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Abstract

Three V.H.F. receivers of high gain stability and low internal noise designed and constructed at the Kodaikanal Observatory are described. The receivers which operate at $1\frac{1}{2}$, 3 and 5 metre wavelengths are being used for the measurement of extra-terrestrial emission of solar and galactic origin and also for observations of radio-star scintillation. A report on the performance of one of the receivers over long periods together with details of aerial systems used and calibrating equipment is also given.

Introduction

THE Astrophysical Observatory at Kodaikanal is situated on a hill at a height of 2343 metres above mean sea-level. Observations of solar radio emission at $1\frac{1}{2}$ and 3 metre wavelengths have been in progress here for some years using modified radar and communication receivers. In the course of the last two years, improved receivers have been designed and constructed for the measurement of extra-terrestrial emission of solar and galactic origin at frequencies of 200, 100 and 60 mc./sec. and also for observations of radio-star scintillation. As is well known, even though the resolving power of a radiometer depends upon the size and type of antenna used, the minimum detectable signal and the precision with which this can be measured depend entirely on the design of the receiver. The receivers constructed here have been found to be of high gain stability, low internal noise and adequate bandwidth.

Sensitivity of a Receiver

The sensitivity of a receiving system is determined by the 'noise' in its output. The thermal noise power P_r from a resistance r at a temperature T_o, connected to a receiver is, according to Nyquist's expression,

$$P_r = kT_o\Delta f \qquad \ldots(1)$$

where k is Boltzmann's constant and Δf is the bandwidth.

In a practicable receiver, internally generated noise can be represented by additional noise power P_R at the input. The total noise output of the receiver will, therefore, be

$$g(kT_o\Delta f + P_R)$$

g being the power gain of the receiver. The ratio of the total noise to that in an ideal system is the noise factor of the receiver, viz.

$$N = \frac{kT_o\Delta f + P_R}{kT_o\Delta f} = 1 + \frac{P_R}{kT_o\Delta f}$$

or

$$P_R = (N-1)kT_o\Delta f$$

A noisy receiver may thus be regarded as an ideal receiver with its input circuit at a temperature which is $(N-1)$ times the ambient temperature.

Bandwidth Considerations

It has been shown by Dicke[1] and by Ryle and Vonberg[2] that the receiver output fluctuation ΔT in terms of receiver temperature T_R is given by

$$\Delta T = T_R\sqrt{\delta f_o/\delta f_i}$$

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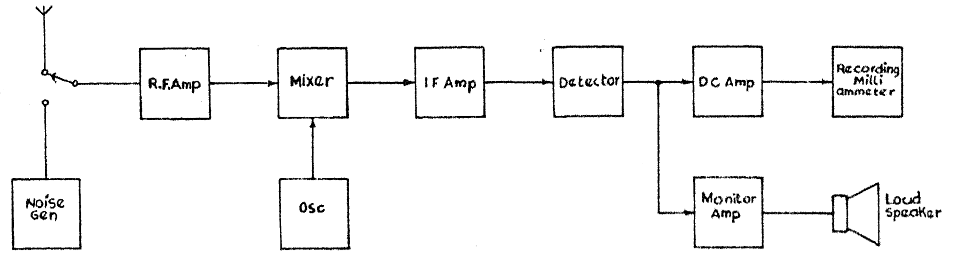

Fig. 1 — Block diagram

where δf_i is the receiver bandwidth and δf_o is the bandwidth of the output recording system. The smallest detectable temperature ΔT can, therefore, be made indefinitely small by increasing the receiver bandwidth and decreasing the output bandwidth. In practice, however, the receiver bandwidth has to be small compared to centre frequency and the time constant of the output circuit cannot be made too large, because, otherwise, rapid changes in the received radiation will be missed.

Gain Variations

In receivers, working in the metre wave region, serious output fluctuations result from receiver gain variations. An increase of ΔT_A in antenna temperature, corresponding to an increase in receiver gain of ΔG is given by

$$\Delta T_A = T_o\left(\frac{T_A}{T_o}+N-1\right)\frac{2\Delta G}{G}$$

Receivers designed to measure small antenna temperatures should, therefore, have the lowest possible noise factors in order to keep fluctuations due to gain variations small. Rigorous stabilization of plate and heater supply voltages of the receiver is necessary to keep these variations small. Frequent calibration of the equipment is also essential for avoiding errors of measurement due to gain variations arising out of tube ageing.

