary antenna at different times of day and in different seasons have shown the accuracy to be about 0.1° in the two directions. The beam width of the antenna at half power points has also been measured with the help of the sun and found to be 2.4° and 1.9° in the declination and hour angle directions respectively. Minor side lobes are found to exist but these are neglected. The gain and resolution obtainable with a parabolic reflector at any one frequency depend on its diameter and restrict the types of observation that can be made with it. The relatively small diameter of our reflector precludes the observation of extragalactic objects of small angular diameter, and limits the detail with which even galactic structure can be studied. It is hoped to acquire a larger reflector soon, but until such time we shall have to content ourselves with the type of work for which the present one is suited. It is more than adequate, for instance, for the study of hydrogen distribution at high galactic latitudes, where great detail is not of paramount importance and where the extension of the source is large enough to fill the antenna beam. The limit in this case is set by the sensitivity of the receiver to the decreasing antenna temperatures obtained with increasing galactic latitude.

The dipole

The dipole, a slot fed type, is connected by an air insulated coaxial line, which also forms its support, to the mixer which is housed in a box mounted on the rear of the parabolic reflector. The characteristic impedance of the coaxial line is 50 ohms. Standing wave measurements made on it looking towards the antenna end give a V. S. W. R. of about 1.05 for a 5.0 Mc/s wide band around the signal frequency. As no image suppression is used in the receiver, the V. S. W. R. in the corresponding band around the image frequency should, ideally, be as low as in the signal band. At the moment, the figure is about 1.3 and is one of the things that will be improved in the very near future. Moreover, the impedance of the antenna varies with frequency in the image band and causes the sloping zero line in the profiles.

The receiver

The receiver proper is a switching type superheterodyne using triple conversion, very similar in design to the receiver used by the Dutch (6) and has in fact been influenced by their design. A schematic diagram of the complete equipment is shown in Fig. 4. With the exception of the mixer, the first I. F. amplifier, and the last tripler in the local oscillator chain which are in the antenna box the rest of the equipment is in the upper halves of five racks in the observation cabin, Fig. 5. The lower halves contain stabilized power supplies each of which feeds one chassis in the upper half of the same rack. This method was adopted in order to minimize undesired cross coupling between different units.

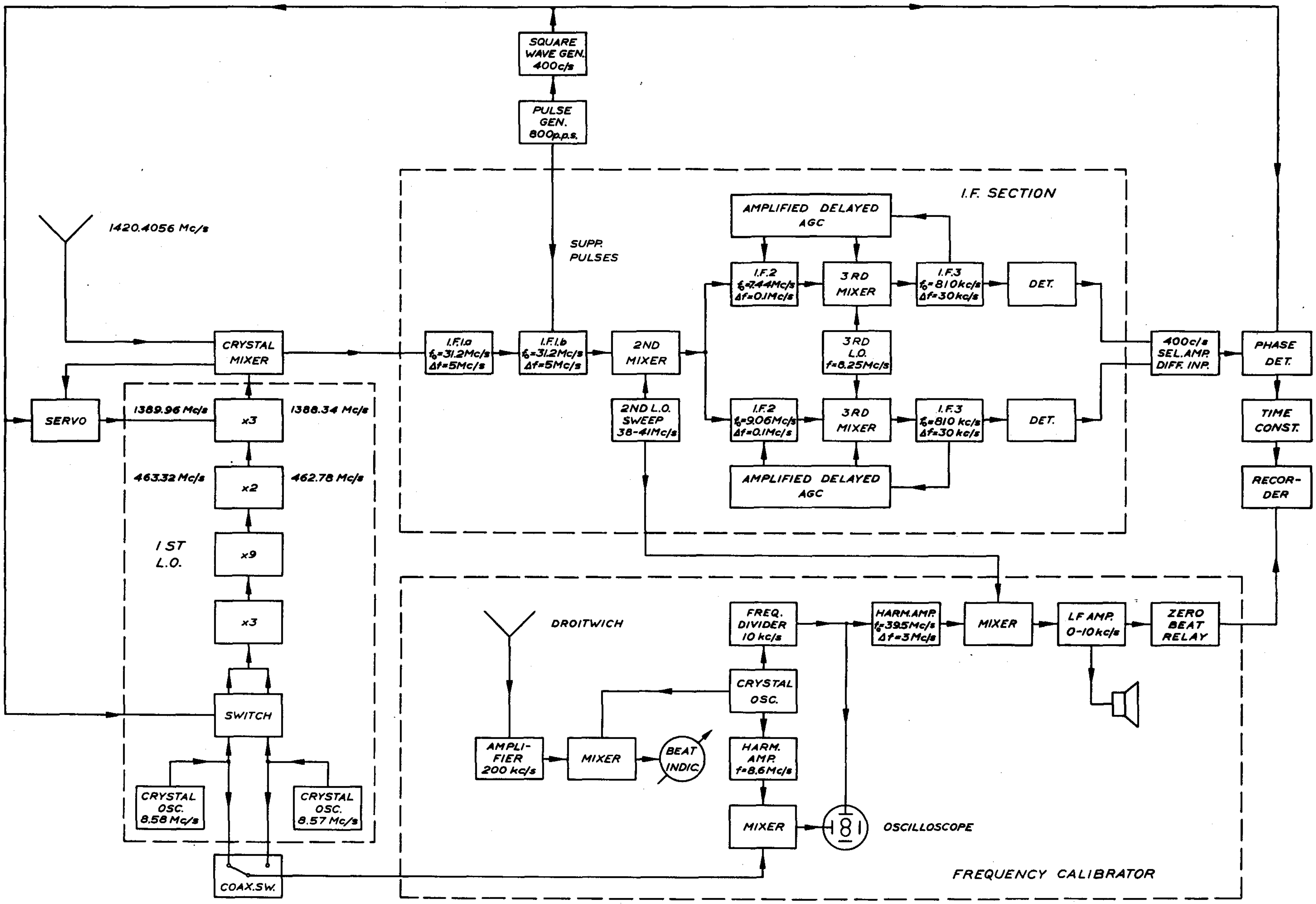

Fig. 4. A schematic diagram of the complete equipment.

