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OBSERVATIONS AND ANALYSIS OF GEOMAGNETIC FIELD VARIATIONS NEAR THE MAGNETIC EQUATOR

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CONTENTS

ABSTRACT

In 1961 a magnetic observatory was established at Freetown, Sierra Leone (13° 13'W, 8° 28'N) just north of the dip equator. Records for H, D and Z for the period July 1961 to June 1965, covering the recent minimum in sunspot activity, have been analysed by the method due to Chapman and Miller to give the first four solar and luni-solar harmonics of the daily variation. The data was divided into three seasonal sets and two groups, firstly the International Quiet Days and secondly all days having magnetic activity index Ci $\leqslant$ 1.2. Probable errors for all harmonics have been determined and plotted on the harmonic dials.

The seasonal changes of the solar terms show a movement of the equatorial current system in opposition to the sun with a larger shift during the northern summer months than during the northern winter months. The seasonal variations of the lunar terms show similar changes indicating that the lunar ionospheric current system behaves in a similar way to the solar current system.

The occurrence of pulsations in the horizontal intensity of period approximately two minutes has been analysed for the year from March 1962 to February 1963. Two maxima were found, one at dawn and the second at noon. The dawn maxima was absent during northern winter months.

A short field survey was undertaken to enable the plotting of magnetic charts for Sierra Leone. Measurements were also made of the daily variations at three field stations in Sierra Leone which confirmed the day-to-day variability of the daily variations of the equatorial ionospheric current system.

2. INTRODUCTION

The Earth's magnetic field has for many centuries been the subject of scientific investigation. Once the directional property of a piece of suspended lodestone had been established, it was merely a question of time and accuracy of observation before the phenomenon of declination was discovered. The exact date is uncertain, but during the middle of the fifteenth century portable sun-dials incorporating a device which allowed for the declination were being used in ships, It was a further hundred years before the concept of inclination was discovered, that is, the angle at which a suspended magnet tilts from the horizontal towards the earth. In 1576 NORMAN constructed the first dip-circle and described it in a work first published in 1581.

Shortly after this GILBERT (1600) published 'De Magnete' one of the most important treatises on the subject of magnetism in general. Apart from a description of ordinary magnetic effects, he dealt with the Earth's magnetic field in great detail, always laying emphasis on the experimental approach to the subject. However, one statement in Gilbert's work was proved to be incorrect when GELLIBRAND (1635) discovered the secular variation in the declination. The secular variation is the very slow change in magnitude and direction of the Earth's total field at any one point on the surface of the Earth. Gilbert had stated that "the variation (i.e. declination) at any one place is constant". Improvements in instrument design and construction must have been relatively slow as a further ninety years were to elapse before the non-secular variations were noticed. GRAHAM (1724) found that the compass needle was continually varying in position. The seasonal nature of these variations was discovered by CANTON (1759), who found that the mean range of the daily variation in the declination at London on undisturbed days was in June nearly twice that observed in December.

In 1741 CELCIUS and HIORTER at Upsala and GRAHAM in London studied the daily variations in the declination on the same days and discovered that large irregular variations occurred at both places simultaneously. At the same time, at Upsala, the occurrence of these large variations was observed to be directly correlated with the incidence of the aurora polaris.

At the beginning of the nineteenth century magnetic observatories were being set up in various parts of the world, including a few in tropical latitudes; and in 1834 the Gottingen Magnetic Union was formed, whereby a number of observatories correlated their work and agreed upon a series of simultaneous, intensive periods of observation. VON HUMBOLDT had previously organized this type of simultaneous observation programme on a world-wide basis. The observations were limited to the declination, chiefly because at that time the only instruments capable of any reasonable degree of accuracy were those for the measurement of this quantity. During the six year period of the Magnetic Union, this situation was rectified in part by LLOYD, who introduced his magnetic balance for the measurement of variations in the vertical intensity. All of the accurate instruments were, by now, using a lamp mirror and scale arrangement for the measurements, the observations being made visually. Altogether some 50 stations participated to a greater or lesser extent in the programme drawn up by the Gottingen Magnetic Union with a world-wide coverage which extended to New Zealand and Tasmania although by far the majority of stations were in the European sector.

The next major advance in the development of magnetic observations was in 1847, when automatic photographic registration was introduced at the Royal Observatory at Greenwich. The instruments and recording arrangements were designed by BROOKE (1847), who was spurred to this work following a meeting of the British Association at Cambridge.

He was also awarded a prize of £500 offered by the Admiralty for the invention of satisfactory magnetic self-recording instruments. Brooke further introduced automatic temperature compensation of the intensity magnetometers four years later. The magnetic observatory by this time had taken on an appearance similar to that of a present day observatory, the main differences being in the accuracy of the recording instruments. Meanwhile the results obtained from magnetic observatories gained in importance as they were found to be related to other phenomena. For example, SCHWABE discovered the existence of the sunspot cycle from a series of observations of sunspots over a period of 24 years and SABINE (1851) soon showed the effect of the 11-year sunspot cycle in an extended series of declination measurements at Toronto.

The full significance of the study of magnetic variations was foreshadowed by STEWART (1882) in his theory of the origin of the daily variations of the Earth's field. Stewart reviewed explanations of the phenomena made by FARADAY and others, and came to the conclusion that the daily magnetic variations were due to electric currents flowing in conducting layers in the upper atmosphere. Stewart also suggested that convection currents set up in the atmosphere by the heating effect of the sun should be regarded as 'conductors moving across lines of magnetic force, and are thus the vehicle of electric currents which act upon the magnet'. Stewart's postulate is usually called the 'dynamo theory'. SCHUSTER (1889) supported the theory and went further by proving that the greater part of the daily magnetic variation had its origins outside the Earth, and that the remainder could be reasonably attributed to earth currents induced by the varying external field. CHAPMAN (1919) improved the theory and carried out an extensive analysis of lunar daily magnetic variations. The existence of a lunar effect in the daily magnetic variation had been discovered by KREIL (1850) from a series of nine years' observations of declination at Prague.

Experimental evidence for the existence of the conducting layers in the upper atmosphere, or ionosphere as it is now termed, was forthcoming in 1925. Earlier in 1901, MARCONI had succeeded in receiving wireless signals transmitted across the Atlantic, and this caused considerable interest as to the means of propagation of the electromagnetic waves round the curved surface of the Earth. Once the possibility of diffraction had been eliminated, the existence of some form of conducting layer in the upper atmosphere was given serious consideration by both HEAVISIDE (1902) in England and KENNELLY (1902) in America. Direct evidence for the existence of reflecting layers in the upper atmosphere was found when APPLETON and BARNETT (1925) reflected radio signals back from the upper atmosphere. At about the same time, BREIT and TUVE (1926) investigated the upper atmosphere using short duration 'pulses', receiving the reflected signals at a point a few kilometres from the transmitter.

In 1922 a magnetic observatory was established at Huancuyo in Peru near the magnetic equator by the Carnegie Institute of Washington. From the results obtained at Huancuyo and other stations having small dip angles it soon became apparent that the magnitude of the daily variations in the horizontal intensity was considerably enhanced in a narrow zone near the magnetic equator. Further discussion of these results (EGEDAL 1947, CHAPMAN 1951, MARTYN 1948) led to the conclusion that the abnormal values at Huancuyo were due to a narrow band of current flowing in the ionosphere close to the dip equator. This current band was called the equatorial electrojet by Chapman. Measurements in recent years have shown that the electrojet exists in all longitudes near the dip equator.

The discovery of this anomalous equatorial region stimulated theoretical studies of the dynamo problem which had not at that time been confirmed quantitatively. The earlier discovery of the ionosphere had made it likely that the dynamo theory would be confirmed quantitatively but PEDERSON (1927) had pointed out that the conductivity values which might be expected in the ionosphere were deficient for the purposes of the dynamo theory due to the influence of the Earth's magnetic field. The spiral motions of the ions and electrons in these regions would slow up their motion parallel to an electric field. However, PEKERIS (1937) showed that the amplitude of atmospheric oscillations should increase with height thus increasing the magnitude of tidal velocities to be expected in the ionosphere. This increase in tidal amplitude with height still did not produce conductivity values suitable for the purposes of the dynamo theory. This was confirmed by work on current induction by ASHOUR and PRICE (1948).

MARTYN (1948) then suggested that if COWLING's (1933) work on the solar atmosphere could be applied to the ionosphere then the apparent deficiency in conductivity values might be made good. Cowling had considered the effects of the inhibition of the transverse current (Hall current) by polarization of the ionized medium; he found that the electron conductivity increased from the 'Pedersen' value to that which would be present in the complete absence of a magnetic field. It was soon apparent that this situation would only be really effective in equatorial regions where the magnetic field lines are nearly horizontal. At other latitudes, the polarization which was necessary to inhibit the Hall current would leak away horizontally.

BAKER and MARTYN (1953) and BAKER (1953) attempted a complete quantitative solution of the dynamo theory for a spherical sheet ionosphere of finite thickness.

They found that for the semi-diurnal tide in the equatorial ionosphere the enhancement of the current was by a factor of just less than two. They further stated that the factor was more likely to be between two and five. Thus the anomalous magnetic variations in equatorial regions were included in a theory of ionospheric conductivity based on the dynamo theory. HIRONO (1950, 1952) and MAEDA (1951) attacked the same problem from a similar viewpoint and produced results in agreement with Baker and Martyn's work.

Experimental observations in regions close to the magnetic equator were few and far between at that stage. The establishment of new observatories for the investigation of the magnetic field in these regions is described in the next section. It became apparent that the establishment of an observatory at Freetown in Sierra Leone would be of value in the world-wide study of equatorial phenomena and in 1961 the work which is described in this thesis was started.

3. THE GEOMAGNETIC OBSERVATORY AT FREETOWN

3.1 Reasons for establishment and site

The study of the variations in the Earth's magnetic field in equatorial zones was shown to be of importance by the results obtained at Huancuyo in Peru in the period 1922-30. However, it was not until compar~~i~~atively recently with the establishment of new universities and consequently an increase in research facilities that the number of observatories in equatorial regions was increased. More permanent stations and a large number of temporary stations have since been established to provide data for the world-wide projects of the I.G.Y., I.G.C. and I.Q.S.Y.

In the African equatorial zone, permanent observatories were started at Ibadan (Nigeria) in 1955, Addis Ababa (Ethiopia) in 1958, Zaria (Nigeria) in 1958 and at M'Bour (Senegal), Fernando Po, Bangui (Congo) and Nairobi (Kenya). Of these, Addis Ababa and Zaria are closest to the magnetic equator. Freetown with a dip angle of 1° North is ideally situated for this work being the farthest point west on the African continent near to the magnetic equator. Freetown is nearly 1000 miles west of Ibadan.

The choice of a site for the observatory was unfortunately governed by economic factors and also the fact that the

Department of Physics possessed no equipment with which to carry out a preliminary magnetic survey. On the arrival of the instruments it was discovered that there were large field gradients in the vicinity of the observatory. However by this time the observatory building was complete and the site had to be accepted. The observatory building was completed in October 1960 and the first photographic records obtained in June 1961.

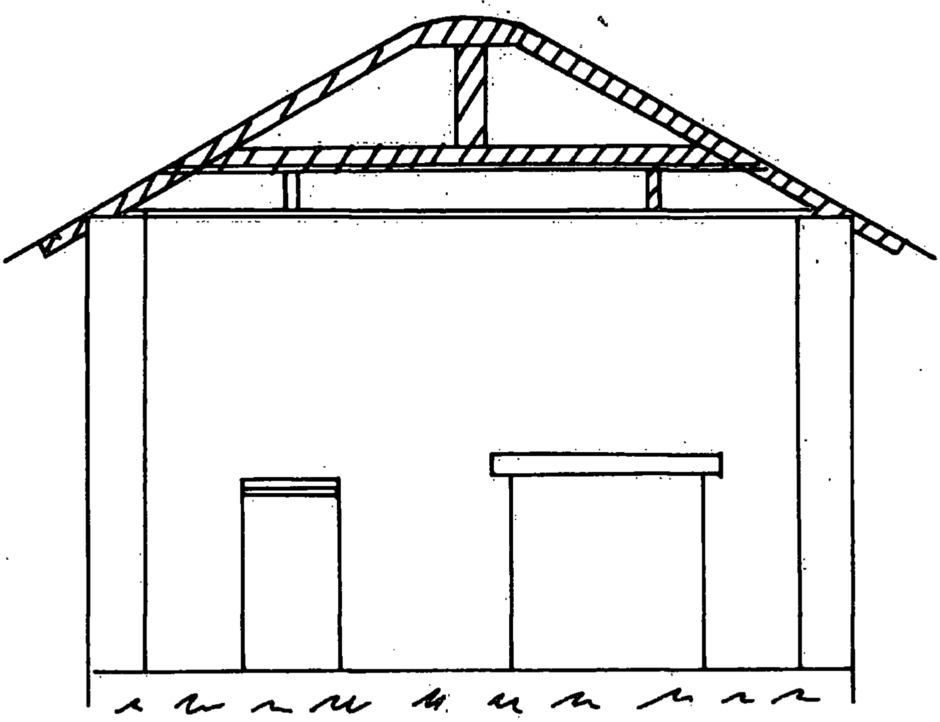
The geographic coordinates of the observatory were obtained by triangulation from the three most distant visible survey points using an accurate theodolite. The position of the observatory was determined as 08° 28' 24"N, 13° 12' 57"W and 1150 feet (350 metres) above mean sea level.

3.2 Observatory design

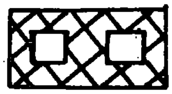
The structural design of the observatory is shown in Diagram 1 which follows, non-ferrous being used throughout. The walls of the hut were constructed from sandcrete blocks shown in section in Diagram 1, the air holes in the block assisted in reducing the effect of the external temperature variations on the instruments in the observatory. The ceiling of the hut was one inch thick fibreboard with a second fibreboard layer above a six inch air space, The air in the roof space above this second layer was able to

FREETOWN OBSERVATORY

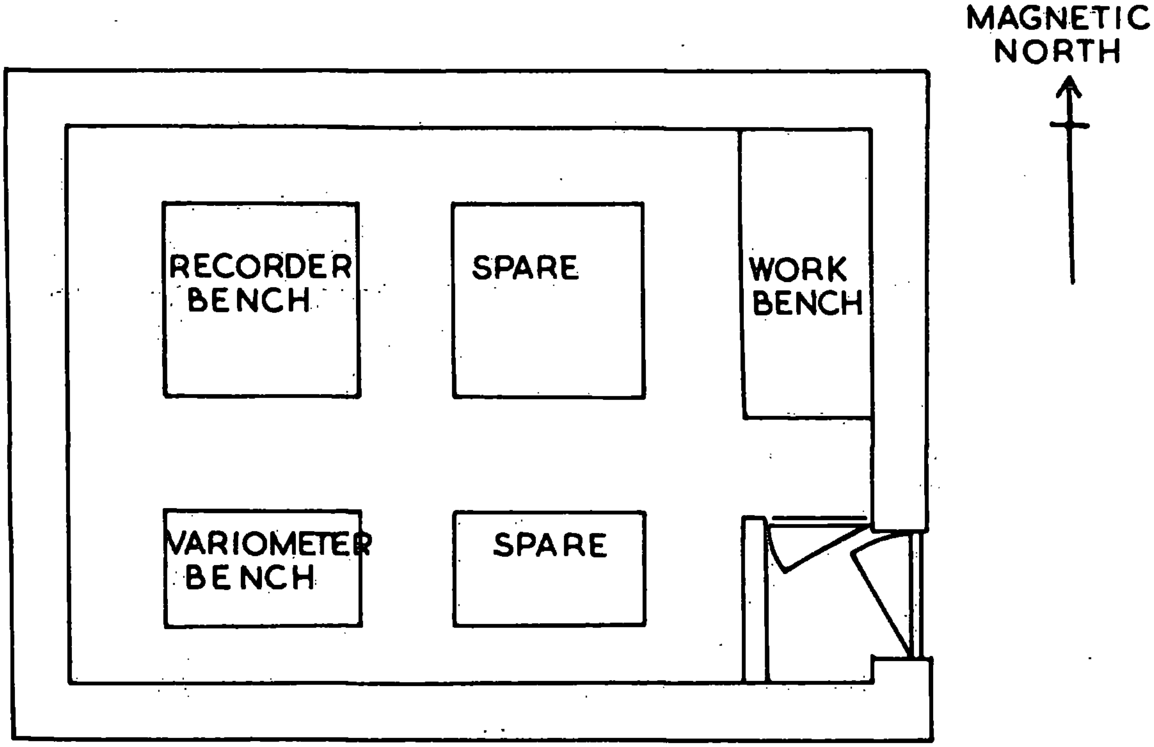
DIAGRAM.I.



EAST - WEST ELEVATION



SECTION
SANDCRETE
BLOCK



PLAN

circulate freely, there being a ventilator at each end of the roof space. The roof was of large asbestos tiles fitted to the wooden framework by aluminium hook bolts. Copper nails and brass screws were used throughout the construction of the hut, the door locks also being made entirely of brass.

The control hut, 110 metres from the observatory, consisted of five rooms one of which was allocated to the geomagnetic work. The magnetic research room contained dark room facilities for processing the photographic records, a pendulum clock for the time marks and the power supplies for the lamps, The clock produced 30 second electrical pulses which powered a control unit. The time mark circuit was closed every hour for eight seconds which was sufficient time for a clear line to be produced on the record. The time of closure could be adjusted from five to twelve seconds, the complete circuit being capable of closure every five minutes. To enable the time marks to be identified apart from log book entries, two additional closures were arranged in addition to the regular hourly closure, one five minutes before noon and the other five minutes after midnight.

The use of simple rectified mains units for the lamp supplies was not possible due to the large variations in the mains supply voltage which usually reached a maximum value of 240 volts in the early hours of the morning, falling to a minimum in the region of 190 volts during the day and in the early evening. In addition there were frequent supply failures. To overcome these problems car batteries continuously trickle-charged from the mains were used. Electrical connections between the two huts were by a single eight-way cable, two wires for the trace lamp supply, two for the time mark circuit and the remaining four for the calibration circuits.

3.3 Observatory instruments and preliminary adjustments

The variometers used for the continuous measurement of the horizontal and vertical intensities and the declination of the Earth's magnetic field have been described in detail before (LA COUR and LAURSEN), therefore only a brief description is given here. Both the horizontal intensity and declination variometers consist of magnet systems incorporating a mirror suspended by fine quartz fibres. The magnet system in the horizontal intensity variometer is adjusted so that the magnet is perpendicular to the direction of the meridian through the variometer; the magnet system in the declinometer is suspended so that the magnet lies in the meridian with the suspending fibre torsionless. The magnet system in the vertical intensity variometer is of integral construction with two knife edges for balancing on agate planes and a smooth ground upper surface which acts as the reflecting mirror. The magnet is oriented so that its axis of rotation is near to the meridian through the variometer.

The magnetic meridian within the observatory was obtained in the following way. A hole had been left in the northern wall of the observatory which allowed direct vision of one of the trigonometrical survey points already used. With a Q.H.M. (Quartz Horizontal Intensity Magnetometer) the angle between magnetic north and the survey point was obtained, the Q.H.M. was then replaced by the theodolite and the theodolite adjusted to be magnetic north-south. This line was then transferred to readings on metre rules permanently fixed to the insides of the north and south walls of the observatory. The hole in the observatory wall was then closed.

Knowledge of the magnetic north-south line within the observatory was necessary for the correct setting of the variometers. For the horizontal intensity variometer the line from the reflecting mirror to the recording drum was at an angle of 7^{o} 30' to the meridian. The magnet system was thus adjusted to be at an angle of 7^{o} 30' to its reflecting mirror so that when the variometer was in use the magnet axis was truly perpendicular to the direction of the field. If this adjustment had not been correctly made then spurious recorded changes in horizontal intensity are found due to normal declination variations. For example, at Freetown where H is of the order of 30,000 γ, if the magnet were 2^{o} out of adjustment then a change in declination of ten minutes of arc would produce a spurious apparent change in horizontal intensity, as recorded, of 3 γ (McCOMB 1952, p.224). The ex-meridian angle for the declination variometer was found to be 1^{o} 11'; this angle was small enough for the reflected trace from the variometer to be well within the available range on the recording drum so that no adjustment to the magnet system was necessary. A torsion test was carried out on the variometer to ensure that there was no residual torsion in the fibre (McCOMB 1952).

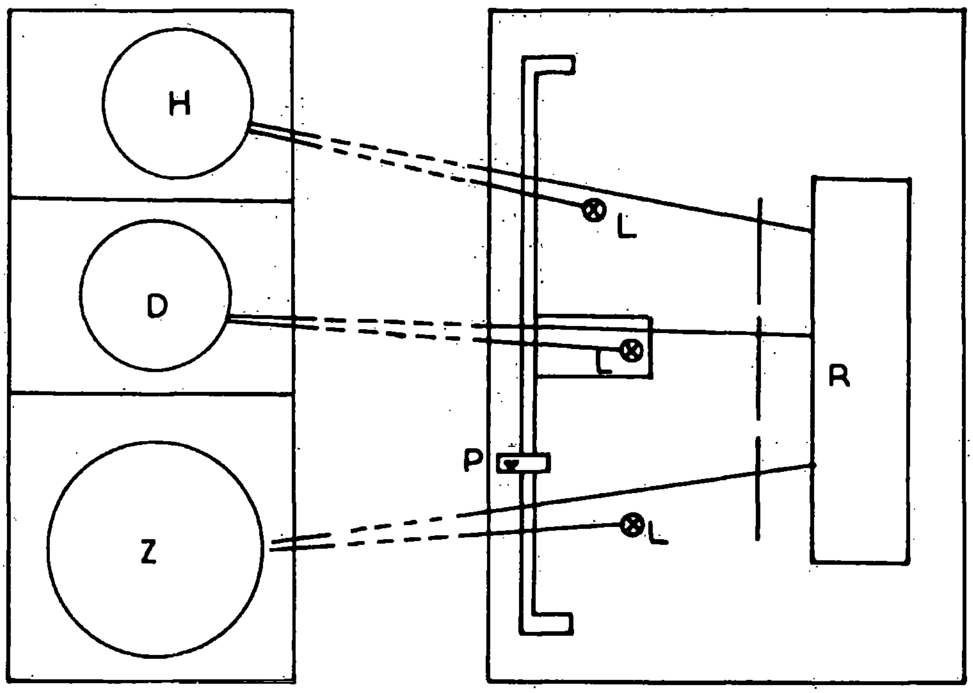
The vertical intensity variometer, or magnetic balance was adjusted to the horizontal position as described in La COUR (1942) and its axis of rotation brought to be near the meridian.

Compensation for temperature variations was achieved in the horizontal and vertical intensity variometers by means of bimetallic strips which supported a prism in the optical system. The length of the bimetallic support was adjusted so that the motion of the prism due to temperature changes corrected the deviation of the light path due to changes in magnetic moment of the magnet system caused by the temperature changes. To ensure good compensation, the temperature of the variometers was artificially varied by wrapping a heating coil round them. The heating supply, a few volts a.c., was controlled by an automatic switching device with a four hour cycle, two hours on and two hours off. The temperatures of the variometers were raised by approximately 10°C during these cycles. Adjustments were made to the length of the bimetallic strips until the effect of these temperature variations was almost eliminated from the normal daily variation trace. It was not found possible to completely compensate for a temperature change of this magnitude, however, as the normal diurnal temperature variation within the observatory was 3°C or less it was considered that sufficient compensation had been achieved. The compensation was less satisfactory for the horizontal intensity variometer due to its high sensitivity and large daily variation. As the declination variometer is purely a direction recorder temperature compensation is not necessary.

In the normal La Cour variometer arrangement one lamp is used to provide all of the traces from the three variometers and one lamp to provide the time marks on the record. This system was not used, individual lamps being used for each of the three variometers and three time mark bulbs used instead of one. The diagram of the instrument arrangement, Diagram 2, shows the positions of the trace lamps, these were all single filament bulbs. Three time mark bulbs were used to eliminate the problem of parallax from the time-marks. The construction of the time mark bulb holders is shown in Diagram 2. Each holder was screwed to the southern wall of the observatory behind the variometers approximately on the same straight line as that between the recording drum and the variometer lens. Final adjustment was made by rotating the wooden base of the holder about the single screw holding it to the wall and by adjusting the screws holding the bulb holder to the wooden base. The intensities of the three trace lamp bulbs were controlled individually from a control board inside the observatory which also contained an on-off switch. In this way it was easier to obtain a balanced intensity record. The intensity of the hour mark bulbs was controlled from the control hut. The use of six bulbs instead of two reduced considerably the loss of records due to bulb failure.

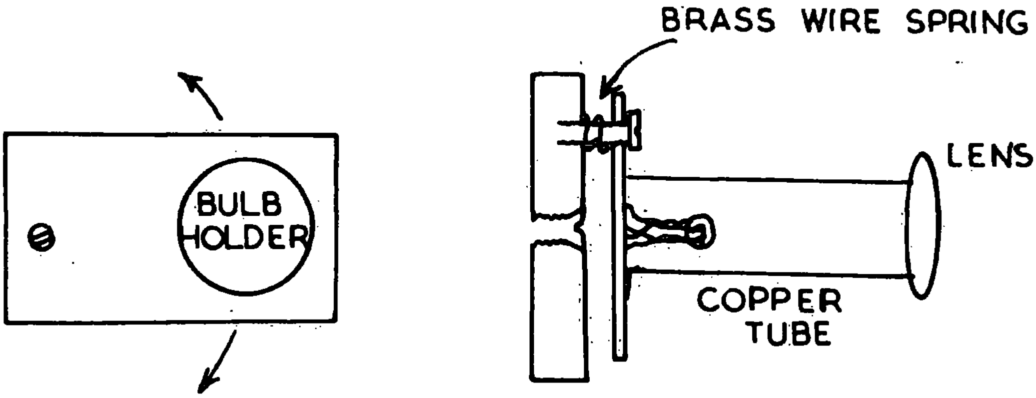
Calibration of the variometers was carried out using two Helmholtz coil arrays, one permanently in position round the vertical intensity variometer, the other usually round the horizontal intensity variometer but also used on the declination variometer. The calibrating current in the Helmholtz coils was adjusted from the control hut, the

FREETOWN OBSERVATORY DIAGRAM. 2.



R– RECORDING DRUM L–TRACE LAMP BULBS
P– PRISM FOR RESERVE TRACE

INSTRUMENT LAYOUT



TIME MARK BULB ARRANGEMENT

current being measured on an accurate milliammeter which had been previously checked by a potentiometric method. Visual and photographic calibrations were carried out for all three variometers. As the horizontal intensity variometer suspension is under torsion during normal use, no attempt was made to calibrate the variometer until some months after the magnet system had been suspended and the torsion introduced. The fibre was under torsion for six months before the commencement of routine recordings in June 1961.

Two magnetometers for the direct determination of the two intensities and the declination were also obtained. The Q.H.M.(Quartz Horizontal Intensity Magnetometer) was used for determinations of horizontal intensity and declination, and the B.M.Z. (Magnetometric Zero Balance) for the vertical intensity. A set of three Q.H.M.'s were used to cover the possibility of malfunctioning of one instrument. The Q.H.M. and the B.M.Z. are secondary instruments having been calibrated at Rude Skov, the magnetic observatory maintained by the Danish Meteorological Institute. During the four year period 1961 to 1965, each of the Q.H.M.'s and the B.M.Z. were returned to Rude Skov for checking and recalibration.

Due to the field gradients in the vicinity of the observatory it was essential that all readings from the

Q.H.M. and B.M.Z. were carried out at a well-defined position. Funds were not available for a separate building so a concrete base was laid with holes for the tripod legs near to the observatory. The tripod was always used with its legs fully extended so that the magnetometers were at a constant height above the surface of the base. A concrete pillar was erected twenty-five metres from the base with a fixed vertical line to allow declination measurements to be made; the azimuth of the line joining the centre of the base platform to the vertical line on the pillar was obtained using a theodolite and the same survey points used during the earlier survey.

The principles and constructional details of the Q.H.M. and the B.M.Z. have been given by La COUR in numbers 15 and 19 of the Communications Magnétiques of the Danish Meteorological Institute.

4. SOLAR AND LUNI-SOLAR DAILY VARIATIONS IN THE GEOMAGNETIC FIELD AT FREETOWN

4.1 Description of the data

Magnetograms were first obtained on a regular daily basis at Freetown during June 1961, and apart from a period in August and September 1964 a complete series of records were available to the end of 1966. As all of the computations were to be carried out with only limited mechanical aids, a balance had to be found between the desirability of having a large amount of data and the practicability of managing the computations in a reasonable length of time. Data from 1st July 1961 to 30th June 1965 was chosen for this analysis. This period was almost symmetrically placed about the recent minimum in sunspot activity, thus enabling a high proportion of the days available to be used in the analysis. The magnetograms were scaled to provide mean hourly values of Horizontal Intensity (H), Magnetic Declination (D) and Vertical Intensity (Z). The monthly mean curves for the three components for this four year period are shown in Figures (1-12). The ordinates in these curves represent the distance in millimetres of the mean of the element concerned, for the interval between successive hours of Greenwich time, from an arbitrary baseline on the photographic record. For various reasons the baseline traces of all three elements were altered at different times during the four year period, thus the actual numerical value of any ordinate as shown in these figures has no significance.

Bihourly data was used for 20 out of the 24 sets analysed, hourly data being used in the remaining four sets. The omission of alternate hourly values provides a considerable saving of labour and introduces only a slight loss of accuracy as the omitted values are highly correlated with their neighbouring hourly values.

4.2 Method of analysis

The method of analysis used was that due to CHAPMAN and MILLER (1940). It is not considered necessary to give the development of the analysis in full, but a description of the practical treatment of the data and a discussion of the determination of the errors involved is given.

The purpose of the analysis is the determination of S_p and σ_p, the amplitude and phase of the solar daily harmonic and L_n and λ_n, the amplitude and phase of the luni-solar daily harmonic.

These quantities are expressed in the following way:

$$S_p \sin(pt + \sigma_p) \tag{1}$$

and

$$L_n \sin\left[nt - q(t-\tau) + \lambda_n\right] \tag{2}$$

where t is the mean solar time measured from local midnight,

τ is the mean lunar time measured from local lower transit,

p, n and q are small integers.

The solar daily variation is expressed in a series of terms of type given by equation (1). In this analysis the first four terms of the series have been determined (i.e. p = 1 to 4).

The lunar daily variation is expressed in a series of terms of type given by equation (2). The only harmonics yet detected in previous determinations of this series for large quantities of data are those for which q = 2. This ascribes the lunar magnetic effect to the influence of a purely semi-lunar-diurnal gravitational tide. It is a reasonable assumption that the effect of the moon on the Earth's atmosphere is purely gravitational. The magnetic variations which are observed at the surface of the Earth are due to variations in the electrical state of the atmosphere. The largest variations are expressible as harmonics of the solar day and are due to the effect of the sun's gravitational, ionizing and thermal actions on the atmosphere. Therefore, magnetic effects due to the moon's influence are a consequence of the action of the lunar gravitational tide on the electrical state of the atmosphere. In this analysis the first four terms of the series have been determined (i.e. n = 1 to 4).

4.3 Treatment of the data

The data for each magnetic element at Freetown was divided in the following way. Initially all days with magnetic activity index $C_i > 1.2$ were omitted from the analysis. The number of such "disturbed" days during the period of the analysis was small and it was not therefore thought reasonable to attempt a separate analysis for this group of days.

The remaining data (Group II) was analysed as a whole and also as three sets when divided according to Lloyd's seasons. The International Quiet Days were then separated from the data and analysed in a similar way (Group I). Lloyd's seasons are:- D set (Northern Winter): November, December, January, February; E set (Equinox): March, April, September, October; J set (Northern Summer): May, June, July, August. Thus a total number of 24 sets have been analysed. Further subdivisions of the data were not considered advisable due to the large probable errors which would arise owing to the small number of days in the individual sets.

The practical method of analysis used for the determination of the solar and lunar harmonics followed closely that proposed by TSCHU (1949). Each day in a particular set was assigned a μ number. μ, the Greenwich hour angle of the mean moon at 1200 U.T. is a measure of the age of the moon, and is given by

$$\mu = 24 \left[1 - \frac{(t-\tau)}{2\pi} \right] .$$

μ therefore decreases from 24 to 0 in the interval from one new mean moon to the next. Values of μ to the nearest integer have been compiled by BARTELS and FANSELAU (1937) for the period 1850-1975.

The days in the set were then rewritten in 24 groups according to their μ number. Days with μ numbers differing by 12 were grouped together to form 12 groups, these 12 lunar-age groups were denoted by r where $r = \mu$ or $\mu -12$ and $r = 0-11$. In addition to the 12 bihourly values written down for any one day, the first value from the following day was also included in that day to enable the average non-cyclic change of the element during the day to be removed.

The sums of the columns in the groups were then formed giving a series of 12 group sum sequences which for group r may be denoted by $g_{s,r}$ ($s = 0-S$) where s denotes the position of successive values of the element in the sequence. Where bihourly values were used $S = 12$. The group sum sequences have been plotted for the three components for each of the twelve lunar ages for each season and each group of days in Figures 13-42. The number of days in each group, N_r, was also determined.

The group sum sequence $g_{s,r}$ for each r, was then harmonically analysed to determine the following quantities:-

$$A_{p,r} = \tfrac{1}{2}(g_{S,r} - g_{0,r}) + \sum_{s=0}^{S-1} g_{s,r} \cos \frac{2\pi ps}{S} \qquad (3)$$

$$B_{p,r} = \tfrac{1}{2}(g_{S,r} - g_{0,r}) \cot(\frac{\pi p}{S}) + \sum_{s=0}^{S-1} g_{s,r} \sin \frac{2\pi ps}{S} \qquad (4)$$

where p = 1 to 4.

The same analysis was then applied to the total sum sequence, $g_{s,N}$, of the number of days in each lunar age group giving eight numbers $A_{p,N}$, $B_{p,N}$. These independent analyses were then checked for each value of p according to the following equations.

$$A_{p,N} = \sum_{r=0}^{11} A_{p,r} \quad ; \quad B_{p,N} = \sum_{r=0}^{11} B_{p,r} \qquad (5)$$

Solar Terms The first four harmonics of the solar daily variation were then determined using the quantities $A_{p,N}$ and $B_{p,N}$ in the following way:-

$$S_p \sin \sigma'_p = \frac{2\,A_{p,N}}{S\,N} \quad ; \quad S_p \cos \sigma'_p = \frac{2\,B_{p,N}}{S\,N} \qquad (6)$$

where p = 1 to 4.

A phase correction was necessary to the values of σ'_p to obtain the true phase values σ_p as defined in equation (1). This was because the values σ'_p are the phases of the solar harmonics referred to mean solar time reckoned from the initial value of each daily sequence and mean lunar time reckoned from Greenwich lower transit of the mean moon. The true phases were obtained from the following equation

$$\sigma_p = \sigma'_p - p(15^\circ .\ H' - L + L') \qquad (7)$$

where L is the Longitude West, in degrees, of the station to which the data refer;

L′ is the Longitude West, in degrees, of the meridian of time - reckoning with respect to which the data were tabulated;

H′ is the solar hour of the initial value of each daily sequence, according to the same time - reckoning as L′.

For the Freetown data the above parameters had the following values:-

$L = 13^\circ\ 13'$, $L' = 0^\circ$, $H' = \frac{1}{2}$ hours.