Design Considerations

The design requirements for the receivers were: (i) best possible sensitivity, because only thermal radiation is received most of the time and the received noise is often less than internally generated noise; (ii) lowest possible noise figure; (iii) bandwidth of the order of 1-1·5 mc./sec.; (iv) highest possible stability of gain.

High sensitivity and low noise figure were achieved by careful design of R.F. and I.F. amplifiers and a high degree of gain stability by well-regulated supplies and proper mechanical construction of the receivers. The sensitivity of the complete receiver is determined by the smallest variations that can be identified on the recorder. The fluctuations in the output are mainly contributed by the noise generated in the receiver, variation of receiver gain and man-made interference. It has been indicated earlier that fluctuations arising from the internal noise of the receiver can be reduced by the use of large bandwidth and large time constant in the output. Due to considerations of interference, however, the receiver bandwidth was restricted to 1-1·5 mc./sec.

A block diagram of the receiver is given in Fig. 1. The signal from the antenna or noise generator was fed to a low noise R.F. amplifier converter through an auto-transformer coupling circuit. The overall gain of the converter was increased by incorporating a single stage of I.F. amplification. The converter was followed by a five-stage broad band I.F. amplifier and a second detector the output of which was used to actuate a pen recorder through a D.C. amplifier. For the purpose of detecting interference, a monitor amplifier-speaker was also incorporated in the equipment.

The design of the different units of the 60 and 100 mc./sec. receivers is fully discussed in the following sections. The converter for 200 mc./sec. receiver is described later.

R.F. Amplifier Converter

For all practical purposes the overall noise figure of a receiver is determined by the noise generated in the input stages because the gain in these stages increases the signal and noise powers to levels where noise contributions from succeeding stages are insignificant. The overall noise factor of a receiver is given by

$$N = N_1 + \frac{N_2 - 1}{G_1}$$

where N_1 is the noise factor of the input stage, G_1 its power gain and N_2 the noise factor of the rest of the receiver. It, therefore, follows that the noise factor of the receiver approaches that of the first stage if its gain is large. Careful selection of the first tube is, therefore, of utmost importance.

Choice of Tubes — The selection of a tube for input stage depends on several considerations, the most important of these being the equivalent noise resistance R_{eq} (which is a measure of the noise produced by shot effect in the plate current). The other important consideration is the available power gain; to obtain this, the transconductance has to be large and the input and output conductances have to be small. It, therefore, follows that the input and output capacities of the tube should be small. Further, triodes are preferable to pentodes as the only source of random variations of plate current in these tubes is the shot effect; in pentodes, partition noise resulting from random variations in the distribution of total current between the plate and the screen makes their total noise power output several times larger than that of triodes for the same amplification. For space charge limited triodes, the equivalent noise resistance is given by

$$R_{eq} = \frac{2 \cdot 5}{g_m}.$$

g_m being the transconductance of the tube.

These requirements of an input tube are admirably met by triode-connected 6AK5/EF95 tube which has small physical dimensions and a short cathode lead. For this tube (triode-connected), $g_m = 6670$ μmhos, $R_{eq} = 385$ ohms and $C_{in} = 4$ $\mu\mu$F.

The only difficulty in utilizing a triode is the large grid-plate capacity, but this can be neutralized and for non-criticalness the tube can be operated at a gain slightly below optimum. In order to keep the contribution of the second stage noise to the overall noise figure small, a triode was used in the second stage also.

