EQUIPMENT FOR THE OBSERVATION OF SOLAR RADIO EMISSION AT 9400, 3750, 2000 AND 1000 Mc/s

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Summary–

Equipment for the observation of solar radio emission at 9400, 3750 and 1000 Mc/s are completed. A radiometer for use at 2000 Mc/s is now in construction. To facilitate intercomparison, all the paraboloids are made in similar figures. Each has a similar feed-antenna of a circular waveguide connected to a turnstile circuit for separating polarizations. Equipment for use at 1000 (also at 2000) Mc/s has a device to indicate directly the percentage polarization of outstanding occurrences. Static modulators are used for 9400 and 3750 Mc/s radiometers.

I. Introduction.

It is well known that the solar radio emission originates in the solar atmosphere which surrounds the optical sun. At high-frequency band, only the radiation from upper corona can go out of the sun, so that the observations at these frequencies are helpful to study the circumstances of this layer. In the same way, the observation at a higher frequency is useful for investigating the lower atmosphere of the sun. Thus, for a complete survey of the solar atmosphere, it is essential to observe the frequency spectrum of solar radio emission. Though many observers are continuously observing the sun at various frequencies, it is far from completing a satisfactory frequency spectrum, especially at microwave frequencies. To fill the gap of observations to some extent, we have intended to construct a series of radio telescopes for use at 9400, 3750, 2000 and 1000 Mc/s. Among these frequencies, 3750 Mc/s is the frequency at which we have observed the sun for more than five years.[1] The equipment, however, has been renewed and improved recently. On the other hand, a radiometer for use at 2000 Mc/s is now in construction.

Photo. 1. A group of radio telescopes.

Undoubtedly, the most ambiguous factor in calculating absolute flux density is the antenna gain. Though the absolute gain of each antenna is hard to measure or calculate, the relative value should be estimated as accurately as possible. For this requirement, all the paraboloids are made in similar figures having the same aparture angle of 160 degrees.

They also have similar feed antennas, each an end of H_{11}- mode circular waveguide. A turnstile circuit is connected to the circular waveguide and it is possible to receive E-W and N-S or right- and left-hand polarizations simultaneously. By utilizing this characteristic, the equipment for use at 1000 Mc/s (also 2000 Mc/s) has a device to indicate the percentage polarization of outstanding occurrences directly on the recording paper. The equipment for use at 9400 and 3750 Mc/s, can yet receive one of the four polarizations by selecting switches, but they will have devices to record percentage polarization dynamically in the near future.

II. 9400 Mc/s Equipment

1. General Description

A block diagram of the 9400 Mc/s radiometer is shown in Fig. 1. General principles are similar to those used for 3750 Mc/s radiometer previously described.[2][3] However, a practical circuit construction is somewhat different and the 9400 Mc/s equipment has the following features.

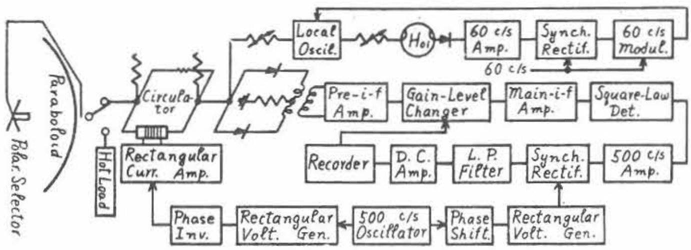

Fig. 1. A block diagram of the 9400 Mc/s radiometer.

(1) To be able to select one of the E-W, N-S, right-hand or left-hand polarization.

(2) A static modulator or circulator is used for Dicke-type modulation.

(3) Owing to the nonreciprocal characteristic of the circulator, the receiver noise is isolated from input impedance, so that the spurious error (or substitution error[3]) is negligible.

(4) According to a high modulation frequency (500c/s), the amplifier is free from power-line induction and, probably, the gain variation noise is decreased.

(5) As the frequency of a klystron 2K25 is instable, a simple AFC is applied.

2. Antenna

A photograph of the antenna assembly for use at 9400 Mc/s is shown in Photo. 2. A polar-mount paraboloid, 1.2 m in diameter, is controlled by a common shaft so as to follow the sun. Like any of the other antennas, the aparture angle is 160 degrees. A matched end of a circular waveguide of H_{11} mode is placed very close to the focus and the waveguide is connected directly to a turnstile circuit for selecting polarizations. A rectangular waveguide connects the turnstile circuit to the receiver mounted in the box behind the paraboloid.

