AN INVESTIGATION

OF THE

POLARIZATION

OF SOLAR RADIO NOISE

A thesis presented for the degree of

Master of Science

of Rhodes University

by

G.L.Verschuur B.Sc. (Hons.) Rhodes

Physics Dept.,
Rhodes University,
GRAHAMSTOWN.

December 1960.

On Monday, when the sun is hot,
I wonder to myself a lot;
"Now is it true, or is it not.
That what is which, and which is what."

Winnie the Pooh.

CONTENTS


EVEREA

FRONTISPIECE

Rear view of instrument rack.

INTRODUCTION AND ACKNOWLEDGEMENTS.

In the beginning of radio astronomy research at Rhodes University several single frequency receivers were operated, in turn, to obeserve solar radio noise. When the author of this thesis decided to continue research in this field, Dr. E.F. Stack-Forsyth suggested that rather than to construct another simple radiometer, a polarimeter, operating on 300 Mc/s could be designed and built as part of a research project for the Ph.D. degree. It was thought that the polarization of solar radio noise would provide an interesting and fruitful field of study and, as very little polarization data was available at 300 Mc/s, the records obtained would be a useful complement to those taken in other parts of the world.

With these aims in mind, the author proceeded to build such a polarimeter, Dr. Stack-Forsyth directing initial stages of the design. His invaluable guidance continued from the beginning of 1959 when the project was started, to the end of that year, when he left the University. During 1960 direction was taken over by Prof. J.A. Gledhill. The author would like to express his sincere appreciation for the assistance that both were ready to give and the many helpful suggestions they made.

The building part of the research project could not have followed the course that it did had it not been for the inestimable aid rendered by Mr. A.R. Scanlen, Senior technician in the Physics Department, and much time was saved by adopting his ideas.

The/......

The author is further indebted to him for constructing the tunable coaxial lines used in the project. The author would also like to express his gratitude to Mr. G. Walters of the Physics Department workshop and Mr. J. West of the Maintenance Workshop for advice and assistance during the project. Also to Miss K. Mostert for typing of the thesis.

Although the project was expected to last a minimum of three years if sufficient results were to be obtained for the preparation of a Ph.D. thesis, the work was limited to 2 years when the author decided to continue his studies overseas. For this reason the polarimeter was never actually operated as a whole, but one channel was operated as a straight forward receiver (radiometer). This was initially done as an intermediate step in the testing of the polarimeter. The first record was obtained on 16th March 1960 and the last on 6th October during which the 86 successful records were made.

Finally the author wishes to thank the C.S.I.R., for a research grant during 1959 and 1960 and a bursary during 1959.

SUMMARY.

CHAPTER I

A description of the sun and the type of radio radiation it emits is given. The relation that exists between this and other events occurring on the sun's surface is studied.

CHAPTER II

The literature dealing with the origin of solar radio noise is reviewed.

CHAPTER III

The method of specifying polarized radiation and the effect of a magneto-ionic medium on such radiation is discussed. The possible origin of the polarization of solar radio noise is examined and the literature relating to this and to the observations of polarization of solar noise is reviewed. A short outline of the methods used in measuring polarization is given.

CHAPTER IV

A detailed outline of the construction of a polarimeter is given together with full circuit diagrams and illustrative photographs.

CHAPTER V

A brief discussion of the operation of the polarimeter, the results obtained and suggestions for its future operation is given.

CHAPTER I

SOLAR RADIO EMISSION AND IT'S RELATION TO FEATURES ON THE SOLAR DISC.

As early as 1936 certain radio amateurs had noticed the presence of a steady hiss on the higher frequency bands that appeared to be related to the sun in some way. It was not until the war years however that radar operators, on pointing their antennas at the sun, showed that the spurious effects they had observed were in fact related to the presence of sunspots on the sun's surface. Appleton and Hey (1), the first to make a study of the effect, mentioned some preliminary results obtained and noted a correlation between certain flares, radio radiation and sudden ionospheric disturbances (S.I.D's).

Before the relation between solar disc features and radio radiation from the sun is undertaken, a short description of the structure of the sun will be followed by a discussion of the radio radiations which it emits.

The structure of the sun.

The visible disc of the sun is the edge of the region known as the photosphere. Below the photosphere the atoms are so highly ionized that the gas is opaque to visible light and the conditions in the interior have to be deduced by methods similar to those used for distant stars. The radius of the photosphere is of the order of 696,000 km., while the temperature is 5,500^{O}K.

Immediately above the photosphere there occurs a region known as the chromosphere, extending aproximately 10,000 km

above/......

above the former region. This region consists mainly of ionized hydrogen at temperatures varying from 5,000° to 10^5 °K.

Above the chromosphere there occurs a region, whose density decreases with increasing height, known as the corona. Early workers thought that this corona, which can be seen at times of total eclipse as a series of streamers radiating away from the sun for distances of several thousand kilometres, extended about two million kilometres at most. But, in the light of recent discoveries by means of satellite borne instruments, it is now thought to extend well past the region of the earth's orbit (2) possible as far as Jupiter's orbit. The temperature of the corona in the proximity of the chromosphere is of the order of 10^6 °K, and decreases slowly with distance. At the earth it may still be several hundred thousand degrees.

It is in the lower corona and the upper chromosphere that most of the radio frequency radiation from the sun originates. (See Table II).

Observable effects on the solar surface.

.he photosphere does not, under high resolution, appear uniformely bright, but shows a granular structure. Each bright nodule averages about 200 km in diameter, being the top of a rising column of gas. The turbulence observed is not unlike that observed in a pan of boiling water.

Further dark regions, known as Sunspots, consisting of a

dark/......

dark central portion, the umbra, surrounded by a less dark regim the penumbra, are often observed.

These sunspots generally occur in groups consisting of two major spots, one "leading" the other during the rotation of the solar surface. They may last for several weeks, changing gradually in overall size and dimensions until they finally disappear. It has been found, over an observing period of several hundred years, that the number of sunspots per annum follows an 11 year cycle.

The two sunspots in a group have been found to be of opposite magnetic polarities. During any one 11 year cycle leading spots in the northern hemisphere are always of the same polarity, north pole say, while during the next cycle the leading spot will be reversed in polarity to become a south magnetic pole. At the same time a leading spot in the southern hemisphere is always opposite in polarity to that of a leading spot in the northern hemisphere.

As yet no entirely satisfactory theory has been propounded to account for either the 11 year cycle or the polarity effects.

This cycle has several effects observable on the earth, the main one of interest to radio astronomy being that number, as well as the mean intensity, of bursts of radio noise seems to increase towards sunspot maximum and decreases very rapidly after maximum has been reached. The maximum in the present cycle was reached in 1958. The frequency of occurrence as well as the brightness of the aurorae are also related to this cycle, as are the amounts of radio static observed, the occurrence of geomagnetic storms and the intensity of ionization in the ionosphere.

Another observable surface phenomenon on the sun is the presence of large tongues of luminous gas, extending outwards from the chromosphere for distances of several hundred thousand kilometres, known as prominences.

Floating clouds of calcium and hydrogen, called flocculi, may be seen by spectroheliographic means and appear brighter or darker than the surrounding medium, depending on whether they are hotter or cooler than their surroundings.

Flocculi, in the vicinity of sunspots, sometimes increase enormously in brightness, temperature and size. They are then known as flares. These produce a great deal of ultra-violet and corpuscular radiation whose effect is ultimately observed on the earth's ionosphere.

B. Radio emission from the sun.

Radio radiation from the sun is divided into three main categories, the "quiet" thermal radiation, the "active" radiation at metre wavelengths, and the "active" radiation at centimetre wavelengths.

The quiet sun.

The quiet sun emits a steady amount of radiation

spread/......

spread over the whole radio frequency spectrum, known as the "thermal component". This thermal radiation is due to the thermal motion of the electrons that go to make up the solar atmosphere.

The Rayleigh-Jeans law, valid for radio applications, states that the spectral density of radiated power (watts per cps) is proportional to T_b/λ^2, where T_b is known as the brightness temperature for a given wavelength λ.

Now any ray that propagates in the solar atmosphere in the absence of a magnetic field, travels through ionized regions whose refractive index varies, according to Lorentz theory, as follows:

where $x = \frac{4\pi N e^2}{E_o m w^2}$

$N =$ electron density.

$e =$ charge on the electron.

$E_o =$ permitivity.

$m =$ mass of electron.

$W =$ angular frequency.

The plasma frequency W_o is defined by $W_o^2 = \frac{4\pi N e^2}{E_o m}$

so that $x = \frac{W_o^2}{W^2}$

If $W = W_o$ the index of refraction is zero and there is no propagation of electromagnetic waves but there is the possibility "of plasma oscillations". It is believed that such oscillations are responsible for many of the radio bursts from the sun. However, in regions where $\mu = 0$, propagation is impossible except/......

sible except under certain conditions which will allow coupling of the energy in the oscillation into a propagating mode. The theory of such coupling requires sharp gradients of electron density or gradients in the superposed magnetic fields. It will be discussed in Chapter II.

It is possible, by using Snell's Law, to calculate ray trajectories through the corona for rays that reach earth and much work has been done in this field. It is thought that some rays travel inwards from their point of origin, are then gradually deflected as they approach regions of low refractive index and subsequently, (after a considerable amount of absorbtion has taken place along their paths at these levels of low refractive index) reach earth.

The attentuation constant is proportional to $(n_e^2 \nu^{-2} T_e^{-3/2})$ when $n \ll 1$. T_e is the kinetic temperature of the electrons. As the kinetic temperature varies along the path, this expression must be integrated since each element of path absorbs energy from below, which will add to the emissivity. It is convenient to express the result in terms of a power absorption coefficient k (Nepers per unit length), which itself is a function of distance s, along the ray. An elementary section of length ds will absorb an amount (k ds) of the incident power and in turn will emit an amount proportional to (T_e kds). This follows from Kirchoff's Law combined with the Rayleigh -

Jeans/......

Jeans Law; the ratio of the emission coefficient to the absorption coefficient of any body in thermodynamic equilibrim is proportional to the temperature.

The flux density from this section that escapes to the "outside" is proportional to

$$(T_e \; k \; ds) \; \exp \; (-\int_0^s k \; ds)$$

This is the contribution to the total brightness temperature from the element ds. The total brightness temperature is

$$T_b = \int_0^\infty T_e \; (s) \; e^{-\tau s} \; d\tau \; .$$

where

$$\tau s = \int_0^s k \; (s) \; ds = \text{optical depth to point } s.$$

Brightness distribution.

It is found that at different frequencies the sun varies in brightness across the disc. At low frequencies it appears brightest at the centre while the "radio-disc" appears larger than the optical disc. At higher frequencies (200 Mc/s) the limb appears brighter (limb-brightening), the brightness falling off very rapidly beyond this limb. Above, about 10 kmc this effect practically disappears.

This limb-brightening is explained by the fact that rays that leave the sun in the direction of earth from near the limb have been deflected gradually by levels of low refractive index and do not approach these levels as closely as do the rays that are more nearly normally incident. As a result, less

absorption/......

absorption takes place along these paths.

It can be shown (Pawsey and Bracewell, page 15) that the flux density due to thermal radiation is given by:

$$S = 1.88 \times 10^{27} \times \frac{T_b}{2} \text{ watts meter}^{-2} \, (c/s)^{-1}$$

At metre wavelengths T_b is of the order of 10^6 °K and S is of the order of 10^{-21} watts/m^2/cps.

Activity at metre wavelengths.

At metre wavelengths the sun emits "bursts" of radiation which are superimposed on the steady background, due to the quiet sun. The intensity of these bursts varies between a level just detectable above the thermal radiation and one 10^5 times the intensity of the quiet sun. The sources of these bursts generally occupy only a small fraction of the sun's surface and their brightness temperatures may be as great as 10^{10} degrees. The frequency of occurrence of bursts varies between no major bursts for months at a time at sunspot minimum to almost continuous "activity" for weeks on end at sunspot maximum.

Activity at centimetre wavelengths.

Superimposed on the thermal background is a slowly varying component appearing as an enhancement of the continuum radiation varying from 2% at 3cm to 100% at 50 cm. It has components periodic with the sun's period of rotation (27 days) and interferometers have been able to localize the sources as occurring in the region of calcium plages. Bursts are also found at these wavelengths.

Table/ ......

Table I gives a summary of the types of solar radio waves observed on earth.

Types of bursts of solar radio noise.

Wild and McCready (3), working with a swept frequency spectrograph covering the 70 to 130 Mc/s band 3 times per second, discovered that bursts of solar radio activity could be readily classified into several spectral types. This spectrograph was later modified to cover the 40 to 240 Mc/s band (Wild, Murray and Rowe (4)) and more recently a paper describing some results obtained with this, pointed out that its lower frequency limit was 24 Mc/s (5). The spectral features of the bursts described in the original paper have all been identified on the records obtained with the later versions of the spectrograph and these, together with several other classifications of bursts since made, will now be briefly summarized.

Bursts of spectral type I.

These are sometimes known as storm bursts which appear on a varying background, known as "enhanced radiation". The two phenomena together go to make up what are known as noise storms.

Storm bursts are characterized by a narrow spectrum, only a few megacycles wide, the frequency of maximum intensity remaining approximately constant throughout the lifetime of the storm, which can be of the order of several minutes to several days in extreme cases. On single frequency records they appear

as/.....

-TABLE I-

CLASSIFICATION OF SOLAR RADIO WAVES

CLASS	DURATION	WAVELENGTHS	POLARIZATION	ASSOCIATED PHENOMENA
Thermal component	....	Unlimited	Random	....
Slowly varying component	....	10,000-500Mc/s	Traces of circular	Sunspots
Noise Storm Enhanced radiation	Hours or days	Decimetre and Metre regions	Circular	Sunspots
Type I burst (Storm burst)	Tenths of seconds	Decimetre and Metre regions	Circular	Sunspots
Type II burst (Outburst)	Minutes	Centimetres to tens of metres	Usually not polarized	Flares
Type III burst (Isolated)	Seconds	Centimetres to tens of metres	Irregular elliptical or linear	Unknown (possibly micro-flares)
Type IV burst	Minutes or hours	Centimetres to tens of metres	Often circular	Large Flares
Type V burst	Minutes	Broadband at centimetre wavelengths	Variable	Often follow Type III bursts.

as a large number of short-lived peaks superimposed on the slowly varying background. See plate I.

Bursts of spectral type II.

These are alternatively named outbursts and appear relatively rarely, the spectrum showing a sharp "cut-off" in frequency with little or no radiation being received immediately below the critical frequency. This critical frequency varies gradually with time, tending to drift towards the lower frequencies at the rate of about $\frac{1}{4}$ Mc/s per second. The bursts show a fairly broad band (tens of megacycles) and last only a few minutes. Their appearance on single frequency records, shown in plate I, is of several peaks closely spaced on a quiet background.

Bursts of spectral type III.

In this type of burst the frequency at maximum intensity drifts rapidly toward lower frequencies at the rate of about 20 Mc/s per sec. The bursts are of extremely large bandwidth (not less than 50 Mc/s) and they last only a few seconds. They are generally known as isolated bursts. On single frequency records they appear as short lived increases as shown in plate I.

It should be pointed out that amongst the earlier attempts to classify the observed radiations from the sun were those by Payne-Scott (6) who sub-divided all bursts into either circularly or not-circularly polarized radiation. She identified the enhanced radiation accompanying noise storms as

circularly/......

circularly polarized. The bursts of type II and III of Wild were classed as "not-circularly-polarized".

Because type II events appeared to be related to flares in some way they were called "outbursts" and type III bursts became known as "isolated bursts" because they did not appear to be related to flares.

Two further spectral types were only identified several years later by other workers.

Bursts of spectral type IV.

In 1957 Boischot (7) published the first of a series of papers (8) dealing with a new type of radio emission that is always associated with flares. He named these bursts of spectral type IV. On single frequency recorders the intensity of these events was found to increase over a period of 20 to 40 minutes and then to decrease more slowly, disappearing after a few hours. The radiation was found to be very stable during the lifetime of this type of event and was marked by the complete lack of superimposed storm bursts which would have been characteristic of noise storms.

Bursts of spectral type V.

Wild, Sheridan and Neylan (9) found that certain type III bursts were followed by a broad band diffuse afterglow which they named bursts of type V. This type of emission appeared to occur together with about 1 in 3 or 4 groups of type III bursts. These bursts lasted for about 1 minute, and appeared to radiate

most /......

most strongly at frequencies less than 150 Mc/s. A marked correlation between type III bursts, occurring simultaneously on centimetre and metre wavelengths, and type V events, has been noted by Neylan (10).

On single frequency records these bursts would appear as low intensity radiation following a burst of type III whose intensity might be less than or greater than the associated type III burst. It would hardly appear likely that these bursts would be readily distinguishable on such records however.

Several further types of radio events not adequately covered by the above classifications have been described in the literature and will now be briefly summarized.

Inverted U bursts.

Maxwell and Swarup (11) described a phenomenon observed on swept-frequency spectrograph records which, unlike the bursts of types II and III, drifted first towards lower frequencies, reached a minimum, and then started to increase in frequency again. The bandwidth was found to be of the order of 20 Mc/s and the lifetime of the order of seconds. The majority of these bursts observed at the time of their paper (32 out of 42) had turning points between 100 and 150 Mc/s and only 4 had turning points in the 300 Mc/s range. Recently these bursts have been observed at frequencies as low as 35 Mc/s (5). On single frequency records they would appear as two apparently unrelated

peaks/......

peaks within seconds of one another.

Reverse drift pairs.

Roberts (12) found a class of bursts that exhibited only a drift in frequency towards higher frequencies. The burst consisted of two elements, the second being a repetition of the first after a few seconds delay. They were of very short duration and occurred at the longer wavelengths, appearing to be associated with type III events. They, too, would not be readily identifiable on single frequency records.

Harmonic bursts.

Wild, Murray and Rowe (13) found that the spectral features of bursts of type II or III were sometimes duplicated with a 2:1 frequency separation. They observed this effect in two type II events and in a large number of isolated type III bursts. On single frequency records these bursts appeared as a single large peak followed immediately by a smaller peak which lead to the description of "double-humped bursts".

Radio pips.

Reber (14) was first to report the occurrence of a great number of small transients or discrete pips that occur during burst activity and which were detectable with high speed recorders. They appeared to be of fairly narrow band width (less than 10 Mc/s) and were of extremely short duration, usually less than 1 sec. De Jager and van't Veer (15) pointed out that about 90% of all pips seemed to occur in groups, the number

of pips/......

of pips per group being distributed according to Poisson's Law. They found the bandwidth to be about 7 Mc/s.

They performed an interesting analysis on about 600 of these pips to determine an "echo" effect. If a pip originated above the plasma level associated with the frequency of the pip one might have been able to differentiate between a direct signal and an echo from this plasma level. A statistical analysis did not reveal any significant effect however. This led to the conclusion that the pips probably originated in a layer where the plasma frequency equaled the pip frequency.

Scintillations.

A "peculiar type of scintillation of solar radio radiation" has been described by Fokker (16). This effect was observed on a wide range of frequencies between 140 and 545 Mc/s. Fluctuations or fadings within the rapid scintillations were recognized and there appeared to be correlation between the fadings on different frequencies. It appeared strongest during the months May to August and Fokker claimed that instrumental faults were not the cuase, these having been carefully eliminated

Another "remarkable solar radio event" has also been described by the Dutch workers (17). This phenomenon appeared similar to that described above and it too occurred over a wide frequency band and was only detected with high speed recorders. The more conventional recorders would only have indicated a blur

for/......

for events such as these which might explain the lack of previous reference to such events, in the literature. The presence of the earth's ionosphere has set a lower limit to the frequency of radiation that can be received with a conventional radiometer, but bursts have been observed at frequencies as low as 18 Mc/s. This was an extremely rare occurrence during which a receiver directed at Jupiter suddenly detected a large increase in the received flux and this was attributed to reflections off the moon's surface during a strong outburst on the sun which was detected in the sunlit parts of the world at the same time (18).

Although a thorough discussion of the effect is beyond the scope of this work, it should be pointed out that Takakura (19a) has succesfully managed to explain the background continuum, as well as the storm bursts associated with noise storms in terms of the superposition of many "spikes", which have identical shape occur at random and whose amplitudes are distributed according to Gaussian curve. He found that if two parameters, the frequency of occurrence of bursts and the range of distribution of the amplitude, varied with time, all noise storms were in good agreement with this hypothesis. The storm bursts were the fluctuation about the mean level and the superposition of at least a few spikes. The similarity in polarization of bursts and continuum was then adequately accounted for. The spikes were thought to occur with a frequency of several hundred

to/......

to several hundred thousand per second. A second paper (19b) dealt with some experimental results, veryfying the hypothesis.

C. The relation between surface disc features and radio emission.

The first positive correlation between sunspots and "sudden increases" or bursts was obtained in 1947 by McCready, Payne-Scott and Little (20). By performing their observation during sunrise, they were able to show that certain radiations came directly from the region of sunspots.

Payne-Scott and Little (21), in 1951, found that the noise storms were associated with sunspots and that the size of the largest spot was a criterion of emission. They found that even if the total area of the spots was large and the size of any individual spot was not large enough, no noise storm would occur. A single large spot was, however, likely to produce storms. It was a well-known fact that the size of a spot was closely related to the strength of its associated magnetic field, and this appeared to be a reason why the size of single spots should be important in the production of noise storms. It further appeared that spots near the limb were more likely to produce storms than those nearer the centre of the disc.

Wild (22) in the fourth of a series of papers dealing with the observation of high-intensity solar radiation at metre wavelengths also noted the correlation between noise storms and sunspots.

There/......

There was much speculation as to the reason why only some sunspots seemed to be associated with noise storms. Fokker (23) cast new light on the matter by considering it as a question of whether the noise storm sources were "visible" or not. He showed that certain storm radiations could be prevented from reaching the earth as a result of the ray paths being deflected by the presence of "coronal structures", large clouds of denser plasma. The ray paths through these structures may be such that the radiation finally reached earth, or it may be deflected in a direction that prevented its detection at earth. He believed that every centre of activity (sunspot) was the source of a noise storm. This had been found to be the case at decimetre wavelengths from observations made with a radio heliograph at Sydney. He further considered the possibility that these coronal structures were continually being replenished by fresh material from below and that this process might involve some emission of radiation, which would be able to escape in the direction of earth as the result of purely accidental circumstances. Consequently, only some sunspots would appear to have associated noise storms. This, he suggested accounted for the fact that there were no visible differences between quiet and noise-active spots.

Possibly this hypothesis might be extended to apply equally well to the observed relation existing between flares and radio bursts. A recent paper by Edelson et al (24) pointed out that

99%/......

99% of 10 cm bursts were coincident with flare activity whereas only a 25% of flares were coincident with 10 cm bursts. A detailed study of this relation bearing in mind the above hypothesis might well prove to be fruitful.

Flares.

The correlation between flares and outbursts of radio noise has drawn considerably more attention than the relation between sunspots and radio noise, the largest volume of work that has been published to date being that of Dodson, Heneman and Owren (25). In their paper dealing with solar flares and associated 200 Mc/s radiation they quoted distinctive radio events occuring with 78% of the 194 flares they observed. They subdivided these "distinctive events" into narrower categories than Wild's spectral types, including "major bursts", "minor bursts", "onset of noise storm", "noise storm in progress" and "simple rise in base level". A "burst with second part", indicating a double rise in flux was also distinguished. Their correlations were extended to include flares of varying importance. (The importance of a flare is given as a measure of its duration and size).

Class (Importance)	Average Life	Size in Millionths of Sun's area
1-	17 minutes average life	<100
1	17 minutes average life	>100 <300
2	29 minutes average life	>300 <750
3	62 minutes average life	>750 <2000
3+	approx. 180 minutes average life	>2000

They found, 79% of Imp. 1 flares had distinctive events.
77% of Imp. 2 flares " " "
50% of Imp. 3 flares " " "

This showed no particular tendency for the association with any one class of flare.

They also found that the occurence of S.I.D's with flares, bore no relation to whether the flare had an associated radio event or not. (38% of flares with associated radio events and 37% of null cases were associated with S.I.D's).

There appeared to be no correlation between the occurence of 200 Mc/s radiation and the position of the flares on the solar disc. They found that spectral type II bursts were most closely associated with flares. (Type II bursts after Wild).

Loughead, Roberts and McCabe (26) in their paper entitled "The Association of Solar Bursts of Spectral Type III with Chromospheric Flares", examined 300 flares of which 85% were microflares. (Class 1-). They found that 20% of the flares were associated with type III events, whereas 60% of the bursts occurred at the onset of a flare or preceded it slightly. They also found that the more active regions of the sun tended to produce bursts and flares simultaneously over periods of a few days at a time. They found that the larger the flare, the more likely was the occurrence of burst activity.

The relation between flare puffs, i.e. flares showing sudden bright expansions or puffs, and type III bursts, has recently been investigated by Giovanelli (27). Type III bursts were found to

occur/......

occur within $\pm$ 2 minutes of $\frac{2}{3}$ of the observed puffs. Giovanelli was unfortunately not able to observe puffs on the smaller flares by his methods and as a result, it is not known whether flare puffs are the cause of all type III bursts. Giovanelli and McCabe (28) have shown that flare puffs were the first stages in the ejection of particle streams with velocities of the order of 100 km/sec. Such ejections are known as surges, and Loughead, Roberts and McCabe, too, found that surge associated flares were more likely to have bursts associated with them, although their results were far from conclusive.

In a very recent paper by Rabben (29) on "Type III Solar Bursts and their Relation to Eruptions (flares)", 372 flares and 136 burst events were recorded during a 200 hr period, and by combining his records with high frequency records from other stations, he was able to look for correlation over a very wide range of frequency down to micro-wavelengths. About 20% of the flares coincided with type III bursts and 88 of the remaining 96 burst events occurred within the lifetime of a flare extended by about 5 minutes.

A number of conclusions were reached and are here summarised

a) The greater the flare importance, the greater the number of bursts per event.

b) Large bursts occurred near onset of a flare, whereas lesser bursts were independent of the flare's phase.

c) The burst intensity and frequency drift per sec. were independent of the flare's importance.

d) /......

d) The number of bursts per event, intensity and frequency drift per sec. increased with total spectral range of burst.

e) The centre to limb decreases of no. of bursts exceeded that of flares and showed, in addition, a strong east-west asymmetry.

f) The contribution of bursts of medium intensity and frequency drift per sec. increased with central meridian distance.

g) The radio efficiency of flares increased with importance.

h) Burst-producing flares prefered certain centres of activity.

Giovanelli and Roberts (30) identified several optical events as being related to type II bursts, notably the ejections of particle streams near or at the limb of the sun's disc with velocities exceeding that of sound in the corona. For an event on the disc, there has usually been a very bright flare. Over a two year period (1956-57) they observed 18 type II bursts, and in 13 of these cases they definitely identified the optical disturbance responsible. In 2 of the remaining cases, there were alternative identifications and in the remaining 3, their optical records were poor or interrupted. Of the former 13 cases, 9 were associated with flares on the disc, 2 with surges on the limb and 2 with ejected prominences on the limb.

The relation that exists between cosmic rays observed on earth and the occurrence of solar flares and radio bursts, has also drawn considerable attention and in a recent paper Thompson and Maxwell (31), working with the results of an interferometer covering the 100 to 580 Mc/s range, concluded that, though current theories of the origin of type III bursts suggested generation by emission of particles with velocities of the order of cosmic ray velocities, there was no correlation between fast drift type III bursts and cosmic ray increases observed on earth. Solar flares that appeared to be associated with type III bursts were not related to cosmic rays. Increased in low energy cosmic rays observed by balloons and satellites, appeared to be related to type IV bursts, however, Thompson and Maxwell further pointed out that Forbush type decreases in cosmic ray intensity. Large unusual decreases usually associated with magnetic storms and first recorded by Forbush (32), as well as magnetic storm activity, were regularly preceded by slow drift type II bursts, the mean time delay being 33 hours. Of 26 well defined Forbush type decreases at least 56% were preceded by type II bursts within a 4 day period, the mean time delay being 35 hours.

The author of this thesis feels that, as these results were not based on 24 hour records of solar activity, they should not be stressed too much.

Kamiya and Wada (33) since found that almost all cosmic ray storms(i.e. large increases of cosmic ray intensity), were associated with flares having an accompanying type IV outburst. They further found that other types of outbursts were not rela-

ted/......

ted to cosmic ray storms, and that the size of these storms was independent of the meridian distance of the radio source. They concluded that a large corpuscular cloud together with a magnetic field was emitted simultaneously with type IV bursts.

The increase of low energy cosmic rays as observed by balloons has been definitely associated with solar flares; and in their paper Reid and Leinbach (34) stated that this type of event was invariably followed by strong low frequency noise storms lasting several hours.

(1)	Appleton and Hey.	"Solar Radio Noise".	Phil. Mag. 37,73 (1946)
(2)	Parker.	"Extension of the Solar Corona into Interplanetary Space".	J.G.R. 64,1675 (1959)
(3)	Wild and McCready.	"Observations of the Spectrum of High Intensity Solar Radiation at Metre Wavelengths".	Aust.J.Sci.Res.A. 3,387 (1950).
(4)	Wild, Murray and Rowe.	"Harmonics in the Spectra of Solar Radio Disturbances".	Aust.J.Phys. 7,439 (1954).
(5)	Wild, Sheridan and Trent.	"The Extension of Solar Radio Spectroscopy to Decametre Wavelengths".	Observatory 79,51 (1959).
(6)	Payne-Scott.		Aust.J.Sci.Res. A2, 214 (1949).
(7)	Boischot.	"Characteristics of a type of Radio Emission Associated with Certain Chromospheric Flares".	Comptes Rendus. 244,1326 (1957).
(8)	Boischot and Denisse.	"Radiation Type IV and the Origin of Cosmic Rays Associated with Flares".	Comptes Rendus. 245,2194 (1957).
(9)	Wild, Sheridan and Neylan.	"Speed of Solar Disturbances Responsible for Type III Radio Bursts".	Aust.J.Phys. 12,369 (1959)
(10)	Neylan.	"An Association between Solar Radio Bursts at Metre and Centimetre Wavelengths".	Aust.J.Phys. 12,399 (1959).
(11)	Maxwell and Swarup.	"A New Spectral Characteristic in Solar Radio Emission".	Nature. 181,36 (1958)

12/.....

