

AN ABSOLUTE FLUX DENSITY SCALE

AT 408 MHz.

A Thesis presented at the
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for the degree of
Doctor of Philosophy.



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SUMMARY

The work in this thesis describes the absolute measurement of the flux density of five radio sources visible from the southern hemisphere: PKS 0408-65, PKS 1932-46, PKS 0521-36, MSH 06-04 and 3C 273. The standard errors in the flux densities are believed to lie between 5 and 6%.

The measurements were made using two methods, which are variations on a method used by Little (1958) in conjunction with the 85.5 MHz Mills Cross. The present measurements employed the east-west arm of the Molonglo cross-type radio-telescope in conjunction with a reference aerial the gain of which was calculated. The methods have several important advantages over alternative methods of measurement, namely, good resolution and sensitivity.

In order to make the scale more useful the flux densities of a further 37 sources were found by accurate relative measurement to the five reference sources. These 42 sources are the calibration sources for a flux density scale which is called the Molonglo scale.

The flux densities of a further 260 sources were determined by relative measurement to the scale calibration sources. The standard errors in these relative flux densities are about 6%. The measurements were made with the east-west arm of the Molonglo radiotelescope used as a total power instrument.

The Molonglo scale flux densities of sources near the equator were compared with the source flux densities based on northern scales. This comparison reveals a difference of about 10%; flux densities based on the Molonglo scale being the higher. This result is discussed in the thesis.

The discrepancies between the northern and M.S.H. scale flux densities at the lower frequency of 85.5 MHz are also discussed.

PREFACE

The work described in this thesis was carried out during the years 1966 to 1968 inclusive, in the Chatterton Astrophysics Department of the School of Physics, University of Sydney.

I was responsible for the establishment of the absolute flux density scale at 408 MHz described in this thesis; the flux densities of southern radio sources at this and most other frequencies had previously been based on northern scales. I developed a suitable method of absolute flux density measurement for use with the Molonglo radiotelescope, made the necessary observations and reduced the data. The critical comparison with the other flux density scales is also my own work.

I am greatly indebted to my supervisor, Professor B.Y. Mills, for the opportunities to use the Molonglo radiotelescope and for the much helpful criticism and advice received throughout the course of this work. I should also like to thank the other members of the department for their many valuable suggestions.

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CHAPTER I

INTRODUCTION.

An important astrophysical datum relating to a discrete radio source is its radio spectrum, which is the relationship between the power radiated per unit frequency interval and the frequency. The radio spectrum of a discrete source provides information on the emission mechanism, location and age of the radiating object, as well as its physical properties and is therefore one of its principal characteristics.

On the basis of source spectra it is possible to identify two classes of radio sources, thermal and non-thermal. The classification is based on the emission mechanism within the source: free-free electron-ion collisions are responsible for the emission from thermal sources while the acceleration of relativistic electrons in weak magnetic fields results in non-thermal emission; other non-thermal processes may exist but as yet have not been identified. In non-thermal sources the emission is related to the energy distribution of the electrons; this distribution in turn must be related to the electron accelerating mechanism within the source. High frequency curvature and cut-offs in the spectrum are related to the age of the radiating source while low frequency cut-offs contain information on the location of the source, especially if it is a galactic object and/or on the fields and electron energies in the source. The spectra of some sources vary with time.

With such a variety of spectral forms possible and their obvious association with the physics of the radiating body it is important to determine spectra precisely. This entails the absolute measurement of the energy radiated per unit frequency interval at a number of frequencies in the radio region. The frequency interval between absolute measurements would depend only on the complexity of the features of the particular source spectrum. The limits of the radio region are dictated by ionospheric reflections at the lower frequency limit (1 MHz to 10 MHz) and by atmospheric absorption at the high frequency limit.

A further need for absolute measurements at metre wavelengths has recently assumed importance; that is the direct measurement of the brightness temperature of emission nebulae (Mills and Shaver, 1968). At sufficiently low frequencies the brightness temperature is equivalent to the electron temperature. Conventional methods of temperature determination depend on the population of the excited levels of atoms and ions and currently give discordant values.

The absolute measurement of any quantity is the expression of that quantity in standard units. The well known difficulties in making absolute measurements and the comparative ease in making relative measurements of any physical quantity hold true in the case of source flux density measurements. Consequently, absolute measurements are only made on a small number of sources and the flux density of any other source at the same frequency determined by relative measurement techniques.

The present work describes the absolute flux density measurements at 408 MHz made on five sources, PKS 0408-65, PKS 1932-46, PKS 0521-36, MSH 06-04 and 3C 273, using two methods, which are slight variations on that used by Little (1958), in his absolute measurements at 85.5 MHz. The technique employs one or two large aerials together with a small reference aerial of known gain. One method (I) employed three aerials in interferometer pairs, the other method (II) employed a large aerial and the reference aerial in an interferometer pair and the large aerial separately. The theory of both methods is given in Chapter 3.

The aim of these absolute measurements is the establishment of a flux density scale at 408 MHz. No other absolute flux density measurements have been made at this frequency on southern radio sources and up to the present time flux density calibrations have been based on northern scales.

The flux densities of a large number of sources were then determined by relative measurement to the five, scale flux density calibration sources. Comparison of the flux densities of sources common to the present and northern scales reveals a difference of approximately 10%; flux densities given by the present scale being the higher.

Northern flux density scales are based on absolute flux density measurements on the strong discrete sources Cassiopeia A, Taurus A and Cygnus A using reference aerials of low but accurately known gain. In general, weaker sources cannot be

easily measured because it is difficult to determine precisely the gain of an aerial sufficiently large to overcome the noise and confusion problems. For a variety of reasons (Kellermann 1964a) these strong sources are not the most suitable flux density reference standards; the principal objections are the location of the sources on the galactic plane, their finite angular size, their high intensity, their polarisation and finally, the decrease with time of the Cassiopeia A flux density. Relative flux density measurements to the standard source are therefore quite difficult and subject to error.

The present technique has two important advantages over alternative methods of measurement, namely, a negligible confusion problem and an improvement in sensitivity. Together these factors make possible measurements on sources with flux densities much lower than any of the above three sources. This means that sources can be chosen for which the objections, just given, are no longer valid: the five sources actually chosen are all of very small angular extent; they have flux densities in the neighbourhood of 40 f.u., several orders of magnitude less than the flux density of Cassiopeia A at the same frequency; their relative strengths are not time dependent and the radiation polarisation is negligible at this frequency; only MSH 06-04 lies in the vicinity of the galactic plane. Thus these five sources can be intercompared accurately with a large number of other sources of not too different flux

density to provide a practical and useful scale.

The only other absolute flux density measurements made on southern radio sources are those of Little (1958) at 85.5 MHz. He employed an identical method of measurement to the present one. The measurements provided the flux density calibration sources for the M.S.H. catalogue flux densities. The scale defined by these measurements is higher than northern scales, in agreement with the present results. In view of the important advantages of the present method of measurement, the discrepancies with the results based on northern scales suggests serious uncertainties in low frequency flux density calibrations.

I.I PRINCIPLES AND DEFINITIONS

I.I-a Noise:

It is common when referring to noise with a constant spectral density over a finite bandwidth to use the terms temperature and noise power synonymously. This practice will be used throughout this discussion. The available power per unit frequency interval from a resistor at a temperature T is given by,

$$P/\Delta f = kT.$$

The noise power from a radio source over a finite bandwidth is similar to the Johnson noise from a resistor except that for a radio source the power spectral density, $w(\nu)$, is a slowly varying

function of frequency. For limited bandwidths it is possible to write

$$\omega_0(\nu_2 - \nu_1) = \int_{\nu_1}^{\nu_2} \omega(\nu) d\nu$$

$$\text{where } \omega_0 = \omega \left(\frac{\nu_1 + \nu_2}{2} \right).$$

Flux density $[S(\nu)]$ is the term used in specifying the intensity of radio noise from a small diameter source of radio emission. It is defined as the power received per unit area per unit frequency interval. For extended sources the brightness, $b(\nu)$, may also be specified. These two parameters are related by the expression

$$S(\nu) = \iint b(\nu, \theta, \phi) d\Omega,$$

where the integral is taken over the solid angle subtended by the source. An alternative way of specifying brightness at radio wavelengths is in terms of temperature: the two are related, in the radio region, by the Rayleigh-Jeans approximation of Plank's radiation law:

$$b = \frac{2kT_B}{\lambda^2}$$

T_B is the brightness temperature

k is Boltzmann's constant.

Since we shall only be considering small diameter sources only the term flux density will be used; the units are watts per metre² per Hz ($\text{Wm}^{-2}\text{Hz}^{-1}$). The practical unit of

flux density is the flux unit:

$$I_{f.u} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}.$$

The use of the terms small diameter and extended sources is somewhat loose in that it depends on the beam dimensions of the telescope used in the observations.

I.I-b Aerial Parameters:

The directional radiating properties of an aerial are described by the radiation intensity $\Phi(\theta, \phi)$, which is the power radiated per unit solid angle in the direction (θ, ϕ) . The directivity in any direction (θ_o, ϕ_o) , defined relative to the isotropic radiator, is the ratio of the powers radiated by the two aerials such that they produce the same radiation intensity in that direction:

$$\text{Power radiated by the aerial} = \int_{4\pi} \Phi(\theta, \phi) d\Omega \quad 1.1$$

$$\text{Directivity } D(\theta_o, \phi_o) = \frac{4\pi \Phi(\theta_o, \phi_o)}{\int_{4\pi} \Phi(\theta, \phi) d\Omega} \quad 1.2$$

The gain of an aerial includes the resistive losses in the aerial structure and feeding cables. For a loss factor α , the gain is defined as

$$G(\theta_o, \phi_o) = (1 - \alpha) D(\theta_o, \phi_o). \quad 1.3$$

For a receiving antenna it is more convenient to introduce the concept of effective area. The relationship between the

gain and the effective area, $A(\theta, \phi)$, of an antenna is obtained by the use of the reciprocity theorem and is found to be

$$A(\theta_o, \phi_o) = \frac{\lambda^2}{4\pi} G(\theta_o, \phi_o). \quad 1.4$$

I.I-c Principles of Absolute Flux Density Experiments:

Most absolute flux density determinations are based on a reference aerial or aeriels of known gain and the calibration of a temperature scale by the use of matched loads at known temperatures. We firstly consider the relationship between the temperature and flux density scales. An effective aerial temperature (T_A) may be defined which provides the same power to the receiver terminals as the radio source under observation. Thus for an elementary bandwidth $\Delta\nu$ and a randomly polarised source of flux density $S(\nu)$, the aerial temperature is given by (e.g. Findlay, 1966)

$$kT_A \Delta\nu = \frac{1}{2} \int_0^\infty S(\nu) \cdot B(\nu) \cdot A(\nu) \cdot d\nu, \quad 1.5$$

where $A(\nu)$ is the effective area of the aerial and $B(\nu)$ is the normalized response function of the receiving equipment. Both $S(\nu)$ and $A(\nu)$ are slowly varying functions of frequency and can be assumed constant if $\frac{\Delta\nu}{\nu}$ is less than about 0.01. In the present experiment the system has a bandwidth of 2.5 MHz at the central frequency (ν_o) of 408 MHz, which satisfies this criterion. Equation 1.5 then reduces to

$$kT_A \Delta\nu = \frac{1}{2} S \cdot A \cdot \Delta\nu: [S = S(\nu_o), A = A(\nu_o).]$$

this gives

$$S = \frac{2kT_A}{A} Wm^{-2}Hz^{-1}. \quad 1.6$$

The temperature calibration of the receiver in most experiments is carried out by replacing the aerial with matched loads at known temperatures. Alternatively noise power can be injected into the aerial signal path through a calibrated directional coupler. At sufficiently low frequencies (less than approximately 100 MHz) the shot noise from a current limited diode can be used as an absolute temperature reference. These noise sources have the advantage over thermal loads of being able to provide large noise powers or alternatively high temperatures.

1.2 ORGANISATION OF THE THESIS

I have in this chapter discussed the importance of absolute flux density measurements, as well as outlining the principles of the experiments used in such measurements. In the next chapter I shall review the calibration techniques of the early source surveys and then discuss in detail the techniques employed in the most recent absolute measurements which claim high accuracies.

In Chapter 3 the theory of both methods used in the present absolute flux density measurements will be given. The equipment used in these measurements will be discussed in

Chapter 4; this chapter contains a detailed discussion of the reference aerial gain determination, and the reference noise source calibration.

The results of these measurements, together with estimates of the accuracy achieved, are presented in Chapter 5. Relative flux density measurements based on the present scale, as well as the results of these measurements, are given in Chapter 6. At this stage the flux density scale has been defined by the absolute measurements, and the flux densities for about 300 sources determined by relative measurement.

In Chapter 7 the present scale flux densities are compared with those based on northern scales for common sources. The results of other absolute flux density measurements are also intercompared in this chapter. A detailed discussion of the discrepancies between the relatively low frequency flux density scale define by Little's (1958) measurements and northern scale flux densities is also given.

CHAPTER 2FLUX DENSITY MEASUREMENTS2.1 INTRODUCTION:

In this chapter I propose to review flux density calibration procedures. The first part will be concerned with a discussion of the calibration of the early radio-astronomical source surveys, while in the second part the more recent absolute flux density experiments designed specifically to achieve high accuracy, will be reviewed and classified according to the technique employed. Included in this classification will be the technique used in the measurements which form the basis of the present work. Finally, measurements made in the very high and very low frequency parts of the radio spectrum will be discussed, together with the special problems pertinent to these parts of the spectrum.

2.2 HISTORICAL DISCUSSION:

In 1932 Karl Jansky discovered the existence of extra-terrestrial radio waves; this discovery marked the beginning of radio-astronomy. Further observations (1933, 1935) showed that the direction of maximum intensity of this radiation, at his frequency of 20 MHz, coincided with the centre of the Galaxy.

The first major survey of the Galactic radio noise or cosmic static - so called because of its audio similarity to normal receiver noise hiss - was carried out by Grote Reber (1944), who commenced observations about 1942 at a frequency of 160 MHz.

In 1948, Hey, Parsons and Phillips, using a Yagi array, surveyed the sky at 64 MHz. As a result of the early analysis of this survey the discrete source in the constellation of Cygnus (Cygnus A) was discovered, (Hey et al. 1946); an estimate of the source flux density was not provided. This initial discovery led to the discoveries of a further six sources by Bolton (1948) and of the strong source in Cassiopeia (Cas.A) by Ryle and Smith (1949). The flux densities published by Bolton (1948) were determined by a calibration procedure given by Bolton and Stanley (1948); the procedure is presented later in this section. Ryle and Smith provided no calibration details at all.

Inevitably thoughts were turned to mechanisms responsible for both the source and background radiation and plots of intensity versus frequency (radio spectra) produced. The first such plot was published by Moxon (1947). Measurements were made of the "cosmic radiation intensity" at frequencies of 40, 90 and 200 MHz. He provides no information on his calibration procedure at any of these frequencies. Herbstreit and Jahler (1948) introduced a technique, which in principle is the best means for determining the spectrum of the background radiation; this is the method of scaled antennae. They used half-wave dipoles for observations at 25 and 110 MHz and used noise diodes for the receiver calibrations; the Galactic background temperature was found to vary as $\lambda^{2.1}$. Single

dipoles are, however, unsuitable for discrete source or localized background temperature measurements because of their large radiation patterns.

Bolton and Stanley (1948) investigated the radiation from Cygnus A at 60, 85, 100 and 200 MHz using Yagi aerials in the sea-interferometer; no information is provided on the Yagi gain determination. The receivers were calibrated by replacing the aerial by a matched load (see page 15). The importance of these spectral measurements lie only in the fact that they were the first on a discrete radio source.

By 1954 nine major source surveys (Table 2.1) had been carried out at frequencies in the range 18.3 MHz to 3200 MHz. In these, published calibration details range from comprehensive - (Shain and Higgins, 1954 : 18.3 MHz) - to negligible - (Ryle, Smith and Elsmore, 1950 ; 81.5 MHz).

Shain and Higgins employed a square array of dipoles, measured the phase and amplitude of the currents in these dipoles and computed the array directivity; the loss in the dipole feeders was measured in order to obtain the array gain. The receiver was calibrated using a noise diode. At this low frequency the flux density measurements have added problems due to ionospheric effects, (absorption and scintillation); these effects are discussed in more detail at the end of this chapter. The intensities of the strongest sources were believed to be accurate to 20%.

TABLE 2.1.SIX MAJOR EARLY SOURCE SURVEYS

<u>Observer(s)-</u>	<u>Frequency (MHz)</u>	<u>Region Covered</u>	<u>No.of Sources.</u>
1. Stanley & Slee (1950)	100	50° to -50°	22
2. Ryle Smith & Elsmore (1950)	81	90° to +10°	50
3. Mills (1952)	101	50° to -90°	77
4. Brown & Hazard (1953)	158	70° to 40°	23
5. Shain & Higgins (1954)	18.3	10° to -90°	37
6. Bolton Stanley & Slee (1954)	100	50° to -50°	104
7. Kraus, Ko and Matt (1954)	250	60° to -40°	207
8. Haddock, Mayer & Sloanaker (1954)	3200	90° to -50°	24
9. Hagen, McClain & Hepburn (1954)	1420	90° to -40°	24

Bolton et al. (1954) did not calibrate their 100 MHz source survey directly but made all their flux density measurements relative to Virgo A. The Virgo A flux density used is that given by Stanley and Slee (1950), who give no details of their calibration procedure, even though they published the spectra of the strong sources Taurus A, Cygnus A, Virgo A and Centaurus A. The calibration procedure was almost certainly that given by Bolton and Westfold (1950). The aerial gain is determined by the integration of the aerial radiation pattern (Equation 1.2) and the temperature calibration performed using the measured receiver noise figure:

For a square law detector the deflection, D_i , on the receiver output indicator with a source in the aerial beam is given by

$$D_1 \propto \eta T_A + (1-\eta)T_o + (N-1)T_o,$$

where η is the feeder efficiency (feeder loss $\alpha = 1-\eta$). With the aerial replaced by a matched load at the ambient temperature, the deflection becomes:

$$D_2 \propto NkT_o.$$

Thus

$$\frac{D_2 - D_1}{D_2} = \frac{\eta}{N} \cdot \frac{T_o - T_A}{T_o},$$

where T_A is the increase in aerial temperature due to the source in the aerial beam. The receiver noise figure (N) is measured using a noise diode. The source flux density at any observation is then given by (Equation 1.6)

$$S = \frac{2kT_A}{A}.$$

Hanbury-Brown and Hazard used a 218' fixed paraboloid at 158 MHz for measurements on 23 discrete sources found in their general survey. The effective area of the dish was both computed and measured; the measurement was made using a transmitter in an aircraft. The aerial temperature calibration was made using a noise diode, particular care being made to eliminate impedance effects. No estimate, however, is made in the paper of the absolute accuracy of the source flux density measurements.

Haddock et al. (1954) and Hagen et al. (1954) used a 50 ft aperture fully steerable paraboloid at frequencies of 3200 MHz and 1420 MHz respectively. At each frequency the gain of the dish was estimated by the use of the observed aerial beam half-power widths in two orthogonal planes. The flux densities of the strong sources in the catalogues were believed accurate to about 25%. The uncertainty in the aerial gain figure was about 20% in each case and thus accounted for most of the uncertainty in the source flux densities.

In the source survey at 101 MHz, Mills (1952) mentions that the incident power from a source is determined by the knowledge of the aerial gain and receiver noise factor but provides no more calibration information.

No calibration details at all are given by Ryle et al. (1950) in the report of their source survey at 81.5 MHz or by Kraus et al. (1954) in their 250 MHz source survey.

Prior to 1954, a wide variety of techniques were employed to calibrate source intensity measurements but no great accuracy was achieved. It is probably true and in fact stated in some of the papers, that the surveys were more concerned with the measurement of source position, rather than flux density.

This led to difficulties in the comparison of measurements made at different frequencies and almost invalidated the determination of source spectra, since the absolute flux density scale at any frequency was not known to better than about 50%. Production of source spectra under these conditions led to attempts to explain spectral effects, which in the light of better measurements did not exist. For example Roman and Haddock (1956) attempted to explain the apparent deficiencies in source flux densities observed about 400 MHz.

The difficulty in comparing source flux density measurements at different frequencies persisted until Whitfield (1957) introduced a method suggested to him by Adgie: realizing the difficulty in making absolute measurements, it was proposed that the spectrum of a strong source be determined from accurate absolute measurements and the flux density of any other source at any frequency be deduced by far simpler relative measurement; the measurement to the standard source can be made using uncalibrated systems. The spectra of a large number of sources can be established in this manner; Whitfield determined the spectra of 31 sources using flux density values derived from about 50 source surveys.

Whitfield derived a power law spectrum for Cas.A., using all available measurements at all frequencies, but giving special weight to the measurements of Adgie and Smith (1956), and Seeger (1956). These experiments were designed specifically to make absolute flux density measurements and were the only measurements on the Cassiopeia A source, which claimed an accuracy of 20% or better. Surveys, which included measurements on Cas.A., could be normalised by finding the correction factor needed to bring the survey value onto the straight line spectra (on a Log-log plot) derived by Whitfield. Even though this technique has many pitfalls, Whitfield's paper is the first serious attempt to produce reliable source spectra. In brief, his spectra are based on measurements relative to the spectrum of Cas.A., which is based on a limited number of absolute measurements. It is rather unfortunate that Cas.A. subsequently turned out to have a slowly varying flux density.

It is interesting to note the range of correction factors needed to normalize the fifty source surveys to Whitfield's curve. The factors range from 0.29 to 4.8: the mean normalization factor differs from unity by about 40%. Most of these fifty source surveys have been calibrated in the same incomplete manner as the six surveys studied previously. Several of these nine are included in Whitfield's list.

The general conclusion to be reached regarding the calibration of most source surveys is that, while some attempt

was made to calibrate the receiver sensitivity by replacing the aerial by matched loads at known temperatures, the effective area of the aerial was determined by making either a rough estimate or probably even rougher measurement.

Whitfield's method for determining the spectra of radio sources by relative measurement to a reference spectrum based on accurate absolute measurements, is the method adopted universally today. The catalogues of Conway, Kellermann and Long (1963) and Kellermann (1964 c) are examples. Later source surveys generally make no attempts to calibrate the radiometer used in the observations, but rather accept flux density values for one or several strong sources; Cassiopeia A, Cygnus A, Taurus A and Virgo A are the sources most used.

At this stage the discussion can be diverted from survey equipment calibration techniques, to specific experiments designed to measure the absolute flux density of strong sources. I shall no longer discuss the experiments in chronological order, but rather classify them according to the method used; only those experiments which claim to provide flux densities with an accuracy of about 10% or better will be discussed.

2.3 ACCURATE ABSOLUTE MEASUREMENTS:

Reference to all absolute flux density experiments, claiming a measurement accuracy better than about 10%, is made in Table 2.1. The experiments are grouped in the following

manner:

A. Experiments making direct use of low gain standard aeri^{als}.

B. Experiments where a large aerial, whose properties cannot be directly calculated, is calibrated by careful measurement. The calibration of the large aerial is carried out by one of the following methods:

1. Using a standard aerial
2. Blackened Disc
3. Polar diagram integration.

C. A technique in which a standard aerial is used in conjunction with larger aeri^{als} whose properties need not be known.

This classification is based on the calibration of the aerial system used in the absolute measurements. The principal factors determining the accuracy and usefulness of the results of all the experiments will be related to the aerial system; these factors will be shown to be the aerial gain accuracy, and the aerial system resolution and sensitivity. The thermal calibration is discussed separately in the next section.

All of the experiments in Table 2.2 make measurements on Cas.A and/or on the other strong northern sources unless marked by an asterisk, in which case, the source or sources measured will be given in the text. Discussion of the experiments

TABLE 2.2
ABSOLUTE FLUX DENSITY MEASUREMENTS.

Observing frequencies in MHz.

<u>A</u>	<u>B</u>	<u>C</u>
Long, 38. Adgie & Smith (1956), 38, 81.5.	Williams et al. (1967), 38.	
Parker (1968), 38, 81.5, 152.		*Little (1958) 85.5
MacRae & Sequist, (1962), 320	Seeger (1956), 400	*Wyllie (1968) 408.
	Lastochkin et al. (1963a), 562, 708, 860, 1190.	
Findlay et al. (1965), 1440	Mezger (1958), 1419.	
	Altenhoff (1960), 2700	
	Khrulev (1963), 2920	
	Stankevich (1962), 3060	
	Medd & Ramana (1965a&b), 3150, 3200.	
	Brotten & Medd (1960), 3200.	
	Penzias & Wilson (1965), 4080.	
	Medd & Ramana (1965b), 6660.	
	Allen & Barrett (1967), 8250.	
	Stankevich (1962), 9380.	
	Lastochkin et al. (1963b), 9380.	
	Lazarevskii et al. (1963), 9380.	
	Allen & Barrett (1967), 15,500.	
	Tolbert & Straiton (1965), 35,000, 70,000.	

will be based on the methods used rather than the results at this stage; a discussion of some of the results will be given in Chapter 7.

The most obvious feature of the table is that experiments using standard aerials directly are applicable only at low frequencies; these aerials have insufficient gain to detect even the strong sources at high frequencies. Above 1,000 MHz it is necessary to calibrate a larger aerial using one of the three methods given in B. The technique in group C is most useful at low frequencies, but can be used at frequencies up to several thousand MHz.

2.3-a Thermal Calibration:

Before discussing these experiments in detail the noise power standards used in the thermal calibration of the experiments in Table 2.2 will be reviewed.

The thermal noise from a resistor is normally accepted as the fundamental noise source. It is quite difficult, however, to make a practical noise source for use at radio frequencies. The difficulties are two-fold: firstly, the thermal load must be matched at some temperature and remain matched over a range of temperatures and secondly, it must be possible to calculate the effective temperature of the noise output. This depends on the temperature of the resistor and on the effects of the transmission line connected to the resistor. The effects of the transmission line in turn depend

on the temperature distribution along the line, on the temperature dependence of the line losses and on the presence or otherwise of condensation in the transmission line.

For frequencies up to about 1,000 MHz, co-axial terminations connected by a rigid co-axial transmission line have been used as primary standards (e.g. Wielebinski, 1967). The space between the inner and outer conductors can be evacuated to prevent condensation. At lower frequencies the resistor is immersed in water, which is heated through a known temperature range, while at higher frequencies the resistor may be immersed in a cryogenic liquid (liquid nitrogen or liquid helium). The effective temperature at the output of the transmission line can then be estimated, (e.g. Stelzried 1961). At frequencies above about 10^3 MHz terminated waveguides, with the termination immersed in liquid nitrogen or helium, have been used as the thermal reference sources: e.g. Penzias (1965) developed a waveguide termination used by Penzias and Wilson (Table 2.2). A more complete review of this field is given by Miller et al (1967): "Noise Standards and Measurements".

A temperature-saturated noise diode has long been used as a noise standard at low frequencies. Below 20 MHz it is a fairly simple matter to construct a diode noise source, where the power output is a known function of the diode current. At higher frequencies care is required: the diode is a source of noise current, not power, and so the load through which this

current flows must be known. Stray reactances (van der Ziel, 1954) modify the load impedance and produce an uncertainty in the available noise power. With careful design, a diode source can be built for operation up to about 1,000 MHz (e.g. Harris, 1961), and used as a primary calibrator for frequencies up to about 100 MHz; their high temperatures make them particularly useful in this frequency range and probably more useful than thermal loads. At metre wavelengths aerial temperatures are high since the sky background temperature is high; at 85.5 MHz, temperatures in the range 1,000 to 2,000^oK are normally found away from the galactic plane; on the plane the temperatures are far greater. The noise source, used to replace the aerial when calibrating the change in aerial temperature due to a source, should have comparable temperatures if receiver non-linearity problems are to be avoided. It is not practical to provide a resistive source at temperatures of about 1,000^oK.

At higher frequencies diode noise sources need to be calibrated against more fundamental noise standards and are thus used only as stable sources of noise power. Above 1,000 MHz gas discharge tubes (Mumford, 1949), in either co-axial or waveguide mounts, are normally used as reference noise sources (e.g. Findlay et al., 1965); they must be calibrated against standard resistive loads.

All of the experiments in Table 2.2 used one or other of the noise standards, outlined above, in the thermal

calibration of the receiver. Under ideal conditions it is possible to achieve an accuracy of about 1% in this calibration. In Chapter 4 I shall discuss in some detail the temperature calibration of the diode reference used by Wyllie (1968).

2.3-b Group A:

The choice of standard aerial is divided between the simple dipole and horn antenna. Single dipoles or arrays of dipoles are used at frequencies up to about 300 to 400 MHz while horns are used at higher frequencies. More information on the accuracy with which the gain of these antennae can be determined will be given in Chapter 4; the accuracy is, however, quite good (better than 0.2 db).

Parker (1968) used pairs of single dipoles over flat reflectors in a phase-switched interferometer arrangement with element spacings in the range 40λ to 140λ . Observations were made on Cas. A and Cyg. A at the three observing frequencies (38, 81.5 and 152 MHz), while observations on Taurus A were made only at 81.5 and 152 MHz. The temperature calibration was performed using a noise diode which was calibrated using thermal loads. The quoted mean errors in the flux densities of Cas. A and Cyg. A were about 3%, while for Taurus A the quoted mean error was about 10%. The uncertainty in the Cas. A and Cyg. A flux densities depends principally on the aerial gain (quoted accuracy 2.5%) and thermal calibration (1% to 1.5%) accuracies.

Adgie and Smith observed Cas. A and Cyg. A at four frequencies (38, 81.5, 210 and 500 MHz) using low gain horizontal arrays, again in a phase-switched interferometer arrangement. The quoted accuracy at the lower pair of frequencies is 10% and at the higher pair 20%. The aerial gain was computed at each frequency but no indication is given of the accuracy expected.

The improvement in accuracy achieved by Parker while using basically the same technique as Adgie and Smith, is due to the more accurate thermal and aerial gain calibration, and to an overall improvement in technique.

A similar experiment was performed at 320 MHz by McRae and Sequist, who used horn antennae as interferometer elements. The horns have higher gains than the dipoles used in the above experiments; consequently the sensitivity is improved and the confusion error reduced. A pyramidal horn at this frequency is a fairly large structure if its aperture dimensions are greater than several wavelengths; this criterion must be satisfied if Schelkunoff's gain calculations are to be accurate (Section 4.3). They claim an overall accuracy of 5% in the Cas. A flux density value.

The low gain antennae used in these experiments result in low sensitivity and poor resolution. It is extremely fortunate that several very strong discrete sources of radio

emission are visible in the northern hemisphere. The confusion error in measurements on Cas. A and Cyg. A, due to the large number of weak unresolved sources is negligible ($\sim 0.5\%$), since they are almost 3 order of magnitude stronger than the flux density level at which discrete sources occur in significant numbers (~ 10 per steradian). These two strong sources, however, confuse measurements made on each other and corrections must be made for this effect. Measurements made on the weaker sources Taurus A and Virgo A with the above equipment have significant confusion errors ($\sim 5\%$). Confusion due to background variations is almost entirely eliminated by the use of phase-switched interferometers with moderate element spacings (greater than 40λ).

A unique experiment to measure the flux density of Cas. A was performed at 1440 MHz by Findlay, Hvatum and Waltman (1965) using a large fixed pyramidal horn built especially for these measurements. Drift scans were made at the source declination over a period of 4 years. Each scan was calibrated using an argon discharge tube noise source. The discharge tube output was calibrated by replacing the aerial with a resistive load, which was heated through measured temperature ranges.

This experiment is a direct application of equation 1.6. The gain of the horn was calculated using the theory developed by Schelkunoff (1943); at 1440 MHz the gain is 43.7 db.

Since only total power measurements could be made, a high resolution background survey was made in the region surrounding Cas. A, using an 85' dish. The source and background contributions to the horn output could then be separated.

An overall accuracy of 3.4% was attained in the final Cas. A flux density, the major contribution to this error arising from the uncertainty in the effective area (quoted accuracy 2.5%) of the standard aerial. This experiment is probably among the most reliable absolute flux density measurements at any frequency on any source.

The primary limitations on all experiments which employ standard aerials directly, are confusion and sensitivity. Measurements are thus restricted to the strongest sources. These strong sources are, however, not the most suitable flux density reference sources for the following reasons:

1. The strongest discrete sources Cas. A, Cyg.A and Taurus A are at least several orders of magnitude stronger than the flux density level at which sources occur in significant numbers. This introduces problems when making accurate relative flux density measurements to these strong sources, due to receiver non-linearities. Either the receiver response has to be known precisely or accurate attenuators have to be available.

2. These three sources are resolved by most survey aerials at high frequencies and by high resolution low

frequency aerals (e.g. The Molonglo Cross), since they have diameters of the order of several minutes of arc. In order to measure the source flux density for calibration purposes it is necessary to measure either the integrated flux density or the peak flux density and correct for the source intensity distribution. Both these alternatives introduce added errors into the relative measurement.

3. At high frequencies Cygnus A and Taurus A show some degree of linear polarisation. This requires a small, but often uncertain correction when making relative measurements with polarised aerals.

4. The sources all lie on or near the galactic plane. This complicates the determination of the background level in the vicinity of the source, when making total power measurements.

5. It is very unfortunate that the flux density of Cas. A shows a decrease with time. Comparison of measurements made at different epochs using different techniques, either at the one frequency or at differing frequencies, is difficult because of the uncertainty in the decrease rate. Table 2.3 shows a number of measurements of this decrease rate as well as the frequency of observation. The accuracy of the observations marked by an asterisk is such that they only confirm that the flux density is decreasing with time. The obvious conclusion is that Cas. A is an unsuitable choice for a standard source (Högbom and Shakeshaft, 1961).

TABLE 2.3Measurements of the Cas. A Flux Density Decrease Rate.

<u>λ(m)</u>	<u>Decrease Rate (%)</u>	<u>References.</u>
1.5	1.91	Sanamyan and Aslanyam (1965)
3.5	1.89	Sanamyan and Aslanyam (1965)
3.6	2.14	Sanamyan and Aslanyam (1965)
4.2	1.83	Sanamyan and Aslanyam (1965)
4.2	2.03	Sanamyan and Aslanyam (1965)
3.68	1.06 $\pm$ 0.14	Högbom and Shakeshaft (1961)
0.21	0.9*	Heeschen and Meredith (1961)
0.21	1.75 $\pm$ 0.52	Findlay et al. (1965)
0.094	1.12*	Mayer et al. (1965)
0.032	1.7*	Lastochkin and Stankevich (1965)

* Authors claim low accuracy. Result only confirms that flux density is decreasing with time.

6. Cas. A and Cyg. A are too far north for use as flux density reference sources for relative measurements made in the southern hemisphere. Even when they appear above the horizon their elevation is too small for accurate relative measurements. What is required are flux density reference sources nearer to the equator.

The overall conclusion is that the three strongest discrete sources of radio emission Cas. A, Cyg. A and

and Tau. A are not the most ideal flux density reference sources. The choice, however, has been dictated by the limitations of the experiments used to measure the absolute flux density.

2.3-c Group B:

At frequencies above about 400 MHz the interferometer type of experiment employing low gain standard antennae, no longer has adequate sensitivity to detect even the strongest discrete sources. The result is that the techniques employed in the present group of experiments are used.

The properties of medium to high gain aerials are measured by several methods; these calibrated aerials are then used as standards in the flux density measurements. The aerials include parabolic reflectors and horn-reflector antennae; the properties of these aerials cannot be calculated to an accuracy of better than 10% and usually the accuracy is considerably worse than this. The aerial calibration procedure is an additional source of error in the final flux density value.

1. Seeger (1956) calibrated a 7.5m paraboloid using a pyramidal horn. This calibration was carried out by the direct comparison of the total power received by both aerials using the sun as the reference source. Corrections to the measured dish power were necessary to allow for resolution effects. The horn and dish were then used in a simple interferometer for measurements of the Cas. A flux density at 400 MHz. The

temperature calibration was performed using matched loads at known temperatures. This experiment was one of the most accurate of the early absolute flux density experiments. In this paper, Seeger proposed that pyramidal horns be adopted as reference aeriels in the decimetre and centimetre wavelength ranges.

Broten and Medd (1960) used an identical calibration technique to that above, at 3200 MHz. They used the calibrated aerial, which was a 10ft dish, directly for total power observations of Cas. A, Cyg. A and Tau. A. The accuracy claimed in the flux density measurements is 5%. However, total power observations with an antenna of such low resolving power (Beam width $\sim 2\frac{1}{2}^\circ$) would lead to problems in separating the source and background contributions to the aerial output; this could lead to systematic errors in the flux densities. They did not use a procedure similar to Findlay et al., who were faced with an identical problem.

A number of absolute measurements have been made in the centimetre wavelength band using horn-reflector antennae, which have been directly calibrated against standard horns. Jull and Delohi (1964) describe the technique used in the calibration of a 9ft aperture horn-reflector used by Medd and Ramana (1965 a,b). The gain of the horn-reflector was determined at a number of frequencies by comparing the powers received by a

standard horn and by the horn-reflector on a special "mirror" test range. An important problem in direct power comparisons, using a ground based transmitter, is that as well as the direct radiation between the two antennae there can also exist a ground reflected component. It is possible to overcome this problem by eliminating the ground reflected wave completely (at centimetre wavelengths, pine forested regions are almost perfect radiation absorbers). Alternatively if the ground is flat and perfectly reflecting the reflected wave can be taken into account.

Jull and Deholi made use of the latter technique. They placed the transmitting horn close to a large perfectly reflecting ground plane. The reference horn and horn-reflector were situated on a tower some distance from the transmitter. The interference fringes produced by this arrangement were very broad so that the field at the horn-reflector site was essentially independent of position (i.e. over dimensions of the order of the horn-reflector dimensions). Since the measurements were made in the Fresnel zone of the horn-reflector the measured gain required a near-zone correction.

The error in the horn-reflector gain contains the errors in the reference horn gain and those arising in the comparison method. The gain of the reference horn was determined by a method given in Chapter 4 (4.3) and was believed to be accurate to about 2%. The quoted accuracy of the comparison technique was 1%. Medd and Ramana determined the flux densities at

3150 and 6660 MHz of Cas. A, Cyg. A and Tau. A; the quoted accuracy of the results is 4% (probable error).