According to the measurement using the sun as a signal source, the

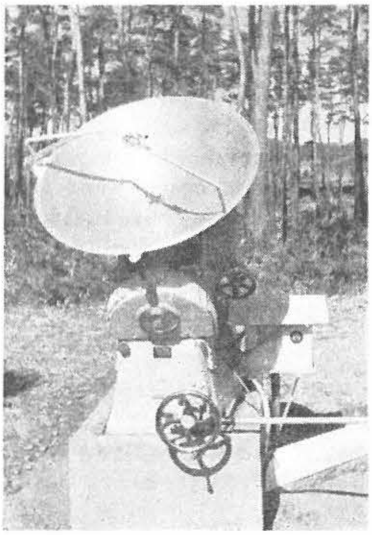

Photo. 2. A 9400 Mc/s radio telescope.

directive pattern is circularly symmetrical and has the half-power width of 2.0 degrees. The aerial gain is 8870, which is determined as follows. First of all, we take the gain of 1.5 m paraboloid for use at 3750 Mc/s as a standard. It was determined by the comparison with the calculated gain of a horn antenna. The value obtained is 1863. Though all the paraboloids are of similar figures, each aerial assembly is not strictly similar in shape, so that the rate of disturbances caused by feed systems are not all the same. Consequently, the intercomparison of the gain should be made under the imaginary conditions that the disturbances are eliminated. As the second step, therefore, the rate of disturbances must be estimated. The estimation was made by placing similar disturbances in front of the paraboloid. The results are 74.8% and 88.6% as for the antennas used at 3750 Mc/s and 9400 Mc/s respectively. The idealized gain of the 1.5 m paraboloid is then 1863/0.748=2490. Then, the idealized gain of the 1.2 m paraboloid can be calculated accordiog to the simple relation among gain, size and frequency, and the value $2490\ (1.2/1.5)^2\ (9400/3750)^2 = 10014$ is obtained. By multiplying the rate of disturbances, 88.6%, the gain of the 9400 Mc/s paraoloid is esimated at 8870.

3. Polarization Selector

A turnstile[4] circuit as shown in Fig. 2 is used for selecting polarizations. The circuit is matched to a line by placing a post at the centre of the waveguide crossing. The VSWR is less than 1.05 within the necessary frecuency range of ± 65 Mc/s.

In Fig. 3, assume that the arms A, B, C and D are of rectangular waveguide and that there are reference planes distant "a" apart from the centre. When an incident wave enters the circuit from the reference plane of arm A, a part of the wave passes the reference planes of arms C and D in the same phase. The planes marked 1, 2, 3, 4, and 1', 2', 3', 4', are $\lambda g/8$ apart from each other. when the waveguide is short-circuited at

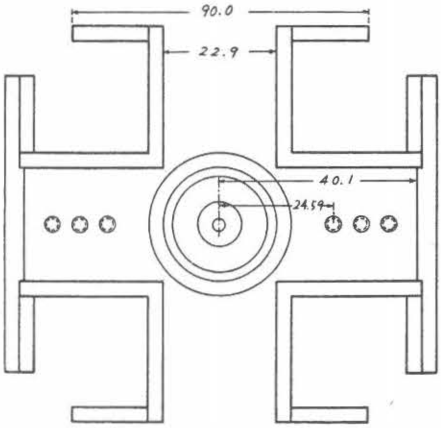

Fig. 2. A turnstile circuit with a feed antenna for use at 9400 Mc/s.

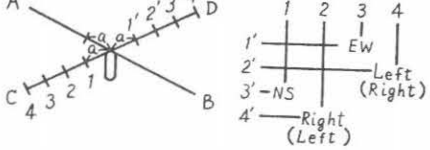

Fig. 3. Shorting planes of a polarization selector.

two planes in arms C and D with the combination shown in Fig. 3, the corresponding polarization can be received from the arm A. A remarkable feature of this circuit is to be able to receive two polarizations at a time and for 1000 and 2000 Mc/s radiometer, this characteristic is effectively used. At 9400 Mc/s. however, only one polarization can be received at a time by inserting tuned stubs in the corresponding holes.

It must be noted here that the right- or left-hand polarization reverses when then the signal is reflected by a paraboloid. The content of the inverse polarization is less 1 % in power and it is practically permissible to receive two bands of signals on either side of the local-oscillator frequency.

4. Modulator

Instead of the mechanical modulator developed by Dicke, a static or electric modulator (3) (5) is used. There are several types of switch circuit using ferrite which are called circulator. Two types of this circuit are

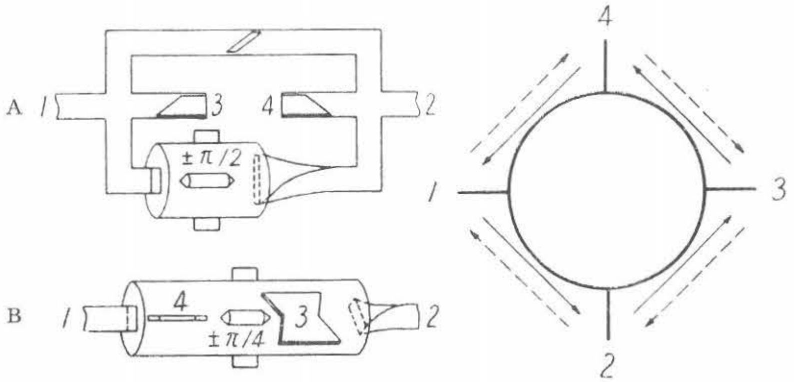

Fig. 4. Circulators.

shown in Fig. 4, in which type A is used for 9400 Mc/s radiometer and B for 3750 Mc/s.