(12)	Roberts.	"Evidence of Echoes in the Solar Corona from a New Type of Burst".	Aust.J.Phys. 11,215 (1954).
(13)	Wild, Murray and Rowe.	"Harmonics in the Spectra of Solar Radio Disturbances".	Aust.J.Phys. 7,439 (1954)
(14)	Reber.	"Fine Structure of Solar Radio Transients".	Nature. 175,132 (1955).
(15)	de Jager and van't Veer.	"Some Properties of Solar Radio Transients on Fast 200 Mc/s Records".	Symp.IV. I.A.U. Radio Astr. p. 366.
(16)	Fokker.	"A Peculiar Type of Scintilation of Solar Radio Radiation".	ibid pg 371
(17)	Staff of Ionos. and R/A section of the Neth.P.T.T.	"A Remarkable Solar Radio Event".	Nature. 183,542 (1958).
(18)	Smith, Carr and Perkins.	"Anomalous Night-time Reception of a Major Solar Radio Burst".	Nature. 183,597 (1959).
(19)	Takakura.	"Polarized Bursts and Noise Storms of Solar Radio Emission".	Pub.Astron.Soc.Japan.
		(a) "II Storm Bursts and Background Continuum".	11,55, (1959).
		(b) "III The Post-detection Low Frequency Spectra of Noise Storms".	11,71. (1959).
(20)	McCready, Payne and Little.	"Solar Radiation at R/F and its relation to Sunspots".	Proc.Roy.Soc. 190,357 (1947).

(21)	Payne-Scott and Little.	"The Position and Movement on the Solar Disc of Sources of Radiation at 97 Mc/s. II Noise Storms."	Aust.J. of Scien.Res. 4,508 (1951).
(22)	J.P. Wild.	"Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. IV.Enhanced Radaition."	Aust.J. of Scien.Res. 4,36 (1951).
(23)	Fokker.	"Studies of Enhanced Solar Radio Emission at Frequencies near 200 Mc/s".	Ph.D.Thesis. Univ. Utrecht. (1960).
(24)	Edelson, McCullough, Santini and Coates.	"Solar Flare-Burst Association".	Paper presented to XIII U.R.S.I. Conf.
(25)	Dodson, Heneman and Owren.	"Solar Flares and Associated 200 Mc/s Radiation".	Astrophys. J. 118,169 (1953).
(26)	Loughead, Roberts and McCabe.	"The Association of Solar Radio Bursts of Spectral Type III with Chromospheric Flares".	Aust.J. Phys. 10,483 (1957).
(27)	Giovanelli.	"Flare Puffs as the Cause of Type II Radio Bursts".	Aust.J.Phys. 11,350 (1958).
(28)	Giovanelli and McCabe.	"The Flare-Surge Event".	Aust.J.Phys. 11,191 (1958).
(29)	Rabben.	"Type III Solar Bursts and their Relation to Eruptions".	Z.Astrophys. 49,95 (1960) Physics Abstracts.
(30)	Giovanelli and Roberts.	"Optical Observations of the Solar Disturbances Causing Type II Radio Bursts".	Aust.J.Phys. 11,353 (1958).

(31)	Thompson and Maxwell.	"Solar Radio Bursts and Cosmic Rays".	Plan.Sp.Sci. 2,104 (1960).
	Others.		
	Leif Owren.	"Observations of Radio Emission from the Sun at 200 Mc/s and their Relation to Solar Disc Features".	Ph.D. Thesis. Cornell Res. Rep. No. EE 200.
	Pawsey and Bracewell	Radio Astronomy. 1955.	(Clarendon: Oxford)
	Kuiper (Editor)	The Sun. 1953	(Univ. of Chicago Press)

CHAPTER II.

THE ORIGIN OF BURSTS OF SOLAR RADIO NOISE.

Before investigating the possible origins of the non-thermal component of solar radio emission, the main features of the radiation are listed. A comprehensive theory would have to account for:

(a) The observed intensities.

(b) The observed frequency spectrum and frequency drift of certain types of bursts.

(c) The observed polarization characteristics. (This will be considered in detail in the next chapter).

(d) The frequency doubling observed with certain type II and III events.

Two chief lines of approach appear to have been adopted.

The first of these is that the radiation is due to excitation of various plasma levels in the corona, each plasma level having its characteristic frequency which is determined by the electron density at that particular level.

Secondly, the possibility has been considered by several workers that electrons spiralling about magnetic lines of force associated with sunspots, emit radiation.

The former approach has been loosely termed the plasma-oscillation-theory while the latter is known as the gyro-theory.

The possible theory of Cerenkov radiation by electrons travelling through the plasma has also been considered.

Ryle and Vonberg (1) were amongst the first to realize that

any/......

any theory of the origin of the sun's non-thermal radiation would involve the presence of localized regions with temperatures of the order of 10^8 to 10^{10} °K. They were concerned with results obtained at frequencies of 80 and 175 Mc/s and found that the intensity of the radiation was much greater than that predicted for a black body at a temperature of 6000°K, which was the temperature usually associated with the chromosphere.

A. Plasma oscillations.

An electro-magnetic wave travelling in a magneto-ionic medium (a medium consisting of electrons and ions and acted on by a magnetic field) is found to be propagated as two oppositely polarized waves known as the ordinary and extraordinary waves. The refractive index for radiation of frequency of the medium varies according to

$$\mu^2 = 1 - \frac{4\pi N e^2}{\varepsilon_0 m \omega(\omega \pm \omega_H)}$$ for radiation of frequency w

$$\omega_H = \frac{He}{\varepsilon_0 m c^2}$$ = gyro-frequency of the electrons.

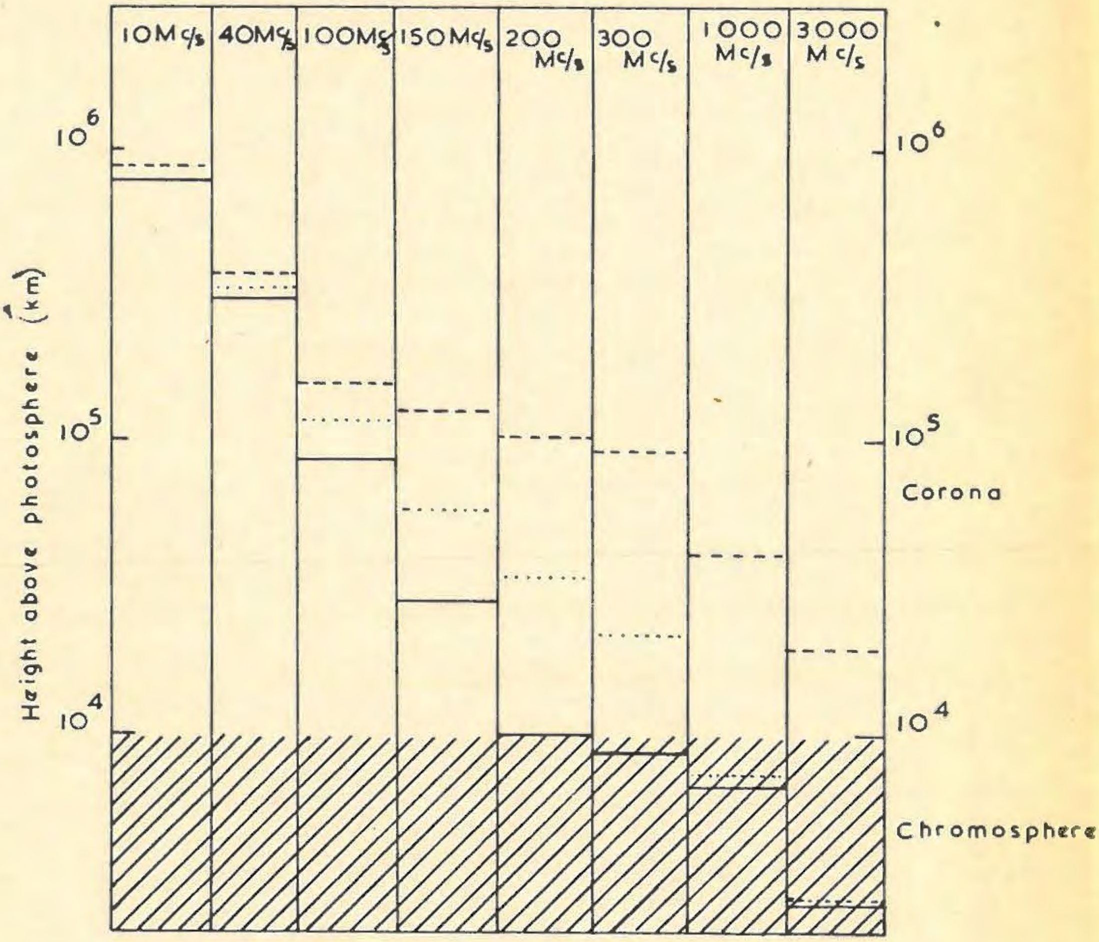
where H is the magnetic flux and N the electron density at any particular level. The + and - sign denote the value of for the ordinary and extraordinary waves respectively. As is shown in table II the refractive index for the ordinary and extraordinary waves vanish at different levels in the corona.

These levels of zero refractive index occur at:

x=1 for the ordinary ray, and
x=1 ± y for the extra-ordinary ray where;

x=/......

TABLE II



Levels of zero refractive index in the solar atmosphere. Full lines: x=1, the only level in the field free case as well as the "ordinary" level above a large sunspot (3600 gauss) and in the general magnetic field. Dotted lines: x=1−y, the "extraordinary" level in the general magnetic field. Broken lines: the "extraordinary" level above the sunspot.

$$x = \frac{W_o^2}{W^2} \qquad y = \frac{W_H}{W}$$

W_o the plasma frequency is given by $\frac{Ne^2}{E_o m}$.

The level of zero refractive index for the extraordinary mode of propagation is generally above that for the ordinary mode, the distance between these two levels increasing with increasing magnetic field. As these levels of zero, or near zero, refractive index absorb radiation they are therefore capable of emitting radiation, whose polarization would correspond to that of the mode that is absorbed at that particular level.

Because radiation cannot pass regions of zero refractive index, the term "stop bands" has been applied to such levels.

Ryle (2) considered the possibility of generation of radiation in these regions of zero refractive index. At any particular frequency one of these regions was situated at a lower altitude, higher density region where the absorption coefficient was appreciable so that considerable radiation could occur. This radiation was polarized, the sense of polarization corresponding to the ordinary mode and the intensity corresponding to the electron temperature in the region. The other region was at a greater height thought to be less dense so that the absorption coefficient might be insufficient to allow production of radiation of appreciable intensity. However, if the gas density was raised as the result of the elevation of prominence material radiation would result whose intensity could exceed that of the

ordinary/......

ordinary wave. This radiation, too, would show polarization, the sense corresponding to the extra-ordinary mode. The polarization observed at the earth would then correspond to the most intense component.

Although it was realized that regions of high absorption were also good emitters, no theory had been put forward as to how the region could be induced to emit radiation. Possibly the presence of extremely high temperatures might have accounted for some of the radiation, but it was Ryle (3) who suggested that coherent oscillations of large quantities of electrons in the corona (plasma oscillations) could account for the observed emissions, although it was still difficult to formulate a mechanism whereby such oscillations could be set up. He concluded that the observed radio frequency radiation arose from the purely random motion of the electrons in the corona at temperatures of 10^6 ^oK. Previous explanations of the cause of such plasma oscillations had all been based on laboratory phenomena and he suggested that the situation in the corona was not sufficiently similar to those existing in discharge tubes to merit the extrapolation of the laboratory theories. He felt, however, that ionic plasma oscillations of very low frequencies might be capable of causing local excitation of the electrons, this then leading to the production of bursts of radiation.

Westfold (4) was able to show that three types of plasma oscillation could exist in an anisotropic medium. He did this

by/......

by deriving the Appleton-Hartree equation for the refractive index by taking a system of axes where one axis was taken parallel to the magnetic field direction rather than along the direction of propagation. These three types of oscillations would give rise to radiations that exhibited right-handed, left-handed and linear polarizations, the former two corresponding to the two modes already considered. It can however be shown, by application of magneto-ionic theory, that only the former two could escape (12).

A slightly different approach was adopted (1949) by Jaeger and Westfold (5), who attempted to describe the observed phenomena in terms of transients produced by concentrated disturbances at various levels in the plasma. Their paper gave the solutions of a number of transient problems on propagation in a homogeneous medium both in the presence and in the absence of a magnetic field. Correlations with bursts on 85, 60, 65 and 19 Mc/s were studied and they found that bursts showed good correspondence with theory on the different frequencies with respect to predicted shape and time of arrival. The decay of bursts was approximately exponential and they quoted a damping constant of $0.6\,\mathrm{sec}^{-1}$ in the corona. Smerd, in a private communication to Westfold, has apparently been able to show that the general features of type II and III radiation could be accounted for by the emission of transient radiation sucessively from each plasma level. Again, no mention was made of the origin of these localized

disturbances./......

disturbances.

In a later paper Jaeger and Westfold (6) calculated the trajectories, equivalent path and absorption of rays in the 20 to 100 Mc/s frequency range neglecting magnetic fields and assuming spherical symmetry. They interpret the double-humped burst as a superposition of a direct and echo signal, the echo coming from the level of zero refractive index which was thought to be below the level of origin. The time delays and intensity ratio between these two alternative paths were found to agree reasonably with experimental observations provided the magnitude of the source angle was taken into consideration; large source angles were shown to produce effectively single humped bursts.

Smerd (7) pointed out that radiation at any frequency f would not be transmitted unless it originated at a height in the corona where the plasma frequency f_o was less than, or equal to, f . The radiation must be produced above these stop-bands.

Wild, Murray and Rowe (8) attempted to explain the production of harmonic bursts in terms of plasma oscillations. Outbursts frequently occurred in what appeared to be harmonic pairs the characteristic features at frequency f being duplicated at a frequency 2f. The frequency ratio was found to be just less than 2:1 (1.90-1.99) and the second harmonic intensity could be greater than, equal to or less than that of the fundamental. If it was postulated that the radiation at central frequency f_o was produced at a level in the corona having plasma frequency f_o

it/......

it followed that the lower half of the band of radiation would be cut off and the peak frequency f would appear a little higher than f_o, while the second harmonic would be less attenuated since it would be further from its level of zero refractive index. The cut-off of the lower half of the fundamental band would also explain the frequency ratio of just less than 2:1.

By combining their theory with a table showing plasma frequency variation with height in the corona the authors were able to postulate a source travelling outward through the corona with speeds of several hundred kilometers per second. Although source velocities of 3000 km per sec were needed to explain the observed time delay between a flare and terrestrial disturbances they felt that these higher velocities could be explained in terms of the asymmetry of the corona.

A similar approach was adopted by Wild, Roberts and Murray (9) who concentrated on type III bursts. They were able to localize sources to within 10^5 km of the photosphere, i.e. at the base of the corona, and source velocities of $5 . 10^4$ km/sec were postulated.

A different approach was adopted by Sen (10) who proposed that storm bursts of narrow bandwidth that originate in shock fronts of an ionized gas constituted the elementary fine structure of solar radio noise bursts. These shocks were thought to originate as weak shocks from the convective cells in the subphotospheric layers that were responsible for the granulation observed on the sun's surface. He did not, however, tackle the problem

of/......

of whether the conditions were favourable for coupling from these shock fronts (effectively space charge waves, which are waves of varying electron density) to an electromagnetic mode of propagation. He felt that discontinuities in the shock front might have favoured such coupling. His approach also required the movement of some disturbance as suggested by Wild et al (above), but the source velocities would be those of the associated shock front rather than of the actual disturbance.

Wild, Murray and Rowe (11) published a further paper, dealing with the harmonics in the spectrum of solar radio disturbances and were able to show that for the harmonic bursts, showing a frequency ratio of 2:1, the fundamental frequency corresponded to the natural frequency of plasma oscillation in the vicinity of the source. They claimed that their results suggested generation by longitudinal plasma oscillations excited by fast streams of charged particles. The harmonics suggested that the emitting process was one involving oscillations of charge which were non-linear in character. (Non-linear oscillators are known to produce harmonics. The greater the non-linearity the greater the harmonic content). Electrons gyrating in a magnetic field with orbital velocities approaching that of light could generate such harmonics.

Alternatively, they considered plasma oscillations but were unable to see how the fundamental radiation could escape from the regions of production, except along a narrow cone normal to the

surface/......

surface of zero refractive index. No such restriction had to be placed on the harmonics generated at these levels. At each level a band of radiation would be produced as has already been mentioned in referring to their earlier paper. The higher frequency components would be able to escape and on this criterion they concluded that the plasma oscillations would be likely to produce radiation.

They went further and proposed that the streams of ionized matter that have been observed visually would provide the explanation for the frequency drift, a stream exciting different frequencies at different plasma levels. A source rising in the solar atmosphere would produce a steady decrease in frequency of the received radiation. They pointed out that for large amplitudes of plasma oscillations the charge density exhibited excess bunching which might provide the necessary non-lineary and asymmetry for the generation of harmonics.

Bohm and Gross (12 a&b) have been able to show theoretically that the afore mentioned ion streams were in fact capable of exciting plasma oscillations.

Furthermore Field (13) was able to show that longitudinal plasma oscillations could be coupled to an electro-magnetic mode of oscillation provided discontinuities of density existed. He applied the theory to the production of type II bursts.

He pointed out that in a plasma two types of wave motion could exist. His discussion followed that of Piddington (14).

The/......

The first was the longitudinal or irrotational motion and the second the transverse or toroidal motion. In a homogeneous field free plasma the modes were independent, the former corresponding to what have been termed plasma oscillations and the latter corresponding to electro-magnetic waves. The two modes were in fact two ways of maintaining an electric field.

a) In plasma oscillations the source of the field was an accumulation of charge.

b) In electro-magnetic waves the source of the field was a changing magnetic field.

The plasma oscillations in themselves did not propagate but simple extensions of them, to include the effects of electron pressure on the oscillations, did propagate as plasma waves.

He was able to show that these two modes could be coupled under certain conditions. Hence the energy available in the plasma oscillation could be propagated as an electro-magnetic wave. These conditions included the presence of electron density discontinuities or the presence of static magnetic fields. (Gradient coupling or magnetic coupling). The coupling is discussed further in chapter III.

In applying this to the case of type II outbursts he adopted as a model a finite region in the corona having a sharp boundary, the whole region moving outwards to account for the frequency drift and having a density discontinuity at the boundary. Plasma waves were thought to arise behind the boundary of this region which then coupled into the electro-magnetic mode due to

this/......

this density discontinuity. The flare ejections reported by Dodson et al were thought to provide the travelling region. The region might be the actual stream of particles or the associated shock waves as mentioned before.

The presence of the second and yet not the third harmonic in type II events was again explained in terms of a moderately non-linear plasma oscillation.

A magnetic field in the regions under consideration was said to enhance the conversion from the one mode to the other. Outbursts have however been observed with no sign of polarization over their entire frequency bands showing that a magnetic field need not necessarily be present.

Although theoretically predicted energies did not correspond very well with observations, it was thought that a more realistic model of the source region and a more accurate knowledge of the variations of density across the boundary might have enabled a more exact estimate to have been made.

Westfold (15) published a further paper dealing with the presence of these associated shock waves and in turn applied his results to the analysis of bursts. He too felt that the frequency drift shown by bursts of type II and type III should rather have been associated with the velocities of the shock waves that accompanied the motions of large regions of particles in the corona. These waves travelled with velocities exceeding that of the particle clouds and also exceeding that of sound in

the/......

the medium. Across these shock fronts there would be abrupt transitions in the values of the physical quantities, such as velocity, density and pressure, that specified the state of the gas. Such disturbances might have given rise to transient radiation as considered by Jaeger and Westfold. These density changes could almost certainly have promoted coupling between the modes discussed by Field. One interesting result that also arose from his paper was the concept of magnetic fields being "frozen" into the particle clouds as they moved outwards.

The idea that the rate of frequency drift was associated with a shock front rather than with the actual moving particle cloud was suggested relatively early on by Takakura (16) who pointed out that Wild's "critical frequency hypothesis" could not satisfactorily be applied above 200 Mc/s. Takakura pointed out a serious discrepancy in the frequency drift rates from 200 Mc/s to 3000 Mc/s and for Wild's hypothesis to have been correct, very sudden changes in drift velocity would have been necessary at the base of the corona.

He then attempted to explain the features of outbursts in terms of the rate of expansion of a dense ionized cloud, the centre of which might drift or remain fixed. The rate of frequency drift was associated with the rate of density variation in the expanding gas front. He also suggested a means by which electro-magnetic waves could have been generated in such a front. This was in terms of an electric double layer that might grow in

the/......

the shock front due to the difference in mobilities of electrons and ions. The electric field so set up might retard the expanding motion of electrons causing plasma oscillations which would lead to the emission of radiation.

Gyro-theory.

An alternative source mechanism that was proposed was based on the well known experimental fact that an electron rotating about a magnetic line of force emits radiation of a frequency given by $\frac{eH}{E_o mc^2}$.

Ryle (2) was the first to consider this posibility. He pointed out that the more intense radiation associated with the presence of large sunspots was usually circularly polarized, and that the sense of rotation was different for different spots and suggested that the rotation of electrons around a magnetic field of the sunspot played a part in the production or propogation of the radiation.

The results of magneto-ionic theory showed that an electromagnetic wave travelling in any direction relative to a magnetic field was split into two characteristically polarized waves (the ordinary and the extra-ordinary waves) propagated with different phase velocities and undergoing different absorptions.

When the wave travelled parallel to the magnetic field direction the two waves were oppositely circularly polarized. The extra-ordinary wave was that wave whose electric vector rotated in the same direction as the freely gyrating electrons. Absorption/......

tion occurred when accelerated electrons collide with ions, thereby losing energy abstracted from the incident wave.

Now the radiating and absorbing powers of bodies were closely related, hence a heated electron gas would radiate a wave whose frequency equaled that of the free gyration of electrons and whose polarization corresponded to that of the extra-ordinary wave. Since absorption was great, a relatively thin layer was suffieient to produce a wave whose intensity corresponded to the mean temperature of the electrons.

There was also the possibility that an electron in gyrating freely about the magnetic field of a sunspot generated circularly polarized radiation, magnetic fields of 20 to 80 gauss being needed for the generation of frequencies of 50 to 200 Mc/s.

The expression for the refractive index μ in a plasma in the presence of a magnetic field can be written as

$$\mu^2 = 1 - \frac{Ne^2}{E_o m (W \pm W_H)}$$

where W_H, the gyro-frequency, $= \frac{eH}{E_o mc^2}$

It was assumed that the magnetic field intensity H decreased with height above a sunspot with the result that the value of the gyrofrequency decreased so that the expression for μ^2 was always negative. Thus would be imaginery in regions above the source of gyro radiation with the result that such a wave, propagated in the extra-ordinary mode, could only escape from the sun by being propagated as an exceptionally attenuated evanescent wave. This

would/......

would permit the transmission of very little energy. The wave could be propagated downwards provided the refractive index of the plasma level in the immediate neighbourhood was not zero or imaginary. This would be the case if the source of radiation was above the region where x=1.

Ryle pointed out that Alfven (17) had shown that a potential difference between the sun's pole and equator was set up due to the existence of differential rotation of surface matter in the presence of the sun's permanent magnetic field. He pointed out that provided there was a small angle between the magnetic field axis and the axis of rotation, potential difference of 10^7 V could appear between two points on a magnetic line of force. This, would lead to the maintenance of temperatures of the order of 10^6 to 10^{8} °K and, in the neighbourhood of sunspots, 10^{10} °K due to the increased distortion of the lines of force relative to the axis of rotation.

This heated gas would emit radiation at those frequencies which were appreciably absorbed. The greatest radiating power would occur at the frequency of free gyration of the electrons in the magnetic field and thus it was expected that each region above a sunspot would emit elliptically polarized radiation whose intensity would correspond to the electron temperature at that level, and whose polarization would correspond to the extra-ordinary wave.

Kruse, Marshall and Platt (18) argued that synchrotron radia-

tion/......

tion was in fact propagated in both the ordinary as well as the extra-ordinary modes. The extra-ordinary band still encountered a stop band as mentioned above, but the ordinary mode could escape provided it was produced in a region where $\frac{W_o}{W} < 1$ (W_o the plasma frequency, W the signal frequency). The polarization depended ordinarily on $\frac{W_o}{W}$ but the polarization of synchrotron radiation depended only on the electron velocity and the orientation in the magnetic field. The polarization was independant of the medium whereas the propagation depended on the medium. The polarization could therefore be expressed in a linear combination of polarizations of the two modes for the appropriate values of $\frac{W_o}{W}$ and $\frac{W_H}{W}$, and the synchrotron radiation, in general, propagated in both modes. If $\frac{W_o}{W} > 1$ both modes were strongly absorbed, but for $\frac{W_o}{W} < 1$ the ordinary mode could escape without travelling through a stop band.

Magnetic fields in large sunspots may be as large as 5000 gauss. In a field of only 50 gauss the fundamental gyro-frequency is 150 Mc/s.

The presence of the second harmonics in harmonic bursts was satisfactorily explained if the electron velocities lay between the limits $0{\cdot}002 < \beta < 0{\cdot}2$ where $\beta = \frac{v}{c}$ and v= velocity of the electron and c is the velocity of light. The lower limit was obtained from considerations of the temperatures (10^4 ^oK) that were thought to exist in the regions above sunspots.

This mechanism has also been successfully used to explain

certain/......

certain non-thermal galactic radio emissions.

Twiss and Roberts (19) published a paper in which they discussed the results obtained by Kruse et al. The latter , in explaining that non-thermal radiation was synchrotron in origin, claimed that the radiation could be emitted in both modes so that previous objections to this theory were overruled. Twiss and Roberts pointed out that the estimates made by Kruse et al were based on the hypothesis that an electron gyrating in a plasma radiated in the same manner as an electron gyrating in free space. These assumptions were thought to be invalid and they discussed the propagation in the plasma in detail. They concluded that the phenomena observed with type II and III events could not be explained in terms of the gypo-theory, but that radiation of type I might be. As will be pointed out in the next chapter, this theory can in fact not account for the observed effects of type I bursts either.

C. Cerenkov radiation.

Another different approach has been tried by Marshall (20) who proposed that Cerenkov radiation might account for the observed radiations.

He suggested that jets of electrons were created in sunspots and directed at arbitrary angles to the associated fields. If the electron jets had such a direction that the electrons spiralled up out of a sunspot, the frequency of emission would decrease, corresponding to decreasing magnetic field and decreasing plasma

density/......

density. The radiation would be of short duration because the high speed electrons soon reached distances at which the magnetic field was too low to allow emission of Cerenkov radiation.

If the electrons moved at right angles to the magnetic field they would remain circling in this high magnetic field and would emit high-frequency radiation for a considerable time. The variation of emission frequency then depended on the variations of electron density and the magnetic fields associated with a particular spot. Electron jets could follow the lines of force up out of a spot causing a steady decrease in the frequency of the emitted radiation and at the top of the line of force, the axis of the helix would be parallel to the sun, with the result that the frequency of radiation would remain constant for some time. As the electrons spiralled down the other side they would not broadcast in the direction of earth as Cerenkov radiation was emitted mainly in the forward direction.

Marshall showed that there were two limits to the frequencies of emission, one corresponding to the gyro-frequency W_H and the other to the plasma frequency W_o. He found that over large regions W_o was approximately equal to $\frac{W_H}{2}$ but did not believe that the frequency doubling observed by Wild et al was related to this. Radiation at two or more frequencies could be attributed to different electron jets spiralling up out of the spot. The predicted intensity of the received radiation was in good agreement with observations.

Summary/......

Summary.

It is generally felt that the gyro-theory cannot adequately explain the non-thermal radiation from the sun and the plasma oscillation theories are still being developed, more attention being paid to the possible coupling that can occur between the various modes of propagation in an anistropic plasma.

REFERENCES CHAPTER II.

(1)	Ryle and Vonberg.	"An Investigation of R/F Radiation from the Sun".	Proc.Roy. Soc.A. 193,98. (1948)
(2)	Ryle.	"The Generation of R/F Radiation in the Sun".	Proc.Roy. Soc.A. 195,82. (1948),
(3)	Ryle.	"The Significance of the Observations of Intense R/F Emission from the Sun".	Proc.Phys.Soc.A. 62,483. (1949).
(4)	Westfold.	"The Wave Equations for Electromagnetic Radiation in an Ionized Medium in a Magnetic Field."	Aust.J.Sci.Res.A. 2,169. (1949).
(5)	Jaeger and Westfold.	"Transients in an Ionized Medium with Applications to Bursts of Solar Noise".	Aust.J.Sci.Res.A. 2,322. (1950).
(6)	Jaeger and Westfold.	"Equivalent Path and Absorption for Electromagnetic Radiation in the Solar Corona".	Aust.J.Sci.Res.A. 3,376. (1950).
(7)	Smerd.	"A R/F Representation of the Solar Atmosphere".	Proc.I.E.E. 97,447. (1950).
(8)	Wild, Murray and Rowe.	"Evidence of Harmonics in the Spectrum of a Solar Radio Outburst".	Nature. 172,533. (1953).
(9)	Wild, Roberts and Murray.	"Radio Evidence of the Ejection of Very Fast Particles from the Sun".	Nature. 173,532. (1954).
(10)	Sen.	"Space Charge Wave Amplification in a Shock Front and the Fine Structure of Solar Radio Noise".	Aust.J.Phys. 7,30. (1954).
(11)	Wild, Murray and Rowe.	"Harmonics in the Spectra of Solar Radio Disturbances".	Aust.J.Phys. 7,30. (1954).

(12)	a) Bohm and Gross	"Theory of Plasma Oscillations."	Phys.Rev. 75,1851 (1949).
	b)	"Effects of Plasma Boundaries in Plasma Oscillations."	Phys.Rev. 79,992 (1950).
(13)	Field.	"Radiation by Plasma Oscillations."	Astrophys.J. 124,555 (1956).
(14)	Piddington.	"The Four Possible Waves in a Magneto-ionic Medium."	Phil.Mag. 46,1037 (1955).
(15)	Westfold.	"Magneto-hydro-dynamic Shock Waves in the Solar Corona."	Phil.Mag. 2,1287 (1957).
(16)	Takakura.	"Frequency Drift of Solar Radio Bursts."	Publ.Astr.Soc.Japan. 6,185 (1954).
(17)	Alfven.		Z.Phys. 105,633 (1937).
(18)	Kruse,Marshall & Platt.	"Synchrotron Radiation in the Sun's Radio Sepctrum."	Astrophys.J. 124,601 (1956).
(19)	Twiss & Roberts.	"Electromagnetic Radiation from Electrons Rotating in an Ionized Medium undar the Action of a Uniform Magnetic Field."	Aust.J.Phys. 11,424 (1958).
(20)	Marshall.	"Production of the Sun's Non-thermal Emission by Cerenkov Radiation."	Astrophys.J. 124,469 (1956).