<u>Lunar Terms</u> The sequences N_r and $A_{p,r}$, $B_{p,r}$ obtained from equations (3) and (4) were then subjected to a simple harmonic analysis to determine their first harmonic component which give the following quantities:-

$$N_{1,A} = \sum_{r=0}^{11} N_r \cos\frac{2\pi r}{12}\ ; \quad N_{1,B} = \sum_{r=0}^{11} N_r \sin\frac{2\pi r}{12} \qquad (8)$$

$$A_{p,A} = \sum_{r=0}^{11} A_{p,r} \cos\frac{2\pi r}{12}; \quad A_{p,B} = \sum_{r=0}^{11} A_{p,r} \sin\frac{2\pi r}{12} \qquad (9)$$

$$B_{p,A} = \sum_{r=0}^{11} B_{p,r} \cos\frac{2\pi r}{12}; \quad B_{p,B} = \sum_{r=0}^{11} B_{p,r} \sin\frac{2\pi r}{12} \qquad (10)$$

where p = 1 to 4.

At this stage in the analysis, before taking the final steps in the calculation of the lunar amplitudes and phases, a further check was made to eliminate calculation errors in the following way. Calculation of the 18 numbers to be derived from equations (8)-(10) was carried out for the seasonal set groups at the same time as the 'all-days' group. The sum of the corresponding values of $N_{1,A}$, $A_{1,A}$ etc. for the three seasonal sets had to be equal to the appropriate value obtained from the 'all-days' group. After this check the following quantities were determined:-

$$U_p = (A_{p,A} - B_{p,B}) - \frac{1}{N}(A_{p,N} \cdot N_{1,A} - B_{p,N} \cdot N_{1,B}) \qquad (11)$$

$$V_p = (B_{p,A} - A_{p,B}) - \frac{1}{N}(B_{p,N} \cdot N_{1,A} + A_{p,N} \cdot N_{1,B}) \qquad (12)$$

where $N = \sum_{r=0}^{11} N_r$, the total number of days in the set.

The values of L_n and λ'_n were then calculated from

$$L_n \sin \lambda'_n = \sum_{p=1}^{4} \frac{D_{mps}}{K} \cdot U_p \qquad (13)$$

$$L_n \cos \lambda'_n = \sum_{p=1}^{4} \frac{D_{mps}}{K} \cdot V_p \qquad (14)$$

for $n = 1,2,3,4$,

where $$K = 0.4943\ S\ N \left\{ 1 - \frac{\left[(N_{1A})^2 + (N_{1B})^2\right]}{N^2} \right\} \qquad (15)$$

Values of D_{mps} are given in TSCHU (1949), Table 2 which is an abstract from CHAPMAN and MILLER (1940). It should be noted that the terms $p = 1$, $n = 3$ and $p = 2$, $n = 3$ in Tschu's Table 2 are incorrect. The correct values are given in LEATON, MALIN and FINCH (1962) and are incorporated in the following statement of D_{mps} for bihourly data.

D_{mps} where $m = n - \frac{2}{M}$; $n = 1,2,3,4$; $M = 29.5306$; $S = 12$.

	p = 1	2	3	4
n = 1	1.0720	0.1445	0.1163	0.1112
2	-0.0360	1.0286	0.0994	0.0710
3	-0.0118	-0.0495	1.0150	0.0871
4	-0.0061	-0.0184	-0.0556	1.0114

As previously mentioned hourly data was used for the first four of the 24 sets analysed so that D_{mps} had to be calculated for the case $S = 24$. The factors D_{mps} are expressible in terms of the determinant whose elements are $(-1)^{n-p}\, d_{mps}$ where

$$d_{mps} = \frac{1}{S} \cdot \sin\left[\pi(m-p)\right] \cdot \left\{\cot\left[\frac{\pi(m-p)}{S}\right] + \cot\left(\frac{\pi p}{S}\right)\right\}$$

where as before $m = n - \frac{2}{M}$, $n = 1, 2,3,4$, $p = 1,2,3,4$ and M the number of mean solar days in the mean period of the moon is equal to 29.5306.

D_{mps} for $S = 24$

	p = 1	2	3	4
n = 1	1.0735	0.0347	-0.0103	0.0049
2	-0.1479	1.0313	0.0460	-0.0160
3	0.1194	-0.0102	0.9973	0.0506
4	-0.1188	0.1696	-0.0908	1.0169

The figure $0.4943 \times S$ in the quantity K in equation (15) is the product $\frac{1}{1.01152} \times \frac{S}{2}$ where the factor 1.01152 corrects the quantities A_{pA}, B_{pA}, etc. for the effect of grouping according to the integer r (CHAPMAN and MILLER (1940) section 13) and $\frac{2}{S}$ is the factor applicable to summations for determining Fourier coefficients.

A factor $\frac{\theta_p}{\sin \theta_p}$ where $\theta_p = \frac{p\pi}{24}$ is sometimes used to compensate for the use of mean hourly values rather than instantaneous values. This factor, however, is very small and was not included in this analysis, and will not affect the phase angles obtained.

In the same way that a phase correction was necessary to the solar term phase angles given by equation (7), a phase correction had to be applied to the lunar term phases derived from equations (13) and (14) to enable the harmonics to be expressed in terms of t and τ as defined in equation (2). The appropriate corrections were derived from

$$\lambda_n = \lambda'_n + \frac{2L}{M} + 15^\circ \ . \ m H' + m(L - L') \qquad (16)$$

where $m = n - \frac{2}{M}$ as before and L, L′ and H′ were defined in equation (7).

For Freetown $L = 13^\circ 13'$, $L' = 0^\circ$, $H' = \frac{1}{2}$ hours.

The phase corrections applied to the data for the solar and lunar terms were as follows:-

$\sigma_1 = \sigma'_1 + 5^\circ 43'$ $\qquad \lambda_1 = \lambda'_1 + 6^\circ 13'$

$\sigma_2 = \sigma'_2 + 11^\circ 26'$ $\qquad \lambda_2 = \lambda'_2 + 11^\circ 56'$

$$\sigma_3 = \sigma_3' + 17^\circ\ 9' \qquad \lambda_3 = \lambda_3' + 17^\circ\ 39'$$

$$\sigma_4 = \sigma_4' + 22^\circ\ 52' \qquad \lambda_4 = \lambda_4' + 23^\circ\ 22'$$

The results of the analysis are given in Table 1 to 6 and in the harmonic dials, Figures 44-91.

4.4 Determination of Probable Errors

The determination of the vectors represented by equations (1) and (2) from the observational data inevitably involves a measure of accidental error. The ends of the vectors of a number of determinations form a cloud of points around the end of the mean vector. For a large number of points the error theory developed in CHAPMAN and BARTELS (1940) pages 572-581 may be used and probable error circles drawn indicating equal density of the cloud of points. However, for a smaller number of points, such as the number involved in this analysis, some law of error must be assumed. The method used in this analysis is that developed by MILLER (1934) which assumes that the error vectors have a Gaussian distribution. Slight alterations were necessary due to the fact that here the phases of the individual determinations differ by exactly 30°. The practical treatment of the data for the determination of the errors has been described in TSCHU (1949) and more fully in LEATON, MALIN and FINCH (1962). A brief statement of the method will be given here.

For each value of p the values of $A_{p,r}$ obtained from equation (3) were divided by the corresponding N_r. This was repeated for all values of r. For a particular p the mean of the 12 quantities $A_{p,r}/N_r$ was found and subtracted from each of the original values to give 12 residuals $\Delta a_{p,r}$. The corresponding values $\Delta b_{p,r}$ were determined from the quantities $B_{p,r}/N_r$. The mean, R, of the 12 quantities $\left[(\Delta a_{p,r})^2 + (\Delta b_{p,r})^2\right]^{\frac{1}{2}}$ was then calculated and also $L = \frac{1}{N}\left[(U_p)^2 + (V_p)^2\right]^{\frac{1}{2}}$. The ratio L/R was then calculated and for values of L/R less than 0.75 the corresponding value of f(L/R) obtained from Tschu's Table 3 was multiplied by R to give the vector probable error (p.e.), that is the radius of the probable error circle, for the p^{th} solar harmonic. The corresponding vector probable error for the luni-solar harmonic was obtained by multiplying the solar harmonic p.e. by the following factors according to the value of n.

n	-	1	2	3	4
Multiplying Factor	-	1.09	1.05	1.04	1.03

When the ratio L/R was greater than 0.75 an extension of the method was necessary. This has been shown by MILLER (1934).

From the residuals $\Delta a_{p,r}$, $\Delta b_{p,r}$ obtained above the following quantities were derived for each value of r

$$\Delta' a_{p,r} = \Delta a_{p,r} \cos (30r)^{\circ} - \Delta b_{p,r} \sin(30r)^{\circ} \qquad (17)$$

$$\Delta' b_{p,r} = \Delta a_{p,r} \sin(30r)^\circ + \Delta b_{p,r} \cos(30r)^\circ \qquad (18)$$

The mean of the twelve quantities $\Delta' a_{p,r}$ was then subtracted from each of the values to yield 12 residuals $\Delta'' a_{p,r}$ and similarly for $\Delta' b_{p,r}$ to give $\Delta'' b_{p,r}$. The mean R′ of the 12 quantities $\left[(\Delta'' a_{p,r})^2 + (\Delta'' b_{p,r})^2\right]^{\frac{1}{2}}$ was then found. The vector probable error of the pth solar harmonic was then given by 0.0495 R′. The corresponding vector probable errors of the luni-solar harmonics were obtained in the way outlined in the basic method. It should be noted, as has already been pointed out by CHAPMAN (1952), that in Tschu's Table 4 which corresponds to equations (17) and (18) above, the signs in the columns 'B_r' and 'C_r' should be reversed.

Following the treatment of the data in obtaining the solar and luni-solar harmonics, the vector probable errors have not been corrected for the smoothing due to the use of mean hourly values. The vector probable errors are given in Tables 1 to 6 and the probable error circles are plotted in the harmonic dials, Figures 44-91.

The significance of the vectors obtained in this type of analysis has been fully discussed by LEATON, MALIN and FINCH (1962) who show that a vector can be considered significant if its amplitude is greater than 2.08 times its vector probable error.

4.5 Discussion of the results

(a) Solar Terms

(i) Horizontal Intensity - Table 1 and Figures 44-51.

All of the 32 determinations are clearly significant, the probable error circles on the harmonic dials showing that the seasonal changes of amplitude and phase although not being large are definitely real. The pattern of the changes in the International Quiet Days group (Table 1(a), Figures 44-47) is similar to that of the larger group of days (Table 1(b), Figures 48-51). Nine out of the 16 amplitudes are larger in the Quiet Days group than the corresponding values in the larger group but this is not sufficient evidence to make any statement about the effect of magnetic activity on the horizontal intensity solar variation.

The most marked change is the seasonal change between the D set (November, December, January, February) and the J set (May, June, July, August). In all cases (s_1 to s_4) the amplitudes in the J set are markedly smaller than those for the D set. The first maximum of the first three harmonics all occur later in the J set than the D set. This change is reversed in the fourth harmonic phases. The E set amplitudes are similar to the D set being in all cases larger than the J set values. This seasonal change will be mentioned later in a discussion of the results as a whole.

(ii) Declination - Table 3 and Figures 52-59.

The 32 Declination determinations are all clearly significant, probable errors for the larger amplitudes being only a few per cent. There is no clear difference between the International Quiet Days, G group (Table 3(a) and Figures 52-55) and the larger group of days (Table 3(b) and Figures 56-59) indicating that with the data available little can be said about the effect of magnetic activity on the solar daily variation in the Declination. Eleven out of the 16 amplitudes determined are smaller in the Quiet Days group than in the larger group but the differences are for the most part small and within the probable error values.

There is a large seasonal change both in phase and amplitude between the D set and the J set. For the first three harmonics the amplitude in the J set is approximately double that in the D set. In the fourth harmonic the amplitudes are almost identical. The differences in time of occurrence of the maxima of s_2, s_3 and s_4 are just over two hours with the J set maximum occurring earlier in each case. For s_1 the D set maximum leads the J set maximum by nearly three and a half hours, a reversal of the situation in the other three harmonics. The E set amplitudes are similar to the D set values for s_1, s_2 and s_3 with phases approximately midway between the D set and J set figures.

For s_4 the amplitudes are approximately one half the D set and J set values with the phase being almost the same as the D set.

(iii) Vertical Intensity - Table 5 and Figures 60-67.

The 32 Vertical Intensity determinations are again all clearly significant. The pattern of changes in the International Quiet Days group (Table 5(a) and Figures 60-63) is similar to that of the larger group of days (Table 5(b) and Figures 64-67). Fourteen out of the 16 amplitudes are smaller in the Quiet Days group than the larger group but only three of the differences are larger than the sum of the two probable errors involved. The remaining two amplitudes are almost identical so that it may be said that the data suggest that the solar harmonic amplitudes for the vertical intensity increase slightly in magnitude with increasing magnetic activity. Further analysis particularly of a large enough group of 'Disturbed' days would make this trend clearer.

The seasonal change between the D set and the J set is again the most obvious feature of the harmonic dials. For s_1, s_2 and s_3 the J set amplitude is larger than that of the D set, for s_4 the difference is reversed. The phase differences between the D and J set values increase from 20 minutes in s_1 to 2½ hours for s_4, in s_1 the D set leads but in the remaining three harmonics the J set leads.

(b) Lunar Terms

(i) Horizontal Intensity - Table 2 and Figures 68-75.

All but one of the 32 determinations of the lunar harmonics are significant. The amplitudes are in all cases larger in the Quiet Days group (Table 2(a) and Figures 68-71) than in the larger group of days (Table 2(b) and Figures 72-75). The differences are larger than the sum of the probable errors involved. However, before any conclusions can be drawn concerning the effect of magnetic activity on the amplitudes it must be remembered that the horizontal intensity Quiet Days group was analysed using hourly values and not bihourly values which were used for all the other groups, Even though the omitted hourly values are strongly correlated with the neighbouring values it is possible that by using all 24 hourly means that the relevant features are accentuated. The corresponding difference in the solar term amplitudes is far from clear so that it may be reasonable to say that increasing magnetic activity causes the amplitudes of the lunar harmonic terms in the horizontal intensity to decrease. Once again, further analysis and the inclusion of 'Disturbed' days would make this clear.

In the Quiet Days group the E set amplitudes are the largest for the first three harmonics, for L_4 the D set amplitude is the largest. The differences are of the same order of magnitude as the sum of the probable errors.

The seasonal phase changes between the D set and the J set decrease in magnitude from four hours for L_1 to just under one hour for L_4. In all cases the D set values lead the J set. The D set amplitudes are also in all cases larger than the J set values, a similar result to that obtained for the solar terms.

(ii) Declination - Table 4 and Figures 76-83.

The lunar harmonics in the Declination show a phase change of almost 180° between the D set and the J set. This phase change is apparent in both the Quiet Days group (Table 4(a) and Figures 76-79) and the larger group (Table 4(b) and Figures 80-83). The E set values are in many cases similar to either the D or J set so that when the seasonal sets are brought together for the 'All Days' set the resultant amplitudes are very small. This is particularly the case with the Quiet Days group where none of the four All Days determinations are significant with the probable errors being an order of magnitude greater than the amplitudes. These figures have not been included in the harmonic dials.

For the larger group of days the amplitudes are larger and are just significant. The E set values in this group for L_2 and L_3 are similar in phase to the J set and it is only the first and fourth harmonics that have individual characteristics.

Thirteen out of the 16 J and D set determinations are significant, L_4 for the J set in both groups being very small with probable error in both cases larger than the amplitude and phase similar to the D set rather than exactly opposite as one would expect from the pattern of the first three harmonics.

(iii) Vertical Intensity - Table 6 and Figures 84-91.

Twenty out of the 32 determinations are significant. Thirteen of these are in the larger group of days (Table 6(b) and Figures 88-91) with L_1, L_2 and L_3 being significant for all sets. In the Quiet Days group (Table 6(a) and Figures 84-87) there is a phase change between the D and J sets of nearly 180^o for L_1, L_2 and L_3, and 120^o for L_4. Thus the resultant amplitudes in the All Days set are small and only one of these, L_2, is significant. In the larger group of days the phase differences are also present but with differing magnitudes, being 130^o for L_1, 90^o for L_2, 150^o for L_3 and 140^o for L_4.

The amplitudes for the J set are mostly larger than those of the D set, a similar result to that obtained for the solar terms. These changes in amplitude depend on the mean seasonal position of the intensification of the equatorial ionospheric current system and, as will be seen in the following section, agree with the seasonal changes observed in the horizontal intensity terms.

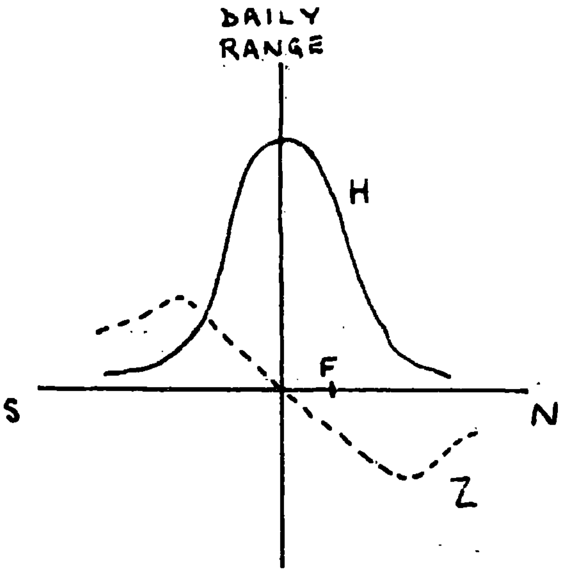
4.6 General comments on the results

The daily magnetic variations measured at an observatory on the Earth's surface are due to the circulating current systems in the ionosphere above the station and the corresponding current systems induced in the Earth in the region of the station. For stations with low magnetic latitudes, i.e. close to the magnetic equator, the situation is more complex than for mid-latitude stations. Middle latitude station daily magnetic variations are mainly caused by one circulating current system, either the northern or southern hemisphere vortex. Stations near the magnetic equator lie underneath the region of the ionosphere where the two vortices combine to produce a strong east-west current during the sunlit hours. In addition, due to the closeness to the horizontal of the magnetic field lines in this region, there is an enhanced conductivity in the east-west direction giving rise to a very strong narrow region of current flow known as the equatorial electrojet. The equatorial electrojet is part of the middle latitude current system and as this is subject to seasonal variations in strength and position it is to be expected that daily magnetic variations observed within the region of influence of the electrojet will have variations of a seasonal nature. Thus as Freetown is a station lying just to the north of the magnetic equator, one would expect the variations in northern summer (J set) to be strongly influenced by the northern current system. In northern winter (D set) the variations would still be influenced by the northern system but to a lesser extent.

However, it has been shown by HAGAN and SUGUIRA (1967) and other authors that the northern hemisphere current system is stronger in northern summer than the southern system in southern summer. This asymmetry means that the 'centre line' of the joining of the two current systems will be farther to the south of the mean equinox position in the northern summer than it will be to the north of this position during northern winter. In the horizontal intensity at Freetown this would mean D set daily variations of larger amplitude than J set values. This is found to be the case for all of the solar and lunar harmonics determined in this analysis. The equinox values (E set) for the solar and lunar harmonics are all similar in magnitude to the D set values and considerably larger than the J set values again showing the larger shift of the current system during the northern summer months.

As the position of the current system varies with season, the daily variation that will be observed at any fixed station will depend on the variation with latitude of the daily variation. This latitude dependence is of great importance in the narrow zone near the magnetic equator due to the effect of the equatorial electrojet. Experimental determinations of the latitude dependence of the daily variation of the horizontal intensity have been made in recent years in Africa by

ONWUMECHILLI (1959) in Nigeria, GODIVIER and CRENN (1965) in Tschad, in South America by FORBUSH and CASAVERDE (1961) and in India by YACOB and KHANNA (1963). Experimental surveys have also been made of the latitude dependence of the daily variation of the vertical intensity in Nigeria by RIVERS (1964) and in South America by FORBUSH and CASAVERDE (1961). This work has been summarized by CHAPMAN and RAJA RAO (1965) who have shown that there are longitudinal variations in these parameters. In considering the effects of this latitudinal variation on the results obtained at Freetown one must only consider results obtained in the African zone and more particularly West Africa. The general form of the latitude variation for the horizontal and vertical intensity is given in the rough Sketch A where the daily range for both intensities is plotted against latitude north and south of the position of maximum H range and zero Z range.



Sketch A

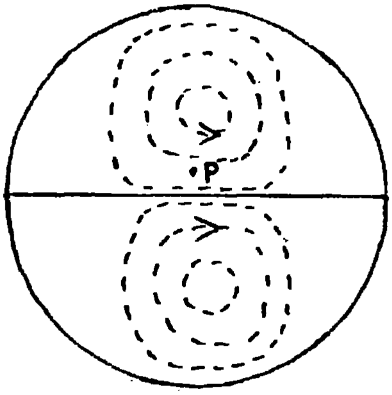
The approximate position of Freetown is marked on the latitude axis, being in the region of 1° latitude north of the magnetic equator and therefore slightly more than 1° north of the position of maximum horizontal intensity range as the position of maximum horizontal intensity daily range lies between the magnetic and geographic equators. Thus a seasonal shift of the 'origin' of the sketch would affect the observed daily ranges of the two intensities at a single station like Freetown in opposite senses. If the 'origin', or centre of the current system, moved south then the daily ranges in the horizontal intensity would decrease. However, for the same southward motion, provided it was small, the vertical intensity ranges would increase. If the movement were very large, i.e. of the order of two or three degrees of latitude then the vertical intensity ranges could decrease as well, For a northward motion of the centre of the system the horizontal ranges would increase whilst the vertical intensity ranges would decrease. These considerations assume a constant current strength and distribution for the equatorial current system which is not the case as the strength has been found to be greatest during the Equinox period (ONWUMECHILLI and OGBUEHI) so that the application of this sketch to the results obtained at Freetown is not straightforward. In addition the day-to-day variability of the entire worldwide current system is well established. To investigate seasonal changes it is therefore best to consider the Group II data as there are then approximately 400 days in each of the seasonal sets and a reasonable mean situation should be apparent. Figure 18 shows the seasonal set mean daily variation for the horizontal intensity. Visual inspection shows clearly the smaller magnitude of the J set daily variation as compared to the E and D set values which has already been seen from the results of the analysis. It can thus be said that the horizontal intensity results show that there is a seasonal movement of the centre of equatorial current system in opposite sense to that of the sun, and that the shift of the system from the equinoxial position is greater in the northern summer months than in the northern winter months. To emphasize thise difference, a plot has been made (Figure 43) of the differences between the equinoxial daily variation and the other two seasonal daily variations for both Groups I and II. For this graph the values have been converted into gammas with arbitrary zero levels. The two pairs of graphs have similar shapes with the largest difference being 35 gamma for J-E in Group II. This difference is not just an amplitude difference as the phase of the maximum occurs later in the J set than in the E set.

The vertical intensity curves show the same effect (Figure 38). In this case the J set range is approximately 30°/o greater than the E set value indicating that during the northern summer months the centre of the equatorial current system has moved south so that Freetown is nearer to the position of maximum vertical intensity daily variation.

The difference curves are also plotted on Figure 43 with the J-E value being the largest difference, in this case positive.

The similar figures for the Declination (Figures 28 and 43) show different features of the daily variation which need to be explained more fully. The Declination at Freetown is West of North and an increase in ordinate in Figure 28 corresponds to a decrease in the value of the angle of declination. Variations in the angle of declination at the surface of the Earth indicate the presence of north-south currents in the ionosphere. A southward directed current component would decrease the angle of declination at Freetown whereas a northward directed current would increase the angle of declination.

If the magnetic equator coincided with the geographic equator then the daytime equinoxial ionospheric current system which would result in this idealised situation would be as shown in rough Sketch B taken from CHAPMAN and BARTELS (1940), p.696. In



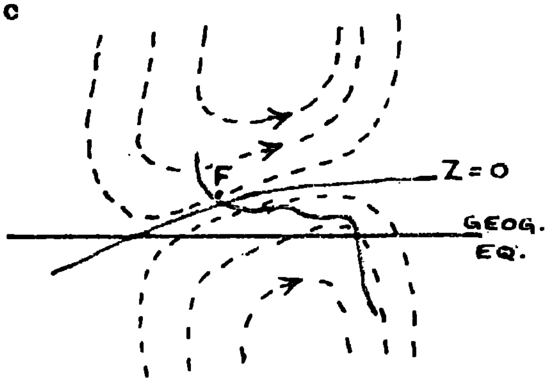
SKETCH B

SKETCH C

this case the daily variation in the declination at a station situated at point p would be of the form shown in Sketch C.

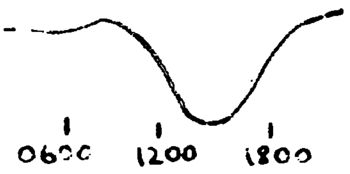
The magnetic equator does not, however, coincide with the geographic equator and in the region of Freetown the departure in the northward direction is large and the direction of the magnetic equator at the surface of the Earth makes an angle of approximately 30° to the lines of latitude. The situation in the upper atmosphere over the South Atlantic Ocean and West Africa is therefore complex and the actual flow patterns of the ionospheric current system will not conform to the idealized picture of Sketch B.

HAGAN and SUGIURA (1967) have shown that the northern ionospheric current vortex is modified in this region in the way shown in Sketch D which gives an impression of the current systems at approximately 1000 hours U.T. on a day near the equinoxes.



SKETCH D

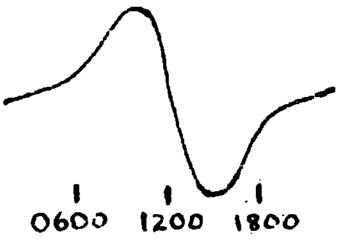
The variation in the Declination on such a day would be of the form found at Freetown and shown in Sketch E (from Figure 28). The current system shown in Sketch D tends to follow the line of the



SKETCH E

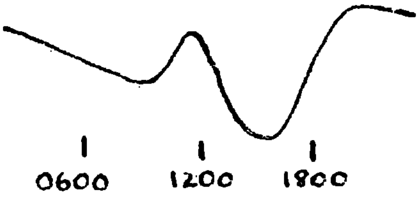
magnetic equator so that in the early morning there is a small southward directed current component. This southward component is soon changed into a northward component which increases in magnitude with the increasing strength of the equatorial electrojet system. The northward component then decays with the approach of sunset.

The horizontal and vertical intensity results have indicated a southward shift of the centre of the current system during the northern summer and a smaller northward shift during the northern winter. Sketch F shows the northern summer Declination daily variation being the mean of 432 days. This shows a strong southward current component existing until nearly 0900 U.T. By this time the equatorial enhancement of ionospheric conductivity is well established and from 1100 U.T. onwards the northward component takes over having a maximum at about 1400 U.T. then decaying towards sunset. This curve agrees well with the relatively large seasonal southward shift of the centre of the equatorial current system.

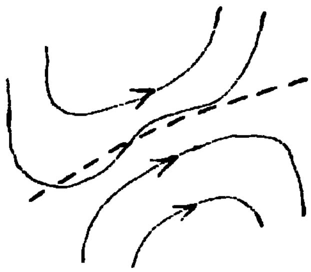


SKETCH F

The mean daily variation of the Declination from 425 days for northern winter is shown in Sketch G (from Figure 28). This shows a northward directed current component in



SKETCH G



SKETCH H

the morning which reaches a maximum at 0900 and decays to the nighttime level by 1100 and then a much stronger northward component which reaches a maximum at 1500 and then decays towards sunset. Such a variation would be observed if Freetown was underneath the region of the current system shown by the dotted line in Sketch H which would agree with the centre of the system having moved slightly northward from the equinoxial position. The difference curves plotted for the two groups in Figure 43 show the seasonal change very clearly. In the curve depicting the difference between the northern summer mean daily variation and the equinoxial mean daily variation (J-E) in the morning hours, there is a net southward current whilst in the other difference curve (D-E) there is a net northward current at the same time in the morning.

The Declination variations as observed at Freetown thus confirm the existence of the distortion of the northern current vortex due to the shape of the magnetic equator and also confirm the results from the horizontal and vertical intensity data on the seasonal shift of the centre of the equatorial current system.

4.7 Induced ocean currents

In recent years geomagnetic variation results from some coastal observatories have been shown to contain considerable contributions from induced currents in the nearby ocean. These effects will be much greater in the shorter period variations than in the variations of periods six hours and longer. The magnitude of these effects will also depend on the proximity to the station of the deep ocean. Off the coast of Sierra Leone the continental shelf is approximately 100 kms from the shore line with the water depth out to that distance being 50 metres or less. This very wide continental shelf extends up the West African coast to the Gambia and south of Freetown for a distance of 150 kms so that induction effects at the Freetown observatory, which is 10 kms from the coastline, should be small.

4.8 Comparisons with other low-latitude stations

(i) Solar daily variations

In the tables given below the results obtained from the analysis of the Freetown data are given together with corresponding results from other low-latitude stations for the three components.

TABLE A

Horizontal Intensity - Annual Values

Unit - 1 Gamma

Station	s_1		s_2		s_3		s_4	
Freetown	37.1	290°	20.6	107°	8.9	305°	2.8	168°
Ibadan[1]	41.0	266°	19.0	113°	8.7	334°	3.4	198°
Huancuyo[2]	53.2	282°	28.6	106°	12.5	304°	12.5	163°
Kodaikanal[3]	38.8	277°	22.5	103°	9.5	308°	1.7	150°
Singapore[4]	21.5	285°	9.6	112°	4.3	322°	-	-
Bombay[4]	18.6	280°	9.8	114°	3.5	316°	-	-

1 - ALEXANDER and ONWUMECHILLI 1959(1)
2 - JOHNSTON and McNISH 1932
3 - THIRUVEGADATHAN 1954 4 - SCHMIDT 1926

It should be pointed out that the Freetown and Huancuyo results refer to periods of sunspot minimum activity, the Singapore and Bombay results refer to a period of relatively low sunspot activity, while the Ibadan results refer to a 20 month period ending in June 1957, a period of relatively high sunspot activity. Thus the Freetown figures would be slightly higher than the Ibadan figures if results for comparable sunspot activity periods were available. This is to be expected due to Freetown having a slightly lower magnetic latitude than Ibadan. There is a clear distinction between the magnitude of the amplitudes at the first four stations which all lie within the region of influence of the equatorial electrojet and Bombay and Singapore which although being low latitude stations are not close enough to the magnetic equator for the electrojet to have any great effect on the horizontal intensity.

TABLE B

Vertical Intensity - Annual Values

Unit - 1 Gamma

Station	s_1		s_2		s_3		s_4	
Freetown	7.0	258°	5.8	59°	2.2	250°	0.6	78°
Ibadan[1]	18.7	272°	12.4	104°	4.6	311°	2.5	219°
Singapore[2]	6.9	278°	3.9	93°	1.7	315°	-	-
Bombay[2]	5.3	84°	4.5	309°	4.2	148°	-	-

1 - ALEXANDER and ONWUMECHILLI 1959(1)
2 - SCHMIDT 1926

The Freetown results when compared with Ibadan clearly show the effect of the distance of the stations from the centre of the equatorial current system. Ibadan lies in the region of maximum vertical component effect to the south of the current system. The Singapore and Bombay amplitudes are comparable to the Freetown results even though the stations are much farther away from the centre of the current system. This is due to the fact that the vertical intensity effect of the electrojet extends to much wider range of latitude than the horizontal intensity effect (see Sketch A). For some distance outside the latitude of maximum vertical intensity effect the amplitude is greater than that at a station such as Freetown which is relatively close to the centre of the system.

TABLE C

Declination - Unit 1 Gamma

Seasonal Values - Northern Summer (J), Northern Winter (D)

Station		S_1	σ_1	S_2	σ_2	S_3	σ_3	S_4	σ_4
Freetown	J	12.4	40°	8.1	239°	4.3	91°	1.3	339°
	D	6.6	87°	4.7	173°	2.1	353°	1.5	206°
Ibadan[1]	J	10.3	232°	9.1	95°	4.1	314°	3.6	217°
	D	2.9	341°	6.5	237°	3.5	127°	1.5	5°
Singapore[1]	J	4.4	359°	5.7	230°	3.0	107°	-	-
	D	10.5	189°	8.0	15°	3.3	233°	-	-
Bombay[2]	J	10.4	31°	10.9	255°	8.1	94°	-	-
	D	1.3	184°	1.3	113°	1.9	51°	-	-

1 - ALEXANDER and ONWUMECHILLI 1959(1)   2.- SCHMIDT 1926

Seasonal values have been given in this case as the variation between the J and D months is an important phenomenon. Freetown, Ibadan and Bombay have similar seasonal changes both in amplitude and phase whilst at Singapore the amplitude changes are in the opposite sense. Freetown and Bombay are both north of the magnetic equator with Bombay being more than 10°N of the magnetic equator during the period analysed by Schmidt. Ibadan and Singapore are both south of the magnetic equator. The above results, however, indicate that the seasonal changes in the declination are not governed, to such a large extent as the other components, by the position of the station with respect to the magnetic equator. Simple inspection of the above figures does not in fact give the full picture. As has been mentioned in the previous section, the shape of the mean daily variation curves for the two seasons (e.g. sketches E and F) show that the strong southward current component in the morning in J months produces a larger daily range than that in the D months which on analysis gives the seasonal differences shown in Table C above.

(ii) Lunar daily variations

Determination of the terms in the daily magnetic variations which are related to the phase of the moon provides information which allows study of the lunar wind system which produces the tides. The lunar tides being purely gravitational in origin are thus more amenable to mathematical analysis. However, the lunar effects are usually very small when compared with the solar daily variations so that long periods of data are normally required before a satisfactory determination can be made. Fortunately in equatorial regions the enhancement of the ionospheric conductivity produces a much larger lunar effect in the daily magnetic variations and reasonable determinations may be made with relatively short periods of data. Thus lunar harmonics have been determined for equatorial stations that have only been established in recent years. The Group II values from the present analysis have been used in the following comparisons.

TABLE D

Horizontal Intensity - Unit 1 Gamma

Annual Values

Station	L_1	t_1	L_2	t_2	L_3	t_3	L_4	t_4
Freetown	2.77	4.5	4.33	8.2	2.75	1.2	0.69	3.8
Ibadan[1]	0.88	6.6	3.99	7.2	0.50	5.5	0.07	0.9
Huancuyo[3]	-	-	5.24	9.1	-	-	-	-

Horizontal Intensity - Unit 1 Gamma

Seasonal Values of L_2

Station	L_2	t_2	L_2	t_2	L_2	t_2
	J		E		D	
Freetown	3.20	9.1	4.58	8.2	5.76	7.4
Ibadan[1]	3.37	7.3	3.82	7.3	4.70	7.0
Addis Ababa[2]	2.30	6.6	6.17	8.5	6.36	7.1
Huancuyo[3]	2.55	9.9	5.53	9.1	7.62	8.2
Kodaikanal[4]	1.43	5.1	2.28	8.1	3.32	4.3

t_2 - Lunar hour of the first maximum

1 - ALEXANDER and ONWUMECHILLI 1959(2)   2 - GOUIN 1960

3 - MATSUSHITA 1967   4 - RAJA RAO 1961

The semi-diurnal term (L_2) is the dominant amplitude, although at Freetown the first and third harmonics are relatively much larger than those found at Ibadan for the period 1955-57.