When a rectangular current flows through the coil so that the electric vector rotates just as much as $\pm\pi/2$ (type A) or $\pm\pi/4$ (type B), microwave signals entering from the arms 1 and 3 go out alternately from the arm 2. Accordingly, if the arm 1 is connected to the antenna and arm 3 to a reference resistor, a conventional modulation can be made. Furthermore, as the output impedance of the arm 2 is always matched to the receiver having no relation to the impedance of the arm 1, a spurious error caused by substitution is negligible. Type A used for 9400 Mc/s receiver requires comparatively large ampare-turns as compared with type B, but it has the advantage of having a separate reference arm. The wall of the circular waveguide containing a ferrite is partly insulated so that it does not act as a secondary short ring of the coil in which 500 c/s rectangular current flows. The inductance and resistance of the coil is 1.3 H and 1.7 KΩ respectively. The required current $\pm$ 47 mA is generated by a push-pull circuit as shown in Fig. 5. As L_2 is chosen so that $L_2 \gg L_1$, the time constant is of the order of 2×10^{-5} and the percentage transit time is only a few percent. A 10% current variation has no serious effect

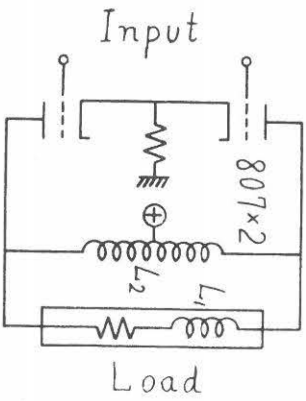

Fig. 5. A rectangular-wave current amplifier.

on the record, since the ferrite is almost saturated at $\pm\pi/2$. In a waveguide opposite to the Faraday plate, a balancing attenuator is inserted and the total insertion loss of the circulator is 0.8 db.

5. AFC

As a high accuracy of the local-oscillator frequency is not required, a simple type of AFC is applied to the 2K25 klystron. A simplified circuit diagram is shown in Fig. 6. A fraction of 60 c/s power-line voltage, 0.04 V, is superimposed on the reflector and a part of the output is conncted to a H_{01} cylindrical resonator. As the 60 c/s component of the detector output is zero at the centre frequency and the phase reverses on each side of it, an AFC loop is completed by feeding the output of a synchronous rectifier back to the reflector. The loop gain is about 100 and the local-oscillator frequency is stabilized within a few hundred kilocycles.

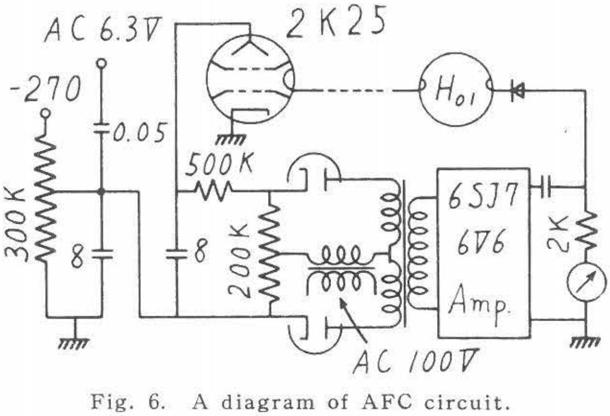

Fig. 6. A diagram of AFC circuit.

6. Other Circuit Elements

A hot load(3) for daily calibration is almost the same as has been used for 4000 Mc/s radiometer except that a choke flange is used for thermal isolation. The temperature is kept at 150° C.

For an intermediate-frequency amplifier, a stabilized circuit developed by N. W. Broten(6) is used and the frequency band is 60 ± 5 Mc/s. A square-law detector is of the simplest type using a 6AQ5 tube operating at a curved portion of the characteristic curve.

An automatic gain-level changer is a set of snap-switch attenuators driven by an induction motor operated each time when a recorder pen is thrown off-scale.

7. Over-All Characteristics

The noise figure of the receiver is 13 db for two bands reception on both sides of the local-oscillator frequency and the r-m-s output fluctuation (2) (7) is about 4 °K when the time constant is set at 0.5 sec.