CHAPTER III

THE POLARIZATION OF SOLAR RADIO NOISE

In the previous chapter several theories as to the possible origin of solar radio noise were outlined. The polarization aspect had not be considered.

A knowledge of the polarization characteristics of the various types of bursts would enable one to understand more fully the source mechanisms that might be operative and it might also be possible to obtain a better understanding of the sizes of the magnetic fields that are known to be present in the region of sunspots.

This chapter has been divided into the following sections.

(A) Specification of polarization, outlining the description of polarization in terms of 4 simple parameters.

(B) The Faraday Effect, being a discussion of the influence of a magneto-ionic medium on a polarized radio wave.

(C) The Polarization of Solar Radio Emission, being a short review of the results of other workers in this field.

(D) Polarization Mechanisms. The possible mechanisms producing polarization are discussed.

(E) The Measurement of Polarization. A short discription of the principles of radio polarimetry, as an introduction to chapter IV, is given.

A. Specification of Polarization

The wave theory of electro-magnetic radiation leads to the concept of electrical and co-existing magnetic disturbances

being ....../

being propagated with a velocity "c", these vibrations (disturbances) being transverse to the direction of propagation in free space and mutually at right angles.

Unpolarized radiation consists of waves in which the vibrations are transverse with no preferential direction of vibration. If one can picture the source as being electrons in motion, then one must picture completely random motion of these electrons in the case of unpolarized radiation. However, under various circumstances, these motions can become more ordered with the result that the direction and characteristics of the electro-magnetic vibrations are more restricted.

In plane polarized radiation (i.e. linearly polarized) the motions of the electric and magnetic vectors are in straight lines.

Sometimes the vibrations are in elliptical or circular paths due to the rectangular composition of vibrations of equal periods with appropriate phase differences. Such waves are said to be elliptically or circularly polarized.

It should be noted that a single plane wave is always "polarized", having constant orientation of its electric and magnetic field vectors. Any wave can then be thought of as consisting of a combination of plane waves of different magnitudes, phases and directions of propagation. An unpolarized wave then is a combination of a number of plane waves in the same direction, but of arbitrary magnitudes, phases and orientation of field vectors, whereas elliptically polarized

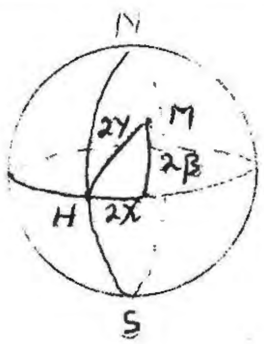
radiation....../

radiation could be thought to consist of two uniform plane waves of different phases, magnitudes and orientations of field vectors.

To describe the radiation field fully we need to specify 4 parameters; the intensity I, the degree of polarization m $(=\frac{I_e}{I})$ (where I_e is the intensity of the polarized part and I the total intensity), plane of polarization or orientation, and the ellipticity or axial ratio r.

In the general case of a partly polarized wave being received from the sun the radiation will have a noise spctrum which can be defined as a purely random time rate of variation of intensity. The polarized part will have a noise spectrum and will have coherence between components at right angles, whereas the components at right angles in the case of the unpolarized part are independent. For elliptically polarized radiation the electric vector will continually sweep out an ellipse whose size will vary according to the noise spectrum but whose orientation, axial ratio and sense of rotation will remain constant.

A convenient way of representing the state of polarization of any wave is the use of Poincare's sphere.



The ....../

The shape of the ellipse, $\mathcal{E}$, locus of the extremity of the electric vector, can be specified by the axial ratio

$$r = \frac{\text{minor axis}}{\text{major axis}}$$

To indicate the sense of rotation at the same time this ratio can be given a + or - sign (+ indicates right handed.) Further the ellipticity angle β is defined as $\beta = \tan^{-1} r$. $(-45^\circ < \beta < 45^\circ)$

The orientation angle χ is the angle between the x axis and the major axis and is always positive and less than 180°. These two angles completely specify the state of polarization for a completely polarized wave.

Poincare's representation consists of taking 2γ and 2β as longitude and latitude of a point on a sphere. Each point then represents a particular state of polarization. It can be seen that on the "equator" points are equivalent to linear polarizations, the points at the "poles" circular, and points on the rest of the surface represent elliptical polarization.

It can be shown (1) that if the polarization ratio P .. - can be written as $\tan\gamma\, e^{j\phi}$ then

$$\cos 2\gamma = \cos 2\beta \cos 2\chi \qquad P = -\frac{H_x}{H_y} = +\frac{E_y}{E_x}$$

$$\tan \phi = \tan 2\beta \operatorname{cosec} 2\chi$$

These are well known formula of spherical trigonometry showing that the difference in phase ϕ between the vertical and horizontal components of the field is the angle H on the sphere, while the amplitude ratio Tan γ is determined by the distance HM=2Y

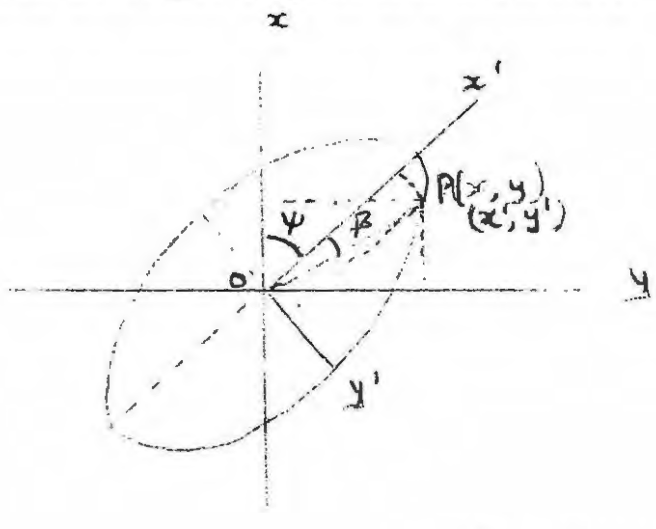
This ....../

This notation is useful in the case of waves travelling through an anisotropic medium, since points such as M are obtained by stereographic projection of the complex plane of P onto the sphere and in transversing such a medium one need only perform the correct type of transformation, enabling the new state of polarization to be determined.

It is rather difficult to derive symmetrical formula containing the 4 parameters previously mentioned, i.e. an intensity, ratio, angle and a pure number, so it is convenient to introduce 4 parameters relating the above and which can in turn be related to antenna measurements. These new parameters are named after their originator, Stokes, and are here derived.

Stokes Parameters (2)

If we consider an elliptically polarized beam then, in the plane transverse to the direction of propagation, the vibrations of the electric and magnetic vectors are such that the ratio of the amplitudes and the difference in phase of the components in any two directions at right angles are constant.



The ....../

The radiation can then be resolved into two components at right angles to one another (x and y axes say) which are given by

$$x = X \,\mathrm{Sin}(wt - \epsilon x)$$
$$y = Y \,\mathrm{Sin}(wt - \epsilon y) \qquad \ldots\ldots\ldots(1)$$

where the ratio of amplitudes X,Y and the difference in phases ϵx and ϵy are constant. Note that for right hand polarization the electric vector rotates in a clockwise direction when viewed along the direction of propagation. (z axis).

If these axes coincide with the major and minor axis of the ellipse, the components become

$$x' = A \,\mathrm{Cos}\,\beta \,\mathrm{Sin}\, wt$$
$$y' = A \,\mathrm{Sin}\,\beta \,\mathrm{Cos}\, wt \qquad \ldots\ldots\ldots(2)$$

i.e. the components are in time, as well as in space, quadrature.

We have also:

the amplitude of the x' component $= A \,\mathrm{Cos}\,\beta$: of x component = X

" " " " y' " $= A \,\mathrm{Sin}\,\beta$: " y " = Y

$\therefore$ if intensity of beam = I

then $I = A^2 = X^2 + Y^2$ ....(3)

The axial ratio is defined by $\beta = \tan^{-1} r$ ....(4)

If r is positive, β lies in the first quadrant; $\mathrm{Sin}\,\beta$ and $\mathrm{Cos}\,\beta$ are both +ve, and hence, by (2), y' leads on x' by $\pi/2$ and the ellipse is traced out anti-clockwise and the radiation is left-handed.

Since (1) and (2) represent the same vibration (2) can be transformed into (1) by rotation of the axes through angle χ.

counterclockwise..../

counterclockwise.

If P is the point (x,y) and (x',y') we have,

$$x = x'\cos\chi - y'\sin\chi$$

$$y = x'\sin\chi -- y'\cos\chi$$

and then from (2)

$$x = A\cos\beta\cos\chi\sin\omega t - A\sin\beta\sin\chi\cos\omega t$$

$$y = A\cos\beta\sin\chi\sin\omega t - A\sin\beta\cos\chi\cos\omega t$$

but from (1)

$$x = X\cos\epsilon_x\sin\omega t - X\sin\epsilon_x\cos\omega t$$

$$y = Y\cos\epsilon_y\sin\omega t - Y\sin\epsilon_y\cos\omega t$$

and since these must hold for all 't' we can say

$$X\cos\epsilon_x = A\cos\beta\cos\chi \qquad Y\cos\epsilon_y = A\cos\beta\sin\chi$$

$$X\sin\epsilon_x = A\sin\beta\sin\chi \quad \text{and} \quad Y\sin\epsilon_y = -A\sin\beta\cos\chi \quad \ldots\ldots(5)$$

$\therefore \quad \tan\epsilon_x = \tan\beta\tan\chi \qquad \tan\epsilon_y = -\tan\beta\cot\chi$

and $\quad X = A(\cos^2\beta\cos^2\chi + \sin^2\beta\sin^2\chi)^{1/2}$

$$Y = A(\cos^2\beta\sin^2\chi + \sin^2\beta\cos^2\chi)^{1/2} \quad \ldots\ldots(6)$$

$\therefore$ The intensities I_x and I_y can now be rewritten as

$$I_x = X^2 = A^2(\cos^2\beta\cos^2\chi + \sin^2\beta\sin^2\chi)$$

$$I_y = Y^2 = A^2(\cos^2\beta\sin^2\chi + \sin^2\beta\cos^2\chi)$$

which simplifies to give

$$I = I_x - I_y = X^2 \text{ as is to be expected.} \quad \ldots\ldots(7)$$

Similarly $I_x - I_y = A^2[\cos^2\beta(\cos^2\chi - \sin^2\chi) - \sin^2\beta(\cos^2\chi - \sin^2\chi)]$

$$= A^2(\cos^2\beta - \sin^2\beta)(\cos^2\chi - \sin^2\chi)$$

We call this quantity Q

$$Q = I_x - I_y = I_r\cos 2\beta\cos 2\chi \quad \ldots\ldots(8)$$

These two quantities I and Q are the first two of the Stokes

parameters ....../

parameters and have been derived by simple manipulation of the two basic equations.

Further by multiplying the equations (5) together we get,

$$XY \cos \varepsilon_x \cos \varepsilon_x = A^2 \cos^2 \beta \sin \chi \cos \chi$$

$$XY \sin \varepsilon_y \sin \varepsilon_y = -A^2 \sin^2 \beta \sin \chi \cos \chi$$

adding

$$2XY \cos(\varepsilon_x - \varepsilon_y) = 2A^2(\cos^2 \beta - \sin^2 \beta) \sin \chi \cos \chi$$

$$= I \cos 2\beta \sin 2\chi$$

Call this U.

i.e. $U = 2XY \cos(\varepsilon_x - \varepsilon_y) = I \cos 2\beta \sin 2\chi$

$$= (I_x - I_y) \tan 2\chi \qquad \ldots\ldots\ldots(9)$$

Finally,

$$XY \sin \varepsilon_x \cos \varepsilon_y = A^2 \sin \beta \cos \beta \sin^2 \chi$$

$$XY \cos \varepsilon_x \sin \varepsilon_y = -A^2 \sin \beta \cos \beta \cos^2 \chi$$

subtracting

$$2XY \sin(\varepsilon_x - \varepsilon_y) = 2A^2 \sin \beta \cos \beta (\sin^2 \chi + \cos^2 \chi)$$

and calling this V,

$V = 2XY \sin(\varepsilon_x - \varepsilon_y) = 2I \sin \beta \cos \beta$

$$= I \sin 2\beta \qquad \ldots\ldots\ldots(10)$$

$$= (I_x - I_y) \tan 2\beta \sec 2\chi$$

These 4 parameters I,Q,U and V are the Stokes parameters and completely specify the wave. They apply to partly polarized waves and only difference being that $I = I_e - I_u$ and I_e replaces I in equation above. The quantities m, r and χ are given by

$$m = \frac{(Q^2 + U^2 + V^2)^{1/2}}{I} \qquad \ldots\ldots\ldots(11)$$

$$\sin 2\beta = \frac{V}{I_e} \qquad \ldots\ldots\ldots(12)$$

$$\tan 2\chi = \frac{U}{Q}$$

If......../

If we now concern ourselves only with phase differences we can rewrite (1), neglecting the constant phase terms, thus;

$$x = X \sin \omega t \qquad y = Y \sin(\omega t - \delta)$$

If now we introduce a constant phase retardation ϵ into the y component we get

$$x = X \sin \omega t \qquad y = Y \sin(\omega t - \delta - \epsilon)$$

and resolving the resultant vibration in the direction making an angle ψ with the x axis, we get,

$$\begin{aligned} A_{(\psi,\epsilon)} &= X \sin \omega t \cos \psi + Y \sin(\omega t - \delta - \epsilon) \sin \psi \\ &= [X \cos \psi + Y \cos(\delta + \epsilon) \sin \psi] \sin \omega t - Y \sin(\delta + \epsilon) \sin \psi \cos \omega t \\ &= P \sin \omega t \cos \alpha - P \cos \omega t \sin \alpha \\ &= P \sin(\omega t - \alpha) \end{aligned} \qquad \text{.......(14)}$$

where $P \cos \alpha = X \cos \psi + Y \cos(\delta + \epsilon) \sin \psi$
$P \sin \alpha = Y \sin(\delta + \epsilon) \sin \psi$

ie. $P^2 = X^2 \cos^2 \psi + Y^2 \cos^2(\delta + \epsilon) \sin^2 \psi + 2XY \cos(\delta + \epsilon) \sin \psi \cos \psi + Y^2 \sin^2(\delta + \epsilon) \sin^2 \psi$

$$= X^2 \cos^2 \psi + Y^2 \sin^2 \psi + 2XY \cos(\delta + \epsilon) \sin \psi \cos \psi \qquad \text{.......(15)}$$

∴ The momentary intensity in the ψ direction is equal to P^2. For arbitrarily polarized light, X and Y are variable quantities and hence the mean intensity in the ψ direction is

$$I(\psi, \epsilon) = \overline{X^2} \cos^2 \psi + \overline{Y^2} \sin^2 \psi + \{2\overline{XY \cos \delta} \cos \epsilon - 2\overline{XY \sin \delta} \sin \epsilon\} \times \sin \psi \cos \psi$$

In the x direction $\psi = 0$; in the y direction $\psi = \frac{\pi}{2}$

$$\therefore I_x = \overline{X^2} \quad \text{and} \quad I_y = \overline{Y^2}$$

and if we put $U = 2\overline{XY \cos \delta}$ $\quad V = 2\overline{XY \sin \delta}$

from (9) and (10)

we ..../

we get:-

$$I(\psi,\epsilon) = I_x \cos^2\psi + I_y \sin^2\psi + \tfrac{1}{2}(U\cos\epsilon - V\sin\epsilon)\sin 2\psi$$

$$= \tfrac{1}{2}\Big[(I_x\cos^2\psi + I_x\sin^2\psi) + (I_y\cos^2\psi + I_y\sin^2\psi) + (I_x\cos^2\psi - I_x\sin^2\psi) - (I_y\cos^2\psi - I_y\sin^2\psi)$$

$$+ \tfrac{1}{2}(U\cos\epsilon - V\sin\epsilon)\sin 2\psi$$

$$= \tfrac{1}{2}\Big[(I_x + I_y) + (I_x - I_y)(\cos^2\psi - \sin^2\psi) + (U\cos\epsilon - V\sin\epsilon)\sin 2\psi\Big]$$

$$= \tfrac{1}{2}\Big[I + Q\cos 2\psi + (U\cos\epsilon - V\sin\epsilon)\sin 2\psi \quad \ldots\ldots(16)$$

where

$$I = I_x + I_y$$
$$Q = I_x - I_y$$
$$U = 2\overline{XY\cos\delta} \qquad \ldots\ldots\ldots\ldots(17)$$
$$V = 2\overline{XY\sin\delta}$$

If we had chosen two axes at 45° to the x and y axes used above the equations (17) would have become

$$I = I_s + I_t$$
$$Q = 2\overline{ST\cos\delta_t}$$
$$U = I_t - I_s \qquad \ldots\ldots\ldots\ldots(18)$$
$$V = 2\overline{ST\sin\delta_t}$$

where we call the axes the s and t axes. δ_t = phase difference

If we measure circular polarizations in two directions, i.e. R.H. and L.H., I_r and I_l

$$I = I_l + I_r$$
$$Q = 2\overline{RL\cos\delta_r}$$
$$U = 2\overline{RL\sin\delta_r} \qquad \ldots\ldots\ldots\ldots(19)$$
$$V = I_l - I_r$$

The intensities I_n are all directly measurable, being proportional to the powers in the appropriate antennas.

The measurement techniques will be discussed in detail in

the....../

the next section and it is sufficient to point out briefly that the Stokes parameters can be obtained by measuring either with aerials polarized in the x,y, s and t axes or a combination of two of these together with circularly polarized aerials. Another alternative is to measure with one set of aerials and place varying phase delays into the lead from one of them (e.g. the y oriented aerial). Cohen (3) has shown that the products XY are proportional to the amplitudes of the cross-correlation function of the signals in oppositely polarized aerials. He defined a new parameter ρ as the measure of coherence between the right and left circularly polarized components. The cross-correlation function between these two was written as $\gamma = \rho \cos \tau$ where τ was the phase difference plus any differential time lag. The factor ρ, the amplitude of the cross-correlation function turned out to be related to the Faraday dispersion angle.

He also defined a second new parameter, a, the ratio of the intensities of the two circular components. Then, for quasi-longitudinal propagation, 'a' was a measure of the difference in optical depths of the two magneto-ionic modes. In terms of (I,m,r,χ), ρ and a are given by

$$\rho = \frac{m \cos 2\beta}{(1 - m^2 \sin^2 2\beta)^{1/2}}$$

$$a = \frac{1 \pm m \sin 2\beta}{1 \mp m \sin 2\beta} \qquad \text{.....(20)}$$

B......./

B. The Faraday Effect on Polarized Radiation

As has been mentioned in a previous chapter, bursts of solar radio noise have been thought to be circularly polarized or to be a mixture of a circularly polarized component and a randomly polarized component and often appeared entirely unpolarized.

However Hatanaka (4) has found that some bursts are linearly polarized and that the state of polarization seems to show some dependence on the position of the source on the sun's disc. He found that the ellipticity was correlated with the position of the source of the disc, the degree of polarization was less correlated with the position of the source on the disc and that the orientation of the ellipse appeared to show no correlation whatever.

If a beam of electromagnetic radiation is incident on an anisotropic plasma, i.e. a medium consisting of electrons and positive ions under the influence of an magnetic field, it is found that the wave is propagated as two waves, known as the characteristic waves or characteristic modes of propagation, each with their own phase velocities. These two rays, known as the ordinary and extraordinary rays, experience different effects in such a medium. Due to their different phase velocities the refractive index of the medium appears different to the two rays and their phases alter relative to one another as they travel through the medium. It is further found that when these two modes are propagated through such a medium they

are....../

are each elliptically polarized with opposite senses of rotation.

If one ray suffers a phase change of any sort and, on leaving the medium, recombines with the other mode, the resultant will differ from the original incident ray. Provided the applied magnetic field is not transverse to the direction of propagation it is found that the orientation of the ellipse is not the same as for the incident ray.

It is found that for low frequencies, of the order of tens of Mc/s, the ellipticity may also alter.

Bursts of solar radio noise, in their passage from the source on the sun's surface to the recording radiometer, have to pass through two such regions of anisotropic plasma; the solar corona with magnetic fields either due to sunspots or the normal dipole field of the sun, and the earths ionosphere, (in the presence of the earth's magnetic field).

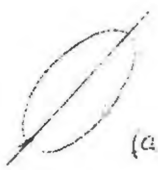
Firstly the effect of the earth's ionosphere on an elliptically polarized wave from the sun will be considered in detail.

If we consider an incident elliptically polarized beam of radiation whose orientation is γ and if the orientation on emergence is $\gamma + \phi$ then the angle ϕ is known as the rotation of the ellipse, at the particular frequency concerned. A receiver has, however, a finite bandwidth and both Hatanaka(4) and Cohen (5) have shown that the amount of rotation is proportional to the inverse square of the frequency and that even for two closely spaced frequencies the difference in rotation can be considerable.

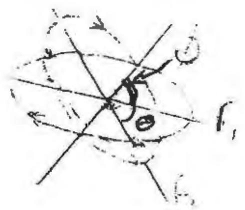
The....../

The effect of a finite bandwidth is now briefly examined.

If we have initially a wave polarized as shown in the figure a below and if we assume that the spectrum is uniform with frequency over the bandwidth under consideration, which, for solar radio bursts, is an entirely reasonable assumption, then after traversing the medium the ellipses at each frequency over the bandwidth would experience a different degree of rotation, and the emergent beam would appear as shown in figure b



(a)



(b)

The ellipses have rotated by different amounts for different frequencies between f_1 and f_2, the limits of the pass band of the receiver. The angle θ in figure b is known as the dispersion angle. If this angle is sufficiently large the resultant ellipses may have all possible orientations spread over 360°. The result of this is that the receiver, which sees only the total of the radiation spread over this frequency range, interprets the radiation as being unpolarized. A similar depolarizing effect may occur for an initially linearly polarized wave.

From the expression $\phi = \frac{c}{f^2}$

we may obtain a measure of the angular dispersion from

$$\frac{d\phi}{df} = -\frac{2c}{f^3} = -\frac{2\phi}{f}$$

If $\frac{\Delta f}{f} = \frac{f_1 - f_2}{f} \ll 1$ then $\frac{d\phi}{\phi} = -2\frac{df}{f}$

becomes $\frac{\theta}{\phi} \approx 2\frac{\Delta f}{f}$

where....../

where θ is the dispersion angle corresponding to the frequency band limited by f_1 & f_2

The actual expression for ϕ has been used by Murray and Hargreaves (6) to explain the fading of moon echoes and is derived by both Cohen and Hatanaka. The exact expression is

$$\phi = 2.36 \times 10^{-4} f^{-2} \int_0^z n B_L dz$$

where ϕ is in radians

f is in megacycles per second

n = no of electrons per cc

B_L = longitudinal component of magnetic flux (Gauss)

z is in kilometres.

This is the rotation over a distance z, in the medium.

As the ionosphere acts as a medium that can cause such a rotation for polarized radio waves from the sun it would be useful to know the total effect that the ionosphere in fact has, so that an idea can be formed as to the state of the wave as it entered this dispersive medium, assuming that we will then have indirect information about the orientation of the plane of polarization of the wave as it left the solar corona. This presupposes that there does not exist another, possibly unknown, region of plasma in the sun-earth' space which is at the same time under the influence of an appreciable magnetic field. This point will be discussed further later.

To obtain a measure of the rotation and dispersion in the ionosphere it will be necessary to have information about the total electron content as well as the strength of the earth's

magnetic....../

magnetic field in the ionosphere. The latter is relatively constant over the region under consideration, it being of the order of 0.5 gauss.

Knowledge of the electron densities existing up to level of the f_2 maximum region has been available from interpretations, by many workers, of the records from conventional ionosphere sounding equipment. Information about the densities at heights greater than the maximum that echo sounding apparatus could observe, have been based on conjecture. The major breakthrough occured when several workers succeeded in obtaining radio echoes from the moon. They were able to determine the total electron content of the ionosphere by measuring the amount of rotation of their echo signal. These workers discovered that the intensity of the echo observed on a plane polarized aerial showed a slow cyclic variation which they rightly attributed to the change in the orientation of the received signal due to a change in the electron density in the ionosphere. Their original experiments only gave a measure of the variation of electron density, but by performing the experiment on two closely spaced frequencies simultaneously the actual electron content could be calculated.

For suppose that Ω_L and Ω_H denote the phase angles at the low and high frequencies respectively.

Then for a minimum on the lower frequency

$$\Omega_L = (2n+1)\pi \qquad n = 0, 1, 2 \ldots$$

$$\Omega_H = [2(n-q)+1]\pi \pm \pi \frac{t}{T} \qquad q = 0, 1, 2 \ldots$$

If....../

If the two frequencies are

$$f\sqrt{1-\delta} \quad \text{and} \quad f$$

But $f^2 \delta\Omega_H = f^2(1-\delta)\,\delta\Omega_L$

$$(2n+1)\pi(1-\delta) = [2(n-q)+1]\pi \pm \frac{\pi t}{T}$$

$$\therefore \delta\Omega_H = \frac{2q \pm t/T}{\delta} \text{ radians}$$

By this method the rotation could only be calculated to ½ a rotation in 4.

Another method was to use the signals received from artificial earth satellites(7). The received signals from a satellite show several fading patterns caused either by the spinning of the satellites or the Faraday effect in the ionosphere. By observing on two mutually perpendicular aerials the effect of satellite spin could be eliminated and further, by observing on two discrete frequencies, values for total electron content have been calculated from the amount of Faraday rotation observed. Typical values of electron content have been found to be of the order of 2×10^{13} electrons during the day.(8) Assuming a field strength of 0.5 gauss over the whole path, we may derive a value for ϕ and θ

$$\phi = \frac{2.36\times10^{4} \times 0.5 \times 2\times10^{13}}{9\times10^{16}} \quad \text{for } 300 \text{ Mc/s}$$

$$= 2.6 \text{ radians}$$

$\frac{\theta}{\phi} = 2\frac{\Delta f}{f}$. If we assume a bandwidth of 30 kc/s

$$\therefore \theta = \frac{2\times30}{3\times10^{5}} \times 2.6 = 5.2\times10^{-4} \text{ radians.}$$

Although....../

Although the depolarizing effect due to dispersion can be seen to be negligible (5.2×10^{-4} radians) the orientation of the plane of polarization will have been changed by several radians. In comparison with the amount of rotation due to propagation through the solar corona (10^{3} - 10^{4} radians) this too is negligible so it appears that an accurate knowledge of the electron content of the earth's ionosphere is not as essential as it was in the case of lunar radio echo experiments.

Although the effect in the earth's ionosphere is negligible compared to the corona, the depolarizing effect of even small receiver bandwidths is considerable and Cohen (5) has outlined methods whereby it is possible to obtain an indication of the orientation of the plane of polarization and the axial ratio at the source. This can be done by measuring, either at two frequencies, or with two bandwidths at the same frequency.

If we let the Stokes parameters for radiation between the frequencies f and f+df be Idf, Qdf, Udf and Vdf. The parameters for the total radiation received by the receiver from f_1 to f_2, the limits of its band, are given by integrating Idf etc. from f_1 to f_2.

$$I = \int_{f_1}^{f_2} I\,df \text{ etc.}$$

We then have expressions of the form $Q\,df = I \cos 2\psi \cos 2\beta_o\, df$, $U\,df = I \sin 2\psi \cos 2\beta_o\, df$ and $V\,df = I \sin 2\beta_o\, df$ where the suffix o refers to conditions at the origin.

Also $\psi - \psi_o = \frac{A}{f^2} = \phi$

therefore $df = -\frac{f^3}{2A}\, d\psi$

Evaluating....../

Evaluating $\bar{I}$, $\bar{Q}$, $\bar{U}$ and $\bar{V}$ we get

$$\bar{I} = I\,(f_2 - f_1)$$

$$\bar{Q} = \left(-\frac{f^3}{2A}\right)\frac{I}{2}\left(\sin 2\psi_2 - \sin 2\psi_1\right)\cos 2\beta_0$$

$$\bar{U} = \left(-\frac{f^3}{2A}\right)\frac{I}{2}\left(\cos 2\psi_1 - \cos 2\psi_2\right)\cos 2\beta_0$$

$$\bar{V} = I \sin 2\beta_0\,(f_2 - f_1)$$

If $|f_2 - f_1| \ll f$, we can write

$$f_2 - f_1 = (\psi_2 - \psi_1)\left(-\frac{f^3}{2A}\right)$$

$$= \Theta\left(-\frac{f^3}{2A}\right)$$

By suitable manipulation Cohen has derived an expression giving the degree of polarization in the following form

$$\frac{\bar{I}_e}{\bar{I}} = \left[\frac{\sin^2\Theta}{\Theta^2} + \sin^2 2\beta_0\left(1 - \frac{\sin^2\Theta}{\Theta^2}\right)\right]^{1/2}$$

Also an expression for the ellipticity in terms of the initial axial ratio

$$\sin 2\beta = \frac{\bar{V}}{\bar{I}_e} = \left(\frac{\sin^2\Theta}{\Theta^2}\cot^2 2\beta_0 + 1\right)^{1/2}$$

and the tilt angle ψ given by

$$\tan 2\psi = \frac{\bar{U}}{\bar{Q}} = \tan \tfrac{1}{2}(\psi_1 + \psi_2)$$

These are the values for degree of polarization, ellipticity and tilt angle as measured by the antenna.

Cohen gave curves that allowed calculation of the values of these parameters at the source from a knowledge of the values β ψ and $\frac{I_e}{I}$ when measured with two bandwidths at the same central frequency. As will be described in the later chapter on apparatus, facility was made for measurement with at two bandwidth values so that Cohen's curves could be usefully employed.