It is known that the cascode or Wallman[3] circuit using a grounded cathode triode in combination with a grounded grid triode is very satisfactory for low noise figure, good gain, large bandwidth and non-criticalness of adjustment. The R.F. amplifiers of the 3 and 5 metre converters were, therefore, designed using a triode-connected 6AK5 followed by one-half of a 6J6 in ' cascode ' circuit. The selection of a 6J6 in grounded grid stage was mainly on considerations of low cathode-

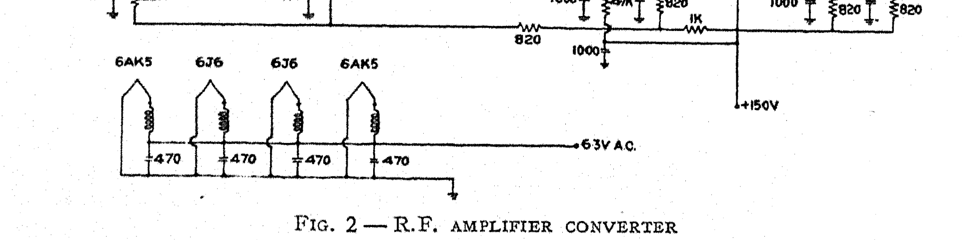

FIG. 2 — R.F. AMPLIFIER CONVERTER

plate capacitance of this tube. In this circuit, a very large conductance (of the order of transconductance of the second tube) is presented to the plate of the first triode so that a large bandwidth is possible with good stability of the circuit. The second tube also is stable in operation because of the shielding provided by the grounded grid between the input and the output.

One-half of a 6J6 was used as local oscillator in Colpitts circuit and the other half as mixer, the injection being through the inter-electrode capacity. A complete circuit diagram of the R.F. amplifier converter is given in Fig. 2. The design was for a source impedance of 75 ohms. The tap of the antenna lead on the input coil L_1 was adjusted experimentally and the adjustment of the neutralizing coil L_N was done by replacing the first 6AK5 with a similar tube with a heater pin broken and adjusting the turns and spacing for minimum signal from a generator at the signal frequency. The plate coils L_2 and L_3 were tuned by adjustment of the spacing. In the oscillator, the tank coil was directly soldered to the tuning condenser stator plates. A sufficiently high parallel capacitance was connected to the tuning condenser for stability of frequency.

The mixer plate coil was slug-tuned. A gain control was incorporated in the cathode circuit of the 6AK5 I.F. amplifier following the mixer.

The I.F. Amplifier

The design considerations for the intermediate frepuency amplifiers were:

(i) Adequate gain with bandwidth of the order of 1-1·5 mc./sec.
(ii) Low noise figure
(iii) Non-criticalness of adjustment
(iv) Freedom from regeneration

For low noise figure, the first two stages consisted of a triode-connected 6AK5 and a 6J6 in cascode circuit. The succeeding three stages were 6AK5 pentodes in synchronous single tuned stages for simplicity of construction and for tolerance of these amplifiers to tube capacity variability. The figure of merit of a pentode which is the product of voltage gain and bandwidth is given by $g_m/2\pi c$. The 6AK5 tubes were utilized for their excellent gain-bandwidth product which, using a conservative figure of 4200 μmhos for transconductance and 10·8 $\mu\mu$F. for inter-stage capacitance, is about 62 mc./sec.

The last I.F. stage was followed by a 6AK5 diode detector with all positive electrodes used as anode and a load resistance of 10 Kohms. The diode output, after suitable filtering, was brought to a coaxial connector. A fraction of the output was taken to the monitoring amplifier.

A circuit diagram of the I.F. amplifier is given in Fig. 3.

The D.C. voltage across the diode load was brought to a differential amplifier utilizing two 6AC7 pentodes. The output recorder was an Evershed & Vignoles recording milliammeter of range 0-1 mA. A 75 ohm R.F. attenuator was constructed for insertion between the converter and I.F. stages when necessary — such as for recording high flux densities during noise storms.