Hogg and Wilson (1965) calibrated the large 20ft aperture horn-reflector used by Penzias and Wilson (1965). The reference horn was mounted on the horn-reflector and the combination pointed at a transmitter borne aloft by a helicopter. This procedure immediately eliminates the problems with direct ground reflections. Penzias and Wilson claimed an accuracy of 2% (p.e.) for measurements made on Cas. A at 4080 MHz.

To summarize, the results of the horn-reflector experiments must be considered accurate absolute flux density measurements. The major uncertainty will normally arise in the aerial gain; this includes the uncertainty in the gain of the standard and in the gain comparison.

It is claimed that the latter measurement is accurate to about 1% (e.g. Jull and Deholi). This accuracy is due to the use of "earth" based transmitters as power reference sources. When the Sun is used, assumptions are needed regarding the intensity distribution over the Sun's surface, since it is resolved by the dish antennae; the accuracy is therefore reduced.

2. An alternative method of calibrating the gain of large antennae has been proposed by Krotekov et al. (1961) and employed in absolute flux density experiments making measurements in the frequency range 562 MHz to 9380 MHz. The method was first used by Troitsky and Tseitlin (1962) to measure the gain of a small paraboloid.

The antenna temperature is measured with and without a perfectly absorbing disc in the far field of the antenna. The disc is at a known temperature and subtends a known solid angle at the antenna. Providing diffraction effects can be ignored (this is the case if the disc diameter is greater than about 20λ) the measured temperature difference is related to the gain of the antenna:

(i) Aerial temperature with the disc in the far field:

$$T_1 = (1-\beta)\eta T_D + \eta\beta T_B + (1-\eta)T_O.$$

(ii) Aerial temperature with the disc removed:

$$T_2 = (1-\beta)\eta T_S + \eta\beta T_B + (1-\eta)T_O.$$

(iii) Temperature difference:

$$\Delta T = (T_D - T_S)(1-\beta)\eta.$$

T_D - disc temperature

η - ohmic efficiency of the dish

T_S - sky temperature behind the disc

T_B - mean background temperature

Now,

$$(1-\beta) = \frac{\int_{\Omega_d} \Phi(\theta, \phi) d\Omega}{\int_{4\pi} \Phi(\theta, \phi) d\Omega}.$$

Ω_d - disc solid angle

$$K = \frac{\Omega_d \Phi(o, o)}{\int_{\Omega_d} \Phi(\theta, \phi) d\Omega} \sim 1$$

The disc centre is in the direction $\theta = o, \phi = o$.

Gain from equation 1.2 is given by:

$$G = \frac{4\pi}{\Omega d} \cdot K \cdot \left(\frac{\Delta T}{T_D - T_S} \right).$$

All of the quantities in this expression, except T_S , can be directly measured. Since the difference $(T_D - T_S)$ is large ($\sim 270^\circ\text{K}$), T_S need not be known very accurately.

The technique is not suitable for aerial calibrations at frequencies less than about 500 MHz since practical disc sizes no longer satisfy the diffraction criterion. It was claimed by the authors that the gain should be measurable to an accuracy of between 5 and 10%.

Lastochkin et al. (1963a) made measurements on Cas. A, Cyg. A and Tau. A at frequencies of 562, 708, 860 and 1190 MHz. They claimed accuracies in the range 6 to 8% in their measurements. An 8 metre dish was calibrated and used in the observations. The receiver was thermally calibrated using resistive terminations at known temperatures. The quoted errors appear to be consistent with the expected accuracy of the technique.

Khrulev (1963) made measurements at 2.92 GHz, Stankevich (1962) at 3.06 GHz and 9.38 GHz, Lazarewskii et al. (1963) at 9.38 GHz and finally Lastochkin et al. (1963b) also at 9.38 GHz, using this technique. The latter pair of measurements made at 3.2 c.m. (9.38 GHz) were made in order to check the earlier measurements of Stankevich. All these experiments measured the Cas. A flux density, except that of Lazarewskii et al., who measured Taurus A.

The interesting point regarding the high frequency flux density measurements above, is that the estimated accuracy in the result is better than 5% in each case even though no improvement in gain calibration technique was mentioned since the initial paper by Troitsky and Tseitlin. They claimed, that the aerial gain could be determined to an accuracy of 5 to 10%. The marked improvement, which must have taken place in the technique, has not been noted in any of these experiments. The above experiments, however, have mutually consistent results.

It should be noted that in none of the above reports is there a discussion of the disc blackness. If there is a small amount of reflection from the disc it is most likely that the apparent disc temperature will be less than assumed. This would result in an underestimation of the aerial gain and a corresponding underestimation of the measured source flux densities. This result is relevant to the following discussion.

An interesting comparison, which highlights the difficulty in making estimates of the true error in any absolute flux density experiment, is that of the results of the experiments of Medd and Ramana and the Russian investigators at or near 3200 MHz. The Cas. A flux density derived using the two different methods show a systematic difference (Medd and Ramana, 1965a); results obtained using the "Blackened Disc" calibration technique are about 12% higher than those obtained using the horn calibration technique. In view of the low combined standard

error, this result suggests that there is a systematic difference between the results of the two methods of measurement. Fewer measurements were made on Cygnus A; they show a difference of about 4% in the same sense. On the basis of the Cygnus A measurements it would be impossible to decide whether there is a systematic difference between the results of the two techniques. It is not unlikely that the differences are due to the random errors in both sets of measurements since the errors may well have been underestimated.

This discussion results in two problems: firstly does a systematic difference exist between the results of the two techniques and secondly if it does exist is one or other or are both techniques in error? The problems have not been resolved up to the present time.

3. The third technique in group B is that of aerial calibration by polar diagram integration i.e. the evaluation of the factors in equation 1.2. The measurement of the distribution of the radiated energy from a medium to high gain antenna is a difficult problem since the energy radiated per unit solid angle outside the main beam is generally quite small, while the total energy radiated outside the main beam is a significant fraction of the total. It is necessary to measure the low level radiation, 60 to 70 db below the forward power level, in order to achieve a high accuracy in the gain

value. The tendency is to underestimate the wide angle radiation, thus overestimating the gain and underestimating the source flux density. A major difficulty in these measurements is due to reflection or scattering of the radiation from objects in the vicinity of the antenna.

Laboratory measurements at high frequencies on models of large antennae is a technique, which is often used for antenna radiation pattern analysis and antenna gain determination. No absolute measurements have been made using this technique, which is potentially moderately accurate.

The directivity of the 25 metre Dwingeloo radio telescope (Higgs, 1967) has been measured at 820 MHz using the field integration technique; an accuracy of 0.13 db was claimed. The full beam¹ response for the two orthogonal planes of polarisation was determined using an astronomical radio source. The response outside the full beam was determined using a transmitter on top of a 300 m. high, TV mast situated 10 km from the dish. The transmitter permitted field measurements over 2π steradians down to a level 65 db below the forward response. The transmitter was in the far field of the dish:

1. The full beam response is the response out to a level which generally includes the first and second sidelobes. The definition is quite arbitrary and is made to suit a particular telescope.

ground reflections between the dish and the transmitter were claimed to be non-existent (owing to existence of a pine forest between them). This is probably the most serious attempt to measure the directivity of a large aerial. The measurements were performed in order to make a survey of the celestial radio emission, however, if the accuracy is as good as claimed the aerial would be ideal for making absolute flux density measurements. At the present time no published accounts of such measurements have appeared.

Williams et al., (1967) performed absolute flux density measurements at 38 MHz on a number of sources using a long east-west array. The radiation pattern was determined by measuring the response to strong sources for different declination settings of the array; the array directivity could be deduced by integration. Again there would be a tendency to overestimate the directivity and consequently underestimate the source flux densities because of the low level response underestimation. The absolute aerial temperatures were found by comparing drift scans in R.A. after smoothing, with aerial temperatures, observed with a 4λ corner-reflector (Turtle et al. 1962 as corrected by Purton, 1966a). The absolute flux density of twelve sources was determined to a quoted accuracy of 10%. The experiment cannot be really classified as a reliable absolute measurement, since it depends on other absolute measurements (aerial temperatures).

The results agree remarkably well with the results of other absolute measurements at this frequency (e.g. Parker, 1968), but the agreement is undoubtedly fortuitous.

Mezger (1958) determined the flux densities of Cas.A, Cyg. A, Tau. A, Vir. A and Hyd. A at 1419 MHz. He determined the full beam gain (G_H) of the steerable paraboloid used in the observations and the stray factor (β). These factors are related to the aerial gain G by the relation

$$\beta = 1 - G/G_H.$$

G_H was determined by integrating under the full beam response pattern of aerial. This response pattern was found from observations of a small diameter radio source.

β was determined by measuring the aerial temperature with the paraboloid pointed towards a pine forested region (absorbing load):

$$T_A = (1-\beta)T_O + \frac{1}{2} \beta T_O + \frac{1}{2} \beta T_S.$$

T_S is the sky temperature. (Ohmic losses in the aerial are assumed to be zero i.e. $\eta = 1$).

It was claimed that the gain measurement was accurate to 8%. High accuracy measurements would not be expected to be made using this particular technique.

In conclusion it would appear that it is far simpler and probably more accurate to calibrate an aerial using a power comparison rather than a field integration technique.

2.3-d Group C:

Considerations of sensitivity and confusion restrict all the techniques so far described, with the exception of polar diagram intergration, to measurements on the strongest discrete radio sources. The unsuitability of these sources as reference sources for relative measurement has been pointed out. A technique of absolute measurement first used by Little (1958), which helps overcome the sensitivity and confusion problems, will now be described. This technique permits measurements on sources for which the objections to Cas. A, Cyg. A and Tau. A no longer apply.

Little made absolute flux density measurements at 85.5 MHz on five radio sources: Hydra A, Virgo A, Pictor A, Hercules A and Taurus A. The measurements were made using a simple dipole above a reflector as the reference aerial in conjunction with the two arms of the 85.5 MHz Mills Cross (Mills et al., 1958). The use of the arms improved the sensitivity and resolution in the experiments; their properties need not be known.

During an observation of a source three records were taken using the aerials in three interferometer pairs. If A_R is the effective area of the reference aerial, A_E the effective area of the one arm and A_W that of the other, we have for the receiver outputs of the three phase switched interferometers:

$$D_1 = K_1 (A_E A_W)^{\frac{1}{2}} S.$$

$$D_2 = K_2 (A_W A_R)^{\frac{1}{2}} S.$$

$$D_3 = K_3 (A_E A_R)^{\frac{1}{2}} S.$$

S is the source flux density.

The thermal calibration of the receiver was performed by replacing the pairs of aerials by a diode noise power source.

A further set of deflections is then obtained:

$$D_1^{\text{CAL}} = K_1 kT; D_2^{\text{CAL}} = K_2 kT;$$

$$D_3^{\text{CAL}} = K_3 kT.$$

The above sets of equations lead to an expression for the source flux density in terms of measurable receiver output deflections and calibration factors, T and A_R :

$$S = \frac{D_3 D_2}{D_1} \cdot \frac{D_1^{\text{CAL}}}{D_2^{\text{CAL}} D_3^{\text{CAL}}} \cdot \frac{kT}{A_R}.$$

Observations made using the reference aerial have good sensitivity, since they are all made with an interferometer comprising the reference aerial and one arm of the cross; the effective area of the configuration is twice the geometric mean of the two aerial effective areas. The resolution is high since the radiation pattern of the combination is essentially the voltage polar diagram of the large aerial.

Little claimed an accuracy of 10% in each source flux density. These measurements provided the absolute basis for the flux densities at 85.5 MHz given in the MSH source catalogues

very flat spectrum over the entire radio region.

Measurements have been made by Allen and Barrett (1967) at 8.25 GHz and 15.5 GHz on both Cas. A and Taurus A. They claimed an accuracy of between 5 and 6% in the measurements. Tolbert and Straiton (1965) determined the Taurus A flux density at the frequencies, 35 and 70 GHz; at the higher frequency the signal to noise was so poor that the estimated accuracy of the result was ~60%, while at the lower frequency the accuracy was 14%. Ignoring for the moment the sensitivity problem, all of the difficulties associated with absolute measurements at lower frequencies are magnified in the high frequency region; the provision of noise power standards, attenuation measurements and aerial calibration (B (a)) are all more difficult. In addition, large uncertain corrections need to be made to the measured source flux density for atmospheric attenuation (Hogg, 1959) and for source polarisation.

These factors undoubtedly account for the scarcity of absolute flux density measurements in the cm to mm wavelength range.

2.4-b Very Low Frequencies:

A number of absolute flux density measurements (Table 2.4) have been made in the low frequency part of the radio spectrum on Cas. A; the accuracy claimed is rarely greater than 20%. Below 10 MHz there exists only two references to discrete

source flux density measurements: Ellis (1962) and Ellis and Hamilton (1966). In the first paper only the intensity ratio at 4.8 MHz of two strong sources (Fornax A and Centaurus A) were given. Ellis and Hamilton give the 4.7 MHz flux densities of nine sources. Comprehensive calibration details were not provided with these latter measurements.

TABLE 2.4

Very Low Frequency Flux Density Measurements.

<u>Observer</u>	<u>Frequency (MHz)</u>	<u>Source(s)</u>	<u>Accuracy</u>
Bridle (1967)	10.05	Cas. A	10%
		Cygnus A	25%
Braude et al (1962)	19.5,20.5,22,24, 25,28,29.5,31	Cas. A	20-30%
Brazelyon et al. (1963)	20,25,30	Cas. A	20%
Lamden & Lovell (1956)	16.5,19.0,22.6, 30	Cas. A	20 to 30%
Purton (1966b)	13.1	Cas. A	25%
		Cygnus A	50%
Wells (1958)	18.7,27	Cas. A	20%

Studies of the radiation in the decametre range are complicated by a number of factors peculiar to this range. Interference from radio stations, ionospheric disturbances and ionospheric attenuation are all important. Interference effects

are minimized by the use of narrow bandwidths (1 to 10 KHz), sometimes in conjunction with a swept frequency receiver which records the minimum signal strength (e.g. Ellis 1960) received over the swept frequency band (10 to 100 KHz). Ionospheric scintillation, due to irregularities in the ionosphere, produce observational problems up to frequencies of about 60 MHz and are detectable at frequencies up to at least 400 MHz. Both the man-made and natural interference effects result in the loss of many records in this low frequency range.

The lowest frequency at which observations can be made is dictated by the F_2 -layer critical frequency (f_0F_2). The value of f_0F_2 depends on a number of factors: geomagnetic latitude of the telescope, local solar time, the presence or otherwise of solar disturbances and the time of observation relative to the sunspot cycle; these last two factors are obviously related. Ionospheric attenuation is fairly small (≤ 1 db) providing the observing frequency is more than three times f_0F_2 (Ellis, 1963) and providing the observations are made during the night, when the D-layer absorption is negligible; the D-layer is almost non-existent in the hours between midnight and sunrise. Approximate corrections can, however, be applied to take into account the radiation attenuation in these layers.

In general, observations are made using dipole arrays in a phase-switched interferometer configuration. The directivity

of the array is computed and the losses in the feeders measured and those in the dipoles and ground plane computed. Owing to the difficulty in providing a large (in terms of the wavelength) highly conducting ground plane, the loss in the ground plane can be quite significant.

Thermal calibration is carried out using noise diode sources. The temperature of such sources is far less than the increase in aerial temperature due to a strong source. In order to avoid non-linearity problems the noise source generally includes a wide-band amplifier, the gain of which must be accurately calibrated. The use of thermal loads is virtually impossible in this frequency region.

In conclusion, this region while having the usual problems associated with absolute measurements has several others, which severely limit the accuracy of the results.

CHAPTER 3

THEORY OF THE PRESENT TECHNIQUE

3.1. INTRODUCTION:

The theory of the two methods used in the present measurements will be given in this chapter; two methods were employed in the hope that systematic errors could be minimized. The present absolute flux density values are based on a reference aerial of known gain and a temperature scale calibrated using matched loads at known temperatures. In order to improve the sensitivity and resolution the reference aerial was not used directly, but in combination with a much larger aerial or aerials of unknown gain(s); the unknowns are eliminated by making measurements with different configurations. A set of simultaneous equations is obtained for each method from which factors containing the unknown properties of the large aerials can be eliminated. The resulting equations for the flux density are similar in form to equation 1.6.

3.2 METHOD I:

Two large aerials are used together with the reference aerial in three interferometer pairs. The signals from the aerials in a pair are combined with arbitrary phase differences $\theta(\phi \text{ or } \xi)$ and $\theta + \frac{\pi}{2}(\phi + \frac{\pi}{2} \text{ or } \xi + \frac{\pi}{2})$ providing two quadrature outputs; these are referred to as the sine (S) and

cosine (C) components. These components are detected and recorded; D_{iS} , D_{iC} ($i = 1$ to 3) are the recorder deflections from detectors iS , iC .

Consider for the moment two aerials with effective areas A_1 and A_2 connected together by cables with attenuations α_1 and α_2 (corresponding efficiencies η_1 and η_2). A pre-amplifier with a gain g_i is situated in each signal path. In one arm of the interferometer there is a phase switch with zero insertion loss (fig.3.1). The modulated signal at the hybrid output, due to a discrete source in the aerial beam, produces a D.C. voltage at the output of a switch frequency receiver, which is proportional to the product of the geometric mean of the effective areas of the two antennae and the source flux density:

$$\text{Output} \propto 2(g_1 \eta_1 A_1 g_2 \eta_2 A_2)^{\frac{1}{2}} \cdot \left(\frac{S}{2}\right). \quad 3.1$$

The phase lengths of the signal paths are assumed identical.

In the present method the recorder deflections obtained using a large aerial, subscript E(W or E-W) and the standard aerial are,

$$D_{1S} = 2g_{1S} \left(\frac{S}{2}\right) (g_E A_E g_R A_R)^{\frac{1}{2}} \sin \theta \quad 3.2$$

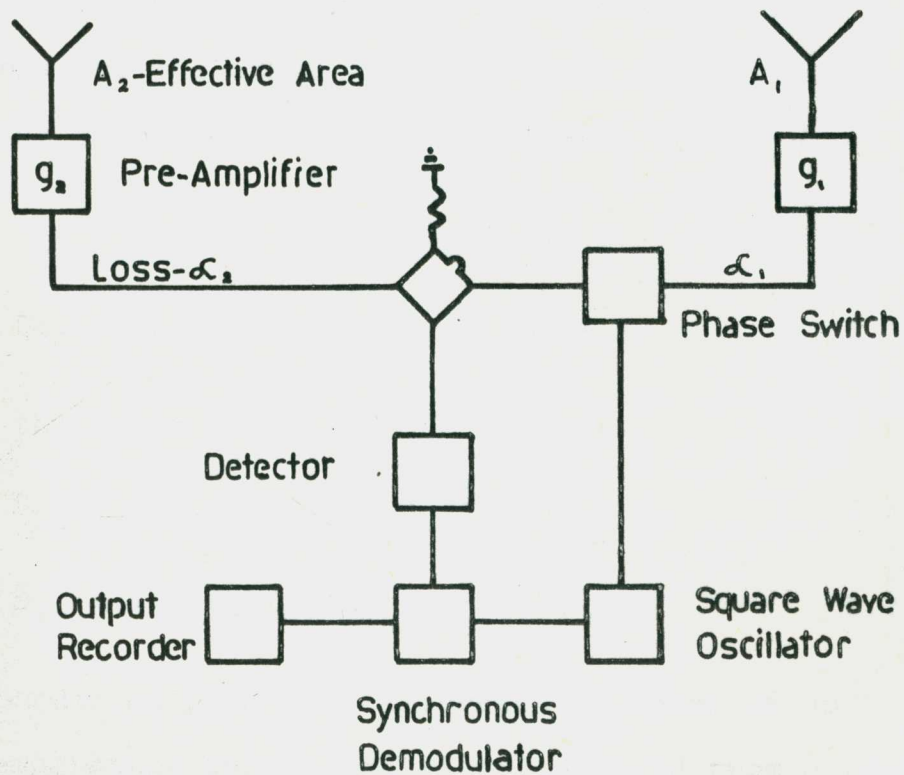
$$D_{1C} = 2g_{1C} \left(\frac{S}{2}\right) (g_E A_E g_R A_R)^{\frac{1}{2}} \cos \theta. \quad 3.3$$

The symbols g_{iS} , g_{iC} , are factors describing the equipment from the signal addition hybrids to the output recorder; they include losses, amplifier gains and recorder efficiencies.

FIGURE 3.1

A schematic diagram of a phase-switched interferometer system. A small diameter source with a flux density S , produces a peak deflection at the receiver output given by:

$$\text{Output} \propto 2(g_1 \eta_1 A_1 \cdot g_2 \eta_2 A_2)^{\frac{1}{2}} S.$$



PHASE-SWITCHED INTERFEROMETER

FIG. 3.1

The factors g_E (g_W, g_R) are associated with the equipment from the aerial outputs to the hybrid summing points; they include cable losses, conversion losses and amplifier gains.

A_R is the effective area of the standard aerial while A_E (A_W A_{E-W}) is the effective area of the large antenna.

Similarly for the other two interferometer records: firstly for the standard aerial and the large aerial W,

$$D_{2S} = 2g_{2S}\left(\frac{S}{2}\right) \cdot (g_W A_W g_R A_R)^{\frac{1}{2}} \sin \phi \quad 3.4$$

$$D_{2C} = 2g_{2C}\left(\frac{S}{2}\right) (g_W A_W g_R A_R)^{\frac{1}{2}} \cos \phi \quad 3.5$$

secondly for the large aerials E and W,

$$D_{3S} = 2g_{3S}\left(\frac{S}{2}\right) (g_W A_W g_E A_E)^{\frac{1}{2}} \sin \xi \quad 3.6$$

$$D_{3C} = 2g_{3C}\left(\frac{S}{2}\right) (g_W A_W g_E A_E)^{\frac{1}{2}} \cos \xi . \quad 3.7$$

The recorder outputs are calibrated in terms of an equivalent temperature by a noise signal derived from a temperature-saturated diode and injected into the reference aerial through a directional coupler at the reference aerial output. The noise signal is 100% modulated at the switching frequency. The diode was calibrated by thermal methods, described later. Detector IS is used as the reference and the resulting calibration deflection is given by

$$D_4 = \frac{1}{2} g_{1S} g_R kT . \quad 3.8$$

One half of the power into the hybrid junction from the noise calibration source is dissipated in the hybrid termination.

Since detector 1S is used as the reference all the other detector outputs are calibrated by measuring their gains relative to that of detector 1S. Defining calibration factors n_{iS}, n_{iC} ($i = 1$ to 3) which are measurable gain ratios where,

$$n_{iS} = \frac{g_{iS}}{g_{1S}}, \quad n_{iC} = \frac{g_{iC}}{g_{1S}}. \quad 3.9$$

These factors can be measured by providing a modulated noise source, with a number of equiamplitude outputs with identical output impedances, into which all the detectors can be plugged.

The unknown and unmeasurable factors g_E, g_W and g_R , and aerial parameters A_E, A_W can be eliminated from the above set of equations to give an expression for the flux density S :

$$S = \frac{1}{2} \frac{\left(D_{1S}^2 + \frac{D_{1C}^2}{n_{1C}^2}\right)^{\frac{1}{2}} \left(\frac{D_{2S}^2}{n_{2S}^2} + \frac{D_{2C}^2}{n_{2C}^2}\right)^{\frac{1}{2}} k T}{\left(\frac{D_{3S}^2}{n_{3S}^2} + \frac{D_{3C}^2}{n_{3C}^2}\right)^{\frac{1}{2}} \cdot D_4 A_R}. \quad 3.10$$

A quantity D_i^2 can be defined as the sum of the squares of the normalized quadrature component deflections:

$$D_i^2 = \left(\frac{D_{iS}^2}{n_{iS}^2} + \frac{D_{iC}^2}{n_{iC}^2}\right). \quad 3.11$$

Equation 3.10 is then written as,

$$S = \frac{1}{2} \frac{D_1 \cdot D_2}{D_3 \cdot D_4} \cdot \frac{kT}{A_R} . \quad 3.12$$

3.3 METHOD II

An interferometer record is taken employing a large and standard aerial as the interferometer elements. A total power record is also taken using the large aerial alone. The equations are similar in form to those derived in Method I and the symbols are identical, except where otherwise indicated. The large aerial will be referred to by the subscript E-W.

The peak recorder deflections for the interferometer pair are given by

$$D_{1S} = 2g_{1S} \cdot \left(\frac{S}{2}\right) (g_{E-W} A_{E-W} g_R A_R)^{\frac{1}{2}} \sin \theta \quad 3.13$$

$$D_{1C} = 2g_{1C} \left(\frac{S}{2}\right) (g_{E-W} A_{E-W} g_R A_R)^{\frac{1}{2}} \cos \theta \quad 3.14$$

for the total power,

$$D_2 = g_2 g_{E-W} \cdot A_{E-W} \left(\frac{S}{2}\right) \quad 3.15$$

and for the noise power calibration

$$D_4 = \frac{1}{2} g_{1S} g_R kT . \quad 3.16$$

The relative, final stage receiver gain factors are defined as

$$n_{1S} = 1 ; n_{1C} = \frac{g_{1C}}{g_{1S}} ; n_2 = \frac{g_2}{g_{1S}} . \quad 3.17$$

The combination of the above set of equations yields for the flux density:

$$S = \frac{1}{4} \frac{(D_{1S}^2 + \frac{D_{1C}^2}{n_{1C}^2})}{D_2 \cdot D_4} \cdot n_2 \cdot \frac{kT}{A_R} \quad 3.18$$

$$= \frac{1}{4} \frac{D_1^2}{D_2 D_4} \cdot n_2 \cdot \frac{kT}{A_R}, \quad 3.19$$

$$\text{where } D_1^2 = D_{1S}^2 + \frac{D_{1C}^2}{n_{1C}^2}. \quad 3.20$$

An entirely equivalent expression for D_1^2 , which proves to be more convenient when analysing the records, is obtained if we first estimate the phase angle from

$$\tan \theta = \frac{D_{1S}}{D_{1C}} \cdot n_{1C} \quad 3.21$$

and substitute into

$$D_1^2 = D_{1C}^2 / \cos^2 \theta. \quad 3.22$$

This value is then used in equation 3.19.

3.4 DISCUSSION:

Equations 3.12 and 3.19 contain only the calibration factors, T and A_R , and the measurable recorder deflections D_i ($i = 1$ to 4). The calculation of the reference aerial effective area and the thermal calibration of the diode noise signal will be dealt with in the following chapter.

Method I is almost identical to the technique employed by Little except that in the present case the calibration signal was modulated and injected only into one side of an interferometer pair, while Little used a correlated noise reference.

Method II is a variation of Little's method, replacing two of the interferometer measurements by a single total power measurement.

In the following chapter we shall discuss fully the equipment used in making the absolute flux density measurements by the methods given in this chapter.

3.5 BIAS PRODUCED IN THE ANALYSIS:

The flux density values derived by application of equation 3.12 and 3.19 are in fact overestimates of the true flux density. A bias is present even though the quantities D_{iS} and D_{iC} contain only random errors.

The error arises in the following manner (Mandel, 1964):

Method I: The normalised detector output deflections can be written

$$\frac{D_{iS}}{n_{iS}} = A_i + \epsilon_i$$

where ϵ_i is the r.m.s. noise on a record and A_i is the signal deflection in the absence of noise.

Similarly,

$$\frac{D_{iC}}{n_{iC}} = B_i \pm \xi_i.$$

Squaring and adding,

$$\frac{D_{iS}^2}{n_{iS}^2} + \frac{D_{iC}^2}{n_{iC}^2} = A_i^2 + B_i^2 + \epsilon_i^2 + \xi_i^2 \pm K,$$

where K is the random error.

The process therefore, systematically overestimates the true value, $A_i^2 + B_i^2$ by an amount, $\epsilon_i^2 + \xi_i^2$ (in general $\epsilon_i^2 = \xi_i^2$) even though there is no initial bias in the measured quantities D_{iS} , D_{iC} . Note that we have assumed that the calibration factors n_{iS} , n_{iC} are measured exactly.

This bias is only important when the signal to noise on a measurement is poor. In equation 3.12 there are two terms which contribute to the bias in the source flux densities:

$$\left(D_{1S}^2 + \frac{D_{1C}^2}{n_{1C}^2}\right)^{\frac{1}{2}} \cdot \left(\frac{D_{2S}^2}{n_{2S}^2} + \frac{D_{2C}^2}{n_{2C}^2}\right)^{\frac{1}{2}}$$

both are approximately of equal magnitude.

The product is an overestimation of the true value by an amount $2\epsilon^2$, where ϵ is the r.m.s. noise on the output recorder of detector 1S. Source flux densities determined by Method I were corrected by a factor, the magnitude of which was dependant on the estimated record signal to noise.

Method II: Flux densities determined by the use of equation 3.19 require identical correction to those obtained by the previous method (Equation 3.12). The signal to noise (A_i/ϵ_i and B_i/ϵ_i), however, on records obtained using Method II was better than in the previous method. This is due to the fact that A_{E-W} (equations 3.13 and 3.14) is twice the magnitude of A_E or A_W (equations 3.2 to 2.5). The percentage correction factors therefore are about one-half the values required in Method I.

The magnitude of the correction factors required for both Methods I and II for all the sources observed are given in Chapter 5.

CHAPTER 4

EQUIPMENT AND CALIBRATION

4.1 INTRODUCTION:

This chapter is divided into two main sections: (i) The first deals with aerials used in the present methods and deals in detail with the reference aerial directivity calculation and the estimation of the accuracy of the result. (ii) The second part deals with the receiver and the thermal calibration of the noise diode source. The diode provides the reference signal for the individual observations.

The gain of the aerial and the temperature of the noise power reference source are the basic calibration factors for the absolute flux density scale.

4.2 REFERENCE AERIALS:

The foremost restriction placed upon the choice of reference aerial is the accuracy with which the gain can be determined. This accuracy is almost the limiting accuracy for precise flux density determinations; an error in the gain value for the reference aerial will appear as a systematic error in the resulting flux density scale. These considerations restrict the choice to simple dipoles above reflectors and horn antennas; the gain of these antennas can be computed to an accuracy of better than 0.2 db. An alternative procedure might be to measure the gain of a more complicated aerial structure by a

field integration technique, either using the actual antenna or a scaled model. This was not attempted in the present investigation; it was felt, in any case, that the above accuracy could not be achieved by these means.

Another consideration in the choice of reference aerial was that the gain should be greater than about 12 db. This assures adequate signal to noise on the available radio sources using the methods given in the last chapter. We are thus left with the possibility of using either a horn antenna or an array of dipoles above a reflecting screen. The ultimate choice was based on practical considerations.

A brief review will be given of the theory and experimental results for horn antennas and the accuracy which can be attained in a gain determination, before discussing the dipole array employed as the reference aerial in the present investigation.

It is important that in this region of the radio spectrum (about 400 MHz), there exists the possibility of using either dipoles or horns. The region then provides a link between the high frequencies (centimetre wavelengths), where only horns can be used as gain standards and the low frequencies (metre wavelengths), where dipoles provide the standard. Absolute measurements made using these standards at decimetre wavelengths, are thus quite important.

4.3 HORN ANTENNAS:

The directivity of a pyramidal horn is calculated (Schelkunoff and Friis, 1952) from the assumed aperture field distribution. This assumed aperture field distribution is that which would exist in a plane intersecting a horn of infinite extent; this plane contains the aperture of the actual truncated horn. Furthermore it is assumed that the tangential components of the electric and magnetic fields are related by the free space impedance (Z_0) at all points in the aperture:

$$|\underline{E}^t| = Z_0 |\underline{H}^t|.$$

It is the degree to which these approximations are valid, which places the limit on the reliability of the gain calculations. Fairly obviously, diffraction effects associated with edges of the aperture have been neglected, as well as mismatch effects in the aperture. It is very difficult to assess quantitatively the error involved in the gain calculation for a horn, owing to the difficulty of estimating the effects of the above approximations. The only conclusion that can be drawn is that the calculation is likely to be more exact, the larger in terms of the wavelength, are the dimensions of the horn aperture.

The horns discussed in this section are "optimum horns" i.e. horns which have maximum gain for a given overall length.

The gain of a horn has generally been determined experimentally by a technique in which the transmission loss

versus separation is measured for two identical horns. Jakes (1951) noted that the rough criterion for the far field region (distances greater than $\frac{2D^2}{\lambda}$: D is the aperture dimensions of the antenna) did not appear to apply for the case of electromagnetic horns, since the expression

$$\left(\frac{P_T}{P_R}\right)^{\frac{1}{2}} = \frac{4\pi r}{\lambda} \cdot G \quad 4.1$$

did not yield a unique value for G for different aperture separations(r): P_T is the transmitted power and P_R is the radiated power. The expression (4.1) held approximately, if r was defined as the separation of the points in the two horn antennas at which the flared waveguide meets the feeding waveguide. Using this empirical procedure it was claimed that the gain could be determined to 0.1 db.

The first estimate of the corrections, which must be made to the near - field gain determined from the expression

$$G(r) = \frac{\lambda}{4\pi r} \cdot \left(\frac{P_T}{P_R}\right)^{\frac{1}{2}}, \quad 4.2$$

were made by Braun (1953). His correction curves were used in measurements made on a series of horns, with gains in the range 13.7 to 24 db, by Slayton (1955). Slayton noted that when the experimental conditions were good the greatest discrepancy between the corrected measured gain and that calculated using Schelkunoff's method was approximately 0.2 db; in general the

difference was much less. He did observe, however, that the gain did not vary monotonically (as $\frac{1}{\lambda^2}$) with wavelength but showed variations of ~ 0.2 db, which probably could be attributed to higher order modes in the horn or currents outside the horn aperture; these are not accounted for in Schelkunoff's theory.

Chu and Semplak (1965) computed gain correction terms for use in their measurements using an exact form for the near-field transmission formula. In order to apply this formula several assumptions need to be made: the field in the aperture plane of the radiating horn is that which would exist in this plane if the horn was of infinite extent; the field in the aperture of the receiving horn is that which would exist if the receiving horn was not present; the tangential components of the electric and magnetic fields in the aperture planes are connected by the free-space impedance. Using this correction factor the far-field gain of a pyramidal horn was measured at relatively small distances. The discrepancy between the corrected measured value and that calculated was about 0.04 db.

While agreement between the expected (from Schelkunoff's theory) and measured values above appear to be good, it must be remembered that the proximity corrections, which may be as large as 1 db are themselves only approximations, based on the same kind of assumptions as the theoretical gain determinations. The variations noted by Slayton, which are unaccounted for by

Schelkunoff's theory, together with experimental effects, such as the interaction between the two horns and multipath interference, leads Bowman (1967) to doubt whether the experiments can claim to agree with the theoretical results to better than 0.3 db; the theoretical gain estimates are thus confirmed only to this accuracy.

Jull (1968) measured the gains, as a function of frequency, of a number of Slayton's horns using the more accurate near field corrections of Chu and Semplak. He observed that the resulting gain oscillations were reduced as the horn dimensions increased, his overall conclusion being that Schelkunoff's gain calculation is accurate to 0.1 db for a horn with a gain greater than 18.5 db; the accuracy improves as the gain increases. On the basis of these results, Jull deduced that edge diffraction effects were responsible for the gain oscillations.

Jull concluded (Jull and Bowman, 1968) that Bowman's estimate of the errors is unduly pessimistic. Bowman in the same paper defends his error estimates stating that they are based on total error limits and not on percentage confidence limits as are most error estimates. He claims that the latter error procedure is unsuitable for reference standards.

Russo et al (1965) made the first effort to include edge diffraction effects in horn calculations, when they computed the E-plane pattern of a horn using Sommerfeld's (1954) results

for knife edge diffraction. At the present time these effects have not been included in gain computations.

In conclusion it would appear that for a horn with a gain of 20 db, Schelkunoff's calculated results have been confirmed to an accuracy of about 0.1 db (standard error). This would represent the limiting accuracy on flux density measurements made using horn antennae.

4.4 DIPOLE ARRAY:

An array of dipoles was used as the reference aerial in the present absolute flux density measurements. The decision to use an array was based on the availability of a set of dipoles and feed system, since at 408 MHz a horn with comparable gain (~ 19 db) is a moderately large structure. Fig.4.1 gives the horn dimensions for one of Slayton's (1955) horns with a gain of 18 db at 408 MHz. Furthermore, it will be shown that the accuracy with which the gain of such an array can be computed is comparable to that for a horn antenna.

The array consists of sixteen, half-wave, in-line, dipoles separated by about three-quarters of a wavelength and spaced about one-quarter wavelength above a large flat reflecting screen. The sixteen dipoles are fed in groups of eight from two resonant waveguide cavities connected together and to the feed input by trough line; there is a matching section incorporated into the trough line at the input to the feed.

The feed and dipoles are shown in fig. 4.2a. The overall system has a bandwidth of approximately 20 MHz. This feed system is identical to the 176 feed modules used at the focus of the east-west arm of the Molonglo Cross (Mills et al 1963).