When the antenna is directed toward the zenith on a fine day, the equivalent antenna temperature is 12 °K. The equivalent antenna temperature on January 1, 1957 is 927 °K which corresponds to the flux 357×10^{-22} W M^{-2} $(c/s)^{-1}$.

The record does not fluctuate even when a shorting plunger is inserted into the antenna circuit and moved slowly along the waveguide.

III. 3750 Mc/s Equipment

1. General Description

The observation at this frequency has been made here every day for more than five years since 1951. In the middle of 1956, however, the whole equipment was replaced by a newly designed instrument. The circuit construction is simiar to that of the 9400 Mc/s radiometer except for the following features.

(1) One of the four polarizations can be selected by a switch placed at a remote place on a rack.

(2) A different type of modulator is used and the modulation frequency is lowered to 125 c/s.

(3) An AFC circuit is omitted, because the frequency of an outside-cavity klystron 6GF1 is sufficiently stable when the cavity is connected directly to a waveguide.

(4) No hot load is prepared for daily calibrations, since an equivalent sky temperature can be used as a standard at this frequency.

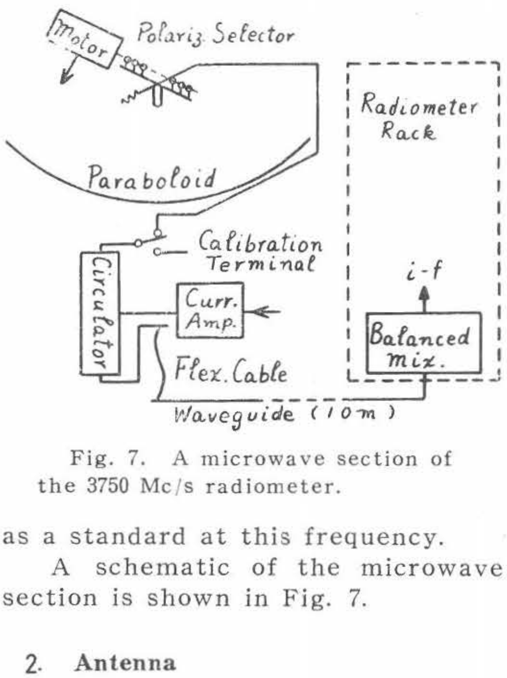

Fig. 7. A microwave section of the 3750 Mc/s radiometer.

A schematic of the microwave section is shown in Fig. 7.

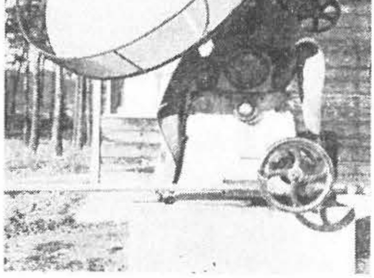

Photo. 3. A 3750 Mc/s radio telescope.

2. Antenna

A photograph of the antenna for use at 3750 Mc/s is shown in Photo. 3. The paraboloid, 1.5m in diameter, has a cylindrical shield of wire-netting, 20cm high. It reduces interference caused by reflected waves from the earth and it is also effective to avoid thermal radiation from the earth when the antenna is directed toward the zenith for calibration.

The calculated gain of the antenna is 1863. It was calculated from the records for about a month simultaneously obtained by old and new equipment. The gain of the old 2.5 m paraboloid was measured formerly by comparing it with the calculated gain of a horn antenna. [2]

3. Polarization Selector

A turnstile circuit connected to the circular waveguide has a similar form to that of the 9400 Mc/s radiometer except that the mechanical construction is somewhat different. A set of switching stubs are prepared at each hole and they are driven by a motor controlled at a remote place on a rack.

4. Modulator

A circulator type B, shown in Fig .5, is used at this frequency. As the reference resistor is placed inside of the circuit, it is compact and easy to construct at this comparatively low frequency. The inductance of the coil is about 4H and the necessary current is about 45 mA. The modulation frequency is lowered to 125 c/s so that the percentage transit time does not exceed 10 %. The insertion loss is about 1.1 db.

5. Over-All Characteristics

The noise figure of the receiver is 11.5 db for two band reception on both sides of the local-oscillator frequency. The r-m-s output fluctuation is about 2.8 °K at a time constant of 0.5 sec. When the antenna is directed toward the zenith, the equivalent antenna temperature is 3 °K. The equivalent antenna temperature on January 1, 1957 is 846 °K, which corresponds to the flux 246×10^{-22} W M^{-2} $(c/s)^{-1}$. The isolation of the receiver noise from input impedance is practically perfect.

IV. 2000 Mc/s Equipment

A paraboloid for use at 2000 Mc/s is shown in Photo. 4. It is a remodelled figure of the former 2.5 m paraboloid for use at 3750 Mc/s [2]. The former wire-netting paraboloid was replaced by a solid one, 2.2 m in diameter. Like any of the other paraboloids, the aparture angle is 160 degrees. The equipment is to be completed in May 1957. The circuit construction is to be almost the same as is used for 1000 Mc/s equipment.