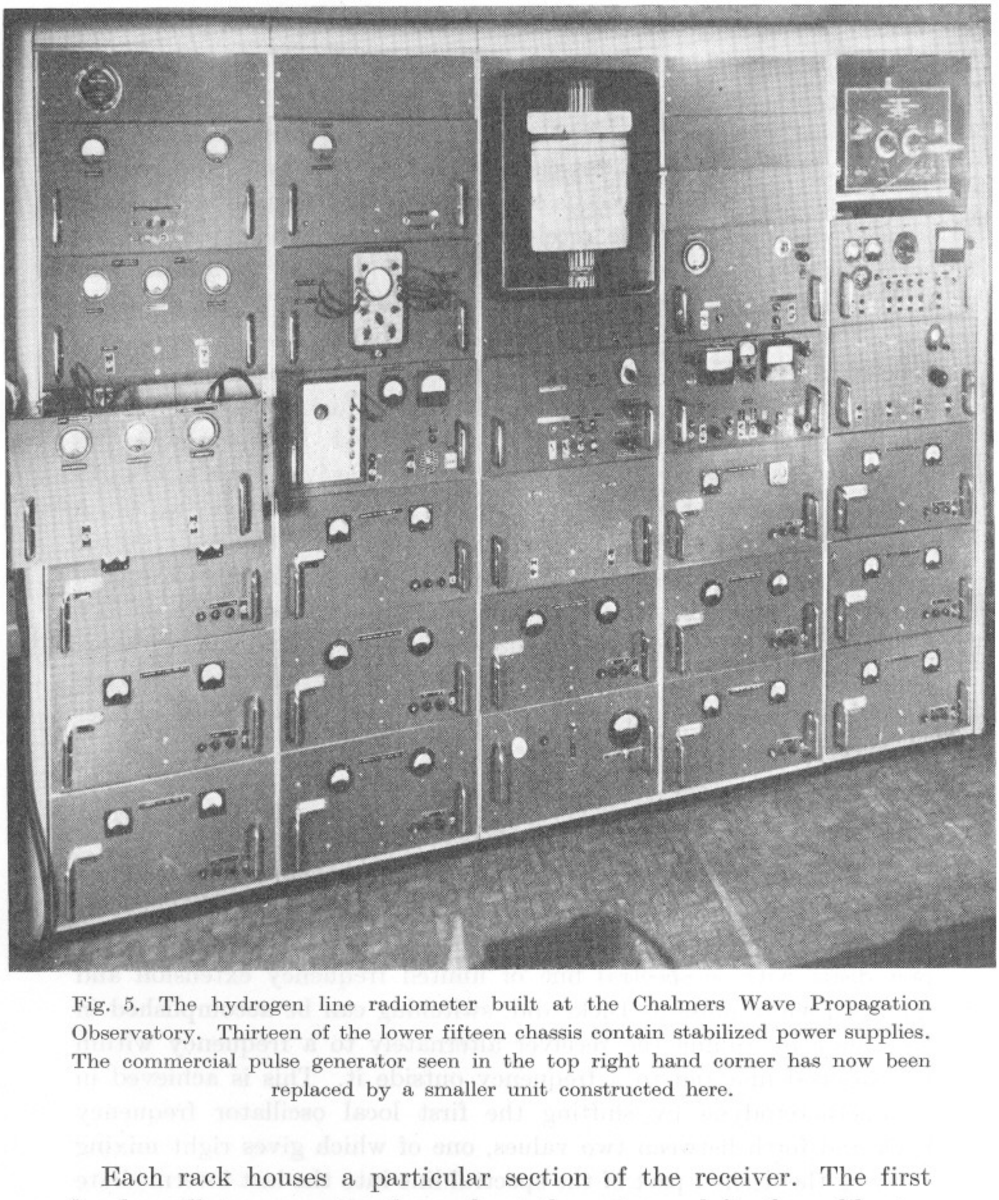

Fig. 5. The hydrogen line radiometer built at the Chalmers Wave Propagation Observatory. Thirteen of the lower fifteen chassis contain stabilized power supplies. The commercial pulse generator seen in the top right hand corner has now been replaced by a smaller unit constructed here.

Each rack houses a particular section of the receiver. The first local oscillator occupies the rack at the extreme left, the calibrator section the next one and so on. Together, they consume about two kilowatts of power which is fed to them from the mains through an a. c. stabilizer which holds variations in the supply voltage down to less than one percent.

The principle of switching

Noise signals received by the antenna are of the same nature as the inherent noise in the receiver and in the case of noise signals from galactic hydrogen many times smaller. The presence of a signal in the input therefore leaves the output from the amplifier qualitatively unchanged and succeeds only in effecting a diminutive increase in the noise level. If the receiver noise in the absence of a signal remained perfectly constant, it would be possible to balance out this amount and to measure the tiny increase caused by the incoming signal. Unfortunately, even in well-designed amplifiers, minor inherent changes in gain and noise factor cause the amplified receiver noise output to vary by amounts far exceeding the increment the weak signal would have caused. One method of overcoming this disadvantage is to switch the input of the receiver back and forth between the signal and a comparison source at a frequency at which system fluctuations have a negligible component. We thereby obtain a noise signal modulated to a degree dependent on the difference between the temperature of the signal and comparison sources. The information is then contained in the weak modulation at the switching frequency. To extract the modulation from the band of noise frequencies, which accompanies it, a phase detector is used at a later stage in the receiver.