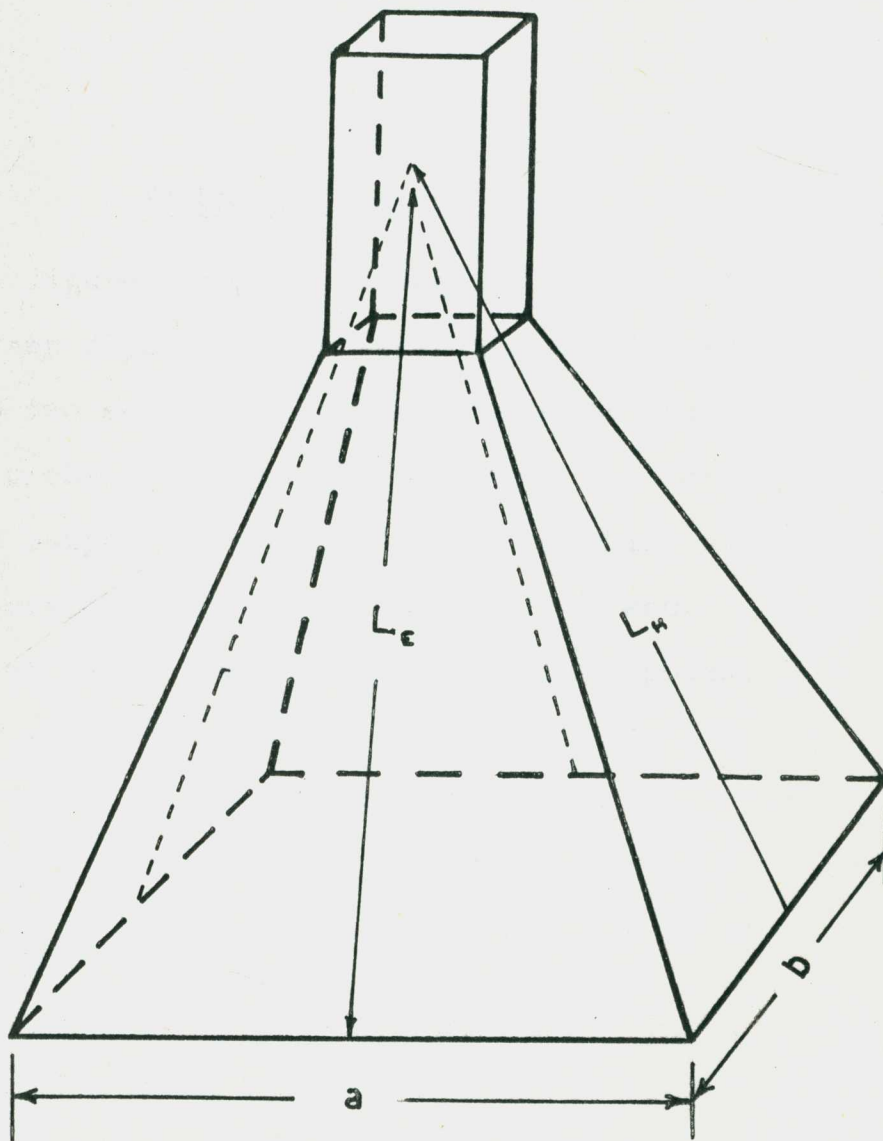
The dipoles are made of aluminium and are shown in detail in fig. 4.2b. The depth of the slot and the arm length have been adjusted for tuning purposes, with the result that the overall dipole length is less than $\frac{\lambda}{2}$.

The ground plane, which rests on the top of the waveguide feed, was constructed from sheets of galvanised iron butted together and joined by strips rivetted beneath the butt joint. The joint was soldered, since it ran normal to the line of dipoles and must not be permitted to disturb the current flow in the ground plane. Surrounding this solid section was a strip of wire mesh, one edge of which was rivetted to the galvanised iron, while the other made contact with the surrounding ground surface. The ground provides an infinite extension to the highly conducting part of the reflector. The dimensions and layout of the ground plane are shown in fig.4.3.

The array is situated approximately 45λ north and 45λ west of the centre of the Molonglo Cross; its axis is parallel to the east-west arm of the Cross. The large ground plane made it impossible to rotate the array about the east-west axis,

FIGURE 4.1

The dimensions of one of Slayton's Gain-Standard Horns scaled to an operating frequency of 408 MHz, are given in this figure. The design gain of this horn is 18 db; the accuracy in this figure is about 0.1 db. (Jull, 1968).



$a = 93.754''$
 $b = 69.434''$
 $L_e = 121.918''$
 $L_w = 137.267''$

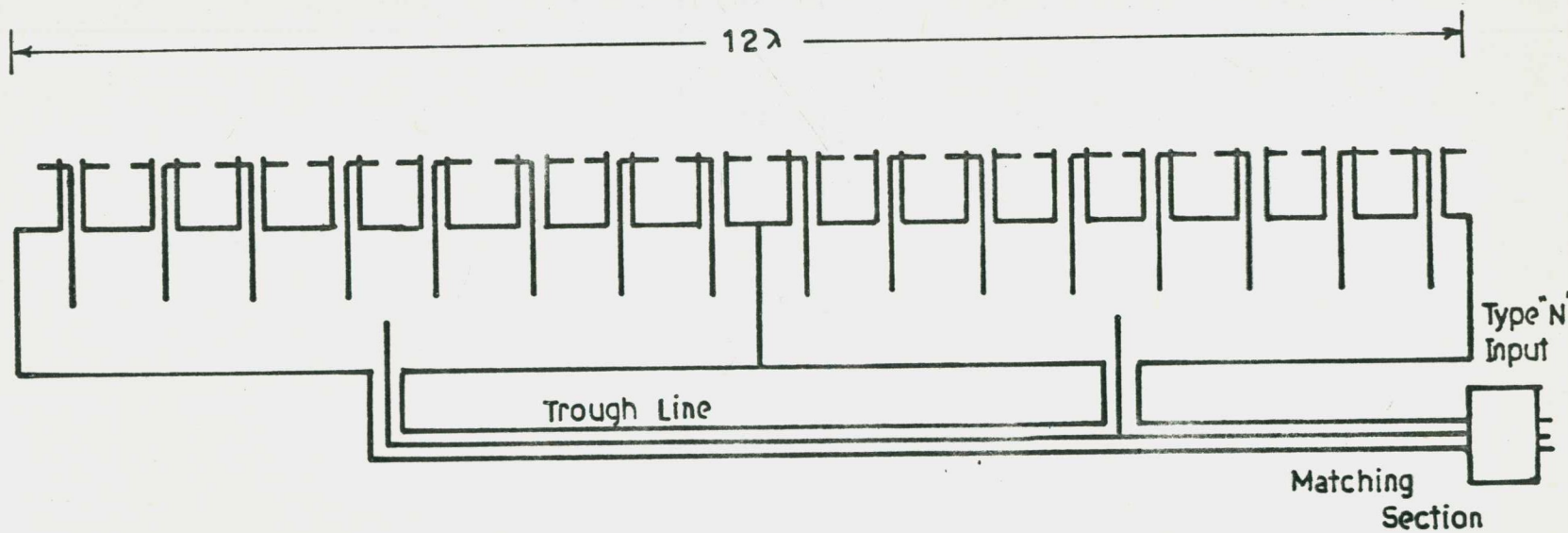
Gain at 408 MHz = 18.0 db

PYRAMIDAL HORN

FIG. 4.1

FIGURES 4.2-a and 4.2-b.

- a. This figure shows the waveguide feed and the sixteen dipoles. The waveguide is divided into two sections, each with a probe output. The probes are connected together and to the feed output by trough line. A matching section is provided near the output of the feed.
- b. One of the sixteen array aluminium dipoles.



WAVEGUIDE FEED

FIG. 4.2a

ARRAY DIPOLE

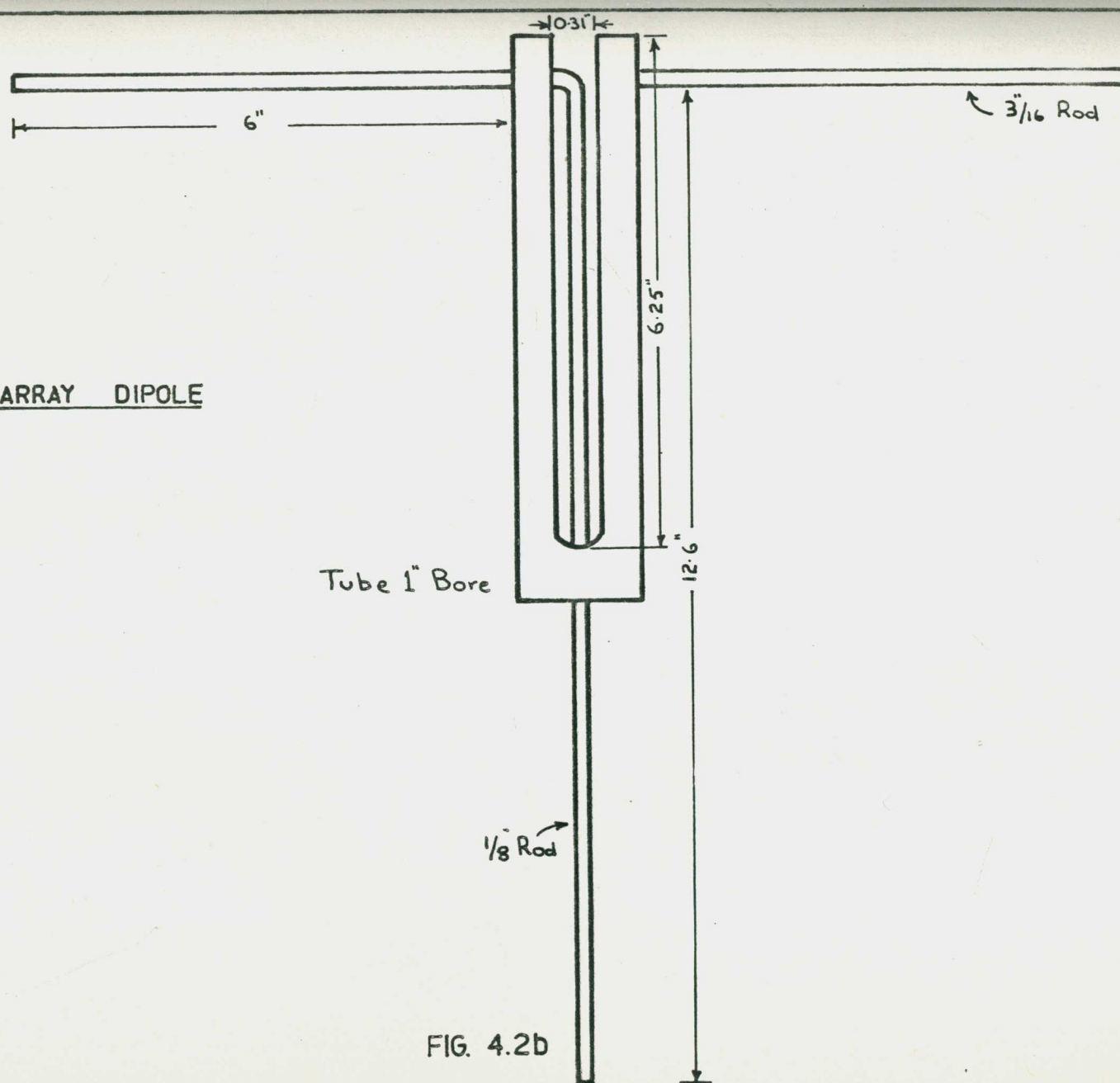
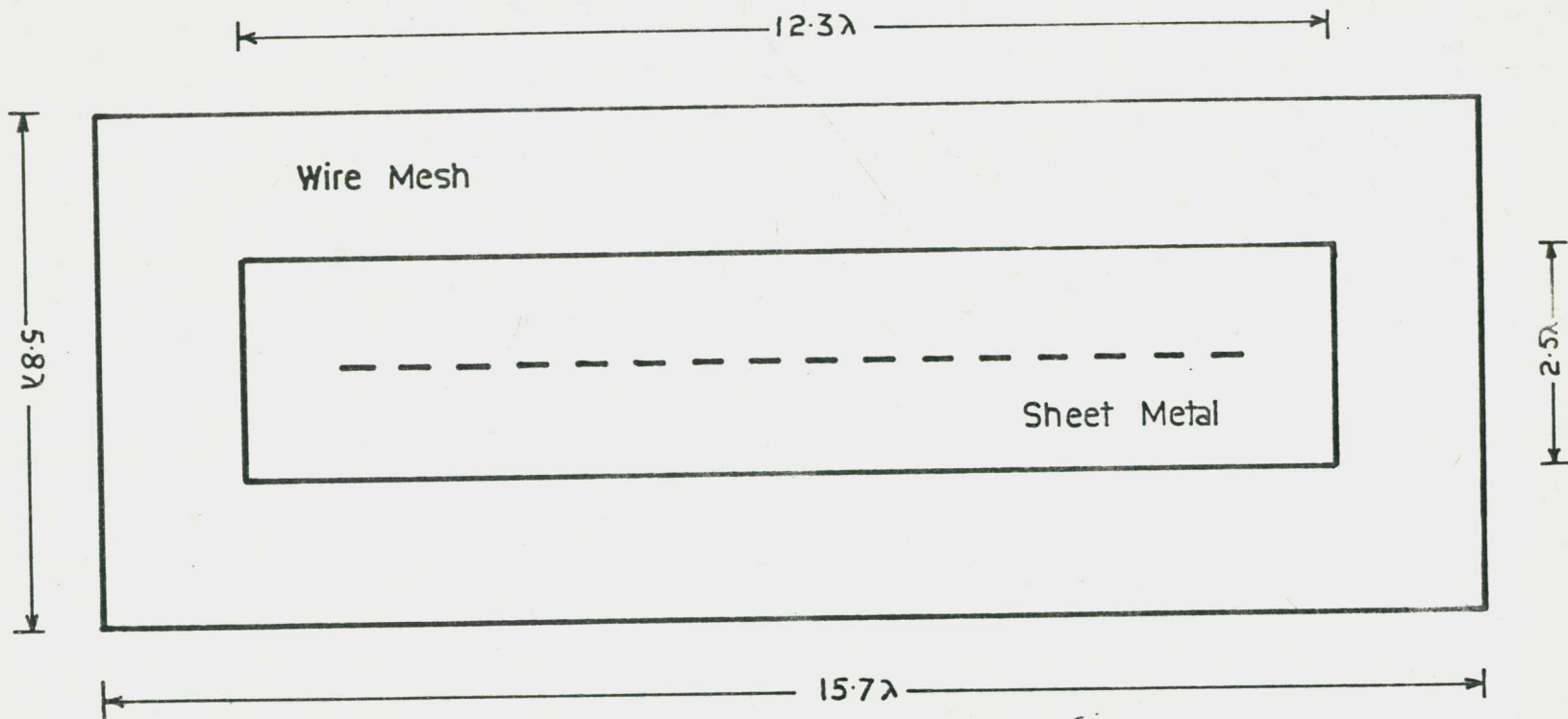


FIG. 4.2b

FIGURE 4.3.

The highly conducting parts of the array ground plane: galvanised iron sheets surrounded by wire mesh. The outer edge of the mesh is in contact with the surrounding ground surface.



GROUND-PLANE LAYOUT

FIG. 4.3

so that the north-south shape of the array fan beam, as well as the forward gain, was computed.

4.5 THE ARRAY GAIN

4.5-a Theory:

To compute the array directivity the following properties of the array are assumed:

- (i) Ideal half-wave dipoles as the array elements.
- (ii) The relative phase and amplitude of the dipole currents known accurately.
- (iii) Physical dimensions of the array known precisely.
- (iv) Highly conducting ground plane of infinite extent.

The effects of the real properties of the array on the computed directivity are discussed later.

The spherical co-ordinate system used in the calculation is such that the polar (θ) angle is measured from the axis of the array, and the azimuth angle (ϕ) from an axis in the plane of the reflecting screen (fig. 4.4).

The directivity of the array is given by (Schelkunoff and Friis, 1952)

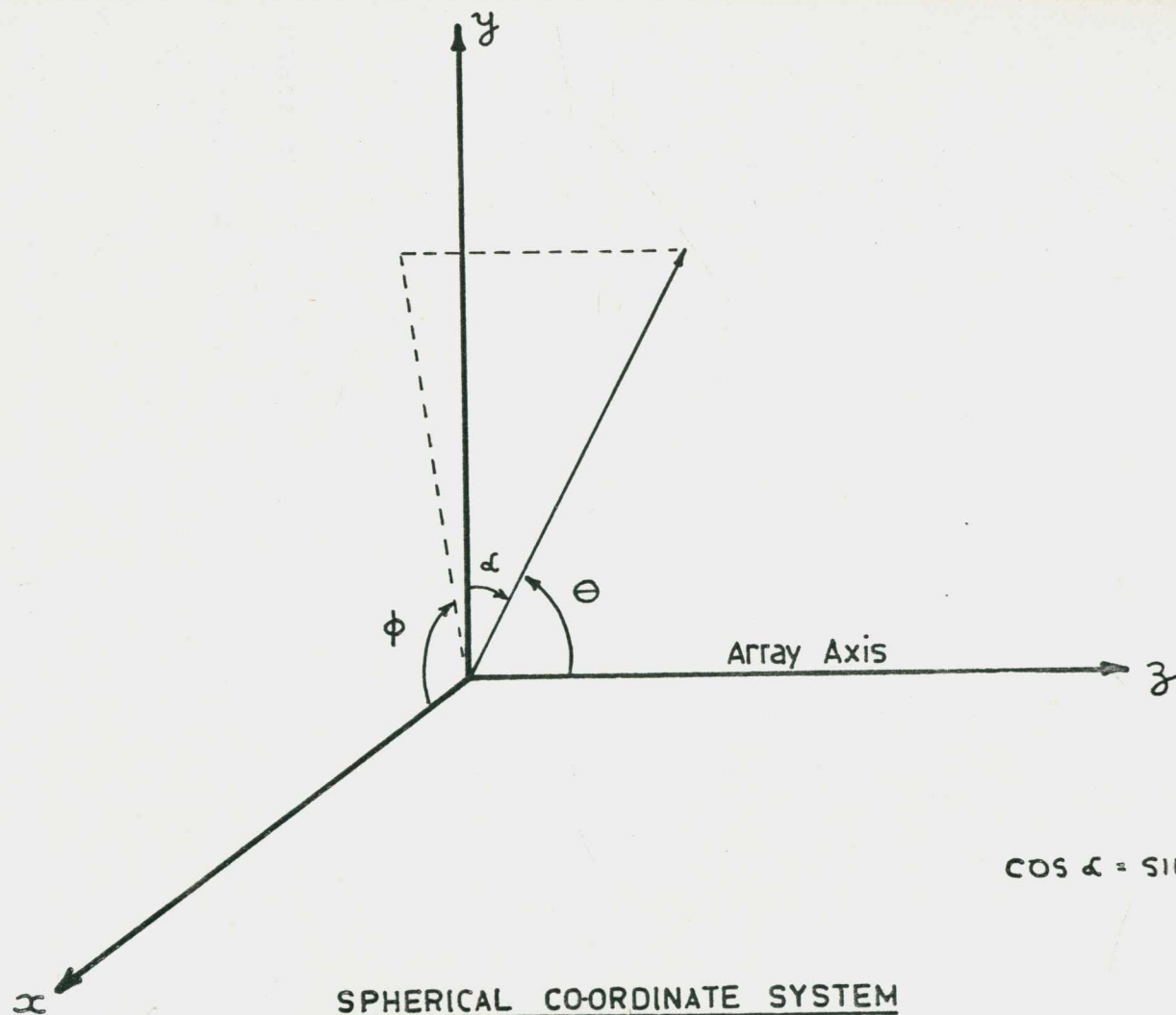
$$D(\theta_o, \phi_o) = \frac{4\pi \Phi(\theta_o, \phi_o)}{\int_{4\pi} \Phi(\theta, \phi) d\Omega}, \quad 4.3$$

where

$$\Phi(\theta, \phi) = \xi(\theta)\xi^*(\theta) B(\theta) \sin^2\left(\frac{2\pi}{\lambda} h \cos \alpha\right). \quad 4.4$$

FIGURE 4.4

The co-ordinate system used in deriving the expressions given in Equation 4.4.



$$\cos \alpha = \sin \theta \cdot \sin \phi$$

FIG. 4.4

1. $[\xi(\theta) \xi^*(\theta)]^{\frac{1}{2}}$ is the space factor of the array
2. $B(\theta)$ is the radiation pattern for a simple dipole in a plane containing the dipole arms:

$$B(\theta) = \frac{\cos^2\left(\frac{\pi}{2} \cos \theta\right)}{\sin^2 \theta} . \quad 4.5$$

3. The last factor takes into account the presence of the reflector; spaced a distance h from the dipoles. α is the angle between the vertical and the direction (θ, ϕ) . It can be shown that

$$\cos \alpha = \sin \theta \sin \phi .$$

If the origin of the co-ordinate system is situated at the physical centre of the array the space factor becomes

$$|\xi(\theta)| = \left| \sum_{n=-8}^{+7} E_n \exp j\left(\frac{2\pi}{\lambda} \cdot d \cdot (n+\frac{1}{2}) \cos \theta\right) \right| , \quad 4.6$$

where d is the dipole spacing and E_n describes the phase (ξ_n) and amplitude (a_n) of the current in each dipole:

$$E_n = a_n e^{j\xi_n}$$

(a_n and ξ_n are the deviations from the mean of the amplitude and phase of the current in the n th dipole).

$\xi(\theta)$ can be expanded to give

$$\xi(\theta) = \sum_{n=-8}^{+7} a_n \{ \cos [\gamma(n+\frac{1}{2}) \cos \theta + \xi_n] + j \sin [\gamma(n+\frac{1}{2}) \cos \theta + \xi_n] \} \quad 4.7$$

where $\gamma = \frac{2\pi}{\lambda} \cdot d$.

The directivity of the array is computed from equation 4.3 after the substitution of the above expressions into equation 4.4 and the value of the integral is found. The integration was performed using a Simpson rule procedure on the KDF9 computer.

4.5-b Measurement of the Current Phase and Amplitude:

The method employed in these measurements is based on a null technique; the measuring equipment is shown in figure 4.5-a. The signal from a magnetic loop probe, placed on top of the dipole, is compared in a slotted line with a reference signal derived from the same oscillator. A null is recorded with the detector on the slotted line probe when the amplitudes of the two signals are the same and the probe is positioned at a zero in the resultant standing wave pattern on the line. It is possible with the present equipment to achieve an accuracy in the phase measurements of $\pm 1^\circ$ and in the amplitude measurement of ± 0.2 db.

The dipoles were adjusted so that the phase of the current differed by no more than 4° from the mean phase along the array and the amplitude by no more than 0.4 db. The actual phase and amplitude distributions along the array are shown in figure 4.5-b; these are the values used in equation 4.7.

The measurements were repeated throughout the period of the observations, but the form of the distributions did not change significantly.

4.5-c Results:

Using equation 4.3, the above phase and amplitude information and the data

$$d = 55.36 \text{ cm and } h = 17 \text{ cm,}$$

the forward directivity of this array at 408 MHz is found to be

$$\begin{aligned} D\left(\frac{\pi}{2}, \frac{\pi}{2}\right) &= 79.4 \\ &= 19.0 \text{ db.} \end{aligned}$$

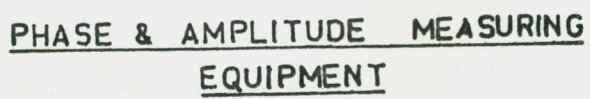
4.5-d Real Array Gain:

It is now necessary to see whether or not the result just derived is a useful estimate of the actual array directivity, remembering that this value is based on the assumptions (i) to (iv) in section 4.5-a.

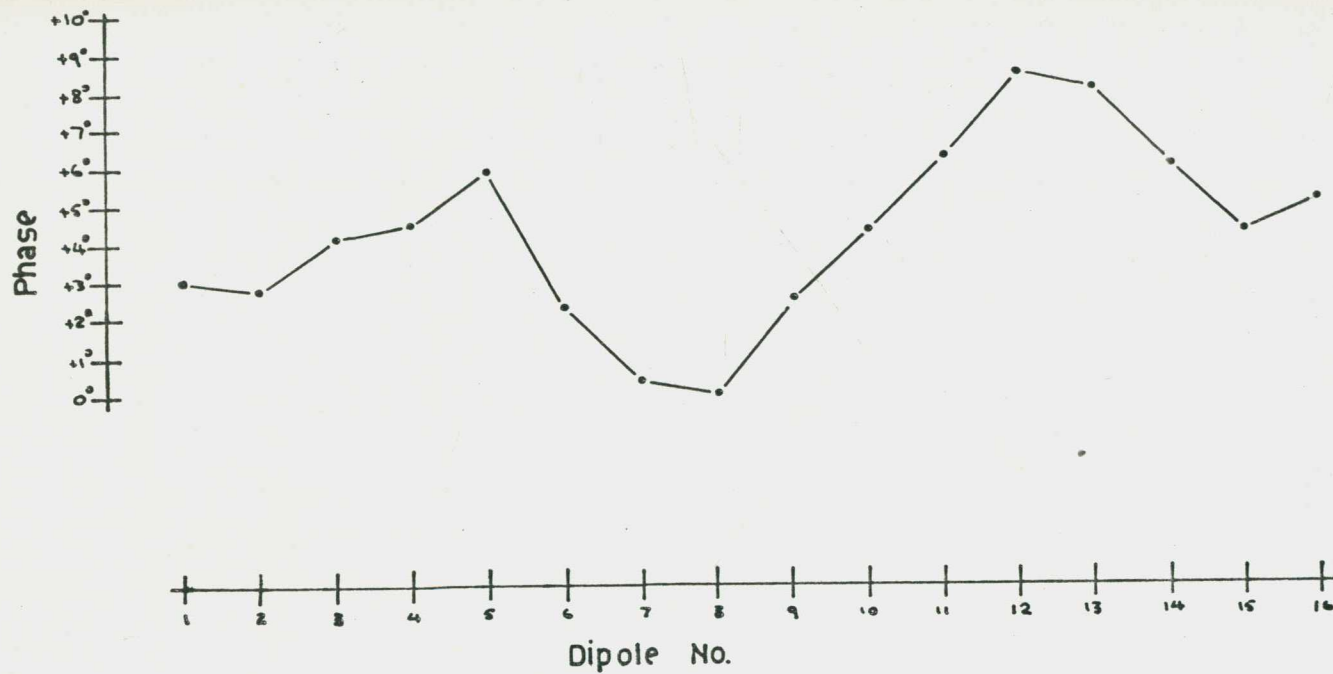
(i) The radiation pattern of an actual array element is not expected to be the same as that for an ideal half-wave dipole: the array dipoles arms are not $\frac{\lambda}{4}$ in length and their diameter, while small, is not infinitesimal. Both these factors together with the proximity effects of the other dipoles in the array, the finite resistance of the dipole arms and spurious effects

FIGURES 4.5-a and 4.5-b.

- a Amplitude and Phase measuring equipment.
- b Plot of the dipole current amplitude and phase distribution along the array.



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PHASE & AMP DISTRIBUTION

FIG. 4.5b

associated with the dipole input region affect the current distribution and hence the radiation pattern of the actual array elements. Fortunately, I am saved from the impossible task of determining the exact radiation pattern by the well known fact, that the directivity of an array, for a range of array element separations, is fairly insensitive to the form of the array element radiation pattern (or to the array element directivity). This is demonstrated below.

The first two factors mentioned above, which affect the radiation pattern, can be accounted for, at least to first order, by making use of an expression given by Schelkunoff and Friis: the radiation pattern of a dipole, with arm length (l), arm diameter (a) and a sinusoidal current distribution is given by

$$B(\theta) = \frac{[\cos(\beta\delta)\cos(\beta l \cos\theta) - \cos\beta(1+\delta) - \sin(\beta\delta)\cos\theta\sin(\beta l \cos\theta)]^2}{\sin^2 \theta}$$

4.8

where $\beta = \frac{2\pi}{\lambda}$ and δ is a function of $(\frac{\lambda}{a})$, given by Schelkunoff and Friis.

In the present case: $l = 6.00''$

$a = 0.094''$

$\delta = 0.64$

The directivity of an individual dipole in free space is 1.618: the gain of the idealized half-wave dipole is 1.64. The corresponding array directivities, with these dipoles as array elements, are given in table 4.1. The corresponding pairs of values are also given for the current element and the non-physical isotropic radiator. Note that the array directivities in this table have been computed for the equiamplitude, equiphase case.

TABLE 4.1.

THE EFFECT OF DIFFERENT ARRAY ELEMENTS ON DIRECTIVITY

ARRAY ELEMENT	ARRAY ELEMENT DIRECTIVITY	ARRAY DIRECTIVITY
Ideal $\frac{\lambda}{2}$ Dipole	1.64	79.8
Dipole (Eqn.4.8)	1.618	79.8
Current Element	1.50	79.5
Isotropic Radiator	1.00	78.4

These figures confirm in part the above statement that the array directivity is not critically dependent on the directivity of the array elements. Of course for large array element separations each element is unaffected by the presence of the others (d of the order of several wavelengths). The expected array directivity would then be the directivity of an individual array element, times the number of array elements. This is

demonstrated in Figure 4.6 which shows the array directivity versus array element separation for elements which are in turn, the ideal half-wave dipole and the current element. For separations less than about 1λ , the array directivities are within several percent, while for separations greater than 2λ each curve converges to a separate directivity value. Using data from the curves in figure 4.7 it can be seen that each curve in figure 4.6 converges to the expected value of 16 times the gain of an individual array element, which in these cases is either a dipole or doublet above a large reflecting screen. The curves in figure 4.6 were computed using the present field integration programme. They differ slightly from curves, based on impedance calculations, given by Kraus (1950).

It is interesting to note that the array element spacing, which gives the maximum array gain, is approximately one wavelength.

The statement above, which is equivalent to saying that for separations less than one wavelength the directivity of the array depends almost completely on the geometry of the array, is not surprising if we consider the factors in the integral in equation 4.3. The integrand is the product of the square of the space-factor, the array element radiation pattern and a term depending only on the geometry of the array (Equation 4.4). The space factor has a finite value for only a small

FIGURE 4.6

Array directivity as a function of array element separation. Curves are provided for both dipoles and current elements.

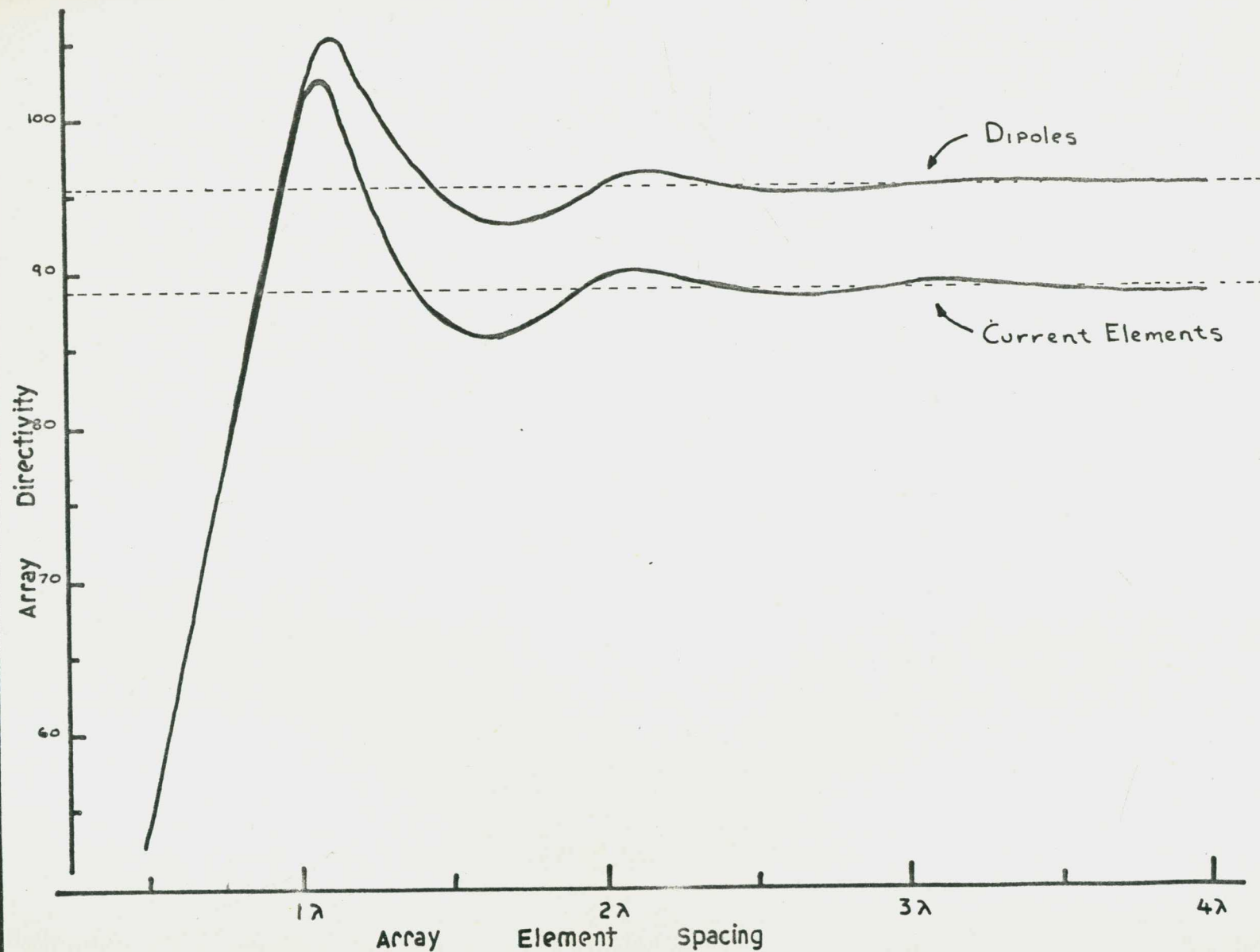


FIG. 4.6

FIGURE 4.7

Array element directivity as a function of height (h/λ). Curves are given for both dipoles and current elements.

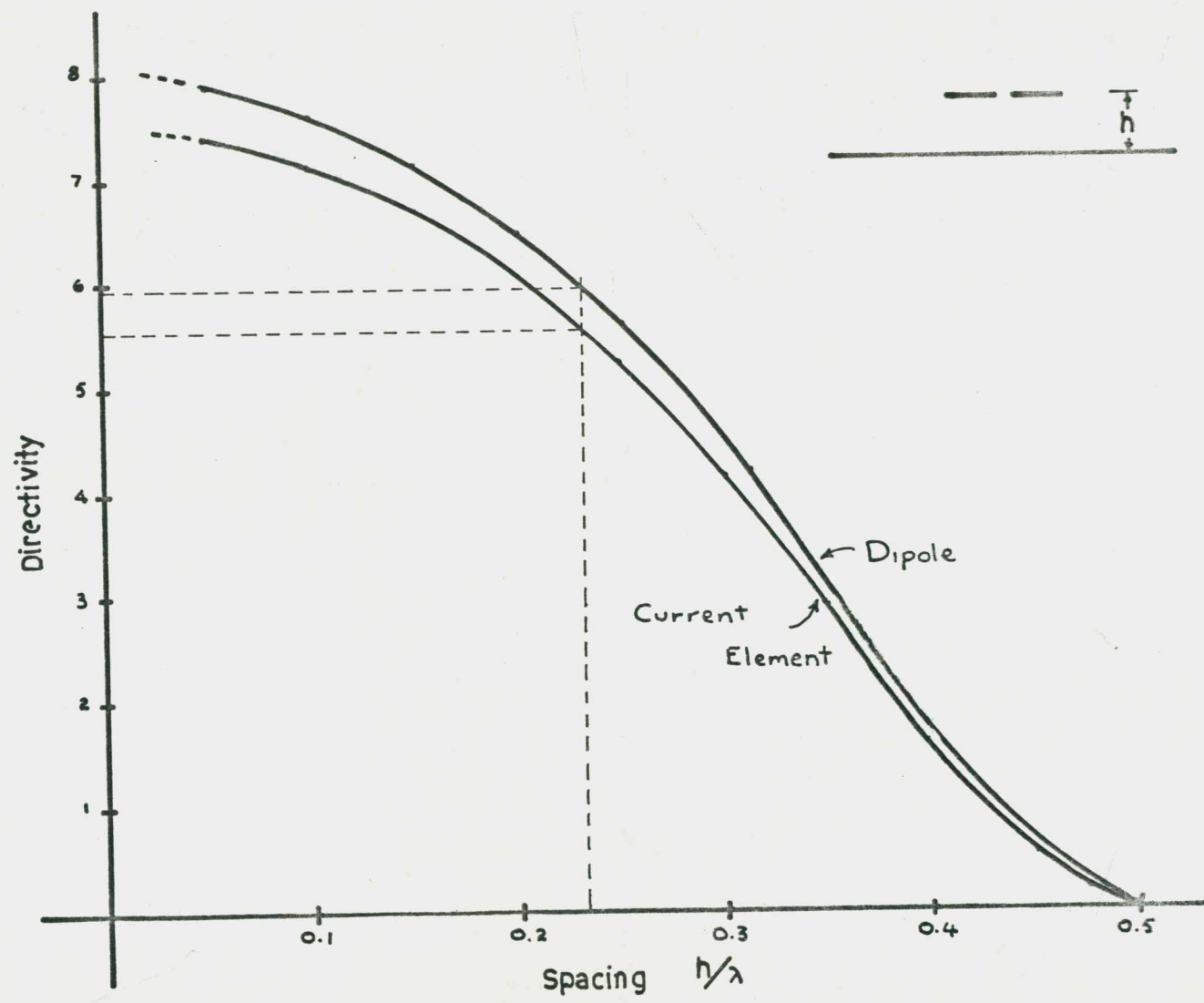


FIG. 4.7

range of θ while $B(\theta)$, for all of the array elements we have considered, is a very broad function of θ . It is possible, to the first approximation, to assume that B is independent of θ . The value of the integral and hence the array directivity is thus independent of the form of $B(\theta)$ i.e. independent of the actual array element directivity.

(ii) Comparison of the directivity value given in table 4.1 for an array of ideal half-wave dipoles, with the result given in section 4.5-c (where the measured phase and amplitude of the dipole's current had been taken into account), shows quite clearly that errors of this magnitude in the phase and amplitude measurements contribute negligible error to the final array gain:

Equi-amplitude and Equi-phase case (Table 4.1)	$D = 79.8$
Actual phase and amplitude distribution (Section 4.5-c)	$D = 79.4$

The errors of measurement are far less than the variations in the relative phase and amplitude down the array, hence the resulting error due to measurement errors will be less than the difference between the above two figures; this difference amounts only to 0.5%.

(iii) Having shown that the array directivity is principally dependent on the geometry of the array it is now necessary to estimate the effect that the errors in the two parameters, h

and d , will have on the accuracy of the array directivity. The spacing between the array elements (d) is defined by holes in the top of the waveguide which have a positional tolerance of ± 0.05 cm.