The seasonal variations of the semi-diurnal lunar tide in the second part of Table D show for the stations concerned that in every case the amplitudes increase from northern summer months through the equinox months to northern winter months. Freetown (8.5°N), Ibadan (7.5°N) and Addis Ababa (9°N) are all situated north of the geographic equator on the African continent. Huancuyo (12°S) is some 20° south geographically of these stations and in South America. Freetown and Huancuyo have North dip latitudes while Ibadan and Addis Ababa are south of the dip equator. The range of dip latitudes being approximately 4° so that all of these stations are directly influenced by the equatorial conductivity anomaly.

MATSUSHITA and MAEDA (1965) have shown that this type of seasonal variation is shown by all low magnetic latitude stations. They also showed that there is a slight shift of the position of maximum lunar semi-diurnal variation towards the winter hemisphere.

TABLE E

Vertical Intensity - Unit 1 Gamma

Seasonal Values of L_2

Station	J		E		D	
	L_2	t_2	L_2	t_2	L_2	t_2
Freetown	1.78	10.5	1.47	9.8	0.87	7.5
Ibadan[1]	2.69	7.8	2.07	7.6	3.04	7.2
Addis Ababa[2]	0.64	11.1	0.79	7.7	1.62	1.4

1 - ALEXANDER and ONWUMECHILLI 1959(2)   2 - GOUIN 1960

The seasonal variation in the semi-diurnal lunar tide in the vertical intensity for Ibadan and Addis Ababa are similar with respect to amplitude changes but there are large phase differences. Both the Ibadan and Addis Ababa results were obtained during periods of high sunspot activity. The Freetown figures refer to a period of minimum activity, and would therefore be expected to be slightly smaller although the lunar tide is less affected by sunspot activity than the solar harmonics. The important factor for the vertical intensity is the position of the station with respect to the region of maximum vertical intensity daily variation either side of the equatorial conductivity anomaly. When viewed in this way the above results are consistent and show a general movement of the equatorial electrojet northwards from J months to D months.

TABLE F

Declination - Unit 1 Minute

Seasonal Values of L_2

Station	J		E		D	
	L_2	t_2	L_2	t_2	L_2	t_2
Freetown	0.15	6.3	0.05	6.1	0.13	0.6
Ibadan[1]	0.18	6.0	(0.07)	6.3	0.20	10.6
Addis Ababa[2]	0.13	7.3	0.20	9.7	0.33	11.8
Huancuyo[3]	0.14	7.9	0.19	8.3	0.08	9.3

1 - ONWUMECHILLI 1960 2 - GOUIN 1960

3 - MATSUSHITA 1967

The semi-diurnal lunar variation in the declination at Freetown is similar to that obtained at Ibadan in that during the Equinoctial months the tide is variable in phase giving rise to a small resultant amplitude. In the case of Ibadan this amplitude is not statistically significant and the Freetown figure is only barely significant. The phase differences between the J and D sets are similar for the three African stations but much larger than that at Huancuyo. The amplitude differences between the solsticial sets are small and within the error limits. It appears that Freetown and Ibadan lie in the transition region between the northern and southern lunar current systems during the equinoctial months and during the solsticial months, J and D, are respectively influenced by the northern and southern systems. This means that the southern lunar current system stretches well into the northern hemisphere during northern winter.

5. SHORT PERIOD VARIATIONS

Short period variations, or pulsations, in the geomagnetic field are normally studied using specially built high sensitive equipment with fast chart speeds. However, certain types of pulsations, the pc 3 and pc 4, can frequently be clearly observed on normal magnetograms. The periods of these pulsations lie within the range 1 to 10 minutes so that the paper speed of the normal magnetogram (15 mm/hour) does not allow investigations of variations in the periods of the pulsations.

Pulsations of this type were apparent on the normal magnetograms at Freetown in 1962 and a study was made of the 12 month period from March 1962 to February 1963. The pulsations were most clearly visible on the horizontal component trace. Pulsations were occasionally to be seen at the same time on the declination trace but only rarely were they visible on the vertical component trace. The different sensitivities of the three traces undoubtedly had an effect on the occurrence of the pulsations in the three components. The horizontal component trace only was studied in detail. Pulsations were said to occur in any hour if they were clearly visible on the magnetogram and persisted for ten minutes or more in that hour. The number of pulsations occurring at each hour was plotted for the 12 months (Figure 93). The probability of occurrence was plotted for the three seasonal sets and for the year's data as a whole. (Figure 94). The curve for the complete year's data shows two maxima, the first at 0700 and the second at 1200 hours. The J set and E set curves have similar characteristics but in the D set curve the morning maximum is completely absent. It is possible that the absence of the morning maximum in the D set months is due to the fact that these months were the last four of the 12 months considered and the number of pulsations visible on the magnetograms was becoming smaller. The January and February 1963 curves show a general low level of pulsation occurrence with no clear maximum or minimum period in the February curve. The midday maximum is not present throughout the year studied with low values being obtained for June, July and October 1962. There is a tendency for an increase in pulsation activity around 1800 hours just before sunset but not nearly as marked as that found by HUTTON (1960) for continuous pulsation activity at Legon in Ghana.

A correlation study has been made of the occurrence of the pulsations with worldwide magnetic activity using the published K_p index values. A total of 2613 three hour periods were available during the 12 month period. The K_p indices were divided into four groups as follows:-

1 - K_p from 0_o to 1-

2 - K_p from 1_o to 2-

3 - K_p from 2_o to 3-

4 - $K_p \geqslant 3_o$

The annual and seasonal curves for the occurrence of this type of pulsation with increasing magnetic activity have been plotted (Figure 95). There is no clear connection between the occurrence of pulsations and magnetic activity. For the northern winter months there is a decrease in occurrence of pulsations with the higher levels of activity which may be associated with the absence of the morning maximum during these months. For the other seasons there is a general increase in occurrence of pulsations with increasing magnetic activity. A more detailed study is necessary to see if particular levels of activity are associated with the norning, midday and evening peaks of occurrence.

OSBORNE and RIVERS (1963) gave a preliminary account of a comparison between the pulsations observed at Freetown and those observed at Tamale, a temporary magnetic station established in Northern Ghana with a dip angle of 1.2° south. Initially records from both Freetown and Tamale for March 1962 were used, taking note only of those times for which magnetograms were good at both stations, 663 hours out of a total of 774 hours. At Freetown, pulsations occurred during 270 hours giving a probability of occurrence of 0.41. At Tamale the pulsations occurred during 100 hours giving a probability of occurrence of 0.15. The difference between these two figures was almost certainly due to different sensitivities at the two stations, 1.3 γ/mm at Freetown and 3.1 γ/mm at Tamale. When pulsations were observed at Tamale the probability that they were also noted at Freetown was 0.85. When pulsations were not recorded at Tamale the probability of occurrence at Freetown was 0.31. These values suggest that essentially the same events were occurring at both stations but that the threshold value for detection was different. The noon maximum observed at Freetown throughout the year was absent at Tamale in the March records and when the comparison was extended to the same period as covered by the Freetown results a similar situation was found with only one maximum of occurrence found at Tamale. In the northern winter months when the Freetown morning maximum was absent the Tamale maximum occurred at 1000, some three hours later than during the rest of the year. It seems likely that the lower sensitivity of the Tamale records did not permit the detection of the noon pulsations observed at Freetown.

The occurrence curves at Freetown are similar to those obtained at M'Bour (HARSCZUS 1965) over a longer period with more sensitive equipment (sensitivity 0.12 γ/mm) specially designed for recording this type of phenomenon. The diurnal variation curves at M'Bour show two principal maxima, one at sunrise and the other at noon. The sunrise maximum varies throughout the year with the time of sunrise being later in northern winter months.

6.1 Secular variation in Sierra Leone

It is not possible to say a great deal about the secular variation in Sierra Leone due to the lack of data. The earliest records of magnetic field measurements in Sierra Leone date from 1911 with the first visit of scientists from the Carnegie Institute of Washington. Four stations were occupied in the period 1911-12 (BAUER and FLEMING 1915), three of these being reoccupied in 1925 (FISK 1927). A comprehensive survey of French West Africa (O.R.S.T.OM. M'BOUR 1958) was carried out during the period 1953-58 and since 1960 the writer has made various measurements throughout Sierra Leone.

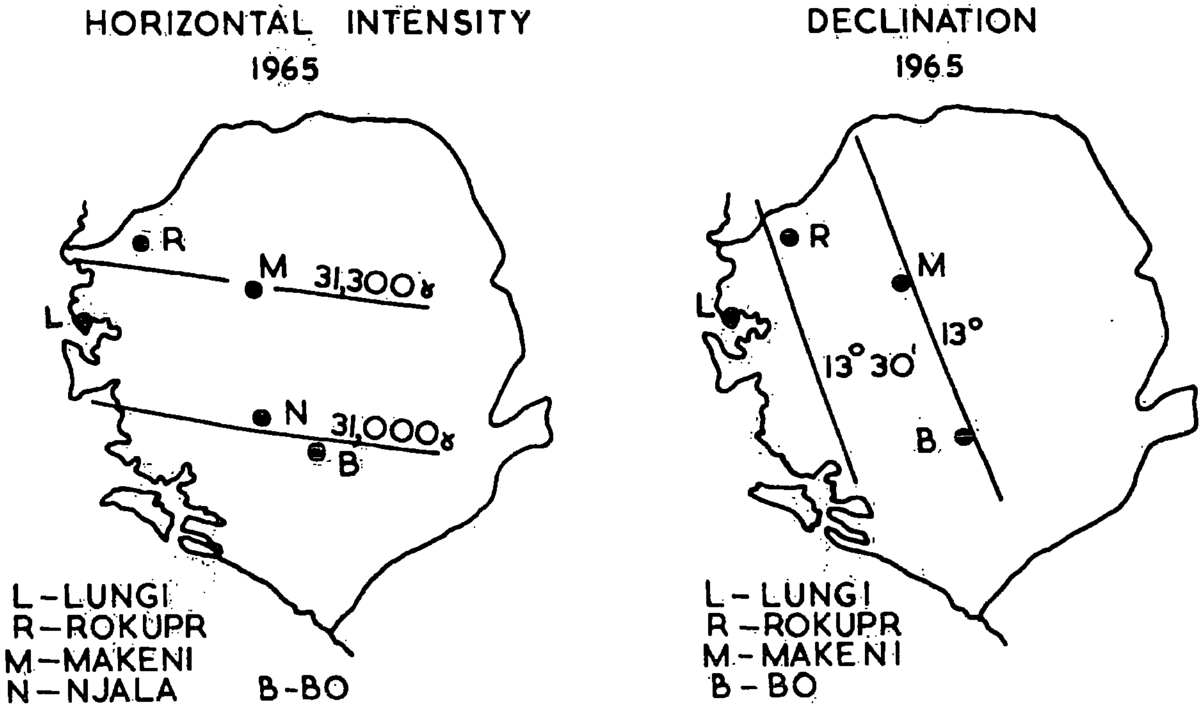
Use has been made of the above measurements and of the results due to VESTINE et al (1959) in constructing the secular variation graphs for the horizontal and vertical intensities and the declination (Figure 92). These graphs have been plotted for Bo which occupies an approximately central position in Sierra Leone. There is a similar amount of data available for Bo as for Freetown but Bo is not affected by local anomalies as is Freetown. As can be seen from the graphs the rate of change of horizontal intensity appears to be smaller in 1965 than during the period 1925-1945, being of the order of 2 gammas per year. The 1965 rate of change of Declination is approximately 10' per year and the 1965 rate of change of vertical intensity is 80 gammas per year. All these results are necessarily uncertain due to the amount of smoothing and extrapolation involved.

6.2 World Magnetic Survey

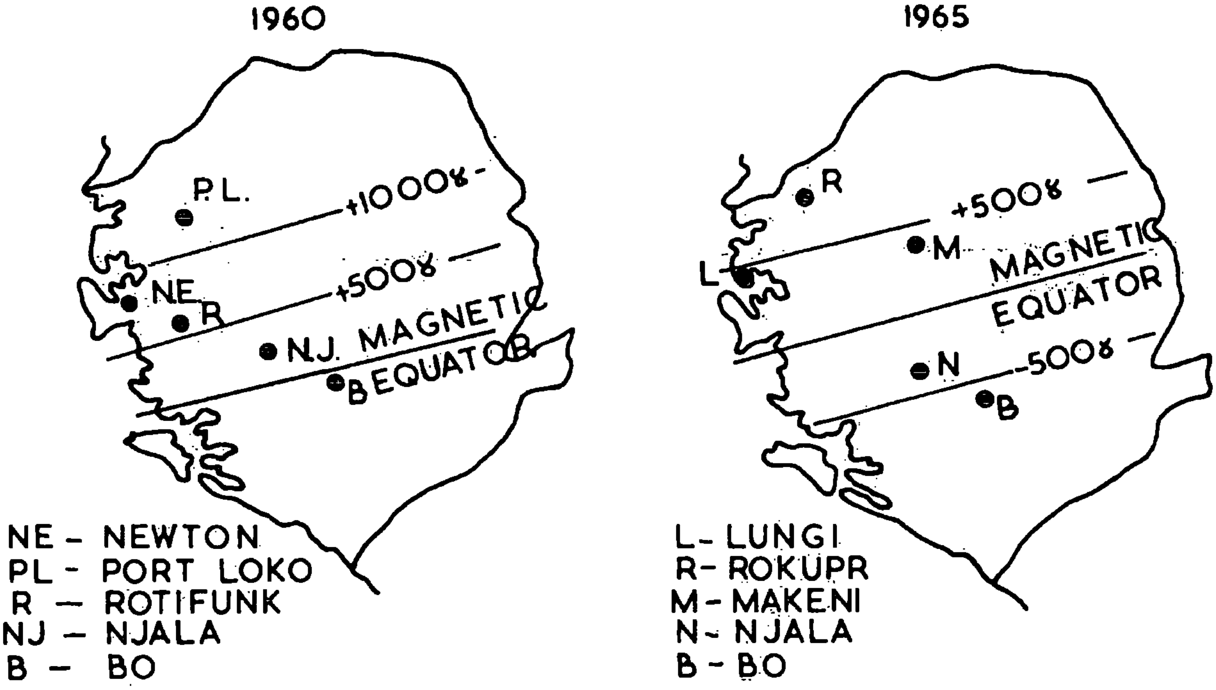
As the Sierra Leone contribution to the World Magnetic Survey it was hoped to reoccupy the early Carnegie sites and to establish new repeat stations in Sierra Leone. Two of the Carnegie sites, Freetown and Bo, were identified but found to be unsuitable for reoccupation due to recent building. The site at Moyamba was located from old maps at the Government Survey Department and found to be now within the building of a large secondary school. The fourth site at Baiima was too far from Freetown to be visited in the time available. New sites were therefore established, where possible using Sierra Leone Government secondary survey points which are less likely to be disturbed and could therefore more easily be reoccupied at a future date.

Readings at the first station visited were initially attempted just before dawn commencing at 0430 GMT but difficulty was experienced in taking the readings with any speed due to considerable condensation on the instruments. All subsequent readings were taken at dusk within a four month period from January to May 1965. In November 1964

Dr, K. A. Wienert, Director of the Geophysical Observatory at Fuerstenfeldbruck in Western Germany, spent four days at Freetown during a UNESCO-IAGA sponsored tour of magnetic observatories in Africa. The purpose of the tour being to check observatory standards and to compare the instruments in use with a standard set of QHM's which he carried with him. As a result of these comparisons, small corrections were derived for Freetown's QHM 506 and QHM 507. These are the corrections mentioned in the results table which follows. It should be noted that the declination measurements at Bo are almost certainly incorrect. This may be due to incorrect readings or an incorrect bearing supplied by the Survey Department. Every effort will be made to check this reading by site reoccupation in 1968. The magnetic charts shown overleaf have been drawn from this survey data and the O.R.S.T.O.M. survey data mentioned earlier.



VERTICAL INTENSITY



MAGNETIC CHARTS OF SIERRA LEONE SHOWING FIELD OBSERVATIONS POINTS.

SUMMARY OF W.M.S. READINGS

1. **ROKUPR** 9° 00' 44" N 12° 57' 16" W
62.0' above M.S.L.

Site description:- At the Rice Research Institute, Rokupr, part of Njala University College, University of Sierra Leone. Next to the Meteorological Station overlooking rice trial paddies to the Great Scarcies river. Fifty feet from centre of road past Meteorological Station, marked by concrete beacon set just below ground level and inscribed W.M.S. 1965. Bearings - W.M.S. 1965 to corner of air temperature thermometer screen nearest road N 310° 22' 40" E, W.M.S. 1965 to concrete survey beacon R.C.S. 167 at edge of road N 28° 14' 30" E.

Readings

(a) Horizontal intensity

Date	QHM	GMT	H	Correction	Final Value
14.1.65	506	0540	0.31338	-8 γ	0.31330
14.1.65	506	1812	0.31335	-8 γ	0.31327
14.1.65	506	1820	0.31334	-8 γ	0.31326
14.1.65	507	1832	0.31343	-16 γ	0.31327
14.1.65	507	1838	0.31342	-16 γ	0.31326
15.1.65	507	0446	0.31350	-16 γ	0.31334
15.1.65	507	0455	0.31351	-16 γ	0.31335
15.1.65	506	0518	0.31341	-8 γ	0.31333
15.1.65	506	0530	0.31338	-8 γ	0.31330

(b) Declination

Date	QHM	GMT	D	Correction	Final Value
14.1.65	506	0547	N 13° 36'.0 W	-2'.0	N 13°34'.0 W
14.1.65	506	1824	N 13° 24'.5 W	-2'.0	N 13°22'.5 W
14.1.65	507	1835	N 13° 23'.8 W	+1'.8	N 13°25'.6 W
15.1.65	507	0450	N 13° 33'.5 W	+1'.8	N 13°35'.3 W
15.1.65	506	0518	N 13° 33'.0 W	-2'.0	N 13°31'.0 W

(c) Vertical intensity

All readings using BMZ 246.

Date	Time	Value	Date	Time	Value
14.1.65	0446	0.01193	15.1.65	0421	0.01200
14.1.65	0452	0.01195	15.1.65	0424	0.01201
14.1.65	1749	0.01189			
14.1.65	1754	0.01193			

2. LUNGI

Bench Point SLS 71/58/BP1.
08° 37' 17" N 13° 12' 33" W
85.0 ft. above M.S.L.

Site description:- Existing bench point BP1 of SLS 71/58 used. Bench point situated 12' from centre of road outside Airport Manager's house near to tennis court next to the old Airport Hotel, approximately one mile from Airport Terminal buildings. Bearing used for Declination readings BP1 to BP9 N 335° 21' 04".

Readings

(a) Horizontal intensity

Date	QHM	GMT	H	Correction	Final Value
13.4.65	506	0805	0.31255	-0.00008	0.31247
13.4.65	506	0811	0.31257	-0.00008	0.31249
13.4.65	506	1807	0.31250	-0.00008	0.31242
13.4.65	506	1813	0.31250	-0.00008	0.31242
14.4.65	506	0746	0.31246	-0.00008	0.31238
14.4.65	506	0752	0.31247	-0.00008	0.31239
14.4.65	506	1826	0.31247	-0.00008	0.31239
14.4.65	506	1833	0.31248	-0.00008	0.31240

(b) Declination

Date	QHM	GMT	D	Correction	Final Value
13.4.65	506	0807	N 13°40'.2W	-2'.0	N 13°38'.2W
13.4.65	506	1810	N 13°39'.7W	-2'.0	N 13°37'.7W
14.4.65	506	0749	N 13°43'.0W	-2'.0	N 13°41'.0W
14.4.65	506	1831	N 13°41'.6W	-2'.0	N 13°39'.6W

(c) Vertical intensity BMZ 246

Date	Time	Value
13.4.65	0745	0.00442
13.4.65	1821	0.00449

3. BO Bench point PB C512

07° 59' 01" N 11° 44' 26" W

325 ft. above M.S.L.

Site description:- Existing bench point PB C512 used. Bench point situated at the side of the road from Bo to Magburaka approximately five miles from the railway station, at the main entrance to Christ the King College, the Roman Catholic Secondary School at Bo. Bearing used for declination C512 to C514 N 185° 29' 45" E. C514 is 330 yards towards Bo town from C512 on the same side of the road.

Readings

(a) Horizontal intensity

Date	QHM	GMT	H	Correction	Final Value
24.4.65	506	1804	0.31019	-0.00008	0.31011
24.4.65	506	1810	0.31025	-0.00008	0.31017
25.4.65	507	1828	0.31019	-0.00016	0.31003
25.4.65	507	1831	0.31014	-0.00016	0.30998
25.4.65	506	1854	0.31011	-0.00008	0.31003
25.4.65	506	1859	0.31008	-0.00008	0.31000

(b) Declination

Date	QHM	GMT	D	Correction	Final Value	
24.4.65	506	1807	N 19°13'.8W	-2'.0	N 19°11'.8W	?
25.4.65	507	1830	N 19°13'.4W	+1'.8	N 19°15'.2W	?
25.4.65	506	1856	N 19°15'.4W	-2'.0	N 19°13'.4W	?

(c) Vertical intensity

Date	GMT	Value	Date	GMT	Value
24.4.65	1755	-0.00582	25.4.65	1814	-0.00568
24.4.65	1820	-0.00575	25.4.65	1843	-0.00569
25.4.65	1810	-0.00568	25.4.65	1845	-0.00568

4. **MAKENI** Bench Point PB B411
08° 52' 43" N 12° 02' 08" W
300 ft. above M.S.L.

Site description:- Existing bench point PB B411 used. Bench point situated outside Government Forestry Office on road from Makeni to Teko. Bearing used for declination B411 to B412 N 157° 32' 16" E. B412 is 429 ft. towards Teko from B411 on the same side of the road.

Readings

(a) Horizontal intensity

Date	QHM	GMT	H	Correction	Final Value
29.5.65	506	1823	0.31193	-0.00008	0.31185
29.5.65	506	1829	0.31193	-0.00008	0.31185
29.5.65	506	1851	0.31194	-0.00008	0.31186
29.5.65	506	1857	0.31193	-0.00008	0.31185
30.5.65	507	1757	0.31218	-0.00016	0.31202
30.5.65	507	1807	0.31211	-0.00016	0.31195
30.5.65	507	1828	0.31215	-0.00016	0.31199
30.5.65	507	1834	0.31207	-0.00016	0.31191

(b) Declination

Date	QHM	GMT	D	Correction	Final Value
29.5.65	506	1825	N 13°6'.3W	-2'.0	N 13°4'.3W
29.5.65	506	1855	N 13°6'.7W	-2'.0	N 13°4'.7W
30.5.65	507	1802	N 13°5'.6W	+1'.8	N 13°7'.4W
30.5.65	507	1831	N 13°6'.2W	+1'.8	N 13°8'.0W

(c) Vertical intensity BMZ 246

Date	GMT	Value
29.5.65	1758	0.00467
29.5.65	1802	0.00464
29.5.65	1841	0.00459
29.5.65	1907	0.00454

7. FIELD MEASUREMENTS

7.1 Introduction

Various surveys of the daily ranges of the horizontal intensity have been made in equatorial regions as part of the study of the equatorial electrojet current system. Early measurements were made in South America, various parts of Africa and in India using the Quartz Horizontal Force Magnetometer (Q.H.M.). These surveys provided series of instantaneous readings with the inherent uncertainty of whether the actual daily range had been measured or whether the readings had been unduly affected by the fluctuations which often occur in these regions even on very quiet days.

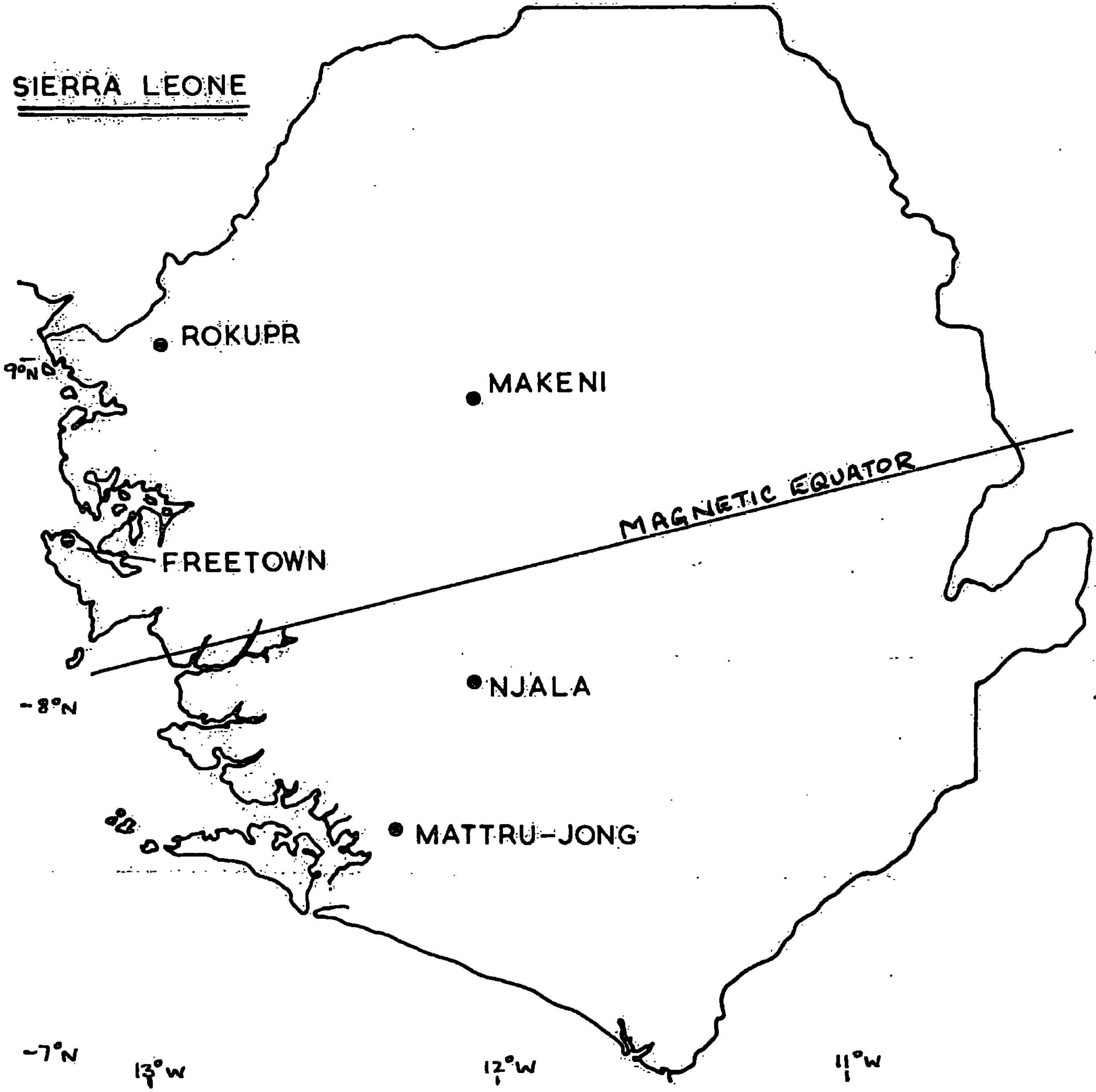
ONWUMECHILLI (1959) in 1956 first used a portable horizontal intensity magnetometer incorporating continuous photographic registration in his study of the equatorial electrojet in Nigeria. RIVERS (1964) in 1958-59 carried out a similar survey of the vertical intensity in this region using the same method of continuous registration. FORBUSH and CASAVERDE (1961) backed by greater resources and using commercially made equipment carried out an extensive survey of three components (H,D,Z) in South America during the I.G.Y.-I.G.C. period. It was apparent that the information which could be obtained from such surveys was of greater reliability if at least two components were simultaneously measured, preferably the horizontal and vertical intensities. The survey made in Sierra Leone was thus planned to measure the horizontal and vertical intensities using continuous photographic registration during the magnetically quiet period of early 1964. This period was also chosen as the time of year when the roads in Sierra Leone were in their most reasonable state. It was decided to attempt to measure H and Z at four field stations simultaneously in addition to the permanent observatory at Freetown.

The situations of the field stations in relation to the magnetic equator are shown in map overleaf. Unfortunately for various reasons it was not found possible to establish the most remote station at Mattru-Jong, so that records were only obtained from the stations at Rokupr, Makeni and Njala.

The magnetometers used in the survey were designed by the author and constructed in the department workshop, which at that time possessed only a small lathe and a half inch drill, so that construction was slow and accuracy difficult to achieve.

7.2 Magnetometer design

The magnet systems used were identical to those used in the observatory magnetometers and were obtained from the Danish Meteorological Institute. Apart from mechanical design problems the chief difficulty was to produce variometers with little or no temperature coefficients.


SIERRA LEONE
ROKUPR
MAKENI
MAGNETIC EQUATOR
FREETOWN
NJALA
MATTRU-JONG
9°N
8°N
7°N
13°W
12°W
11°W

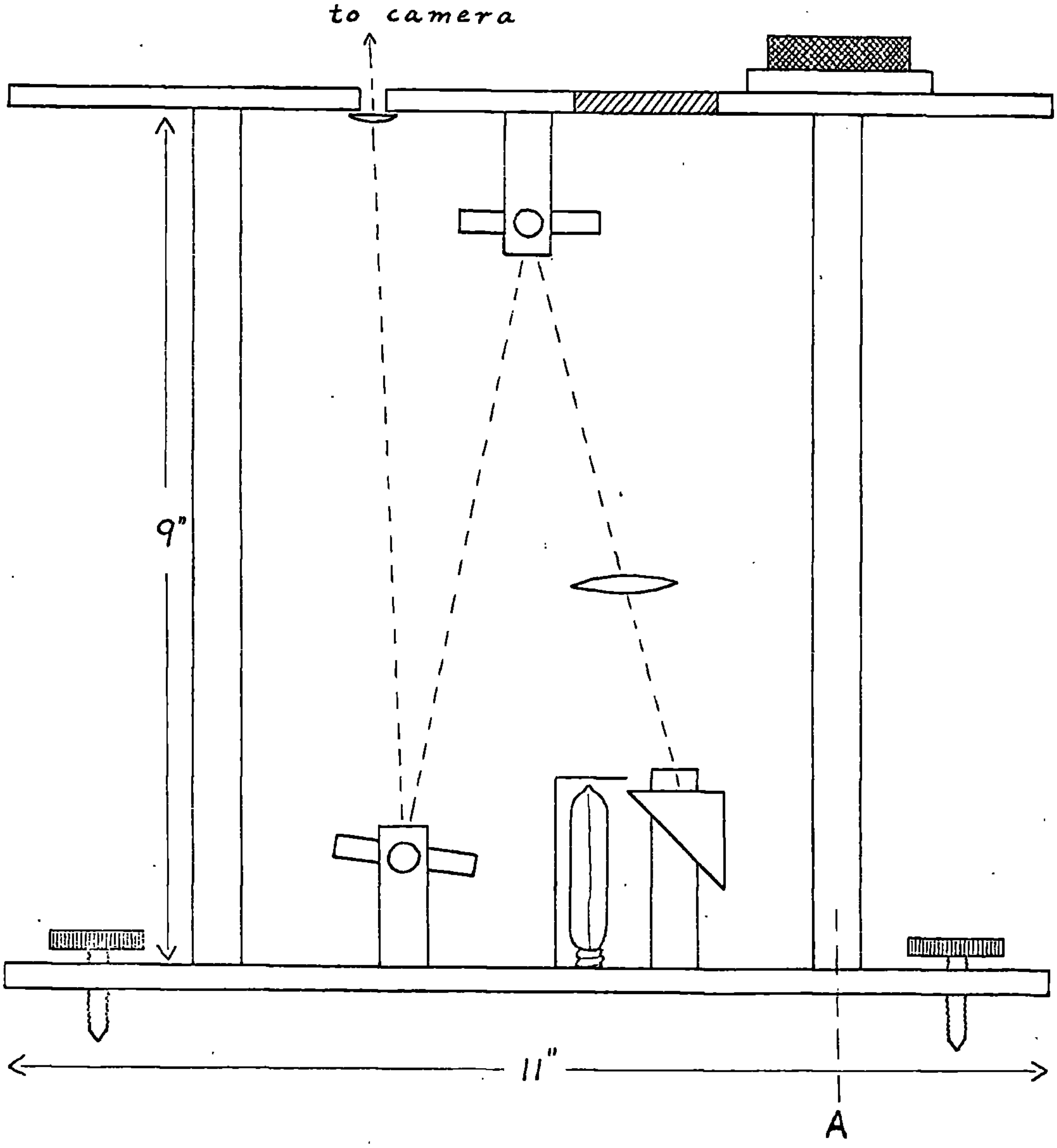
Temperature compensation is achieved in various ways in commercial magnetometer systems, the optical method used in the observatory arrangement having already been described. These systems are expensive and almost impossible to construct in a small workshop. It was therefore decided to attempt to eliminate the daily temperature variation by placing the variometers in holes in the ground shielded from direct sunlight by trees and other cover. A surface daily temperature variation of 20°C is barely measurable at a depth of four feet. Clearly, the daily temperature variation at the bottom of a hole will be larger than that in the solid earth at the same depth; however, a considerable reduction in the magnitude of the variation was achieved by this method, the daily temperature variation within the magnetometers being reduced by an order of magnitude to the region of 2-3°C.

7.2.1 Horizontal Intensity Magnetometer

The following diagrams show the main features of the horizontal intensity magnetometer. Diagram 1 shows the optical system which was used to give reasonable sensitivity values. The single filament lamp at the base of the magnetometer was shielded apart from a narrow slit in the direction of the suspended magnet system. The reflected ray from the mirror of the magnet system then passed into the right angle prism, which could be rotated, through a lens which could be adjusted to focus the image then via

DIAGRAM. I.