Switching in frequency

In the method first used by Dicke (7), the receiver was switched between the antenna and a resistor, the noise output of which at constant temperature constituted the comparison source. When one deals with a spectral line of limited frequency extension and not with white noise as Dicke did, switching can be accomplished in frequency by tuning the receiver alternately to a frequency within the spectral line and to a frequency outside it. This is achieved in a superheterodyne by shifting the first local oscillator frequency back and forth between two values, one of which gives right mixing to bring the desired part of the spectral line into the last intermediate frequency channel and the other to move the entire spectral line out of the channel. When the second local oscillator frequency is changed slowly, the two frequencies seen by the last I. F. channel are also moved and it is thus possible to scan the spectral line and determine its intensity versus frequency distribution. A further advantage of this method is that the background radiation from the galaxy, which varies very slowly with frequency, is balanced out since the radiation is present in both channels in the same amount.

The amount by which the first local oscillator frequency is shifted every switching half cycle must be large enough always to keep one channel outside the line if the profile obtained is to represent the true distribution. Too great a frequency separation, on the other hand, would carry one of the frequencies outside the flat part of the antenna impedance diagram and introduce undesired complications. In our receiver the separation has been chosen to be 1.62 Mc/s and is obtained in the following way.

The local oscillator

The output from two stable crystal oscillators working at 8.57 Mc/s and 8.58 Mc/s is multiplied 162 times to give the two local oscillator frequencies of 1388.34 Mc/s and 1 389.96 Mc/s respectively. An electronic switch inserted between the oscillators and the first of the multiplier circuits lets through only one of the frequencies at a time cutting out the other completely. The electronic switch is triggered by a square wave generator operating at 400 c/s, and consequently admits each frequency for a period of 1/800 of a second before switching over to the other. Of the series of multiplying and amplifying tubes that follow, all but one are in the local oscillator rack. The final tripler is in the antenna box adjacent to the mixer. A lighthouse tube in a coaxial circuit has so far functioned reasonably well as the final tripler but will be replaced very soon. The particular type of lighthouse tube used not only has a short life when operated continuously but also is difficult and expensive to replace since the type has now become obsolete. The construction of the tripler unit itself is not as rigid as it might have been. Slight detuning of the circuits takes place when the antenna is tilted at odd angles. Moreover, the unit was designed before a servo system for the receiver was envisaged and it is now found that the tuning of the coaxial line in its present form is not adaptable to control by a servo motor. A new tripler which is adaptable to servo control and which uses a more modern tube type is being made and with its installation a noticeable improvement in the quality of the recordings is expected1).

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1) The new tripler using a DET 24 tube was installed in June 1959.

The mixer

A commercial broad band mixer containing a IN2IB crystal converts the signals received in the antenna down to an intermediate frequency of around 30 Mc/s. The feeder from the dipole and a length of coaxial cable from the final tripler tank circuit provide the two inputs to the mixer. A few centimetres of cable connect its output end to the input of the cascode stage of the first I. F. amplifier. A capacitive probe feeds the local oscillator power to the crystal. The degree of coupling can be adjusted by a screw on the mixer. Far more power than is actually used in the crystal is needed to make the coupling as loose as possible in order to minimize the loss of antenna signal to the oscillator.

An important condition for the success of the frequency switching method is the equivalence of the two switching positions. A number of crystal parameters such as noise temperature, conversion transconductance and output impedance are dependent on the current through the crystal. A slight change in the value of the crystal current between the two switching positions alters one or more of these parameters sufficiently to modulate the receiver noise in the same manner as a signal from the antenna would have done and cause a spurious deflection on the record. To keep the crystal current in the two switching positions as nearly equal as possible a servo system has been recently constructed.

The servo system

For reasons mentioned in connection with the final tripler the servo system is not yet in actual operation. Some points of interest in its design might, however, be mentioned. A 400 c/s two phase motor is used. One of its windings is fed with a 400 c/s sine wave derived from the switching square wave and shifted 90° in phase. The other winding is connected to the output of a high gain amplifier containing a 400 c/s filter between two of its early stages. The voltage drop over a low resistance in series with the mixer crystal forms the input to the high gain amplifier. The presence of a 400 c/s component in the voltage waveform from the resistor means that more crystal current is present in one switching position than in the other. The amplified output of the component actuates the motor which will retune the last tripler for equality in both positions. A two phase motor is by its nature a phase sensitive device and consequently