The dipole height above the reflector (h) was set with a tolerance of about ± 0.2 cm. Figure 4.8 gives an indication of the change in array directivity for systematic changes in d and h . No error is introduced into the directivity due to uncertainties in d while for h , a systematic uncertainty of $\frac{1}{4}$ cm, which is larger than the maximum error in h , produces a percentage change of only 1% in the array directivity. The conclusion is that uncertainties in these parameters are unlikely to produce an error in the array directivity, approaching one percent.

(iv) The radiation pattern of the array was computed on the assumption, that the highly conducting ground plane extended to infinity. The metallic reflector, however, is only of finite extent (Fig. 4.3): it is now necessary to determine what effect this will have on the array radiation pattern used in equation 4.3.

It will be assumed that the actual array ground plane can be approximated by a highly conducting sheet of infinite length but finite width; the end effects of the ground plane are thus being neglected. This is reasonable, since only the

FIGURE 4.8

Array Directivity as a function of array element height (h) and separation (d).

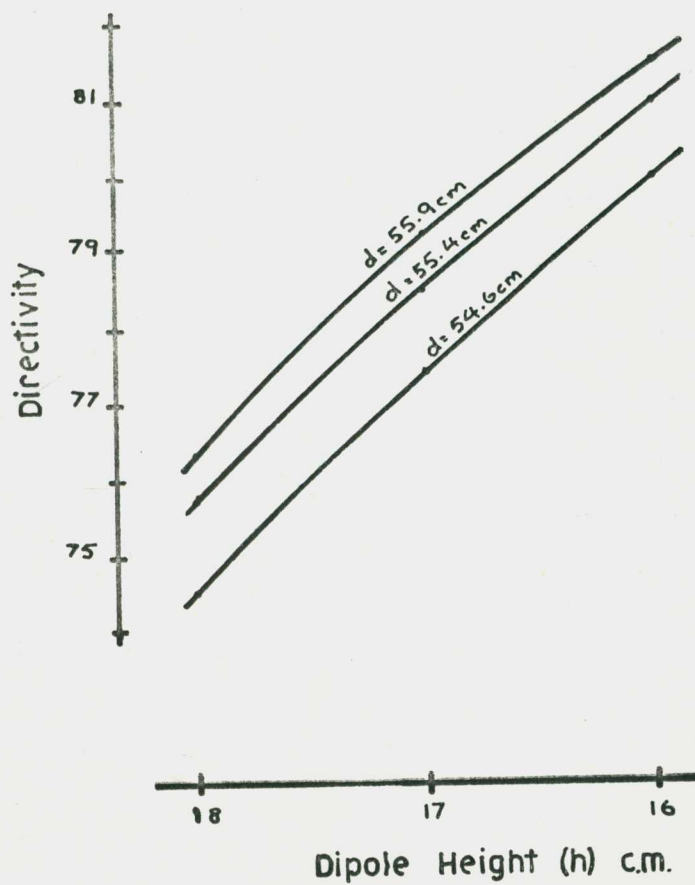


FIG. 4.8

end dipoles in the array would be disturbed by any ground plane end effects; the overall effect on the array is probably quite small. Certainly the finite width of the ground plane is the most important of the two influences. Any affect of this finite width, has double importance, as it affects the forward gain of the array, as well as the shape of the north-south radiation pattern; both these factors are important for the present absolute flux density measurements.

The expression for the radiation pattern of an array with a reflector of finite width but infinite length is simplified if we choose the co-ordinate system in the following manner: the polar angle (θ) is measured from the vertical while ϕ is measured from an axis in the plane of the array (Fig.4.9).

In this new co-ordinate system equation 4.4 becomes,

$$\Phi(\theta, \phi) = \xi(\theta, \phi) \xi^*(\theta, \phi) B(\theta, \phi) H(\theta) H^*(\theta) \quad 4.9$$

where

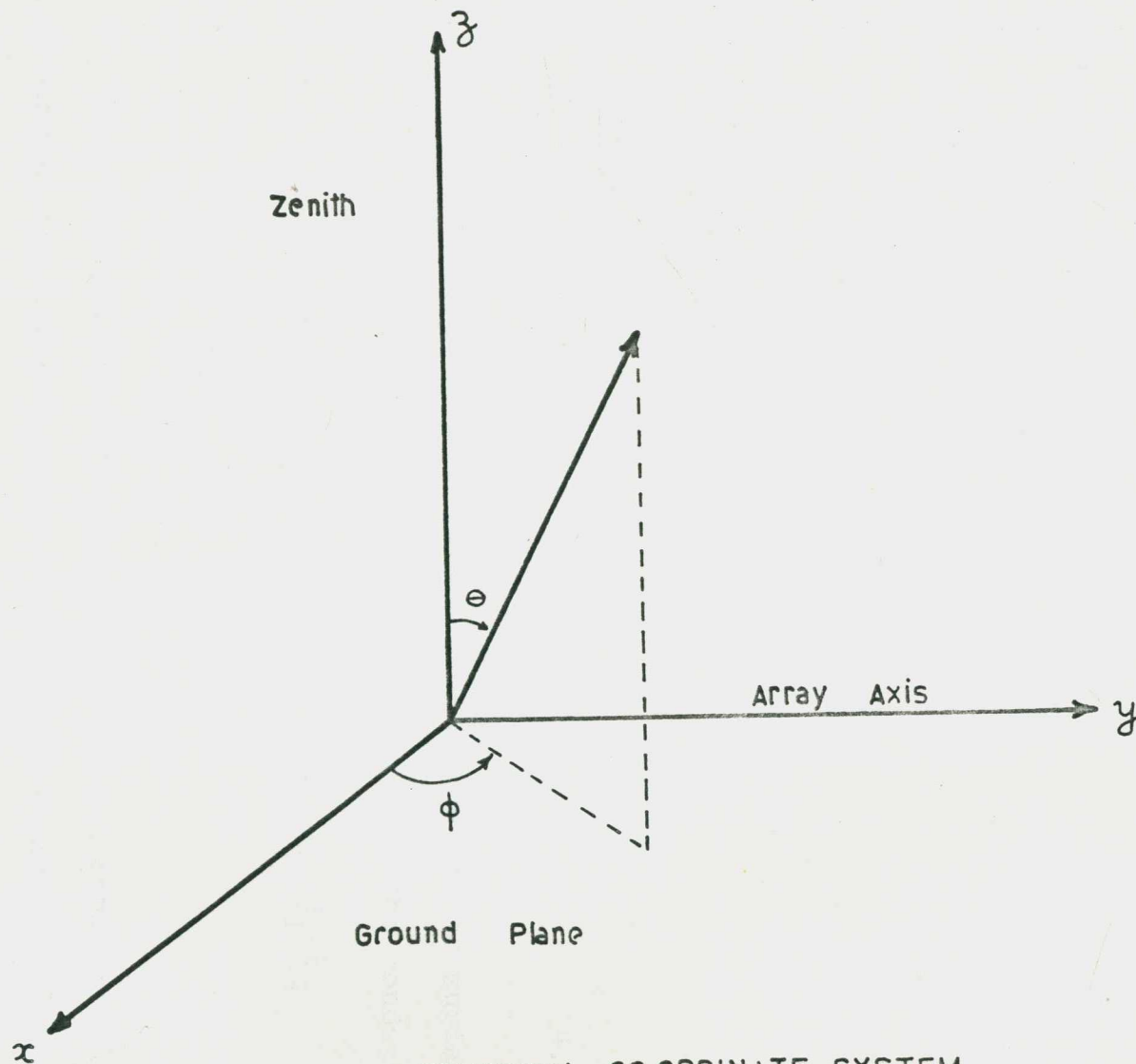
$$H(\theta) = 1 + q \exp(-j\alpha\beta h \cos \theta) \quad 4.10$$

and q is the reflection co-efficient of the ground plane. For a perfectly reflecting ground plane ($q = -1$) we have

$$H(\theta), H^*(\theta) = 4 \sin^2\left(\frac{2\pi}{\lambda} h \cos \theta\right).$$

FIGURE 4.9

The co-ordinate system used in the derivation
of the expression in Equation 4.9.



SPHERICAL CO-ORDINATE SYSTEM

FIG. 4.9

Schelkunoff and Friis give the following expression for q for the case of the E-vector parallel to the ground plane

$$q = -(1 - e^{j\delta} \cos \theta \sin \Delta_c)(1 + e^{j\delta} \cos \theta \sin \Delta_c)^{-1} \quad 4.11$$

Writing

$$q = |q| e^{j\psi} \quad 4.12$$

we find

$$|q| = \frac{[(1 - a^2)^2 + 4a^2 \sin^2 \delta]}{1 + a^2 + 2a \cos \delta},$$

where

$$a = \sin \Delta_c \cos \theta$$

and

$$\psi = \tan^{-1} \frac{2a \sin \delta}{a^2 - 1}. \quad 4.14$$

Δ_c and δ are related to the properties of the ground surface: ϵ_r is the relative dielectric constant and g is the conductivity;

$$\delta = \frac{1}{2} \tan^{-1} \frac{\lambda}{\lambda_c}; \quad \sin \Delta_c = \epsilon_r^{-\frac{1}{2}} [1 + (\frac{\lambda}{\lambda_c})^2]^{-\frac{1}{4}};$$

$$\lambda_c = \frac{\epsilon_r}{60g}.$$

No effort was made to measure the ground constants surrounding the array metallic reflector but rather typical values were used from the table given in Schelkunoff and Friis. Table 4.2 gives the computed values of δ and $\sin \Delta_c$ for ground

constants corresponding to wet and dry soil; these values are used to determine $|q|$ and ψ as functions of the zenith angle θ .

TABLE 4.2.

						$ q $		ψ
	g	ϵ_r	λ_c (m)	δ	$\sin \Delta_c$	$\theta=90^\circ$	$\theta=85^\circ$	
Dry Soil	0.015	10	11	2°	0.316	-1	-0.95	180°
Wet Soil	0.015	30	38	$3'$	0.183	-1	-0.97	180°

The ground plane has a reflection co-efficient of -1 for θ in the range 0° to 85° , the latter value corresponding to the rays reflected from the edge of the metal sheet to the dipoles. For values of θ greater than 85° the reflection co-efficient is given by equation 4.11. We note, however, that $|q|$ is very close to unity for θ in this range, while ψ is approximately equal to 180° . The array effectively has a highly reflecting ground plane that extends to infinity; this is the assumption made when calculating the array gain.

It should be noted that diffraction effects, associated with the boundary between the two ground plane surfaces, have not been taken into account in the present treatment. On the basis of the following argument these effects should be small. The magnitude of the current in a highly conducting ground plane of infinite extent decreases rapidly as the distance from the dipoles increases: Moullin (1949) estimates that

for in-line dipoles,

$$\frac{i}{i_0} = \left(\frac{h}{w}\right)^{3/2} ; \quad h = \frac{\lambda}{4} .$$

Thus at a distance $w = 3\lambda$, corresponding to the edge of the reflector, the current (i) has fallen to a value about 2 percent of the value (i_0) beneath the dipoles. The current distribution in the finite ground plane consequently differs only slightly from that in the infinite plane. The radiation patterns are thus almost identical; any uncertainty is allowed for in the estimated gain accuracy.

4.5-e Array Losses:

In order to determine the array gain we need to know the losses in the ground plane, dipoles and dipole feed system. The noise reference signal is injected at the output of the feed so the rest of the system is common to both reference and radio source noise signals.

The loss in the zinc-coating of the galvanised iron ground (Moullin, 1949) is negligible (less than 0.1%) when compared with the loss in the dipoles.

FitzGerrel (1965) provides a set of curves from which the loss at 408 MHz in aluminium dipoles can be deduced for a range of dipole arm diameters; the radiation efficiency of the present dipoles was estimated to be 0.9995.

The feed loss was measured by an impedance technique (Beatty, 1950). In this technique the dissipative and reflective power losses of the system are measured separately.

For a two port network with terminals 1,2 as the input, the following measurements are made:

1. With the output (therminals 3,4) terminated by a matched load, the network input reflection coefficient is measured; this gives the reflective loss of the system:

$$A_R = -20 \log \Gamma_{in} \text{ db.}$$

2. A shorted length of transmission line of variable length is attached to terminals 1,2 and the reflection coefficient at terminals 3,4 measured as a function of the short position. The characteristic impedance of the line across which the short is placed is made equal to the input impedance of the network. The reflection coefficient varies since the phase of the signal reflected from the short varies with respect to the phase of other reflections in the network. The maximum and minimum values of the reflection coefficients are measured and the dissipative loss is related to these measurements by

$$A_D = -10 \log \frac{|\Gamma_{max}| - |\Gamma_{min}|}{2} \text{ db.}$$

The match at output of the array (viewed now as a receiving antenna) is about 30 db, which is equivalent to the match at the array input (dipoles) since the dissipative loss is small. The reflective power loss is thus about 0.1% of the input power.

The dissipative loss is measured by passing a C.W. signal through a reflectometer into the feed at its output with shorting bars inserted into the dipole tube (Fig.4.2-b). It was possible to move these bars over the length of the tube slot: this is equivalent to swinging the phase of the reflected signal through about 180° . The total loss in the feed was found to be 0.2 ± 0.1 db.

One of the principal uncertainties in this measurement arises from the effectiveness of the short in the dipole tube. Any leakage past the short or through the slot in the dipole tube will increase the measured loss; consequently, the measured value is likely to be an upper limit on the actual loss.

4.5-f Results:

The value of the array gain computed from the directivity and the total array loss is given in table 4.3, together with the array effective area.

TABLE 4.3
ARRAY PARAMETER.

Directivity	79.4
Loss	(Ground Plane (Dipoles (Feed
	0.2 db
Forward Gain	75.8
Effective Area	3.26 square metres.

As explained earlier the array gain needs to be known for a range of zenith angles (i.e. $\pm 40^\circ$) in the meridian plane. The form of the radiation pattern in this plane is given by equation 4.4.

4.6 LARGE AERIALS:

The east-west arm of the cross at the Molonglo Radio Observatory, divided into the eastern and western halves for Method I or in full for Method II, provided the large aerial(s) used in the present absolute flux density measurements. The arm is described in detail in Mills et al. (1963), however, a brief description will be given here.

The aerial is in the form of a cylindrical parabola with a length of 2120λ and a width of 15λ . There are 176 feed modules, connected together in "bays of eight", positioned along the focus of the arm; each bay has its own mixer and

first intermediate frequency pre-amplifier (11.05 MHz).

Twenty two half mile lengths of co-axial cable bring the signals from the pre-amplifiers to a hut situated near the centre of the arm, where, after a second frequency conversion to 5.5 MHz, they are combined to produce the total arm output. The E-W aerial produces a fan beam ($1'.5' \times 4^\circ$) which can move in a N-S plane to cover the declination range $+19^\circ$ to -90° .

The eastern and western halves of the arm are separated mechanically by the continuous N-S arm of the cross. The signals from each half arm can be obtained separately at the second intermediate frequency.

4.7 AERIAL POINTING:

It is necessary to ensure that the fan beam of the reference aerial lies in the plane containing the east-west arm fan beam and that the direction of maximum gain of the array coincides with the site zenith.

The array could be moved so that it was parallel to the E-W axis of the east-west arm. The ground plane was levelled in the N-S direction and the whole array tilted in the east-west direction to match the slope on the east-west arm (Sutton, 1967). The array E-W tilt was adjusted after simultaneous total power observations were made on the sun with the reference and east-west aerals.

The uncertainty in the final flux density values due to pointing errors was expected to be less than 1%, with the

pointing adjusted in the above manner.

4.8 THE RECEIVERS:

The receiving systems for the two methods of observation are shown in Figure 4.10-a and Figure 4.10-b. Only Figure 4.10-b contains the details of the front end of the receiver, since the equipment shown above the broken line in this figure is common to both methods.

Each bay of feed modules, in the east-west arm, is connected to a crystal mixer by 120 ft. of low loss r.f. cable; the array is connected to its crystal mixer in an identical manner. The 11.05 MHz first i.f., after amplification, passes through half-mile lengths of co-axial cable to the second frequency converters in the hut near the centre of the east-west arm. All of the signal paths to this point were made identical to ensure phase stability in the interferometers used in each method. The twenty-two east-west second frequency converters differed from the array converter in that they were tuned and therefore introduced time delay into the east-west signal paths. This, and some other decorrelation effects are discussed later in this section. The array second converter had four outputs in phase quadrature: only the 0° and 90° outputs, which were adjusted to be of equal amplitude, were used; the other two were terminated with matched loads. These converters are used in the beam forming networks of the north-south arm of the Molonglo Cross (Large and Frater, in preparation).

The equi-phase signals from the east-west converters are combined to form two half-arm outputs for Method I or further combined to form the whole arm output for Method II.

Directly following the i.f. pre-amplifier in the array signal path is the phase switch. It is positioned here so that interference at the first and second i.f. does not produce a correlated output, when the various aerials are combined in interferometer pairs: trouble from this cause arose when the phase switch was positioned at the other end of the half-mile long i.f. cable.

4.8-a Method I:

The signals from the three aerials (Fig.4.10-a) are combined in pairs, with arbitrary phase differences θ_i and $\theta_i + \frac{\pi}{2}$, at the second i.f. of 5.5 MHz, providing two quadrature outputs for each interferometer pair. For the east-west interferometer the quadrature components are produced by inserting an extra quarter-wavelength of cable into the indicated hybrid output (Fig. 4.10-a). This extra length of cable results in a reduction in amplitude of this interferometer component due to decorrelation and attenuation; a correction factor was applied to the resulting signal deflection. Another correction factor must be applied to account for the insertion loss in the phase switch shown in Fig. 4.10-a. The remainder of the circuit is completely symmetric; the small insertion loss in the ferrite ~~trans~~former hybrids can thus be ignored.

FIGURES 4.10-a and 4.10-b

The receiving system for Method I (Figure 4.10-a) and Method II (Figure 4.10-b).

N, noise generator; M, crystal mixer, P.A., pre-amplifier; P.S., phase switch; C, second converter; P, power switch; H, ferrite transformer hybrid; T, total power detector; D, detector; S, synchronous demodulator; C.R., chart recorder; A, analogue to digital converter; T.R., tape recorder; O, square wave oscillator.

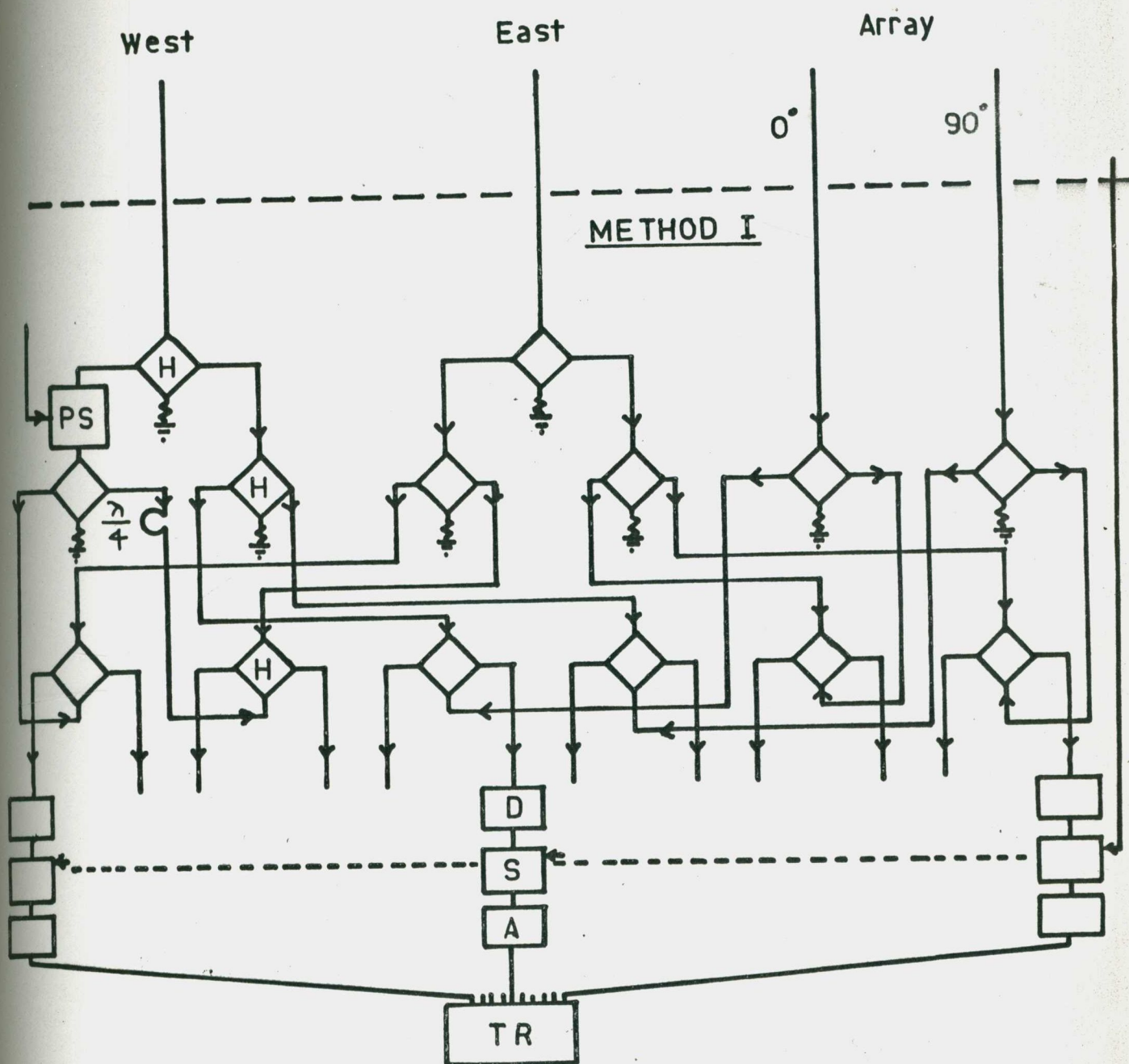


FIG. 4.10a

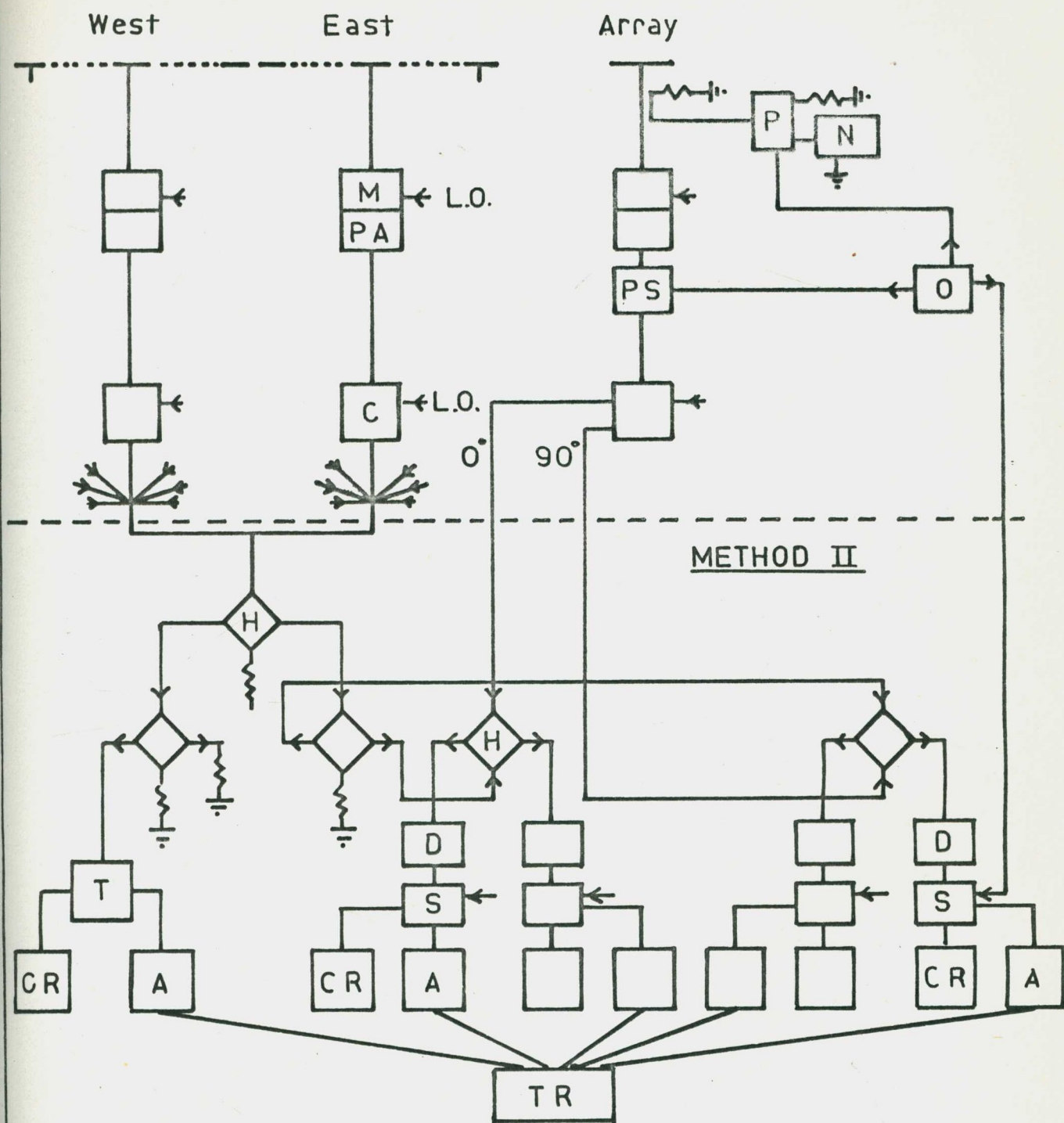


FIG. 4.10b

The resulting six pairs of signals are recorded on magnetic tape after detection in a standard receiver, comprising a 5.5 MHz detector, synchronous demodulator and analogue to digital converters. The pairs of records from one hybrid are combined using the digital data. If the noise powers are adjusted to be the same at the inputs to any hybrid in the last row in Figure 4.10-a, it can be shown that the noise signals at the two outputs of the hybrid are uncorrelated; the outputs thus constitute two independent records (Scott et al., 1961).

The unmarked boxes in Figs. 4.10 are identical circuit elements to those on the same horizontal line.

The time constant on the synchronous demodulator output is approximately 1 sec, while the analogue to digital converters have a signal integration period of 3 sec.

4.8-b Method II

Figure 4.10-b shows the complete receiving system for Method II. The east-west signal is divided in transformer hybrids to produce three equi-amplitude signals: one feeds a total power detector while the other two are combined with the array signal components. Both the total power and switch frequency signals, after detection, are recorded on magnetic tape and paper chart. The interferometer records are treated in a similar manner to those of Method I.

4.8-c Delay Cable:

In an interferometer, decorrelation of the signals result because of differing delay times in the pair of signal paths. The noise signals, while phased at the centre frequency of the operating bandwidth, will have a progressive phasing error towards the edges of this band, if the delay times differ. For a rectangular band pass the following expression relates the phase difference at the edges of the frequency band to the reduction in amplitude:

$$\frac{D}{D_0} = \frac{\sin \theta_0}{\theta_0} .$$

D_0 is output deflection with equal delay paths and

$$\theta_0 = \frac{2\pi}{c} [d \sin \theta + (\ell_1 - \ell_2)] \frac{B}{2} .$$

d is the interferometer element spacing; ℓ_1, ℓ_2 are the air path lengths, equivalent to the cable lengths from each aerial to the signal addition point; θ is the source zenith angle (in the east-west plane).

The signal delay times in the signal path comprising the east-west arm and the array were equalised using a procedure employing the equipment shown in Fig.4.11. Noise power from a high power source is split in a hybrid and fed into a directional coupler at the output to the array and into a point within a bay of feed modules in the east-west arm.

(The 22 bays comprising the east-west arm have been adjusted to have identical delay characteristics). Cable was removed from or inserted into the array i.f. at the section A.A.. After maximising the output, using the phase shifter in the array converter's second L.O., the curve in Figure 4.12 was produced. Small corrections were needed to the measured amplitude to compensate for the increased attenuation in the array signal path when the extra cable was inserted. The east-west and array signal paths were equalised by this means for sources in the site zenith. For observations away from the zenith, lengths of cable were inserted into, or removed from, the array 1st i.f. signal path; the length required being determined from the geometry of the aerials.

4.9 REFERENCE SIGNAL.

The reference noise source consists of a diode noise generator, the output of which can be 100% modulated by an r.f. power switch. The switched output is fed into the array signal path through a directional coupler (Fig. 4.10-b).

The diode noise generator comprises a type CV 2398 G.E.C. diode attached to a length of 50 ohm strip line (Fig. 4.13). A 50 ohm termination, which is capacity coupled to the strip line, provides the anode load for the diode r.f. current. The noise output is capacity coupled off the strip line. This output is matched to about 30 db; the source has a bandwidth of approximately 100 MHz.

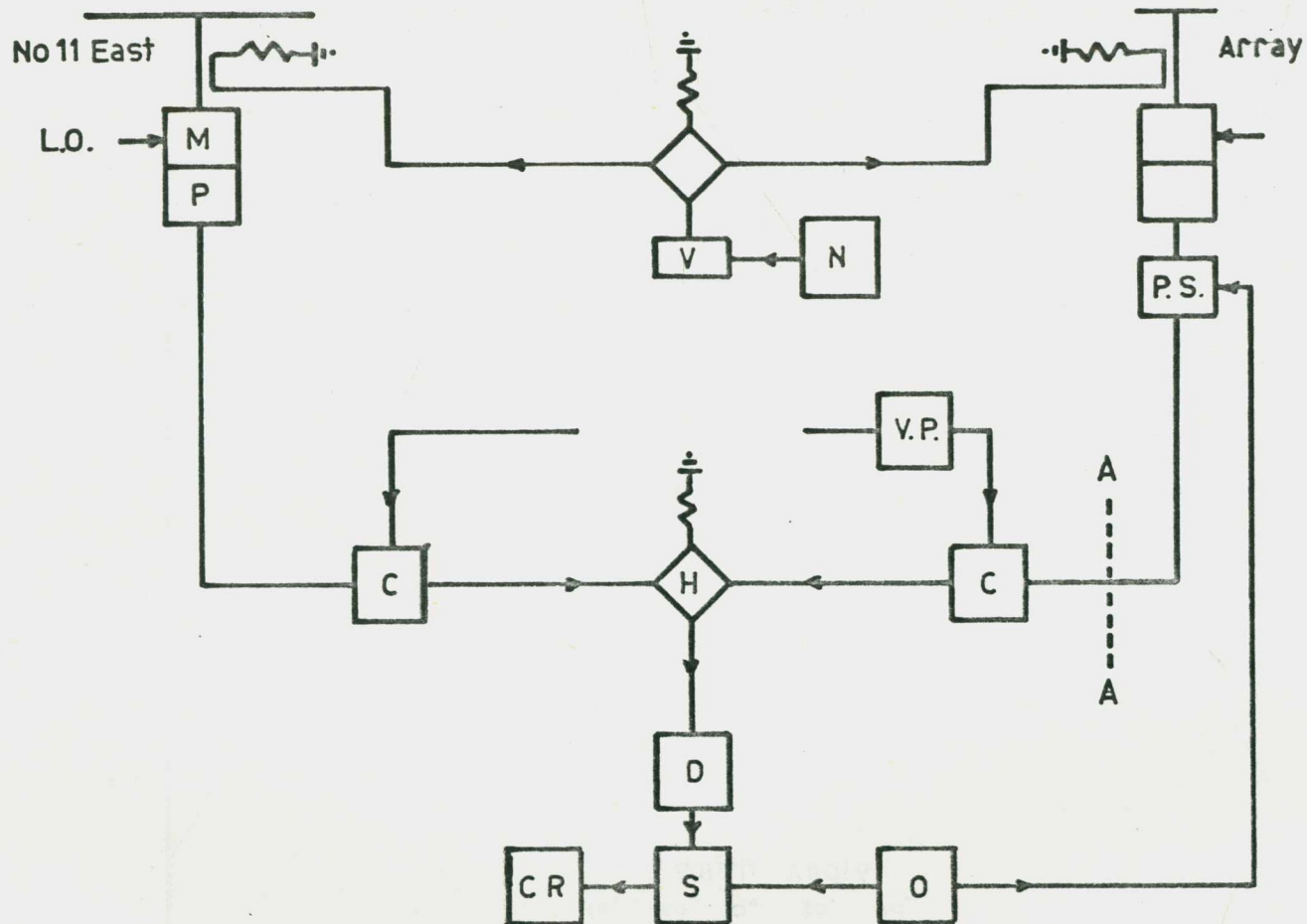
FIGURE 4.11

The delay measuring equipment. Lengths of cable were inserted into the array 1st i.f. and the output maximised by varying the phase of the array 2nd L.O.

M, mixer; P, pre-amplifier; P.S., phase switch; V, variable attenuator; N, noise source; C, second converter; H, hybrid; V.P., variable phase shifter; D, detector; S, synchronous demodulator; O, square-wave oscillator; C.R., chart recorder.

FIGURE 4.12

The receiver output (amplitude) as a function of cable length inserted at the section A-A; the origin is arbitrary. The propagation constant of the cable is 0.8. Cable lengths required for the observation of sources with a range of zenith angles are also shown.



Delay Measuring Equipment

FIG. 4.11

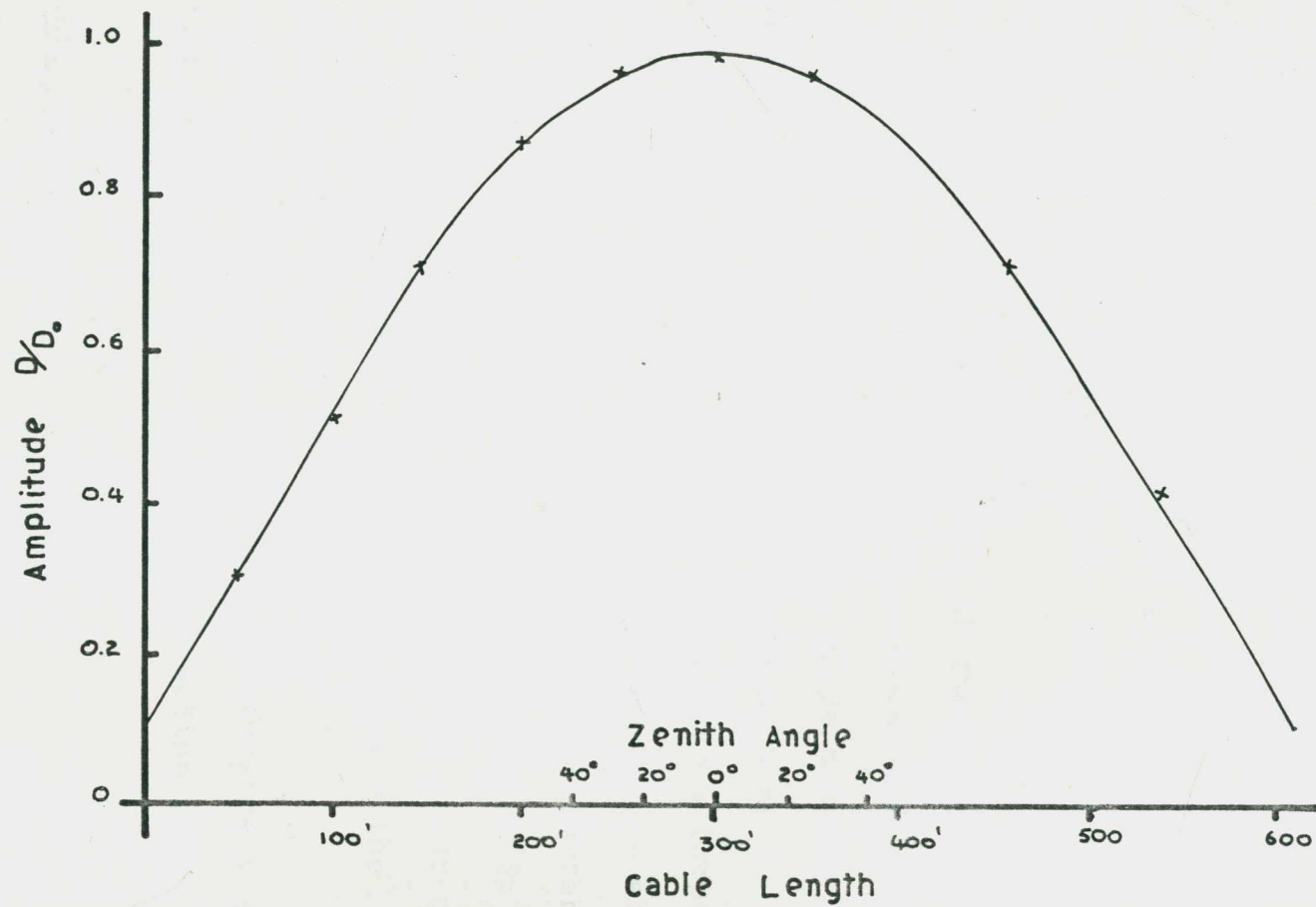


FIG. 4.12

The noise power output over a particular frequency interval could not be related to the D.C. anode current, since the diode load resistance through which the r.f. current flowed, could not be determined even approximately. It is therefore necessary to calibrate the noise output using thermal noise standards; in the present case the noise from resistors and precision attenuators.

In order to ensure the stability of the noise power output the diode mount must be rigid, the anode load impedance stable and the direct current through the diode must be constant. The mechanical construction of the source is such as to satisfy the first condition, while the 50Ω anode load has a temperature coefficient of better than 1 part in 10^4 . Figure 4.14 shows the circuit which supplies and regulates the anode current. It provides a current stability of better than 1 part in 4,000 per $^{\circ}\text{C}$ over the temperature range 0° to 30° . The power output stability of the noise source should exceed $\frac{1}{2}\%$ over the operating temperature range of the equipment.

The power switch incorporated in the reference signal equipment had matched inputs and a power rejection ratio of 28 db.