His first set of curves required a knowledge of Θ but by measurement at two bandwidths Θ could be found independently

C ....../

C. Polarization of Solar Radio Emiosion

Payne-Scott and Little. (9)

These workers claimed to have noticed a relation between the hemisphere in which a spot group occurred and the polarity of the radiation. At first sight such a result might not have been entirely unexpected because there are known to exist various magnetic fields near the spots and the difference in polarities between spots in the two hemispheres has already been pointed out. However, two spots in the same group might have opposite polarities and one would then expect the radiation to exhibit polarization depending on the nature of the associated spot. It does not then seem reasonable to make any generalization about the relation between polarization and position of a spot group in either hemisphere. Nevertheless, if a radio source can be fixed near any one spot in a group some useful conclusions might be drawn. This Payne-Scott and Little succeeded in doing. They pointed out that it might have been expected that if a noise storm was associated with a leading spot in the northern hemisphere or a following spot in the southern hemisphere, their polarizations might have been expected to show the same sense of polarization during any sunspot cycle.

This rule was followed by 75 per cent of the observed events, but this conclusion was based on 29 events and it does not seem to establish anything really conclusive. Of these 29 noise storms, 16 showed right-hand polarization while

occuring ....../

occuring in the northern hemisphere and only 1 showed left-hand polarization. Of the events located in the southern hemisphere 5 showed right-handed and 7 showed left-handed polarizations.

Another phenomenon noticed by these workers was that several storms showed mixtures of right and left-handed polarizations. This phenomenon has since been observed by other workers and has been explained in terms of the simultaneous occurence of two or more storms.

In a separate paper dealing with outbursts (10) they described the polarization as being random during the early stages and often a second increase occurs with elliptical, usually circular, polarization. They have observed two cases of linear polarization in the later stage of an outburst.

They concluded that right-handed polarization originated in a region above a south magnetic pole and left-handed above a north pole, while linear polarization appeared to originate above the central region of a bipolar group. Their results were based on only 6 outbursts, 5 of which were associated with flares.

<u>Christiansen et al.</u> (11)

In their paper they described two very large solar disturbances (type not specified). The interesting fact that emerged from their analysis of the polarization of these events is that at low frequencies (98 Mc/s) the polarization changed during the event.

During the disturbance on Feb. 17, 1950 the polarization varied from random through right-hand circular (40%) to left-hand circular (60%). For the disturbance on Feb. 21-22 the polarization varied from right-hand circular (100%) through random; right-hand (100%), left-hand (60%) elliptical; linear in the direction of the axis of the spot group to left-hand circular (100%). At the higher frequencies, however, (200 Mc/s, 600 Mc/s, 3000 Mc/s) the sense of polarization remained the same throughout the events. Throughout the event on 600 Mc/s on the 17th and on all three of the higher frequencies for the event on the 21-22nd the polarization was right-handed varying from 4% to 40%. Flares and radio fadeouts were observed at the time of both events.

<u>Covington</u>. (13)

He performed measurements on a wavelength of 10.7 cm and was able to measure right- or left-hand circular polarizations. Between May and August 1950, 9 bursts for which the intensities of the two components could be clearly recognised, were recorded during 625 hours of observations.

(1) In 4 cases the difference between the R.H. and L.H. components was less than 10% during the entire burst.

(2) In 4 cases the ratio of intensities of the two components was variable.

(3) In 1 case only one component was present, i.e. the radiation was completely circularly polarized.

Hatanaka ....../

Hatanaka. (13)

Hatanaka has apparently been able to localize radio sources near large sunspots and to measure their polarizations at the same time. He found that the polarization of bursts was circular if the source was near the center of the sun's disc and became non-circular near the edge of the disc.

Hatanaka and Akabane. (14)

They observed a change of polarization of an outbursts at 9000 Mc/s which they felt might have been associated with the shift of the activity centre of the flare relative to the sunspot magnetic field.

Hatanaka. (15)

Using the Japanese polarimeter described elsewhere, Hatanaka here presented some preliminary results obtained. The article concerned itself only with storm radiation. A general summary of the polarizations observed in type I bursts was given.

(1) The radiation was a mixture of 2 components, one elliptically polarized, the other random.

(2) The ellipticity varied from nearly 100% (i.e. circular) to 10% (i.e. nearly linear). This variation from day to day was similar to the ellipticity of a circle put tangentially on the sun's surface at the position of the source and viewed from earth. (Spread over 4-6 days).

(3) The degree of polarization was greater than 90% on

most ....../

most days but sometimes dropped below 50%, to 10%.

(4) The ellipticity and degree of polarization were constant for any one day, but might show scatter, usually for sources near the limb or when the source suddenly became very active.

(5) The tilt angle remained almost constant during an observing period in one day, but might vary from day to day.

Komesaroff. (16)

Komesaroff made observations with a modified version of the spectrograph described by Wild et al and this technique gave simultaneous records of the dynamic spectrum and the polarization. Hence, he could identify the spectral types easily and further he was able to perform rapid measurements enabling the study of short-lived bursts. A broad survey of polarization as a function of both time and frequency was then obtained rather than accurate measurements of the polarization ellipses at distinct frequencies.

His results, briefly, confirmed that there was an association between spectral types and polarization. A considerable number of type III bursts were found to be polarized and a few of the polarized bursts displayed a harmonic structure and in the cases examined the sense of rotation of the harmonic component agreed with that of the fundamental. The degree of polarization differed however.

Results: Type I bursts.

Records for 13 days activity were examined and the conclusions....../

conclusions drawn were that type I bursts showed a high degree of quasi-circular polarization. The radiation was polarized at all frequencies, showing the same sense of rotation throughout the range and on one day. One storm did show a change in rotation on different frequencies during one day. Of 13 observed storms, 9 showed left-hand polarization and 3 showed right-handed polarization. The other showed variable polarization.

<u>Type II bursts</u>

Polarization measurements were carried out on 13 type II bursts of which 8 were found to be completely un-polarized and for 4 others no conclusion could be reached. Only one burst was probably polarized for a short period of time but the polarization never exceeded 30%.

<u>Type III bursts</u>

500 bursts were recorded and 50% exhibited a modulation pattern indicative of fairly strong polarization. Several harmonic bursts were found to be polarized and in general the fundamental was more strongly polarized than the harmonic.

Type III bursts, occuring on the same days as or within a few days of, type I events and showing polarization, generally showed the same sense of polarization as the type I events.

<u>Cohen</u>. (17)

Cohen pointed out in his paper that almost always the reported polarization for type III bursts had been either

circular....../

circular, or nearly so, or un-polarized. In his paper he discussed the "linear polarization in type III bursts".

As was mentioned in the chapter on "the Faraday Effect on Radio emission from the sun," dispersion could cause spreading of the orientations of the polarization ellipses with the result that, for a finite receiver bandwidth, the radiation would appear circularly plus randomly polarized. Cohen used a very narrow receiver bandwidth. (10 kc/s at 200 Mc/s.)

During 1200 hours of observations, only 6 type III bursts were found to be highly elliptically polarized. One of these had an associated type V burst polarised in the same fashion. He does not mention the hemisphere in which any associated events occured. He felt that with better techniques more such events could be detected.

Neubauer and Fokker. (18)

Extensive work on the subject of polarization measurements has been reported in a paper by Neubauer and Fokker (18) and a thesis by Fokker (19). The polarimeter they use provides measures of the circular and linear components of the received radiation.

In the former paper they discussed results obtained on enhanced radiation, noise storms, flare associated outbursts and type III bursts. The later work concerned itself mainly with enhanced radiation and storm bursts.

Enhanced Radiation and Storm Bursts

By comparing their 200 Mc/s records with those obtained by ....../

by the 255 Mc/s interferometer they concluded on the assumption that enhanced radiation observed on the two frequencies simultaneously was associated, that there was no dependence of the polarization sense on the hemisphere of the sun in which the source is situated. This is contrary to the suggestion previously put forward by Payne-Scott and Little which proposed such a dependence. Furthermore, the sense of polarization was found to remain unchanged as the noise active centre passed the central meridian.

An interesting effect that they observed was the result of the simultaneous emission from two sources of enhanced radiation producing large flux enhancement, but little polarization, at the receiver, if the two sources were oppositely polarized. The two sources of opposite polarizations might compensate each other almost exactly. Alterations in the polarization observed from such sources indicated that the sources alterately outweighed one another.

The storm bursts that occured superimposed on the enhanced background had, almost exclusively, been found to show the same sense and degree of polarization, usually 100%. Several exceptions were listed.

(1) Strong polarization of the continuum and unpolarized bursts.

(2) Weakly polarized continuum and strongly polarized bursts.

(3) Steadily unpolarized continuum and unpolarized or weakly polarized bursts which varied in polarization. They have shown that this radiation arises from a single source.

(4) Continuum and/or bursts weakly or moderately polarized.

(5) Mixed polarization; in some cases clearly due to two sources. The continuum and bursts differed in polarization.

(6) Storm bursts with identical sense but widely differing degrees of polarization.

It has been thought that bursts of type III might have been of the same character as storm bursts (e.g. Wild 20) but an analysis of this matter shows that the polarizations of the two types of bursts is totally different. It might be then thought that storm bursts that are un-polarized might show the characteristics of type III bursts, but this approach too has not borne any results as they found no differences between polarized and un-polarized storm bursts besides the polarization characteristics. It has been found, however, that un-polarized storms do not reach high continuum levels.

Polarization has often been found to develop with the storm, always starting as un-polarized radiation and becoming increasingly polarized with time. This would appear as evidence of changing magneto-ionic conditions which probably could be directly related to the changing conditions that caused the storm to develop in the first place.

Fokker....../

Fokker did point out a slight preponderance of left-handed storms in the northern hemisphere and right-handed storms in the southern solar hemisphere. Mixed polarization have however been observed in the presence of two spots in the same hemisphere.

Flare associated outbursts

More than half of the observed events were un-polarized or only weakly polarized. Other events showed a remarkable variety of polarization. There was no relation to position on the disc, size of flares or S.I.D.'s. They concluded that a number of circumstances, probably accidental in nature, governed the polarization behaviour of an outburst. Seven outbursts were described in detail to illustrate the varied behaviour.

They found that the strongly polarized outbursts almost always present a varying degree of polarization. Many large outbursts showed a tendency to be initially un-polarized and then to develop strong polarization in one sense.

Their apparatus was not capable of supplying any reliable information as to elliptical polarization.

Type III bursts

On the other hand their apparatus was very sensitive to small degrees of circular polarization, and although they found that most of the type III radiation was un-polarized, some of these bursts showed small degrees of circular polarization.

A ..../

A special case

An unprecedented increase of radiation was observed on 4 Nov. 1957 and was characterised by confinement to metre wavelengths, complete lack of flare activity and S.I.D.'s, and by very short period fluctuations altogether different from noise storms. The event was 100% left-hand circularly polarized and they felt that the polarization characteristic was somehow related to the mechanism of production of this special phenomenon.

Malinge. (21)

In a very recent paper Malinge reports on the comparison of polarization measurements performed by the Dutch workers and the results obtained from interferometer. Good correlation has been established between events occuring on three frequencies and several important conclusions were drawn.

Of 85 noise storms observed with sources in the northern solar hemisphere, 69 were found to have left-hand circular polarization, 6 right-handed, 9 variable and 1 not polarized. For 21 storms originating in the southern hemisphere 9 showed right-hand, 5 left-hand, 4 variable and 1 not polarization. (These figures are given in the body of the paper as well as being represented diagramtically but the conclusion states in print that the majority of storms observed in the northern hemisphere are right-hand polarised and this conclusion is restated in the abstract of the paper appearing in Physics Abstracts.) (21a)

13 mixed polarizations have been observed and 8 of these were definitely due to multiple sources. The others were sources at low latitudes.

They point out that Payne-Scott and Little had observed an opposite "hemisphere-effect" but that their observations were made before the reversal of the solar magnetic field occured. (Babcock 83). (The results of Payne-Scott and Little show right-hand polarization for northern hemisphere sources.)

The sense of polarization is related to the sense of the magnetic field at the origin and the polarization corresponds to that of the ordinary ray associated with the magnetic field of the lead spot.

D. <u>The Origin of Polarized Radiation</u>

Solar radio waves can become polarized in two ways. The source may emit polarized radiation or the radiation may become polarized while traversing some intervening medium.

As has been pointed out in chapter II there exist regions in the corona where the refractive index of the medium is zero for a particular frequency, these regions being called "stop bands" since this radiation cannot pass through.

If the source of radiation at any one frequency lies between the stop band limits for the ordinary and extra-ordinary waves at this frequency,(see table II) then only one mode, the ordinary mode, will be able to escape from the corona. The polarization will then be determined by the conditions in the

"limiting ...../

"limiting region", i.e. the region where the final polarization is determined due to vanishing electron density or magnetic field.

A convenient way of representing the escape of radiation from a mass of ionized plasma is with the aid of an (X,Y) diagram as shown in figure A (next page). The point A_1 has co-ordinates X_1 and Y_1 which are the values of the X and Y parameters of the magneto-ionic theory at the corresponding point A in the gas. Ray trajectories AB may be represented by continuous curves such as A_1B_1O, A_2B_2O, A_3B_3O as shown in the diagram.

The polarization observed is the polarization after emergence from the gas and depends on the manner in which the electron density and the magnetic field (i.e. in effect X and Y) decay in the limiting region. The three trajectories shown represent cases where the magnetic field decays before the electron density (A_1B_1O), the two decay together (A_2B_2O) and the electron density decays before the magnetic field (A_3B_3O).

The variation of the observed polarization with X and Y for $\theta=60^{\circ}$ (θ = the angle between the magnetic field direction and the direction of propagation) is shown in figure B.

By combining trajectories obtained from figure A with the polarizations as indicated by diagrams such as figure B for suitable values of θ an idea can be obtained as to the polarization that the emergent radiation will exhibit. e.g. a ray

following...../

FIGURE A

Possible modes of decay of electron density (parameter x) and magnetic field (parameter y) along a ray trajectory passing out of a body of ionized gas.

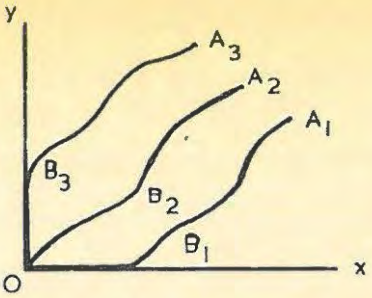


FIGURE B

Variation of polarization with x and y for $\theta = 60^\circ$

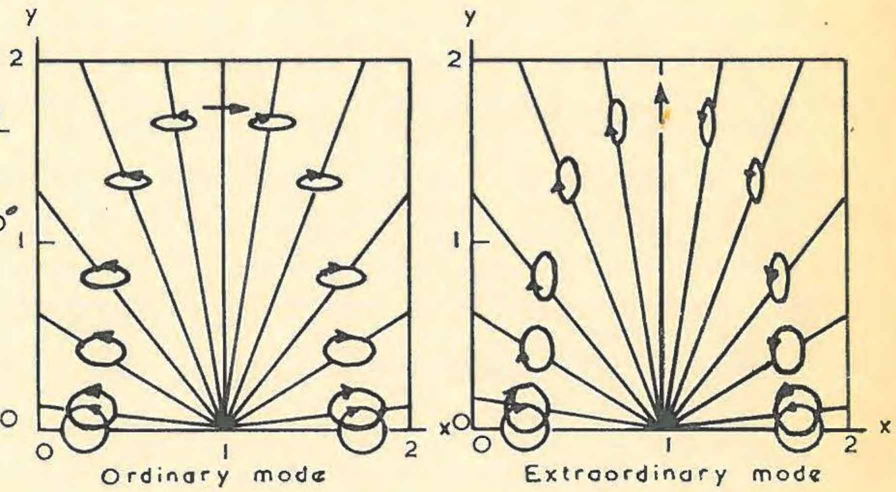
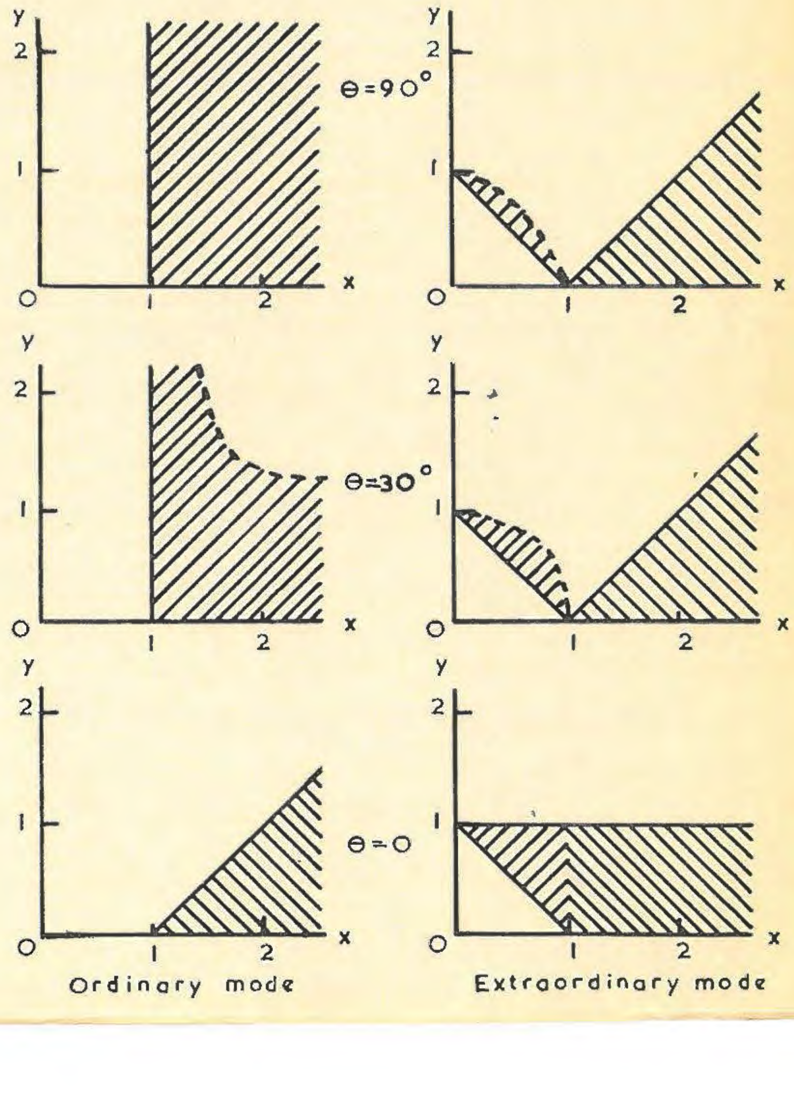


FIGURE C

Stop-bands (shaded) in a magneto-ionic medium.



from Pawsey and Bracewell 1955

following a trajectory such as A_3B_3O will emerge with the ordinary component left-hand elliptically polarized and the extraordinary component right-hand elliptically polarized.

Figure C indicates the stop bands for the two modes of propagation so that, if the source region is known, it can be determined whether either, or both, of the modes can escape from the corona.

Polarization introduced by the medium

Komesaroff (23) suggested that the polarization of type I bursts could be explained in terms of the birefringence of the medium in the manner outlined above. He pointed that it would require the presence of extremely large sources to account for the observed radiation in the 40 to 140 Mc/s frequency band, a radial extension of the source of the order of 10^5 km being needed in this case.

He also investigated the polarization of type II and type III bursts showing harmonic structure. As the fundamental and the harmonic were supposed to originate in the same region it was obvious that the harmonic radiation would, in general, not have to pass stop bands and would therefore not be polarized in the same was as the fundamental. This had not been confirmed by observations and he was led to discard the postulate that polarization of harmonic bursts was due to the birefringence of the medium.

Hatanaka (4) raised another objection. He felt that, as

the/......

the polarization was determined by the excess ordinary radiation over extraordinary radiation, it would be circular as the limiting region was one where the magnetic field was extremely weak. (See fig. A and B) He claimed that this was not in agreement with observations. Since then, however, more observations have been carried out and type I radiation always shows some degree of circular polarization.

Hatanaka was also able to measure the tilt angles of planes of polarization. The Faraday effect in the corona would cause rotation of the plane of polarization, the amount of rotation being dependent on the electron content and the magnetic field intensity along the path of the wave. Unless the source position, the total electron content and the magnetic field intensity along the path through the corona remained constant, the tilt angle would vary randomly. As the observations point to constant tilt angle over long periods of time (up to a day) it seemed unlikely that the radiation could have propagated in two separate modes.

It has been assumed up to now that the radiation is in fact propagated as two uncoupled modes. One might be absorbed and all the energy in the other escape towards earth.

Fokker (19) and Takakura (24) have both discussed the possibility of the coupling of energy from one mode into the other. This would change the polarization of the emergent radiation, the radiation now being the sum of an ordinary and

an....../

an extraordinary component, the amount of extraordinary component depending on the amount of coupling that has taken place. Such coupling would require the presence of steep gradients of either the magnetic field or the electron density along the path and Takakura proposed that these gradients could result from the presence of hydro-magnetic waves. Fokker regarded this as a rather superficial hypothesis as such waves had never been observed on the sun.

It is possible, under suitably turbulent conditions, that the two modes remain coupled for a large part of their path. Cohen (25) has pointed out that in the presence of a magnetic field gradient of 0.04 gauss per km, or more, at 300 Mc/s the modes would remain coupled. He did not consider the matter any further as he felt that such gradients probably did not exist.

Emission of Polarized Radiation

Radiation could be emitted as a result of the ordered gyration of clouds of electrons about a magnetic line of force. This gyration would be clockwise when viewed along the direction of the field and the polarization would correspond to the extraordinary mode. If the electrons gyrate at non-relativistic velocities, the frequency of emission is equal to that of gyration, but, for relativistic electrons, considerable energy is radiated at the harmonics of this frequency as well. It has been shown that the intensity of the harmonics can exceed that of the fundamental under suitable conditions.

Fokker has pointed out that although the electrons gyrate in circular orbits the radiation would only appear circularly polarized when viewed along the direction of the magnetic field. Along a path making an angle θ with the magnetic field direction the radiation would appear elliptically polarized. This elliptically polarized radiation would then propagate as two ellipses with opposite sense of rotation and the radiation would still be mainly in the extra-ordinary mode with a small admixture of ordinary component for small values of θ.

He was forced to discard this theory of emission for noise storms as he had observed some storms to be completely unpolarized. As gyro emission should always show polarization, he could not account for these observations.

Twiss and Roberts (26) have theoretically analysed the electro-magnetic radiation from electrons gyrating in a magnetic field and were led to conclude that neither type II nor type III bursts could be caused by a gyro mechanism. Their arguments are too extensive to be discussed here.

The linear polarization of type III bursts has already been mentioned, and although this could come about from viewing the gyration of the electrons along a direction $\theta = 90^{\circ}$ the objections listed by Twiss and Roberts apply equally to this case.

Linear polarization could be introduced as a result of propagation transverse to the magnetic field in the limiting region. If this is the case there will be no further Faraday

dispersion....../

dispersion in the corona. (The dispersion effect of the earth's ionosphere is negligible for narrow receiver bandwidths.) Then, by observing with several bandwidths, there should be no difference in the measured polarization, there being no depolarizing effect with increased bandwidth because there is no dispersion in the corona. Cohen has found that in all cases the larger bandwidths showed radiation that appeared to be less polarized. This appears to indicate that the radiation does propagate as two separate modes through the corona and the linear polarization was not induced in the limiting region.

To sum up, the gyro-theory cannot account for the observed polarizations, whereas the birefringence of the medium does not appear to account for the polarization of harmonic bursts.

Fokker has, however, been able to account for the polarization of noise storms by adopting an entirely new approach.

He considered the effect of large clouds of denser plasma, called coronal structures, on the radiation that originated near sunspots. By examining the possible trajectories through these condensations, he was able to account for all the possible polarizations of noise storms, that had been observed, varying from unpolarized to completely circularly polarized.

E. The Measurement of Polarization

By having two aerials at right angles to one another along the x and y axes it is possible by inserting phase delays of 0, Π, $\Pi/2$, 0,$\Pi/2$ in turn, to obtain measures of the two

linear....../

linear components and the two circular, R.H. and L.H. respectively, as follows.

If the x and y axes are oriented at 45^{o} to the horizontal it is possible to obtain the vertical and horizontal linear components of the radiation immediately. (w.r.t. earths surface.)

In the analysis we resolve the resultant vibrations in the direction ψ, described before, such that ψ is 45^{o}. Substituting this as well as ϵ, the phase retardation, ($= 0, \pi, \frac{\pi}{2}, -\frac{\pi}{2}$ in turn) and denoting the power received by these connections by I(v), I(h), I(r), I(l) respectively, we get in equation.(16)

$$I(v) = I(o) = I + U$$

$$I(h) = I(\pi) = I - U$$

$$I(r) = I(\tfrac{\pi}{2}) = I - V$$

$$I(l) = I(-\tfrac{\pi}{2}) = I + V$$

That I(r) and I(l) do indeed give a measure of the circular polarization can be seen from the following.

For circular polarization $r = 1$ and $\beta = 45^{o}$

$$\therefore \; U = I_e \text{ Cos } 2B \text{ Sin } 2X = 0$$
$$V = I_e$$

Since the expression $I(\frac{\pi}{2})$ makes $U=0$ it is therefore a measure of circular polarization. Similarly, for linear polarization, $r = 0$ and $\beta = 0$ making $V = 0$. The two alternative $\frac{\pi}{2}$ phase delays with different signs determine the sense of the circular polarization.

The 4th Stokes parameter is determined as follows:

From equation (17, sect A.),

$$Q = I_x - I_y \quad \text{and} \quad I = I_x + I_y$$

$$I_x = \frac{I + Q}{2}$$

$$I_y = \frac{I - Q}{2}$$

Ix and Iy are the intensities as measured on each earial. The Stokes parameter are then found from

$$I = \tfrac{1}{2}\left[I(v) + I(h)\right] = \tfrac{1}{2}\left[I(r) + I(l)\right] = I_x + I_y$$

$$Q = I_{(v)} - I_{(h)}$$

$$U = \tfrac{1}{2}\left[I(v) - I(h)\right]$$

$$V = \tfrac{1}{2}\left[I(r) - I(l)\right]$$

This sytem was outlined by Suzuki andTsuchiya (28). Hence by constructing a system whereby these phase delays can each by inserted in the signal path in turn, and by arranging for the display of each component along a different trace on a multi-beam oscilloscope, the stokes parameters can be calculated from direction measurements on the output traces. Fig. IA shows the block diagram of the polarmeter illustrating the above principles. A system of pulses combined the signals according to the schematic shown in Fig. IB.

Before the construction of the polarimeter is described it is necessary to discuss the bandwidth and gain characteristics that had to be considered in the design of the polarimeter

As has already been pointed out in the chapter on Faraday rotation, a finite bandwidth of the receiver produces dispersion and consequent depolarisation of the received signal. It was then essential to keep the bandwidth as small as possible, and at least of the order of magnitude of that used by Cohen (27)

(10....../

(10 kc/s at 200 Mc/s). The amplifier stages were built without particular attention being paid to making the first stages with narrow bandwidth, as the bandwidth of the overall receiver was determined by the final stages. It was found that, without placing damping resistances across the final I/F transformers, a bandwidth of about 15 kc/s could be obtained.

Another important consideration with regard to the polarimeter design was the amount of amplification needed to detect medium sized bursts, these being defined as about 100 times the level of the background continuum. The calculation of gain required is now given.

Bursts vary in intensity from 10^{-21} watts/metre ^{2}/cycle/sec to 10^{-17} $w/m^2/c/s$. We will consider a burst of intensity 10^{-20} $w/m^2/c/s$.

The intensity at 300 Mc/s will be $300 \times 10^6 \times 10^{-20}$ watts $/m^2$

i.e. $= 3 \times 10^{-12}$ watts per square metre.

The effective area of the serial system has to be calculated. This is done in the section on aerials. The result is that the effective area of 4 Yagi antenna is of the order of 0.3 m^2.

Hence power incident on aerial 10^{-12} watts. By the definition of the effective area of an aerial, all this power was available to the load which, in this case, was 240 ohm. Hence the voltage set up across this impedance is given by

$$V^2 = W.Z = 10^{-12} \times 240$$

therefore $V = 15 \times 10^{-6}$ V.

A reasonable output variation was about 15 volts, hence an

amplification..../

amplification of $20 \log \frac{\text{output}}{\text{input}}$ voltage was needed to provide this amplitude at the output.

Therefore gain required was $= 20 \log \frac{15}{15 \times 10^{-6}}$

$= 120$ dB

The various stages of the polarimeter were thus designed to give an overall gain of about 140 db to compensate for losses that might occur.

Finally, an aspect of polarization measurements that had been examined by Cohen, in some detail was provided for. As Cohen pointed out, if an accurate determination of orientation of the plane of polarization of the incoming signal was to be made, the measurements would have to be made either at two separate frequencies, or with two different bandwidths centred about the same central frequency. He outlined methods that could be used in the case of two-bandwidth measurements to obtain the orientation angle or the signal. For this reason a second amplification channel was provided in the main I/F amplifier that facilitated amplification using another bandwidth, in the event of such measurements being required.

CHAPTER III

REFERENCES

(1) Deschamps "Geometrical Representation of the Polarization of a Plane Electromagnetic Wave". Proc.I.R.E. 39,540 (1951).

(2) Chandrasekhar. "Radiative Transfer". pp. 24-35.

(3) Cohen. "Linear Polarization in type III Bursts". Astrophys.J. 130,221 (1959).

(4) Hatanaka. "The Faraday Effect in the Earth's Ionosphere". Publ.Astr.Soc.Jap. 8,73 (1956).

(5) Cohen. "Interpretation of Radio Polarization Data in terms of Faraday Rotation". Cornell Univ.Res.Rep. E.E. 295.

(6) Murray & Hargreaves. "Lunar Radio Echoes and the Faraday Effect in the Ionosphere". Nature. 173,944(1954).

(7) Aitcheson & Weekes. "Deduction of Ionospheric Information from the Emission from Satellite 1957 $\alpha 2$". J.A.T.P. 14,236 (1959)

Garriott. "Determination of Ionospheric Electron Content and Distribution from Satellite Observation". J.G.R. 65,1139 (1960).

(8) Staff of Mullard R/A Obs.Cantab. "Radio Observation of the Russian Earth Satellite". Nature. 180,879 (1957).

(9) Payne-Scott & Little. "The Position and Movement on the Solar Disc of Sources of Radiation at a Frequency of 97 Mc/s Part II Noise Storms". Aust.J.Sci.Res. A4,508 (1951).