Photo. 4. A 2000 Mc/s radio telescope.

V. 1000 Mc/s Equipment

1. General Description

A remarkable feature of this equipment is that the percentage polarization of outstanding occurrences can be recorded directly. Ass hown in Fig. 8, the right- and left-hand polarization is led to the receiver simultaneously, and they are switched alternately

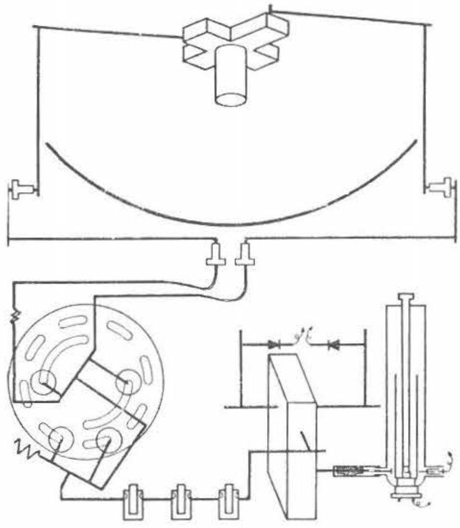

Fig. 8. A microwave section of the 1000 Mc/s radiometer.

at a speed of 40 c/s. Then the signal is led into another high-speed switch (160 c/s), which alternately connects the receiver to the antenna and to a resistor kept at room temperature. After passing through an image-rejection filter, the doubly modulated signal enters a balanced mixer and then is amplified at a frequency of 60 Mc/s. At the output of a low-frequency amplifier, the signal is led into two circuits (Fig. 12). One is a conventional circuit for recording average flux density and the other is a newly designed circuit for indicating percentage polarization. In the first place, 40 and 160 c/s signals corresponding to quiet sun level are all cancelled by adding the output of zero adjustors. The reading of the 40-c/s zero adjustor is used for calculating percentage polarization of the S-component. The remaining signals correspond to the sum and difference of right- and left-hand polarizations of an 'outstanding occurrence' and they are divided by means of an electronic computor. Thus a dynamic record of the percentage polarization of a burst or outburst is obtained.

2. Antenna

A photograph of the antenna assembly for use at 1000 Mc/s is shown in Photo. 5. A paraboloid, 3m in diameter, has the aparture angle of 160 degrees. The height of a cylindrical shield is 40cm. The antenna assembly can be rotated 360 degrees around the polar axis at a fixed declination- angle and it is possible to place the paraboloid just behind the mount.

The primary feed antenna and the turnstile circuit are similar to those used for 9400 or 3750 Mc/s equipment. There are no switches, however, for selecting polarizations and right- and left-hand polarizations are separately led to the receiver through rigid coaxial lines.

The antenna gain without disturbances is 708, which is calculated according to the same method as is used at 9400 Mc/s. By multiplying the rate of disturbances estimated at 85.7 %, the antenna gain 607 is obtained.

Photo. 5. A 1000 Mc/s radio telescope.

3. Transmission Lines

Two coaxial lines connect the turnstile circuit to the receiver. The greater part of the line is composed of rigid 50 Ω coaxial line insulated by polystyrene beads at intervals of about 37.5 cm. The inner and outer diameters are 9.0 and 20.6 cm respectively. On the declination axis, rotary joints as shown in Fig. 9 are inserted. On the polar axis, however,

Fig. 9. A. rotary joint.

there is no space to place these rotary joints in series, so that they are shifted aside and connected to the receiver with flexible cables, about 1 m in length. The total insertion loss is about 1.2 db. The loss of the two lines must be equalized by a loss balancer.

4. Duplex Switch

A duplex switch for use at 1000 Mc/s is shown in Photo. 6. It is a combination of two switching sections of the same type; one is a low-speed switch for connecting a line to the right- and left-hand polarization arms, and the other is a high-speed switch which alternately connects the receiver to the output of the low-speed switch and to a resistor kept at room temperature.