4.10 THERMAL CALIBRATION:

4.10-a Equipment:

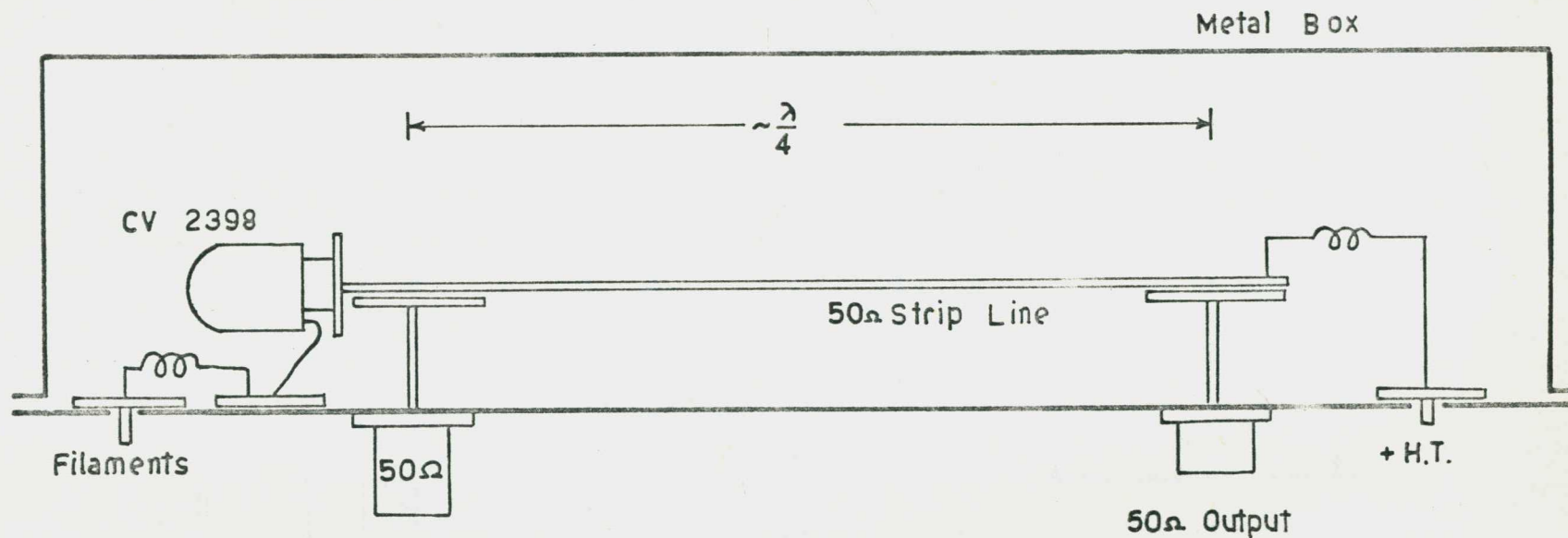
The diode noise power available at the output of the directional coupler, with the aerial port terminated by a matched load, was calibrated by a thermal method using high precision

FIGURE 4.13

The diode noise source.

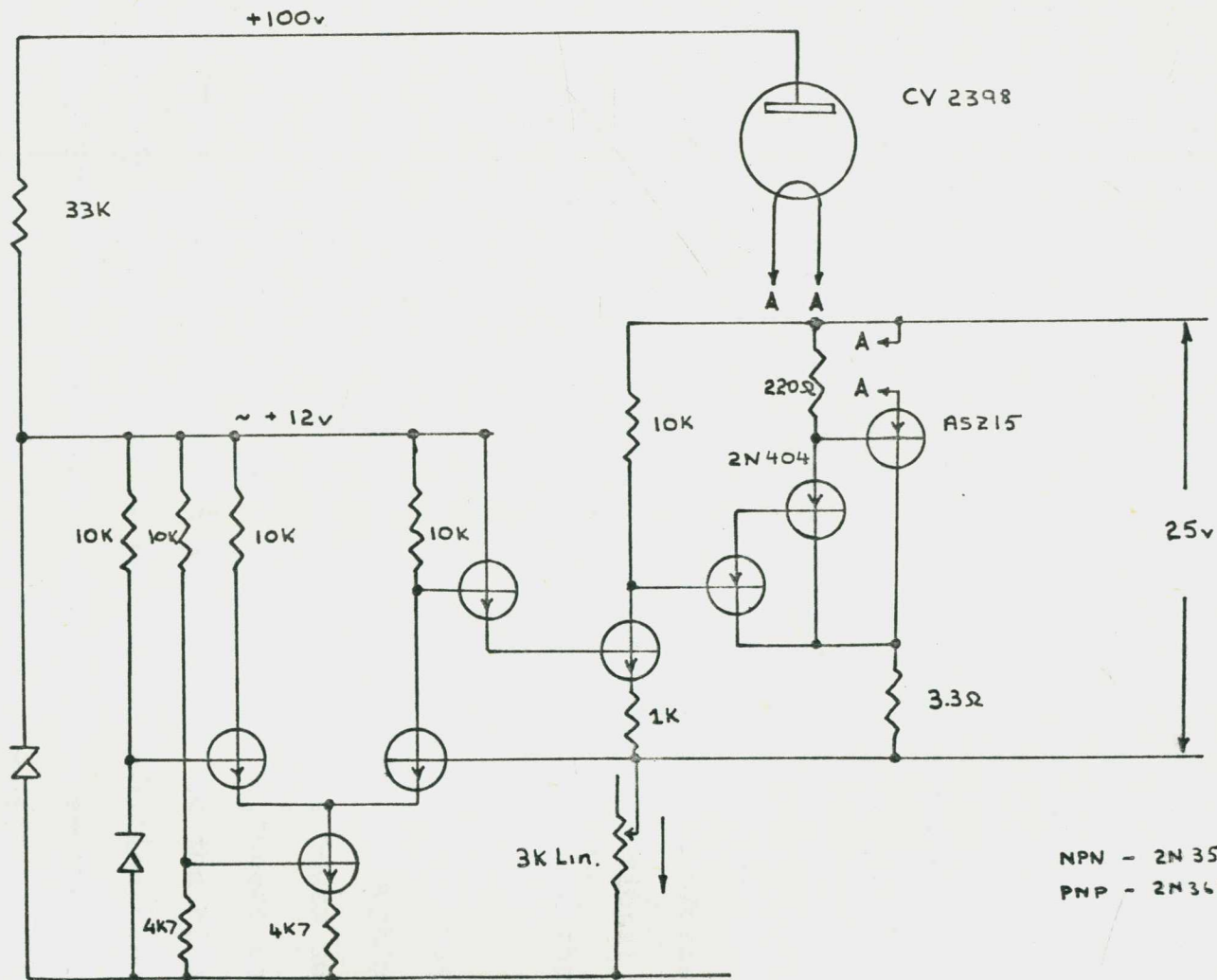
FIGURE 4.14

The circuit diagram of the noise diode filament control circuit. The anode current is stable to 1 part in 4000/ $^{\circ}\text{C}$ for D.C. currents in the range 0 to 60 m.a.



DIODE NOISE SOURCE

FIG. 4.13



NPN - 2N3545
PNP - 2N3638

DIODE POWER SUPPLY

FIG. 4.14

attenuators and matched loads at the boiling point temperature of pure liquid nitrogen.

The experimental arrangement is shown in the block diagram in Figure 4.15 and is based on a system used by Pauliny-Toth and Shakeshaft (1962). The thermal loads (Wielebinski, 1967) comprise a metal film resistor in a high precision mount connected to a type N connector by a half-wavelength of rigid copper co-axial cable with a solid dielectric. With the resistor mount immersed in the liquid nitrogen, the input match was 30 db for the standard load and slightly less for the other cold loads in Fig. 4.15. Either a precision matched attenuator or the reference source directional coupler is inserted between the points A A when calibrating the reference noise signal.

The output of the switch (Fig.4.15) could be matched by injecting noise from a modulated noise source through a reflectometer into the power switch. With the power switch biased into either of its positions, the stub tuners can be adjusted so that the impedance at the input to the circulator is constant and independent of the switch position throughout the experiment. The circulator reduces further the effects of impedance variations at the input to the crystal mixer. Changes in impedance can result in gain and noise figure variations. These variations produce level changes on the output recorder,

severely compromising the accuracy of the calibration result; uncertainties in the present experiment due to this cause should be negligible. Variations in the impedance at the output of the power switch can produce level changes from another cause: The thermal noise generated in the circulator load is in part reflected into the receiver. The matching procedure is adequate to maintain this reflected power constant to within 0.1°K .

The zero level is defined when the attenuation between the points A A is zero; the noise power into both sides of the switch is then almost the same.

The noise at the output of the circulator passes through a crystal mixer and i.f. amplifier to a standard switch frequency detector, the output appearing on a paper chart recorder.

The linearity of the receiver was checked; no corrections were necessary to the measured chart deflections.

4.10-b Theory:

If a matched attenuator α is inserted between A-A and the system matched as above, the deflection from the zero level is proportional to

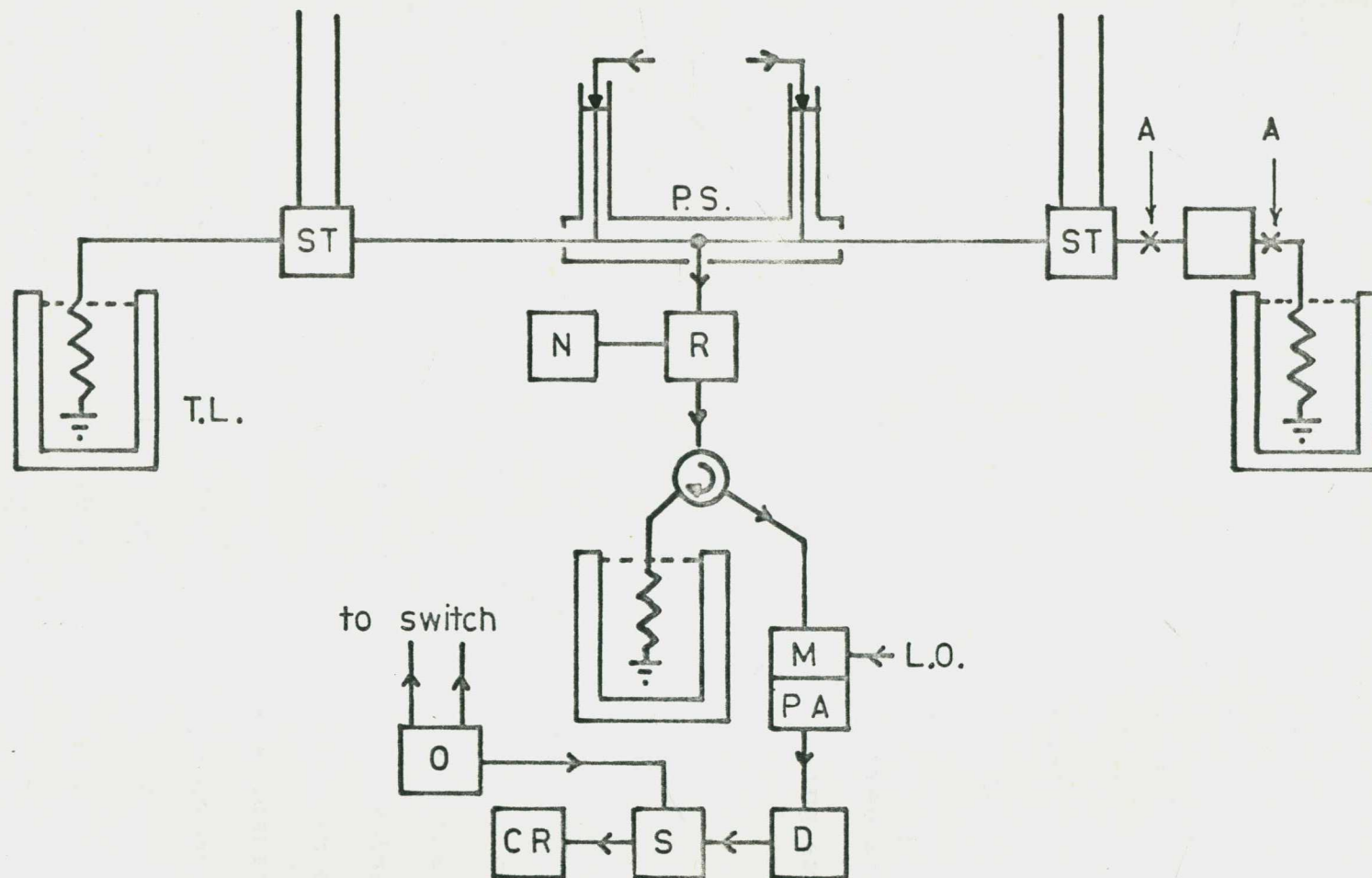
$$(1-\alpha)(T_0-T_N)^{\circ}\text{K}, \quad 4.15$$

where T_0 is the temperature of the attenuator and T_N is the noise temperature at the input to the attenuator.

FIGURE 4.15

Equipment for thermal calibration of the noise signal injected into the reference aerial signal path. Either attenuators or the directional coupler are inserted between points AA.

S.T., stub tuners; R, reflectometer; N, noise generator; M, crystal mixer; P.A. pre-amplifier; D, detector; S, synchronous demodulator; C.R., chart recorder; O, square wave oscillator; T.L., matched load immersed in liquid nitrogen; P.S., power switch; L.O., local oscillator.



THERMAL CALIBRATION EQUIPMENT

FIG. 4.15

If the receiver and recorder have a linear response, this procedure calibrates the chart recorder deflections in $^{\circ}\text{K}$. The on-off deflection obtained when the reference signal directional coupler is inserted between A A, can then be calibrated in temperature units.

T_N was determined from the temperature of the pure boiling nitrogen (T_N'), for the local barometric conditions, and from the measured loss (L) in the cable connecting the load to the attenuator, the loss being measured with the cable immersed in the liquid nitrogen. The following expression can be written for T_N (e.g. Siegman, 1961):

$$T_N = \frac{T_N' + \int_0^L 2\alpha(x)T_x(x)\exp\left[\int 2\alpha(x)dx\right] dx}{L} \quad 4.16$$

where $T_x(x)$ is the temperature and $\alpha(x)$ the attenuation coefficient for a point in the transmission line connecting the load and attenuator α ; x is measured from the load.

In principle, therefore, we need to know the temperature and loss variations down the transmission line to compute T_N . Fortunately, fairly crude estimates of these quantities are adequate since the receiver calibration depends only on the difference $T_0 - T_N$: $T_0 \sim 300^{\circ}\text{K}$ and $T_N \sim 80^{\circ}\text{K}$. Estimates were made of the temperature and loss variations along the cable. One of the methods based on approximate solutions of equation 4.16 by Stelzied (1965), were used to calculate the additional

noise generated in the dissipative losses in the cable connecting the attenuator to the cold load.

4.10-c Results:

T_N was estimated using approximate solutions of 4.16:

$$T_N = 79.5 \pm 1.5^\circ \text{K}.$$

Direct measurements of T_N were made in the School of Electrical Engineering, University of Sydney. (Wielebinski, private communication). The matched load was heated over a known temperature range near ambient temperature in order to calibrate the receiver output and the temperature with the load immersed in liquid nitrogen determined directly. A value of 80°K was obtained. This confirms the calculated value to the quoted accuracy.

The attenuation α was provided by commercial Weinschel Model 50 attenuators in the range 1 to 10 db. The attenuation assigned was that given in the calibration chart supplied with each attenuator; the quoted accuracy being ± 0.1 db. During the course of the absolute flux density measurements the attenuators were recalibrated in the School of Electrical Engineering and found to be within the quoted errors (Wielebinski, private communication).

An estimate of the reference source temperature was obtained for each value of α and a mean taken. The reference source was modified through the observations and the two mean

temperature values are:

January/April $T = 142 \pm 3.7^{\circ}\text{K}.$

September $T = 97 \pm 2^{\circ}\text{K}.$

The quoted errors in T are a combination of the following errors:

- (1) The variation in the measured value of T using different attenuators.
- (2) The uncertainty in T_N
- (3) The uncertainty in T_0
- (4) The errors arising from undetected impedance effects.

The impedance effects in (4) arise because of the small but finite impedance differences between the matched load, the attenuators and the directional coupler. These mismatches can lead to variations in the power transferred to the receiver i.e. variations from the ideal case.

The voltage standing wave ratios at the inputs to the above three circuit elements are all 1.1 or better; several attenuations have values of 1.02. In this experiment these impedances effects produce uncertainties of about 1%. The errors arising in (1) to (4) above are discussed fully in Chapter 5.

4.11 CALIBRATION FACTORS:

The calibration factors n_{iS} , n_{iC} (Equations 3.9 and 3.17), which are the relative gain factors of the equipment from the hybrid outputs to the recording devices, are determined by inserting the cables connecting the detectors to the hybrids (Figures 4.10-a and 4.10-b) into a modulated noise power source. This source was provided with a number of equi-amplitude outputs with identical output impedances. Measurements of these factors were carried out at each source observation. Detector 1S was used as the reference channel.

CHAPTER 5

RESULTS

5.1 INTRODUCTION:

Absolute flux density measurements were made at 408 MHz on the five sources PKS 0408-65, PKS 1932-46, PKS 0521-36, MSH 06-04 and 3C273, using the methods outlined in Chapter 3. These five sources are the most intense small diameter (small relative to the smallest dimension of the east-west fan beam) sources observable with the Molonglo Radio Telescope. Their flux densities are, however, several orders of magnitude less than that of Cassiopeia A at the same frequency.

Observations were made in two periods, January/April and September of 1967, preliminary measurements having been made in June and November of 1966. Method I was used in the September and Method II in the January/April observing periods. The temperature calibration equipment was modified and recalibrated before the second observing period. The only part of the system identical in the two periods was the reference aerial.

The signal to noise ratio obtainable on a single record of any of the five sources employing the reference aerial was not good ($\sim 8:1$) so that a number of observations were made on each source and the results for each combined in order to improve the overall accuracy of the flux density scale. Since the observations were made with a transit instrument the

observing period was necessarily quite extended.

The present 408 MHz flux density scale is based both on the absolute flux density measurements and on flux density ratios determined by relative measurements. The scale flux densities for the five primary calibration sources satisfy these flux density ratios; the mean of the ratios of the scale and measured flux densities is unity.

5.2 OBSERVATIONAL ANALYSIS AND PROCEDURE:

5.2-a Method I:

Before any of the five sources were observed the following operations were carried out:

(1) The gain of the quadrature array signal channels (Fig.4.10-a) were adjusted to be identical.

(2) The delay paths in the pairs of aeriels were equalized by altering the total cable length in the array i.f. signal path. (Section 4.8-c).

(3) Measurements of the relative gains n_{iS} , n_{iC} , were made. These factors remained constant over long periods of time since all of the equipment concerned was in a temperature controlled environment.

The data from each radio source observation were recorded in digital form on magnetic tape and in analogue form on a multichannel facsimile recorder. The output of detector 1S is calibrated by the reference noise source before and after

each source transit. The calibration of the remaining channels is carried out using the values, n_{iS} and n_{iC} . The system gain remained constant (better than 1%) over the whole time taken to observe a source; in general this took about 5 minutes.

A print-out of the numbers on the magnetic tape is obtained and the zero level in the vicinity of each source accurately determined by manually averaging the zero level numbers. The signal channel outputs are then normalized using the appropriate n_{iS} , n_{iC} (determined from the digital print-out) and the two independent records from each of the three aerial configurations combined (Scott et al., 1961). These operations are carried out on numbers corresponding to times when the particular radio source was known to be in the aerial beam; generally about 15 to 25 samples depending on the source declination. Figure 5.1-a shows a typical plot of numbers for the aerial configuration, east versus reference array, for the source 06-04; the quadrature components as well as $(D_i^2)^{\frac{1}{2}}$ are shown.

Theoretical beam shapes were fitted to the array of points D_i^2 using a method given by Large and Murdoch (1967). Shown in Figure 5.1-b are the theoretically computed E-W response patterns corresponding to the spacing used in the interferometer, comprising half the east-west arm and the

FIGURES 5.1-a and 5.1-b

-a Plot of numbers derived from the digital print-out for observations made using Method I. A sample point is obtained every 3 sec; this is the integration time of the analogue to digital converters. The numbers shown were obtained from an observation of 06-04 using the eastern aerial and the reference array. The normalized sine (D_{iS}/n_{iS}) and cosine (D_{iC}/n_{iC}) components as well as the square-root of the sum of their squares are shown ($[D_i^2]^{\frac{1}{2}}$).

-b Plot of theoretically derived points for an interferometer comprising the eastern aerial and the array. The sine and cosine components correspond to the case, $\theta = 0$.

Method I

06-04

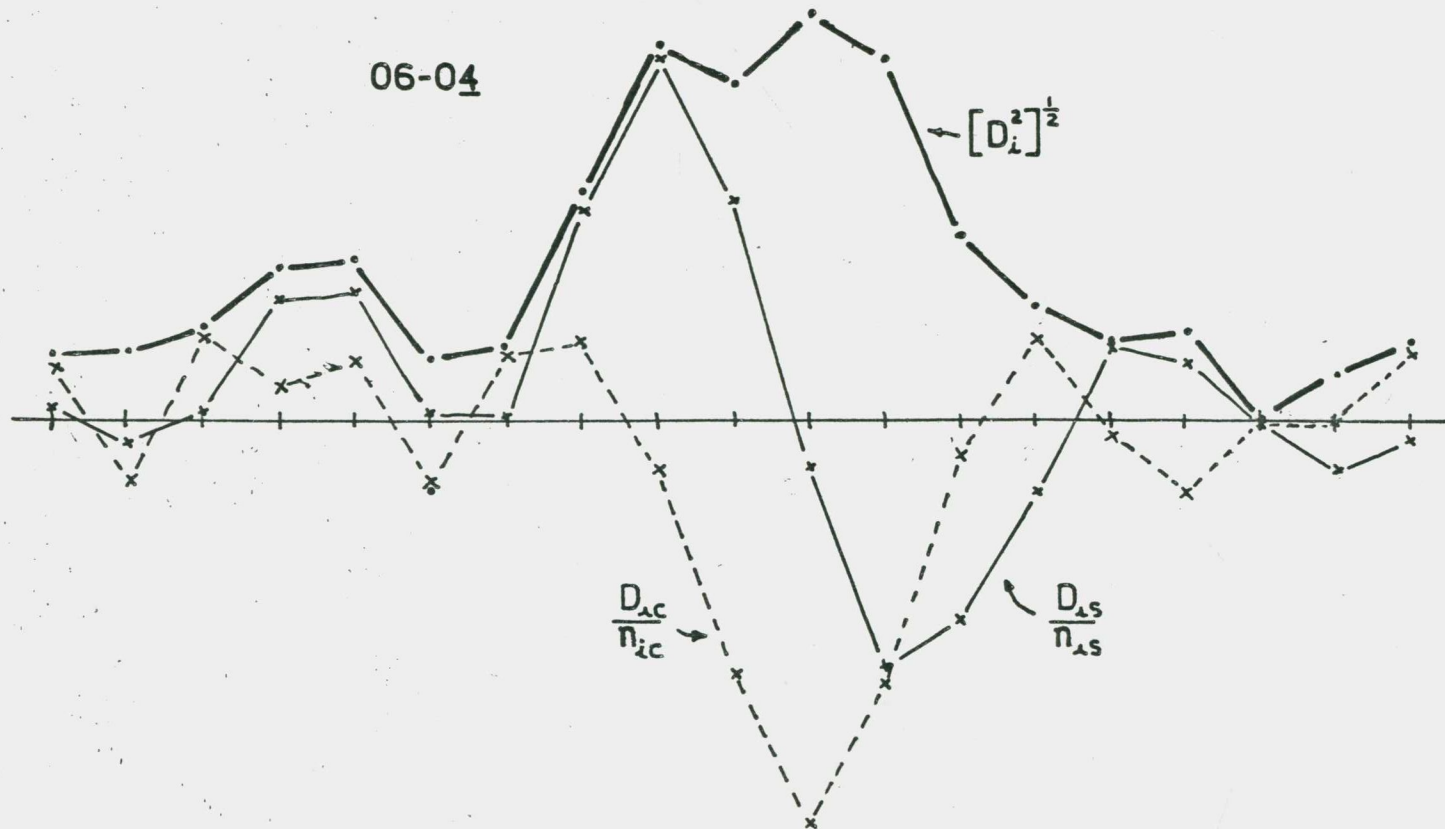


FIG. 5.1a

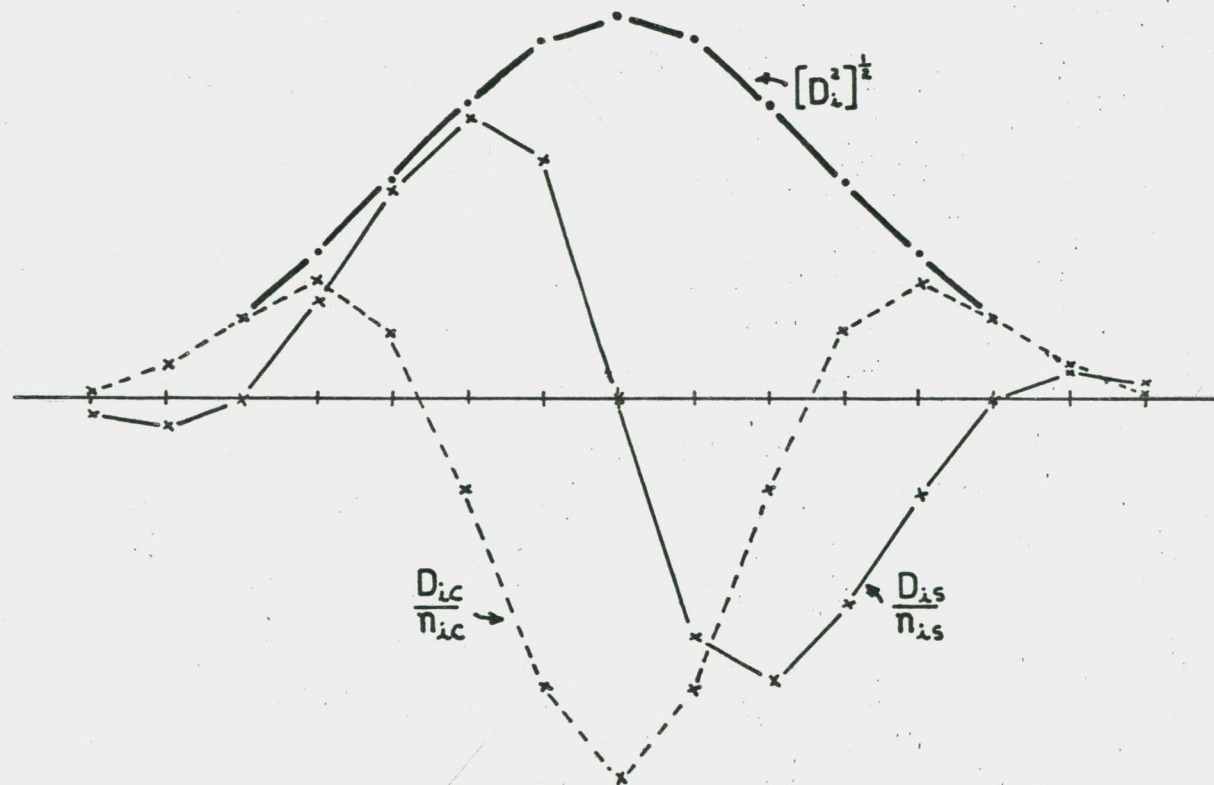


FIG. 5.1b

reference array. In this figure one component is perfectly phased while the other is 90° out of phase.

The peak deflection D_i^2 is determined from the fitted curve and substituted into equation 3.12. (Note that we have used D_i^2 to represent the individual sample values from which the peak value is derived as well as the peak value itself).

A flux density value is obtained from each observation and a mean determined for each series of observations. While this mean has a smaller random error than a value from a single observation, it has been shown (Chapter 3) that this mean value has a systematic bias introduced in the analysis procedure. This bias was such as to produce an overestimate of the source flux density at a single observation.

From the analysis given in Chapter 3 it can be seen that the mean flux density for a source determined from a series of observations is an overestimation of the true value by an amount $2\epsilon^2$; ϵ is the r.m.s. noise on the output recorder of detector 1 S. Table 5.1 gives the expected bias (given as a percentage) in the flux density derived from equation 3.12 for a range of signal to noise ratios.

TABLE 5.1

S/N	5:1	6:1	7:1	8:1	9:1	10:1	11:1	12:1
Bias (%)	8.8	5.5	4	3	2.5	2	1.7	1.4

The flux density values from each series of observations have had the appropriate correction applied. The correction factors range from 1.008 for 3C 273 to 1.06 for PKS 1932-46 and PKS 0521-36, (Table 5.3).

The procedure adopted for the analysis of records obtained with the east-west interferometer (D_{3S} , D_{3C}) differed from that above since the signal to noise was very high and the phase of the signals from the two aerials differed by no more than 5° ; D_{3S} is thus approximately zero.

Measurements of D_{3C} were made directly from the analogue records after correction for the insertion loss (α) in the phase switch (Fig. 4.10-a):

$$D'_{3C} = \alpha^{\frac{1}{2}} \cdot D_{3C}; D'_{3C} - \text{measured deflection.}$$

The measurement or computation of all the quantities appearing in equation 3.12 has now been described.

5.2-b Method II:

The initial setting up operations of Method I (1, 2 and 3) are also carried out in this method. It should be noted that the relative gain of the total power detector n_2 , is twice the value given by the signal ratios obtained in 3.17 since the calibration signal is 100% modulated.

The total power channel was recorded on paper chart and the deflection D_4 determined directly: the interferometer

output was recorded on magnetic tape and monitored on paper chart. The analysis of the latter records is identical with that in Method I, except that instead of squaring and adding the quadrature components (e.g. equation 3.11) the phase angle is determined and used together with one of the components (e.g. equation 3.22).

The percentage bias introduced by the analysis procedure in Method II is less than that in the previous method since the signal to noise on the records is improved. (Section 3.4). The magnitude of the correction factors required are given in Table 5.3.

A typical set of interferometer sample points is shown in Fig. 5.2. The east-west interference fringes in this method are very broad when compared with the east-west aerial beam width since the reference array is quite close to the centre of the east-west aerial. Thus for $\theta \sim 0$, the response pattern is essentially the voltage polar diagram of the east-west aerial.

A correction factor of about 1.02 is applied to the interferometer outputs to account for the extra hybrid losses in the east-west signal paths over that in the total power output (Fig. 4.10-b).

FIGURE 5.2

This figure shows a complete set of data points for an observation of 0521-36 made using Method II. The interferometer (east-west and array) output for the sine and cosine components is shown on the left. On the right, the east-west total power output is shown.

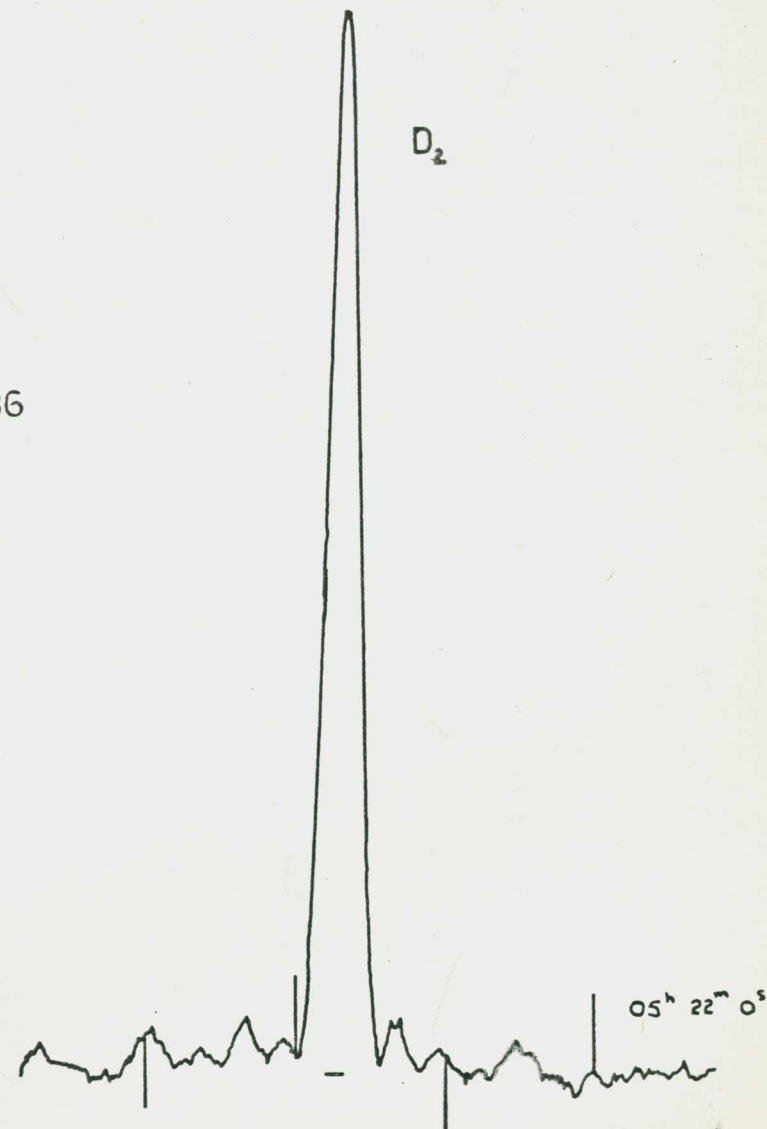
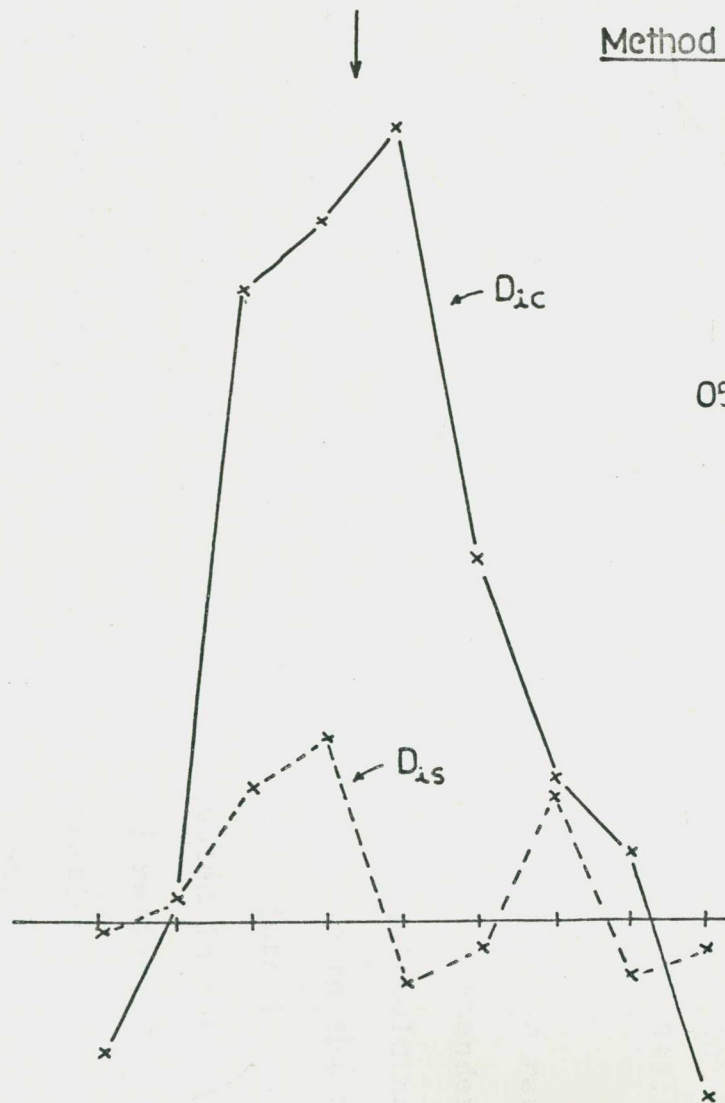


FIG. 5.2

5.3 RESULTS

Table 5.2 gives the flux density in f.u. for each source determined in the January/April and September observing periods.

TABLE 5.2.RESULTS ON THE FIVE BASIC CALIBRATION SOURCES

	PKS 0408-65	PKS 1932-46	PKS 0521-36	MSH 06-04	3C273
1. Jan/April	49.9	35.1	43.4	36.5	66.1
2. Sept.	51.2	36.8	32.6	41.2	-
3. Combined Result	50.7±3.6	36.0±3.0	38.0±3.1	38.9±2.9	66.1±4.6
4. Flux Ratios	1	0.82	0.767	0.876	1.31
5. Scale Flux Density	47.8±2.4	39.2±2.2	36.7±2.0	41.9±2.2	62.6±3.1

The combined results are also given (row 3) and represent the final absolute flux densities determined by independent measurement for these five sources. Observations could not be made on 3C273 in September since it was too close to the Sun.

Each source was observed at least four times in each of the above observing periods. The errors quoted in the flux densities in row 3 are a combination of calibration errors (in A_R and T), which are not reduced by repeating observations and errors due to noise fluctuations, which do reduce. The latter's contribution to the total errors is further reduced

by combining the independent values in row 3, using the flux density ratios determined by relative measurement (row 4). The values given in row 5 satisfy these flux density ratios and are chosen such that the mean ratio of this scale flux density (row 5) to the measured values (row 3), averaged over the five sources, is unity. The flux density scale at 408 MHz is based on these five absolute flux density values. The standard error in these values lies between 5 and 6%.

The flux density values given in the table refer to values outside the earth's atmosphere. A correction factor of 1.004, derived from the extrapolation of curves given by Hogg (1959), was used to correct the measured flux densities: the range of source zenith angles is so small ($\approx 35^\circ$) that this factor is taken to be a constant for all the sources.

5.4 DISCUSSION OF ERRORS:

The flux density of any source at any one observation is estimated from either equation 3.12 or 3.19 and corrected (Table 5.3), firstly for tropospheric attenuation, secondly for the bias discussed in the previous sections and thirdly for the change in the reference aerial response with declination. The first parts of these equations contain recorder deflections and receiver calibration measurements, the second part the temperature of the noise reference source and the effective area of the reference aerial. The last two factors are constants for each observation.