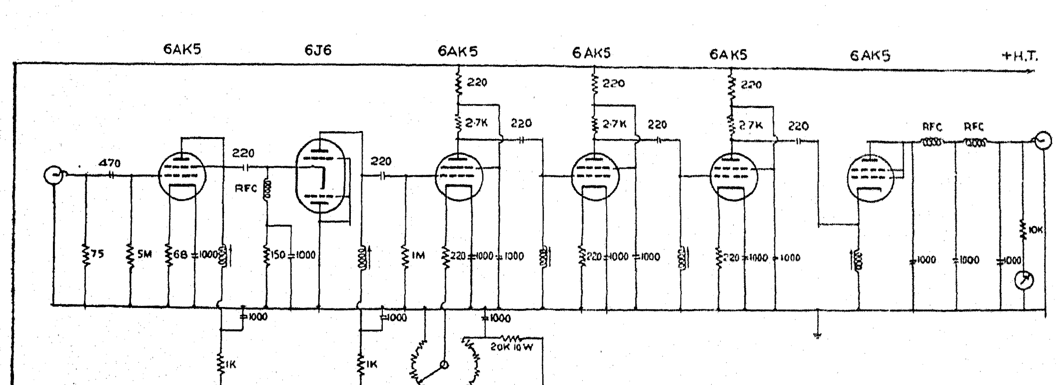

FIG. 3 — I.F. AMPLIFIER

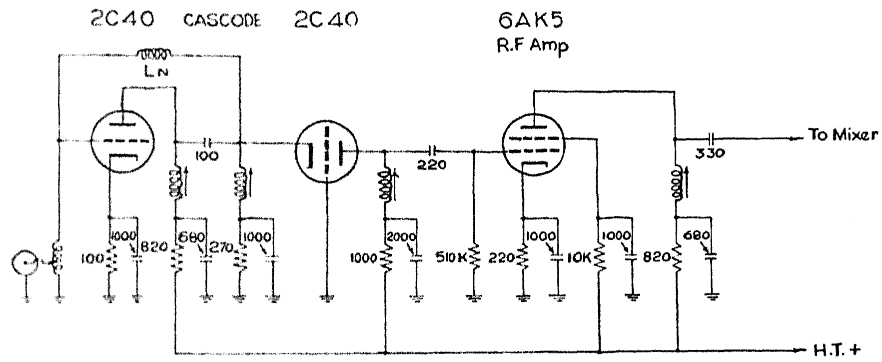

FIG. 4 — R.F. AMPLIFIER FOR 1½ METRE RECEIVER

Mechanical Construction

At intermediate frequencies of 14·0 and 23·7 mc./sec. used for the two receivers, the problem of stability in high gain I.F. amplifiers required a great deal of care in the mechanical layout of the components. To keep the ground currents isolated, all stages were arranged in a straight line. Each I.F. stage had all its circuit components grounded in one place with shortest possible leads. The ground circuits which were not part of I.F. circuits were separated from the circuit ground. The wiring of the heater circuits was likewise done so as to minimize the coupling with signal currents. All coils were tuned with brass slugs moving in the field of the coils. All condensers used were of the ceramic dielectric type.

The main characteristics of the 60 and 100 mc./sec. receivers are given below:

Frequency, mc./sec.	*I.F. used, mc./sec.*	*Noise bandwidth, mc./sec.*	*Noise figure*
60	14·0	1·08	1·60
100	23·7	1·50	2·08

Even though both receivers have been in service for some time now, the 100 mc./sec. receiver has been in continuous service for nearly one and a half years, and it may be pointed out that the performance of the receiver has been absolutely trouble-free. Excepting for periodical replacement of valves on account of ageing, no major servicing has been necessary for the receiver. Calibrations of the receiver show that its performance has been very satisfactory in all respects.

The 200 mc./sec. Receiver

The input resistance of a tube varies inversely as the square of the frequency due to cathode lead inductance and electron transit time. The available power gain, therefore, decreases with increasing frequency. For the 1½ metre receiver where a 6AK5-6J6 combination 'cascode' was tried, it was found that the best noise factor that could be obtained was 5·5. It was, therefore, decided to utilize lighthouse triodes type 2C40 a few of which became available recently. The input conductance of these tubes is much lower but the transconductance is of the same order as that of 6AK5.

A R.F. amplifier converter utilizing two 2C40 tubes in cascode followed by an additional 6AK5 R.F. amplifier stage was designed and constructed. The converter and intermediate amplifiers of the 1½ metre receiver were more or less identical with those of the other two receivers. With this arrangement it became possible to obtain a noise figure of 3·5 corresponding to a receiver temperature of only 725°K at 200 mc./sec. A circuit diagram of the R.F. amplifier is given in Fig. 4.