(10)	Payne-Scott & Little.	"Ibid. Part III Outbursts".	Aust.J.Sci.Res. A5,32 (1952).
(11)	Christiansen, Hindman, Little Payne-Scott, Yabsley & Allen.	"Radio Observations of Two Large Solar Disturbances".	Aust.J.Sci.Res. A4,51. (1951).
(12)	Covington.	"Circular Polarization of 10.7 cm Solar Noise Bursts".	J.R.A.S.Can. 45,157 (1951).
		Abstracted in Bibliography of Extraterrestrial Radio Noise. Supplement for 1951.	Cornell Res.Rep. E.E. 173.
(13)	Hatanaka.	"Position and Polarization of Solar Radio Bursts on 200 Mc/s".	Cornell Res. Rep. E.E. 299.
(14)	Hatanaka & Akabane.	"Polarization of Solar Radio Outbursts".	Nature. 180,1062 (1957).
(15)	Hatanaka.	"Polarization of Solar Radio Bursts".	Symp.No.IV of I.A.U. (Rad.As.) p.358.
(16)	Komesaroff.	"Polarization measurements of the 3 Spectral Types of Solar Radio Burst".	Aust.J.Phys. 11,201 (1958).
(17)	Cohen.	"Linear Polarization in Type III Bursts".	J.Astrophys. 130,221 (1959).
(18)	Neubauer & Fokker.	"The Polarization of Solar Radio Emission at a Frequency of 200 Mc/s".	P.T.T. Bedrijf. 8,177 (1958).
(19)	Fokker.	"Studies of Enhanced Solar Radio Emission at Frequencies near 200 Mc/s".	Ph.D. Thesis. Univ. of Leiden. 22nd June 1960.
(20)	Wild.	"An Investigation of the Profiles of Bursts of Solar Radio Noise".	M.Sc. Thesis. Rhodes (1959).

(21)	Malinge.	"Relation between the Position and the Sense of Polarization of Solar Radio Storms".	Comptes Rendus. 250,1186. (1960).
(22)	Babcock.	"The Sun's Polar Magnetic Field".	Astrophys.J. 130,364 (1959).
(23)	Komesaroff.	"Polarization Measurements of the 3 Spectral Types of Solar Radio Burst".	Aust.J.Phys. 11,201 (1958).
(24)	Takakura .	"Polarized Bursts and Noise Storms of Solar Radio Emission Part I".	Publ.Astr.Soc.Jap. 8,182. (1956).
(25)	Cohen.	"Radio Astronomy Polarization Measurements".	Proc.I.R.E. 46,172 (1958).
(26)	Twiss and Roberts.	"Electromagnetic Radiation from Electrons Rotating in an Ionized Medium Action of a Uniform Magnetic Field".	Aust.J.Phys. 11,424 (1958).
(27)	Cohen.	"The Cornell Radio Polarimeter".	Proc.I.R.E. 46,183 (1958).
(28)	Suzuki and Tsuchiya.	"A Time-sharing Polarimeter at 200 Mc/s".	Proc.I.R.E. 46,190 (1958).

CHAPTER IV.

CONSTRUCTION OF THE POLARIMETER.

A general outline of the principles involved in polarimeter construction has already been given. The block diagram of the polarimeter that was to be constructed by the author is shown in fig. I. It follows very closely that designed and constructed by Susuki and Tsuchiya (1), the main difference lying in the design of the individual elements.

Basically it consisted of the following parts:

1. Two sets of crossed linearly polarized aerials feeding
2. two separate, but similar 300 Mc/s pre-amplifiers.
3. Two separate crystal mixers fed from a common local oscillator.
4. Two 27 Mc/s intermediate-frequency amplifiers (I/F).
5. A "channel mixer" or "modulator" to combine the outputs from the I/F's in the desired way.
6. A generator and a series of directors to provide a system of pulses to operate the "mixer".
7. Main I/F amplifier.
8. A variable bias generator (step generator).
9. Catnode ray display unit with oscilloscope camera.
10. H.T. and L.T. power smpplies.

The Antenna System. (Plate II)

The polarimeter required two sets of linear antennae mounted at right angles to one another. Such antennae may be single dipoles or folded dipoles or arrays of either. The array used consisted of a series of "directors" mounted in front of the "driven element" and a "reflector" mounted behind this element. This combination is known as a "Yagi" aerial, after its inventor. The advantage that a Yagi antennae has over a simple dipole is its increased directivity and increased gain. Smith (2) lists the important features of Yagi antennae which enabled the author to construct the antenna shown in fig. IX.

The arrangement constructed consisted of a folded dipole, as the driven element, three directors mounted parallel to this and in front of it and a single reflector mounted parallel and behind it. All the elements were supported along a length of copper tubing of slightly larger diameter than that used for the individual elements.

A folded dipole was used as the driven element because its input impedance was very nearly equal to that of the feeder tape used to lead the signal to the receivers. Only three directors were used as more would not have increased the directivity very much, but would have increased the physical size unduly which, in turn, would have given rise to unnecessary difficulties in the construction of the array. Other workers had found that the addition of further reflectors produced no difference in the act-

ion of/......

ion of Yagis.

Most of the experimental work performed on Yagis and arrays of Yagis was done during the war, the results being published shortly afterwards (3), (4), (5). Since then nothing further has appeared in the literature and Smith used the results of the early workers in his chapter on Yagi aerials. It was found that a reflector spacing of 0.25 λ (and a director spacing of 0.34 λ) gave the best results. (see fig. IX). Optimum lengths for directors and reflectors were 0.45 λ and 0.51 λ respectively, the diameter of the supporting rod being taken into consideration. (λ was the free space wavelength).

The input impedance of a folded dipole is generally of the order of 300 Ohms but when used in a Yagi this value becomes 240 ohms (Smith p149). As 300 ohm feeder tape was used to connect individual aerials it was necessary to provide some form of matching so that maximum transfer of energy could take place.

Preliminary tests were performed on a single Yagi mounted about 8 feet above the ground, a rough idea of the polar diagram and the type of matching stub required being obtained.

A further 7 Yagis were then constructed and mounted as shown in fig. IX and plate II. There is no appreciable interaction between separate units if their axes are separated by at least 1.5 λ when the units are in the same plane or 3.0 λ when the units are mounted with their planes parallel.

The individual Yagis were then mounted on an aluminium

"Dexion"/......

"Dexion" frame 10ft square. This frame was in turn fitted onto the equatorial mount that was available on the roof of the "shack". The antenna was driven to follow the sun using the mechanism constructed by Shuter (6).

(The author discovered much later that crossed Yagis could readily be mounted along the same axis which would have made for easier construction!)

Measurements on Yagis.

To fit a suitable matching stub it was first necessary to measure the standing-wave-ratio on the feeder tape that was connected to the dipole. The length of feeder tape used was a multiple of a half-wavelength on the line. From the theory of transmission lines the voltage V_r appearing across the terminating impedance Z_r is, if $Z_r = Z_o$ (the characteristic impedance of the line), equal to the input voltage V_i in magnitude, but 180^o out of phase with it for a line whose length is an odd multiply of half a wavelength). It was convenient to use a length $5/2\lambda$, λ being the wavelength along the feeder tape (300 ohm transmission line). It was then necessary to determine the wavelength of a 300 Mc/s signal along this tape.

This was done by using the expression $Z_o = \sqrt{\frac{L}{C}}$ which gives the characteristic impedance (Z_o) of the line in terms of the capacity (C) and inductance (L) per unit length. This, together with the expression for the velocity of propagation along such a line ($v = \frac{1}{\sqrt{LC}}$) gave a method determining λ.

From/......

From above ; $v = \frac{1}{Z_o C}$

Z_o is known to be 300 ohms and by measuring the capacity of several different lengths of the tape the capacity per unit length (C) was readily found. C was found to be 0.13pF/cm.

$$\therefore \quad V = \frac{1}{300 \times 0.13 \times 10^{-12}} \ {}^{cm}/_{sec.}$$

$$= 2.564 \times 10^{10} \ {}^{cm}/_{sec.}$$

Hence $\lambda = \frac{V}{f} = \frac{2.564 \times 10^{10}}{3 \times 10^{8}} = 85.5$ cms.

Length of tape= $^{5}/_{2}\lambda$= 213.5 cms.

A General Radio type 1602B admittance meter was used in conjunction with a type 874 UB balun to measure the input conductance and susceptance of the line and then, by using a suitable version of the Smith circle diagram, the standing wave ratio could be found. It was theoretically possible to design a suitable matching stub, provided the electrical length of the feeder-tape was known, but it was not possible to determine this accurately as no suitable short-circuit (non-radiating) could be made at the termination of the tape. It was in fact found to be a relatively simple matter to determine the position and length of an opencircuit stub, made up of a length of 300 ohm tape, by a method of trial and error after a rough estimate of position and length had been obtained.

For the set of x-orientated aerials a stub, length 16 cm, placed 31.5 cm from the dipole was found to give a standing wave-ratio of 1.1. These measurements were made on one of the set

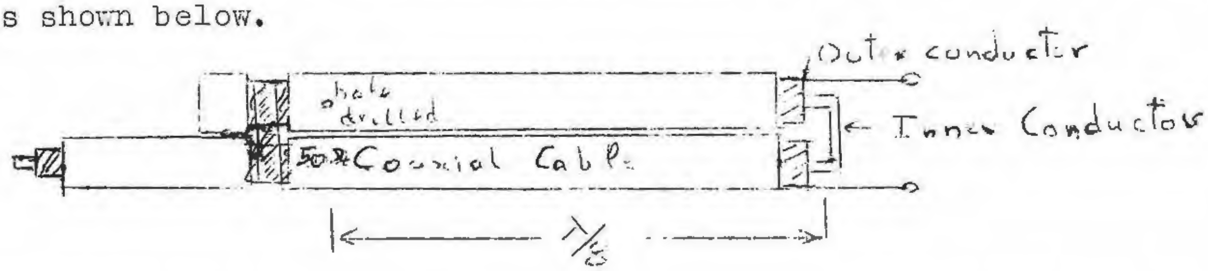
of/......

of Yagis and similar stubs placed along the feeders of the other 3 in the set. This was thought to be sufficiently accurate, as each separate aerial was exactly similar to the others.

A similar prodedure was followed for the set of y-orientated aerials, a standing-wave-ratio of 1.18 being obtained with a stub 15.5 cms long placed 30.0 cms from the dipole.

The lengths of all the feeder tapes were kept equal, so as to preserve the correct phase relationships throughout.

The dipoles each formed a "balanced system" (neither side was permanently at earth potential) and the connection of the feeders from the 4 dipoles in each set did not affect this balanced condition. The input to the amplifying system was however an "unbalanced system" (one side at earth potential) and it was then necessary to construct a "balun transformer" (balanced-to-unbalanced). A simple version of such a transformer was described by Roberts (7) and consists mainly of a $\frac{\lambda}{8}$ length of coaxial cable as shown below.



λ is the wavelength along the cable and was found in a similar way to that described previously for the feeder tape. The cable had a characteristic impedance of 50 ohms and the capacity per unit length was found to be 1.18 pF/cm giving the wavelength

along/......

along the cable of a 300 Mc/s wave as 56.6 cms. The balun described by Roberts was designed to match an unbalanced cable of 50 ohm impedance to a balanced load of 70 ohm impedance. In this case, 4 300 ohm tapes were connected in parallel, giving a load of effectively 75 ohms, this being sufficiently close to 70 ohms to allow the balun to be constructed as specified by Roberts.

Similar baluns, with similar lengths of 50 ohm coax leading to the pre-amplifiers, were constructed for both sets of aerials and standing wave measurements were made on both. The standing-wave-ratios were found to be 1.70 for the x-orientated set and 1.75 for the other set.

Pre-amplifiers.

The choice of 300 Mc/s as the operating frequency was stimulated by the possibility of observing some interesting aspects of solar radio noise at this frequency, as the corresponding source of radiation is thought to lie in the transition region between the corona and chromosphere. It was felt that, as this transition region was under the influence of stronger magnetic fields than the regions higher up, some interesting polarization features might be detected. Obviously the regions where even higher frequencies originated would be nearer the level of sunspot activity but it would not have been possible to build ultra high frequency receivers at Rhodes University. At the same time it was realized that most other polarization measurements had been done at 200 Mc/s or lower, or 2000 Mc/s and higher so

that/......

that 300 Mc/s was relatively unexplored in this field.

There was, however, one big disadvantage in working at this frequency from the point of view of instrumentation. The 300 Mc/s frequency band lay in that part of the radio frequency spectrum which could not be classed as either "very-high-frequency" or "ultra-high-frequency". It lay between these two regions with the result that the conventional circuit techniques of v-h-f work did not serve their purpose successfully any longer, while on the other hand it was too low in the spectrum for microwave circuitry to be usefully applied. It was in fact necessary to try and establish some sort of compromise principle on which to construct a successful amplifier at 300 Mc/s.

However, before such an amplifier was finally constructed, several other avenues of approach were first tried. A short history of these researches will now be given.

During 1958-59 Wild and Poole, of this department, together with Dr. E.F. Stack-Forsyth, had made five attempts to build a suitable 300 Mc/s pre-amplifier for use with their intended radiometer operating at this frequency. Conventional v-h-f circuit techniques were used, but it was not until their mark V amplifier was constructed that they succeeded in obtaining results (8).

As a result of their experiences, the author, at Dr. Stack-Forsyth's suggestion, carried out an extensive investigation as to the action and possible use of a new type of amplifier that had been described in the literature. It was felt that a fresh

approach/......

approach to the problem might well be fruitful. The author's researches into the field of Parametic Amplifiers are now briefly described.

Parametric Amplifiers.

This type of amplifier was an extremely recent development, the first proposal for such an amplifier having been put forward by Suhl (9). Its big advantage lay in the extremely low noise figures that could be obtained and in radio astronomy, where the signals to be amplified were themselves very small, this low noise level was important.

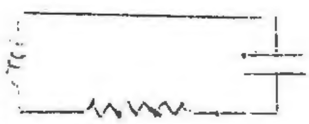
Principle of Parametric Amplification.

Parametric amplification is achieved by periodically varying a reactance in a resonant signal circuit in a non-linear fashion. Such a reactance is found to exhibit a negative resistance characteristic. Non-linear reactances may be either:

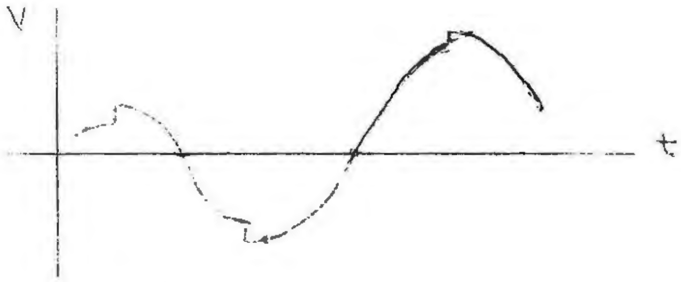
a) ferrites,
b) reverse biased junction diodes,
or c) modulated electron beams.

A junction diode has a layer of separation between the two regions of the crystal known as the depletion layer, and there is a certain capacity across this layer which may be varied by reverse-biasing the diode and varying the applied voltage.

Considering the simple circuit shown an idea of the amplification principle may be obtained. The capacitor in the circuit is free to be varied mechanically.

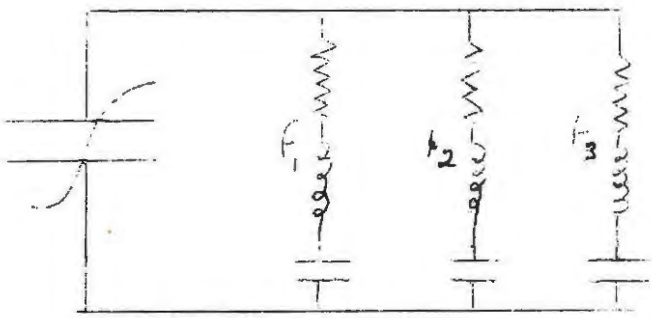


If the voltage V and charge Q on the capacitor vary sinusoidally and the capacitor plates are pulled apart while the charge and voltage are at a maximum, then energy must be spent in overcoming the force due to the field between the plates. This mechanical energy will appear as electrical energy stored in the capacitor and this in turn manifests itself as an abrupt increase in the voltage across the capacitor as shown below.



The voltage and charge then continue their oscillation towards zero and if the plates are then returned to their original position no further work need be done as there is no field between the plates to oppose this motion. If this process is continued at both the negative and positive maxima of the voltage, the amplitude will build up asymptotically to a value where the energy added per separation equals the energy dissipated per half cycle.

In general the reactance is placed in parallel with a number of resonant circuits as shown.



Since the reactance may be considered to be lossless the sum of the load power and power from the external sources must be zero.

ie. $P_1 + P_2 + P_3 = 0$

P_n is the power at frequency f_n

These are average powers, generally given by $\frac{VI}{2}$ Cos Ø. (Ø = phase diff. between voltage and current).

$$P = f\ (\pi\ VQ \cos \phi\ )$$
$$= f\ w$$

V,I,Q, are the amplitudes of voltage, current and charge

w = energy supplied per cycle.

Energies supplied by each source:

$$w_1 = \pi V_1 Q_1 \cos \phi_1 = P_1/f_1$$

$$w_2 = \pi V_2 Q_2 \cos \phi_2 = \frac{P_2}{f_2}$$

$$w_3 = \pi V_3 Q_3 \cos \phi_3 = \frac{P_3}{f_3}$$

Now the load frequency is made either the sum or difference of integral multiples of the other frequencies, ie. $f_3 = mf_2 \pm nf_1$. Combining $P_1 + P_2 + P_3 = 0$ and $P = fw$

we/......

we write $f_1 w_1 + f_2 w_2 + f_3 w_3 = 0$

ie. $f_1 w_1 + f_2 w_2 + (mf_2 \pm nf_1) w_3 = 0$

ie. $f_1(w_1 \pm nw_3) + f_2(w_2 + mw_3) = 0$

Now the amplitudes and phases of the charge components are functions only of the non-linear device characteristics and the amplitudes and phases of the three voltages. But the load voltage and current are connected by the load circuit impedance which is a function of f_3. Therefore the charge and phase amplitudes are functions of f_3, which in turn is a linear combination of f_1 and f_2 and not a function of their ratio.

Thus the only admissible solution to (1) is

$$w_1 \pm n w_3 = 0 \quad \text{ie.} \quad w_1 = - \mp n w_3$$

$$w_2 \pm m w_3 = 0 \quad \quad w_2 = - m w_3$$

Substitute for w_1, w_2, w_3

we get $$\frac{- P_3}{(mf_2 \pm nf_1)} = \frac{P_2}{mf_2} = \pm \frac{P_1}{nf_1}$$

The + sign indicates power into the system.

The $-$ sign indicates power out of the system.

So at f_2 power goes into the system and this is known as the "pump" frequency. At f_3 power goes out into the load, and at f_1 power is either absorbed or given out. This is generally the signal circuit. Thus if the signal is fed in at frequency f_s, the pump is at frequency f_p and the load circuit is tuned to frequency $f_p - f_s$, the latter is then known as the idler circuit

as it/......

as it merely absorbs excess power. The output signal is taken out at a frequency f_s as well.

Alternatively the output is taken at the sum frequency $f_p + f_s$. This is known as the upconverter. These modes of operation together with theory are described in several papers on the subject. (10,11,12,13,14)

Usually f_p is made greater than f_s but low frequency pumping has been used (15).

In practise the pump, signal and idler circuits have almost invariably been resonant cavities operating in harmonic modes that support all three of these frequencies, but coaxial resonant lines as well as conventional lumped circuits have been used. It has been found that the amplifiers usually break into oscillation above a gain of about 35 dB , The gain of a conventional parametric amplifier may be shown to depend on the pump frequency and power.

Noise figures generally are of the order of 3 dB at frequencies around 1000 Mc/s.

By operating on the regenerative principle gains exceeding 80 dB, without accompanying oscillations, have been realized. At 780 Mc/s, noise figures of 1 dB for gains of 56 dB (16) have been realized and 5 dB noise for a gain of 72 dB at 1450 Mc/s (17).

The most recent use of the parametric principle is in the construction of compact digital computers using a parametric

oscillator/......

oscillator operating in one of two modes 180° out of phase (18).

While this investigation on the part of the author was proceeding it was learnt that a parametric amplifier had been built at the National Institute for Telecommunications Research in Johannesburg and, with the kind co-operation of Dr. F.J. Hewitt and Mr. P. Meerholz of the N.I.T.R., the author was able to visit these laboratories and learn more about the construction of such an amplifier. Mr. Meerholz had constructed an amplifier operating at 600 Mc/s and demonstrated its action. He pointed out that a system of R/F filters was needed for both the input and output circuits to prevent oscillation, as the system was very sensitive to stray signals that might enter through output line. For use in a polarimeter an additional circuit element, known as a circulator would become necessary, this being a device that channels R/F signals from one port to another but prevents signals from feeding back into the desired ports and so producing undesirable results.

It became obvious to the author that the construction of 2 parametric amplifiers, together with the filters, circulators and ultra high frequency pump source needed was a task that would require more time than was available and the cost would have been prohibitive. Mr. Meerholz however, suggested, as an alternative the construction of a crystal mixer as the first stage of the polarimeter, thus avoiding entirely the necessity of building 300 Mc/s amplifiers. This project will now be described in some detail/......

detail.

Crystal Mixer.

The use of a crystal mixer as the first stage of an amplifier obviated the necessity of building a pre-amplifier. The signal to be amplified was fed into a tuned circuit, a length of coax in this case, and a local oscillator signal was fed into this tuned line simultaneously, the difference frequency being taken out to the first I/F from a high frequency crystal mounted at the end of the coax.

The diagram of fig. VI show the construction of the crystal mixer as designed by the author.

The coax was designed to have a characteristic impedance of 50 ohms and on measurement was found to be 49 ohms. Allowance was made for this difference in further calculations.

Special low noise crystals were obtained through N.I.T.R. and during his stay at N.I.T.R. the author was able to perform noise measurements on these crystals. (CV2154). They were found to produce between 5 and 6 dB noise at 300 Mc/s which was sufficiently low for the polarimeter.

It was also found necessary to measure the admittance of the crystal when mounted in 50 ohm line so that stubs could be designed to balance out the conductance and susceptance components. This too was first done at the N.I.T.R. laboratories using their standing-wave meter and adjustable stubs. It was found that a stub 46.5 cms long should be used to balance out the susceptance

and/......

and that the R/F should be fed in through 30 cms of line to match the admittance of the crystal. These measurements were repeated at Rhodes and the final values used were a stub of length 47.2 cm at a position 26.2 cm from the crystal, the stub being an adjustable short-circuit.

The crystal mount was specially designed by the author for this mixer line and is also shown in fig. VI. A R/F by-pass condenser was built into this mount and had a capacity of aproximately 20 pf.

The local oscillator injector was placed approximately 5 cm from the crystal. As there did not appear to be any criterion as to the position of this probe it was a random choise.

It was realised that if the aerial was fed straight into the crystal mixer unit all signals received by the aerials within their very wide band limits would reach the mixer and as a result of mixing with the local oscillator frequency, two discrete signals having a difference frequency equal to that of the I/Fs would be received (ie. second-channel interference would be expected). Hence it was found necessary to construct an R/F tuner with a narrow pass band which would allow only the 300 Mc/s signal into the mixer. A suitable length of the type of coaxial line used for the mixer was fitted with an adjustable short-circuit allowing for fine tuning. Considerable difficulty was experienced in constructing exactly symmetrical loops through which the signals were fed into, and taken out of the tuner, as these had to be

as/......

as similar as possible to prevent undue losses.

Testing of the Mixer and Tuner.

A local oscillator had first to be designed and built before any tests could be performed on the mixer. A design for a high frequency oscillator was found in The Radio Amateurs Handbook. This used a low frequency crystal whose frequency was multiplied until the desired value was reached. It was thought that one further doubling would enable the correct frequency to be reached together with sufficient power output. The circuit shown in fig. X was successfully constructed and each stage adjusted to perform satisfactory multiplication. The final stage of the oscillator was a grounded grid tube with a tuned anode lead in the form of a length of copper tubing in a resonant cavity.

On attempting to operate the crystal mixer in conjunction with this oscillator it was found that the oscillator did not produce sufficient output to enable satisfactory operation of the mixer. Lack of sufficient power was almost certainly due to losses that occurred during the frequency multiplication process.

An oscillator built by the author in 1958 was then tried and found to be more successful. Its circuit was similar to the one shown in fig. VII which also shows the lay out of the final pre-amplifier unit.

Extensive tests were performed on the mixer but as a useful first stage it was scrapped for the following reasons:

1) Although it was found to operate successfully as a mixer the stability against mechanical shocks was negligible It was found that the efficiency of the mixer was extremely dependent on the probe depth of the local oscillator injection system and that this adjustment was not very stable, even minute changes disrupting the proper action of the mixer. As the polarimeter would need very uniform and stable first stages, the idea of using this particular design had to be abandoned.

2) It was further found that the position of the local oscillator injector was far from producing the best results and, except for using a process of trial and error where this injector would be moved to different positions along the coax which would entail the building of several such mixers, there did not appear to be a ready method to determine the optimum position for such ejection.

Also, on testing the tuner that had been built it was found to be far too lossy ever to serve any useful purpose, this being due to inefficient coupling into the tuned length of line. Doubtless a satisfactory model could have been built in time, but it was thought that it would be more economical to try another approach to the construction of the first stage of the polarimeter.

<u>Final Pre-amplifier.</u> (Fig. VII and plate III).

The pre-amplifier system finally used is shown in Fig. VII. It was based on a circuit given in the Radio Amateurs Handbook, 1957, p404.

It had also been used as a basis of the amplifier finally used by Wild and Poole.

The main trouble in using conventional lumped circuits (ie. circuits containing ordinary resistors, condensers and inductances) was due to the stray capacitive and inductive effects that appeared at frequencies of 200 Mc/s and over. It was found that the wiring capacities became considerable, the commercially available resistors showed self-inductance effects and the inductance of conventional capacitors became appreciable. These effects combined to produce a large unknown quantity in the circuit and it had been found that oscillations were readily produced in such amplifiers.

The largest single effect was that due to the self-inductance of the condensers, but, as several specially designed condensers for this frequency range had been obtained, it was decided that another attempt should be made using these circuit techniques. (Button condensers and feed-through condensers). Care was taken at all times to keep the wiring as short as possible to keep wiring capacities to a minimum.

The pre-amplifier consisted of a one-stage amplifier operated at 300 Mc/s. To avoid using a tuned circuit consisting of a few turns of wire, the tuned plate load was in the form of $1\frac{1}{4}$" square cavity consisting of copper sheet and with a copper tube $\frac{1}{4}$" diameter of fixed length mounted along the centre of this cavity. The line acted as the tuned plate load and its length

was/......

was determined by the operating frequency. The amplifier tube, a 6AM4, was operated with a grounded grid for better noise characteristics. (Grounded grid circuits give less noise than the grounded cathode circuits).

The tuning of the line was made variable by using the capacity between a circular disc mounted at the end of the line and another, that could be screwed in or out,

The output from this amplifier was taken out by tapping at a suitable point along the line, suitability being determined by whether the position of the tap varied the gain at all. The tap was made at a point where the effect on the gain was least.

This signal was then fed into a similar tuned line and cavity which served as the mixer and reduced the frequency to 27 Mc/s. This line was constructed similarly to the one described above, the length being different and tuning being accomplished by a small trimmer connected at the end of the line. The local oscillator signal was fed into the line by way of a small loop as shown in fig. VII. The intermediate frequency signal was taken from a crystal that was so mounted that its centre element made contact with the tuned line. The crystal mount that had been constructed for the mixer, described previously, was adapted to fit the line mixer.

The local oscillator first used has been described previously (fig X). However, it did not produce sufficient power for this purpose either. An oscillator constructed some years previously/......

viously by Dr. Stack-Forsyth was then tried and found to be successful. It was designed to operate at about 130 Mc/s and the second harmonic of the 136.5 Mc/s oscillation was found to produce enough power to operate the mixer.

The pre-amplifier had, in the meantime, been found to operate stably at 300 Mc/s with a gain of 15 dB.

Before the action of the mixer could be tested, several stages of I/F amplification had to be provided. Two stages of amplification were in fact provided on the pre-amp chassis before the signal was fed to the main instrument panel inside the shack, the pre-amp being housed on the roof of the shack near the antenna system.

I/F Amplifier.

The design used for the I/F amplifier stages at this point was supplied by Mr. T.V. Peter of the N.I.T.R.

It was operated as a cascade amplifier the first stage being a pentode (low noise- EF95) with a grounded-grid triode as the second stage. The circuit is shown in fig. VII as well. Each tuning coil had to be adjusted in turn and then re-adjusted with the amplifier operating as a whole.

A gain of approximately 45 dB was realized in practice.

The combination of the above units was then tested. Although it was found to operate reasonably successfully, the matching between the output of the crystal mixer and the input of the I/F was found to be far from ideal. This was because no

reasonable/......

reasonable estimate of the output impedance of the crystal could be made without some form of impedance measuring device. The matching was accomplished as well as possible by varying the turns ratio of the input coil of the first I/F stage. Nevertheless it was found that a considerable loss occurred, the overall gain of the system being only of the order of 40 dB. This will be discussed further at a later stage.

The signals from this I/F had then to be fed down to the main instrument rack in the shack, the first stage of which was the "channel mixer".

From the block diagram of the polarimeter as a whole it can be seen that each of the crossed sets of aerials required its own pre-amplifier mixer and I/F stages. Thus these three units were duplicated after the first had been found to operate moderately successfully and the gains adjusted to be of the same order as that of the first set. Further developement of this section was left until a later stage.

<u>D. Channel mixer.</u> (Fig. III and plate IV)

The purpose of the channel mixer, or "modulator" as it was called by the Japanese workers (1), was to combine two signals out of the possible six available, in the pre-determined manner. The criterion of addition has been described previously.

Each of the six outputs from the I/Fs was fed into a separate pentode, the outputs of these pentodes all being fed into the grid of another pentode which served to add to the signals that were

passed/......

passed by the series of 6 pentodes. The problem was then one of allowing only two of the pentodes to conduct at any one time, the other being held in a cut-off condition.

The basic design for the channel-mixer was proposed by Dr. Stack-Forsyth, but was extensively modified by the author in the course of construction and testing. The final circuit is shown in fig. III.