H VARIOMETER



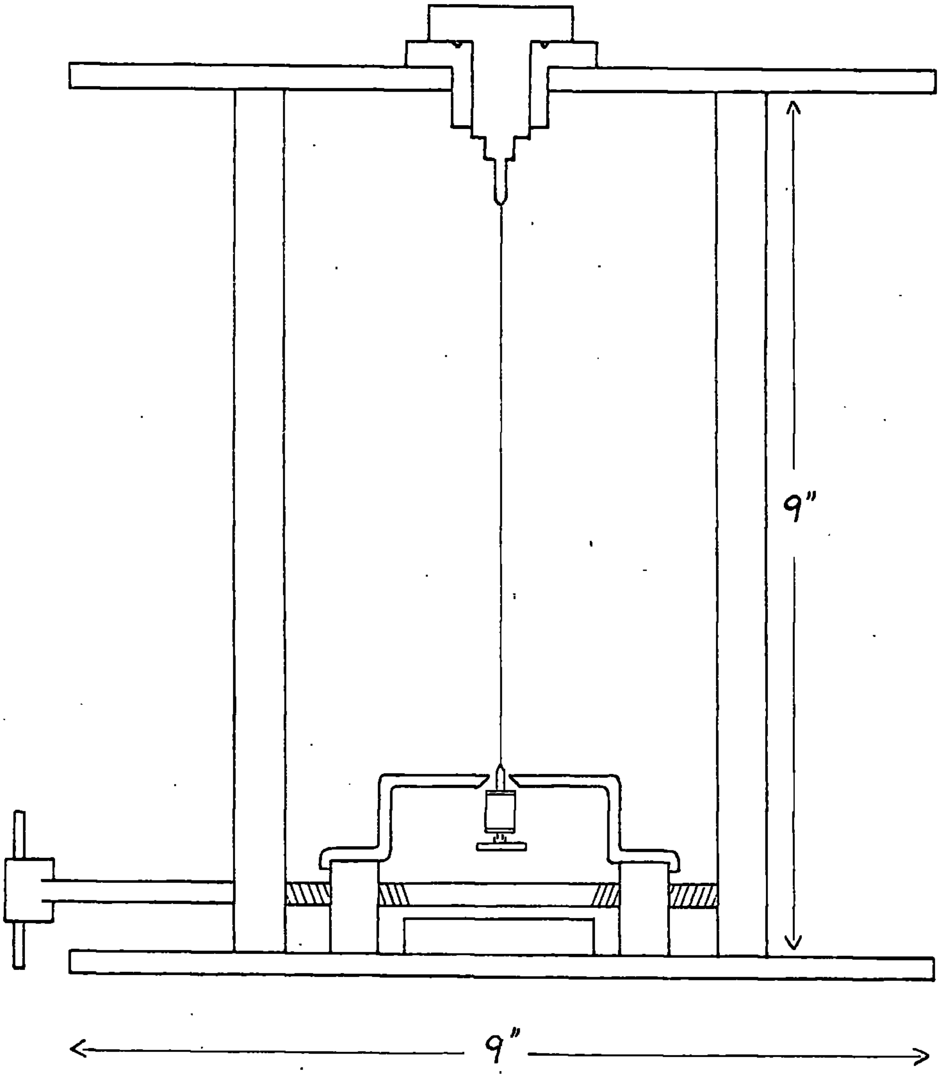
two surface aluminised mirrors to the plano-convex lens fitted to the top of the variometer frame. The plano-convex lens served to focus the line image to a sharp point on the photographic paper inside the camera. A fixed base-line trace was obtained from a 1 cm diameter surface aluminised mirror fixed to the base of the variometer. The reflected ray from this mirror passed through the same optical path as the ray from the magnet system. Diagram 2 shows the suspended magnet system and the clamping device. The fine quartz fibre suspensions were fixed to the upper support and the magnet system in the manner described in CHAPMAN and BARTELS (1940), p.93. The upper suspension support which was turned from a solid piece of brass could rotate within a phosphor bronze collar which was fitted to the top plate of the variometer. A good fit was obtained by lapping the brass in the phosphor bronze collar. To assist smooth rotation during normal use over a long period a high viscosity grease was used.

The clamping device operated on the magnet system at the lower end of the suspension. The wing nut at the left-hand side of Diagram 2 was outside the variometer casing, the shaft having a left-hand thread at one end and a right-hand thread at the other, so that on rotation of the wing nut the two halves of the clamp either moved together or apart. When closed, the ends of the clamp, which were made from copper strip, gripped the small brass cylinder at the

DIAGRAM. 2.

H VARIOMETER

Section at A



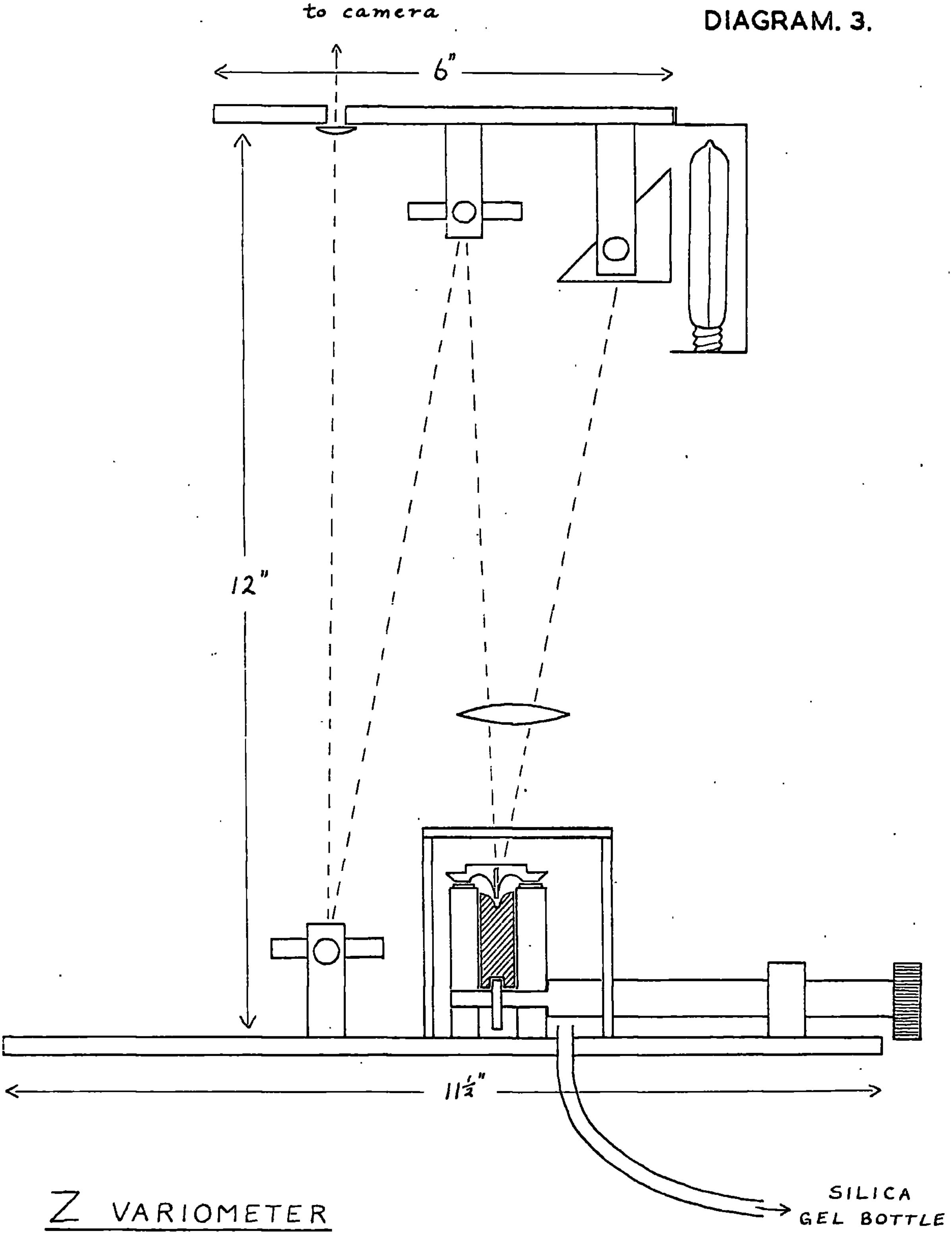
top of the mirror, and on applying a small amount of extra pressure the two halves of the clamp moved upwards slightly, thus freeing the quartz suspension from all stress. After initial attempts at the first field station to mount the suspension in the field, the magnet systems were mounted in the laboratory at Freetown and transported in the clamped position to the field station.

The main structure of the variometer consisted of a base plate and top plate of $\frac{1}{4}$" gauge duraluminium separated by four nine inch brass hexagon section rods. Beneath the suspended magnet a $\frac{1}{2}$" thick block of copper was fixed to assist in damping short period artificial oscillations. There was a hole in the upper plate which allowed direct vision of the suspended magnet system during adjustment of the variometer. During normal use this hole was covered by the camera base. Between the base and top plates the variometer was enclosed in a $\frac{3}{8}$" thick asbestos tube. The upper and lower rims of the tube fitted into grooves in the duraluminium plates with rubber rings to assist in making the joints light tight. The entire inside of the variometer was painted with matt black paint to prevent stray reflections fogging the photographic record.

7.2.2 Vertical Intensity Magnetometer

The main features of the magnetometer are shown in Diagram 3. The magnet system used was similar to that

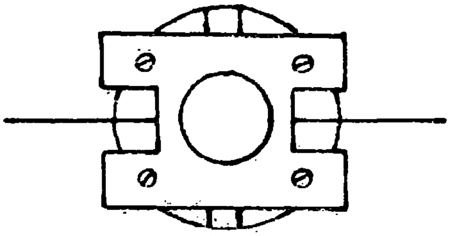
DIAGRAM. 3.



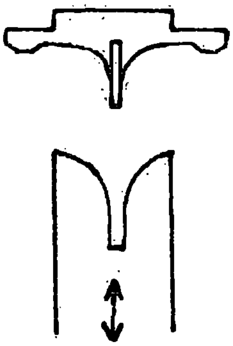
Z VARIOMETER

used in the vertical intensity magnetometer in the observatory at Freetown. Changes in the vertical intensity recorded by the instrument were registered photographically by a spot of light from a single filament lamp which was reflected from the upper surface of the balanced magnetic needle.

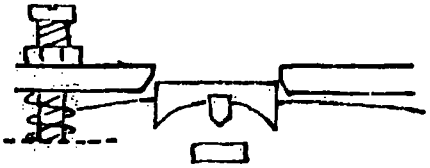
Having reduced the effects of the temperature variation by placing the magnetometer in a hole in the ground, the main problem with the vertical intensity magnetometer was the requirement that the knife edges of the magnetic needle should be consistently in the same position on the agate planes. Only in this way would stability of sensitivity be achieved at each field station. Much time was therefore spent on the design and construction of the device for clamping the magnet and lowering it into position on the agate planes. Details of the final arrangement as it was used at all the field stations are given in the following sketch.



SKETCH A



SKETCH B



SKETCH C

The base of the support was a $1\frac{1}{2}$" diameter brass cylinder with a $\frac{1}{2}$" hole reamed through its centre. The agate planes were mounted in grooves on the top of this cylinder. A second brass cylinder was able to slide smoothly within the cylindrical hole, the top of this cylinder being shaped to fit the underneath of the magnetic needle (Sketch B). The bottom of the cylinder was slotted to take the cam which was used to raise and lower it. The upper part of the clamp consisted of a duraluminium plate which was fixed to the larger brass cylinder (Sketch A). The height of this plate above the agate planes could be adjusted and locked in position by means of lock nuts on the mounting screws. There was a circular hole in the centre of the plate which exactly fitted the top of the magnetic needle (Sketch C). The lower edge of this hole was bevelled so that if the magnet was not in the correct position, raising the central cylinder by means of the cam would centre the needle in the clamp. On lowering, the needle would then be in the correct position on the agate planes. The clamp could be raised and lowered from the outside of the variometer by means of the knob at the bottom right of Diagram 3.

The optical system was similar to that used in the horizontal force magnetometer consisting of a single filament lamp, a lens to focus the line image and two surface aluminised mirrors to extend the optical path. A plano-convex cylindrical lens was used to focus the line image into a spot on the photographic paper in the camera. The fixed base-line trace was obtained from a small surface aluminised circular mirror which was fixed to the upper part of the clamping device.

Due to the extreme humidity values which are encountered in Sierra Leone it was necessary to have the balanced magnet in an artificially dried environment. The magnet support and clamp were enclosed in a perspex box. A hole was drilled through the base plate into the box and a rubber tube connected the box to a bottle of silica gel. In this way the silica gel could be renewed without disturbing the magnet system. The sealing of the box and the various joints in the system was such that the silica gel only needed changing every three or four weeks.

The outer casing of the vertical intensity magnetometer consisted of an asbestos tube one inch in thickness. Apart from assisting in the reduction of temperature effects, the weight of the tube made the magnetometer very stable. The inside of the tube and the magnetometer were painted with matt black paint to reduce the effect of stray reflections.

7.3 The magnetometer cameras

The cameras for all the magnetometers were constructed at Freetown, each one consisting of an adapted barograph clock mounted inside a light tight aluminium box. The base of the box fitted on the top of the appropriate magnetometer located in position by additional strips of aluminium screwed to the top of the magnetometer. A fine slit was cut in the camera base plate to allow the incidence of the spots of light on the photographic paper. The camera shutter was a strip of brass on the inside of the baseplate which could be moved over the slit by means of two rods which protruded from the side of the camera box. When the shutter was closed the camera could be simply lifted from the magnetometer and taken to a suitable place for the development of the record. The barograph clock had interchangeable gears which allowed either one revolution in 25 hours or one revolution in seven and a half days. During the preliminary adjustment and calibration period the faster speed was used, but throughout the normal operation of the magnetometers the slower speed was used so that the records only needed changing weekly. The paper speeds with the different sets of gears were 11.4 mm per hour and 1.7 mm per hour for normal working.

The power supply for the single filament bulbs was obtained from a six volt heavy duty car battery trickle charged from the mains where possible. The intensities of the lamps in the two magnetometers could be varied independently by means of potentiometers at the supply unit.

7.4 Calibration of the magnetometers

The magnetometers were calibrated at the field stations by two different methods. Firstly, by the application of a known field using a Helmholtz coil array and measuring the deflection produced either visually or photographically. Secondly, by taking series of readings with the QHM and BMZ and comparing the values with those of the ordinates on the photographic records at the corresponding times. An example of the sensitivity determinations is given in Figure 96 for the Horizontal and Vertical Intensity magnetometers at Rokupr. Similar graphs were obtained at Njala and Makeni.

7.5 Discussion of the results

The functioning of the magnetometers at the three field stations was not as good as had been expected. The horizontal intensity magnetometer functioned fairly well particularly at Rokupr where several weeks continuous records were obtained. The magnetometers were only installed at Makeni and Njala for six weeks and there were several faults during this period.

Figure 97 shows the records obtained for the horizontal intensity at the three field stations and Freetown for the period 14-20 March 1964. The average ranges for the four stations for this period were as follows:-

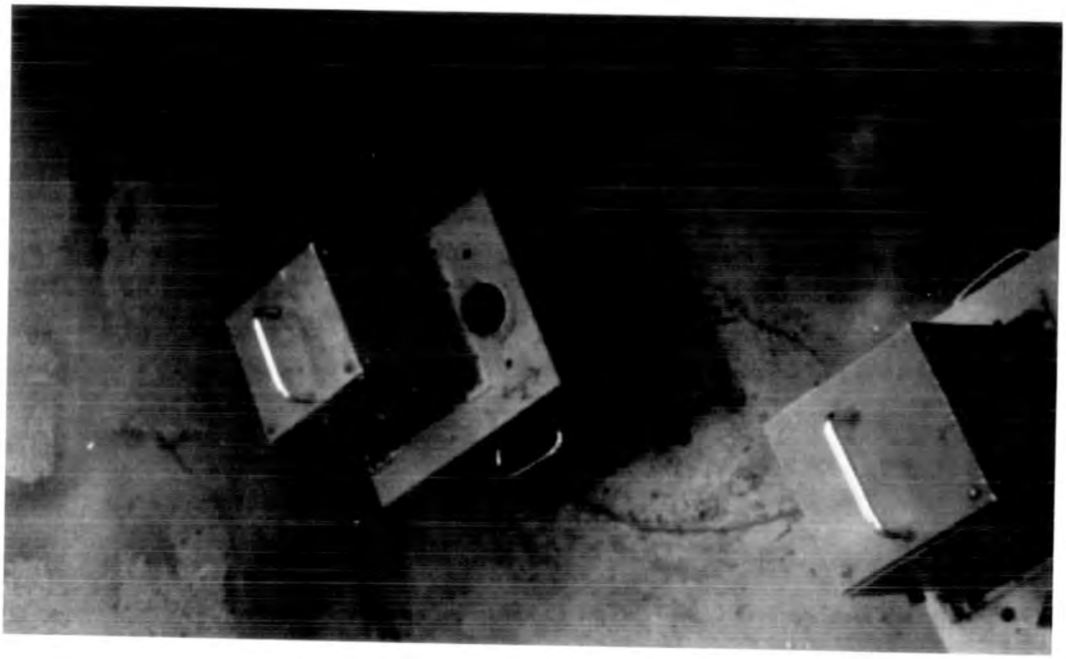
ROKUPR 95 γ, MAKENI 101 γ, FREETOWN 118 γ, NJALA 157 γ. The range being defined as the difference between the mean of the three hour period 1100-1300 and the mean of the values 0000-0100 and 2300-2400 on the same day.

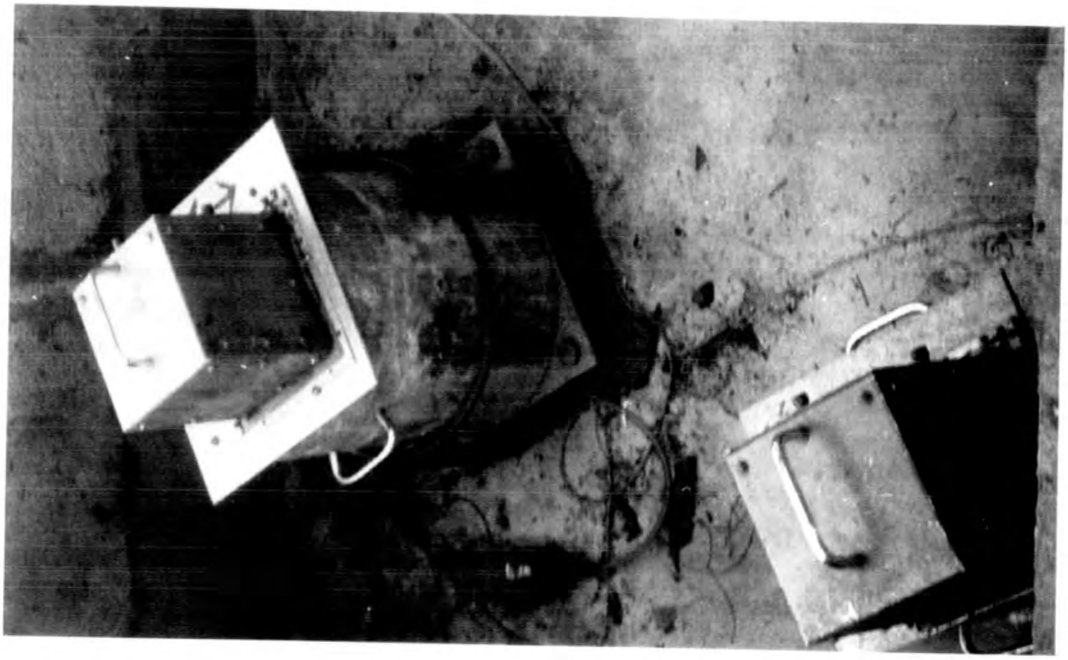
The above values decrease as expected with increasing distance from the magnetic equator. Njala was just south of the magnetic equator during the period of the survey and was probably very close to the position of maximum horizontal intensity range.

Inspection of Figure 97 shows the considerable day-to-day variability of the equatorial current system which has been well established. On some days local features of the variation are apparent. For example, 14 March records for Freetown and Makeni are similar but Rokupr and Njala are of a different type. On 16 March the daily range at Freetown was greater than that at Njala indicating a possible northward shift of the current system on that day. It is clear from this variability and the presence of local features that much more data is required before an attempt could be made to analyse the structure of the current system in this region. The station at Rokupr was functioning intermittently for nearly 12 months but there are very few periods when records were available for all four stations at the same time so that no analysis of this data has yet been attempted.

The vertical intensity magnetometers proved to be very difficult to operate in these regions where the total vertical force is so small. The magnetometer at Njala for example was only just stable when undisturbed so that it was hardly surprising that so few records were obtained. There was, in fact, no single occasion when all three field magnetometers were functioning correctly at the same time. However, some records were obtained at each of the field stations and if it were possible to spend more time with the magnetometers in the field more useful results could definitely be achieved. It is hoped to re-establish these stations in the near future.

The following photograph shows the magnetometers installed in the pit at Rokupr.





8. SUMMARY

The work described in this thesis has provided a fairly comprehensive picture of the variations in the geomagnetic field at Freetown during a period of low solar activity.

The Fourier analysis described in section 4 provides characteristics of the solar and lunar daily variations in a standard form suitable for use in the spherical harmonic analyses that are carried out to provide complete world-wide representative current systems for these variations. Early analyses of this type were unable to include the equatorial anomaly mainly due to lack of data from these regions and also due to the large number of harmonics required to give a complete description of the field. Recent work by MATSUSHITA and MAEDA 1965(1) and (2), and HAGAN and SUGIURA 1967 has improved the accuracy of the fit of the representative current systems to the observed variations in equatorial regions.

A new method of analysis has recently been introduced by PRICE and WILKINS 1963 and applied to data for the Sq field of 1932-3; the same method has been used for I.G.Y. data by PRICE and STONE 1964. This method is more flexible than spherical harmonic analysis as account can be taken of small regional anomalies without affecting other regions, and further, adjustments can be made to the analysis as more data becomes available without the necessity of repeating the whole analytical process. The results from Freetown as presented in this thesis are not in a suitable form for this type of analysis.

Both types of world-wide analysis produce similar representative current systems for the quiet day solar daily variations with one main current vortex in both the northern and southern hemispheres. In all the analyses mentioned above considerable asymmetry between the northern and southern vortices has been found and evidence has also been found for penetration of the vortices into the opposite hemispheres.

The results obtained at Freetown as described in section 4 are such as would be caused by asymmetry in the ionospheric current system in this region.

The seasonal variations are in the same sense as those found for the African zone for the I.G.Y. period by PRICE and STONE but the present results indicate a larger seasonal movement in opposition to the sun during the northern summer months. Price and Stone found that for the I.G.Y. there was a larger shift during the northern winter months. It is likely that the present data shows the local situation clearly, but it would be unwise to assume that seasonal changes throughout the African zone are similar, particularly in view of the known longitudinal variations of the equatorial current system.

Comparison of the results with those from other low latitude stations show that Freetown is a typical equatorial station lying near the boundary between the northern and southern ionospheric current systems.

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TABLE 1

HORIZONTAL INTENSITY

Solar Terms - Unit 1 γ

(a) International Quiet Days - Group I

	Number of Days	S_1	P.E.	σ_1	S_2	P.E.	σ_2	S_3	P.E.	σ_3	S_4	P.E.	σ_4
All Days	220	37.90	±0.67	286°59'	21.62	±0.74	110°04'	9.49	±0.58	306°57'	2.69	±0.23	173°41'
J set	74	32.46	±1.14	283°53'	19.92	±1.04	100°06'	8.55	±0.71	289°40'	1.75	±0.30	174°01'
E set	69	41.10	±1.08	286°32'	22.53	±1.05	115°19'	10.13	±0.74	321°36'	4.17	±0.31	192°24'
D set	77	40.34	±1.07	289°46'	22.87	±1.11	113°42'	10.56	±0.79	307°43'	2.74	±0.34	147°28'

(b) All days with index Ci $\leqslant$ 1.2 - Group II

	Number of Days	S_1	P.E.	σ_1	S_2	P.E.	σ_2	S_3	P.E.	σ_3	S_4	P.E.	σ_4
All Days	1168	37.07	±0.26	289°53'	20.56	±0.28	106°55'	8.89	±0.25	304°31'	2.79	±0.13	168°19'
J set	402	30.08	±0.46	285°50'	18.97	±0.36	94°31'	8.25	±0.28	283°32'	1.84	±0.18	165°10'
E set	338	41.39	±0.52	289°08'	22.61	±0.46	112°54'	10.22	±0.41	321°12'	4.95	±0.26	183°51'
D set	428	40.39	±0.48	293°19'	21.05	±0.37	112°17'	9.32	±0.17	307°20'	2.33	±0.14	144°10'

TABLE 2

HORIZONTAL INTENSITY

Lunar Terms - Unit 1γ

(a) International Quiet Days - Group I

	Number of Days	L_1	P.E.	λ_1	L_2	P.E.	λ_2	L_3	P.E.	λ_3	L_4	P.E.	λ_4
All Days	220	3.93	±0.73	30°35'	5.73	±0.77	209°29'	3.52	±0.60	35°32'	2.47	±0.24	220°51'
J set	74	3.95	±1.24	332°12'	4.79	±1.09	181°38'	2.98	±0.74	9°46'	1.97	±0.31	194°26'
E set	69	5.42	±1.17	42°53'	7.00	±1.10	204°03'	4.21	±0.77	21°04'	2.73	±0.32	206°19'
D set	77	4.32	±1.17	60°21'	6.16	±1.17	231°51'	4.11	±0.82	62°25'	3.13	±0.35	244°30'

(b) All days with index Ci ⩽ 1.2 - Group II

	Number of Days	L_1	P.E.	λ_1	L_2	P.E.	λ_2	L_3	P.E.	λ_3	L_4	P.E.	λ_4
All Days	1168	2.77	±0.28	23°10'	4.33	±0.29	206°49'	2.75	±0.26	33°26'	0.69	±0.13	220°01'
J set	402	2.42	±0.50	339°52'	3.23	±0.38	174°06'	1.95	±0.29	02°09'	0.29	±0.18	200°02'
E set	338	3.13	±0.57	29°02'	4.58	±0.48	203°45'	3.02	±0.43	24°31'	0.75	±0.27	188°24'
D set	428	3.41	±0.52	46°22'	5.76	±0.39	224°07'	3.74	±0.18	51°57'	1.19	±0.14	236°16'

TABLE 3

DECLINATION

Solar Terms - Unit 0.01 minutes of Arc

(a) International Quiet Days - Group I

	Number of Days	S_1	P.E.	σ_1	S_2	P.E.	σ_2	S_3	P.E.	σ_3	S_4	P.E.	σ_4
All Days	228	90.7	±4.0	59°38'	56.9	±3.7	227°15'	26.0	±2.0	66°26'	5.7	±1.0	243°29'
J set	78	127.3	±4.6	45°53'	96.6	±3.9	245°36'	50.2	±2.9	93°18'	13.8	±2.0	342°00'
E set	73	79.7	±6.9	58°13'	49.3	±5.9	228°43'	25.8	±3.4	57°16'	8.2	±2.1	199°06'
D set	77	75.2	±5.7	85°06'	43.2	±6.1	189°13'	20.5	±3.7	358°08'	15.9	±2.6	211°37'

(b) All days with index Ci $\leqslant$ 1.2 - Group II

	Number of Days	S_1	P.E.	σ_1	S_2	P.E.	σ_2	S_3	P.E.	σ_3	S_4	P.E.	σ_4
All Days	1223	95.1	±1.7	56°41'	58.2	±1.1	218°02'	25.5	±1.1	60°30'	6.3	±0.6	249°19'
J set	432	140.8	±2.3	39°40'	93.6	±1.2	239°25'	49.0	±1.2	91°27'	15.6	±0.8	339°22'
E set	366	82.6	±2.3	60°01'	47.3	±1.8	223°25'	24.7	±1.7	52°41'	8.5	±0.9	213°11'
D set	425	75.9	±2.2	86°33'	54.3	±1.7	172°50'	24.7	±1.2	353°19'	16.9	±0.7	206°11'

TABLE 4

DECLINATION

Lunar Terms - Unit 0.01 Minutes of Arc

(a) International Quiet Days - Group I

	Number of Days	L_1	P.E.	λ_1	L_2	P.E.	λ_2	L_3	P.E.	λ_3	L_4	P.E.	λ_4
All Days	228	0.4	±4.3	204°49'	0.5	±3.8	208°24'	0.3	±2.1	58°27'	0.1	±1.1	5°17'
J set	78	16.6	±4.9	93°56'	17.5	±4.1	238°47'	8.8	±3.0	78°38'	0.3	±2.0	60°11'
E set	73	9.4	±7.5	224°18'	9.4	±6.2	271°46'	10.4	±3.6	97°20'	4.4	±2.2	269°03'
D set	77	11.1	±6.2	224°52'	15.6	±6.4	77°31'	12.1	±3.8	266°0'	5.0	±2.7	58°38'

(b) All days with index Ci $\leq$ 1.2 - Group II

	Number of Days	L_1	P.E.	λ_1	L_2	P.E.	λ_2	L_3	P.E.	λ_3	L_4	P.E.	λ_4
All Days	1223	5.5	±1.8	152°59'	2.6	±1.2	278°58'	2.5	±1.1	159°38'	1.7	±0.6	46°13'
J set	432	15.3	±2.5	84°31'	15.2	±1.3	260°34'	8.3	±1.2	108°30'	0.7	±0.8	80°14'
E set	366	10.5	±2.5	160°39'	5.0	±1.9	264°25'	5.5	±1.8	121°29'	2.7	±0.9	334°20'
D set	425	13.2	±2.4	236°57'	12.8	±1.8	70°51'	9.5	±1.2	259°33'	4.1	±0.8	72°51'

TABLE 5

VERTICAL INTENSITY

Solar Terms - Unit 1γ

(a) International Quiet Days - Group I

	Number of Days	S_1	P.E.	σ_1	S_2	P.E.	σ_2	S_3	P.E.	σ_3	S_4	P.E.	σ_4
All Days	222	6.24	±0.49	259°38'	5.35	±0.36	65°37'	1.95	±0.25	256°21'	0.48	±0.10	64°52'
J set	74	7.31	±0.70	257°02'	6.29	±0.53	84°55'	3.06	±0.38	292°31'	0.82	±0.16	211°55'
E set	71	5.59	±0.77	257°29'	4.93	±0.66	66°19'	2.20	±0.39	249°11'	0.99	±0.25	43°40'
D set	77	5.84	±0.54	263°45'	5.57	±0.47	43°58'	1.93	±0.36	206°04'	1.18	±0.19	60°19'

(b) All days with index Ci < 1.2 - Group II

	Number of Days	S_1	P.E.	σ_1	S_2	P.E.	σ_2	S_3	P.E.	σ_3	S_4	P.E.	σ_4
All Days	1187	7.03	±0.21	257°38'	5.78	±0.13	58°45'	2.22	±0.09	250°02'	0.56	±0.06	77°39'
J set	413	9.10	±0.28	256°56'	6.74	±0.16	81°18'	3.03	±0.12	287°47'	1.02	±0.12	203°23'
E set	340	5.80	±0.34	250°37'	4.98	±0.23	57°19'	2.56	±0.15	244°34'	0.96	±0.09	56°50'
D set	434	6.16	±0.16	261°32'	6.44	±0.13	37°17'	2.84	±0.10	208°32'	1.28	±0.07	56°3'

TABLE 6

VERTICAL INTENSITY

Lunar Terms - Unit 1 γ

(a) International Quiet Days - Group I

	Number of Days	L_1	P.E.	λ_1	L_2	P.E.	λ_2	L_3	P.E.	λ_3	L_4	P.E.	λ_4
All Days	222	0.15	±0.53	39°53'	1.07	±0.38	135°53'	0.42	±0.26	291°43'	0.18	±0.10	163°56'
J set	74	1.10	±0.77	295°24'	2.04	±0.55	116°07'	0.98	±0.40	281°47'	0.11	±0.17	338°15'
E set	71	0.56	±0.84	51°29'	1.96	±0.69	149°44'	1.08	±0.41	308°41'	0.46	±0.25	104°32'
D set	77	0.83	±0.58	113°08'	0.68	±0.50	272°29'	0.77	±0.37	108°42'	0.52	±0.20	222°05'

(b) All days with index Ci < 1.2 - Group II

	Number of Days	L_1	P.E.	λ_1	L_2	P.E.	λ_2	L_3	P.E.	λ_3	L_4	P.E.	λ_4
All Days	1187	0.47	±0.23	4°35'	1.11	±0.14	161°26'	0.30	±0.09	346°27'	0.04	±0.06	295°29'
J set	413	0.93	±0.30	298°56'	1.78	±0.17	135°14'	0.81	±0.12	313°08'	0.01	±0.12	50°02'
E set	340	0.86	±0.37	18°02'	1.47	±0.24	156°51'	0.58	±0.16	330°01'	0.10	±0.09	70°02'
D set	434	0.73	±0.18	70°59'	0.87	±0.14	224°41'	0.60	±0.11	102°02'	0.17	±0.07	273°38'

HORIZONTAL INTENSITY

FIG. I.