Recently a new low noise triode A2521 for use up to 900 mc./sec. has been manufactured by the General Electric Co. of England. A few of these tubes have been acquired and a new receiver has been designed utilizing these tubes. When constructed, it is expected that the performance of the 1½ metre receiver will further improve.

Determination of Bandwidth

The bandwidth of a receiver is usually intended to denote the 3 db. bandwidth, i.e.

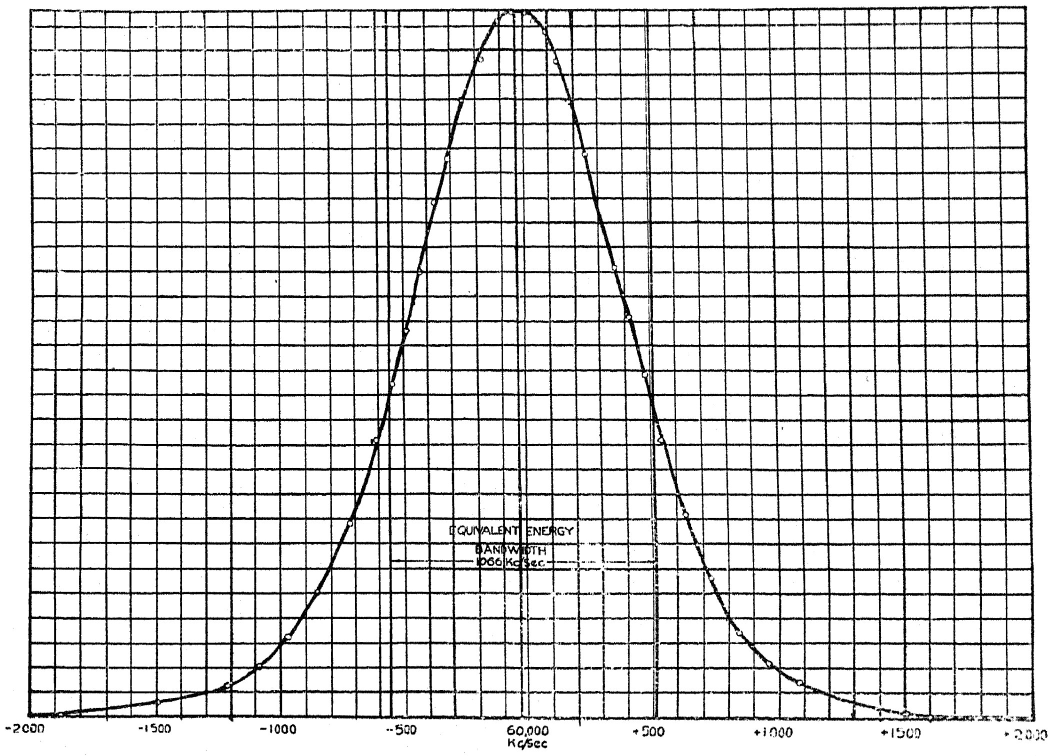

FIG. 5 — OVERALL FREQUENCY RESPONSE CURVE FOR 60 MC./SEC. RECEIVER

the bandwidth at 0·707 voltage or half the power. However, the noise bandwidth Δf in Eq. (1)

$$P_r = kT_o\Delta f$$

is the width of an idealized bandpass filter of the same area as that of power-frequency curve of a receiver and having the same peak value. The noise bandwidths of the receivers, therefore, were determined from the power-frequency curves by planimetering the area of the enclosed curve. The overall frequency response curves for 60 and 100 mc./sec. receivers, as determined experimentally, are given in Figs. 5 and 6 respectively.