The contribution to the total error quoted in table 5.2, arising from the various parts of equation 3.12 and 3.19 will now be discussed (Table 5.4).

5.4-a Effective Area A_R :

It was shown in Chapter 3 that the measurement accuracy of the relative phase and amplitude of the dipole currents, and the dipole separation and height above the reflector was such as to provide negligible error in A_R . The loss in the feed, the dipoles and the ground plane was estimated to be accurate to 0.1 db. A further uncertainty estimated to be about 2% arose because of irregularities in the ground plane, the possibility of small unbalanced currents on the dipole feeders and scattering from objects in the vicinity of the array.

These factors give a total error in the effective area of 3%.

The array gain is a function of the source declination. The uncertainty in the gain at any zenith angle is a combination of the uncertainties in the forward gain and in the form of the radiation pattern in the meridian plane. The form of the gain function in a north-south plane depends only on the height of the dipoles above the reflector, providing the dipoles are accurately in-line; this second condition is certainly satisfied. A systematic error of $\frac{1}{4}$ cm in h ($\sim 1.4\%$) produces a 1% change

TABLE 5.3

CORRECTION FACTORS TO MEASURED SOURCE FLUX DENSITIES.

	<u>0408-65</u>	<u>1932-46</u>	<u>0521-36</u>	<u>06-04</u>	<u>3C 273</u>
1. Atmospheric Attenuation	1.004±0.2%	1.004±0.2%	1.004±0.2%	1.004±0.2%	1.004±0.2%
2. Bias Correction (5.2)					
Method I	0.970±0.7%	0.950±1.2%	0.950±1.2%	0.960±1%	-
Method II	0.990±0.3%	0.983±0.5%	0.980±0.5%	0.985±0.4%	0.992±0.2%
3. Aerial Pattern	1.092±0.5%	1.007±0.1%	1.000±0%	1.088±0.5%	1.182±1%

TABLE 5.4

ANALYSIS OF FINAL ESTIMATED ERRORS.THE FIGURES QUOTED ARE PERCENTAGES.

	<u>0408-65</u>	<u>1932-46</u>	<u>0521-36</u>	<u>06 - 04</u>	<u>3C 273</u>
AERIAL GAIN	3	3	3	3	3
TEMPERATURE CALIBRATION	2.5	2.5	2.5	2.5	2.5
CORRECTION FACTORS (TABLE 5.3)	0.7	0.8	0.8	0.9	1%
ANALYSIS OF RECORDS	5.6	7.2	7.0	6.2	5.5
CONFUSION	0.9	1.1	1.2	1	0.7
FLUX DENSITY VARIATION	0	0	0	0	0
POLARISATION	0.5	0.5	0.5	0.5	0.5
RECEIVER NON-LINEARITY	0	0	0	0	0
STANDARD ERROR.ROW 3	7.1	8.3	8.1	7.4	6.9
FLUX DENSITY RATIOS (TABLE 5.2)			Accurate to 3%		
STANDARD ERROR.ROW 5	5.0	5.5	5.5	5.2	5.0

in the forward gain and a 2% change in the gain at zenith angle 38° , corresponding to the declination of 3C273. The gain (or effective area) thus has a small additional uncertainty for increasing zenith angles. At zenith angle 40° the total uncertainty in the effective area is 3.2%.

5.4-b Reference Temperature T:

This measurement is difficult to perform with high precision. The uncertainty in T arises from the following causes:

- (i) the errors in the effective temperature of the load T_N
- (ii) the errors in the temperature of the attenuators
- (iii) the calibration of the attenuators
- (iv) mismatch effects.

The cold load was matched to better than 30 db at liquid nitrogen temperatures. The liquid nitrogen was pure and efforts were made to prevent the condensation of oxygen into it (Pauliny-Toth and Shakeshaft, 1962); condensation results in a mixture with a higher boiling point temperature. The contribution to the total noise due to the dissipative losses in the cold load transmission line (section 4.10-b) provided the major contribution to the uncertainty in T_N . The effective temperature, T_N , was assigned the value:

$$T_N = 79.5 \pm 1.5^\circ\text{K}.$$

The temperature of the attenuators T_0 was known to about 1.5°K giving a resultant error in the difference $(T_0 - T_N)$ of 1.5%.

The variation in the calibration of the diode noise power determined using different attenuators was consistent with that expected from the quoted calibration errors for the attenuators. This also implied that impedance variations associated with different attenuators were small. The temperatures of the noise source for the two observing periods were

January/April $T = 142 \pm 3^\circ\text{K}.$

September $T = 97 \pm 1.5^\circ\text{K}.$,

the errors quoted being based only on the repeatability of results using different attenuators.

The uncertainty in these temperatures when errors in T_N and T_0 are included become,

$T = 142 \pm 3.7^\circ\text{K}$ $T = 97 \pm 2^\circ\text{K}.$

The estimated random error in the temperature T lies in the range 2.0 to 2.6%.

5.4-c Noise:

The signal to noise on records made with the east-west interferometer (Method I) and the east-west total power instrument (Method II) was excellent and the uncertainty in the chart measurements was less than 1%. The same applies

to the measurement of the gain calibration factors n_{iS} , n_{iC} and the noise reference signal D_4 . Noise fluctuations, however, severely affect the measurement accuracy of the quantities D_{iS} , D_{iC} ($i = 1$ and 2) (i.e. deflexions obtained with an interferometer which includes the reference aerial). The signal to noise on these records is less than 12:1 in almost all cases. The total error in the flux density of a source derived from one observation is about 20%, this error being reduced in each observing period by repeated observations. As noted earlier the random (noise) error in D_{iS} and D_{iC} produces a systematic error in D_i^2 resulting in an overestimation of the source flux densities which amounts to about 2%. The error in this correction factor is quite small (Table 5.3).

The uncertainties in the flux density values given in row 3, Table 4.2, are principally due to calibration errors (in T and A_R), about 4% and to measurement uncertainties due to noise, about 10%. Only the latter uncertainty is reduced by repeating the observations on one source and by combining the values for the different sources using the measured flux density ratios. The quoted accuracy of the flux density values given in row 5 lies in the range 5 to 5.5% (standard error).

5.4-d Confusion:

All the sources lie in regions where the background variations are not severe and all but MSH 06 - 04 lie well

away from the galactic plane. Nearly all the records were made using phase-switched interferometers with moderate element spacings, which further reduce the problems due to background variations (i.e. zero level changes).

The confusion error due to unresolved sources is about 0.5 f.u. in the worst case (Method I). This uncertainty arises mainly in observations made using the reference and east or west aerials; these aerial combinations have the broadest radiation patterns used in the present experiment. The confusion error produces an additional uncertainty of about 1.2% in the flux density of the weakest of the five sources observed using Method I. Observing with both methods reduces this error.

5.4-e Flux Density Variations:

The flux density ratios of these five sources have been measured over the period June 1966 to September 1967. Within the errors of measurement, none of these sources appear to show relative flux density variations at 408 MHz. The relative flux density values are accurate to about 3%. It has been assumed that the sources show no flux density variations.

5.4-f Polarisation:

It is well known that the degree of polarisation of the radiation from a discrete radio source decreases with increasing wavelength (e.g. Gardner and Whiteoak, 1963); this depolarisation takes place either within the source or

in the medium between the source and observation point. The result is that discrete source polarisation at 408 MHz is small and in many cases undetectable; of the 164 sources studied by Gardner and Davies (1966) only 18 had detectable polarisation at 74 cm and only 2 had percentage polarisations greater than 2%.

Table 5.5 gives the percentage polarisation and the position angles for the five calibration sources when given by Gardner and Davies; only PKS 0408-65 was not on their list. No attempt was made to apply polarisation correction factors to the measured source flux densities since the position angle of the polarised component will be unknown; Faraday rotation in the ionosphere will produce changes in the position angle with solar time of observation. The uncertainty in the scale flux densities of the five calibration sources due to linear polarisation was estimated to be about $\frac{1}{2}\%$.

TABLE 5.5.

<u>Source</u>	<u>Degree of Polarisation (%)</u>	<u>Position Angle.</u>
PKS 0408-65	-	-
PKS 0521-36	1.5 ± 0.3	$78 \pm 5^\circ$
MSH 06-04	Negligible $\sim 0.3\%$ at 48 cm.	
3 C 273	2.4 ± 0.7	$162 \pm 6^\circ$
1932 - 46	Negligible $\sim 1\%$ at 30 cm.	

5.4-g Atmospheric Attenuation:

For frequencies up to 8GHz the atmospheric absorption is due principally to oxygen, while for higher frequencies, water vapour becomes important (Hogg, 1959). A zenithal attenuation at 408 MHz of 0.4% was estimated from extrapolation of curves given by Hogg. This value is in agreement with measured values given by Howell and Shakeshaft (1967).

The attenuation in db increases with zenith angle (z) approximately as $\sec z$, for zenith angles less than about 80° . A constant correction factor of 1.004 was applied to all the measured values to give the final flux density values given in table 5.2; the source zenith angle ranges are $\pm 38^\circ$ so that no zenith angle correction was necessary. The error in the absorption correction is negligible (Table 5.3).

5.4-h Receiver Non-Linearities:

The receiver had a response which was almost perfectly linear for the range of signals detected in the present experiment. The departure from a linear response ($\sim 1\%$) occurred at signal levels exceeding by a factor of two those in the present experiment. No corrections were applied for receiver non-linearities.

5.5 THE FLUX DENSITY SCALE:

The flux density of an arbitrary source is based on a scale if its flux density is determined by relative measurement to a source, which is defined to be a scale reference source.

In order to produce source spectra it is desirable to have scales at all frequencies based on reliable, absolute flux density measurements.

For absolute scales, discrepancies in the flux densities assigned to a source at any one frequency arise because of errors in the absolute flux densities of the scale reference sources, and in the relative intensity measurements made to the reference sources.

The present flux density scale is defined by the absolute flux densities of the five sources, PKS 0408-65, PKS 0521-36, PKS 1932-46, MSH 06-04 and 3 C 273 (Table 5.2). In order to make the scale more useful, careful relative flux density measurements were made on an additional 37 sources; these became secondary scale calibrators. The resulting 42 scale calibration sources given in Table 6.1a provide a useful grid of flux density reference sources for declinations in the range $+20^{\circ}$ to -80° . With few exceptions the sources have widths less than $25''$ and lie in relatively uncomplicated regions of the sky; the half-power widths of the large sources are indicated in parenthesis in the table. The relative flux density measurements will be discussed in detail in the next chapter.

The primary scale calibrators have standard errors in their individual flux densities of about 5.5%, while the secondary calibrators have standard errors of about 6.4%.

These errors will be those in the absolute level of the flux density of an arbitrary source determined by relative measurement to one of the scale reference sources. There will, of course, be an additional error in the assigned flux density of this arbitrary source due to the relative measurement. These latter errors are discussed in some detail in the next chapter.

The flux densities of all sources measured with the Molonglo Cross are normally based in this flux density scale. In this thesis the scale will be referred to as the Molonglo flux density scale. When intercomparisons are to be made with published observations based on the Conway, Kellermann and Long scales, the Molonglo flux densities are sometimes adjusted (e.g. Murdoch and Large, 1968).

CHAPTER 6.

RELATIVE FLUX DENSITY MEASUREMENTS

6.1 INTRODUCTION:

The relative flux density measurements described in detail in this chapter were made in two stages.

1. Firstly, the accurate relative flux densities for 37 sources were derived, in order to provide a grid of flux density calibration sources based on the present absolute flux density scale. Together with the five absolute flux densities they define the Molonglo flux density scale.

2. Secondly the flux densities of a further 260 sources were determined by relative measurement to the sources given by 1.

These measurements provide the most accurate flux density values available for southern radio sources at 408 MHz or lower frequencies. The measurements are almost complete for small diameter sources down to a flux density level of about 3 f.u.; sources on or near the Galactic plane are not included.

Finally, the flux densities for sources based on the Molonglo scale are compared with the flux densities given in the Parkes catalogues.

6.2 INSTRUMENT:

The instrument used for the relative flux density measurements was the east-west arm of the Molonglo Cross. A

brief description of the aerial, containing details pertinent to the present discussion, will now be given.

6.2-a Physical Description:

A brief physical description of the arm has been given in Section 4.6. The feed modules, which are located along the focus of the cylindrical parabola, are divided into 22 "bays" of eight; each bay is connected to a mixer and first pre-amplifier (11.05 MHz) combination. The feeds within a bay are connected to the mixer pre-amplifier by a "christmas tree" arrangement of low loss r.f. cable and hybrids. The signals from the pre-amplifiers pass through half-mile lengths of co-axial cable to a hut situated near the centre of the cross. After a second frequency conversion to 5.5 MHz the signals are combined to form the whole arm output. The complete radiometer is shown schematically in Figure 6.1. The east-west signal is then modulated at the 400 Hz switching frequency, amplified and detected: the resulting modulated signal passes into a synchronous demodulator, the output of which is displayed on paper chart. The synchronous demodulator has a 1 sec R.C. time constant, on its output.

The whole arm rotates about an east-west axis to cover the declination range -90° to $+19^{\circ}$. The aerial was used for the measurements in two modes: firstly, as a uniformly illuminated aperture (uniform along any east-west line) producing a fan

beam with dimensions $1'.5 \times 4^\circ$ and secondly, with a tapered east-west excitation (Campbell, 1964), which produces a beam $2' \times 4^\circ$ at half power. The taper was applied to the east-west aerial when it was used in full Cross, but proved to be convenient for the integrated flux density measurements made with this aerial alone.

6.2-b Array Gain:

In this section, I propose to look at the factors, which can produce changes in the gain of this phased array. The importance of this discussion will be obvious when the calibration of individual observations made using the east-west arm is considered.

The aerial forward gain can be written

$$G = \left| \sum_{n=1}^{22} \left[\left(\frac{g_i}{\bar{g}} \right)^{\frac{1}{2}} \cdot G_i^{\frac{1}{2}} \cdot \exp j(\phi_i - \bar{\phi}) \right] \right|^2 \quad 6.1$$

(i) g_i and ϕ_i describe the gain and phase characteristics of the i th signal path from the mixer pre-amplifier to the central signal adding point (Fig.6.1); g_i includes amplifier gains, cable losses and conversion losses. $\bar{g}$ and $\bar{\phi}$ are the mean quantities along the arm

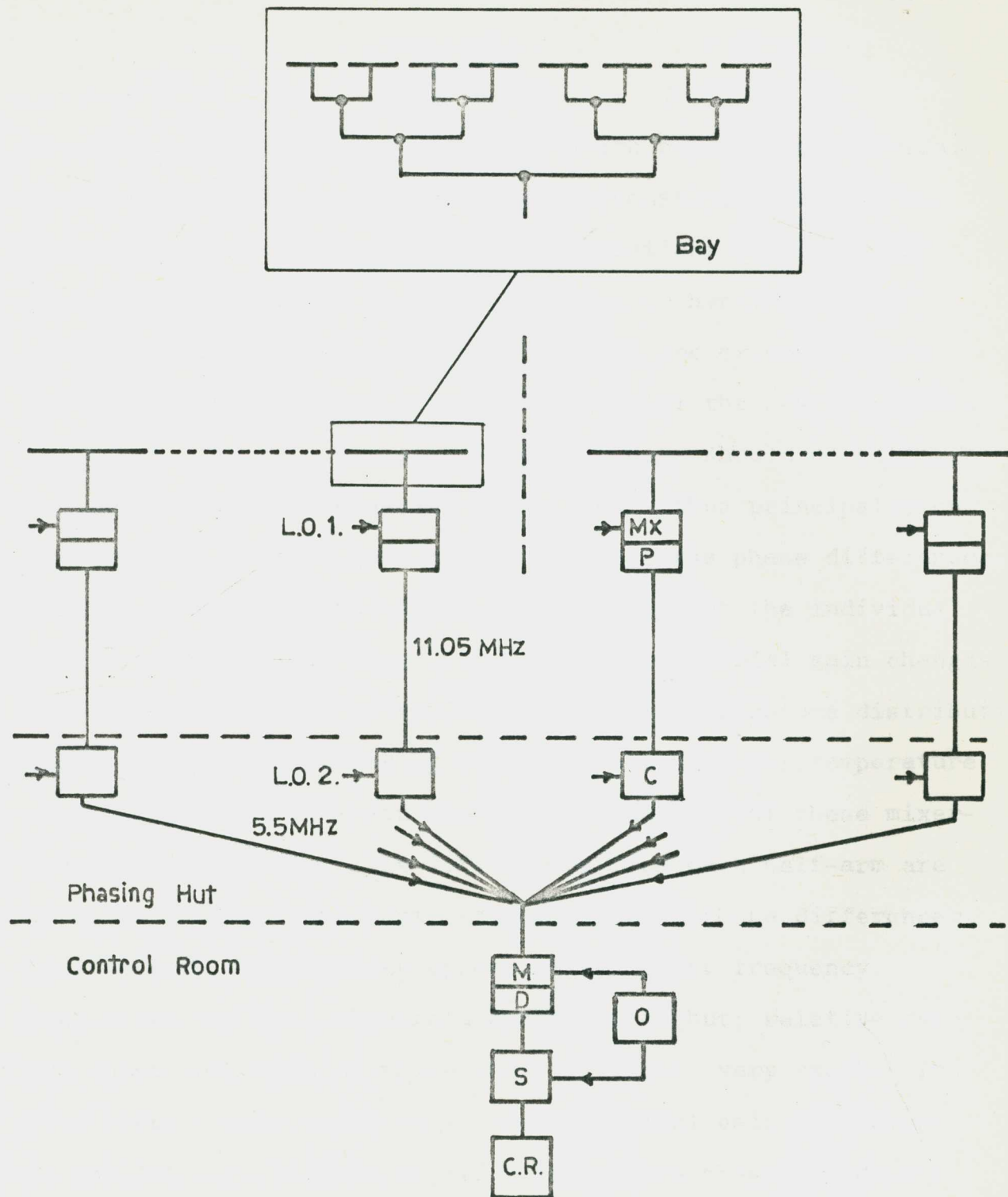
$$\bar{g} = \frac{\sum g_i}{n} \quad \bar{\phi} = \frac{\sum \phi_i}{n} \quad 6.2$$

FIGURE 6.1

The complete E-W total power system:

Mx, mixer; P, pre-amplifier; C, second frequency converter; M, signal modulator; D, detector; S, synchronous demodulator; C.R., Chart recorder.

Circuit elements on the same horizontal line are identical unless marked otherwise.



E-W TOTAL POWER SYSTEM

FIG. 6.1

$$(ii) \quad G_i^{\frac{1}{2}} = |G_i|^{\frac{1}{2}} e^{j\xi_i}$$

G_i is the forward gain of the i th bay of feed modules. The modulus of the gain should remain constant with time and environmental temperature changes; variations would be due to mechanical changes in the cables and/or hybrids within each bay. The phase differences ($\xi_i - \bar{\xi}$) are expected to be stable, since the physical structure of all the bays is identical. Therefore, the gain variations between bays should be negligible.

Changes in the aerial gain (G) are thus principally due to variations in the gain ratios $g_i/\bar{g}$ and the phase differences, ($\phi_i - \bar{\phi}$). The phase and gain characteristics of the individual mixer-pre-amplifiers vary with temperature; aerial gain changes can thus be produced by variations in the temperature distribution along the aerial, and/or by the differences in the temperature co-efficients of the gain and phase parameters of these mixer-pre-amplifier units. The i.f. cables from each half-arm are contained in the same duct; at worst, small phase differences between each half-arm may appear. The second frequency convertors are in a temperature controlled hut; relative gain and phase variation of these units should be very small. The only other factor which could produce aerial gain variations is the 1st L.O. (Little et al., 1966). The phase of the L.O. at each mixer is maintained constant with changing ambient temperature by controlling the frequency of the L.O.. Errors

in frequency result in gain variations; these errors are expected to be negligible, except in the conditions of rapidly changing temperatures immediately after sunset and sunrise.

Random aerial gain variations are most probably due to relative variations in the gain-phase characteristics of the mixer-pre-amplifiers.

6.2-c Response to Small Discrete Sources:

The aerial response to a discrete source with a diameter less than about $\frac{1}{2}^\circ$ will be a function of one variable since the fan beam has essentially a uniform response in the north-south plane. For a source with a brightness distribution $B(x)$ the aerial response is given by:

$$R(x') \propto \int_{-\infty}^{\infty} A(x'-x) B(x) dx \quad 6.3$$

for a symmetric polar diagram $A(x)$.

In the case of the uniformly illuminated aperture, $A(x)$ is approximately given by a sinc^2 function (Bracewell, 1965). Variations from a sinc^2 function are principally due to random phasing errors along the array. Figure 6.2-a shows $R(x)$ for a point source i.e. a source with a half-power diameter less than about 1/10 the aerial half-power beam width.

The tapered aperture distribution leads to an $A(x)$, which is approximately a gaussian function: Fig.6.2-b shows the actual response to a point source (0408-65).

A discrete source produces a peak response given by:

$$R(o) \propto \int_{-\infty}^{\infty} A(x) B(x) dx \quad 6.4$$

For a point source the response can be written

$$R(o) \propto A(o) \int_{\text{source}} B(x) dx, \quad 6.5$$

where the source flux density is proportional to

$$\int_{\text{source}} B(x) dx \quad 6.6$$

i.e. the peak source deflection is proportional to the source flux density.

The value of the integral in equation 6.4 for a discrete source is less than that in equation 6.5. Corrections, therefore, need to be made to the peak flux density obtained with a source of finite diameter (i.e. with respect to the east-west aerial beam width) in order to derive the total source flux density. Figure 6.3 shows the ratio of peak to total flux density for discrete sources as a function of the ratio of source to fan beam width. The sources are assumed to have gaussian brightness distributions. It is not necessary to differentiate between the sinc^2 and gaussian beams, when the corrections are small.

6.2-d Pointing Calibration:

In order to avoid systematic errors in the source flux densities, due to aerial pointing errors, a declination dial

FIGURES 6.2-a and 6.2-b.

- a The E-W aerial response to a point source for the case of a uniformly illuminated aperture.
- b The E-W aerial response to a point source for the case of a tapered, east-west aperture distribution.

FIGURE 6.3.

This graph gives the ratio of the peak to total flux density of a source as a function of the fraction of a beam width for two cases:

- a- fraction of a beam width refers to the ratio of the source east-west half-power width to the aerial beam half-power width. The source is assumed to have a gaussian brightness distribution.
- b- fraction of a beam width refers to the ratio of the separation of two point sources to the E-W aerial beam width.

0408-65

0408-65

E-W RESPONSE PATTERNS

a.

b.

04^h09^m00^s

04^h09^m00^s

FIG. 6.2

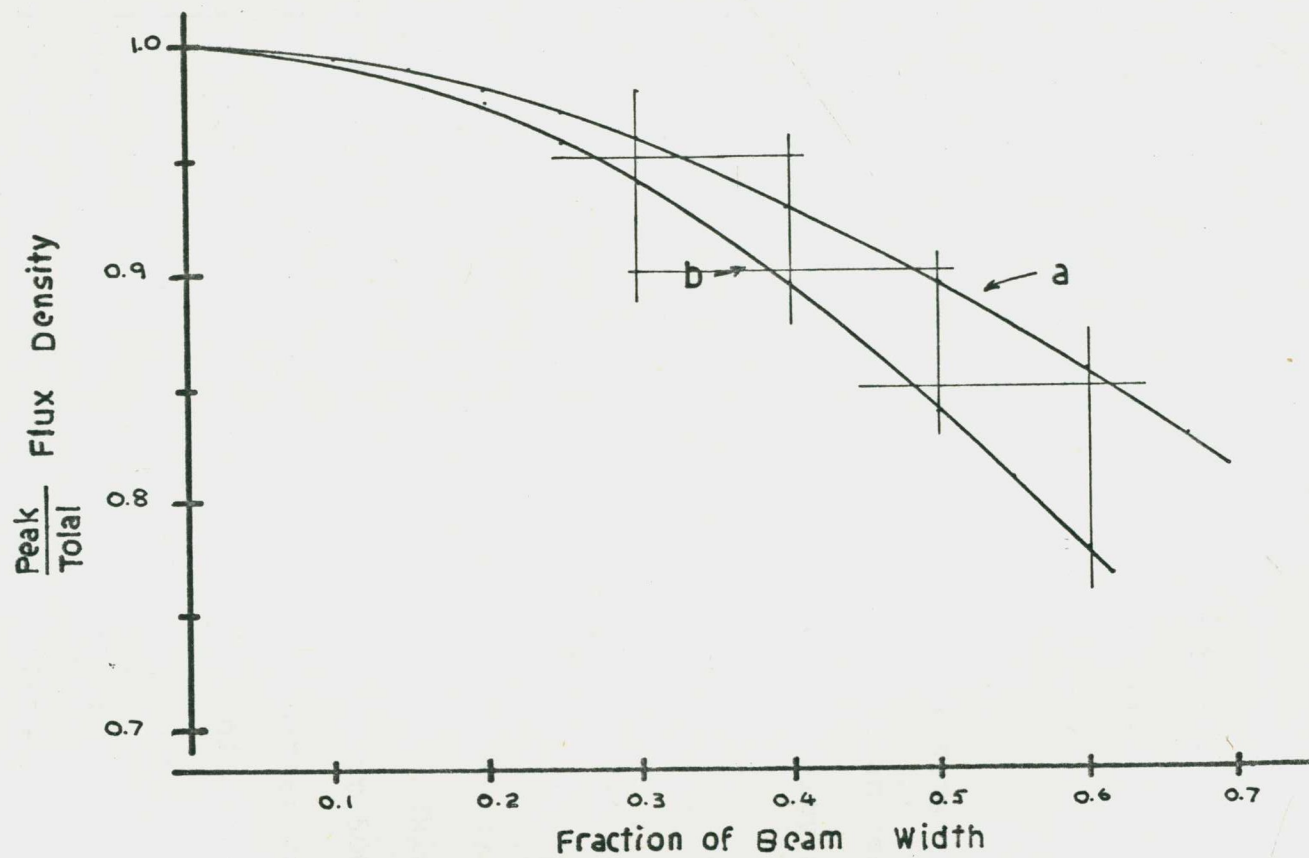


FIG. 6.3

correction curve was constructed. This curve is given in Figure 6.4. The points on the graph were derived by observing a number of sources over the declination range of the aerial. Each source was observed at a number of declination dial settings. The dial reading corresponding to the maximum response to the source could then be deduced and compared with the known declination of the source. The difference in these two values is the quantity plotted in Figure 6.4.

The expected uncertainty in source flux densities due to pointing errors is negligible. The aerial beam need only be set to an accuracy of $\pm 10'$ arc for a flux density error, less than one per cent.

6.3 NOISE REFERENCE SIGNAL:

Individual observations were calibrated by a reference noise signal derived from a noise diode source. The noise source was similar to that previously described (4.9) except that the output temperature was about $600,000^{\circ}\text{K}$. This high output was achieved by making the diode load about 500Ω and transforming down to the 50Ω output using a quarter wavelength of strip line with a characteristic impedance of 158Ω . The noise is fed into the east-west signal path, just in front of the first mixer pre-amplifier (No.11), east of the arm centre.

The noise signal therefore only monitors the gain of one of the twenty-two signal paths to the central adding point

(g_{11}), together with the gain of the final stages of the receiver (g_R). The reference signal deflection at the receiver output is given by

$$D_R \propto g_R g_{11} kT, \quad 6.7$$

where T is the temperature of noise injected into the signal path.

At each observation the noise reference deflection is obtained before and after each source transit.

6.4 OBSERVATIONS:

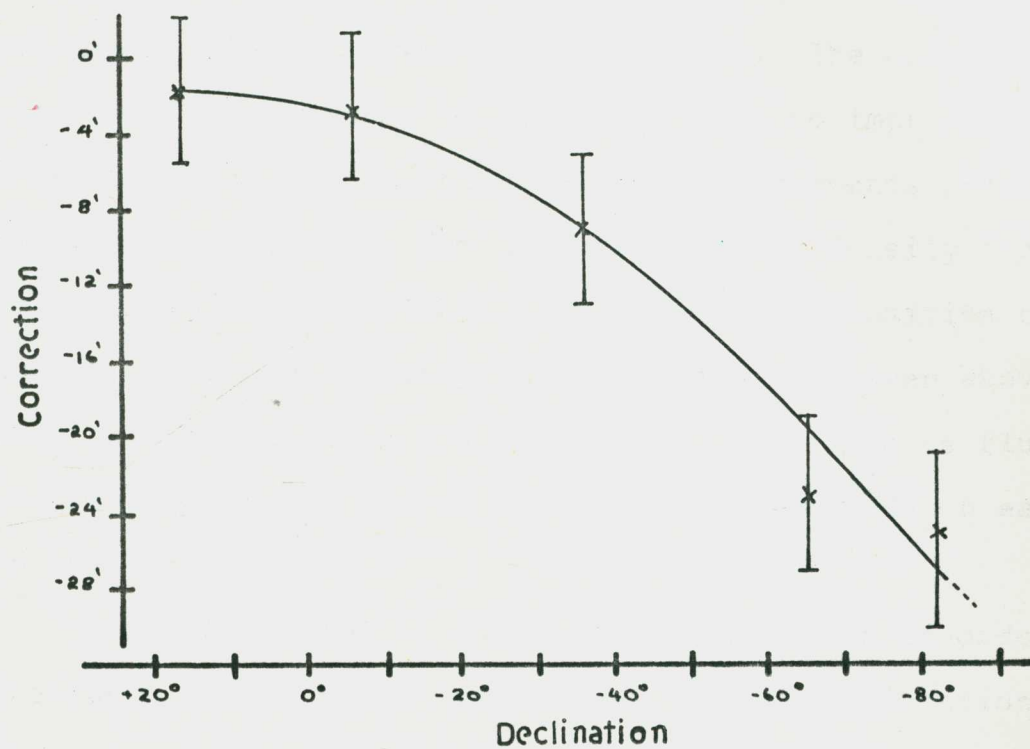
All of the sources observed were selected from the Parkes catalogues of radio sources (Bolton et al., 1964; Price and Milne, 1965; Day et al., 1966; Shimmins et al., 1966); the selected sources have flux densities greater than about 3 f.u.. The selection was based principally on whether or not the particular source has a symmetric east-west profile (sources with asymmetric profiles are probably confused by other source(s) in the fan beam); multiple sources which are given as single sources in the Parkes catalogues, were also deleted.

The flux densities of the remainder were measured with the fan beam at the source declination given in the Parkes catalogues. The use of these declinations, which are accurate to about 1' arc, introduce no uncertainty in the measured source flux densities, providing the east-west aerial declination dial

FIGURE 6.4.

The correction curve for the east-west aerial declination dial. The correct dial setting to observe a source at a declination δ is given by:

$$\text{Dial Reading} = \delta + \text{Correction.}$$



DEC. DIAL CORRECTION CURVE

FIG. 6.4

calibration is correct (Section 6.2-d).

The observations were made in two stages: firstly, a number of strong small diameter sources were selected and their flux densities determined by measurement, relative to the five primary, scale flux density calibrators. The measurements were repeated a number of times in order to improve the accuracy of each source flux density. These measurements provided secondary calibrators for the present flux density scale. The results are given in Table 6.1a. The flux densities of a large number of sources satisfying the conditions given above, were then determined using the sources in Table 6.1a as flux density reference sources. Fewer observations were made on each source in this later list.

The first set of observations were made in order to provide a useful set of flux density scale calibration sources. The second list provides a homogeneous set of flux densities for a large number of southern radio sources. The measurements are made with an aerial, which has the smallest beam area available at this frequency; the beam area is about five times smaller than that of the Parkes 210ft paraboloid at 408 MHz.

Table 6.1a was produced from measurements made over the period June 1966 to July 1967; the larger number of measurements were made in July 1967.

Calibration of the individual observations consisted

of switching the noise reference signal on, before and after each source transit. The noise reference was calibrated in turn by observing flux density reference sources, as frequently as possible.

6.5 ANALYSIS OF OBSERVATIONS:

It is possible to determine the flux density of a source from the observations made above, using one or other of two procedures. The first required the measurement of the source peak and noise reference deflections on the chart output to give the peak source flux density. The second requires the measurement of the area beneath the source trace on the output record, as well as the noise reference deflection. Details of both these techniques, as applicable to the present transit instrument, will be given in the following sections.

6.5-a Peak Measurements:

Reference to equations 6.5 and 6.6, shows that the peak deflection for a point source is a measure of the source flux density.

A flux density equivalent is derived for the noise reference signal, by measuring the peak to calibration deflection on the output recorder for a flux density reference source. The flux density of any point source can then be determined by measuring the peak to calibration deflection obtained at an observation. The peak deflection has first to be corrected

for receiver output time constant effects; these effects are declination dependent. Figure 6.5 shows the corrections necessary: firstly, the correction as a function of the ratio, time constant over beam width and secondly, the correction as a function of declination for a one second R.C. time constant.

This procedure of using the noise source as the intermediary between source observations, is standard practice. In the present case, the calibration procedure depends on a number of additional factors. The factors which affect the stability of the peak to calibration deflection are given by the following:

Source Peak deflection: $D_S \propto g_R \bar{g} G S.$

Reference deflection: $D_R \propto g_R g_{11} kT.$

Therefore
$$\frac{D_S}{D_R} = K \frac{\bar{g}}{g_{11}} \cdot \frac{G}{T} \cdot S, \quad 6.8$$

where K is a constant factor.

The constancy of this ratio depends on the stability of the aerial gain, on the temperature stability of the noise source and on the stability of the ratio $g_{11}/\bar{g}$.

Measurement of this ratio (D_S/D_R), on the same source on many occasions, gives an indication of the variations in the quantity $\bar{g}G/g_{11}T$; the ratio D_S/D_R shows an r.m.s. variation of about 3%. Unfortunately, this figure is derived from measurements

made over a fairly short time interval, so that the observations of any one source are made at approximately the same solar time; the environmental conditions are therefore much the same. There is fairly good reason to suspect that the quantity $\bar{g}G/g_{11}T$ exhibits a greater change between day and night. It is estimated that the variations of about 4% are to be expected. The uncertainty in the peak flux density determined by relative measurement to a reference source is therefore about 5.5%. This error is due entirely to the calibration system and can be reduced by taking additional observations.

The peak flux density is subject to other sources of error: the peak deflection measurement depends on the base or background level determination in the vicinity of the source and on the choice of the source peak, which is affected by source confusion and noise fluctuations. The error, due to the background determination, confusion and noise fluctuations, is about ± 0.3 f.u.

The flux density of a source was only determined from peak measurements when the source was known to have a small diameter; the error in the flux densities due undetected source extension is not expected to exceed 2%.

Peak flux density measurements were only made before the tapered excitation (6.2-a) along the east-west aerial became available. All later measurements were made of the

FIGURES 6.5-a and 6.5-b.

a- This graph gives the correction factor, which must be applied to the peak flux density for a point source, as a function of R.C. time constant over the aerial beam width.

$$\text{Peak flux density} = \frac{\text{Measured peak flux density}}{\text{Correction.}}$$

b- The correction factor in this graph is given as a function of declination for the case of a 1 sec. R.C. time constant and an aerial beam width of 1.87' (7.5 secs of time at the equator).

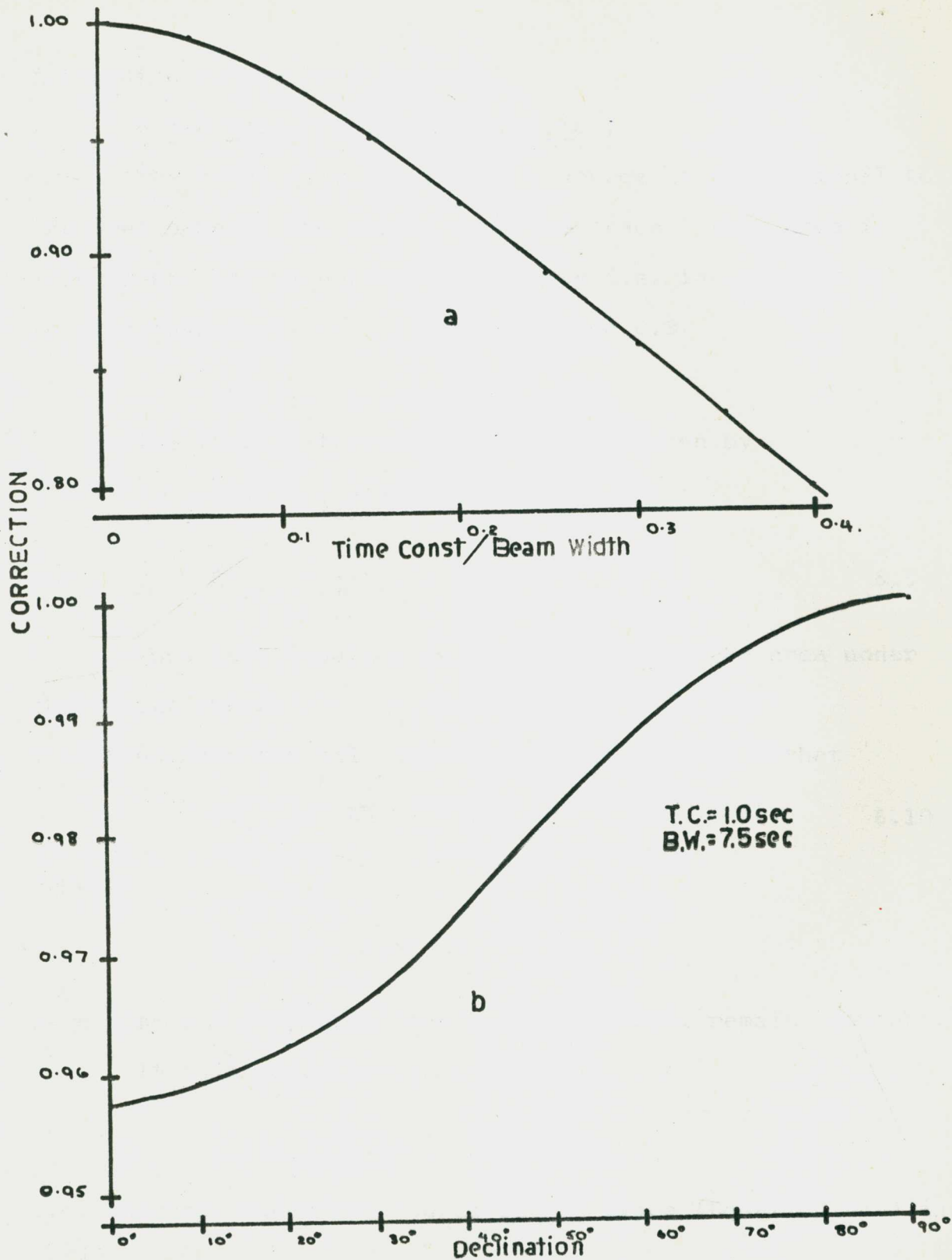


FIG. 6.5

integrated source flux density.