The current flow through a pentode can be controlled by varying the suppressor grid voltage as well as the signal grid voltage. In fact, for the pentodes used (EF94's) the tube could be cut off by applying a voltage of -60V to the suppressor. In the normal conducting state the suppressor would have been at earth potential. Hence the tubes were kept in a permanent cut-off state by keeping their suppressor grid voltages at this large negative potential and then allowed to conduct only when the signal incident at the respective grids, was required at the output stage.

This was achieved by connecting the suppressor to the plate of a triode operating between a negative voltage and ground. When the triode was in a conducting state, a voltage drop occurred across the load resistance, with the result that the voltage on the suppressor was forced down to a sufficiently negative value, determined by the voltages applied across the triode, the magnitude of the "load" resistor and the plate voltage of the pentode.

It was found that this was possible when the triode operated between earth and 125V on the cathode with a positive H.T. supply of 220V on the pentode.

By applying negative pulses to the grids of the triodes they could be cut off, their plate voltages then returning to earth potential with the result that the corresponding pentodes would conduct.

This necessitated a series of pulses appearing at 5 points in turn. A suitable pulse generator and a set of pulse directors that presented negative pulses at 5 different terminals in turn was therefore constructed. Pulses, appearing in a cycle, were then available to operate the mixer.

E. <u>Pulse Generator and pulse directors</u>. (Fig. II and plate V).

Although the mixer was controlled by a cycle of five pulses a sixth pulse in the cycle was needed, which was used as a reset pulse for the variable bias generator. (See later).

The circuit in fig. II shows how this cycle was obtained. It was based on one given by Woods (19).

V_1 was a conventional multivibrator operated at a frequency of 750 cycles per second. Negative pulses from the right-hand section of the double triode, V_1, were fed onto the grid of V_{2A} through a differentiating circuit. The train of sharp positive pulses that appeared at the plate of V_{2A} was then fed onto the grid of V_{2B}. This produced further differentiation and a train of very sharp negative pulses then appeared at the plate of V_{2B}.

The "pulse directors" consisted of a set of 6 bistable multi-

vibrators/......

vibrators connected in a ring circuit, the grids of the A sections of each of the double triodes being connected, through condensers, to a common line.

When the A section of any of these flip-flops was conducting the plate voltage was low, whereas it would be high in the cut-off condition. Hence, if these sections were alternatively non-conducting and conducting a large negative pulse, whose length depended on the time that the tube remained conducting, could be obtained at the plate. By connecting a set of 5 such flip-flops in a ring circuit it was possible to obtain large negative pulses at each of the sections of the double-triodes in turn.

The criterion for correst operation was that before the start of the cycle of operation only one of the A sections should be in a conducting state. The other half of that particular flip-flop was then cut off. The reverse was true for all the other flip-flops in the circuit.

When a pulse, from the pulse generator, was fed into the common line it affected only the A section that was conducting (V_{3A} say). The effect was to cut this section off. As a result a positive going voltage appeared at the grid of V_{3B} which caused this section to become conducting. This then caused a drop in the plate potential, which appeared as a negative going pulse at the grid of the B section of the tube following it in the ring (V_{4B}). The effect was to cut this section off, The positive going voltage appearing at this plate was then fed onto the grid

of/......

of V_{4A} increasing its grid voltage with the result that this section became conducting. In turn, the negative going voltage appearing at the plate of V_{4A} was fed onto the grid of V_{4B}, but, because this section is already non-conducting, there was no further effect. The situation was then one where all the A sections were non-conducting except that of V_4.

At the onset of another pulse the process was repeated, V_{4A} being cut off once more and V_{5A} becoming conducting as the last step in the cycle.

This process was repeated every time a pulse was fed into the common line from the pulse generator. The sequence of events is here indicated diagrammatically, an X denoting a tube in the conducting state.

Tube	V_3		V_4		V_5		V_6		V_7		V_8	
Pulse	A	B	A	B	A	B	A	B	A	B	A	B
0	O	X	O	X	O	X	O	X	O	X	X	O
1	X	O	O	X	O	X	O	X	O	X	O	X
2	O	X	X	O	O	X	O	X	O	X	O	X
3	O	X	O	X	X	O	O	X	O	X	O	X
4	O	X	O	X	O	X	X	O	O	X	O	X
5	O	X	O	X	O	X	O	X	X	O	O	X
6	O	X	O	X	O	X	O	X	O	X	X	O

The initial position, only one left hand section conducting, was achieved by returning the grids of V_{3B} to V_{7B}, as well as the grid of V_{8A}, to earth by means of a specially adapted switch. As a precautionary means this switch was also made to switch on a red light, thus guarding against its being left on accidentally with resultant over-running of the tubes. (The cycle then start-

ed with/......

ed with V_8, instead of V_3 as described above).

An examination of the scheme adopted for mixing appropriate signals showed that certain of the channels, ie. certain of the triodes, had to be operated by more than one pulse in the cycle. To prevent interaction between stages that would, of necessity, be connected together if more than one pulse had to operate the tube, the system of diodes shown in fig. III had to be used. These diodes allowed any pulse to cut off the triode in question, while, at the same time, preventing the pulse to flow to any other point in the circuit. As V_3 and V_6 did not require to be activated by more than one pulse in the cycle, a diode was unnecessary in their circuits.

The common output of these 6 pentodes was then fed through a tuned grid coil to the output pentode. This tube had a tuned plate circuit, at the I/F of 27 Mc/s. The 6 pentodes were not provided with a separate tuned plate load because complications would indoubtedly have set in as a result of interaction of the two tubes that would have been conducting at any other time.

By operating the pulse generator at -250V on the plates it was found possible to obtain negative going voltages, at each of the A section plates in turn, of the order of 80V. The size of the components in the flip-flop circuits were first adjusted so that such a voltage could be obtained and also so that stable action of the flip-flops could be achieved. This was done by testing an individual circuit with a single pulse generator, built

for/......

for the purpose, and then adjusting the components as desired. The other flip-flop circuits were then made duplicates of this.

Six output terminals at which negative pulses, varying between -100V and -180V and of 1.3 msec duration ($\frac{1}{6}$ of the cycle period) appeared in the correct order, were provided at the rear of the chassis. These pulses were then fed straight to the channel mixer.

F. Main Intermediate-Frequency amplifier. (Fig. V and plate VI).

The common output of the channel mixer had still to undergo a large amount of amplification before the signal strength was sufficiently large to be displayed.

An I/F amplifier capable of providing about 100 dB gain was required and the circuit, designed by the author, of the completed unit is shown in fig. V.

The input was fed onto the grid of the first of three stages of amplification at 27 Mc/s through a tuned transformer consisting of about 5:13 turns to provide approximate matching from the 50 ohm cable used to bring the signal from the previous stage.

After these three stages, each producing about 20 dB gain, the signal frequency was further reduced, this time to 1.4 Mc/s. This particular frequency was decided upon as several commercially made I/F transformers operating at this frequency were available. One stage of amplification at the lower frequency was then provided.

It can be seen from the fig. V that the signal was fed into

2 separate amplification channels after the mixer stage. The reason for this was that provision had to be made for two separate bandwidths, since it is hoped that the polarimeter would be used for accurate determination of the orientation of the plane of polarization at the source as discussed in chapter 3. By feeding the signal through two separate amplifying paths, the bandwidth of the one could be adjusted to twice that of the other (both being extremely small). The reasons for this have been discussed in a previous chapter.

If a conventional linear detector had been used the deflection at the output due to a solar burst would also have been affected by background noises including receiver noise and thermal radiation from the sun. This would then have entailed calculating the intensity of each component of the polarimeter output from the deflections of both the burst and the background.

These considerations led Susuki and Tsuchiya (1) to develop a new form of square law detector with a particularly fast response time to suit detection of solar bursts. Their design was incorporated as the next stage in the above I/F amplifier. An E91H formed the new type of detector, the output being tuned to the second harmonic of the input frequency.

If the input signal had the form

$$e_i = E_i \ \mathrm{Sin}\ \omega t \qquad \ldots. (1)$$

and assuming that the characteristics of this non-linear

circuit/......

circuit could be expressed in the form of a series

$$e_o = E + ae_i + be_i^2 + \dots \qquad \dots\dots (2)$$

we obtain, substituting from (1) into (2)

$$e_o = E + aE_i \operatorname{Sin} \omega t + bE_i^2 \operatorname{Sin}^2 \omega t..$$

or

$$e_o = (E + \tfrac{1}{2}bE_i^2) + aE_i \operatorname{Sin} \omega t - \tfrac{1}{2}bE_i^2 \operatorname{Cos} 2\omega t.$$

If the output was tuned to the second harmonic 2ω the output of the detector would be proportional to E_i^2.

This type of detector is shown in both amplifying channels in the diagram (Fig. V).

In channel I, the signal was then passed through a diode detector and fed onto two output terminals A and B as shown. Any dc. voltage appearing at the output could then be bucked out by the control R_3 (fig. IV).

In channel II, however, the signal first underwent a further stage of amplification at the new frequency of 2.8Mc/s, because further amplification had to be provided, to make up for the gain lost by increasing the bandwidth.

A cathode follower stage was also built into each channel, to provide ready monitoring of the signal by means of a small audio amplifier in the shack.

The overall gain of each channel was adjusted to about 105 dB with the bandwidth of channel I about 15 kc/s and that of the other about twice this value.

A variable bias control was used on the final a of channel I so that the gains of the two channels c

adjusted/......

adjusted to the same value from time to time.

It was found, during the course of testing, that, when the mixer was connected to the main I/F amplifier, severe losses occurred because of mismatch between the mixer output and I/F input stages. As no progress was made by repeatedly varying turns ratios of the I/F input transformer a new approach had to be adopted.

As the approximate input impedance of the first I/F tube could be calculated from a knowledge of the grid cathode capacity and as the impedance of the input cable was known (50 ohms), the matching between these two was accomplished by supplying the appropriate turns ratio at the first tuned stage. However, the main source of difficulty was to match the output impedance of the final stage in the "mixer" to that of the 50 ohm cable. The former had an unknown, and probably very large, value and, as no methods were available for its measurement, it was decided, at the suggestion of Prof. Gledhill, to add an additional stage in the form of a cathode follower. The output impedance would then be considerably lower and could be accurately adjusted.

The output impedance of a cathode follower is given by $1/g_m$, where g_m is the transconductance of the tube used. For the EC 80 used g_m was 12mA/V. The output impedance was therefore 83.5 ohms and this in parallel with the 100 ohm load resistor gave an effective output impedance of 45.5 ohms

then/......

then gave better matching into the 50 ohm cable.

G. Step Generator and Display Unit (Fig. IV)

The display unit was a single beam cathode ray tube. By applying a variable voltage, in the form of a staircase to the deflector plates it was possible to display several output signals on the screen, one above the other.

The output from the pulse generator provided the pulses needed to operate the step generator shown in fig. IV. Five pulses were used to provide five steps at the output and every sixth pulse was used to reset the step generator to its initial condition.

The principle of the step generator was to charge a stable condenser by a small amount at a time, discharge being prevented until the arrival of the sixth pulse. The chain of negative pulses was fed onto the grid of pentode V_1. The pulses cut the tube off, the plate voltage rapidly rose to the level of the supply voltage while the condensers C_1 and C_2 charged up through the diode V_{2B}. Between pulses V_1 was conducting and the plate voltage returned to normal, C_1 discharging through V_1 and V_{2A}. The only possible discharge path for C_2 was the thyratron V_4 and, since this was kept in the non-conducting state, discharge was prevented.

When the next pulse arrived at the grid of V_1, C_1 and C_2 again became charged, the charge on C_2 adding to that already present. This process was repeated with every pulse, the

charge/......

charge on C_2 increasing while that on C_1 leaked away between pulses.

When the voltage on C_2 became sufficiently large it caused V_4 to strike, this striking voltage being determined by the bias on the thyratron. C_2 would then discharge rapidly, at the same time extinguishing V_4. The bias on the thyratron was adjusted by means of R_4.

It was found that the charge added to the condenser C_2 varied from pulse to pulse, the thyratron was caused to strike randomly and stable action, i.e. discharge of C_2 at every sixth pulse, was unreliable.

By putting every sixth pulse onto the grid of the thyratron, this tube would be caused to conduct so that C_2 would discharge. This pulse, being derived from output No.6 of the pulse directors, was in the form of a negative square wave and as a positive voltage was needed to operate the thyratron, the wave was differentiated and inverted by V_3. The positive-going leading edge then raised the grid potential of V_4 sufficiently to cause it to conduct.

The voltage on C_2 now had the form of a series of steps which had to be applied to the display oscilloscope. A difference amplifier was used for this purpose, the step wave being fed to one grid and the signals to be displayed to the other grid. The deflector plates of the C.R.T. were connected directly to the plates of the difference amplifier.

It/......

It was found that connection of the output of C_2 to the grid of the difference amplifier provided a ready discharge path, through the grid-cathode resistance, for the accumulating charge with the result that C_2 discharged after every pulse. By employing the pair of high quality condensers, C_3 and C_4, only a fraction of the step voltage was applied to the difference amplifier and the impedance of the discharge path was then sufficiently high to prevent discharge of C_2 between pulses.

The Display

The method of recording the signals that were displayed on the oscilloscope screen was similar to that used by both Shuter (6) and Wild (8).

A continuously driven film was allowed to run through an oscilloscope camera focussed on the screen. About 25 feet of film ran through the camera during an 8-hour observing period. Any variations in the output intensity appeared as variations in the displacement of the spot on the cathode ray tube screen and, in turn, appeared as variations of the trace on the film. These variations are similar to the burst profiles as received by the antennas.

By the addition of the step generator the film records a series of five base lines, one above the other, each displaying a particular component of the radiation received. By adjusting the bias on the oscilloscope it was possible to have

only/......

only the five steps on the screen, the sixth, the return to zero, being off the screen.

The five traces as recorded on a trial run, without any radio frequency input, are shown in plate I.

Power Supplies

Several power supplies providing 250v regulated D.C. were already available in the "shack" and were not being used at the time. A transistorized 6.3V regulated supply was also available and capable of supplying 3A. It was however necessary to modify the existing supply to provide H.T. for the pre-amplifiers and the first I/F's. The diagram of the modified supply is shown in fig. VIII B. By suitable adjustment of the component values it was found to regulate efficiently for variations of input voltage varying from 190V to 250V.

It was also necessary to construct a power supply capable of providing the negative voltages needed for the pulse generator and the gate tubes of the modulator (-220v and -112V respectively). A circuit given in the Radio Amateurs Handbook (1957, p.230) was used as a basis for the design shown in fig. VIII A. This degree of regulation was attained while drawing a current of 30mA at -220V and 11mA at -112V and for output voltages ranging between -210v and -235V.

Although 3A of regulated 6.3V D.C. were available a further 6A were needed to provide all the heaters in the

polarimeter/......

polarimeter. The system adopted was to supply all the tubes with 6.3V derived from a car battery which was continuously charged from a 6V 6A battery charger, the battery then acting as a regulator to the voltage supplied by the charger. This system was found to be trouble free and to regulate sufficiently well.

The E.H.T. supply for the oscilloscope display was also available in the "shack" being a -1500 supply built by P.A.T. Wild.

CHAPTER IV.

REFERENCES

(1)	Susuki & Tsuchiya.	"A Time-sharing polarimeter at 200 Mc/s",	Proc.I.R.E. 46,190 (1958).
(2)	Smith.	"Aerials for Metre Wavelengths".	Cambridge Univ.Press.
(3)	Reid.	"The Gain of an Idealized Yagi Array".	Proc.I.E.E. 93,564 (1946).
(4)	Walkinshaw.	"Theoretical Treatment of Short Yagi Aerials".	Proc.I.E.E. 93,598 (1946).
(5)	Fishendon & Wiblin.	"Design of Yagi Antennas".	Proc.I.E.E. 96,5 (1949).
(6)	Shuter.	M.Sc. Thesis.	Rhodes. (1958.)
(7)	Roberts.	"A New Wide-band Balun".	Proc.I.R.E. 45,1628 (1957).
(8)	Wild.	M.Sc. Thesis.	Rhodes. (1959).
(9)	Suhl.	"Proposal for a Ferromagnetic amplifier in the Microwave Region".	Phys.Rev. 106,384 (1957).
(10)	Manley & Rowe.	"Some General Properties of Non-linear Elements".	Proc.I.R.E. 44,904 (1956).
(11)	Bloom & Chang.	"Theory of Parametic Amplifiers".	R.C.A. Rev. 18,578 (1957).
(12)	Nergaard	"Non-linear Capacitance Amplifiers".	R.C.A.Rev. 20,3 (1959).
(13)	Brand, Matthei & Saad.	"The Reactatron".	Proc.I.R.E. 47,42 (1959).
(14)	Weber.	"The Mavar".	Electronics. 31,65 (1959).

(15)	Chang & Bloom.	"A Parametric Amplifier using low Frequency Pumping".	Proc.I.R.E. 46,1383 (1958).
(16)	Younger, Little Hefner & Wade.	"Parametric amplifiers as Super Regenerative Detectors".	Proc.I.R.E. 47,1271 (1959).
(17)	Bossard.	"Super Regenerative Reactance Amplifiers".	Proc.I.R.E. 47,1269 (1959).
(18)	Goto.	"The Parametron".	Proc.I.R.E. 47,1304 (1959).
(19)	Woods.	"Multichannel Switch for Biological Observation".	Electronics. 28,145 (1955).

CHAPTER V.

DISCUSSION OF RESULTS.

As it was already two years past sunspot maximum the frequency of bursts which could be expected would be considerably less than that observed by previous workers at Rhodes University, who had observed near or during the sunspot maximum.

Roberts (1) has given an indication of the number of type II bursts that could be expected during this part of the sunspot cycle. It would be of the order of 1 burst per 4-500 hours of observation. Type I bursts associated with sunspots would obviously be much less frequent than during 1957-59. Owing to the kindness of the head of the Ionosphere and Radio Astronomy section of the Netherlands P.T.T. 24 hour records of solar noise activity were available for comparison with the Rhodes records. From these 24 hour records it was learnt that for a 12 month period (Oct. '59 - Sept. '60) and on frequencies of 200 Mc/s, 545 Mc/s and 9100 Mc/s only 9 noise storms had been observed, 4 of these during December 1959. None of these occurred while the polarimeter at Rhodes was being operated.

A large number of events that might in general be called type III bursts were, however, recorded. The intensities varied from about 50×10^{-22} watts/m^2/c/s to 38000×10^{-22} watts/m^2/c/s.

Before the Rhodes polarimeter was completed a single channel was operated as a simple radiometer to check on its performance. During this time several difficulties cropped up and, in time,

were/......

were smoothed out. Several burst events were then recorded, and, as these "bursts" were similar in shape to those observed by Shuter, Wild, and Poole, it was felt that they could be attributed to events occurring on the sun rather than to instrumental faults.

An analysis of the frequency of occurrence of these events, neglecting those that seemed to be caused by possible instrumental faults, showed that they were observed at the rate of one every 10 to 12 hours of observing time.

The number of bursts observed by the Netherlands 24-hour patrol on 200 Mc/s would be expected to give an indication of the number of bursts that might be observed on 300 Mc/s and an analysis of their records showed that, at 200 Mc/s only one event per 22 hours was recorded.

During the 86 days (records No's M1-M86) on which records were obtained at Rhodes only two events were recorded both at Rhodes and by the P.T.T., simultaneously, one being a minor burst and the other a large outburst on 29th March (M10). Owing to the fact that a spate of these so-called minor bursts were at one stage recorded, the radiometer was operated first with the aerial pointing away from the sun and secondly at night time to try to account for these "bursts". As none were recorded during such periods of operation it seemed that instrumental faults would not account for the phenomenon. One possible source of these "doubtful" bursts was a university residence

that/......

that had been constructed next to the instrument shack since the latter had been built. Small induction fields, resulting from sparks produced in the residence, might be amplified and appear as minor bursts.

During operation of the radiometer it was found that the pre-amplifier was not stable enough mechanically with the result that retuning had to be carried out periodically. Furthermore, although the overall gain was initially measured to be 140 dB, the gain dropped to about 90 dB due to inadvertent over-running of the crystal. On inserting several new crystals in turn, a gain of only 120 dB could be realized, but it was felt that this was enough to record medium intensity bursts. (10^{-20} watts/m^2/c/s). During the operation of the radiometer a total of 105 events was recorded during 86 days of observation. Some of these are shown in plate I.

Critique of performance of apparatus.

Although several parts of the polarimeter operated successfully certain other components should be modified somewhat for future operation.

The main I/F amplifier was found to give a stable gain of about 100 dB at a frequency of 27.8 Mc/s.

The step generator appeared to operate successfully, provided the two potentiometers in the circuit were correctly adjusted.

The oscilloscope display unit and associated power supply operated normally except that occasional variations of intensity of the spot during some later runs were observed. Replacement of components in the E.H.T. supply would probably have overcome this.

The channel mixer, although not having been tested with 6 input signals, operated successfully to combine 2 signals.

The 6V supply system also appeared adequately stable for the polarimeter, and the negative H.T. power supply built by the author was found to be extremely reliable.

Towards the end of the period during which the author operated the "shack" the power supplies that had been built several years earlier by other workers began to give trouble. In general, the regulation of these supplies ceased to operate and by replacement of valves and resistances, temporary repair was effected. For further successful operation these supplies will have to be rebuilt entirely to avoid the repeated breakdown of old components.

The main causes of trouble that prevented successful operation lay in the matching between the output stages of one polarimeter unit and the input of the next. The matching between the channel mixer and the main I/F amplifier had been accomplished, partly, by insertion of a cathode follower stage, but this was subsequently found to be the main source of noise in the receiver.

Also the matching between the crystal mixer and the first I/F stage of the pre-amplifier was found to be extremely poor but, as no means were then available by which to measure impedances at

a/......

a frequency of 27 Mc/s, no adequate matching system could be designed.

During operation of the receiver as a radiometer it was realized that the complete polarimeter would not have been very successful in operation due to the inadequate display methods. As some of the bursts recorded had gone off scale it was obvious that, if 5 levels on the oscilloscope were to be used simultaneously, a record of such bursts would have been useless for the analysis of polarization characteristics, each level overlapping all the others above it. Therefore, only a narrow range of burst intensities would lend themselves to such an analysis. All large bursts would autmoatically be excluded while small bursts, whose variation of intensity was comparable in magnitude with the width of the trace on the film, could not be accurately analysed.

This latter trouble could be overcome, partly by reducing the spot size (by providing post-acceleration-deflection) and partly by building receivers with considerably lower noise figures. Alternatively a non-linear amplifier (eg. logarithmic) would enable the larger bursts to be contained in the space available for their display. A third alternative, possibly the one that would lead to best results, was to obtain a multichannel pen recorder, which would allow for more detailed analysis of burst profiles.

To sum up, the polarimeter will become a practical proposi-

tion/......

tion provided the following changes are made:

(1) A new, mechanically stable, preamplifier should be built.

(2) Accurate matching between the following units must be ensured.

(a) the crystal mixer and the first I/F stage;

(b) the first I/F stage and the channel mixer;

(c) the channel mixer and the main I/F amplifier.

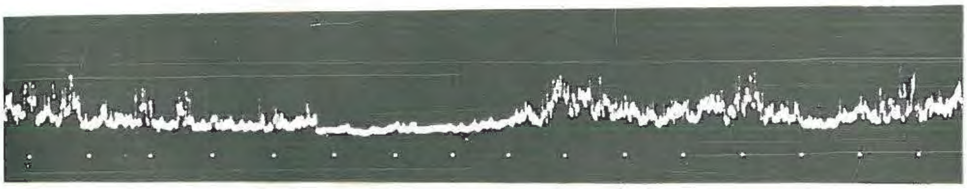
(3) The main power supplies should be rebuilt.

(4) New display methods must be devised.

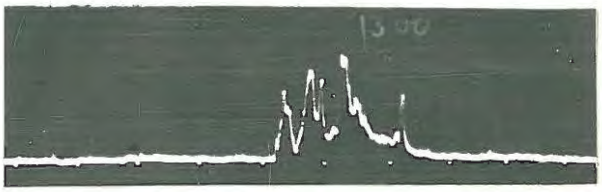
Reference

(1) Roberts "Solar radio bursts of spectral type II." Aust. J. Phys. 12, 327 (1959)

PLATE I

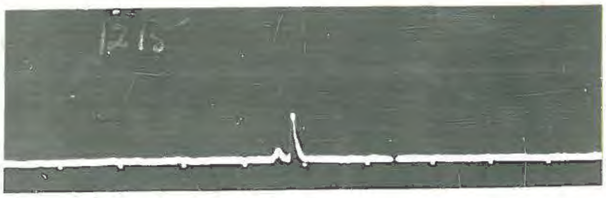


Type I bursts during Noise storm on 125 Mc/s (Shuter)



Type II burst. "Outburst"

On 125 Mc/s. (Shuter)

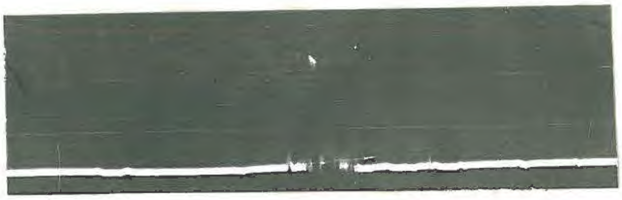


Type III burst. "Isolated Burst"

On 125 Mc/s. (Shuter)

Outburst on 300 Mc/s.

M21 12/5/60



Outburst on 300 Mc/s.

M23 14/5/60

Isolated burst on 300 Mc/s.

M21 12/5/60

Note: Events on 300 Mc/s are more rapid than 125 Mc/s events.

5 traces produced by the step generator

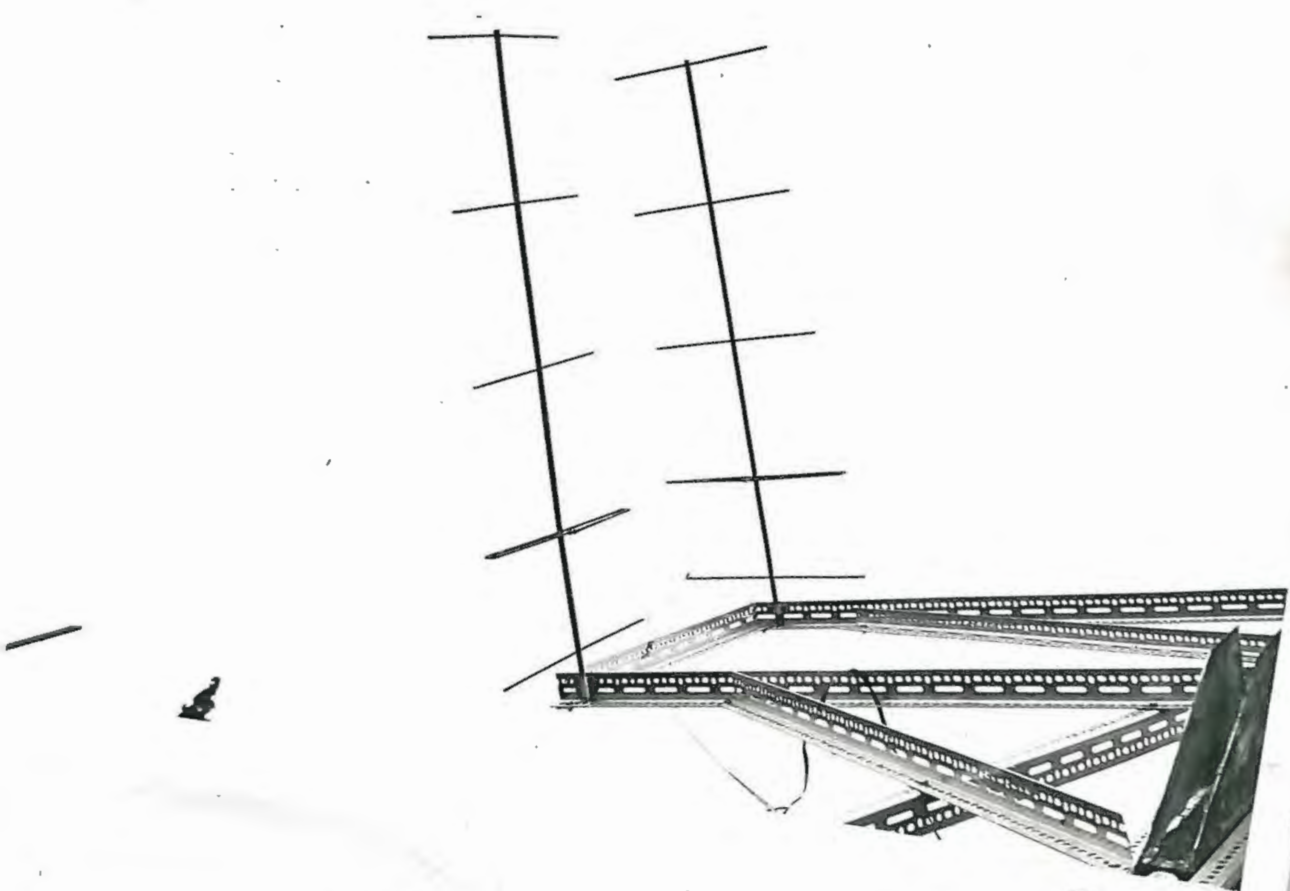
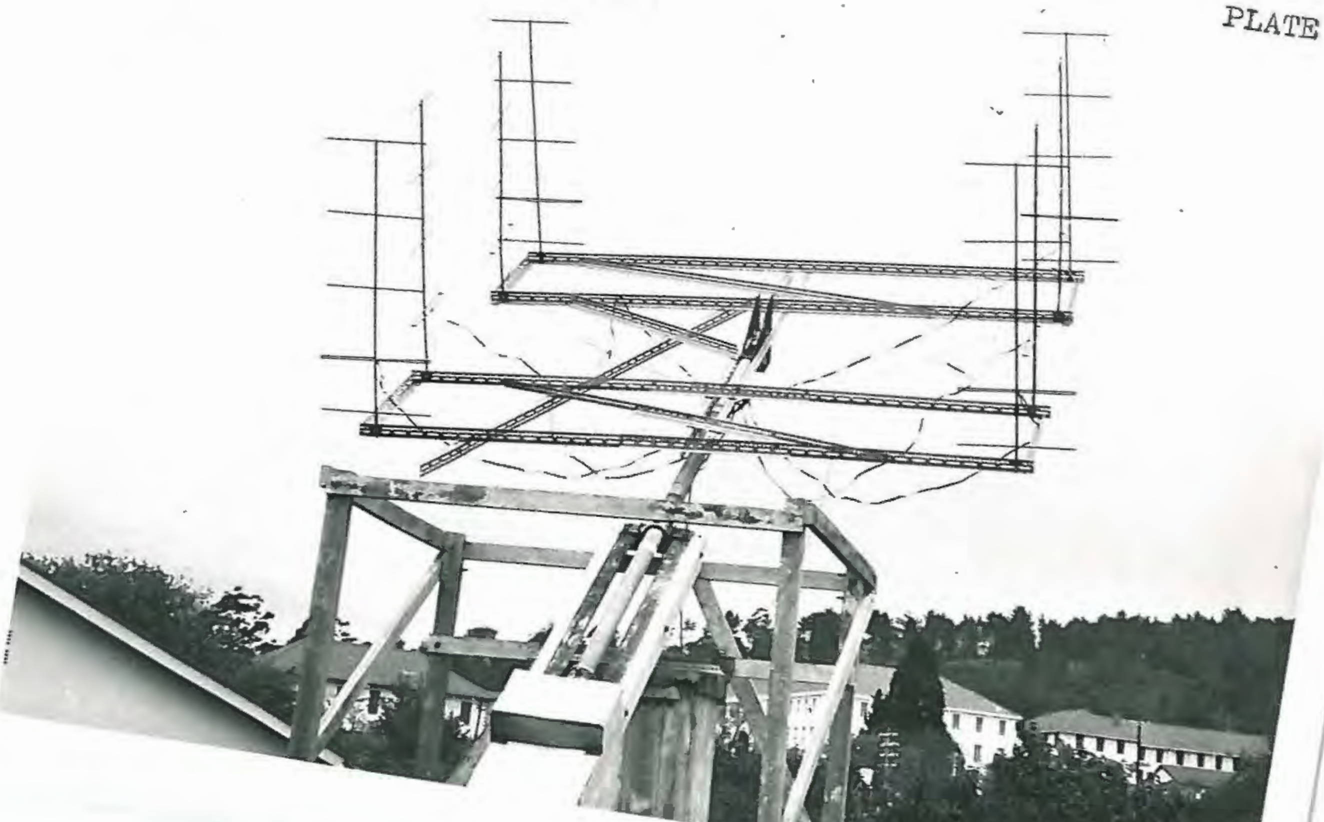