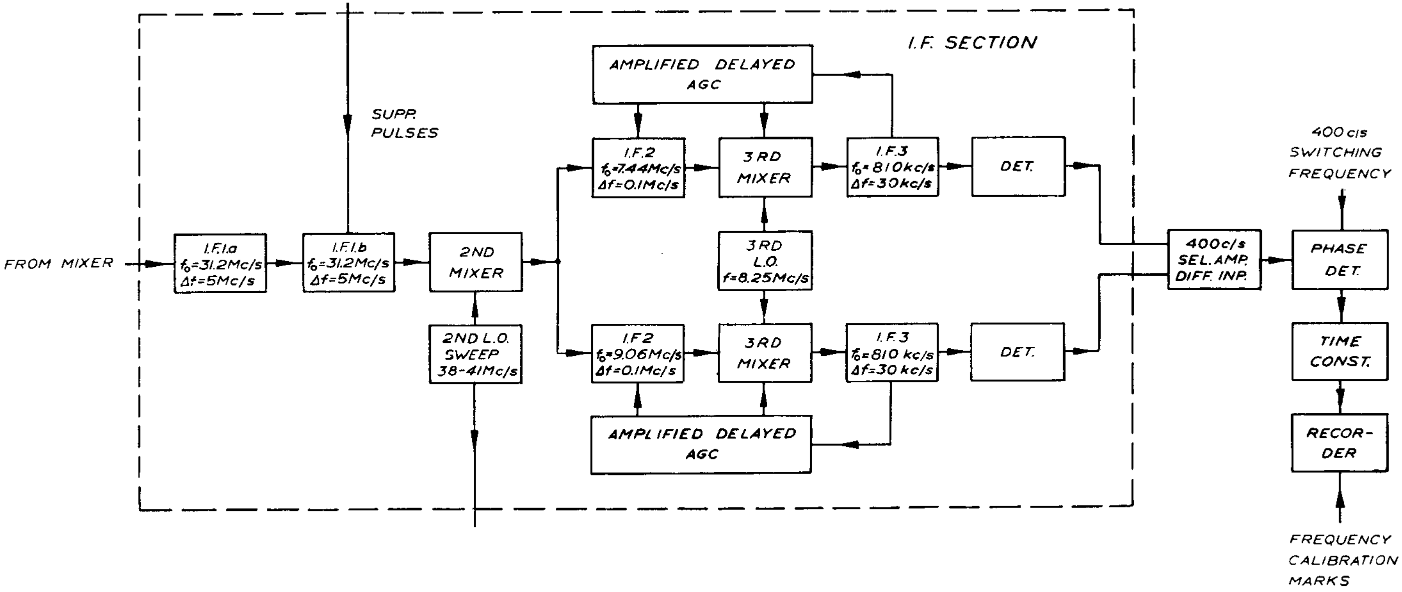


Fig. 6. The intermediate frequency section of the receiver.

the sense in which the retuning has to be done is automatically determined. The results of tests conducted on the servo system in its present state promise a regulation of about one part in a thousand.

The intermediate frequency section

Three stages of frequency conversion precede the final demodulation of the signal. Amplifiers, six in all, follow the mixer stages and provide gain at each of the intermediate frequencies. A block diagram of the I. F. section of the receiver showing the six amplifiers together with the second and third local oscillator and mixer stages is seen in Fig. 6.

The first I. F.

The 30 Mc/s signal from the crystal mixer in the antenna box is amplified successively by two wide band amplifiers. Both are centred at 31.2 Mc/s and have a bandwidth of 5 Mc/s. The amplifiers use conventional 6AK5 tubes. The first amplifier, I. F. 1a in the diagram, which is adjacent to the mixer and has a cascode input stage, has a noise factor of about 1,5. A coaxial cable feeds the output down to I. F. 1 b in the cabin which provides further amplification over the same frequency band.

Transient suppression

Suppressor pulses of about 60 microseconds in duration are also fed to I. F. 1 b from a pulse generator. They suppress the output from the amplifier during the transition periods from one switching position to the other. In the absence of these pulses the transients produced by the switching of the first local oscillator would find their way to the detector along with the signal. Any dissimilarity between the transients obtained in switching from the first to the second position and those obtained in the reverse process would then appear as a 400 c/s component which would be transmitted by the phase detector and be registered on the record.

The pulse generator is synchronized with the square wave switching voltage and the two are accurately phased with respect to each other. To ensure that the suppressor pulses themselves — 800 per second — are all alike and cause no 400 c/s component, the pulse generator is made free running. The pulses, suitably delayed, trigger a bistable multivibrator. The output from the latter, a symmetrical 400 c/s square wave, is used as the switching voltage.

The second I. F.

The signal from the wide band amplifiers goes on to the next frequency conversion stage where it is mixed with the output from a motor driven sweep frequency oscillator. The frequency range, 38 Mc/s to 41 Mc/s, is covered at the rate of about 10 kc/s per minute. The products of the mixing are fed to two narrow band amplifiers centred at 7.44 Mc/s and 9.06 Mc/s respectively. The spacing of the centre frequencies is the same as the spacing of the first L. O. frequencies. Switching between the L. O. frequencies alternately shifts the signal from the part of the spectral line seen by one amplifier by just the right amount to be seen by the other.

Looking back towards the antenna through any one of the two amplifier channels one sees alternately a part of the spectral line as wide as the band width of the amplifier and an equally wide spectral interval outside the line. For one amplifier the spectral interval

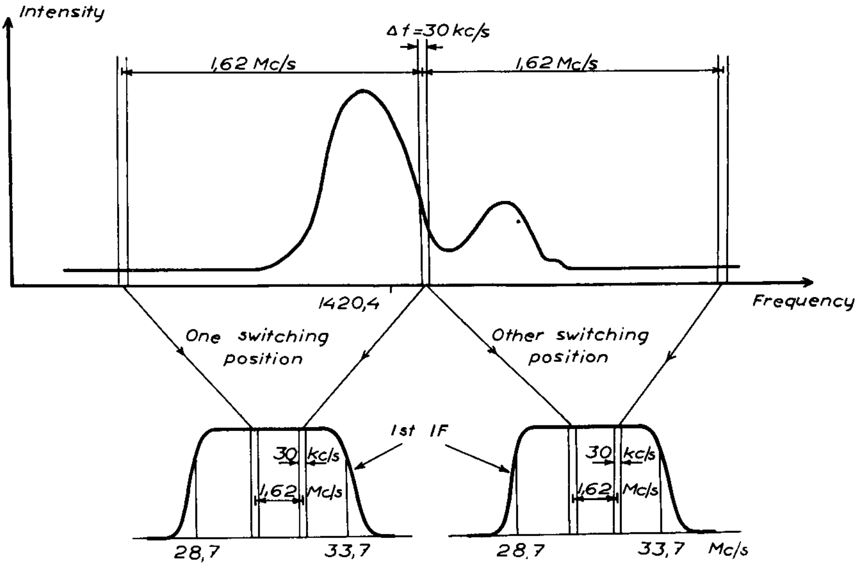


Fig. 7. Diagram illustrating switching principle.