6.5-b Integrated Flux Densities:

The total flux density of a source is proportional to the area beneath the output recorder trace: this area is independent of the aerial directivity i.e. independent of phasing changes ($\phi_i - \bar{\phi}$). From equation 6.3

$$R(x') \propto \int A(x' - x) B(x) dx. \quad 6.3$$

The fourier transform of $R(x)$ is given by

$$\bar{R}(s) = \int_{-\infty}^{\infty} R(x) e^{-2\pi i s x} dx.$$

Now
$$\bar{R}|_{s=0} = \int_{-\infty}^{\infty} R(x') dx'. \quad 6.9$$

This last equation is proportional to the area under the output trace.

It can be seen for this equation and equation 6.3 that

$$\bar{R}|_{s=0} \propto |\overline{AB}|_{s=0} \quad 6.10$$

However,

$$A|_{s=0} = \int_{-\infty}^{\infty} A(x) dx$$

is a constant providing losses in the aerial remain constant.

If this condition is satisfied:

$$R|_{s=0} \propto \bar{B}|_{s=0} = \int B(x) dx.$$

i.e. the area under the source output trace (Equation 6.9) is

proportional to the source flux density (Equation 6.6) and independent of the aerial directivity. Alternatively, the total energy received from a discrete source is independent of the aerial directivity.

The flux density of any source can be determined by making the following set of measurements:

$$\text{Source Area} \quad A_{S_1} \propto \sec \delta_1 g_R \bar{g}_{S_1}.$$

$$\text{Reference Deflection} \quad D_{R_1} \propto g_{11} g_R kT.$$

$$\text{Ratio} \quad \frac{A_{S_1}}{D_{R_1}} \propto \sec \delta_1 \left(\frac{\bar{g}}{g_{11}} \right)_1 \frac{S_1}{kT}. \quad 6.11$$

The $\sec \delta$ (δ is the source declination) term arises in the transformation from angular (x) to time co-ordinates.

The constants of proportionality can be determined by observing a flux density reference source (S_2): the flux density is then given by

$$S_1 = S_2 \cdot \frac{\sec \delta_2}{\sec \delta_1} \cdot \left(\frac{\bar{g}}{g_{11}} \right)_2 \cdot \left(\frac{g_{11}}{\bar{g}} \right)_1 \cdot \frac{A_{S_1} D_{R_2}}{A_{S_2} D_{R_1}}.$$

Providing the ratio $g_{11}/\bar{g}$ remains constant, we have

$$S_1 = S_2 \frac{\sec \delta_2}{\sec \delta_1} \cdot \frac{A_{S_1} D_{R_2}}{A_{S_2} D_{R_1}}. \quad 6.12$$

Note that the reference temperature T is also assumed to be a constant.

The flux density of any source is determined by application of equation 6.12.

This method has a number of important advantages over that described in 6.5-a:

1. The measured flux densities are the total source flux densities and require no correction for source size.
2. Errors due to noise fluctuations are reduced since the integration averages the noise.
3. No correction is required for time constant effects.

The accuracy of flux density determined from 6.12 depends in part on the constancy of the aerial losses and on the stability of the ratio $g_{11}/\bar{g}$.

Variations in the losses in the low loss r.f. cable within each bay produces changes in the quantity G_i (Equation 6.1). The variation is not monitored by the noise reference signal. The loss temperature coefficient of the cable is about 0.03% per °C; the change of aerial gain (G_i) with temperature can therefore be ignored.

Some estimate of the stability of the quantity ($g_{11}/\bar{g}$) can be obtained from the following discussion. The peak to area deflection is obtained for a series of observations on any source or any number of point sources; from equations

6.8 and 6.11,

$$\frac{D_S}{A_S} \propto G$$

i.e. the ratio is proportional to the aerial gain.

Analysis of many records shows that the ratio and therefore the aerial gain exhibits variations with a r.m.s. of about 2%. Since the quantity $\bar{g}_{11}G/g_{11}T$ (Section 6.5-a) has a standard error of about 4% the ratio, $(g_{11}/\bar{g})$ has a standard error of about 3.5%. It is possible that part of the variation in $\bar{g}G/g_{11}T$ is due to changes in the reference temperature; this results in a smaller random error in the ratio $g_{11}/\bar{g}$.

The result of this discussion is that an uncertainty of 4.9% appears in the relative flux densities determined from equation 6.12, due to changes in the ratio $(g_{11}/\bar{g})$. The remaining sources of error will be discussed in section 6.7.

6.6 RESULTS:

The results of the measurements which provided the secondary scale flux density calibration sources are given in Table 6.1a.

The flux densities for about 260 sources are given in Table 6.1-b. This table includes the results of all flux density measurements based on the present 408 MHz flux density scale.

The first column in Table 6.1-b gives the Parkes catalogue number for each source. Sources marked with an asterisk are symmetric (in the east-west direction) have diameters less than 45" arc and therefore are ideal as flux density reference sources. Only sources with flux densities greater than 5 f.u. are marked in this way.

The second and third columns give the declination and beam numbers for epoch 1968.5 required for observations of these sources with the Molonglo Cross. The flux density of each source is given in column four.

TABLE 6.1a.

THE COMPLETE SET OF CALIBRATION SOURCES. NUMBERS IN PARENTHESES
REFER TO THE ANGULAR SIZE OF THOSE SOURCES LARGE ENOUGH TO BE
RESOLVED BY THE AERIAL.

SOURCE	FLUX DENSITY (f.u.)	SOURCE	FLUX DENSITY(f.u.)
<u>Dec. 0° → + 20°</u>			
0347 + 05	7.9 ± 0.5	1226 + 02	62.6 ± 3.1
0758 + 14	7.6 ± 0.5	1416 + 06	25.5 ± 1.6
0947 + 14	11.1 ± 0.7	1514 + 07	28.0 ± 1.8
1005 + 07	16.2 ± 1.0	2144 + 15	8.1 ± 0.5
1008 + 06	10.4 ± 0.7	2230 + 11	7.7 ± 0.5
1040 + 12	8.2 ± 0.5	2313 + 03 (40")	16.0 ± 1.0
<u>Dec. 0° → -20°</u>			
0035 - 02	16.3 ± 1.0	0915 - 11 (55")	135 ± 8.6
0117 - 15	13.3 ± 0.8	1253 - 05	12.8 ± 0.8
0218 - 02	12.2 ± 0.8	1621 - 11	6.0 ± 0.4
0235 - 19	12.7 ± 0.8	1640 - 15	4.5 ± 0.3
0240 - 00	11.7 ± 0.7	1730 - 13	7.7 ± 0.5
0349 - 14	10.3 ± 0.6	2211 - 17	33.2 ± 2.1
06 - 04	41.9 ± 2.2		
<u>Dec. -20° → -60°</u>			
0023 - 26	17.3 ± 1.1	1420 - 27	8.1 ± 0.5
0157 - 31	9.5 ± 0.6	1827 - 36	26.4 ± 1.7
0521 - 36	36.7 ± 2.2	1932 - 46	39.2 ± 2.2
0859 - 25	17.0 ± 1.1	2032 - 35	15.7 ± 1.0
1143 - 48	7.2 ± 0.5	2250 - 41	14.2 ± 0.9
1309 - 22	21.1 ± 1.3	2331 - 41	15.3 ± 1.0
<u>Dec. -60° → -90°</u>			
0408 - 65	47.8 ± 2.4	1754 - 59	12.5 ± 0.8
0410 - 75	33.7 ± 2.1	1814 - 63	34.1 ± 2.1
0842 - 75 (40")	14.8 ± 0.9		

TABLE 6.1b.
RELATIVE FLUX DENSITIES.

$0^{\circ} \rightarrow + 20^{\circ}$.

Source(PKS)	Dec.No.	Beam No.	Flux Density (f.u.)	Source(PKS)	Dec.No.	Beam No.	Flux Density (f.u.)
0010+00	216	1	4.4	0430+05*	186	2	6.2
0035+13*	139	2	6.1	0439+01	212	2	6.5
0038+09*	157	-1	14.8	0505+03	200	1	3.1
0049+17	115	0	6.0	0710+11*	146	0	8.8
0106+13	139	2	33.0	0731+02	206	-1	4.8
0109+14	131	0	3.8	0742+02	206	-2	6.6
0116+08	167	2	4.8	0812+02	207	1	4.8
0124+09	162	0	3.4	0826+09	160	2	2.9
0132+07*	169	2	6.2	0827+07	170	2	5.1
0138+13*	136	2	7.9	0841+15	124	1	2.8
0202+14*	128	-1	5.2	0850+14*	134	0	8.5
0249+08	167	1	2.7	0851+14*	133	0	5.3
0312+10	156	-1	4.2	0855+14*	133	2	9.7
0316+16*	122	2	7.8	0903+16*	119	1	5.7
0320+05*	185	2	6.0	0909+16	121	-1	3.5
0324+11	145	0	3.8	0932+02	206	1	3.8
0333+12*	140	1	5.0	0933+04*	190	-2	5.5
0338+07	172	1	1.9	1039+02*	201	-1	6.5
0340+04*	188	-1	9.0	1044+15	182	-2	3.6
0358+00*	217	1	6.7	1048+00	220	2	3.3
0408+17	117	-2	2.8	1055+01*	209	2	4.3
0411+14	133	0	5.3	1116+12	141	0	3.6
0423+04	189	1	4.5	1120+05*	183	-1	4.7
0428+01	213	2	4.8	1138+01*	211	0	6.6

TABLE 6.1b-Continued.

1152+04	190	-1	2.6	1732+16*	123	-1	5.5
1203+04	192	-1	4.6	1802+11*	151	1	6.3
1241+16*	121	2	9.1	1949+02	204	-1	15.6
1303+09*	162	-1	6.1	2019+09*	157	-1	9.7
1305+06	176	2	3.2	2029+18	109	+1	4.3
1317+17	114	1	3.8	2116+18	112	-2	4.0
1318+11*	149	-1	5.8	2120+16*	118	-2	6.5
1407+17	115	2	2.8	2126+07*	172	-2	6.8
1431+06	178	0	3.3	2150+05	184	-2	3.5
1434+03*	197	1	5.7	2210+01	209	1	3.4
1444+17	114	2	3.2	2251+15*	123	-2	14.3
1519+07	170	1	2.4	2309+09*	143	-2	7.1
1535+13	135	1	4.3	2334+08	165	2	3.5
1611+04	193	2	3.3	2338+04*	205	1	4.7
1641+17*	117	2	8.2	2345+18	110	-2	4.4

0° → -20°.

0005-06	264	-1	4.4	0159-11*	306	2	6.6
0016-12	3.5	1	9.7	0230-06	270	2	3.6
0019-00	220	0	3.1	0232-04	250	1	3.9
0034-01*	230	2	10.0	0310-15	331	0	6.1
0041-16	341	-2	3.0	0312-03	244	-1	3.6
0047-02	240	-3	3.9	0327-16	345	-1	3.7
0051-03*	247	2	6.2	0349-14*	328	-1	10.3
0055-01	231	-1	14.7	0357-16	341	-2	5.7
0056-00*	221	1	3.7	0403-13*	317	-2	6.8
0056-17*	349	2	6.2	0405-12*	310	-1	8.7
0057-18	355	0	3.4	0453-00	220	0	3.1
0102-12*	314	0	6.2	0502-10	295	0	4.5
0105-16*	341	-1	12.0	0508-18	361	1	5.8
0125-14*	325	-1	7.0	0533-12	309	2	3.3
0140-16	344	-2	4.4	0536-13	318	1	4.0
0148-09	287	2	4.6	0544-17	351	1	2.5
0155-10*	300	2	5.5	0600-13	317	0	4.1

TABLE 6.1b-Continued.

0605-08	274	1	4.8	1414-04	251	0	2.3
0636-16	345	-2	4.0	1414-03	248	2	4.5
0806-10*	296	2	11.6	1436-16*	346	0	5.1
0809-05.7	261	0	7.8	1451-19	366	2	4.9
0850-03	245	-2	4.2	1508-05*	260	0	7.7
0852-07	271	-1	2.8	1524-13*	322	2	5.7
0854-03	245	-2	3.8	1537-05	257	2	3.4
0859-05	257	1	3.8	1602-17*	351	0	5.1
0859-14	325	2	3.7	1636-03	243	2	3.7
0946-18	358	0	2.7	1712-03	244	2	3.3
1031-11	308	-1	4.0	2005-10	296	2	3.7
1110-01	235	1	4.4	2025-15*	335	0	5.0
1131-17*	352	2	5.2	2044-02*	239	-2	5.1
1135-12	315	0	3.8	2048-14*	399	0	5.6
1136-13*	321	0	12.4	2146-13*	318	2	5.0
1140-11	305	2	4.3	2154-18*	358	-1	5.5
1148-00	222	0	3.5	2203-18*	361	-1	9.2
1201-04.1*	250	0	6.3	2221-02	236	-1	15.1
1213-17	350	-1	2.9	2223-05	257	2	12.1
1239-04*	253	1	9.3	2234-17	350	-1	4.8
1245-19*	370	1	8.4	2236-17	351	-2	5.0
1306-09*	290	-2	7.8	2313-16	344	-1	4.2
1334-17*	356	2	5.0	2318-16*	344	1	9.1
1339-12	310	0	2.7	2322-12*	310	-2	6.8
1344-07*	277	0	5.8	2325-15	332	0	5.1
1349-05	260	-2	2.4	2329-10	294	1	4.3
1401-05	258	1	3.2	2338-16*	343	-2	5.4
1404-01	233	2	4.1	2347-02*	239	2	5.1
				2354-18	359	1	2.7
<u>-20° → -60°</u>							
0032-20*	373	-1	6.4	0042-35*	501	2	6.0
0035-39	531	-1	5.5	0049-43	565	0	8.4
0039-44*	574	2	9.8	0114-21*	380	2	9.8

TABLE 6.1b-Continued.

0129-51	630	1	3.9	1215-45*	586	1	9.0
0201-44*	571	-1	6.3	1226-21	382	2	3.0
0220-42	557	0	3.7	1232-41*	552	0	5.3
0231-23	400	1	3.9	1240-20*	380	1	5.0
0240-42	556	-2	4.1	1245-19*	370	1	8.4
0354-48	608	0	3.7	1247-40*	540	-1	5.7
0427-36*	509	0	9.3	1254-30	455	-2	4.1
0443-59	695	2	3.7	1328-25*	419	0	5.9
0445-22	389	2	4.0	1329-25	419	-1	3.6
0453-20*	377	2	10.5	1346-39	531	1	7.2
0535-49*	618	2	6.1	1355-41	552	1	12.9
0600-34	493	0	4.8	1359-35	503	2	4.3
0604-20*	374	-1	7.9	1411-30	456	-1	3.9
0614-34*	495	0	5.1	1414-21	382	0	2.6
0709-20*	377	1	7.1	1422-29*	453	2	8.4
0719-55	663	2	5.0	1528-29	449	2	3.7
0718-34	488	1	5.4	1643-22*	391	0	6.1
0825-20*	374	0	10.4	1814-51*	636	3	13.4
0850-20	377	1	9.6	1914-45	584	1	3.2
0903-57	680	-1	4.1	1917-54	657	2	4.8
0909-56*	672	1	5.4	1946-23	400	-1	3.6
0920-39	536	2	4.1	1953-42*	558	1	10.1
0947-24	413	2	5.6	2002-50	623	-1	3.1
1011-31	468	-1	5.5	2009-52	640	-1	5.0
1018-42*	560	1	13.0	2020-57*	680	1	9.9
1030-34*	489	2	6.4	2030-23	396	1	7.1
1116-46	591	-1	4.6	2049-36	511	-1	6.1
1136-32*	472	-1	6.9	2053-20*	372	1	6.5
1139-28*	443	1	7.1	2107-34	487	-1	3.6
1151-34*	495	0	9.7	2113-21*	380	0	8.5
1203-26	424	1	3.7	2128-20*	377	-2	6.8

TABLE 6.1b-Continued.

2150-52*	637	-2	9.7	2252-53*	644	0	5.3
2201-55*	664	1	5.8	2253-52*	638	-1	6.0
2204-54	652	0	3.6	2259-37*	516	2	7.1
2207-45	587	-2	3.9	2305-41	552	0	4.2
2213-45	584	-2	4.4	2319-55*	660	0	6.1
2223-52*	642	2	8.5	2323-40*	543	0	8.0
2244-37	514	-2	3.2	2338-58*	687	2	8.2

-60° to -90°.

0013-63*	725	-2	6.1	0905-68*	761	0	5.8
0119-63*	725	-2	5.0	0943-76	814	-2	5.0
0158-74	804	0	3.6	1010-64	736	-2	6.8
0202-76*	816	-2	8.3	1151-69	770	-2	5.3
0223-71	780	1	4.9	1610-77*	820	1	5.6
0230-66	748	2	4.1	1637-77	820	0	16.0
0420-62*	718	0	10.5	1716-80*	838	-2	6.4
0425-72	791	1	3.9	1737-60	706	2	9.3
0637-75	808	-2	9.9				

6.7 FLUX DENSITY ERRORS:

The uncertainties in the relative flux density values given in Tables 6.1-a and 6.1-b are due to following causes:

(a) Noise; (b) Confusion; (c) Calibration; (d) Source polarisation; (e) Atmospheric attenuation; (f) Ionospheric scintillation. The errors derived, will not include the uncertainty in the absolute level of these flux densities.

6.7-a Noise:

The r.m.s. noise fluctuations on the total power records, due to the system noise, were about 0.07 f.u. The uncertainty due to noise fluctuations in the flux densities determined by peak measurements is given approximately by this figure: the uncertainty in a 3 f.u. source is about 2%. Integrated flux densities have negligible uncertainty, due to system noise fluctuations, for sources with flux densities greater than 3 f.u.

6.7-b Confusion:

Fluctuations in the number of unresolved sources in the fan beam, produce fluctuations on the records with a standard error of about 0.2 f.u. This error is the major source of uncertainty for sources with flux densities near the lower flux density limit of 3 f.u.

An important operation for both peak and integrated flux density measurements is the determination of the background level in the vicinity of a source. In general this operation only becomes difficult when the source lies in a region where the background is changing rapidly or when the receiver gain stability is poor. This last factor is not important in the present case, since the receiver gain stability was excellent.

The Parkes catalogue does not include sources, which are on or near the Galactic plane; background variations are thus never severe. The uncertainty in the peak flux density due to

background uncertainties is about ± 0.1 f.u. For integrated flux densities the uncertainty is greater since the background level must be determined over a region several beam widths on either side of the source position. The total uncertainty in this case was estimated to be about ± 0.2 f.u.

Noise and confusion limit measurements made with the sinc^2 beam to peak flux density measurements. In order to determine the integrated flux density of point source with a sinc^2 beam, the integration interval must extend to at least seven beam widths on either side of the source; the confusion error then becomes quite large. Table 6.2 shows the fraction of the total beam area contained in the main beam plus increasing numbers of sidelobes for a sinc^2 beam; this table indicates the necessity for carrying the integration out to seven beam widths from the source.

For a gaussian beam the integration interval is about three beam widths on either side of the source peak; the confusion error is thus considerably reduced. The total error due to confusion in an integrated flux density is estimated to be ± 0.3 f.u.

TABLE 6.2
AREA BENEATH THE SINC² FUNCTION.

<u>Beam Widths</u> <u>from Peak</u>	<u>Area Include</u>	<u>Fraction of the</u> <u>total area.</u>
	Main Lobe	
	+ 1st sidelobe	0.903
$\sim 3\frac{1}{2}$	+ 2nd sidelobe	0.950
	+ 3rd sidelobe	0.966
	+ 4th sidelobe	0.976
~ 7	+ 5th sidelobe	0.980
	Total area	1

6.7-c Calibration:

It has been shown (6.5) that the ratio of peak to calibration deflection shows variations with an r.m.s. of about 4%. The calibration uncertainty in the relative flux density of a source will then be about 5.5% (the peak to calibration deflection has to be determined for both the reference and the arbitrary source).

Integrated flux density values have calibration uncertainty of about 4.9% (6.5-b).

The uncertainties arise principally because the reference noise signal only calibrates one of the twenty-two signal paths. It is also possible that the noise reference source output shows small variations.

6.7-d Source Polarisation:

The east-west aerial is linearly polarised with a position angle of 90° . Gardner and Davies (1966) investigated the linear polarisation of about 164 sources selected from the Parkes radio source catalogues. At 408 MHz eighteen sources had detectable linear polarisation, but only two had percentage polarisations greater than 2%. On the basis of these measurements it was decided not to make any corrections for linear polarisation, on the sources common to the Gardner's and Davies' list and to assume that the remaining sources at this frequency have negligible linear polarisation. This gives rise to an uncertainty of about $\frac{1}{2}\%$ in the source flux densities.

6.7-e Atmospheric Attenuation:

The present observations covered a zenith angle range of $\pm 55^\circ$. Over this range the apparent source flux density is related to the zenithal source flux density by

$$S(z) = S(o) p^{(f(z)-1)} \quad 6.13$$

where $f(z) \sim \sec z$ and p is the zenithal extinction factor.

Now $p = \exp(-\alpha_z)$, where α_z is the zenithal attenuation coefficient.

The zenithal attenuation at this frequency is about 0.4%.

(Howell and Shakeshaft, 1967). The maximum correction required in the relative flux density values over the above zenith angle range is about 0.3%. In view of this very small value, no correction was made to the measured relative flux densities for atmospheric attenuation. The absolute flux density values of the reference sources have been corrected for this effect.

6.7-f Ionospheric Scintillation:

Movement of irregularities in the ionosphere produce fluctuations in the strength of the signal received from a discrete radio source. The effect, while small at frequencies as high as 408 MHz, may not be negligible. Measurements at 400 MHz by Aarons et al., (1967) indicate that scintillations can produce fluctuation in amplitude of about 2% at this frequency.

No evidence of this effect was found on any of the transit records taken with the east-west aerial. A maximum uncertainty of 0.5% was allowed for in the results of the present observations.

6.7-g Final Errors:

The combined standard error in a relative flux density value determined at a single observation is either 5.5% or ± 0.3 f.u., whichever is the higher (Table 6.3). It is not necessary to distinguish between the errors in the flux densities determined by the peak or integration methods.

TABLE 6.3

ORIGIN OF THE ERRORS IN THE RELATIVE FLUX DENSITIES IN TABLE 6.1-b.

	Peak Flux Densities	Integrated Flux Densities
Noise	0.07 f.u.	negligible
Confusion	0.2 f.u.	0.3 f.u.
Calibration	5.5%	4.9%
Polarisation	0.5%	0.5%
Atmospheric Attenuation	0.2%	0.2%
Ionospheric Scintillation	0.5%	0.5%
Source Extension	2%	-
Areal Measurements	-	1.5%
Combined errors. (Standard error).	$\pm 5.9\% \pm 0.3$ f.u.	$\pm 5.2\% \pm 0.3$ f.u.

The uncertainty in the absolute level of the flux densities in Table 6.1-b is 5% (mean error).

The percentage part of the above error was reduced by repeated observations to give the values $\pm 4\%$ or ± 0.3 f.u. for the standard error in the relative flux densities given in Table 6.1-a. The quoted errors in this table include the uncertainty in the absolute flux densities of the reference sources as well as the uncertainty in the relative measurement. The errors given in the table are about $\pm 6.4\%$ or ± 0.3 f.u. for all sources except the five reference sources.

The uncertainty in the relative flux densities in Table 6.1-b is 5.5% or 0.3 f.u., whichever is the higher. Since the sources in Table 6.1-a provided the reference sources for the flux densities given in Table 6.1-b, the uncertainty in the absolute level of these flux densities is about 6% (standard error).

6.8 COMPARISON WITH PARKES FLUX DENSITIES:

The Molonglo scale flux densities for the 42 sources given in Table 6.1-a were compared with the Parkes flux densities given in the appropriate Parkes catalogue. The results of the comparison are given for each declination range shown in Table 6.1-a.

1. 0° to $+20^\circ$. The mean of the ratios of the Parkes to Molonglo flux densities is 1.00 ± 0.035 .

2. 0° to -20° 1.05 ± 0.05

3. -20° to -60° 0.98 ± 0.035

4. -60° to -90° 0.98 ± 0.05

*Additional ratios were derived in this declination range by making use of Molonglo flux densities from Table 6.1-b. This was necessary to improve the statistical significance of the result.

The results of comparisons in the four declination intervals are mutually consistent. This indicates that there is no declination dependent effect in the Parkes flux density calibration within the errors given above, although the individual surveys were made at different times.

It is interesting to note that the Parkes flux densities are already consistent with the present flux density scale values. This agreement appears to be entirely fortuitous. The Parkes flux densities were not independently calibrated, but rather an attempt was made to adopt the Conway, Kellermann and Long (1963) source flux densities for a number of sources common to both catalogues (Bolton et al., 1964). It has been previously noted by Day et al. (1966) and Shimmings et al. (1966), that the Parkes 408 MHz flux densities are on average about 10% higher than the Conway, Kellermann and Long values for all the common sources.

The agreement with the Parkes scale extends only to the strong sources. It has been shown by Murdoch and Large (1968) that sources with flux densities near the lower limit of the Parkes catalogues tend to be overestimated.

CHAPTER 7.

DISCUSSION OF RESULTS.

7.1 INTRODUCTION:

In this chapter the results of the present absolute flux density measurements will be compared with those of other experiments. This can only be done indirectly since no other absolute flux density measurements have been made on any of the Molonglo Scale calibration sources. The question of systematic error in the Molonglo flux density scale will also be discussed.

Low frequency flux density calibrations will also be reviewed, the stimulus being provided by the lack of agreement between the M.S.H. and northern scale flux densities. Possible sources of systematic error in Little's (1958) experiment will be investigated (this experiment provides the absolute basis for the M.S.H. catalogue source flux densities). The flux density calibration at the high frequency end of the radio spectrum is also discussed in this chapter.

The radio spectra of the Molonglo scale primary calibration sources are given at the conclusion of the chapter.

7.2 COMPARISON OF THE MOLONGLO AND OTHER SCALE FLUX DENSITIES:

No other absolute flux density measurements have been made at this frequency, or at any other frequency on the present five, primary scale calibration sources. The present measurements are only the second serious attempt at absolute measurement to be carried out on sources from the southern hemisphere; the other

measurements were those of Little (1958), who observed five different sources at 85.5 MHz. Consequently, no direct comparison can be made with the results of other absolute flux density experiments.

It is possible, however, to compare the flux densities of sources based on the present scale, with those based on other absolute flux density measurements. The catalogues of Conway, Kellermann and Long (1963) and Kellermann (1964a) provide the best means for doing this. Both these catalogues contain the flux densities at 400 MHz (S_{400}) and the spectral indices of a large number of northern radio sources. The spectra of these sources were derived from measurements, which have as their absolute bases, absolute flux density measurements made on Cas.A. Since the calibration procedure differs in the two catalogues, it is useful to compare the present scale source flux densities (Table 6.1-a) with those in both catalogues.

7.2-a Comparison with Conway, Kellermann and Long:

Conway, Kellermann and Long (hereafter referred to as C.K.L.) give the flux densities of a large number of sources at the following frequencies: 38, 178, 240, 408, 412, 710, 958, 1420 and 3200 MHz. The measurements were made relative to seven reference sources: 3C 123, 3C 161, 3C 196, 3C 348, 3C 353, 3C 380 and 3C 409. These sources were selected since they had small diameters and appeared to have power law spectra in the

frequency range 38 to 1420 MHz. The scale at each frequency was defined in the following manner:

(i) The flux densities of the seven reference sources were determined by relative measurements to Cas.A at the frequencies where absolute flux density measurements existed (38 MHz, Adgie and Smith, Long; 400 MHz, Seeger; 1420 MHz Findlay and Hvatum (1960)); the resulting flux densities define the scales at these frequencies.

(ii) The spectra of the seven sources were then determined; flux densities derived from these spectra defined the scale at intermediate frequencies. Thus the spectra of the reference sources were used only for interpolating to frequencies, where reliable absolute flux density measurements had not been made (1961.0).

(iii) At 3200 MHz the relative flux density measurements of all sources were made directly to Cas.A.

The catalogue gives the spectral index α (defined by $S \propto f^{-\alpha}$) for each source together with the S_{400} flux density value. Sources which have curved spectra (i.e. α a function of frequency) are noted in the catalogue. The C.K.L. flux densities of all sources common to C.K.L. and Tables 6.1-a and 6.1-b (Table 7.1) were adjusted to S_{408} using the S_{400} and α values given and the mean ratio of the C.K.L. to Molonglo flux densities determined;

a value of 0.90 ± 0.03 was obtained. The Molonglo scale flux densities are on average 11% higher than the adjusted S_{400} values given by C.K.L.

An equivalent Cas.A flux density can now be derived; it will be 11% higher than the adjusted S_{400} (adjusted to S_{408}) value given by C.K.L. for epoch 1961.0.

$$S_{408} = 6680 \pm 540 \dots 1961.0$$

$$S_{408} = 6440 \pm 540 \dots 1964.4$$

The 1961.0 value was adjusted to epoch 1964.4 using a decrease rate of 1.1% per annum. (Baars et al. 1965). Use shall be made of these Cas.A flux density values later in this chapter.

7.2-b Comparison with Kellermann:

The flux densities in Kellermann's catalogue bear a different relationship to the absolute measurements than do the flux densities given by C.K.L. Systematic errors, due to the uncertainty in the results of individual absolute measurements, are minimized by Kellermann's calibration procedure (Kellermann 1964a).

The source flux densities and spectral indices in Kellermann's catalogue were derived in the following manner:

(i) The spectrum of Cas.A was determined over the frequency range 38 to 1420 MHz using the best available (1961) absolute flux density measurements.

(ii) The spectra of Cyg. A, Tau. A and Vir. A were then determined by relative measurement to Cas.A. The four sources were the primary standards for the calibration of the flux density scales at each frequency.

(iii) These four strong sources were used to calibrate the power law spectra of five moderately strong, small diameter sources (3C 123, 3C 348, 3C 353, 3C 380 and 3C 409), which become the reference sources for all other relative flux density measurements.

(iv) At 2841 MHz the scale was determined directly from the observed ratios of the five calibration sources to Cas.A and Tau.A at nearby frequencies i.e. not based on the spectra of the five sources.

The 400 MHz flux densities given in the catalogue, for source common to Table 6.1-a, were adjusted to 408 MHz using the spectral indices given. The mean of the ratios of the Molonglo to Kellermann scale flux densities was found to be 1.09 ± 0.03 , for the twenty-two common sources (Table 7.1); the present scale flux densities are an average 9% higher than those based on absolute flux density measurements on Cas.A. Later it will be shown, that this result is a more useful estimate of the differences between the results based on the present absolute flux density measurements and those based on Cas.A measurements.

TABLE 7.1

<u>CATALOGUE CLASSIFICATIONS</u>		<u>FLUX DENSITIES AT 408 MHz.</u>		
<u>PKS</u>	<u>3C</u>	<u>Molonglo</u>	<u>C.K.L.</u>	<u>Kellermann</u>
0010+00	5	4.4	3.7	4.2
0035-02	17	16.3	13.4	14.5
0038+09	18	14.8	13.7	11.5
0218-02	63	12.2	9.1	10.7
0240-00	71	11.7	9.9	10.3
0358+00	99	6.7	6.0	-
06-04 (MSH)	161	41.9	40.1	41.0
0742+02	187	6.6	5.4	5.8
0802+10	191	7.4	5.5	6.1
0915-11	218	135	130.5	134.5
0947+14	228	11.1	10.1	10.6
1005+07	237	16.2	15.1	15.2
1040+12	245	8.2	6.6	7.1
1226+02	273	62.6	58.8	60.7
1239-04	275	9.3	6.5	6.7
1253-05	279	12.8	12.4	12.9
1416+06	298	25.5	24.0	22.9
1514+07	317	28.0	25.0	22.2
1949+02	403	15.5	16.6	15.4
2211-17	444	33.2	27.1	26.8
2221-02	445	15.1	15.1	15.5
2309+09	456	7.1	7.2	8.0
2313+03	459	16.0	12.6	12.9
MEAN RATIOS (Mol/-)		1.00	1.11	1.09

The equivalent Cas.A flux density based on the Molonglo scale will be 9% higher than the adjusted S_{400} value given by Kellermann:

$$S_{408} = 6860 \pm 480 \quad 1961.0$$

adjusted to epoch 1964.4:

$$S_{408} = 6640 \pm 470 \quad 1964.4$$

This value is higher than the C.K.L. value given above, since the S_{400} value given by Kellermann is 5% higher than the value given for epoch 1961.0 by C.K.L.

The results of these scale comparisons show that flux densities based on the present absolute flux density scale are about 10% higher than those based on northern flux density scales.

7.2-c Comparison with Recent Results:

Since the publication of Kellermann's catalogue the results of a number of absolute measurements on Cas.A have appeared. It is proposed therefore, to compute the Cas.A spectrum from all the available absolute flux density measurements: the new spectrum will then be compared with the spectrum, which forms the absolute basis of the flux densities given by C.K.L. and by Kellermann. This method provides the only means of checking whether or not the results of the present absolute flux density experiment, are compatible with recent measurements on Cas.A.

The flux density values used in the computation of the Cas.A spectrum are given in Table 7.2; the flux densities have

TABLE 7.2

ABSOLUTE FLUX DENSITY MEASUREMENTS ON CAS.A.

<u>Frequency MHz</u>	<u>Epoch of Observation</u>	<u>FLUX DENSITY</u>		<u>REFERENCE (Table 2.2)</u>
		<u>Corrected*</u> <u>to 1964.4</u>	<u>Mean Error %</u>	
38.0	1955	39210	10	Adgie & Smith
38.0	1966.9	37200	3.7	Parker
81.5	1955	20910	10	Adgie & Smith
81.5	1966.9	21680	2.9	Parker
152.0	1966.5	13130	2.9	Parker
320	1962.7	7681	5	McRae & Sequist
400	1955.6	5075	15	Seeger
(408(C.K.L.))	1967.5	6440	7%	Present work)
(408(Kell.))	1967.5	6640	6%	Present work)
562	1962.5	4858	3	Lastochkin et al.
708	1962.5	4084	2.5	" " "
860	1962.5	3296	2.5	" " "
1,190	1962.5	2987	4	" " "
1,419	1958.4	2492	12	Mezger
1,440	1963.0	2334	2.4	Findlay et al.
2,390	1961.2	1420	15	Ohm & Snell(1963)
2,700	1960.6	1326	10	Altenhoff et al.
2,924	1962.5	1495	3	Khrulev
3,060	1961.5	1413	3.4	Stankevich
3,150	1964.4	1260	4.8	Medd & Ramana
3,200	1959.4	1268	5.5	Broten & Medd
4,080	1964.8	1091	2.4	Penzias & Wilson
6,660	1965.0	679	4.8	Medd & Ramana
8,250	1966.0	627	3.6	Allen & Barrett
9,360	1961.5	503	2.9	Stankevich
9,375	1962.7	504	5.0	Lastochkin et al.
15,500	1966.0	387	4.8	Allen & Barrett

* Values corrected to epoch 1964.4 using a decrease rate
of 1.1% per annum.

been corrected to epoch 1964.4 using a secular change of -1.1% per annum. All of the experiments listed in this table are mentioned in Chapter 2 of this thesis. Parker (1968) has computed the power law spectrum (a straight line on a log-log plot) which best fits these values over the entire frequency range; he obtained a spectral index of 0.77. This value is in excellent agreement with the value given by Kellermann. However, it was necessary to repeat the Parker computation in order to determine the S_{408} value from this spectrum.

A linear least squares fitting programme, which weights each point according to the square of the standard error, was used in the computation. The parameters of the Cas.A spectrum computed from the values given in Table 7.2 are given in Table 7.3. Results presented by other observers are also given in this table.

TABLE 7.3

CHARACTERISTICS OF SOME SPECTRA COMPUTED FOR CAS.A.

<u>Reference</u>	<u>α</u>	<u>Frequency Range</u>	<u>$S_{408}(1964.4)$</u>	<u>Ratios</u>
Parker	0.77	38 - 15,500	-	
Present Work	0.77	38 - 15,500	6,120	1.00
Kellermann	0.77	38 - 1420	6,110	1.00
C.K.L.	0.77	38 - 1420	5,810	0.95
Baar et al	0.77	320 - 6000	-	
(1965)	1.18	7000 - 14,500		



The Cas.A spectrum derived by Kellermann agrees almost exactly with that based on all recent absolute measurements. The C.K.L. spectrum has an identical slope but the intercept at 408 MHz is about 5% lower than Kellermann's value.

Comparison can now be made of the Cas.A values derived in sections 7.2-a and 7.2-b with the expected value from the spectrum given by the present work in Table 7.2. The Cas.A value derived using Kellermann's source flux densities is about 9% greater than the value given in Table 7.2. Thus, scale flux densities for sources based on the present absolute flux density measurements are on average, 9% higher, than those based on a spectrum of Cas.A derived from all the absolute flux density measurements made on this source (i.e. derived in some manner as Kellermann's scale). This difference amounts to about one standard error in the results compared. The Cas.A flux density derived from C.K.L.'s catalogue flux densities (Table 7.3) is 6% higher than the computed value: the result, while indicating a closer agreement between the sets of absolute measurements, is not as significant as the results of the previous comparison. The calibration procedure in Kellermann's catalogues is more reliable than in C.K.L.'s.