Determination of Aerial Temperatures

If P is the power delivered by the aerial to the receiver, the aerial temperature is defined as that temperature to which a resistance substituted for the aerial would have to be raised to deliver the same thermal noise power P to the receiver. This definition follows from Nyquist's law, viz. that the thermal noise power which a resistance at temperature T can deliver to a matched load is $kT\Delta f$ where Δf is the bandwidth and k is Boltzmann's constant. The

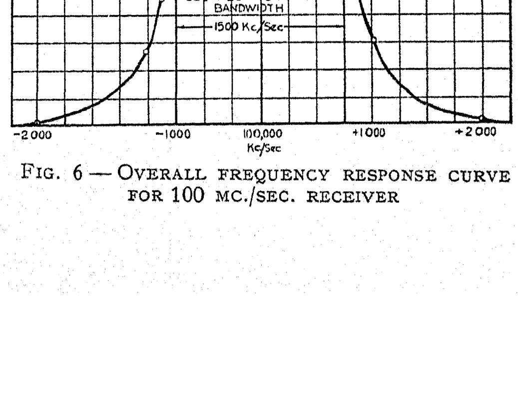

FIG. 6 — OVERALL FREQUENCY RESPONSE CURVE FOR 100 MC./SEC. RECEIVER

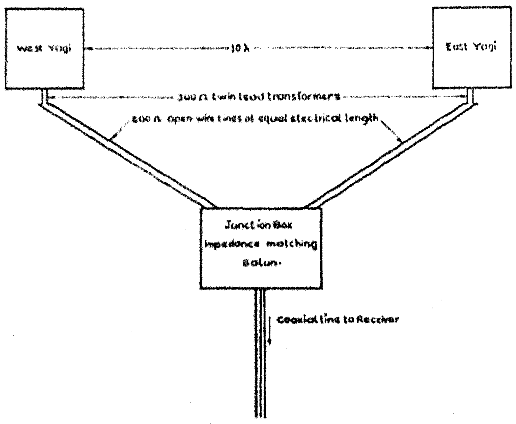

FIG. 7 — INTERFEROMETER AERIAL SYSTEM

absolute value of the aerial temperature is given by

$$T_A = \frac{P}{k\Delta f}$$

This temperature is ideally measured by noting the receiver output meter reading, replacing the aerial by a temperature-controlled resistor and adjusting its temperature to give the original meter reading. In practice, however, it is more convenient to use a non-thermal generator of random noise. The most widely used type consists of a resistor connected to a tungsten filament diode operated under temperature-limited conditions. The advantage of this type of noise generator is that the spectrum over a small interval is identical with that of the waves to be measured and the form of frequency response of the receiver does not affect the relative readings. For quantitative measurements, therefore, the receivers were calibrated at suitable intervals with a generator using a CV172 noise diode and an impedance of 75 ohms — identical to that presented by the aerials. The output of the generator was continuously variable by means of a variable filament temperature without changing impedance conditions and a high output could be obtained. It can be easily shown that the aerial temperature T_A is given by

$$T_A = T_o\,(1+20\,IR)$$

where T_0 is the ambient temperature usually assumed to be 290°K, and I is the diode current required to make the output reading same as with the aerial.

Determination of Noise Figures of the Receivers

The noise figures of the receivers can be determined by the usual method by connecting the noise generator to the receiver input and a D.C. voltmeter across the detector load resistance. The gain setting of the receiver is adjusted to give a convenient reading in the absence of diode current. The diode current is then adjusted to a value I to give a reading $\sqrt{2}$ times the original reading (i.e. doubling the power output of the receiver). The noise factor N is obtained from the relation

$$N = 20\,IR$$

With the above method, however, values of noise figure are obtained which are too optimistic because of the curvature of the detector characteristic. For accurate measurements, therefore, a slightly different method was adopted.

With no current in the noise diode, the receiver gain was adjusted to give a convenient reading V_1 on the voltmeter connected across the diode load. The noise diode current was then adjusted to a value I_1 resulting in a voltmeter reading of V_2 substantially greater than V_1 but avoiding saturation of the receiver. The receiver gain was then turned down to bring the output voltage