outside the line lies on the high frequency side of the line and for the other amplifier on the low frequency side, Fig. 7. The noise output from each amplifier has a switching frequency modulation component proportional to the intensity of the part of the spectral line seen by both. Sweeping the second L. O. frequency causes different parts of the line to come into view and by this means the entire line can be scanned.

It is possible by phase detecting and recording the output of any one of the two amplifiers to obtain a profile of the distribution of intensity in the spectral line. The advantage of using two channels is that the combination of the outputs of the two amplifiers improves the signal to noise ratio by $\sqrt{2}$. Each one sees the line effectively only half of the time; together they see it the whole time. A further advantage of the two channels is that one automatically compares the spectral line intensity with the arithmetical mean of the background radiation exactly on that part of the spectral line being measured. This mean is correct if the background radiation intensity varies linearly with frequency (it need not be constant as in Fig. 7).

Before combining the outputs from the two amplifiers it is necessary to make sure that the contributions from both are equal. The practical difficulties encountered in trying to make amplifiers centred at different frequencies but having identical band pass curves have led to the inclusion of a third frequency conversion stage.

The third I. F.

Signals from the two amplifiers are mixed with the output of a stable crystal oscillator centred half way between their centre frequencies. The oscillator has a frequency of 8.25 Mc/s and one of the two mixing products obtained in each case is 810 kc/s. Two identical amplifiers, I. F. 3, each 30 kc/s wide and centred at 810 kc/s follow the two mixers and deliver equal outputs. The bandwidth of these last two amplifiers determines the bandwidth of the receiver. To make sure that the shape of their band pass curves is not affected by the preceeding amplifiers I. F. 2, the bandwidth of the latter is made 100 kc/s. A. G. C. circuits keep the average output voltage from the two 810 kc/s amplifiers equal and constant. A detector follows each amplifier and their outputs are combined in the next unit.

The low frequency section

The demodulated signals from the two detectors contain, besides a band of noise frequencies, a. c. components corresponding to the switching frequency and to its odd harmonics. The noise frequencies from the two detectors are uncorrelated, whereas the a. c. components are equal and opposed in phase. All the a. c. components contain information concerning the intensity of the radiation in the observed spectral interval. A phase detector followed by a long time constant can, theoretically, collect the contributions from all the components and convert the total contribution into a d. c. voltage which can deflect a recorder pen. The amplitude of the components must be constant, however, if the d. c. voltage is truly to represent their combined contribution. Changing the frequency of the second L. O. to scan the line and to obtain a profile varies the amplitudes of the components which spreads out the information in narrow bands around the a. c. components. To prevent overloading from too much noise, only those frequencies in the neighbourhood of the switching frequency are allowed to reach the phase detector. Since the band around the fundamental of the switching frequency contains practically 90 % of the information, the exclusion of the higher frequencies does not greatly reduce the sensitivity of the receiver.

The selective amplifier

A selective amplifier with differential inputs combines the output signals from the two detectors. A twin-T filter between two of its stages restricts the pass band of the amplifier to about 50 c/s around the centre frequency of 400 c/s. Constancy of the gain of the amplifier is of prime importance if the line profiles are to be correctly interpreted in terms of the temperature of the radiation. Frequent checks of the gain are made with a calibrated 400 c/s square wave.

The phase detector and the time constant

A combination of a phase detector and a time constant converts the signal from the selective amplifier into a slowly varying d. c. voltage. The phase detector uses eight diodes and is a shunt connected full wave type. The same square wave that switches the first L. O. also switches the phase detector. The d. c. voltage from the phase detector is proportional to the amplitude of the 400 c/s component in the signal, and causes a corresponding deflection of the recorder pen. The cut-off frequency of the low pass filter following the phase detector is made just high enough to admit the slow variation caused by the scanning of the profile. Slower scanning would permit a longer time constant and a diminution of the unwanted noise which reaches the recorder, but would increase the time taken for measurements. Even if unlimited time were available, receiver stability would limit the maximum usable time constant. In the present receiver 80 seconds has been chosen as a reasonable compromise.

Calibration

Frequency calibration

In order to determine the frequency of a signal received by a simple superheterodyne, one must accurately measure the local oscillator frequency and the pass band of the I. F. amplifier. In our receiver which is a triple superheterodyne where the first local oscillator is switched between two values and where the frequency of the second local oscillator is varied during observation, more frequencies have to be measured in order to determine the signal frequency. A considerable amount of circuitry has been built into the receiver to provide a continuous and accurate check on the various frequencies involved. Fig. 8 shows a simplified diagram of the calibration equipment.

A temperature controlled crystal oscillator working at 100 kc/s is used as a local secondary standard. Although the oscillator by itself has a stability of better than 1 in 10^6, the second harmonic is continuously checked against the 200 kc/s standard frequency transmitted by the B. B. C. from Droitwich, England. Any difference in the frequencies appears as a slowly varying beat note which is detected on the meter following the mixer and corrected for by adjusting the crystal oscillator.