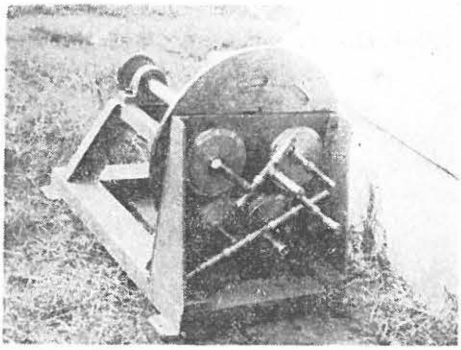

Photo. 6. A duplex switch for use at 1000 Mc/s. (just before installation)

The fundamental principle of the switch is as follows. In Fig. 10, assume that A and B are the arms to be switched and C is the output arm. When the points X and Y are both short-circuited, the points Q, R and P are equivalently open- and short-circuited respectively. In these circumstances, the arm B is connected to the arm C. When the points X and Y are both open-circuited, on the contrary, the points P, R, and Q are open- and short-circuited, so that the arm A is connected to the arm C. At an instant of transition, assume that the admittance at the point X or Y is jx. The admittances at points P and Q are 1 + jx and 1 + 1/jx respectively, so that the output admittance of the arm C is 1/(1+jx) + 1/(1/+1/jx) = 1. It means that the output is always matched to the line.

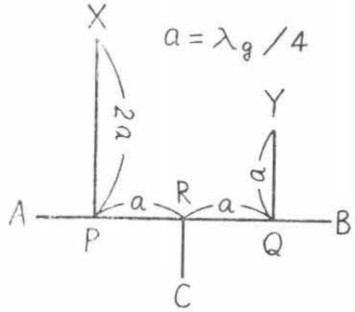

Fig. 10. Principle of a microwave switch.

The actual structure of the points X and Y in Fig. 10 is shown in Fig. 11. The end of the outer conductor forms a quarter-wave choke for preventing leakage radiation, When a surface of the rotating plate approaches the inner conductor, the coaxial line is short-circuited by series tuning of an inductance made by a folded section and a capacitance

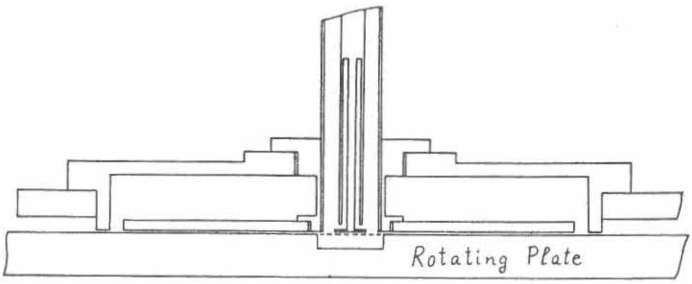

Fig. 11. Short-open end of a coaxial line.

between two plates. When a hollow section of the rotating plate comes at the end of the line, the condition of series tuning is broken and the circuit becomes open. In practice, a precise adjustment is necessary and the surface of the rotating plate must have an accuracy of ± 0.05mm. The rotating plate, 34 cm in diameter, is driven by an induction motor at a speed of about 20r-p-s so that the switching frequencies are about 40 and 160 c/s.

5. Other Microwave Components

The output signal of the switch is led to a balanced mixer after passing through an image-rejection filter. A photograph of a part of these components is shown in Photo. 7. The filter is a Fano-Lawson type band-pass filter composed of three semi-coaxial resonators; the passband is 1000 $\pm$ 10 Mc/s and the insertion loss is 0.3 db. A hybrid circuit for use at 1000 Mc/s is a modified magic tee. The E-arm of the circuit is a rectangular waveguide connected to a local oscillator, while the other arms are of coaxial lines. A pair of crystal IN21 mixers are connected to the side arms, one $\lambda g/4$ longer than the other. The local oscillator is of reentrant-cavity type using 2C40 light-house tube and no AFC circuit is applied. A 30db attenuator is inserted between the oscillator and the mixer, andthe local-oscillator power is controlled by adjusting the depth of coupling loop in the oscillator cavity.

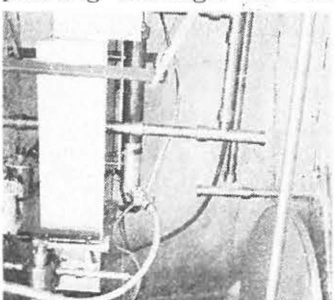

Photo. 7. Inside of the 3-mparaboloid mount.

6. Sum and Difference of Two Polarizations

A block diagram of electronic circuits is shown in Fig. 12 together with diagramic representation of the operation. A signal branched from