The absolute basis of Kellermann's flux density scale at 408 MHz is consistent with recent absolute flux density measurements. The Molonglo absolute flux density scale therefore leads to source flux densities, which are significantly higher

than those based on a northern scale consistent with all absolute measurements on Cas.A.

7.2-d Sources of Systematic Error in the Present Experiment:

The present absolute flux density experiment was performed using the two methods given in Chapter 3, in order to reduce the possibility of systematic errors in the final absolute flux density values.

The two most important factors in any absolute flux density measurement are the temperature of the noise reference source and the gain of the standard aerial. Systematic errors in either of these quantities appear as a bias in the final flux densities. Obviously, one is not aware of the presence of any systematic error in a particular experiment, however, it is possible to estimate the most probably sign of the bias produced by an unsuspected and undetected systematic effect.

The reference aerial was common to both methods used in this experiment: All factors affecting the gain, except the feed loss estimate, would be likely to reduce the real value from that calculated; excluding of course a computational error. Scattering from objects in the vicinity of the array could conceivably increase the aerial response in a particular direction, but the present flux density scale is based on the observations of five sources with a wide range of declinations. If the gain of the actual array is less than the calculated

value the observed flux densities are too low i.e. the source flux densities would be underestimated rather than overestimated. The feed and dipole loss used to determine the array gain is small and an overestimation of more than several percent seems unlikely.

The second factor is the thermal calibration of the reference noise source. The noise source was modified between the January/April and September observing periods and hence required recalibration. The equipment used for the thermal calibration during the second observing period differed almost completely from that used in the first; the only common elements were the attenuators, the values of which were independently checked by R. Wielebinski in the School of Electrical Engineering. It is expected that the thermal calibration of the reference noise source does not introduce a bias in the final flux density values greater than the quoted uncertainty in the temperature values. The conclusion therefore is that the present scale flux densities are most likely to be underestimates of the true source flux densities.

This analysis, together with the results obtained from scale comparisons, suggests that the northern scale flux densities at frequencies about 400 MHz are too low.

It is unfortunate that direct comparisons of the absolute bases of the flux density scales cannot be made. It is not

impossible that there are declination dependent effects in the northern scales since all the comparisons have been made with sources near the equator. Also, the possibility of non-linear effects in transferring from the strong calibration sources to the weaker sources used in the comparisons, should not be ignored.

7.3 FLUX DENSITY SCALES AT OTHER FREQUENCIES:

Some anomalies in the results of the experiments discussed in Chapter 2 and tabulated in Table 2.2 will be given in this section. The flux density calibration at relatively low and relatively high frequencies will be investigated (frequencies relative to 400 MHz).

7.3-a Higher Frequency Calibrations:

The absolute flux density measurements at 1440 MHz of Findlay et al. (1965) probably provided one of the most reliable absolute flux density calibration values over the entire frequency range. It seems unlikely that future measurements at this frequency will disagree with their value by more than the published errors. The only limitation on the usefulness of this result lies in the inherent disadvantages of using Cas.A as the flux density calibration source (2.3-b); the particular disadvantages are the high flux density, the large diameter and most particularly the flux density decrease with time. The method used in the present absolute flux density

measurements provides in principle a means of overcoming these disadvantages by making possible measurements on many sources, from which sources with ideal characteristics can be selected. In practice the only limitation of this method is that an aerial with a large effective area (Method II, Chapter 3) must be available. The present methods provide the best available means for making absolute flux density measurements at frequencies less than about 1,000 MHz.

The majority of measurements claiming accuracies better than 6% (mean errors), have been made in the frequency range 1,000 to 10,000 MHz (e.g. Table 7.2). Apart from the discrepancies between the results of the different measurement techniques at frequencies about 3,000 MHz (section 2.3-c), there is overall agreement between the results of various experiments; even these discrepancies may be due to random errors. In future discussions it shall be assumed that the flux density calibration in this frequency range is fairly satisfactory.

Above 10,000 MHz there exists only three absolute flux density measurements: Allen and Barrett (1967) at 15,500 MHz and Tolbert and Straiton (1965) at 35,000 and 70,000 MHz. Measurements become extremely difficult at these high frequencies (section 2.4-a). At m.m. wavelengths it was only possible for Tolbert and Straiton to determine the flux density of Taurus A; Taurus A is the strongest discrete source in this wavelength

range. These high frequency measurements are compatible with a power law spectrum spanning the metre to mm wavelength ranges.

Many more absolute flux density measurements are required in this very high frequency range. Accurate atmospheric data will be required if the corrections for atmospheric attenuation are not to be a limiting factor on the accuracy of the measurements.

7.3-b Lower Frequency Calibrations:

Little (1958) determined the absolute flux density at 85.5 MHz of five moderately strong radio sources observable from the southern hemisphere: Virgo A, Taurus A, Hydra A, Pictor A, and Hercules A. The experiment provided the flux density calibration sources for all flux density values given in the M.S.H. catalogues (Mills et al. 1958, 1960, 1961). It has been noted (e.g. Kuzmin 1962) that the flux densities in these catalogues are somewhat higher than the flux densities for the same sources based on northern flux density scales. Up to the present time there has not been a complete discussion of these scale differences at this frequency. The important point is that the M.S.H. flux densities are based on careful absolute flux density measurements. The scale discrepancies therefore indicate a serious systematic difference in the absolute bases of the northern and southern flux density scales.

The present discussion will include:

- (1) estimates of the systematic differences between the northern and M.S.H. scale flux densities.
- (2) an attempt to determine the flux density calibration scale at about 80 MHz from source spectra, and
- (3) a critical examination of Little's experiment.

1. Kuzmin (1962) stated that the M.S.H. catalogue source flux densities are too high by 25%. I compared the M.S.H. flux densities with values derived from the C.K.L. catalogue for a number of common sources having power law spectra. $S_{85.5}$ values were derived from the C.K.L. catalogue for these sources, using the S_{400} values and spectral indices provided. The mean ratio of the M.S.H. to derived C.K.L. source flux densities is 1.27 ± 0.07 ; this value agrees with the estimate given by Kuzmin. The error in this ratio makes the difference from unity highly significant. There is a definite indication of a systematic error in at least one of the scales.

The northern flux density scales are all based on absolute measurements made on Cas.A. It should be noted that all of the sources compared are near the equator and are much weaker than Cas.A. As suggested previously it is not impossible that there are both declination and non-linear effects in the northern flux density scales. It is not, however, suggested that these effects account completely for the scale discrepancies. A systematic statistical overestimation of the weaker sources in

the M.S.H. catalogues has been discussed by Mills et al.(1960); this would be particularly serious north of the equator where the sensitivity was decreasing rapidly. This could stimulate an overestimation of the absolute scale, so it is desirable to make intercomparisons on the calibration sources themselves.

The M.S.H. flux density calibration sources are given in Table 7.4 together with the derived C.K.L. values. An absolute flux density value for Taurus A due to Parker (1968), is also given in this table. Parker's value is consistent with the C.K.L. scale at this frequency.

TABLE 7.4

M.S.H. FLUX DENSITY CALIBRATION SOURCES.

Source	M.S.H.No.	<u>FLUX DENSITY</u>		<u>RATIOS M.S.H.</u>	
		Little	Derived C.K.L.	Parker	C.K.L.
VIRGO A		2430	2100	-	1.16
TAURUS A		2300	1875	1880 (S _{81.5}) 1855 (S _{85.5})	1.23
HYDRA A	09 - 14	670	525	-	1.28
HERCULES A	16 + 010	890	670	-	1.33
PICTOR A	05 - 43	570	-	-	-

$$\text{MEAN RATIO} = 1.25 \pm 0.09.$$

The quoted uncertainties in the flux densities given by Little are 10%.

A direct comparison can be made of the flux density values obtained by Little and Parker for Taurus A (Table 7.4). Parker's values were adjusted to 85.5 MHz using a spectral index of 0.25

(e.g. Parker, 1968) for the source. The mean error in Parker's flux density is 10%. The ratio of these Taurus A flux densities is 1.24 ± 0.17 ; the difference from unity is about $1\frac{1}{2}$ times the standard error in the ratio. The large error means that the results of these two absolute flux density experiments are not incompatible. Consequently, it is not possible at this stage to decide whether the scale discrepancies arise in the absolute bases of the scales or in the comparison method.

2. It may be possible to decide whether the northern flux density calibration is too low or, alternatively, the M.S.H. calibration is too high at about 80 MHz, by making use of source spectra. The spectra of four of the M.S.H. calibration sources (Table 7.4) were derived using higher frequency measurements and then extrapolated to lower frequencies. It has been suggested earlier in this chapter that the flux density calibration at higher frequencies (about 1,000 MHz) appears to be satisfactory.

The results of all absolute flux density measurements made on Taurus A are given in Table 7.5. A value based on the present absolute flux density scale is also included in this table. This value is derived in a similar manner to the Cas.A values given in section 7.2. A spectrum, derived from a weighted least squares fit to measurements at frequencies above 562 MHz, is shown in Figure 7.1. The line has a slope of 0.255 ± 0.035 . The large error in the slope means that a scale defined by this

spectrum at 85 MHz, would have an uncertainty of about 10%. Little's value lies about two standard errors from the spectrum shown in Figure 7.1 but would be only one standard error from a spectrum with a slope of 0.29; this value is consistent with the errors in the spectral index given above. It should also be noted that the Molonglo 408 MHz value (Table 7.5) is in good agreement with this latter slope.

The evidence may indicate that Little's Taurus A flux density is too high. It should be noted however, that a value 12% lower than Little's value, but still 12% higher than Parker's value would be quite consistent with the data presented here. The true flux density at 80 MHz may in fact lie between the M.S.H. scale and the present northern scales.

Of course the analysis of the spectrum to give inferences about the low frequency calibration is only indicative. If the source does not have a constant spectral index (i.e. α is a function of frequency) then the comparisons above are invalid. For example, it is known that Taurus A has associated with it a low frequency source with a very steep spectrum. (Hewish and Oke, 1964: Andrew et al. 1964). This makes the above comparisons doubtful. A similar caution applies to the remainder of the spectral analysis.

The only absolute measurements made on the remaining three sources are those of Little, Adgie & Smith (Virgo A) and

Mezger (Virgo A & Hydra A). The flux densities used to compute the spectra are however based on absolute flux density measurements. At 8,000 MHz the flux densities used are those given by Dent and Haddock (1966). These flux densities are based on absolute Cas.A values given by Stankevich (1962) and Lastochkin et al. (1963) at a nearby frequency. Flux density values given in the Parkes catalogues at 1410 MHz and 2650 were also used. At these frequencies the Parkes values are consistent with the C.K.L. scale. Kellermann's (1964a) values at 475, 710, 958 and 1410 MHz were used, when provided for these sources; the scale calibration at each of these frequencies has been described in section 7.2. Flux densities based on the present absolute scale were used at 408 MHz, when available.

The source spectra are shown in Figures 7.2-a and 7.2-b. Little's absolute flux density values agree well with spectra determined for Hydra A and Hercules A. Unfortunately there are too few measurements on Virgo A to arrive at any conclusions.

The significant point from the above analysis is that while Little's flux densities are high in every case, they are never inconsistent with the derived spectra; the values lie less than one standard error from the spectra in two cases, and less than two standard errors in the other. While the M.S.H. flux densities may be high, the analysis above would be consistent with a scale which led to flux densities about 12% lower than flux densities given in the M.S.H. catalogues for the same sources.

TABLE 7.5

ABSOLUTE FLUX DENSITIES OF TAURUS A.

<u>Frequency (MHz)</u>	<u>Flux Density f.u.</u>	<u>Mean Error %</u>	<u>Reference.</u>
81.5	1880	10	Parker (1968)
85.5	2300	8	Little (1958)
152.0	1430	10	Parker (1968)
210	1590	25	Adgie & Smith (1956)
(408	1337	10	Present Work)
500	1000	25	Adgie & Smith (1956)
562	1110	6	Lastochkin et al (1963)
708	910	5	" " "
860	1016	10	" " "
876	1000	3	" " "
1190	980	7	" " "
1419	968	12	Mezger (1958)
2700	811	10	Altenhoff et al (1961)
3150	695	5	Medd & Ramana (1965a)
3200	680	6	Broten & Medd (1960)
6660	565	5	Medd & Ramana (1965b)
8250	567	3.6	Allen & Barrett (1966)
9360	560	5.4	Lazarewskii et al (1963)
15,500	461	4.8	Allen & Barrett (1966)
35,500	420	14	Tolbert & Straiton (1965)

FIGURE 7.1

Plot of the results of all absolute flux density measurements on Taurus A. The spectrum is a weighted least-squares fit to the results at frequencies greater than 500 MHz. A flux density value based on the Molonglo flux density scale is also shown ($\square$).

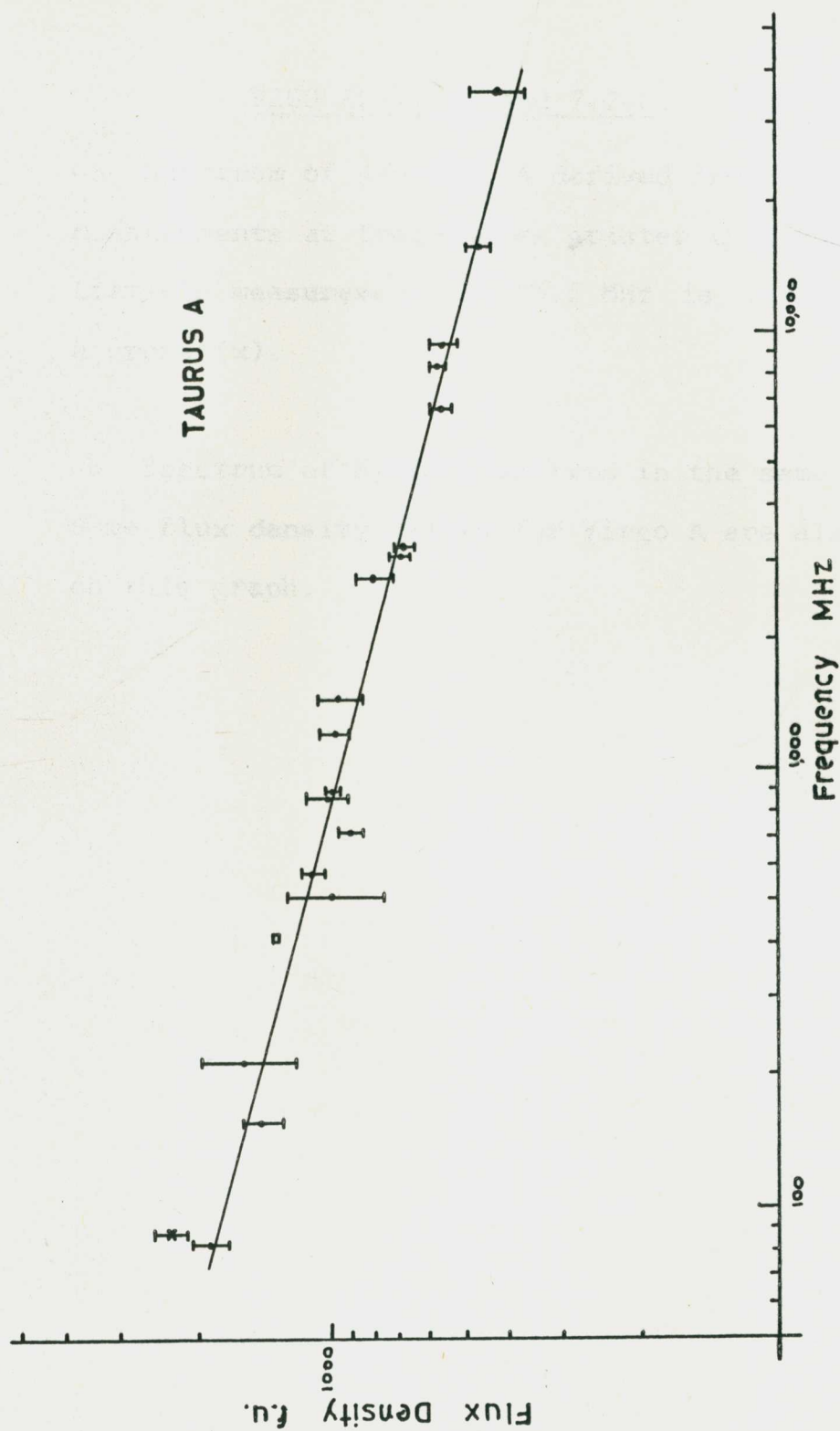


FIG. 7.1

FIGURES 7.2-a and 7.2-b.

-a Spectrum of Hercules A derived from a fit to measurements at frequencies greater than 200 MHz. Little's measurement at 85.5 MHz is marked with a cross (x).

-b Spectrum of Hydra A derived in the same manner. Some flux density values for Virgo A are also shown on this graph.

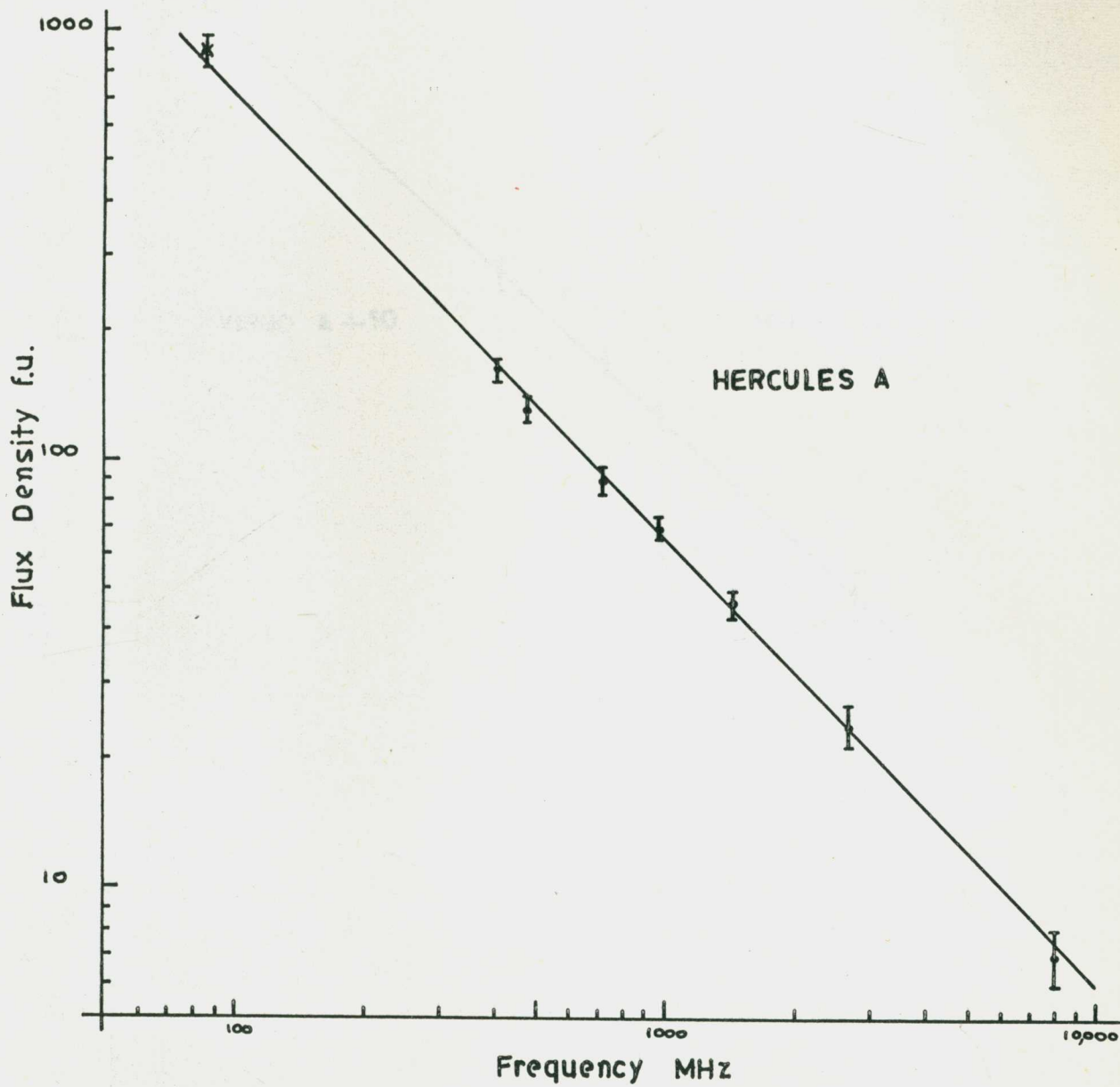


FIG. 7.2a

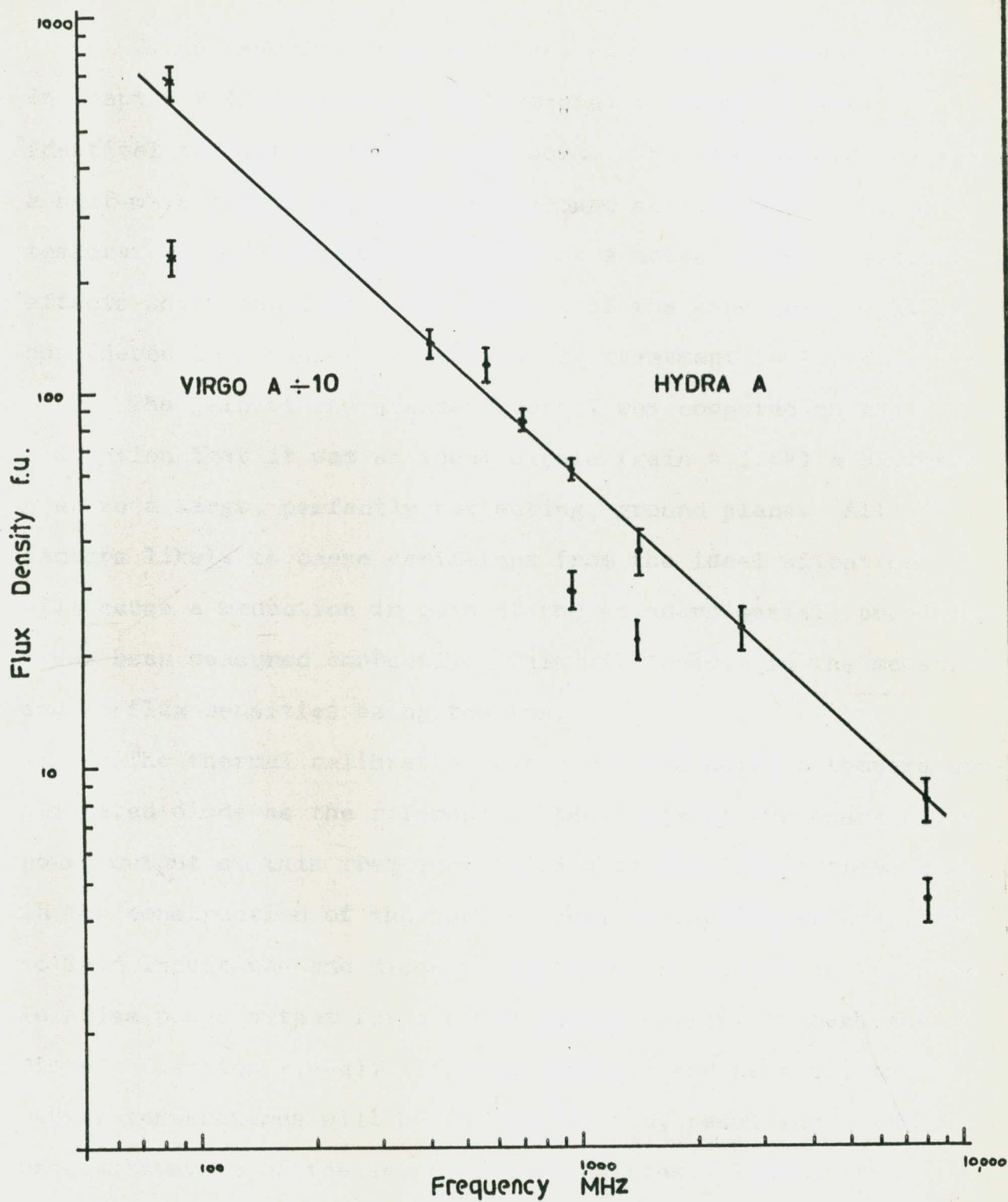


FIG. 7.2b

3. A description of Little's experiment has been given in Chapter 2 (2.3-d); the experimental method is almost identical to that in the present work. The standard aerial was a half-wave dipole above a large ground screen, while the temperature reference was provided by a noise diode. Systematic effects which could bias the results of the experiment will be considered in a manner similar to the treatment in 7.2-d.

The gain of the standard aerial was computed on the assumption that it was an ideal dipole (gain = 1.64) a distance h above a large, perfectly reflecting, ground plane. All factors likely to cause variations from the ideal situation will cause a reduction in gain of the standard aerial; providing h has been measured correctly. This will result in the measured source flux densities being too low.

The thermal calibration was performed using a temperature-saturated diode as the reference. Knowledge of the exact noise power output at this frequency (85.5 MHz) requires extreme care in the construction of the source: series resonant effects, due to lead inductance and diode capacitance, result in an increase in noise power output for a given direct current through the diode. (Section 2.3-a). If these effects are present, the aerial temperatures will be underestimated, resulting in the underestimation of the source flux densities. Transit time effects in a diode, do produce a reduction in noise power output

with increasing frequency, which would result in an over-estimation of measured source flux densities; these effects, however, were negligible with the diode used in this experiment.

Thus, the most likely sources of systematic error in Little's absolute flux density experiment would tend to bias the measured flux densities to lower values, if such errors were present.

The advantages of the method used by Little (and the experiment described in this thesis) for absolute flux density measurements have been enumerated in Chapter 2: the good resolution of the aerial configurations used in the experiment is one of the most important advantages. The possibility of confusion from sources with comparable flux densities to that being measured is negligible in Little's experiment, but of considerable importance in the experiments of Parker, and Adgie and Smith. With these experiments the radiation pattern of the aerals used (2.3-b), cover large regions of the sky. There are several sources (3C 123, 1C 443) near Taurus A with flux densities about 1/5th that of Taurus A: several weaker sources (Orion nebula and 3C 134) should also be considered. The possibility of confusion effects in these latter experiments is quite important.

C.K.L. scale flux densities have as their absolute basis, absolute flux density measurements on Cas.A. The result of the

comparison of the M.S.H. and C.K.L. scale flux densities agrees with the result obtained from the Taurus A comparison (Table 7.4) as previously noted. This agreement makes it difficult to suggest that the low frequency Taurus A flux density measurements are seriously confused; Cas.A at low frequencies is about 10 times stronger than Taurus A and hence less likely to be confused. Cas.A measurements are confused to some extent by the strong source Cyg.A, but allowance can be made for this effect.

The discussion above strongly suggests that the low frequency flux density calibrations are unsatisfactory. The source of systematic error in either the northern or southern or both these flux density measurements is not apparent. The evidence for such an error, however, lies in the significant disagreement between the scale flux densities. The result of the discussion on the M.S.H. calibration source spectra probably indicates that Little's flux densities are high. However, it seems most unlikely that all of the differences between the northern and M.S.H. scale flux densities can be explained in this way.

Southern source flux densities based on northern scales at about 80 MHz are therefore considered to be too low. Additional evidence for this comes from the results of the Molonglo and northern scale (408 MHz) flux density comparisons. These results suggest that the northern flux densities at 408 MHz for sources

near the equator are likely to be low. If the high frequency calibration is regarded as satisfactory, the Molonglo scale would indicate that northern, lower frequency flux density scales are also too low. This is true providing the majority of sources have power law spectra.

Determination of the true scales at frequencies of 100 MHz and less will clearly need more absolute flux density measurements. The measurements should be made on sources which do not have the disadvantages (given in Chapter 2) of the strong sources Cas.A and Cyg.A. The excellent resolution and sensitivity of the method employed by Little and by the author make this method ideal for measurements at about 100 MHz.

7.4 SPECTRA OF THE MOLONGLO SCALE CALIBRATION SOURCES:

The spectra of the five Molonglo scale calibration sources are shown in Figures 7.3-a and 7.3-b. The spectra are presented here merely for completeness, since the characteristics of these spectra have previously been noted.

The flux densities used to produce the spectra are based on the following scales:

85.5 MHz : M.S.H. source flux densities. The calibration of this scale has been fully discussed.

408 MHz : Molonglo scale flux densities,

1410 and 2650 MHz : Parkes flux densities. At these frequencies the flux densities are based on the C.K.L. scale.

8000 MHz : Flux densities given by Dent and Haddock (1966). The calibration of their values was described earlier.

475, 710, 958

1410 MHz : Flux densities given by Kellerman (1964a).

3C 273: The spectrum of this source has been the subject of many investigations (e.g. Von Hoerner, 1966) and has a positive curvature. This curvature is due to the fact that the source consists of two components (Hazard et al. 1963) with differing spectra. At high frequencies the component with the flatter spectrum dominates, while at lower frequencies, the steeper component contributes the majority of the source flux density.

At frequencies above about 1,000 MHz 3C 273 shows flux density variations (Pauliny-Toth and Kellermann, 1966), and hence has a time variable spectrum. At 408 MHz this source appears to have a stable flux density. Obviously 3C 273 is not suitable as a scale reference source at high frequencies or as spectral reference source over the entire spectrum.

06 - 04 (3C 161): This source is the only one of the five which lies near the Galactic plane ($b \approx 8^\circ$). C.K.L. (1963) suggested that this source had a negatively curved spectrum. The values plotted here however would be consistent with a power law spectrum over the frequency range 100 to 5,000 MHz.

FIGURES 7.3-a and 7.3-b.

-a Spectra of 3C 273 and MSH 06-04 derived from flux densities in the frequency range 85.5 to 8000 MHz.

-b Spectra of PKS 0521-36, PKS 1932-46 and PKS 0408-65 derived from a limited number of flux density values in the frequency range 85.5 MHz to 2800 MHz.

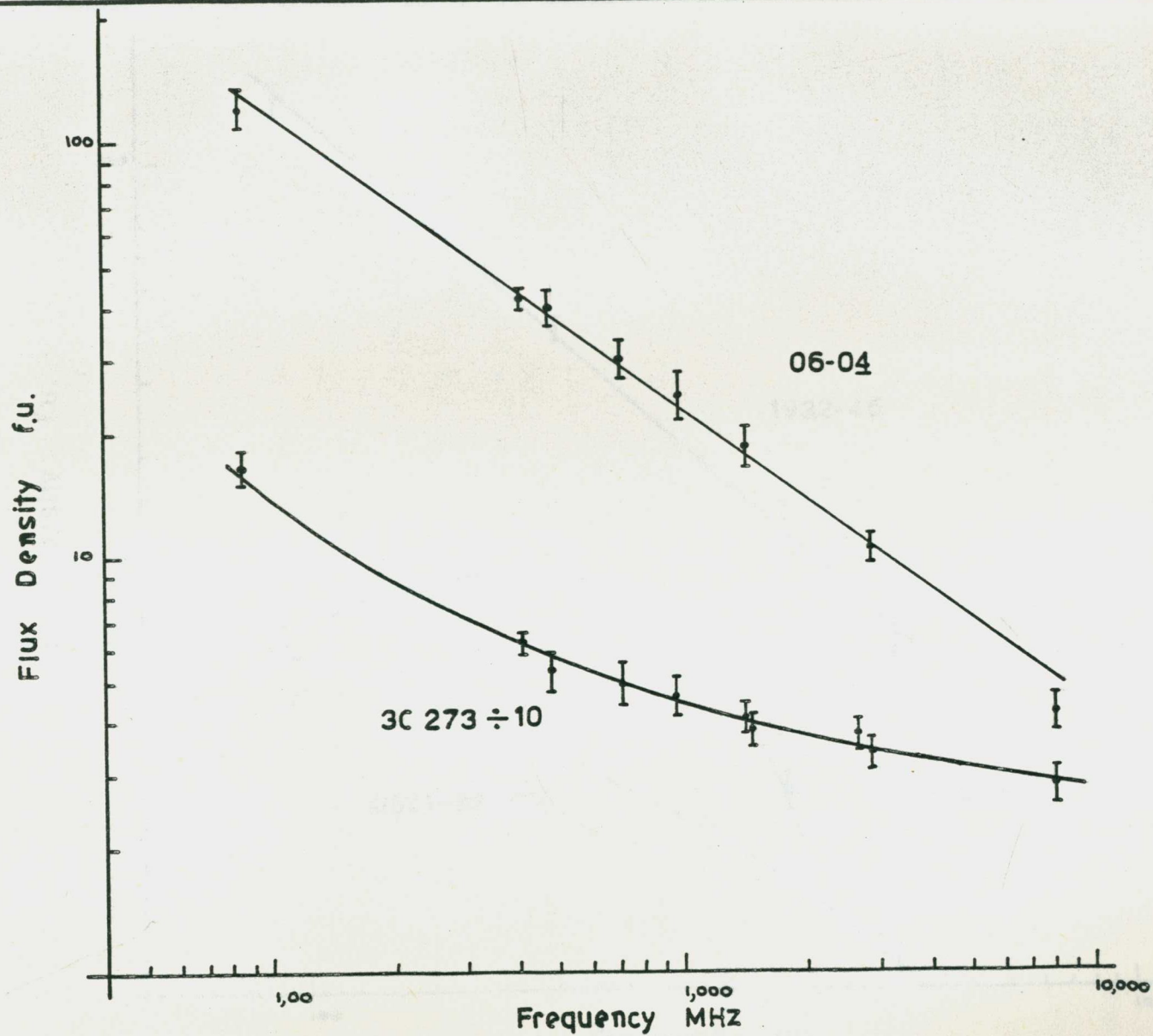


FIG. 7.3a

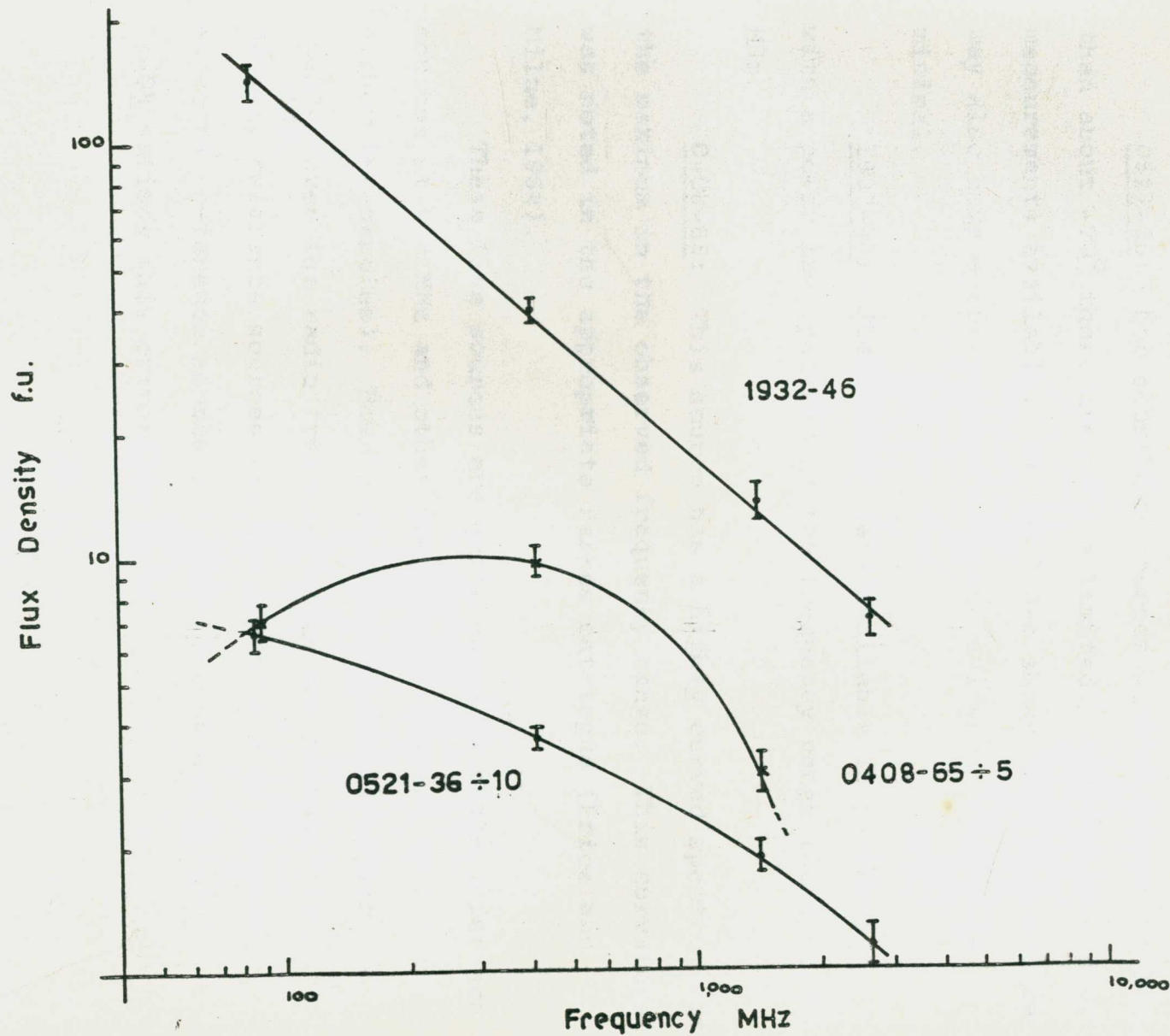


FIG. 7.3b

0521-36: For southern sources with declinations less than about -20° there are only a limited number of flux density measurements available. Figure 7.3-b shows that this source may also have a curved spectrum; the evidence however is minimal.

1932-46: The limited data available is consistent with a power law spectrum in the frequency range 100 to 2,000 MHz.

0408-65: This source has a highly curved spectrum with the maximum in the observed frequency range. This curvature was noted in the appropriate Parkes catalogue (Price and Milne, 1964).

These five sources are quite suitable scale reference sources at 408 MHz and other frequencies (except 3C 273 at higher frequencies). However, only sources with power law spectra over the radio frequency range are suitable flux density reference sources for the production of spectra (spectral reference sources). Only 1932-46 and possibly 06-04 satisfy this criterion.

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