The oscillator triggers a pulse generating unit (not shown separately in the diagram) which generates 100 k pulses per second, rich in harmonics. A narrow band harmonic amplifier centred at 8.6 Mc/s picks out the 86th harmonic of the pulses and feeds it to a mixer where the harmonic is combined with a signal from either one or the other of the two first L. O. crystal oscillators. The mixing product

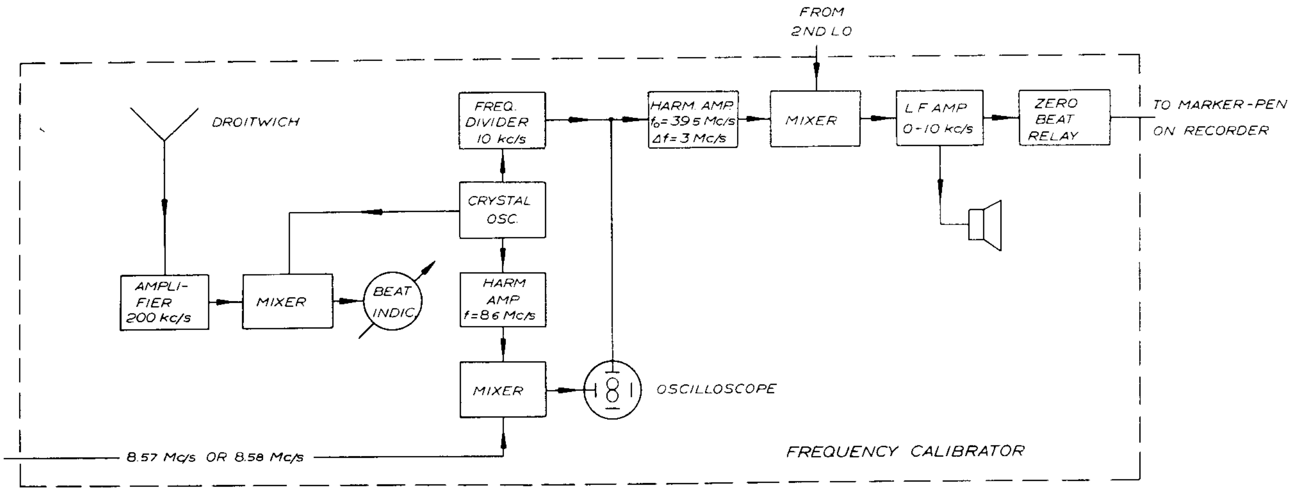


Fig. 8. A simplified diagram of the calibration equipment.

of either 20 kc/s or 30 kc/s is fed to the X plates of an oscilloscope, the Y plates of which receive a 10 kc/s sine wave derived from the 100 kc/s oscillator. A Lissajou figure is then obtained which is stationary if all the frequencies correspond to their nominal values.

The second L. O. varies continuously in frequency and it therefore requires a different method of calibration. A broad band harmonic amplifier fed by the output from the 10 kc/s divider unit generates a spectrum of frequencies spaced 10 kc/s from each other and covering the same range as the second L. O. The spectrum is mixed with the varying frequency from the L. O. and the output of the mixer is fed successively to an audio amplifier, a low pass filter and a relay circuit. Each time the second L. O. frequency passes a 10 kc/s harmonic the relay is closed for a short interval. A second pen on the recorder connected to the relay puts a mark on the top of the record when the relay is closed. A loudspeaker connected to the L. F. amplifier makes the beat notes from the mixer audible. The 100 kc/s pulses go through the divider unit and cause a distinct increase in the loudness of the beat note each time a 100 kc/s multiple is passed. As the accuracy of graduation of the second L. O. scale is better than 100 kc/s, it is possible in this manner to identify the frequencies corresponding to all the marks on the record.

Variations in the frequency of the third L. O. affect the accuracy of the measurement less than in the case of the other two L. O. Nevertheless the third L. O. is periodically checked against a commercial frequency standard in the laboratory and has been found to maintain the needed stability. A calibrated signal generator which is part of the same commercial frequency standard is used once a week to measure the centre frequency and the width of the pass bands of the 810 kc/s amplifiers. Drifts are corrected for by necessary adjustments of the tuned circuits in the amplifiers.

Intensity calibration

No direct method is available for the absolute calibration of the receiver. The usual method is to calibrate the sensitivity indirectly in terms of the noise factor and other receiver constants which can be measured. Measurements made with the antenna pointed towards the earth and then towards a cold part of the sky give a noise factor of 4.5 for reception in both channels. It is assumed here that the earth radiates as a black body and that the sensitivity of the receiver