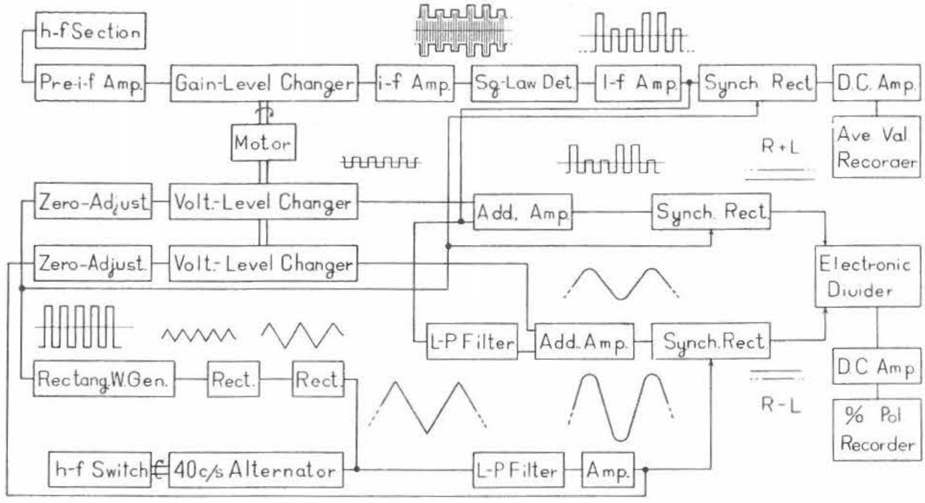

Fig. 12. A block diagram of electronic circuits.

the output of a low-frequency amplifier is used for measuring percentage polarizations of both S-component and outstanding occurrences. As the purpose of using an electronic divider is to record the percentage polarization of quickly-varying bursts or outbursts directly, both 40 and 160 c/s signals concerning quiet sun radiation must be subtracted at each calibration time. Zero adjustors shown in Fig. 12 are prepared for this purpose. They must be adjusted so that the inputs of an electronic divider are usually zero. A reading on the 40-c/s zero adjustor corresponds to the difference of two polarizations and it is used for calculating the percentage polarization of S-component.

When a burst occurs, D.C. voltages proportional to the sum and difference of two polarizations are applied to the electronic divider. However, the divider does not start until the sum-voltage reaches a certain value. In such circumstances, the numerator is left undivided and the deflection on the recorder is simply proportional to the difference-voltage.

A 40-c/s reference voltage of a synchronous rectifier is supplied by a four-pole alternator coupled directly to the modulator shaft. Since the alternator produces a triangular waveform, the frequency can be doubled

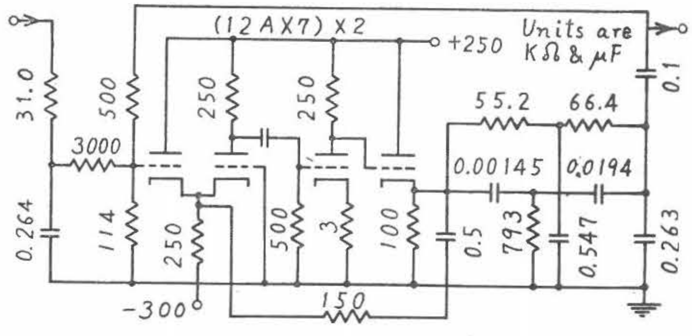

Fig. 13. A circuit diagram of RC low-pass filter.

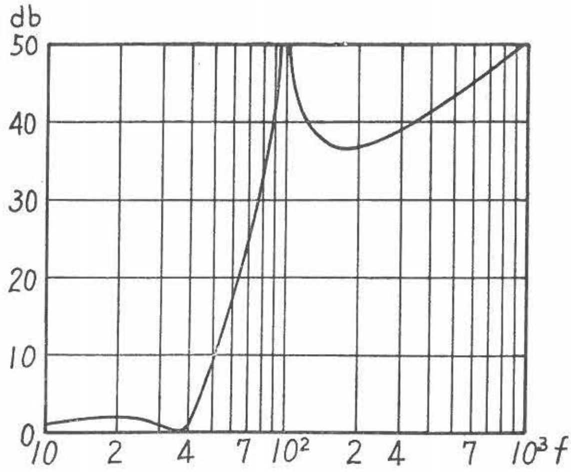

Fig. 14. The characteristic of RC filter.

by means of a full-wave rectification. The frequency is doubled once again by another rectifier, and thus a 160 c/s reference voltage is obtained. In practice, the triangular waveform is converted into a rectangular waveform by a flip-flop circuit. The reference voltages thus obtained are perfectly synchronized to the signal, independent of frequency variations.

A circuit diagram and the characteristic of the low-pass filter for eliminating unwanted signals other than 40 c/s component are shown in Figs. 13 and 14.

7. Electronic Divider

An electronic computer circuit for dividing voltages proportional to the sum and difference of two polarizations is a modified circuit of an electronic multiplier developed by E. A. Goldberg. (8) As the denominator never becomes negative, the circuit is somewhat simplified.