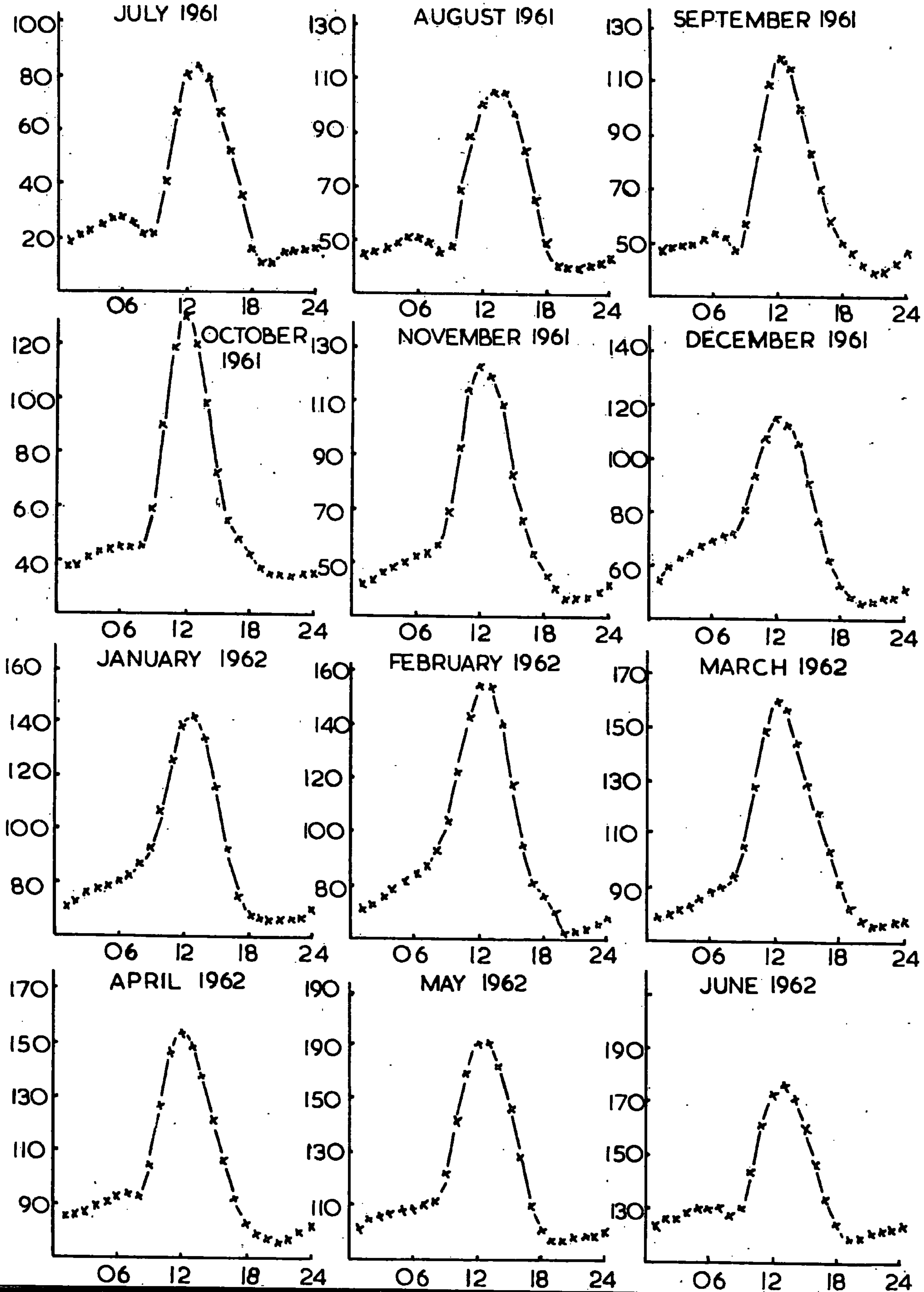
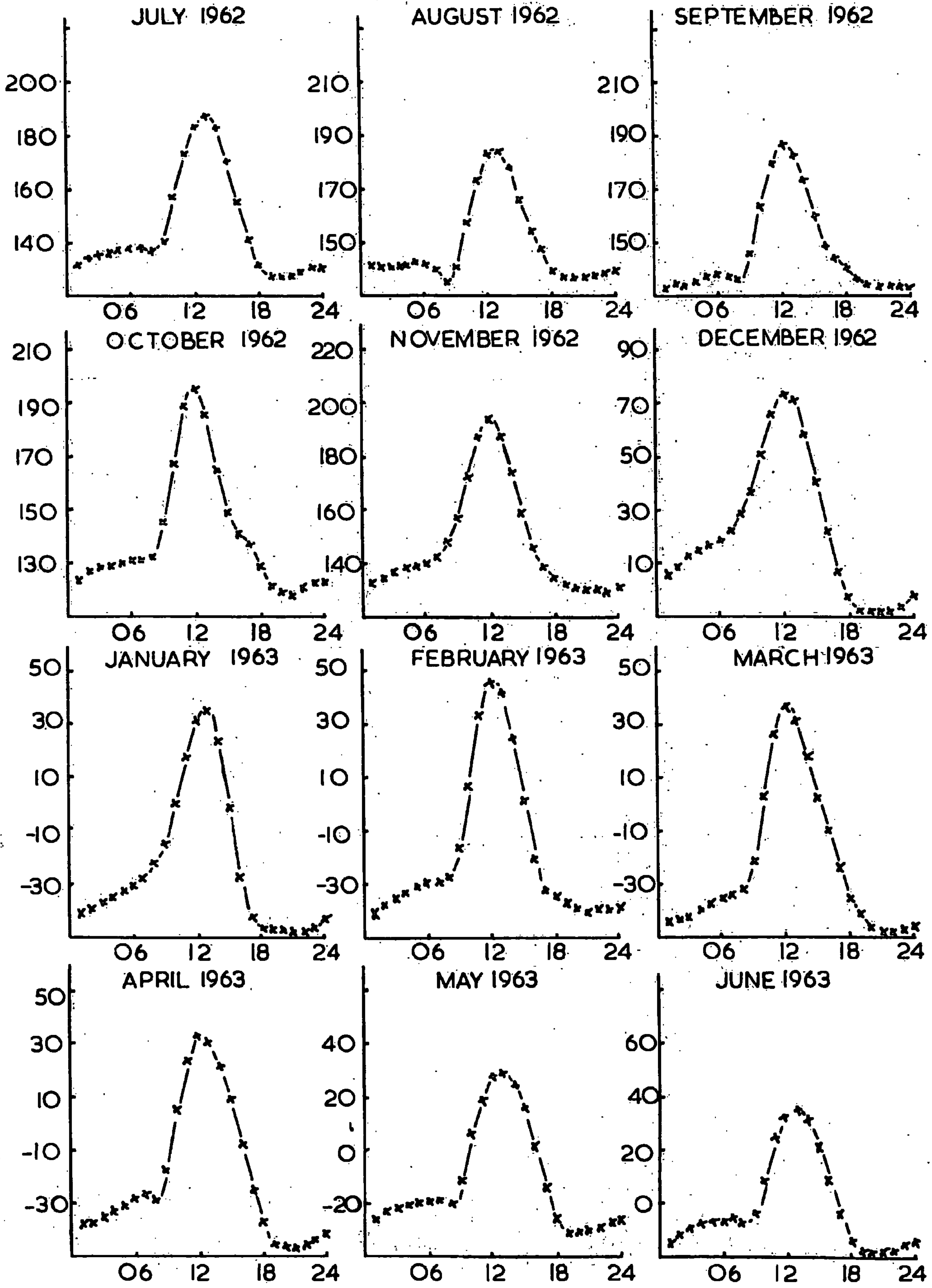


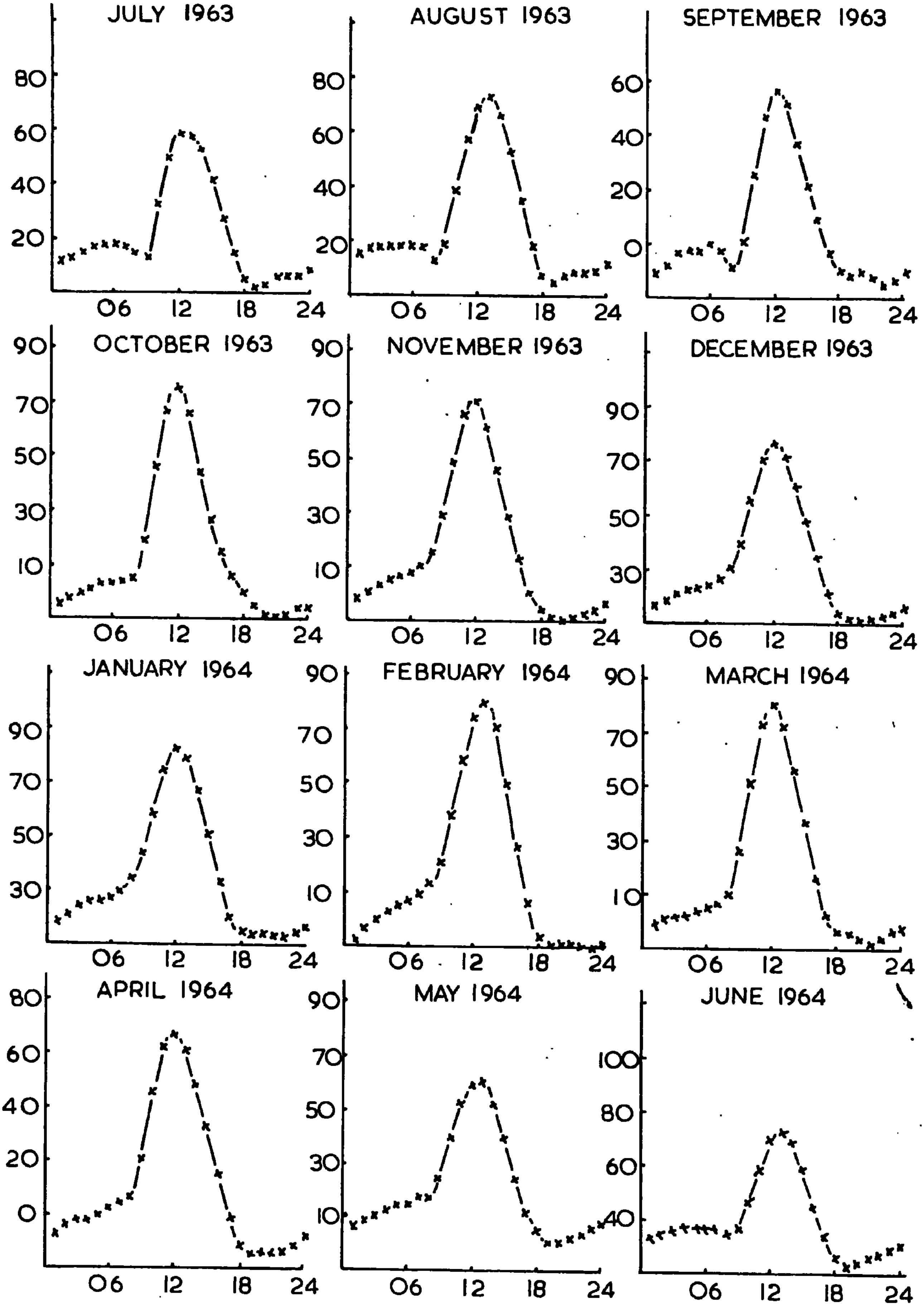
FIG. 2.

HORIZONTAL INTENSITY



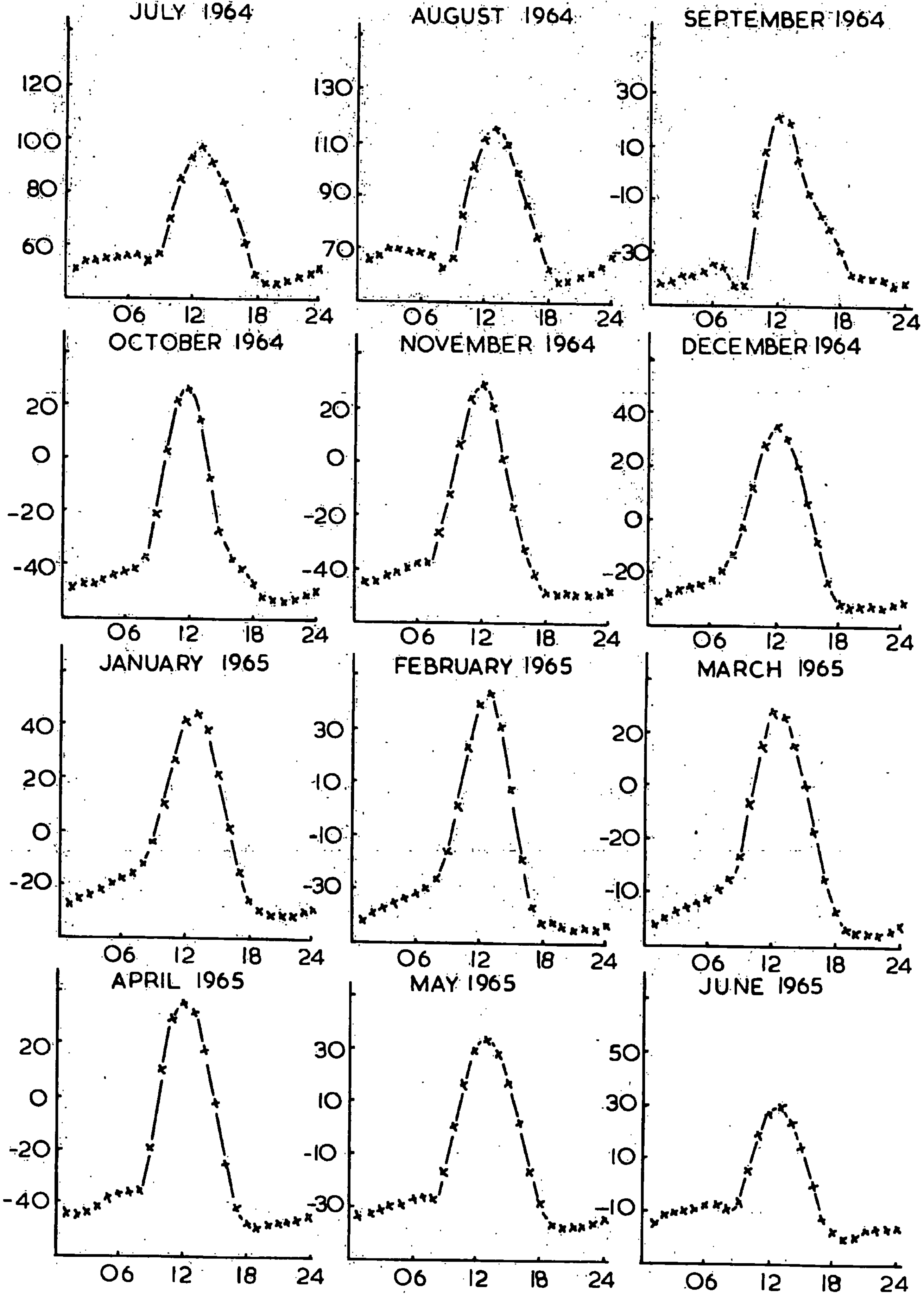
HORIZONTAL INTENSITY

FIG. 3.

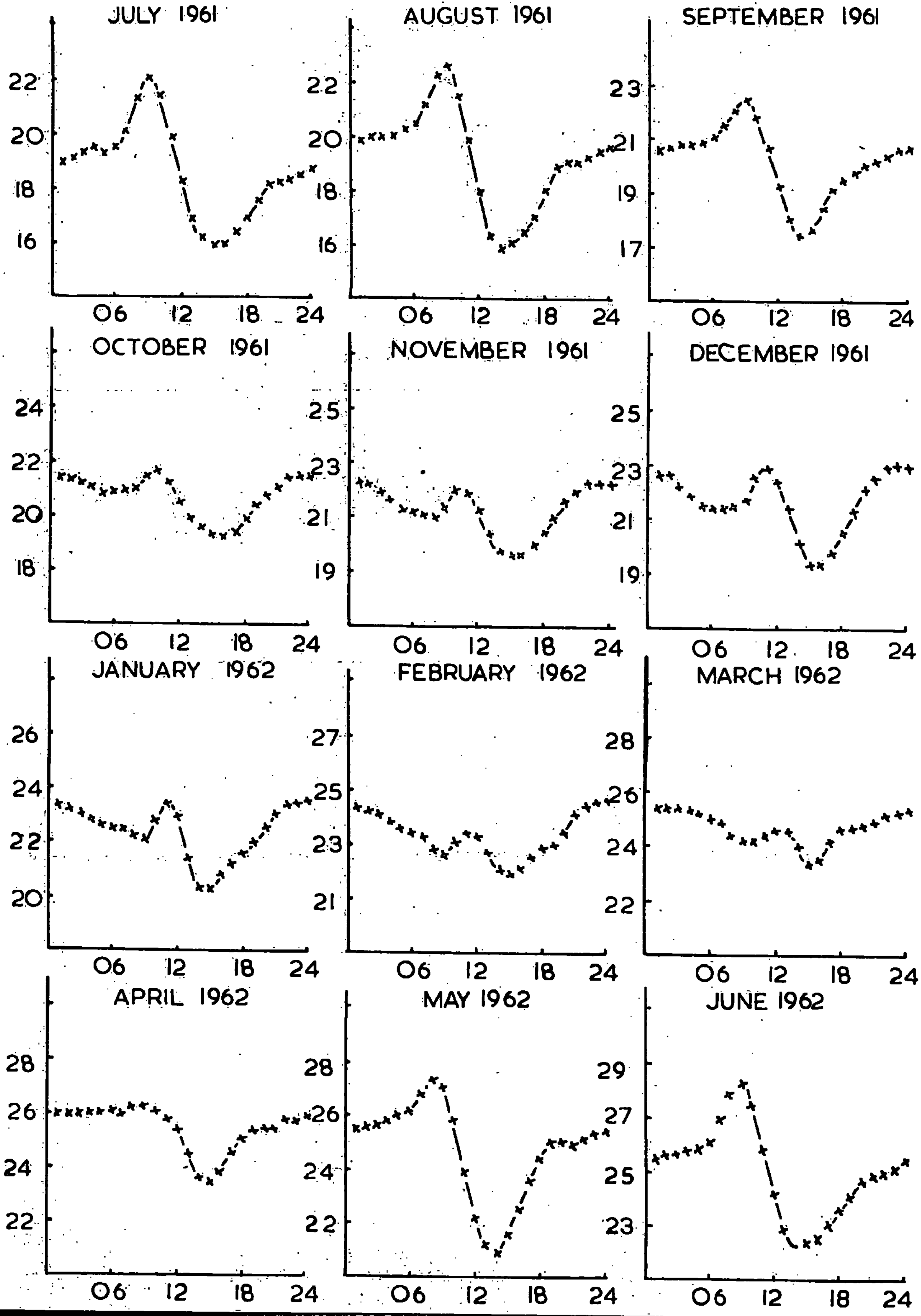


HORIZONTAL INTENSITY

FIG. 4.

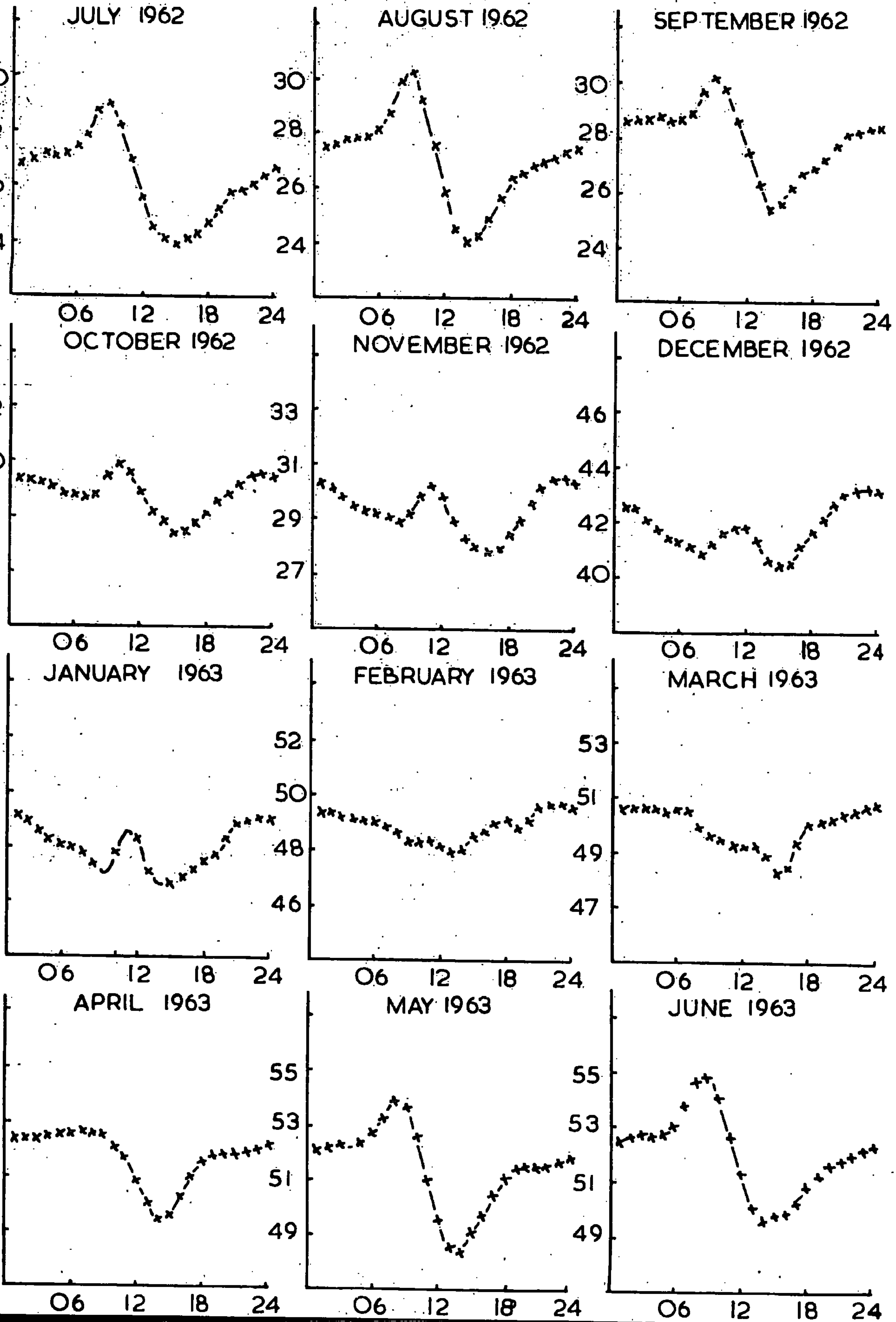


DECLINATION FIG. 5.



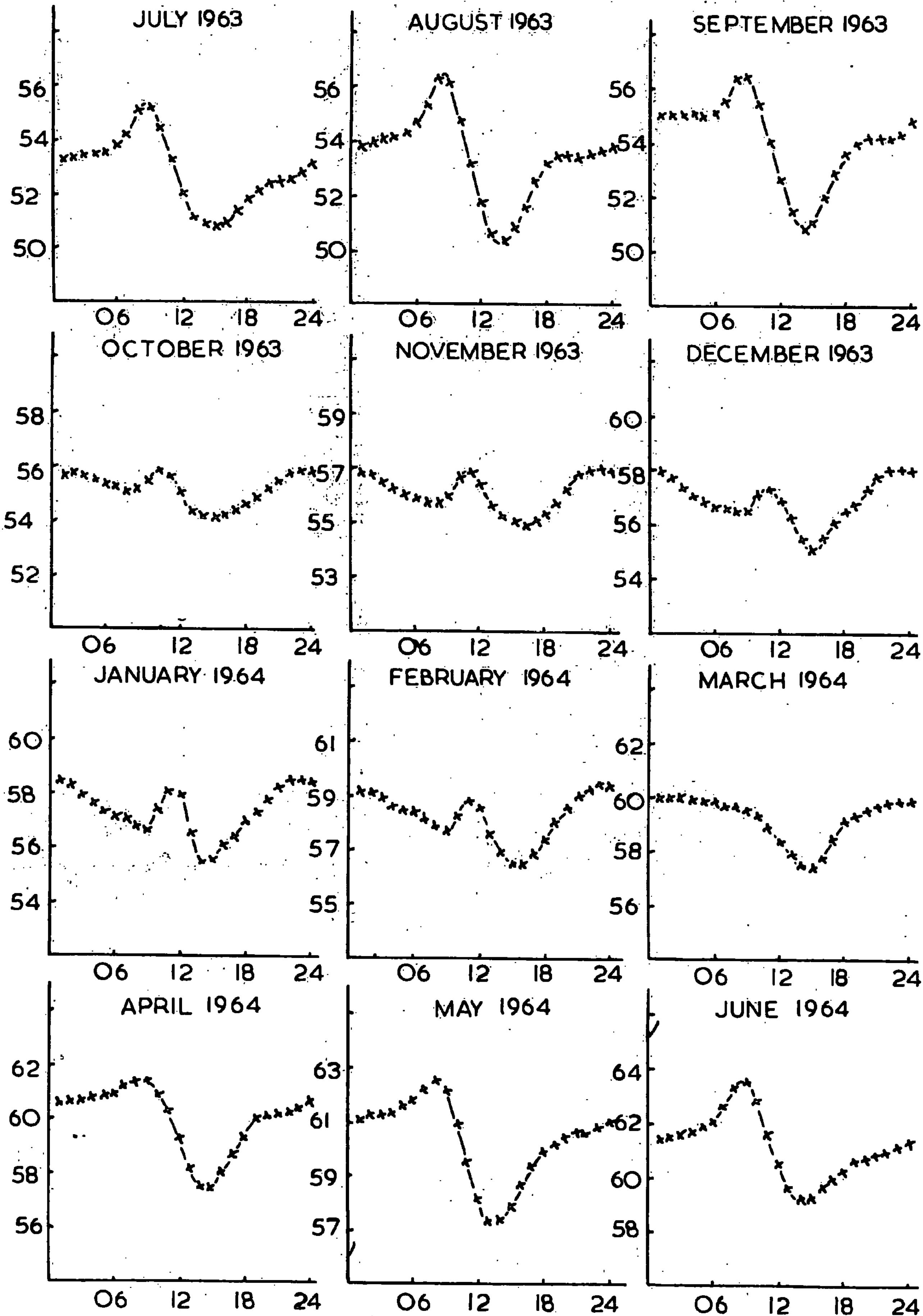
DECLINATION

FIG.6.



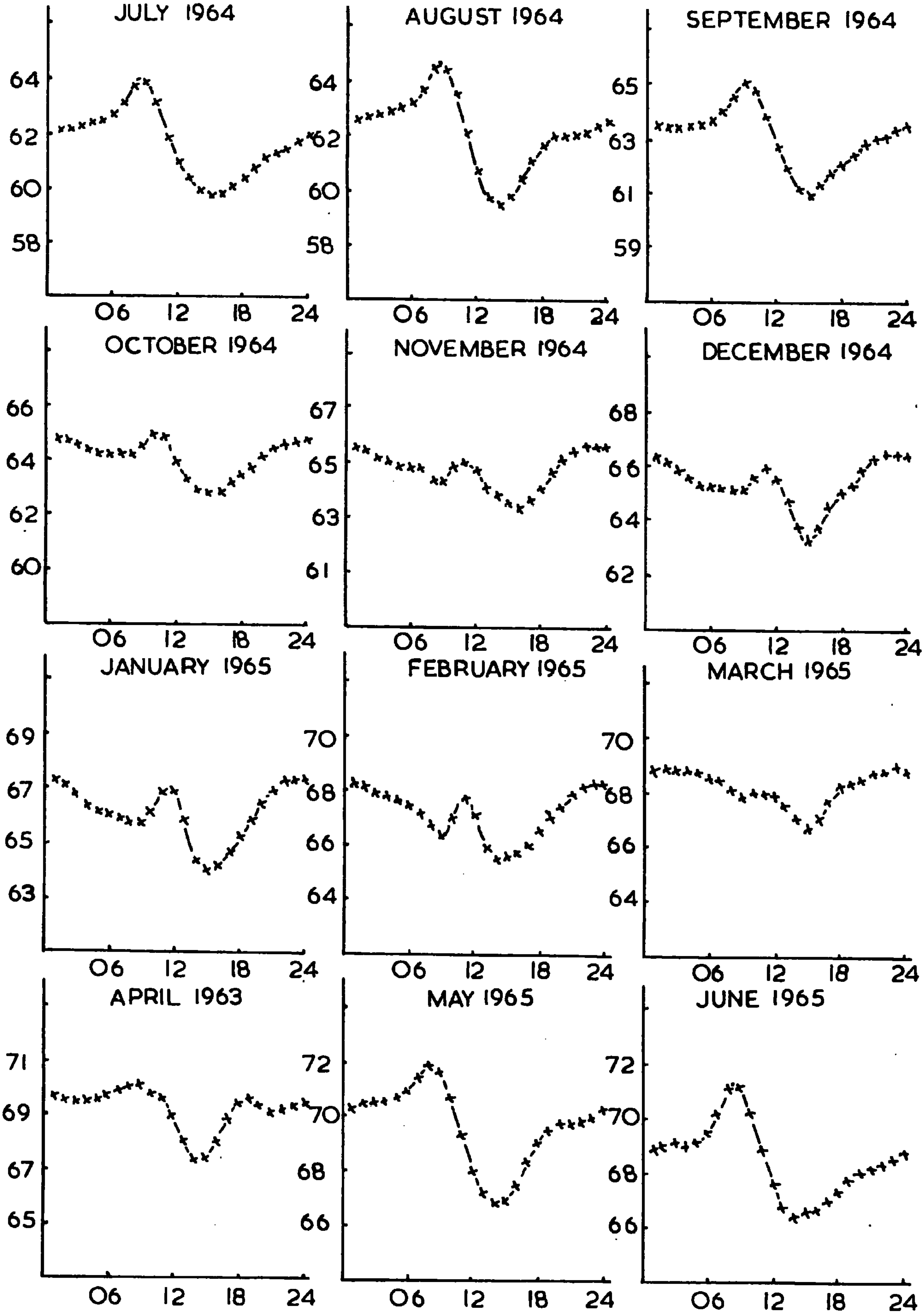
DECLINATION

FIG. 7.



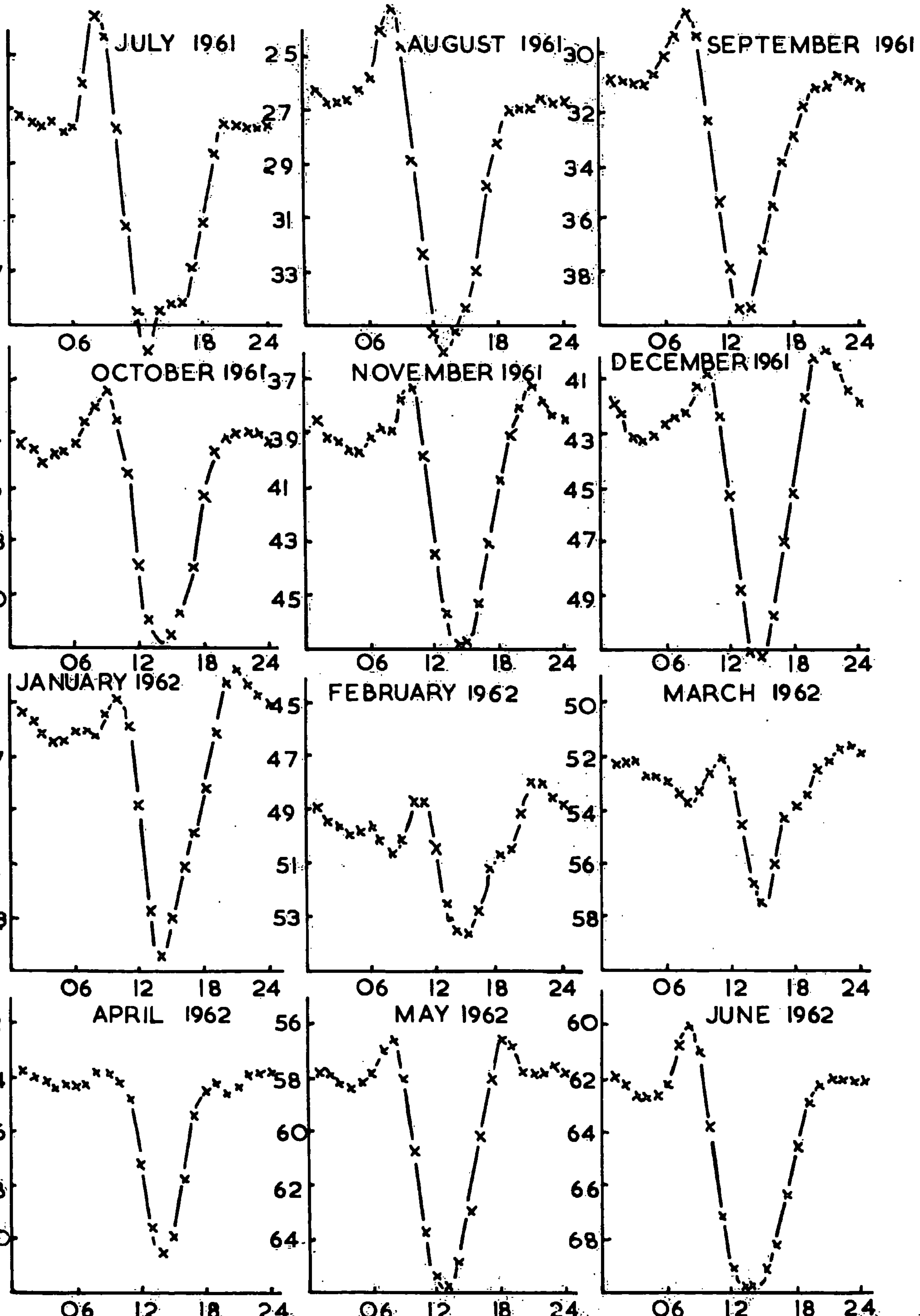
DECLINATION

FIG. 8.



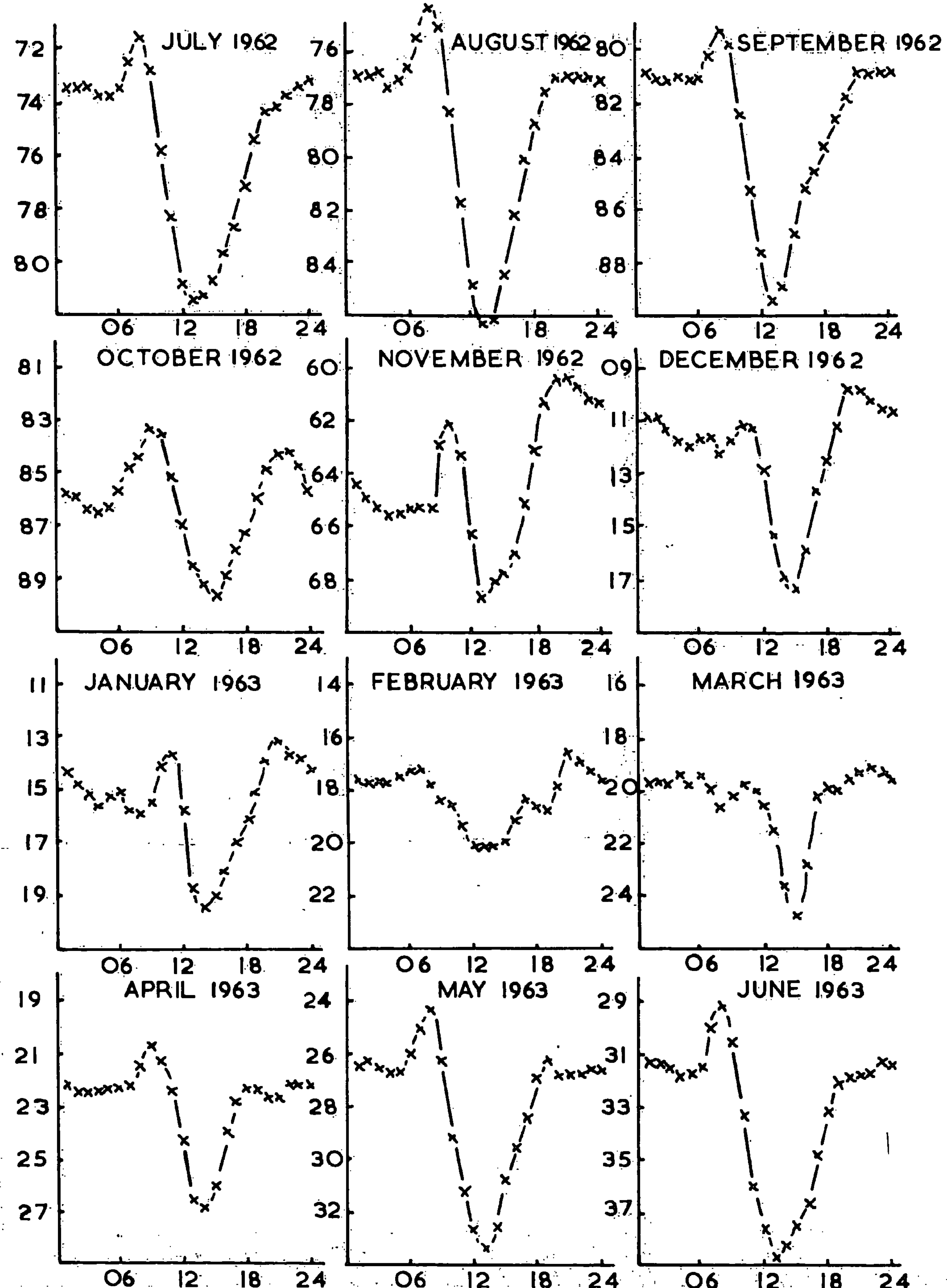
VERTICAL INTENSITY

FIG. 9.