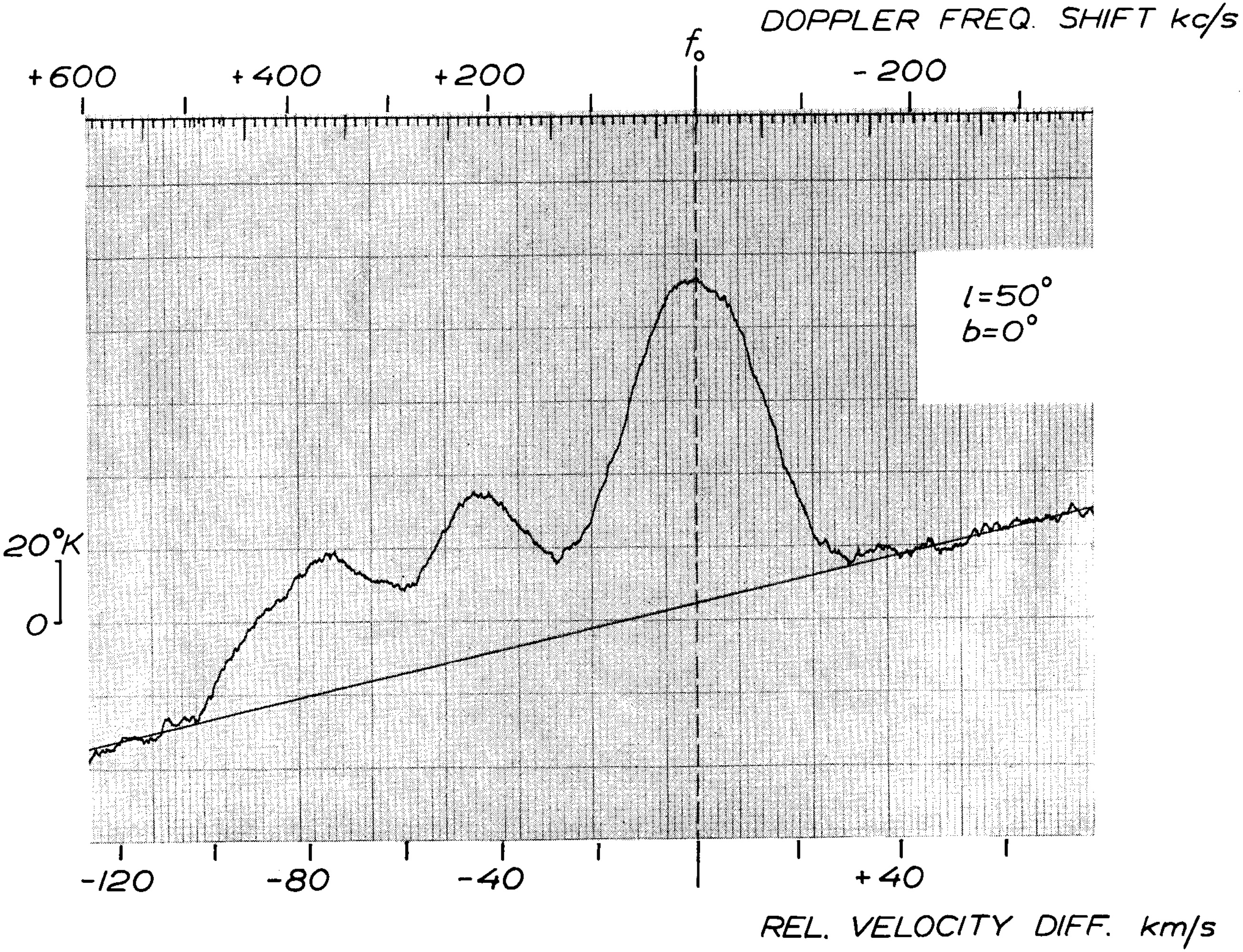


Fig. 9. Sample of hydrogen line profile taken at l = 50°, $b = 0°$. The main peak of this profile is used as the standard reference of intensity.

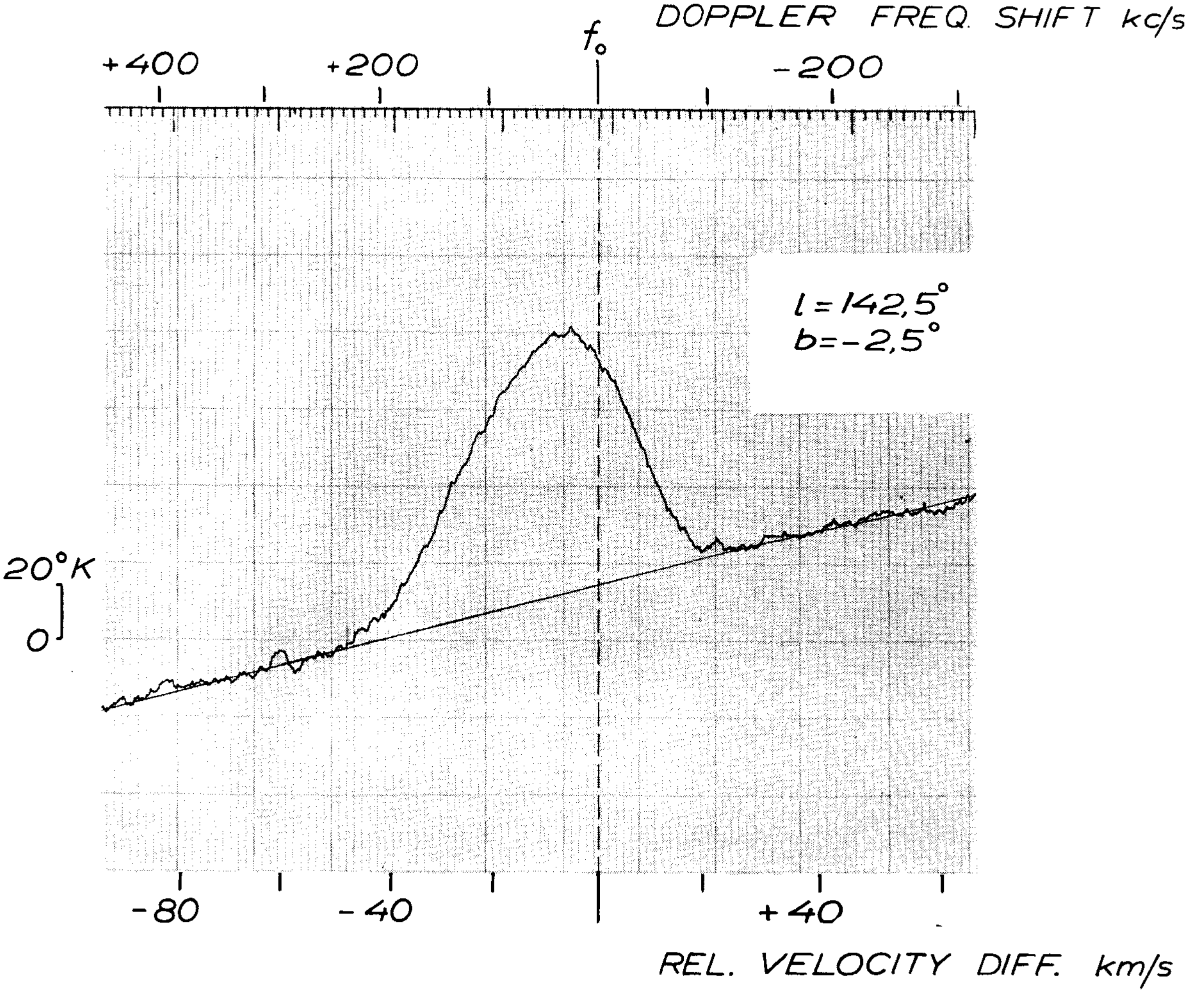
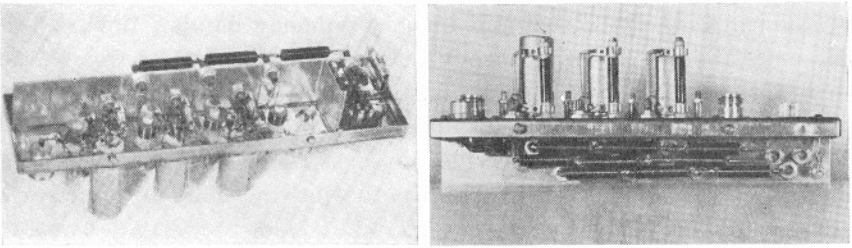
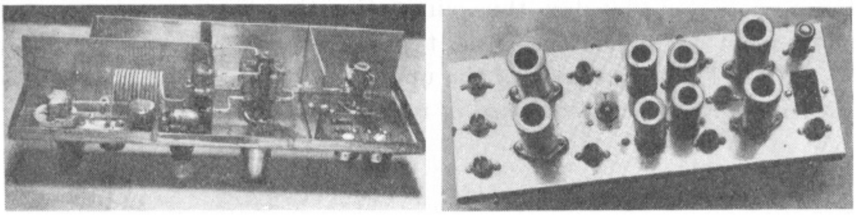