PLATE II



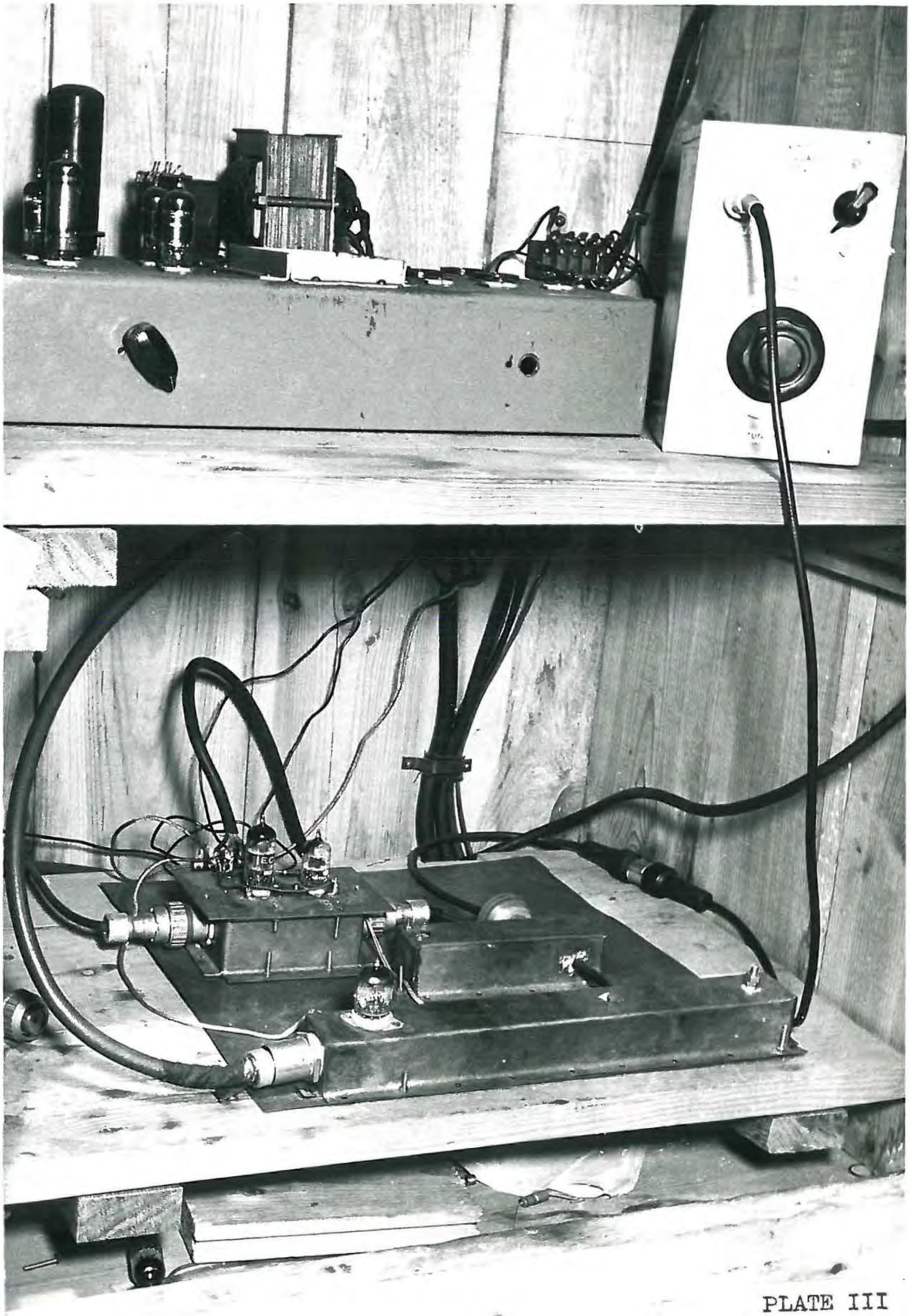


PLATE III

PLATE IV

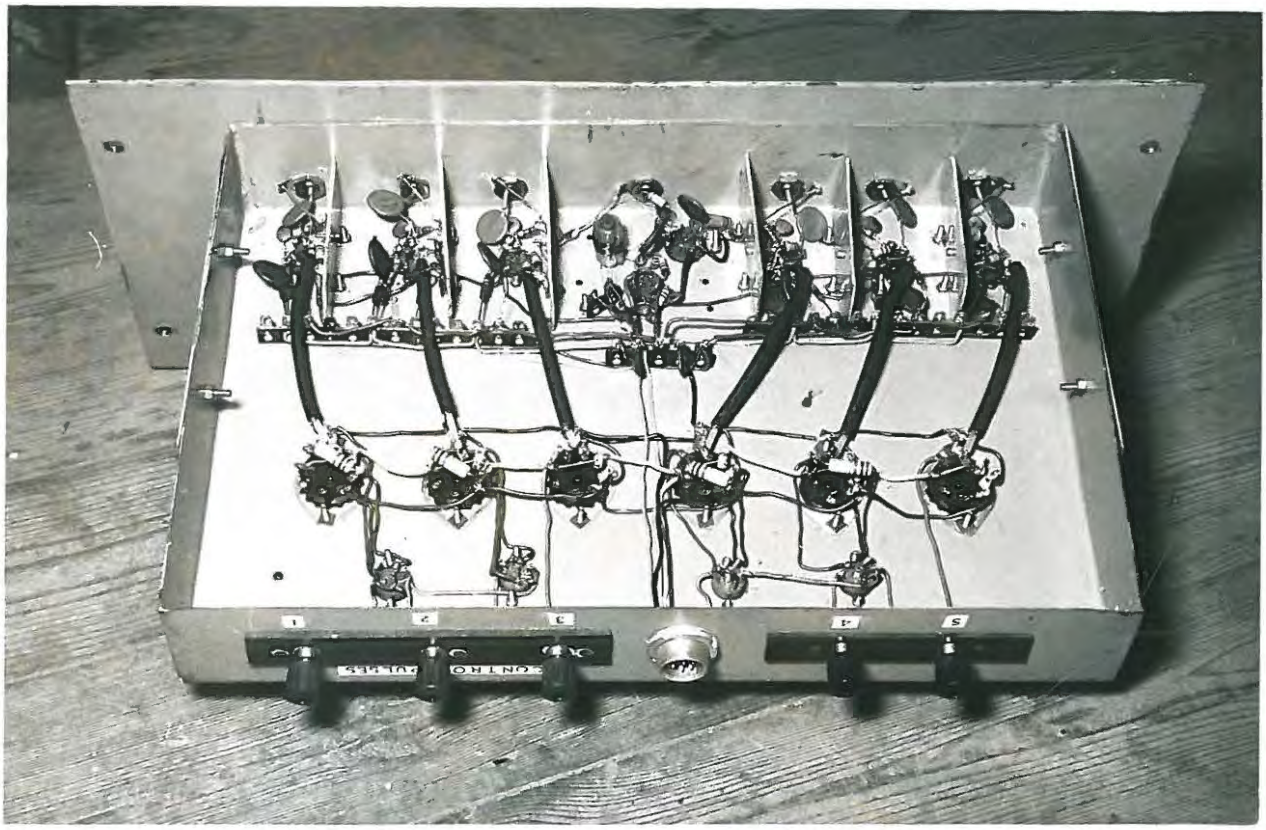
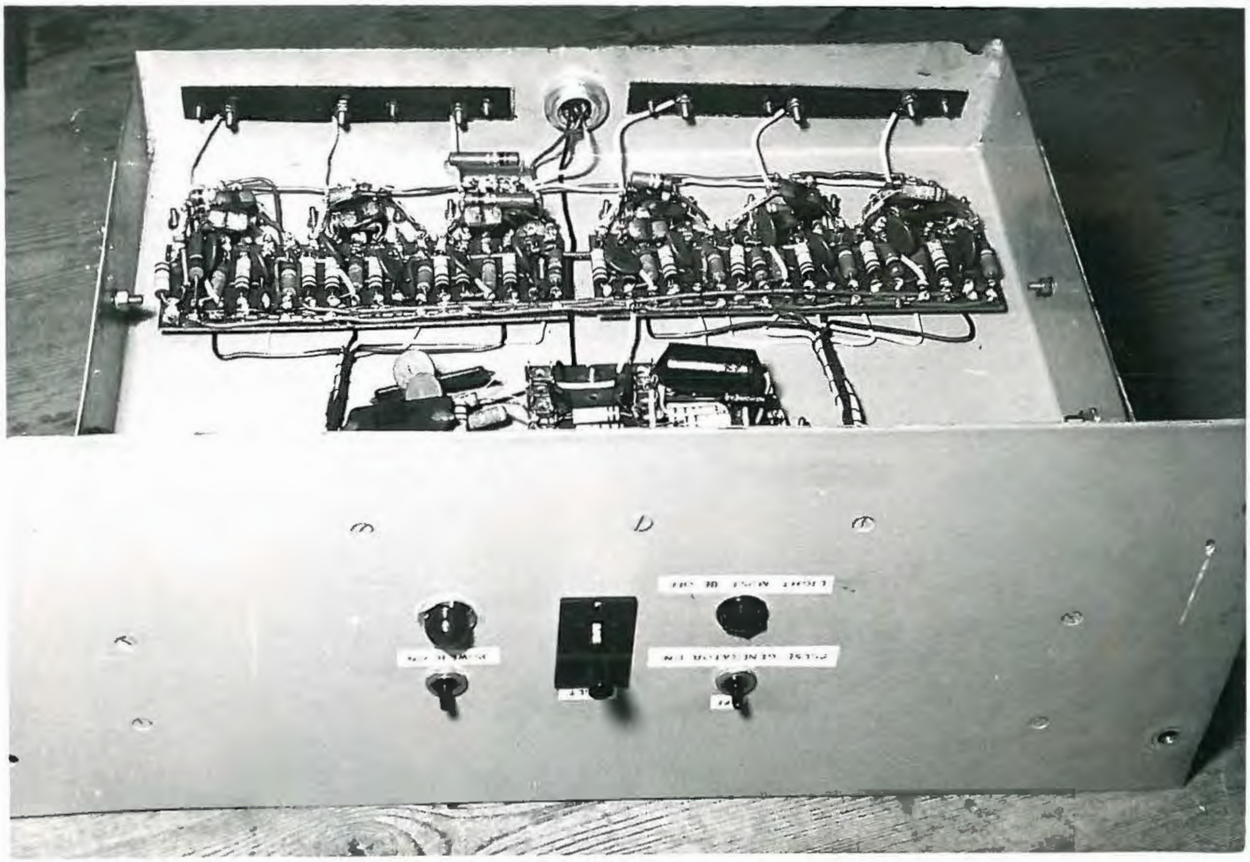


PLATE V



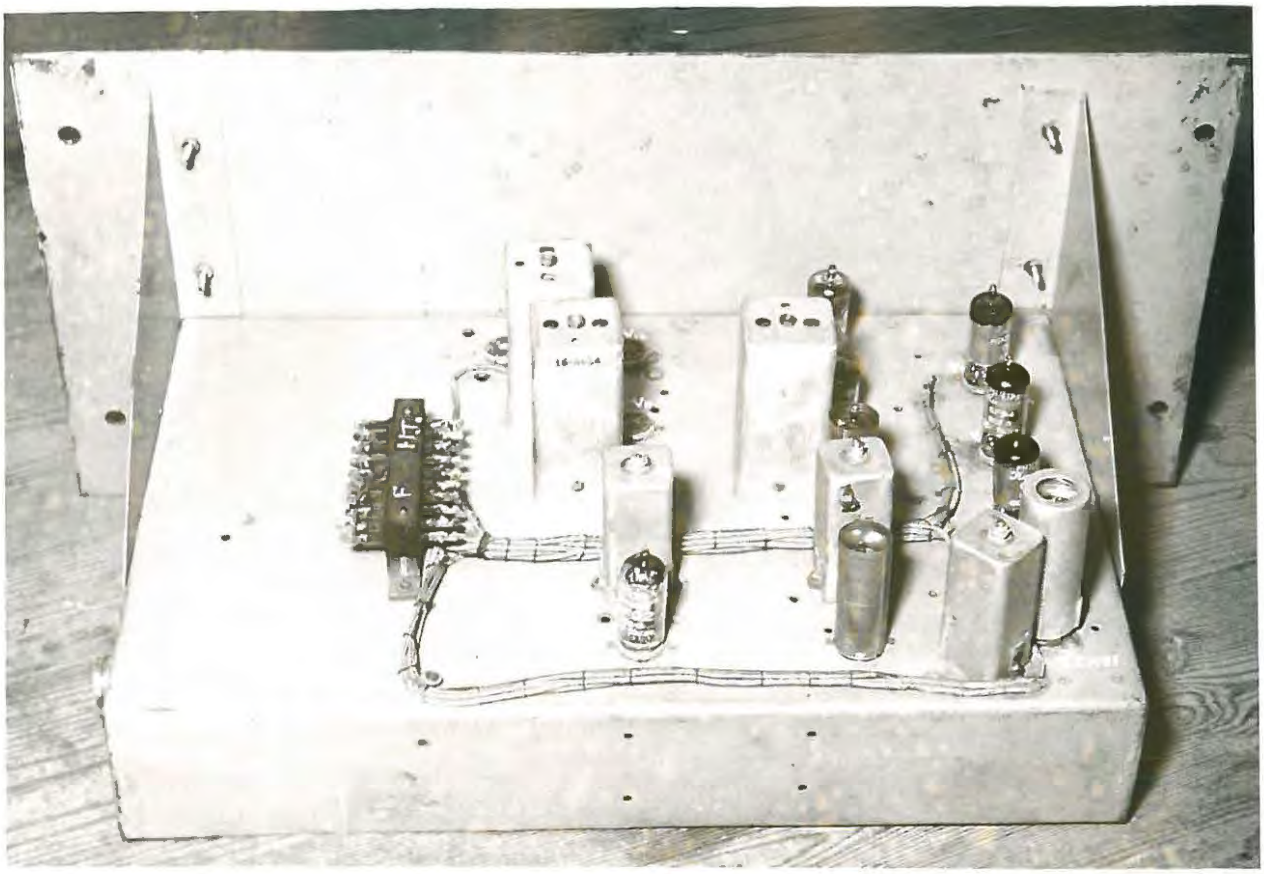
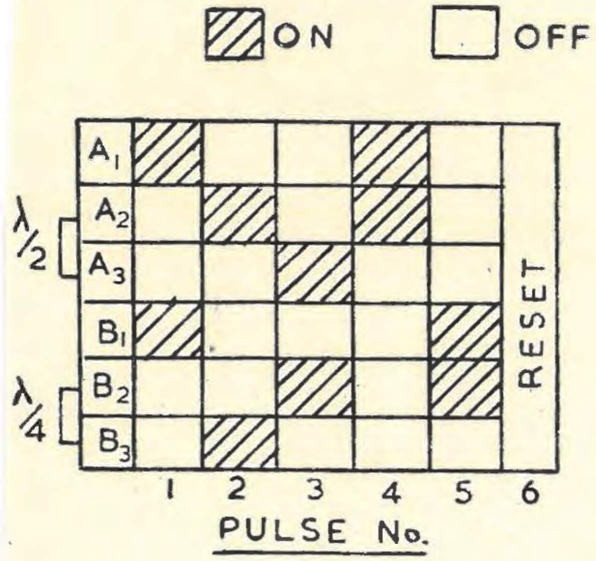


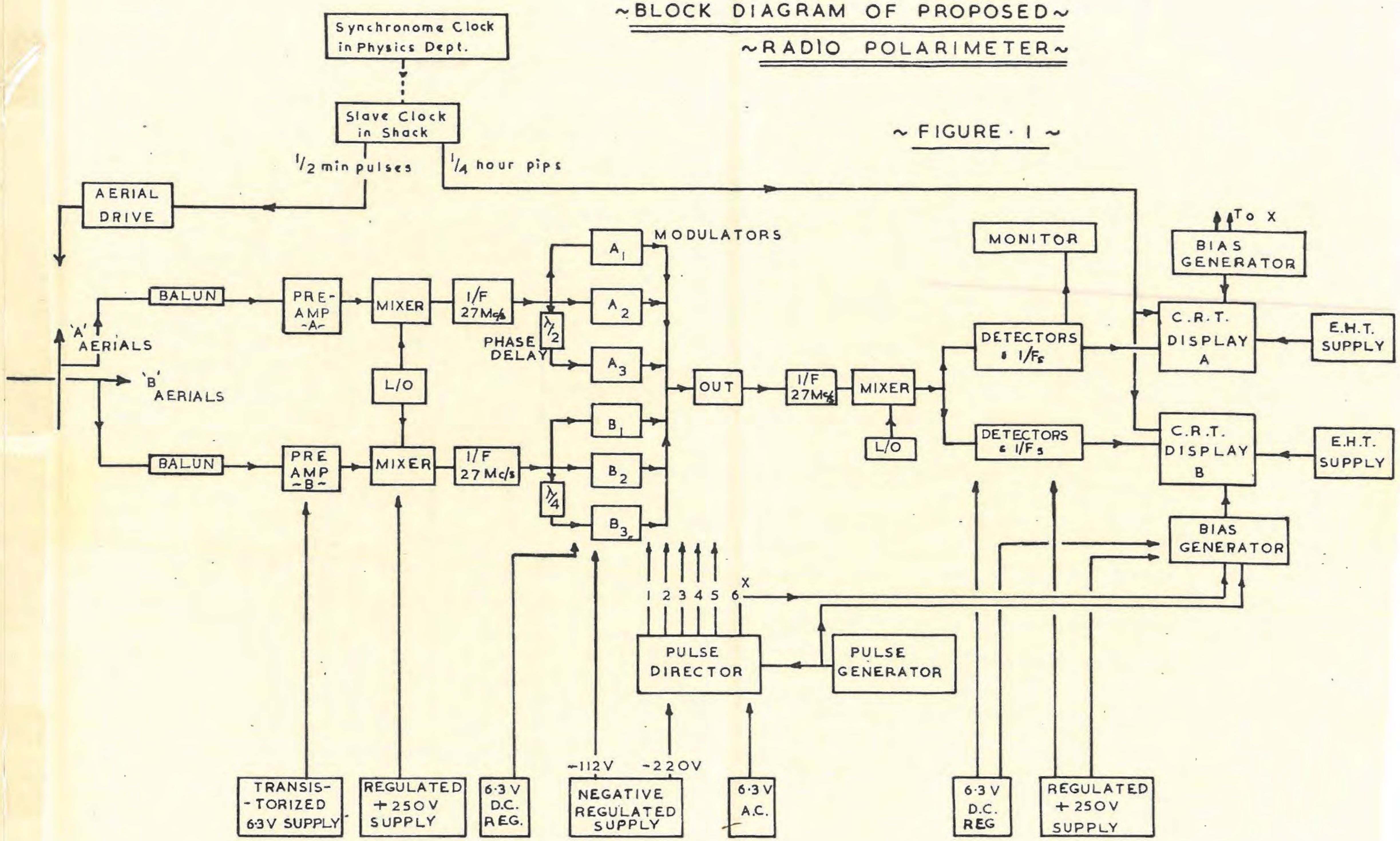
PLATE VI

~SCHEMATIC OF SWITCHING~ ~SYSTEM~



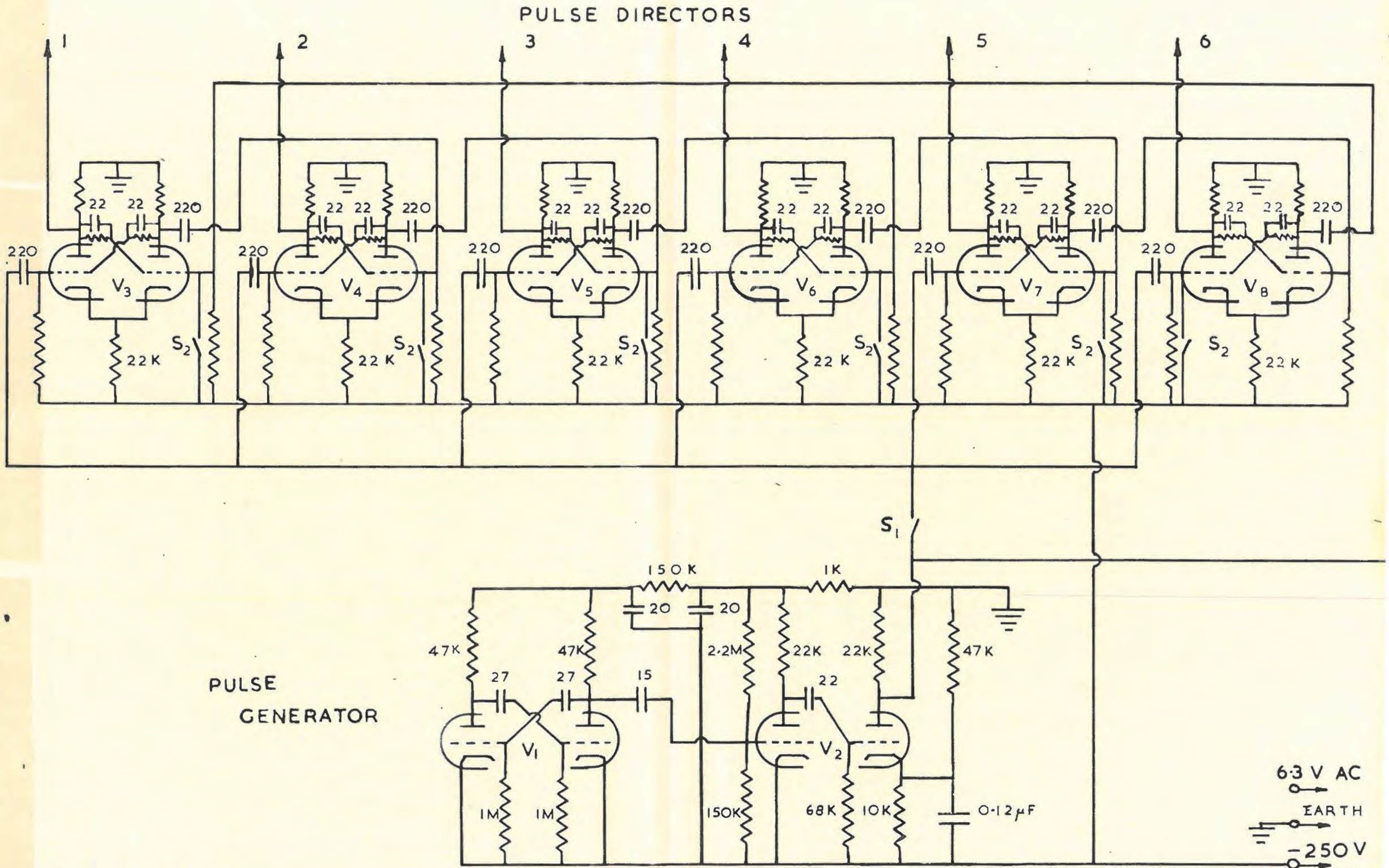
~BLOCK DIAGRAM OF PROPOSED~ ~RADIO POLARIMETER~

~ FIGURE · 1 ~



LEGEND

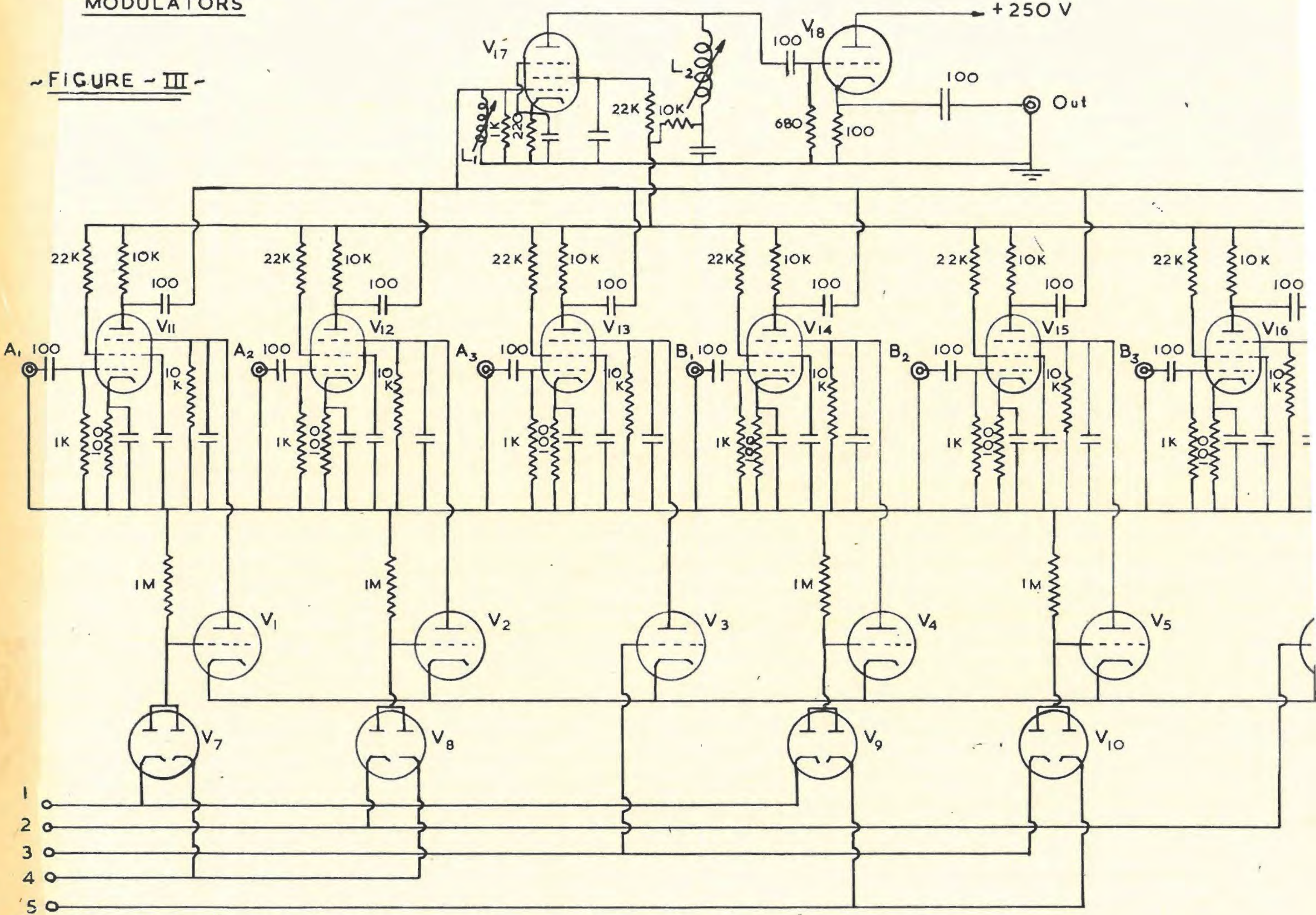
V_1 - V_8	All 6SN7 Double Triodes
All Unmarked Resistors 100K	
All Capacitors in Picofarads	
S_1	Pulse Generator ON
S_2	Reset



- FIGURE-II -

CHANNEL MIXER "MODULATORS"

~ FIGURE ~ III ~



LEGEND

V_1 - V_6	½ - 6SN7 DOUBLE TRIODE
V_7 - V_{10}	EAA 91 DOUBLE DIODES
V_{11} - V_{17}	EF94 PENTODES
V_{18}	EC80 TRIODE
All Unmarked Capacitors 1Kpf Ceramic	
Other Capacitors in pf	
L_1 - 13 turns ¼" slug tuned	
L_2 - 13 turns ¼" slug tuned	