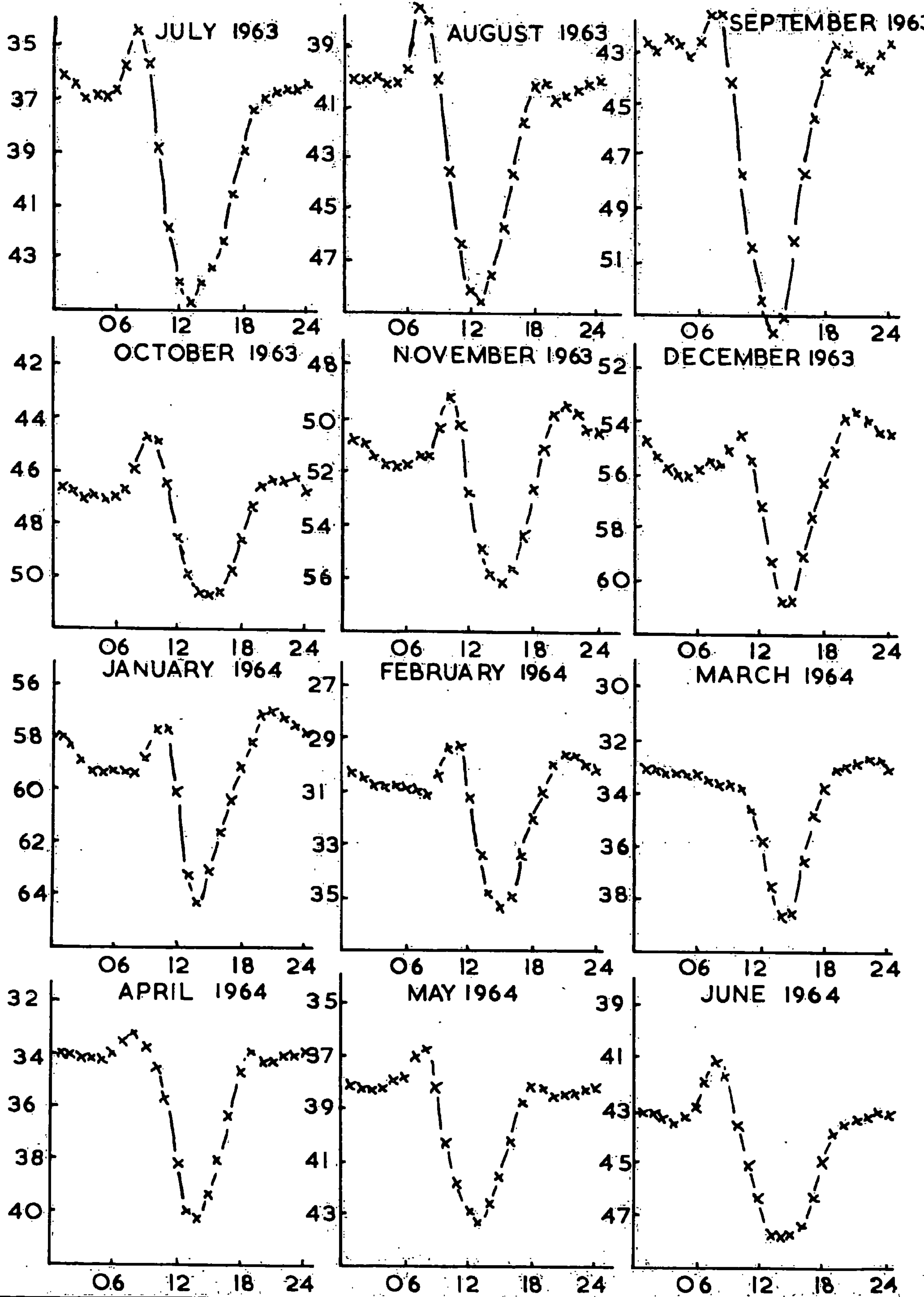
VERTICAL INTENSITY

FIG. 10.



VERTICAL INTENSITY

FIG. II.



VERTICAL INTENSITY

FIG. 12.

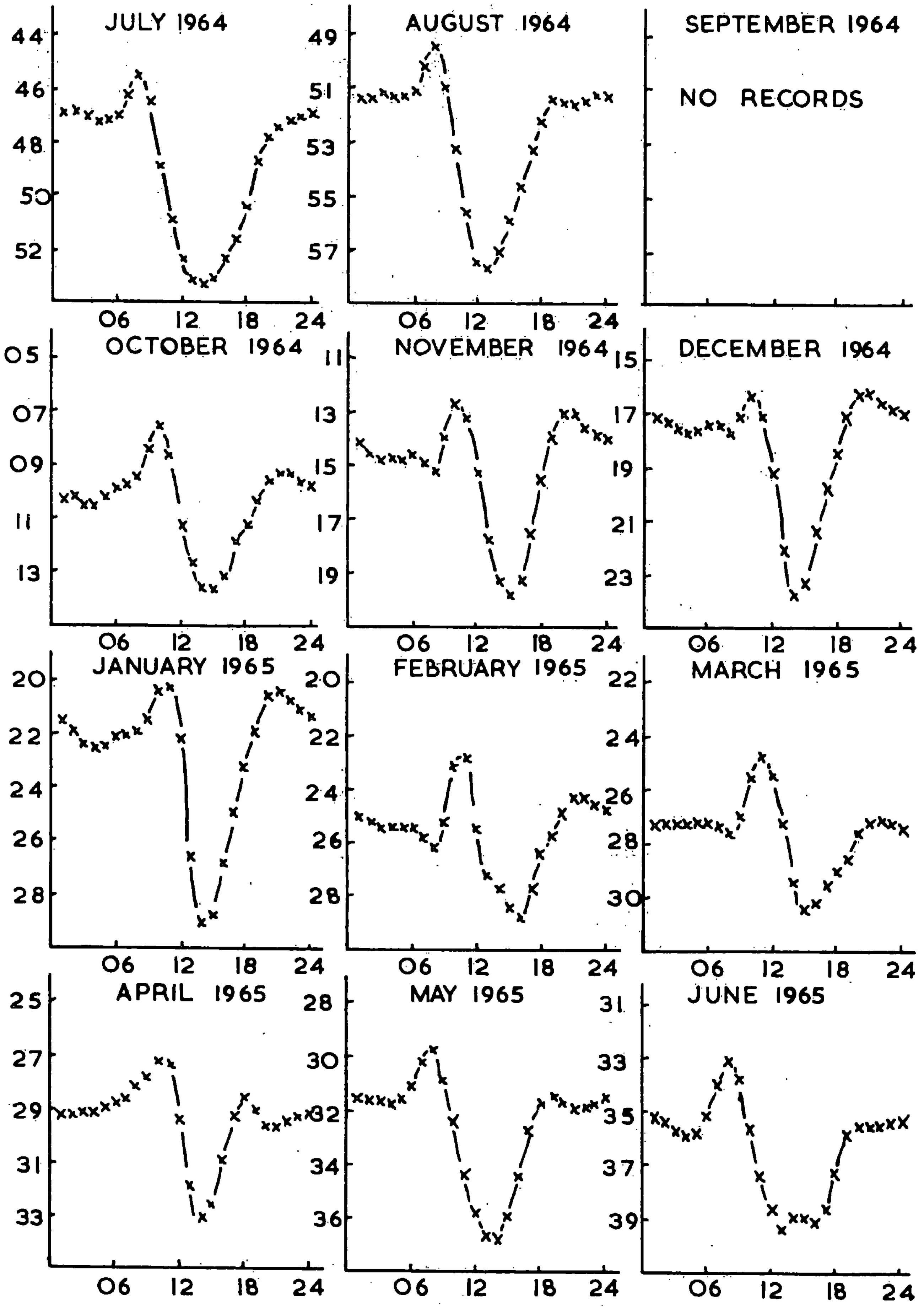
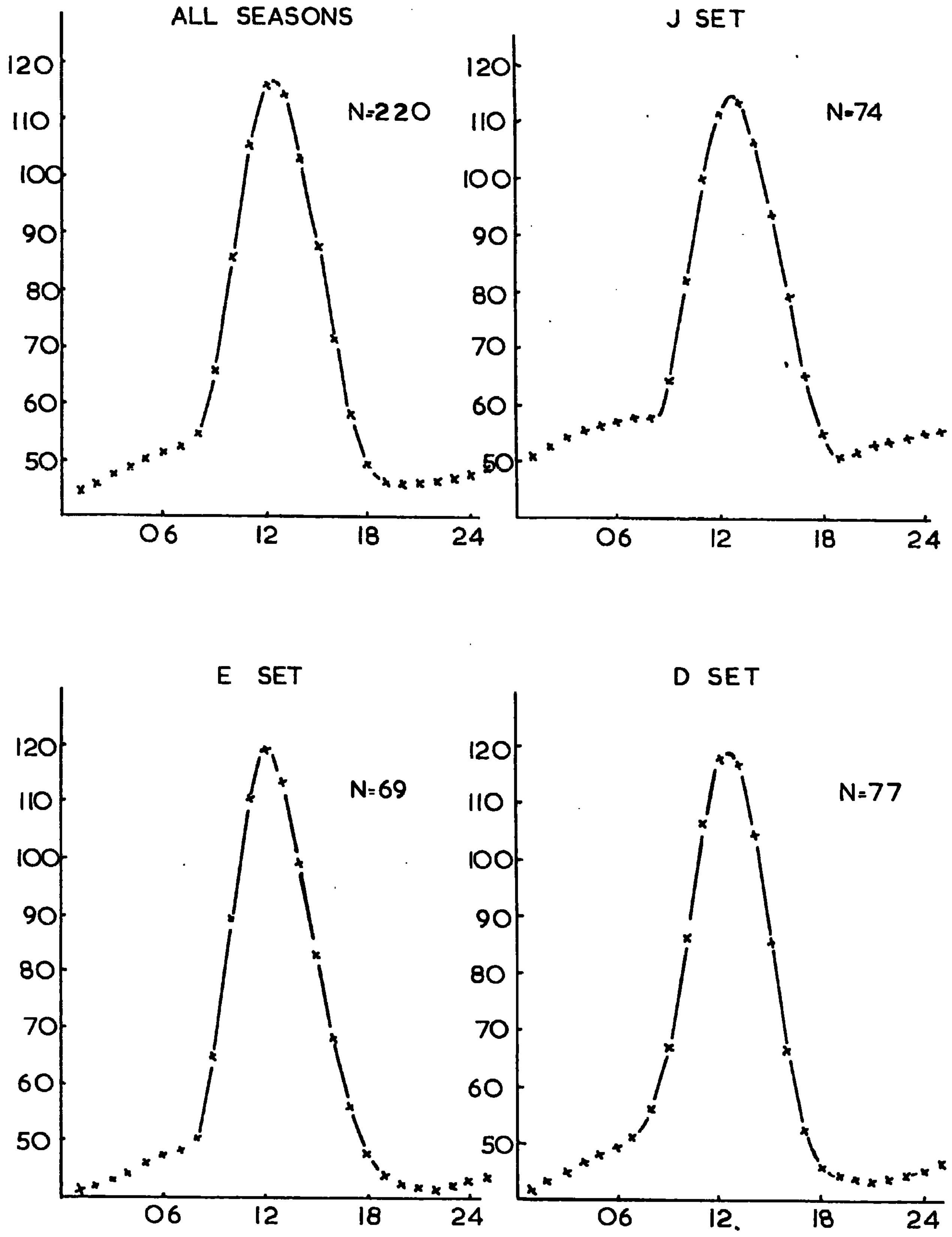


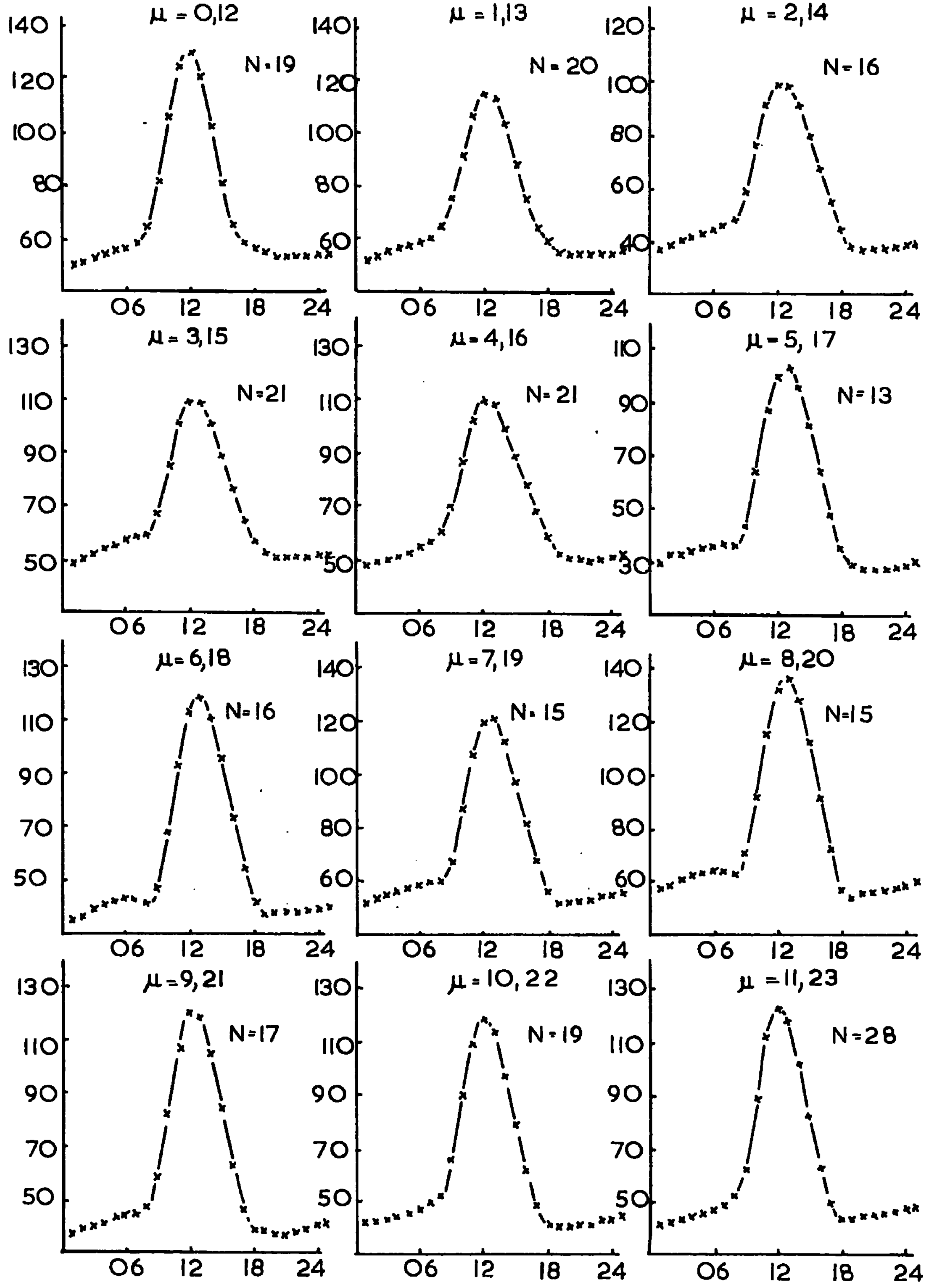
FIG. 13.

HORIZONTAL INTENSITY GROUP I

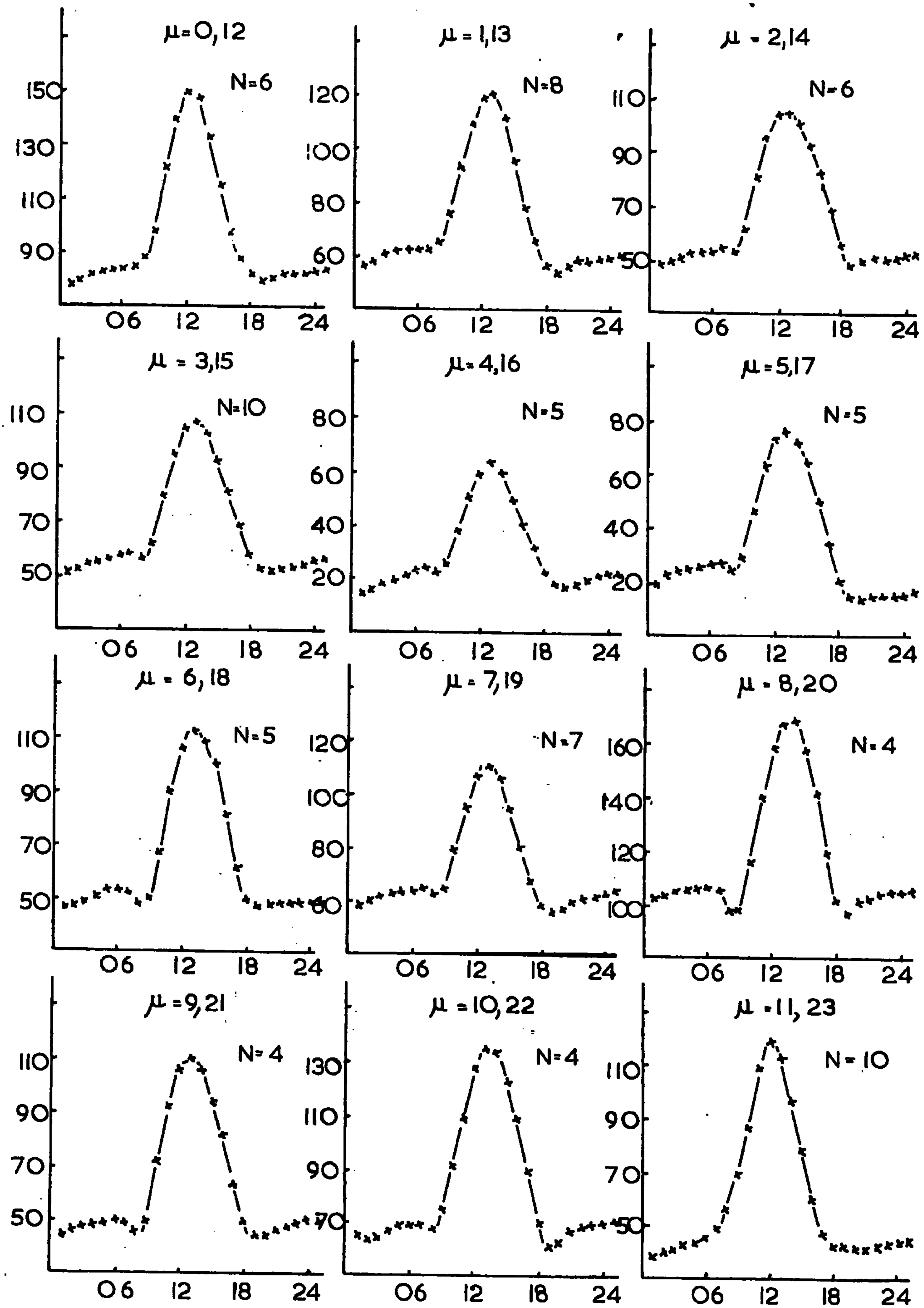


HORIZONTAL INTENSITY – GROUP I – ALL SEASONS

FIG 14

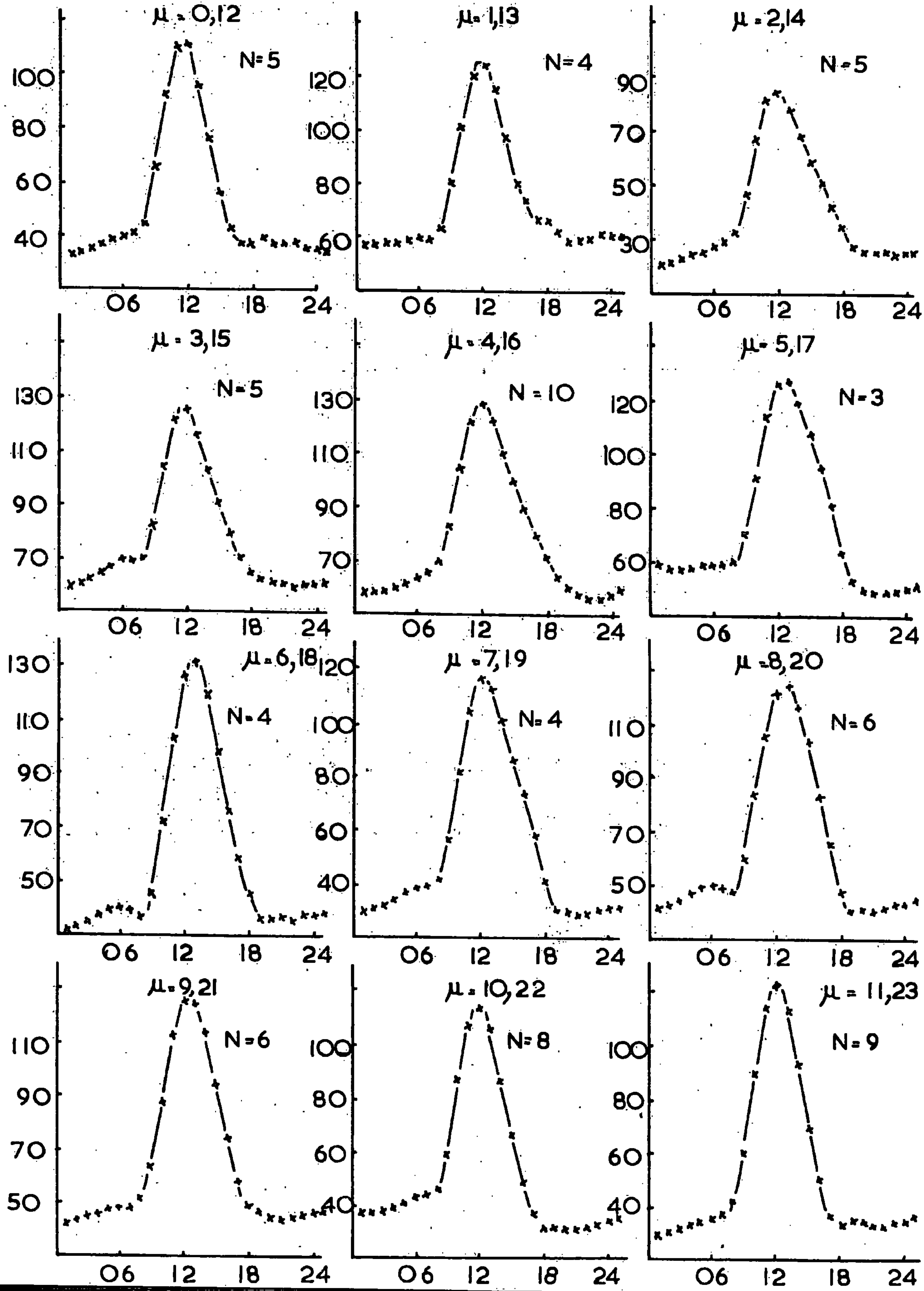


HORIZONTAL INTENSITY–GROUP I– J SET FIG 15



HORIZONTAL INTENSITY – GROUP I – E SET

FIG. 16.



HORIZONTAL INTENSITY – GROUP I- D SET FIG. 17

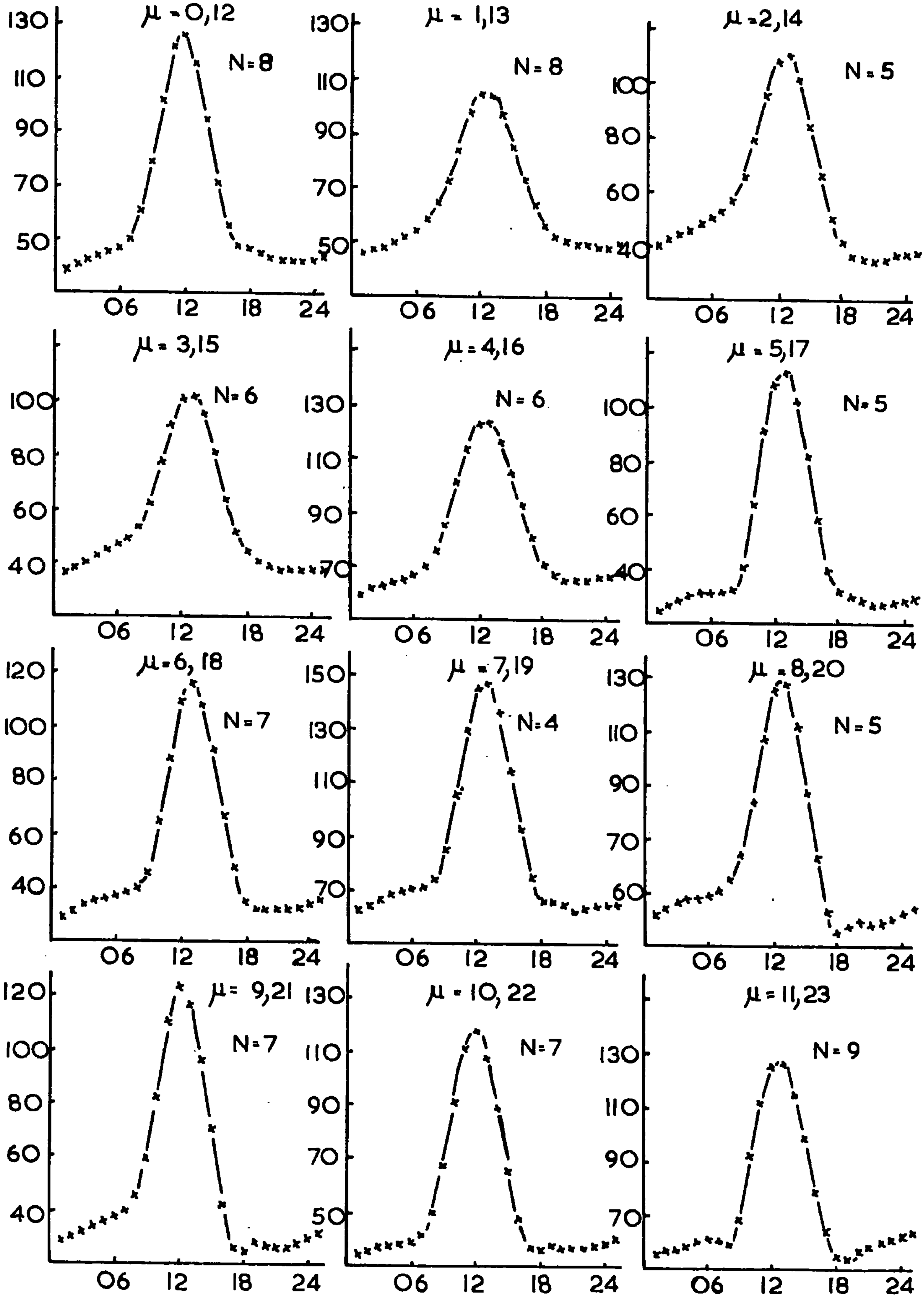
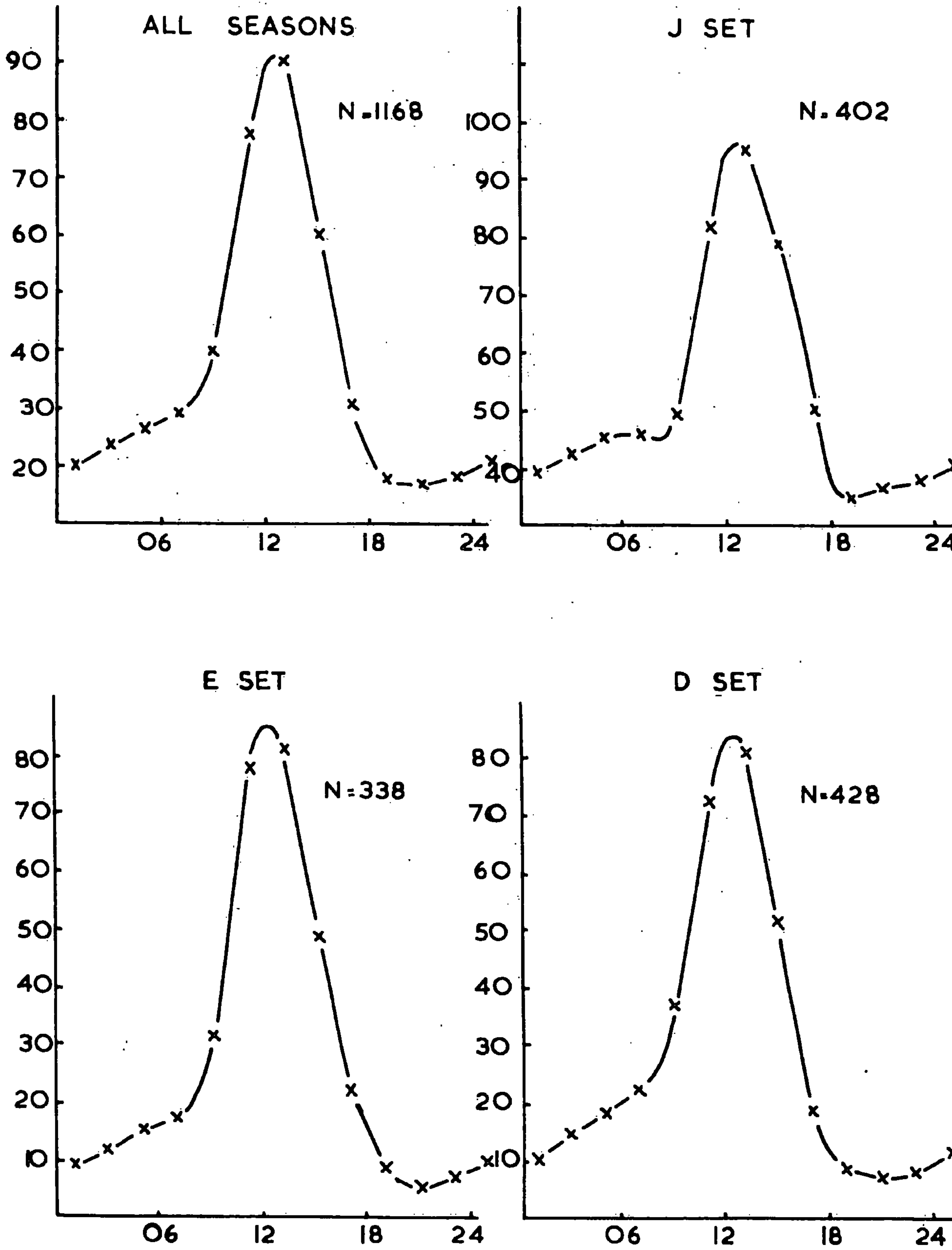
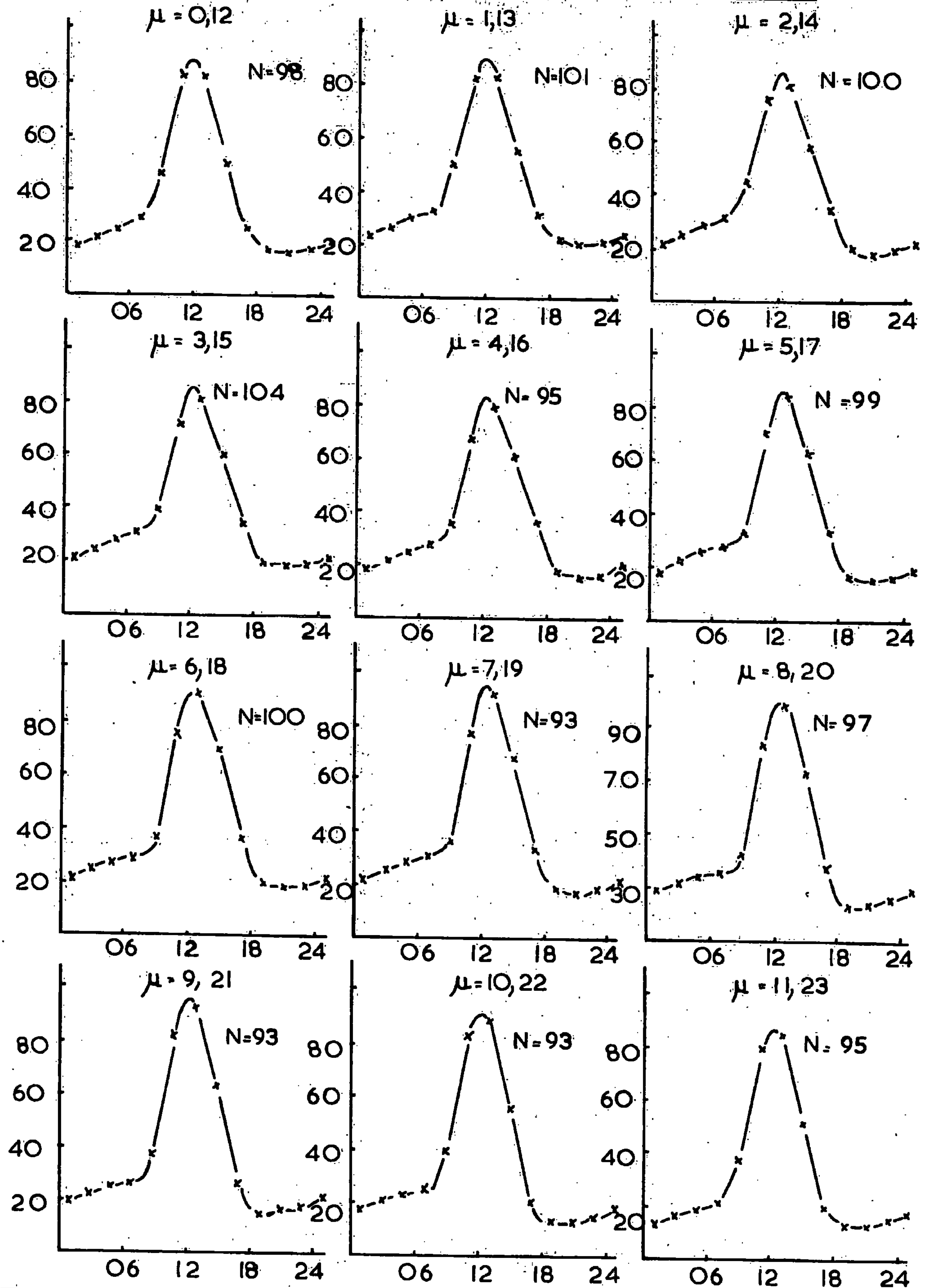


FIG. 18.