Fig. 10. Sample of hydrogen line profile at $l = 142.5°$ near the anticentre direction of our galaxy, but somewhat off the galactic plane, at $b = -2.5°$.



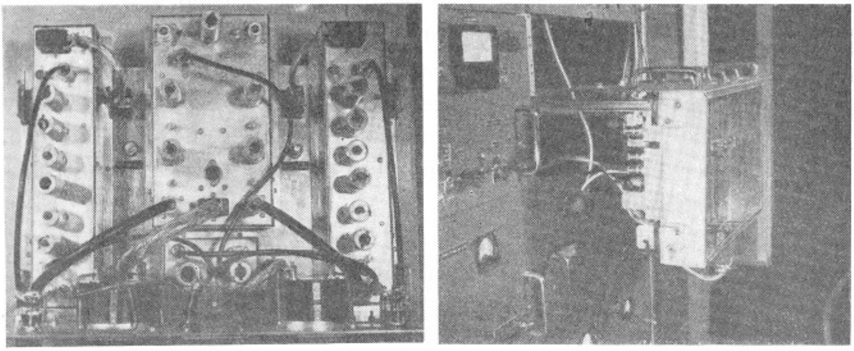
(a) (b)

Fig. 11. (a) The inner side of the lid containing one of the 30 Mc/s amplifiers. (b) The same unit viewed from the side showing the R. F. chokes in the power leads.



(a) (b)

Fig. 12. (a) The 8.58 Mc/s crystal oscillator unit. (b) The phase detector.



(a) (b)

Fig. 13. (a) Top view of the chassis containing the two channel system. The strips at the sides are the two 810 kc/s amplifiers. (b) One of the chassis drawn out and tilted on its telescopic supports.

is equal in both the signal and image frequency bands. With 4.5 as the noise factor for simultaneous reception in the two channels and with the appropriate receiver constants, the theoretical sensitivity calculated according to the formula given by MULLER (6) is 1.5° K. This temperature is the effective value of the noise fluctuations to be expected on the record. The fluctuations actually obtained are estimated at 2° K.

Minor variations of the noise factor of the receiver take place from day to day. The action of the A. G. C. circuits, which keep the average output noise constant, causes these variations to appear as changes in the amplification of the receiver. A standard profile from a fixed point in the sky is taken every day. All the profiles taken on any particular day are reduced to the same scale as the standard profile taken on that day, thus eliminating the effect of the apparent changes in amplification. Two typical profiles are seen in Figs. 9 and 10. The major peak of the upper one is assumed to be 100° K and is adopted as the standard of reference.

* * *

The entire equipment including all the power supplies was constructed at the laboratory by members of the staff. Apprentices did part of the wiring. Students in the final year of the Electronics course designed and built a few units as part of their requirements for graduation. In the construction of the receiver certain principles have been adhered to, e. g. the use of boxes for units. A number of units have been built in duplicate so that replacements can easily be made without bringing the equipment to a standstill during failure. All the upper chassis carrying the units have telescopic supports which allow tilting of the chassis with all cables connected. Figs. 11, 12 and 13 show some of the details of construction. The stabilized power supplies, which are identical, conform to a standard adopted at the laboratory.

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