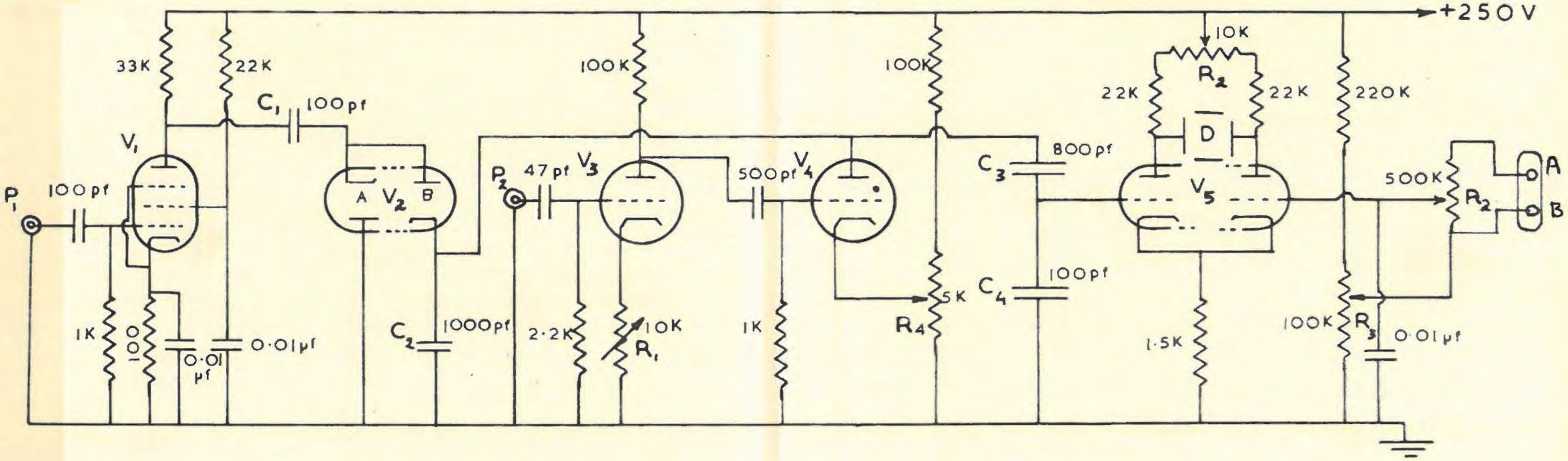
FIGURE IV

STEP GENERATOR

~ Variable Bias Generator ~

~ LEGEND ~

V_1 – EF94	V_2 – EAA91
V_3 – 6J5	V_4 – 884
V_5 – ECC82 – Double Triode	
C_1, C_2, C_3, C_4, – Stable Condensors	
P_1 Output from Pulse Generator No 7	
P_2 Output from Pulse Directors No 6	
D - Y Plates of C.R.O. Display	
R_1 D.C. Amplifier Control	
R_2 Buck Out Control	
R_3 Gain Control	

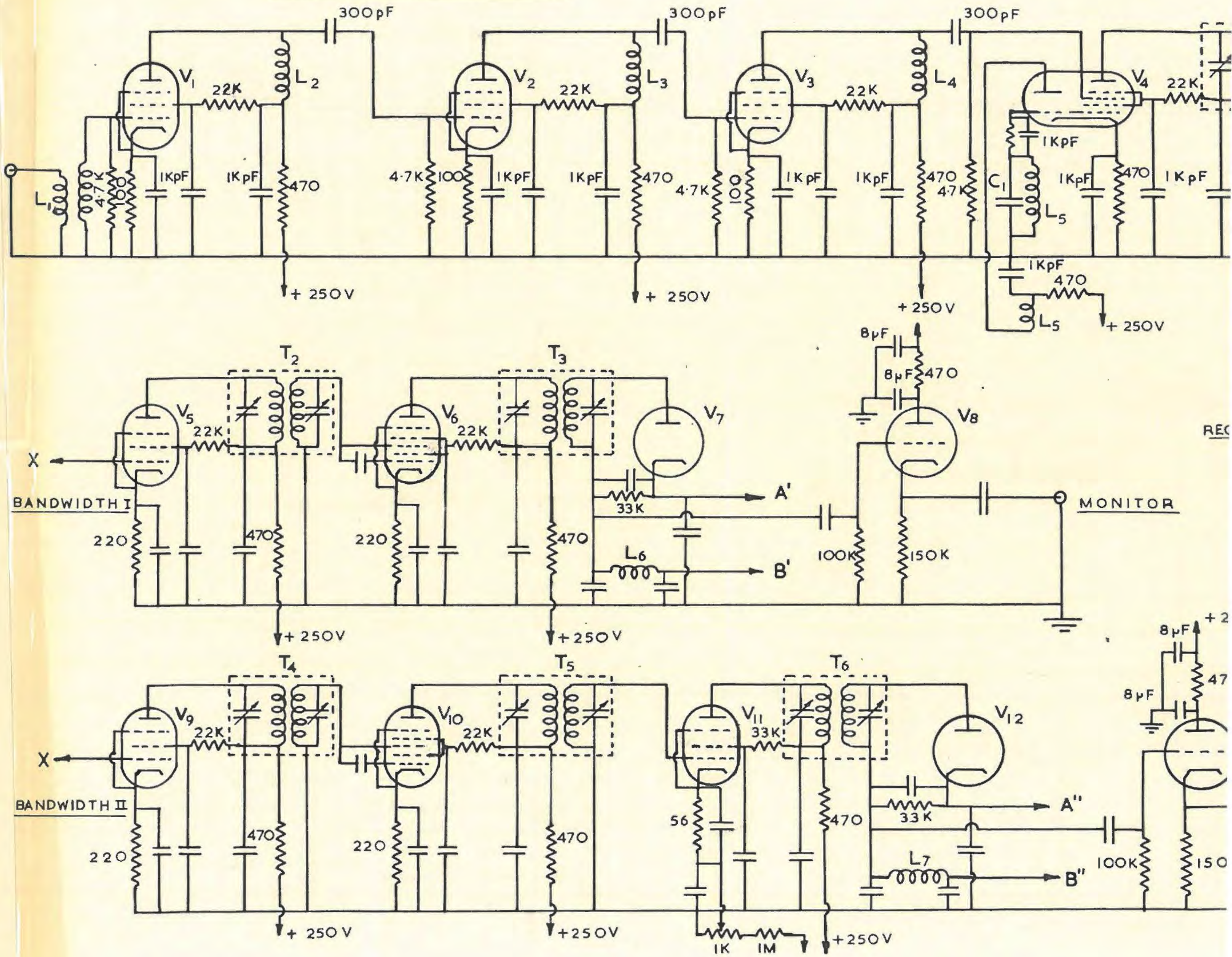


- LEGEND -

V_1-V_3 - EF94	L_1 - 5:13 t ¼" slug tuned - 27·8Mc/s
V_4 - ECH81	L_2, L_3, L_4 - 13t slug tuned - 27·8Mc/s
V_5, V_9 - EF92	T_1, T_2, T_4 - 1·4Mcs I/F Transformers
V_6, V_{10} - E91H	T_3, T_5, T_6 - 2·8Mcs I/F Transformers
V_7, V_{12} - EAA91	L_5 - 6:14 t ¼" slug tuned - 26·4Mc/s
V_8, V_{13} - EC92	L_6, L_7 - 1 μH Chokes
V_{11} - EF93	All unmarked Capacitors 0·01μF

- MAIN - I/F - AMPLIFIER -

- FIGURE - V -



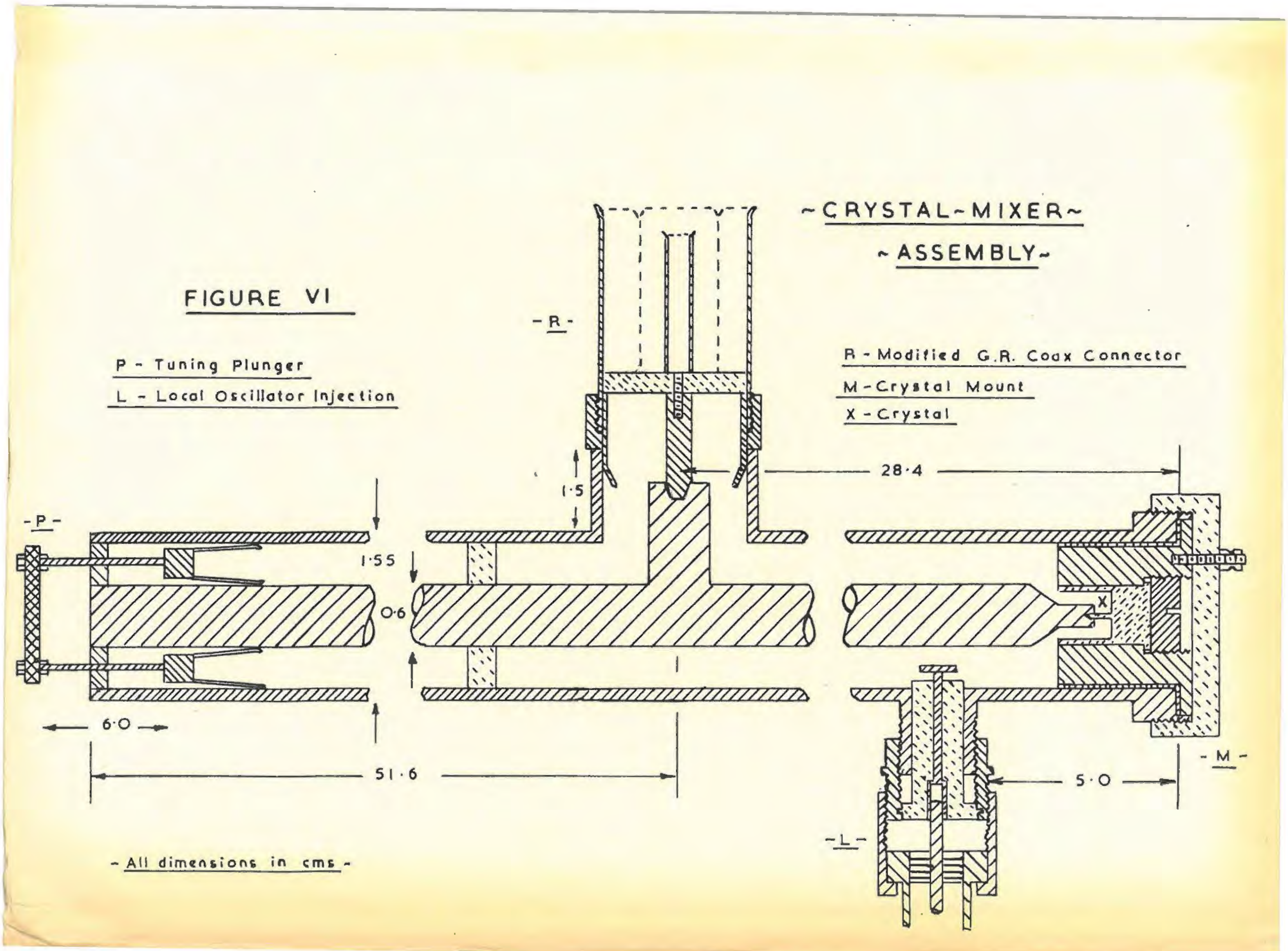
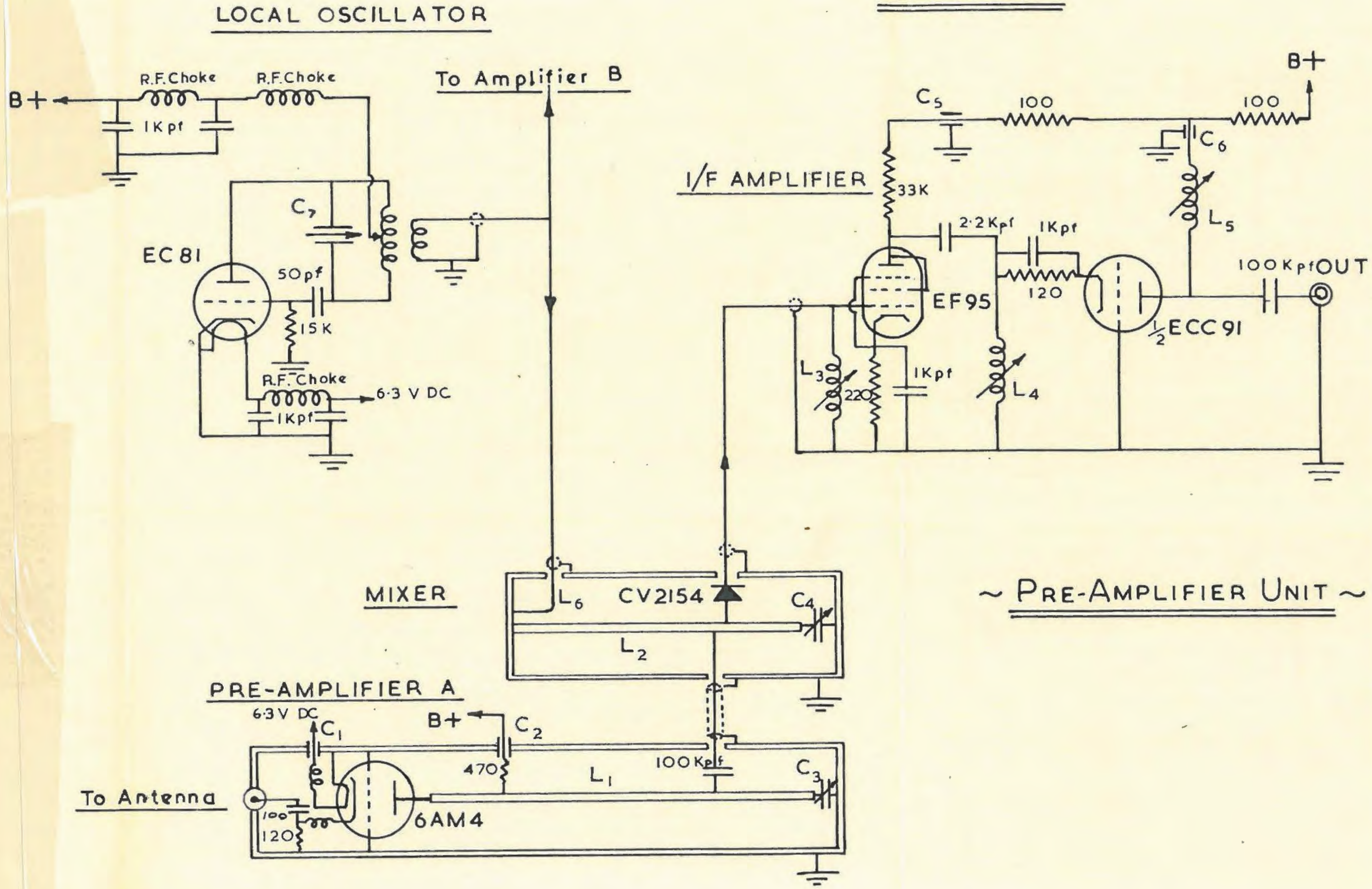

~CRYSTAL~MIXER~
~ASSEMBLY~
FIGURE VI
P - Tuning Plunger
L - Local Oscillator Injection
R - Modified G.R. Coax Connector
M - Crystal Mount
X - Crystal
-R-
-P-
-L-
-M-
X
28·4
1·5
1·55
0·6
6·0
51·6
5·0
- All dimensions in cms -

FIGURE VII

~LEGEND~

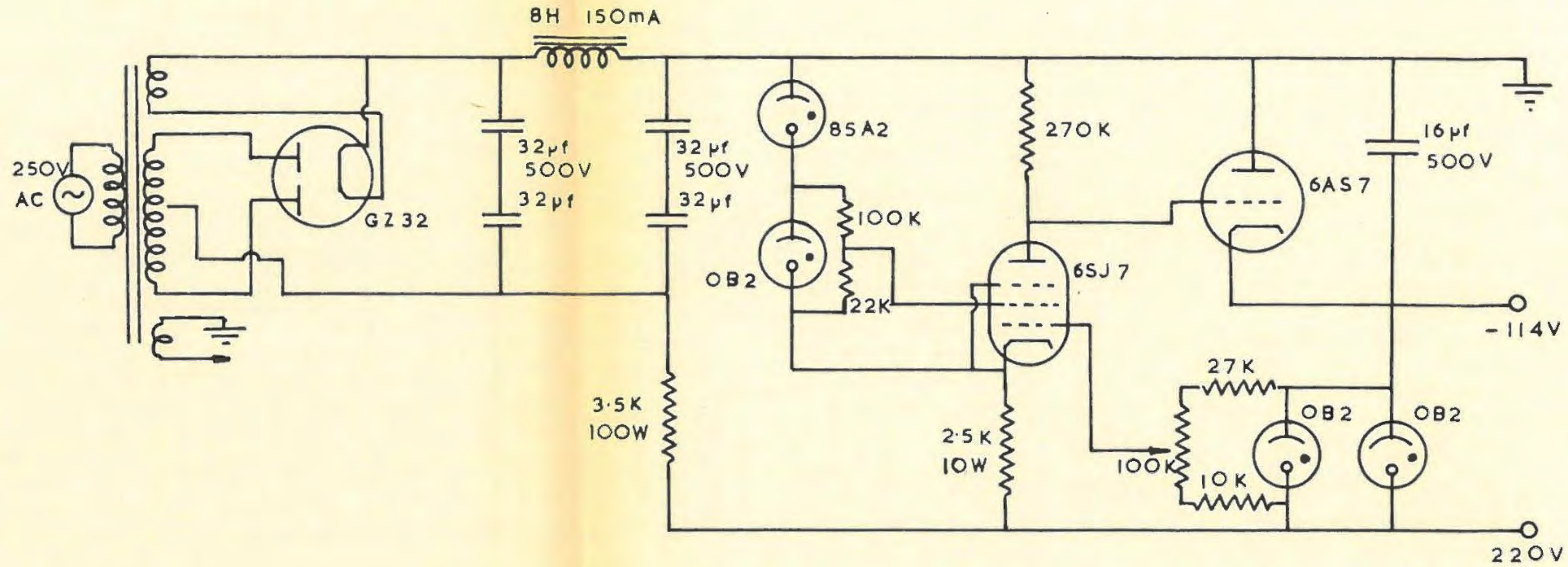
L_1, L_2 — $\frac{1}{4}$" copper tubing see text	
L_3, L_4, L_5 — $\frac{1}{4}$" slug tuned	
L_6 — Injector loop	
C_1, C_2 — 2·2 Kpf Feed through	
C_3 – 5 pf trimmer	C_7 – 30 pf
C_4 — Diam. Copper disc.	
C_5, C_6 – 100 pf feed through	



~ PRE-AMPLIFIER UNIT ~

REGULATED NEGATIVE POWER SUPPLY

FIGURE VIII A



PRE-AMPLIFIER H.T. REGULATOR

FIGURE VIII B

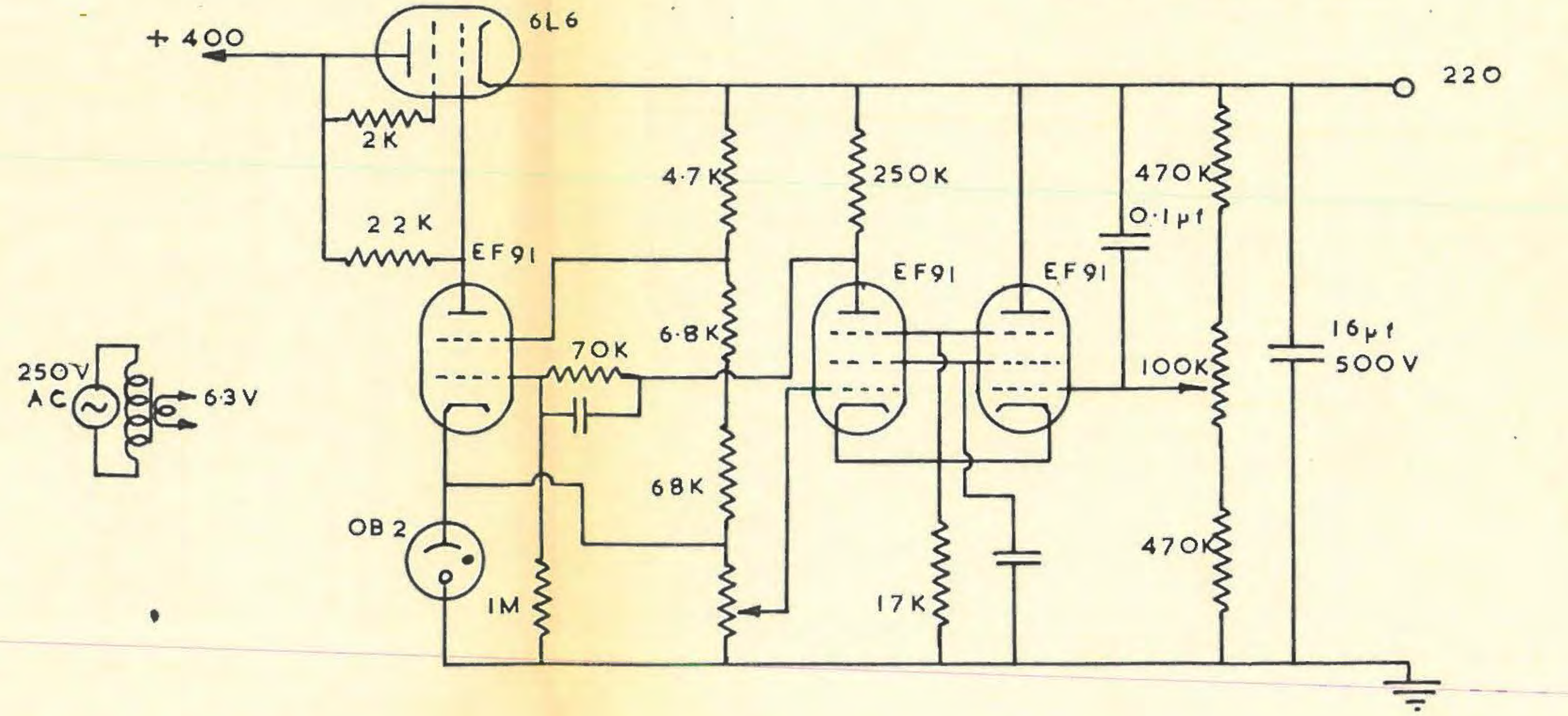
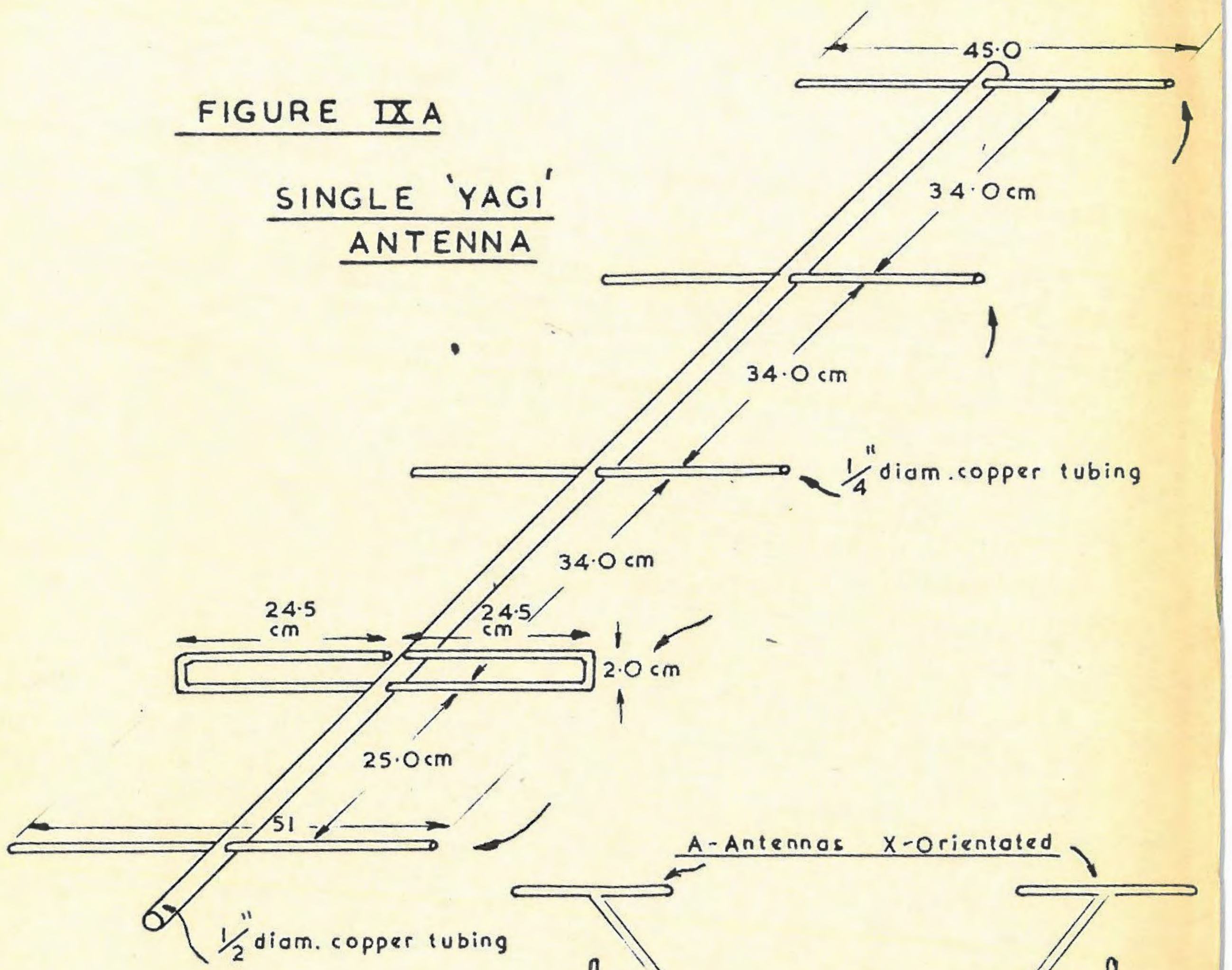


FIGURE IX A

SINGLE 'YAGI' ANTENNA



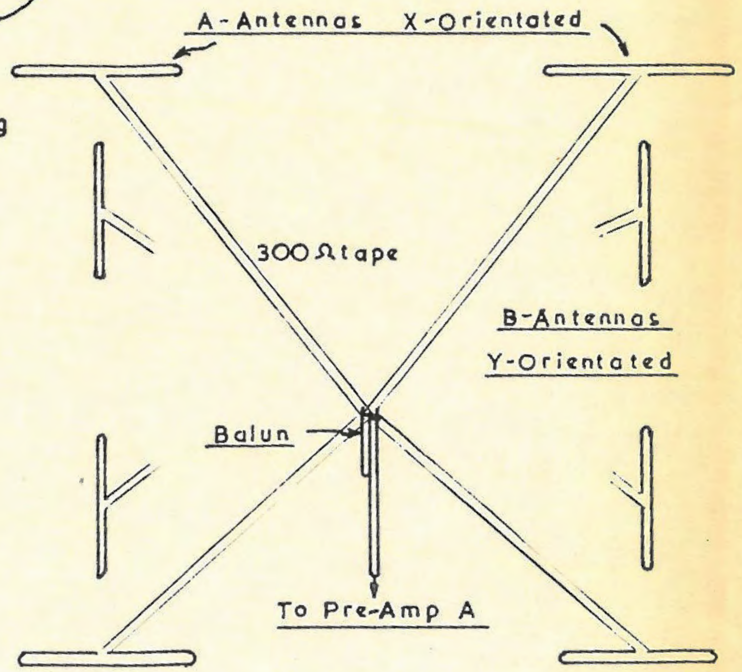
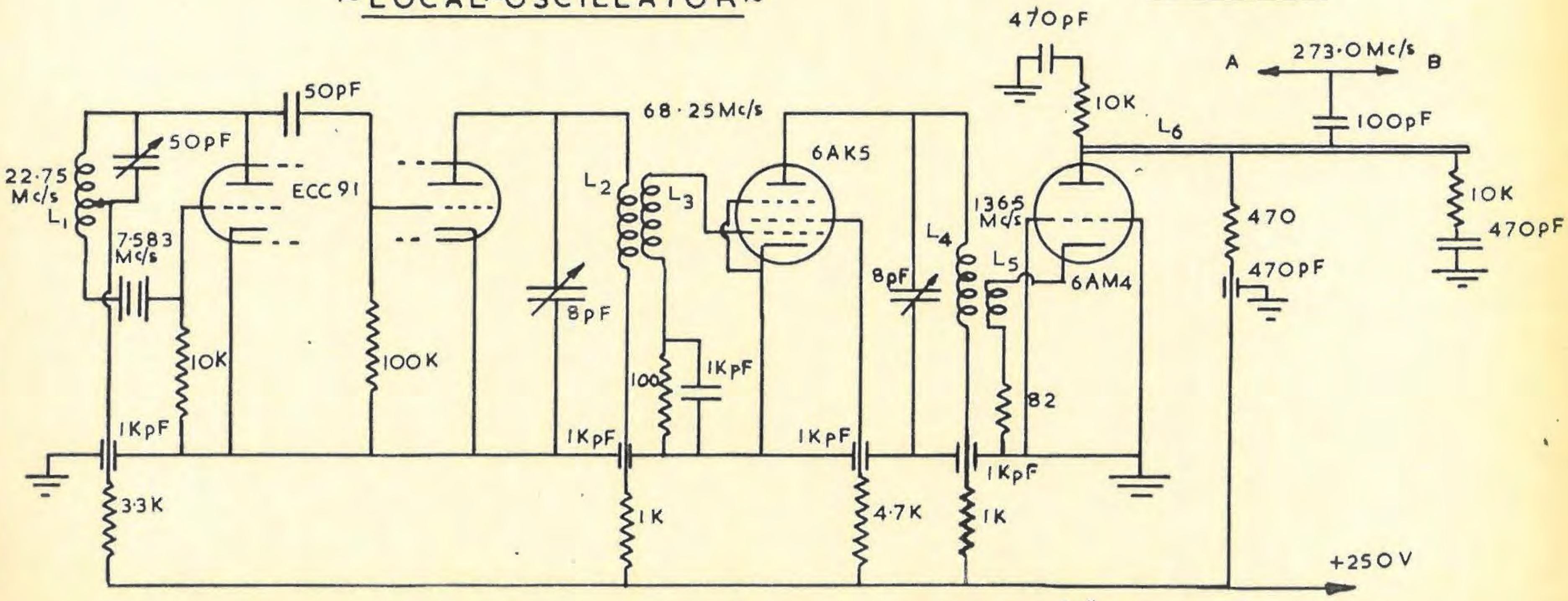


FIGURE IX B

'YAGI' ARRAYS

~LOCAL~OSCILLATOR~

FIGURE X



L1-9 Turns 1/2" diam tap-2t
L6-8 tuned line

L2-11 Turns 3/8" diam
L3-8 Turns-same former

L4-4 Turns 3/8" diam.
L5-2 Turns-same former.