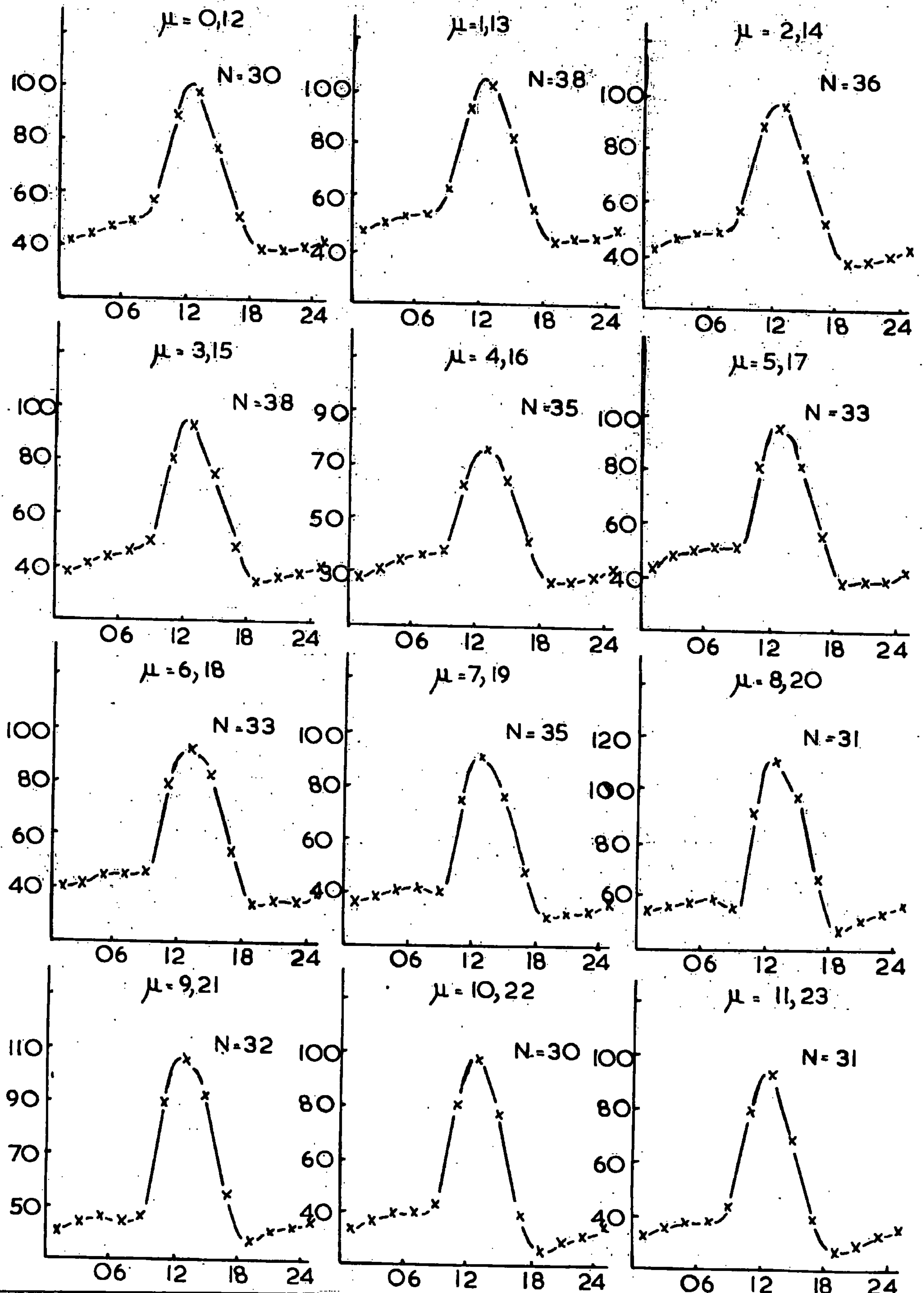
HORIZONTAL INTENSITY — GROUP II



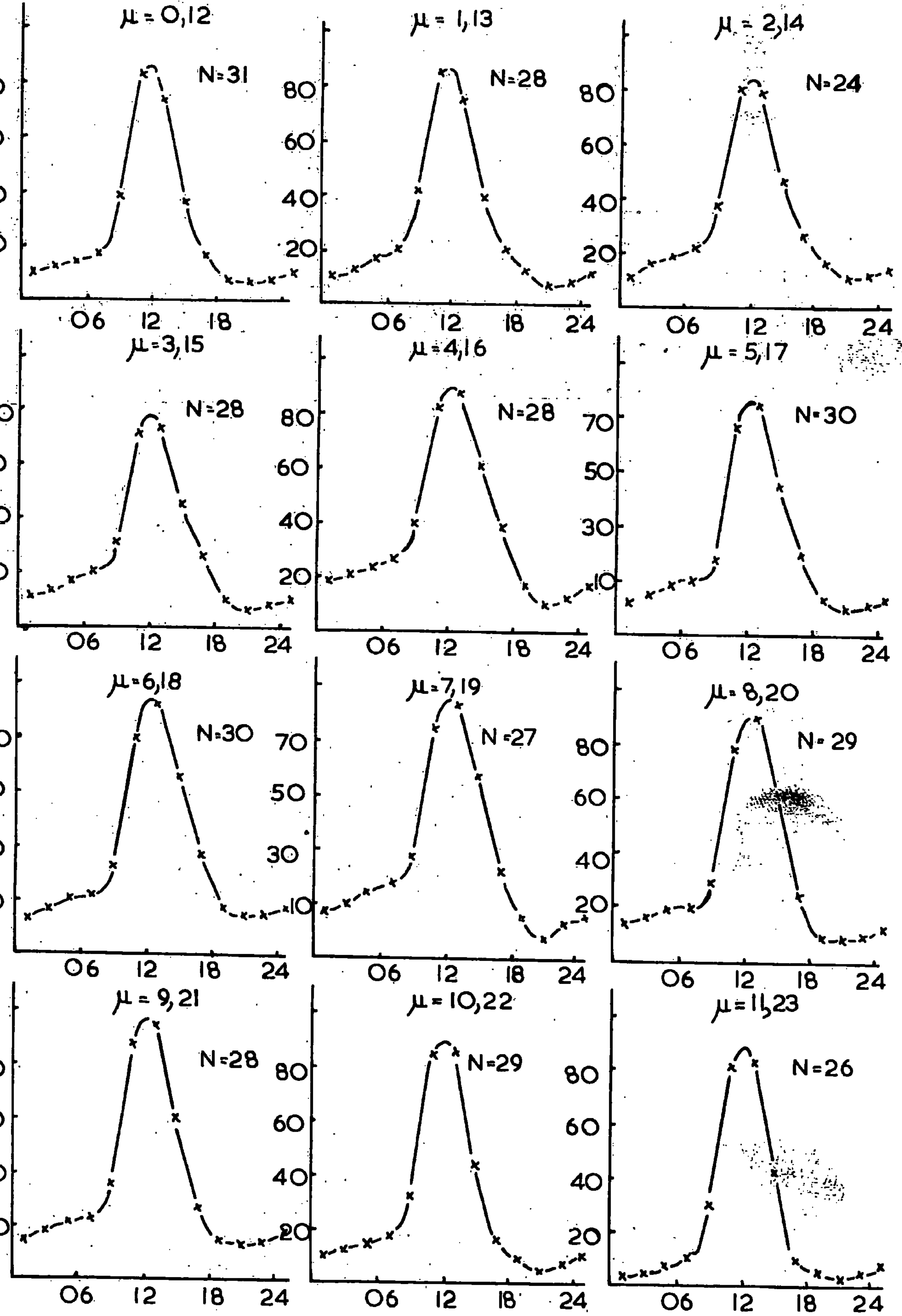
HORIZONTAL INTENSITY – GROUP II – ALL SEASONS FIG. 19.



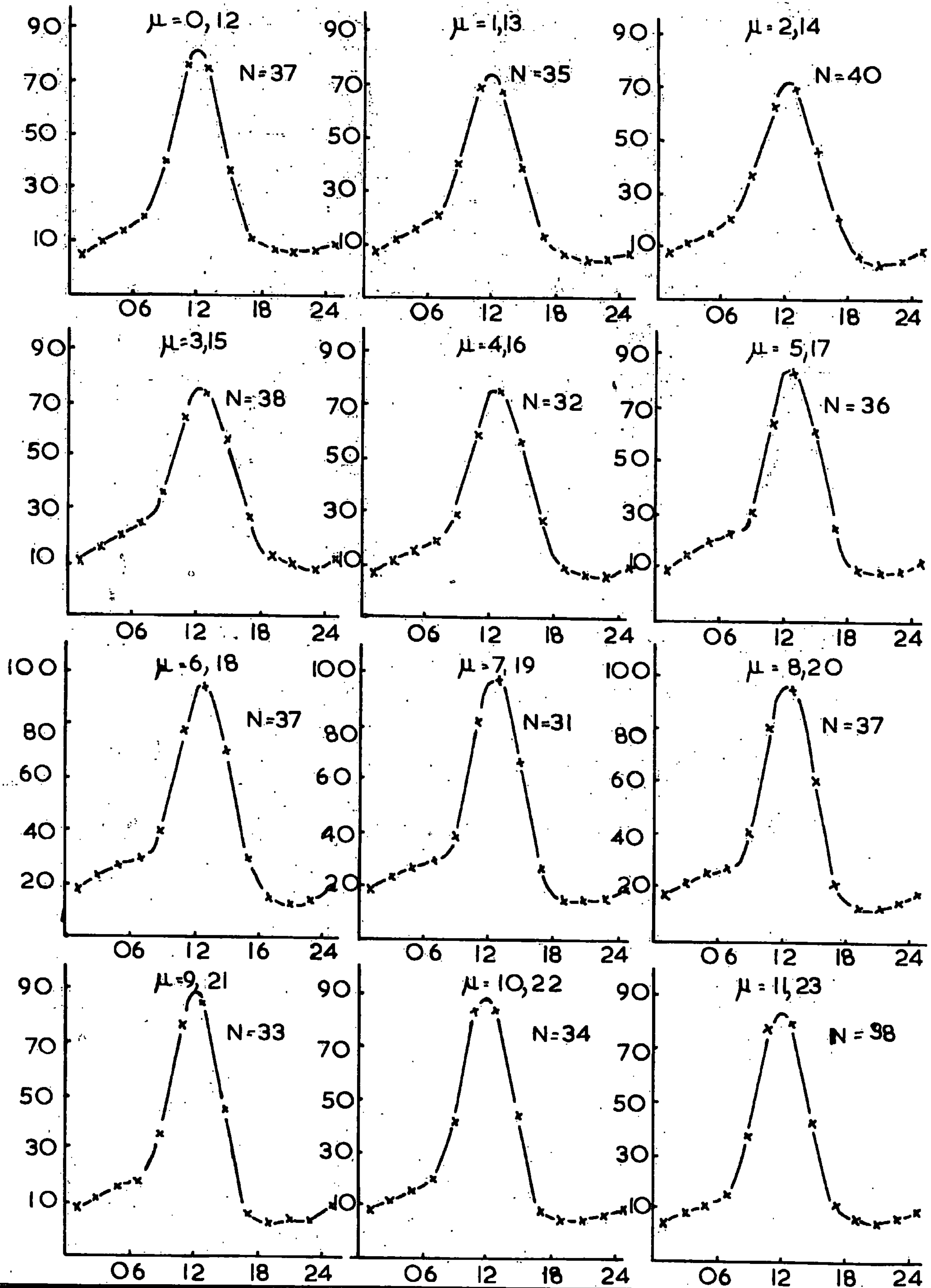
HORIZONTAL INTENSITY – GROUP II – J SET FIG. 20.



HORIZONTAL INTENSITY– GROUP II–E SET FIG. 21.

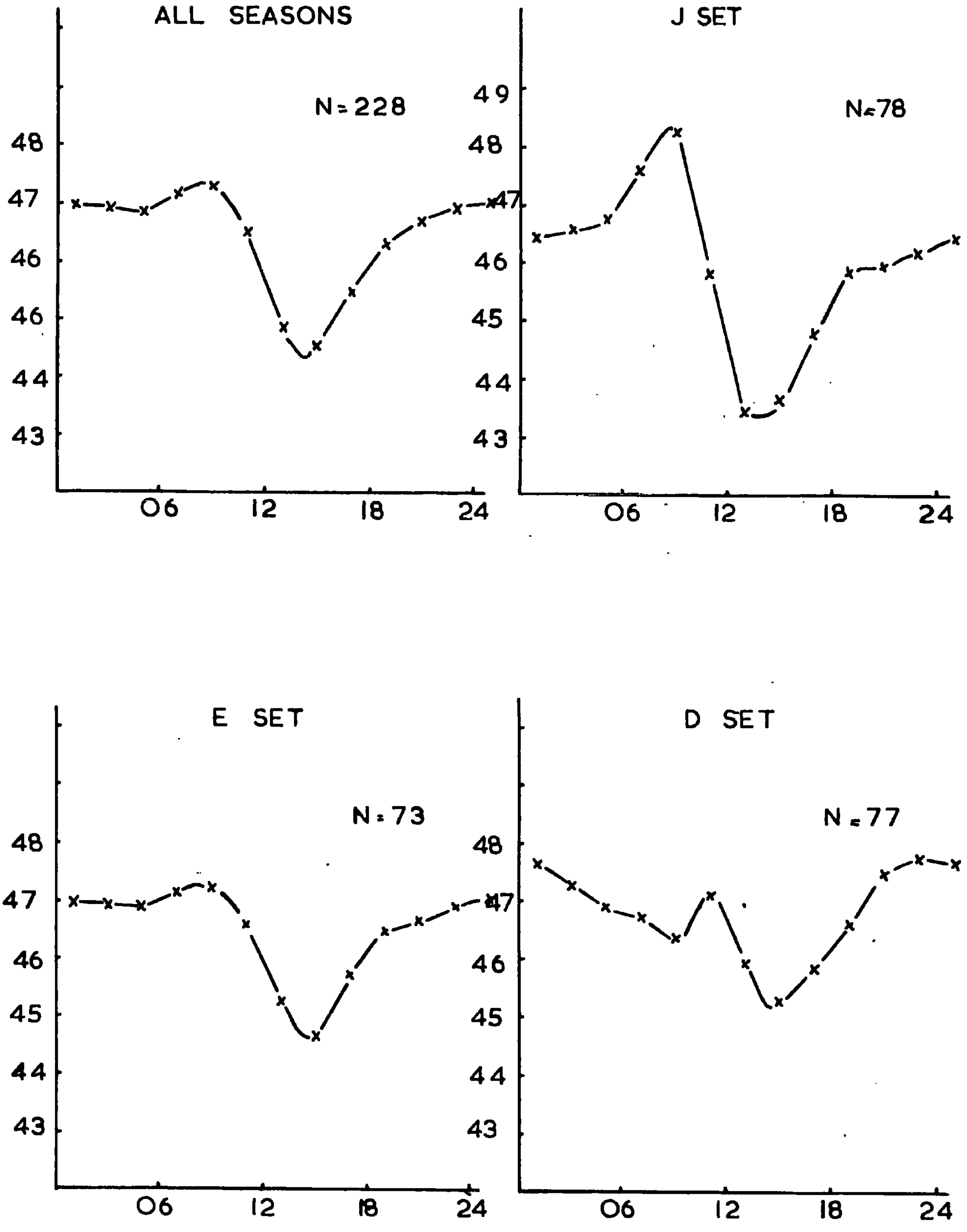


HORIZONTAL INTENSITY — GROUP II - D SET FIG. 22.



DECLINATION — GROUP I

FIG. 23.



DECLINATION - GROUP I - ALL SEASONS FIG.24.

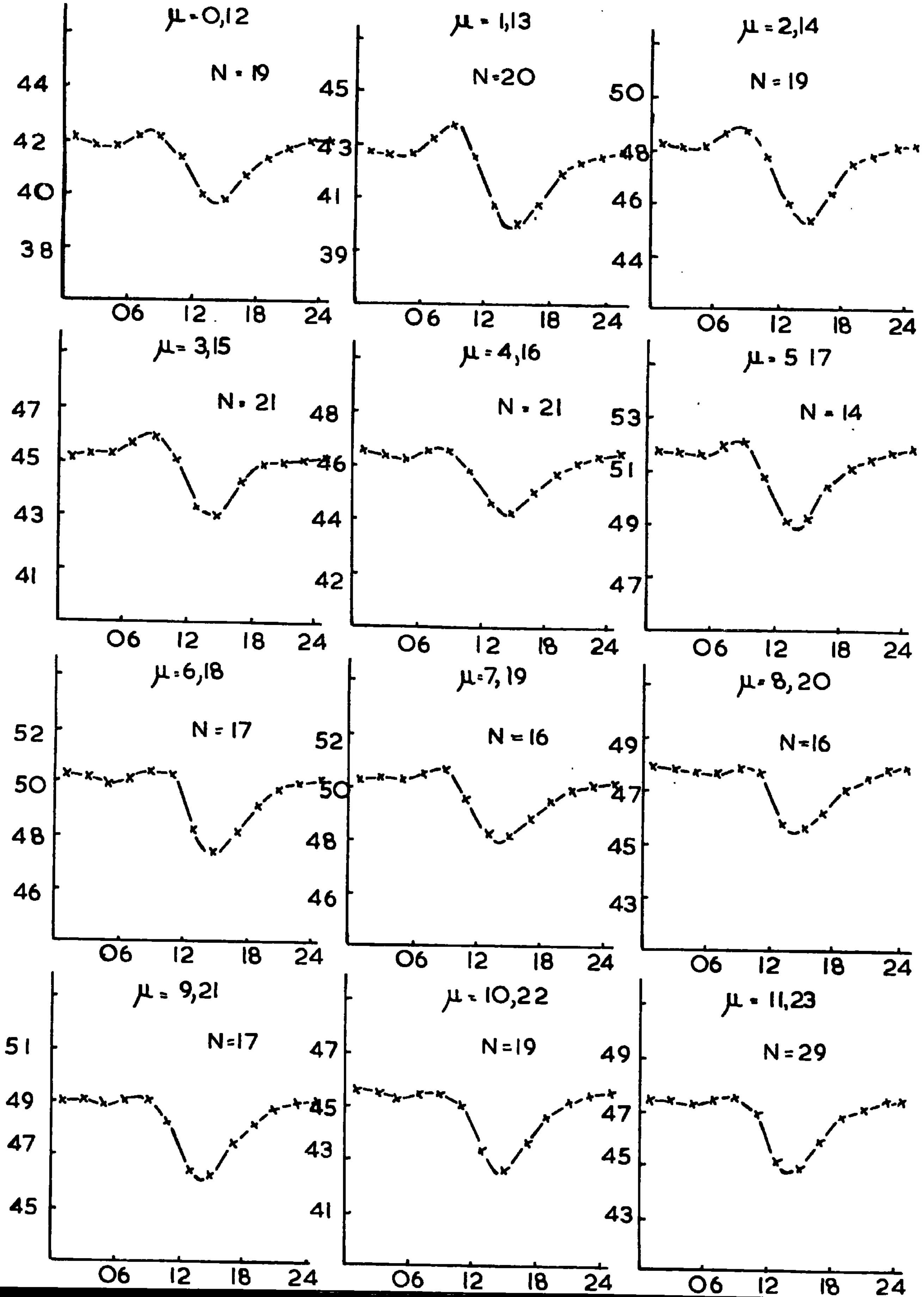


FIG. 25.

DECLINATION — GROUP I — J SET

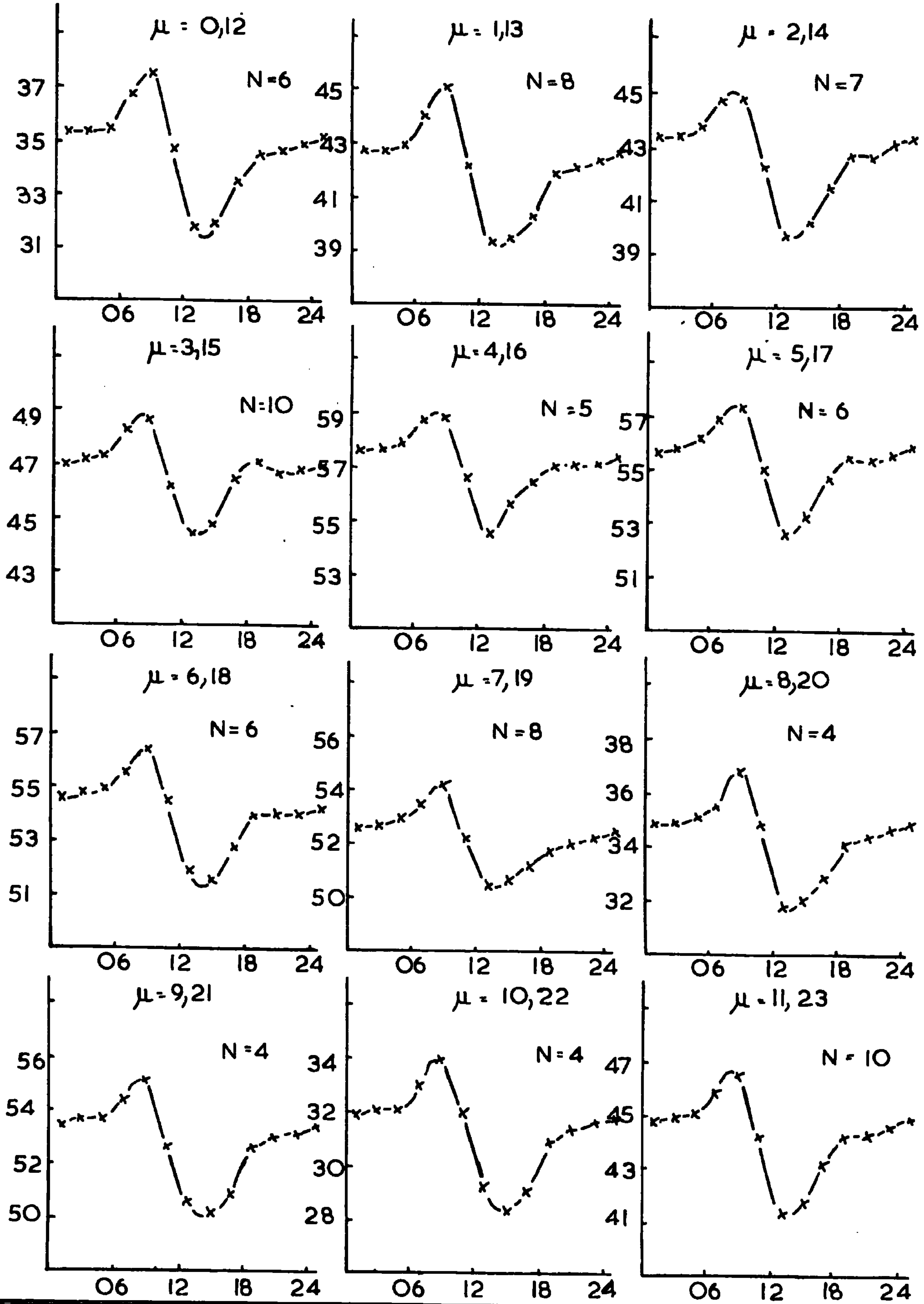


FIG. 26.

DECLINATION — GROUP I — E SET

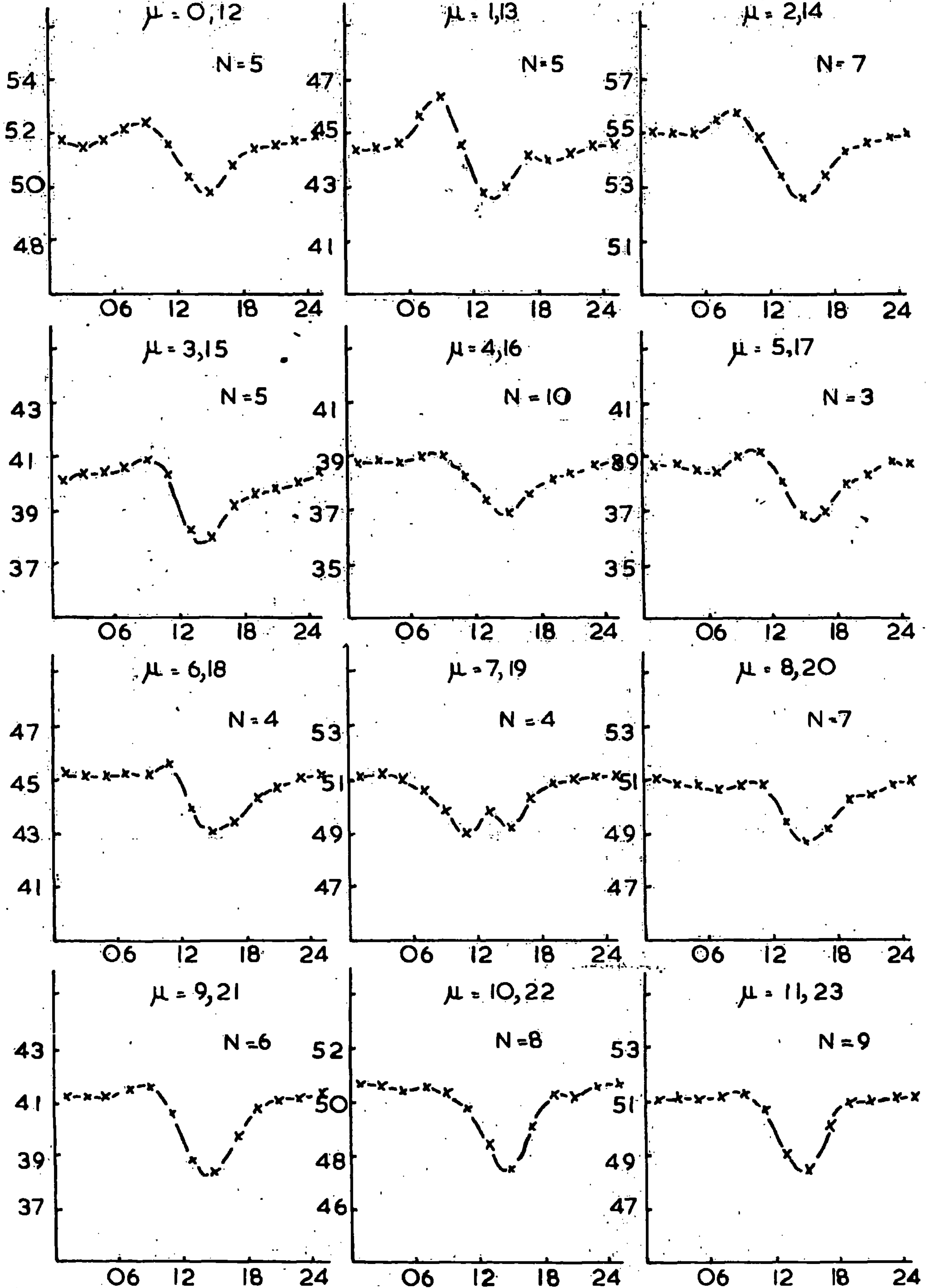
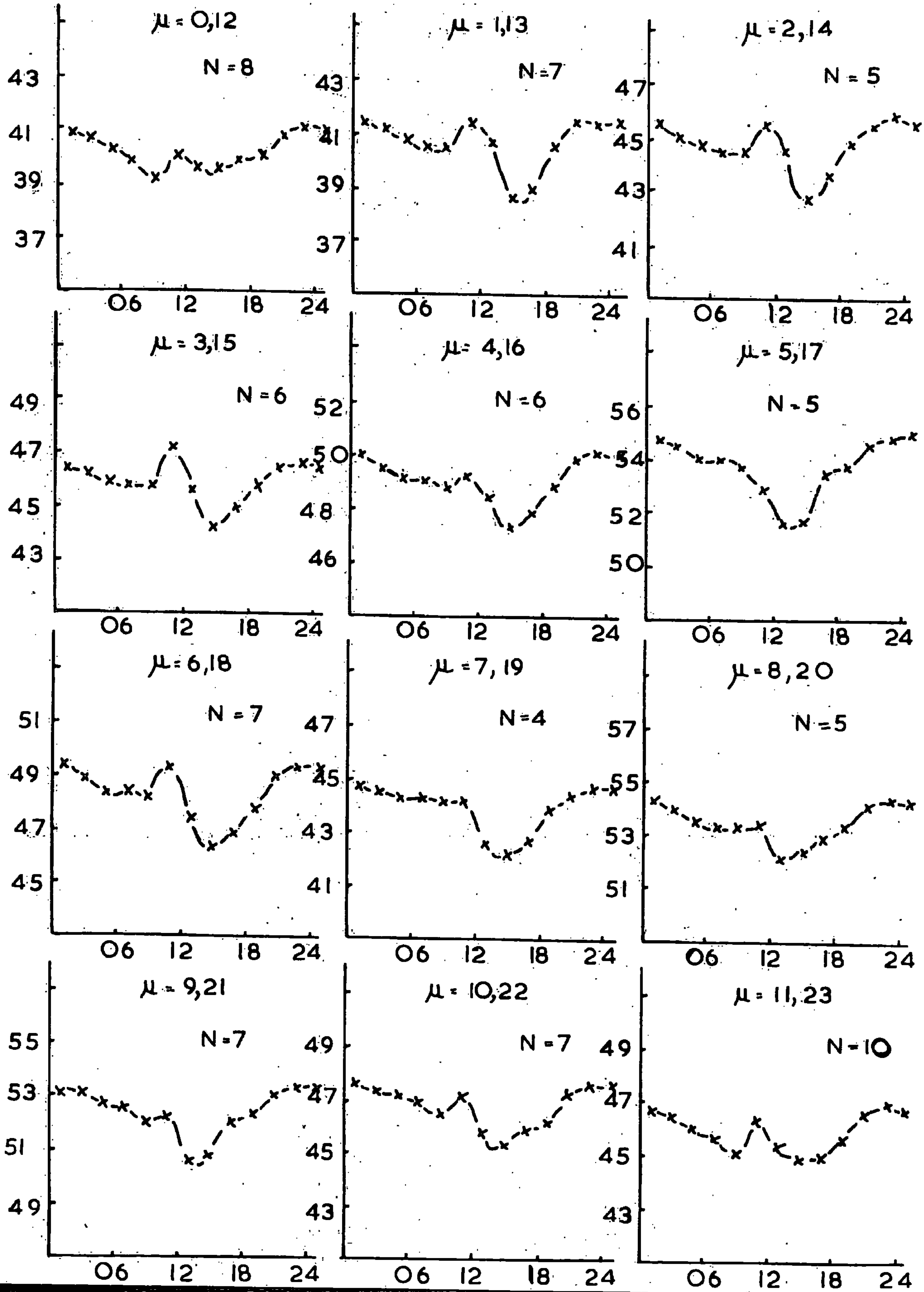


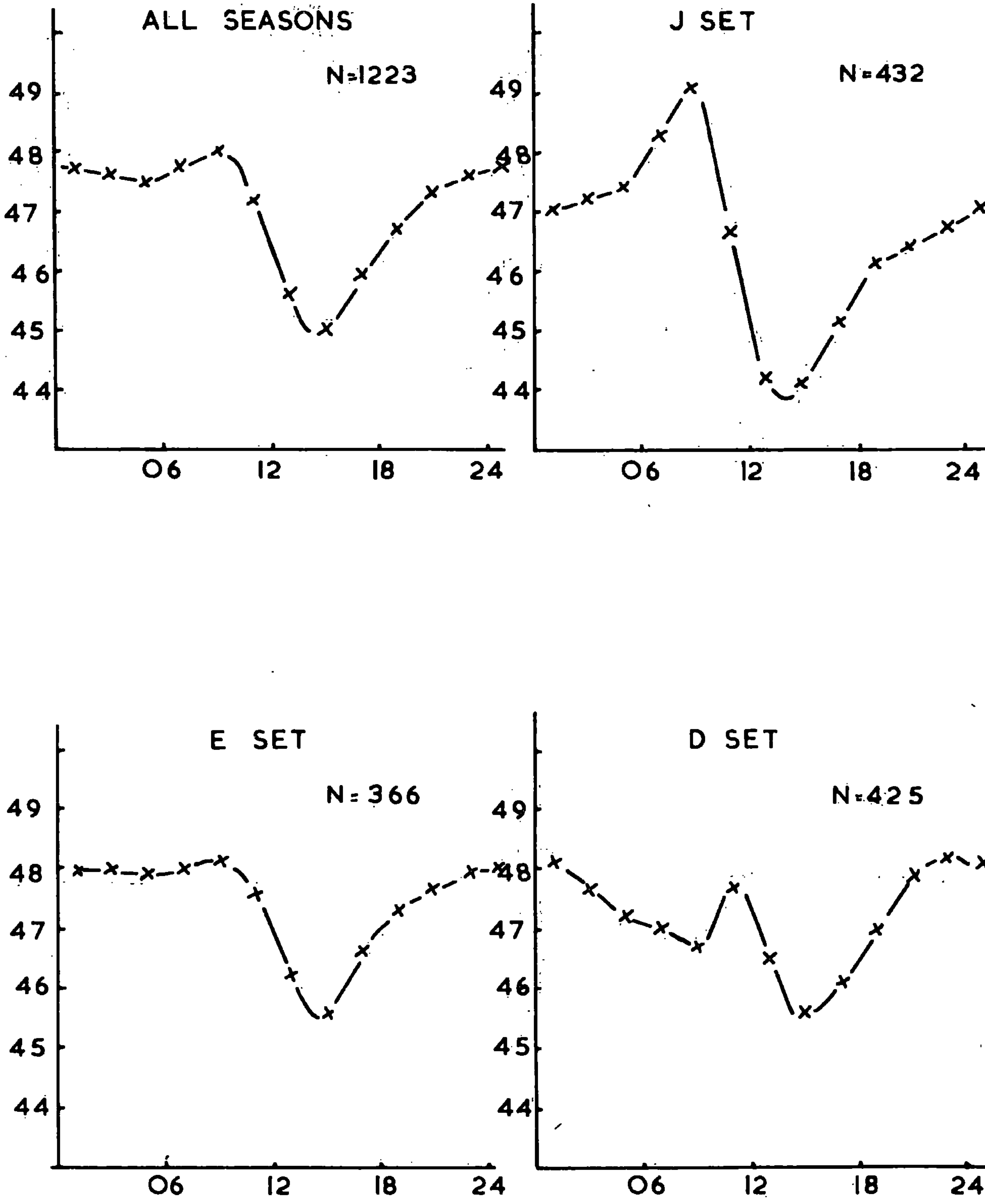
FIG. 27.

DECLINATION—GROUP I—D SET



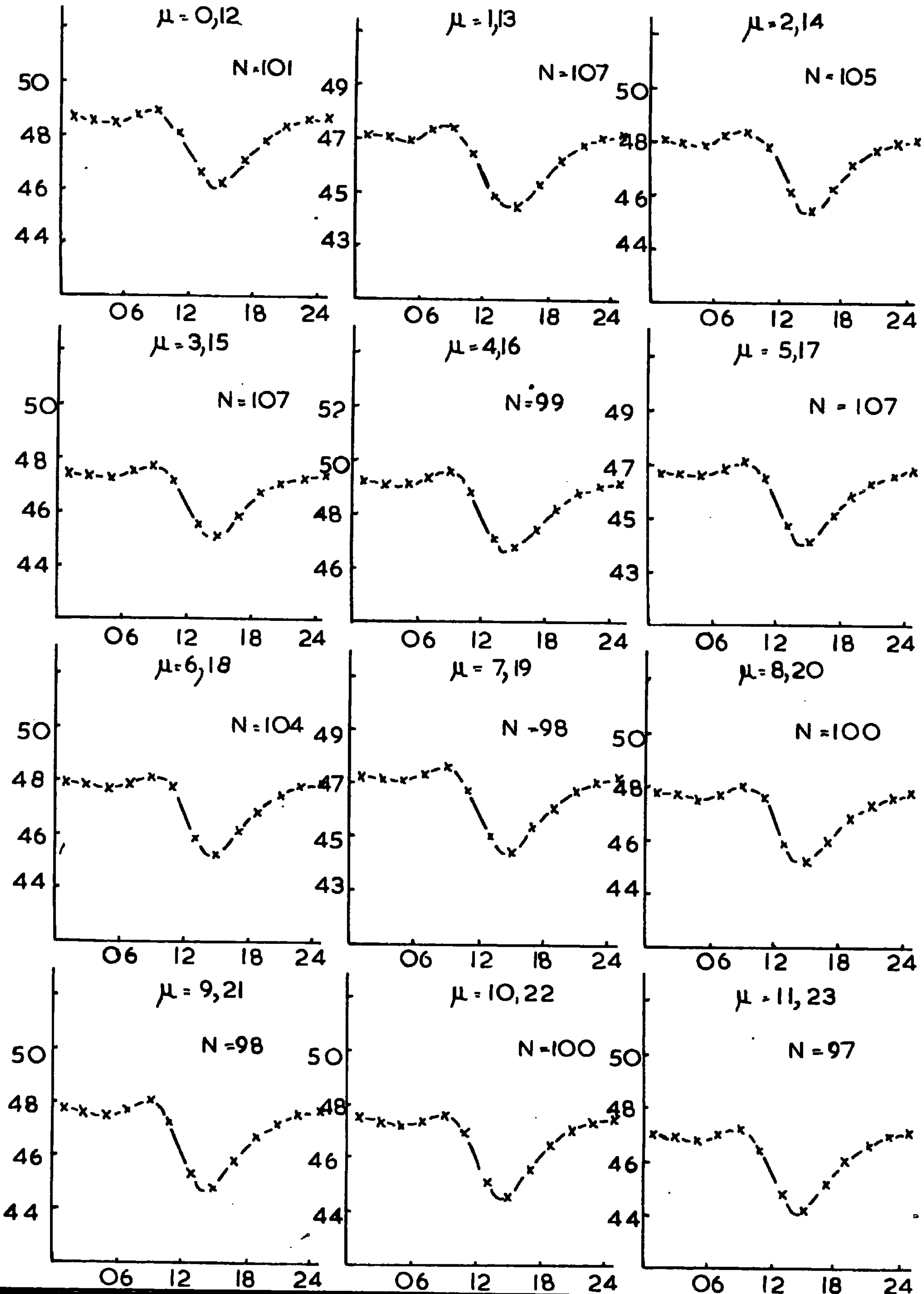
DECLINATION— GROUP II

FIG. 28.