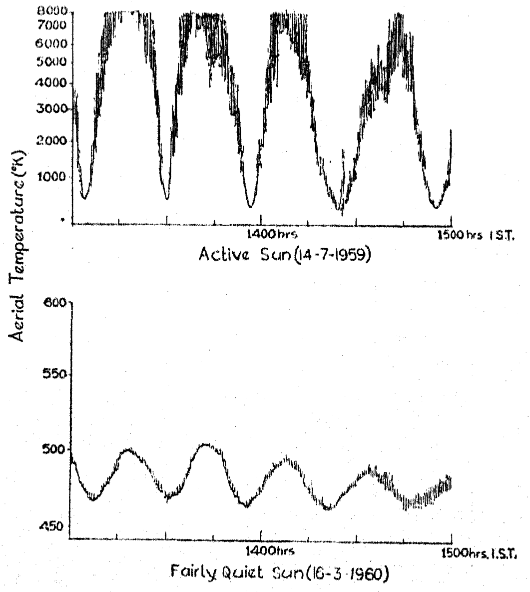

FIG. 8 — TYPICAL RECORDS WITH 3 METRE RECEIVER AND INTERFEROMETER SYSTEM

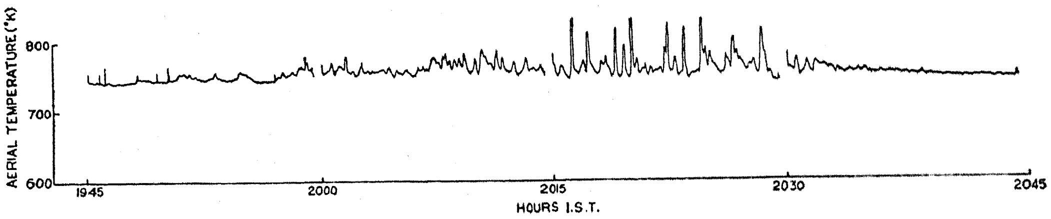

FIG. 9 — SCINTILLATION RECORD ON 15 JANUARY 1960 FROM DISCRETE SOURCE: CASSIOPEIA A

to V_1. The noise diode current was increased to a value I_2 such that the output voltage was V_2. The noise figure is then given by

$$N=\frac{I_1^2}{I_2-2I_1}$$

Aerials for the Three Receivers

(a) For the $1\frac{1}{2}$ and 3 metre receivers Yagis were used. These were mounted on equatorials, the tracking of the sun being done with the help of weight driven clocks. Necessary impedance matching balance-to-unbalance devices were incorporated between the folded dipoles of the Yagis and 75 ohm coaxial lines.

(b) 3 metre Interferometer: In metre wave region, the observation of weak radiation from the undisturbed sun is difficult with Yagis of low resolution because of the presence of strong background noise of galactic origin. Antennae of high resolving power necessarily involve large structures which are difficult to rotate. These difficulties are overcome by observation of solar radiation with an interferometer. This type of aerial system consists of two fixed aerials of relatively small directivity placed at about 10λ apart in an east-west direction. With this aerial, a source of small angular diameter, such as the sun moving across the interference pattern, will deliver to the receiver power, which varies in a periodic way. It can be easily shown that the power P available at the receiver input terminals, for small values of angle θ between the direction of arrival of plane waves and the normal plane, is given by

$$P=P_o\{1+\cos(2\pi d\theta/\lambda)\}$$

where d is the distance between the two aerials, λ is the wavelength and P_o is the power available for a single aerial.

For directional aerials, P_o is a slowly varying function of θ, proportional to the power polar diagram of the aerial.

With the spaced aerial system the above expression for P shows that the pattern will split into lobes of angular width λ/d. A point source in the celestial sphere will, therefore, generate a sinusoidal pattern because of the rotation of the earth. In addition to flux density, the celestial co-ordinates of a point source can also be determined from the pattern of such an interferometer.

A diagram of the aerial system used for routine observation of solar noise is given in Fig. 7. Each one of the five-element Yagis was matched to a 600Ω open wire line through a short length of 300Ω line. The two 600Ω lines of exactly equal electrical lengths terminated in a junction box where a suitably designed balance-to-unbalance network was introduced to match the 300 ohm balanced input to 75Ω unbalanced (coaxial) line connected to the receiver.

Typical records of solar emission obtained with this interferometer are shown in Fig. 8.

A second interferometer with an arrangement for adjustment of declination has been completed recently. This system in which the two elements have much greater directivity is being used for observation of radiostar scintillation for ionospheric studies. A typical scintillation record at 3 metre observed on 15 January 1960, from Cassiopeia A, is shown in Fig. 9.

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