A block diagram of the divider circuit is shown in Fig. 15 together

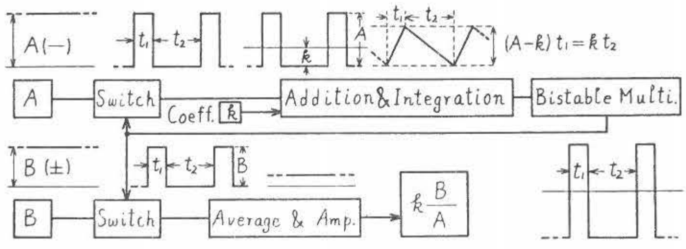

Fig. 15. A block diagram of an electronic divider.

with a diagramic operation. Assume that the denominator (sum) is A and the numerator (difference) is B. The voltage A enters a switch operated by a flip-flop output. The gate of the switch is open for a time t_1 and is shut for t_2. Then the output is integrated after a D. C. voltage k is added. A triangular waveform thus produced has two voltage limitations corresponding to the critical voltages of a bistable muitivibrator, so that an equation

$$(A-k)\ t_1 = kt_2\ (=\text{constant})\ \text{or}\ t_1/(t_1+t_2) = k/A$$

is obtained. If the voltage B passes the same switch, the average value of the output is

$$B\ t_1/(t_1+t_2) = kB/A,$$

and the division is completed. It is to be noted, however, that if $A<k$ the divider does not start and the voltage B passes the switch undivided. The accuracy of this circuit is a few percent for long time operation within a voltage range of 1 to 5. A circuit diagram of the switch is shown in Fig. 16 together with an output circuit of synchronous rectifier.

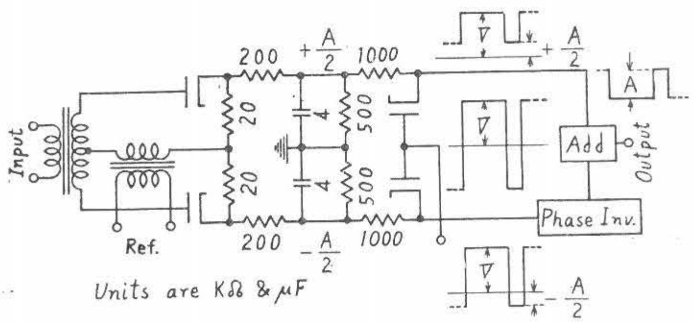

Fig. 16. A gate switch with a synchronous rectifier.

8. Over-All Characteristics

The noise figure is 14 db and the r-m-s output fluctuation is about 5 °K at a time constant of 0.5 sec.. The equivalent antenna temperature when the antenna is directed toward the sky is 30 °K. It is measured by replacing the antenna with a hot load kept at about 300 °C. The hot load is thermally isolated from a cold line by using the same device as is used for the rotary joint (see Fig. 9). The equivalent antenna temperature on January 1, 1957 is 2080 °K which corresponds to the flux 132×10^{-22} W M^{-2} $(c/s)^{-1}$. The distance between the microwave filter and the hybrid circuit as well as the difference in length between two side arms of the mixer is carefully adjusted, so that the record varies less than 50 °K when a shorting plunger is moved slowly in the antenna circuit.

A sample of the record is shown in Photo. 8. As it is recorded during preliminary observations, the percentage polarization is referred to the whole flux density. A full-scale of

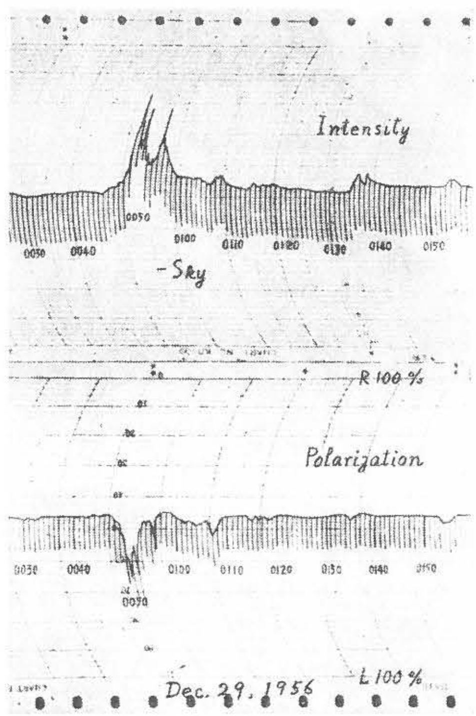

Photo. 8. A sample of record at 1000 Mc/s.

the record is $\pm$ 100 %. A photograph of records simultaneously obtained by other equipments is shown on page 95.

VI. Common Instruments

All power supplies are assembled on a common rack. A 2-KW A. C. regulator supplies all the necessary power at 60 c/s except motors for modulation. The effective value of the output is kept within 100 $\pm$ 0.1 volts.

Regulated D. C. power supplies are divided into three parts, one is for intermediate-frequency amplifier and the others for high- and low-frequency circuits.

A standard 50 c/s is provided for time marks and synchronous motors. It is the output of a 150-watts thyratron inverter controlled by a crystal oscillator.

There are also several relays on the rack for protecting the whole equipment.

VII. Acknowledgement

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