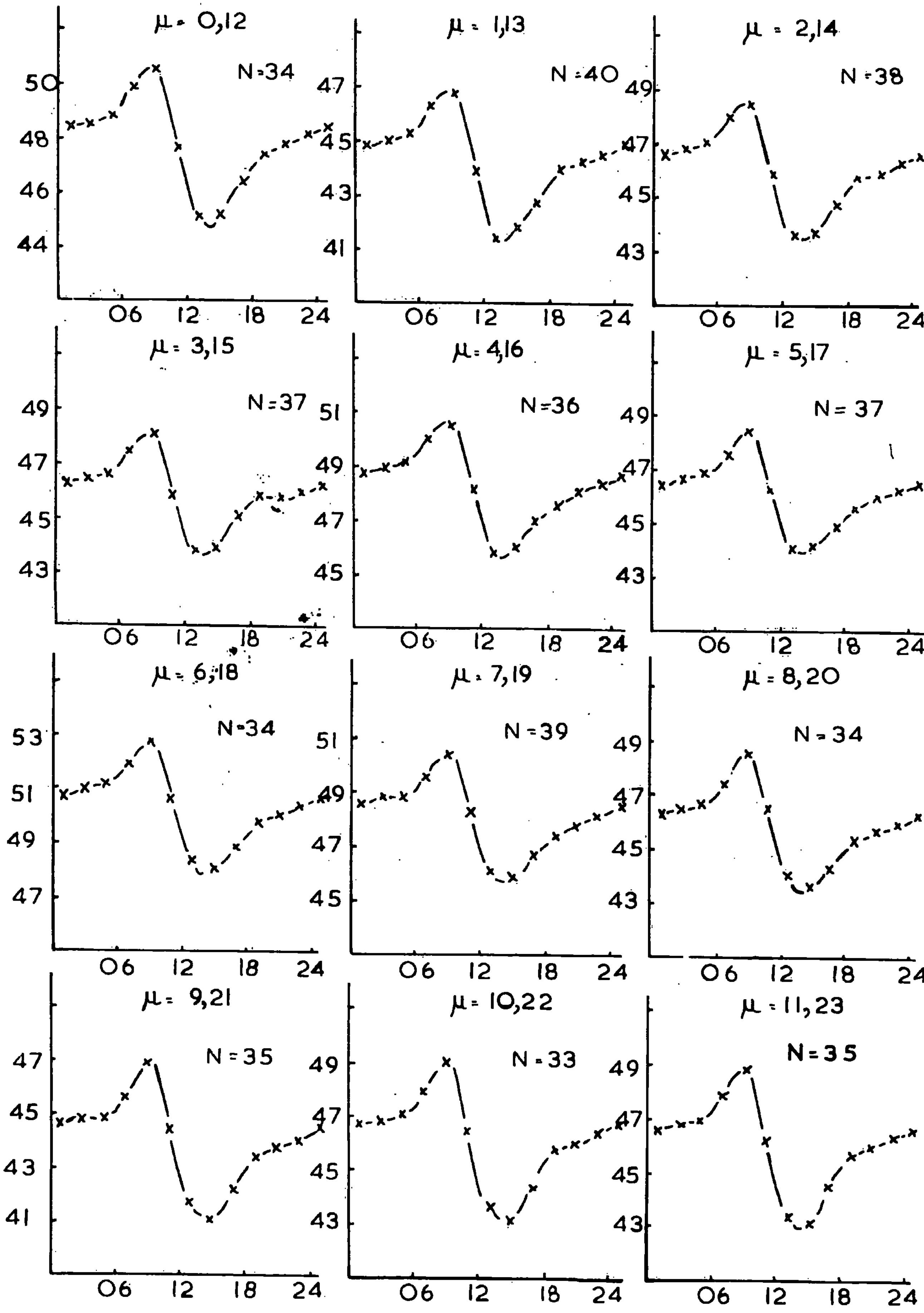


DECLINATION - GROUP II - ALL SEASONS

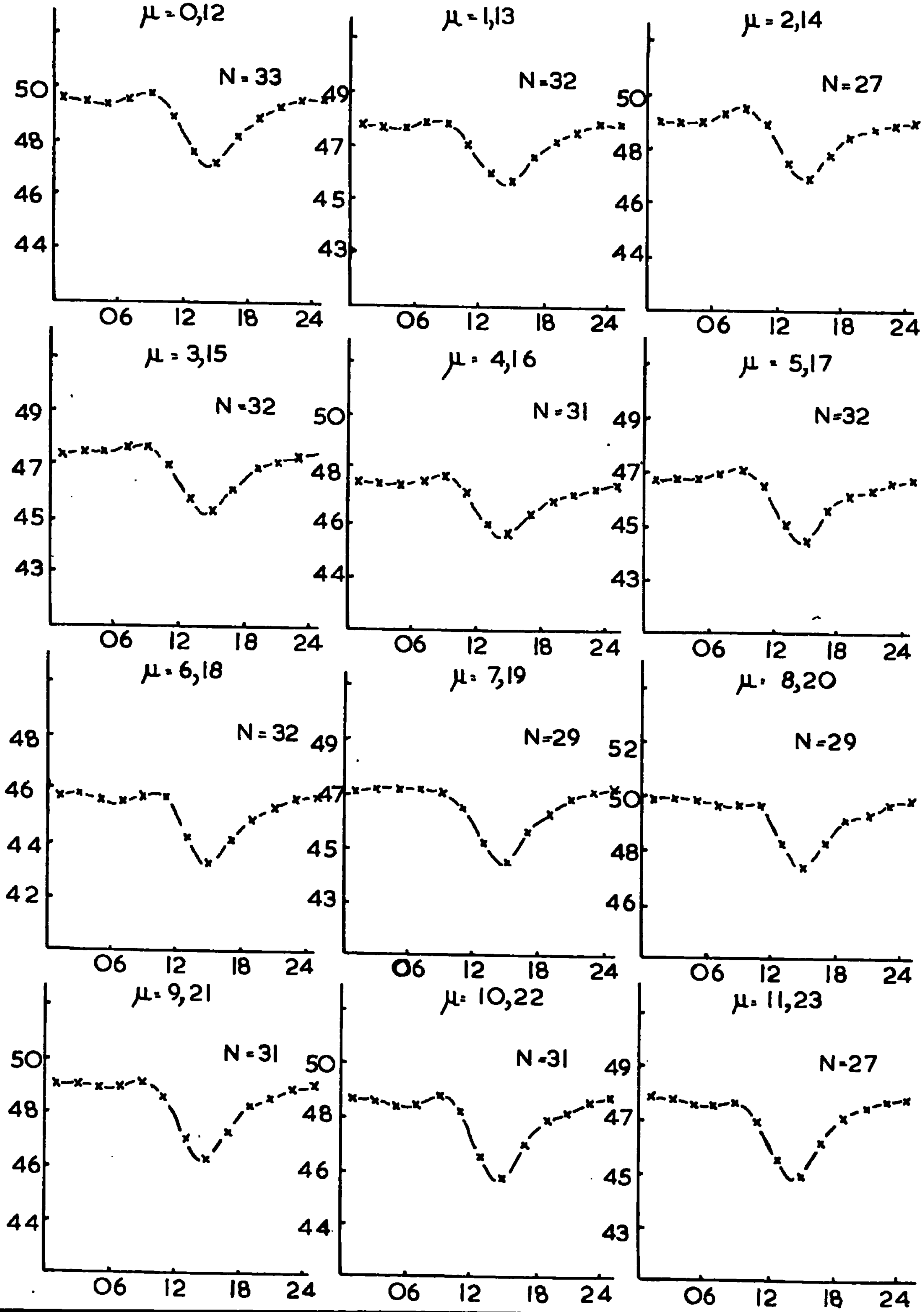
FIG. 29.



DECLINATION - GROUP II - J SET FIG. 30.



DECLINATION — GROUP II — E SET FIG 31.



DECLINATION – GROUP II-D SET

FIG. 3

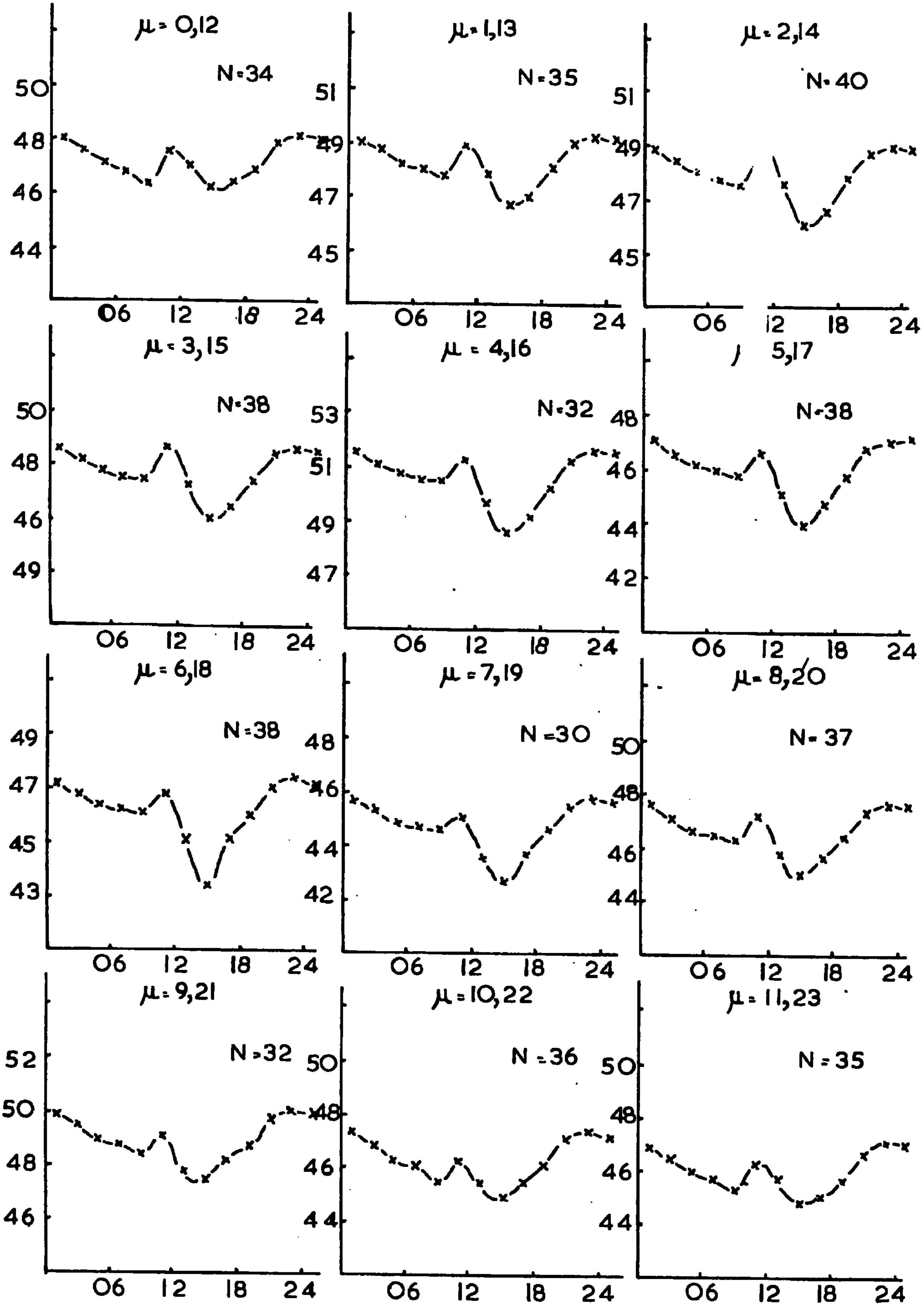


FIG. 33.

VERTICAL INTENSITY — GROUP I

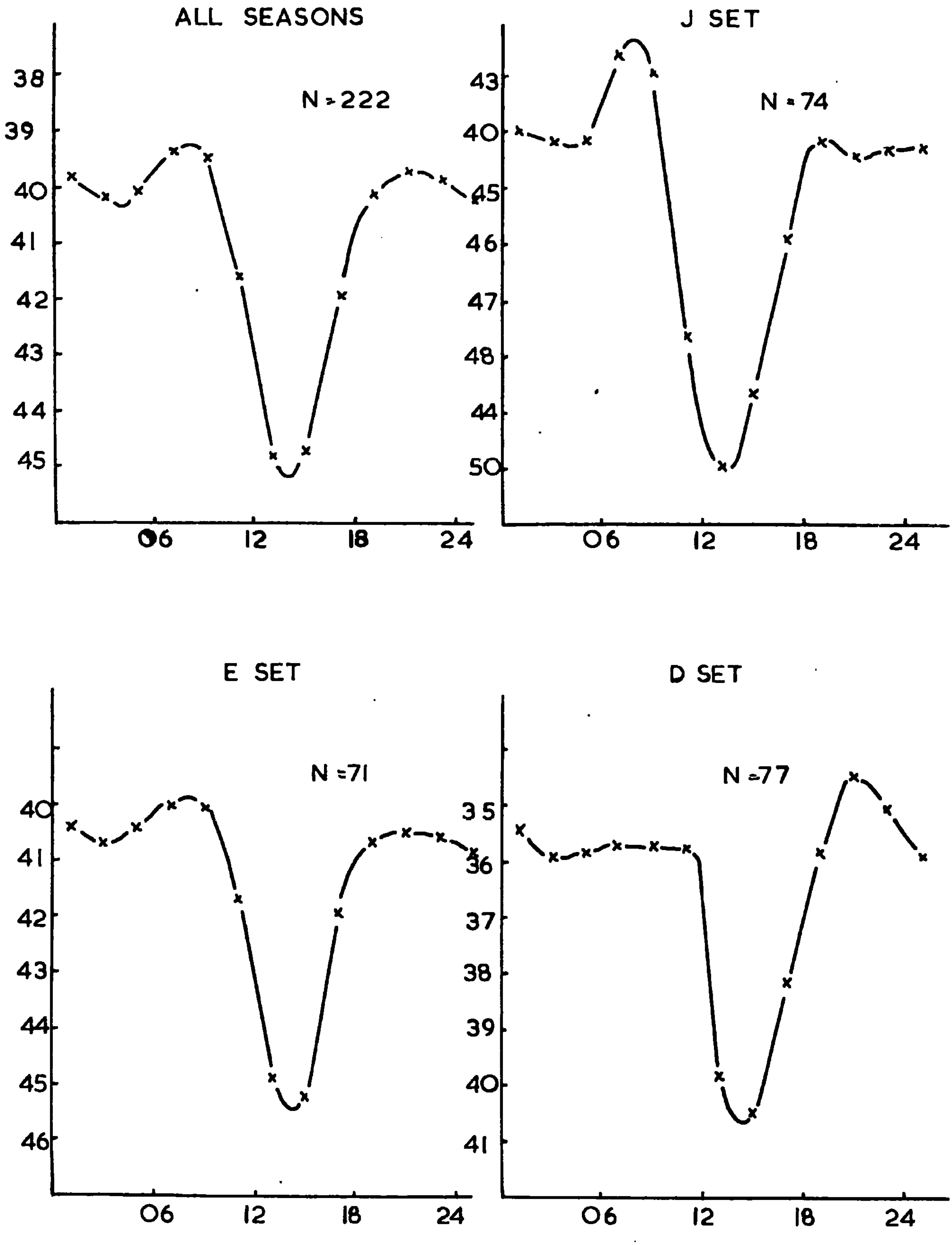
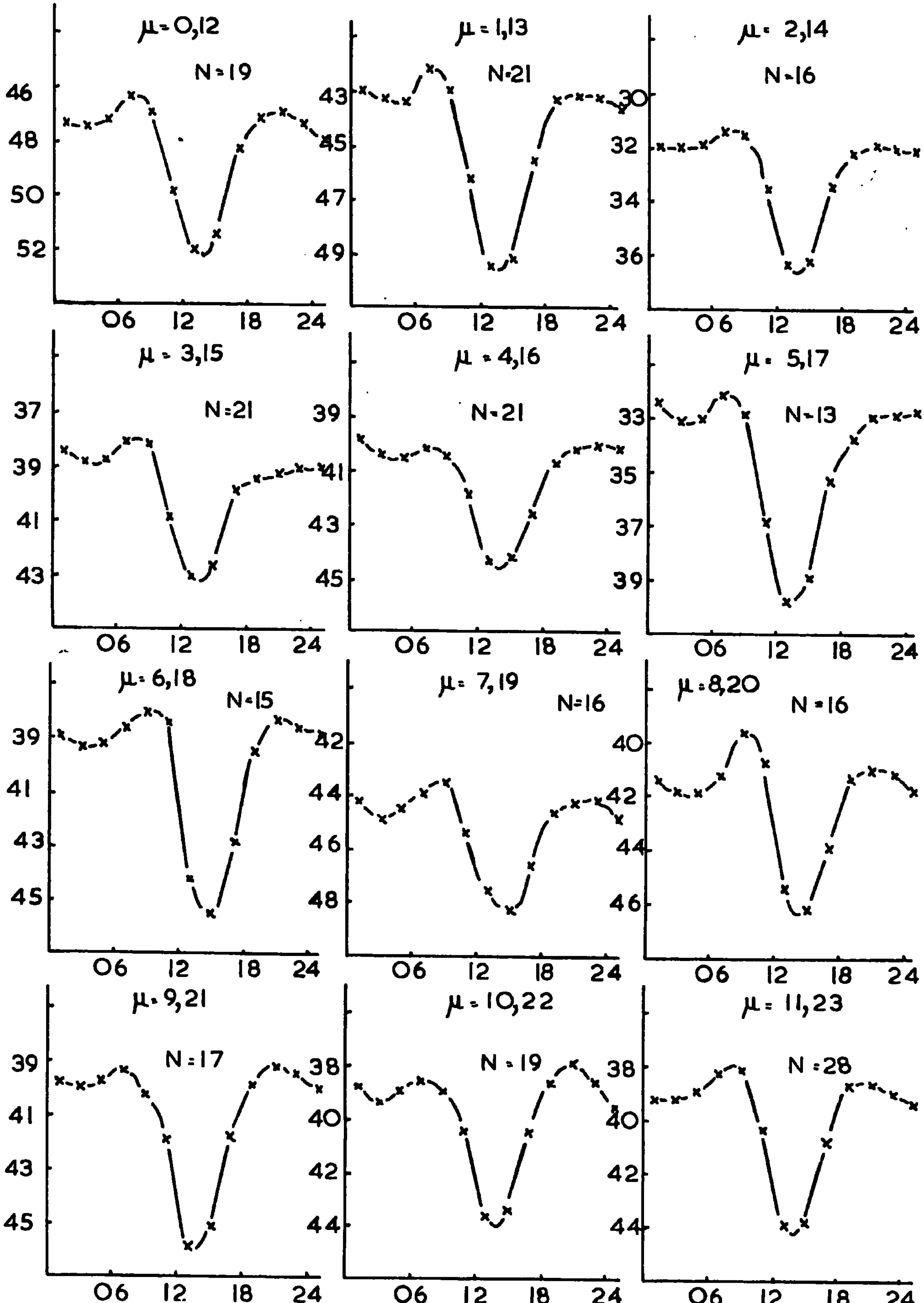


FIG. 34.

VERTICAL INTENSITY – GROUP I – ALL SEASONS



VERTICAL INTENSITY- GROUP I-J SET FIG 35

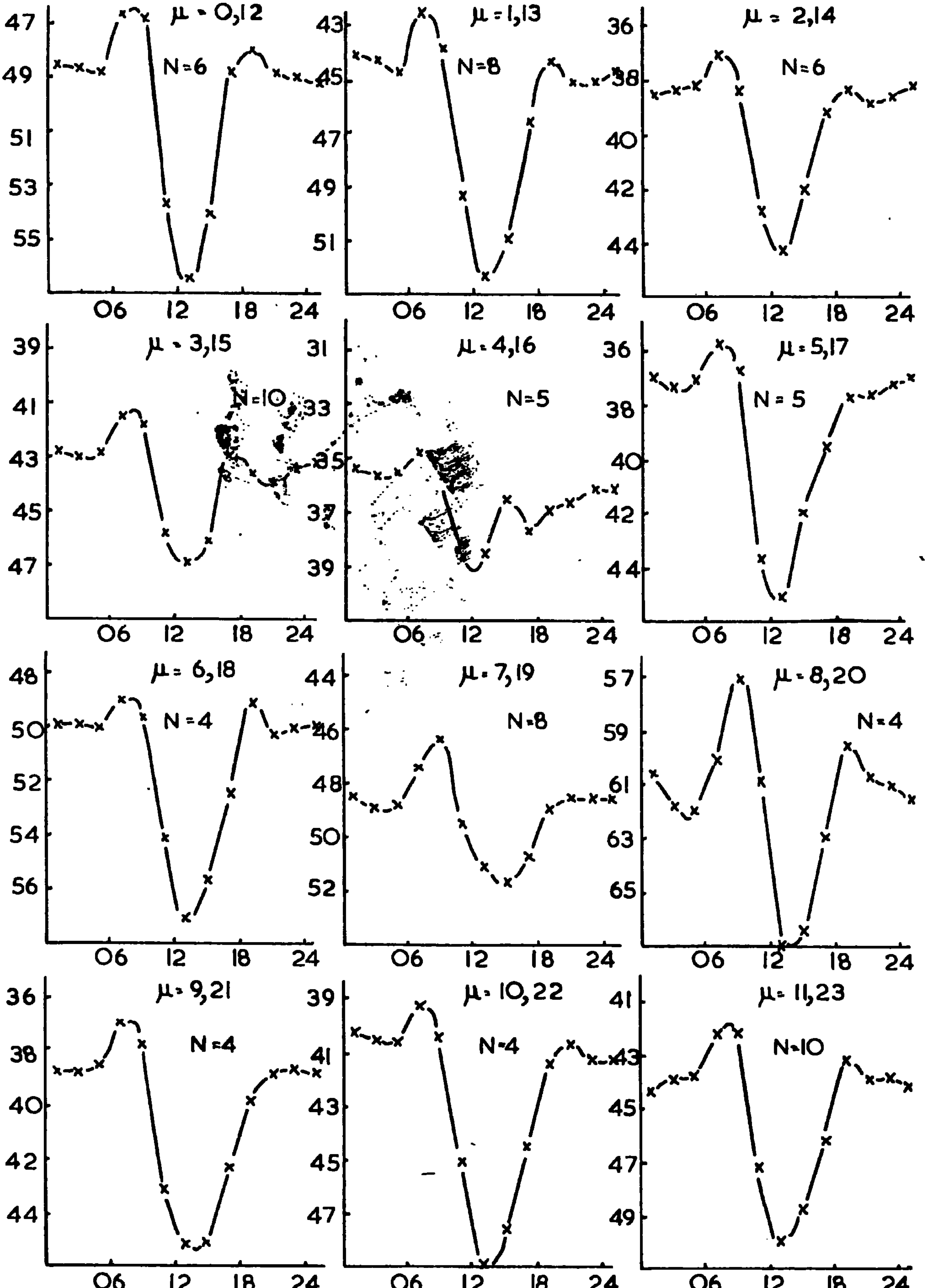
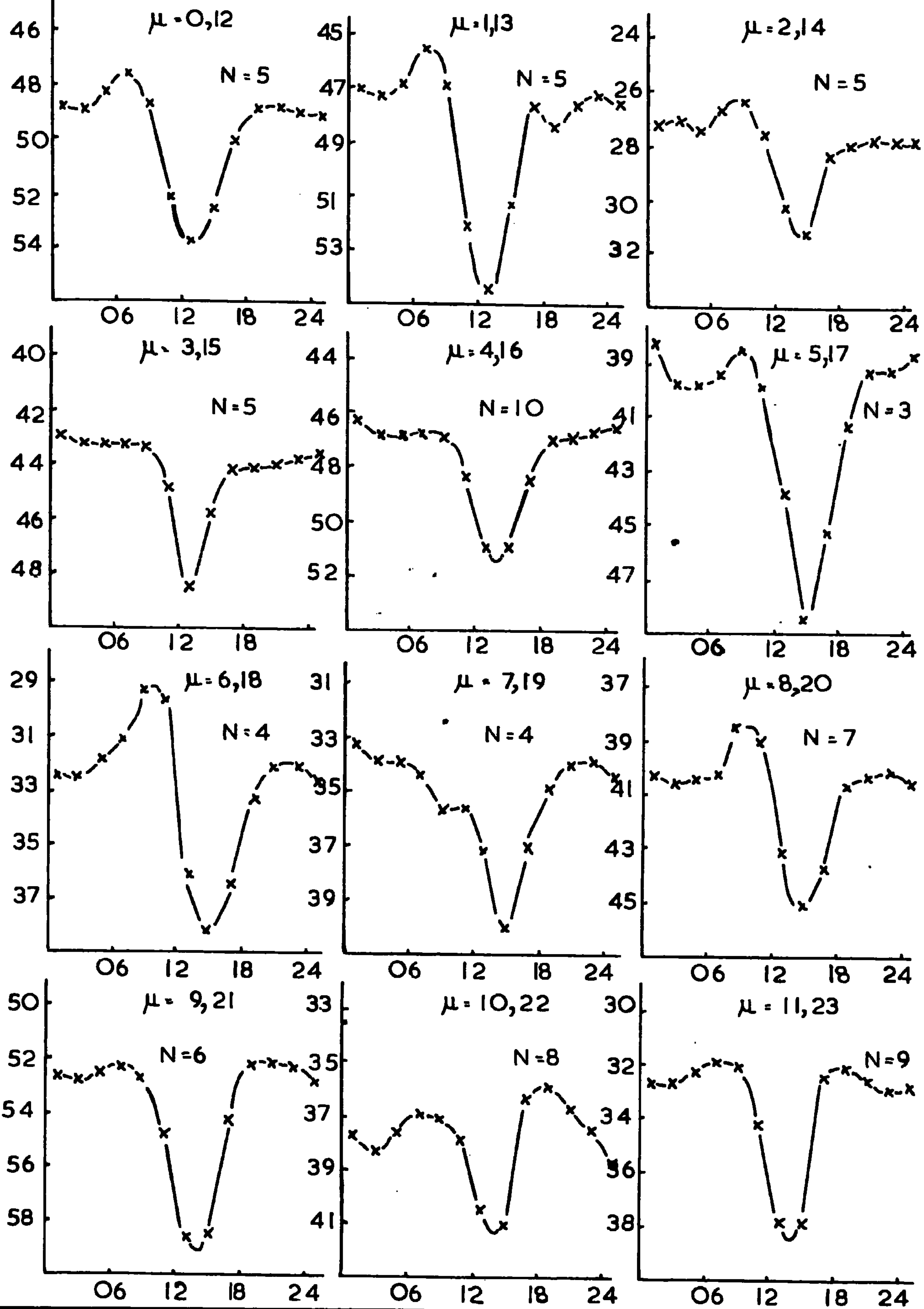


FIG. 36.

VERTICAL INTENSITY – GROUP I – E SET



VERTICAL INTENSITY - GROUP I - D SET FIG. 37.

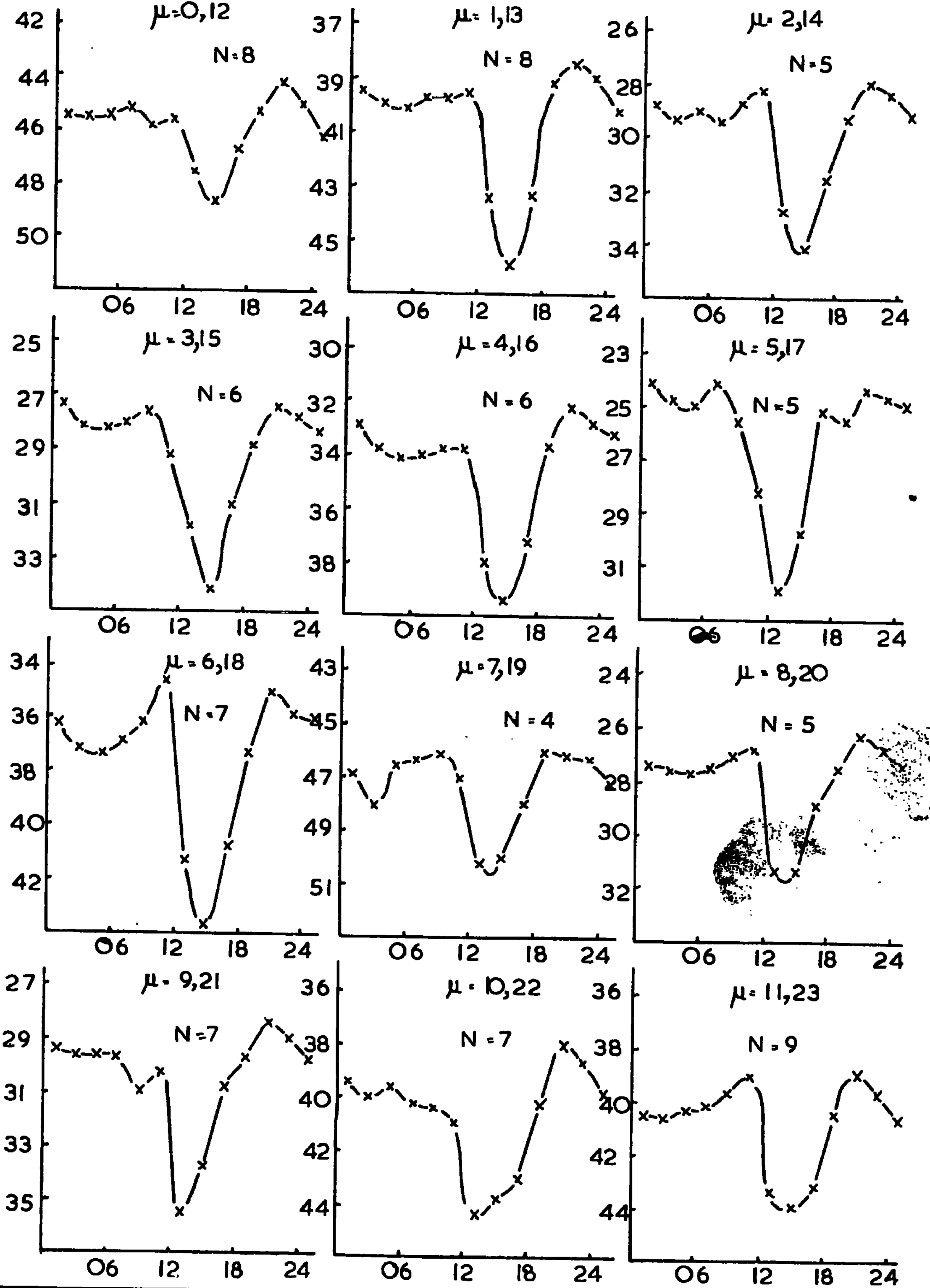
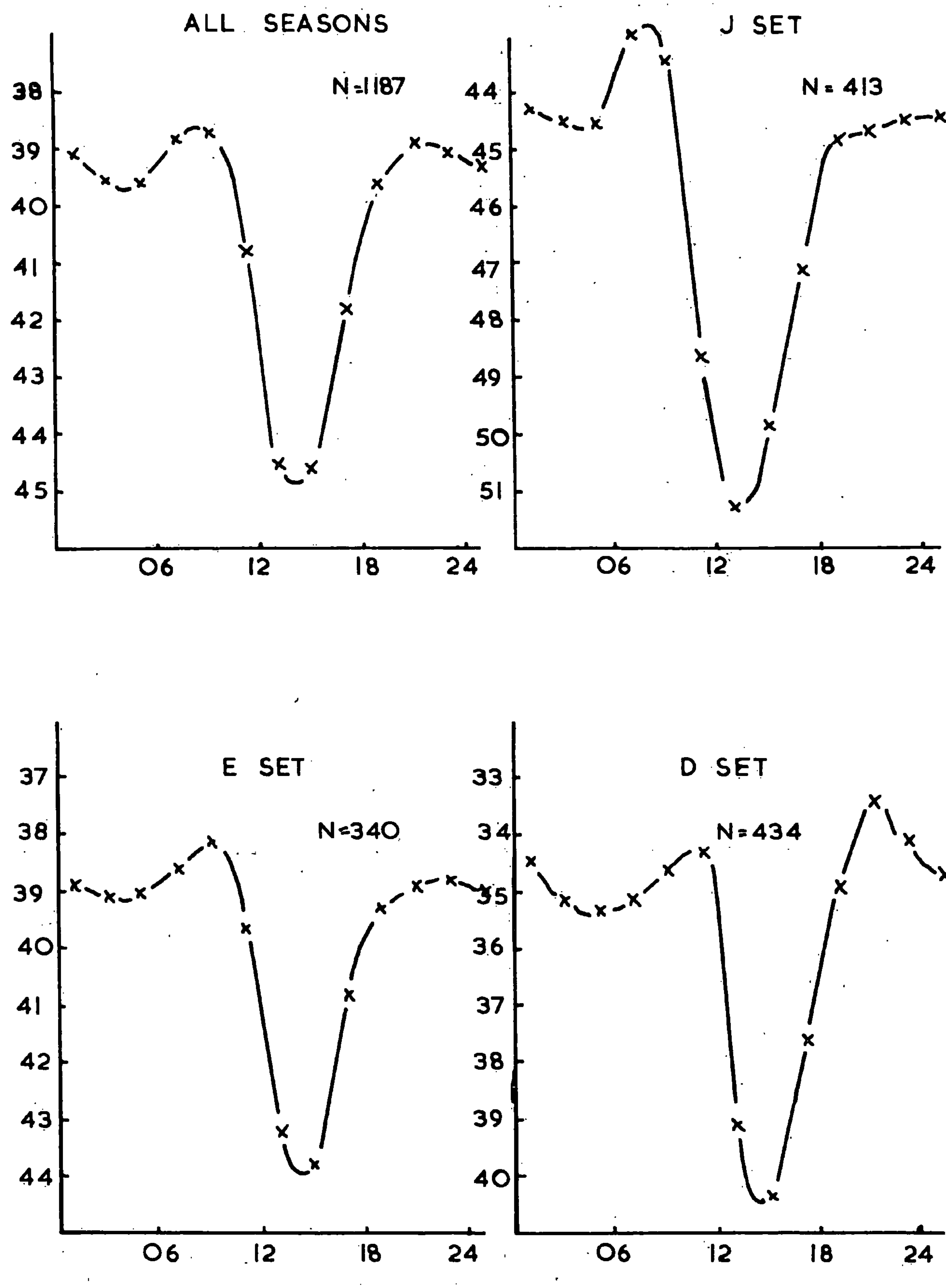


FIG. 38.

VERTICAL INTENSITY- GROUP II



ALL SEASONS

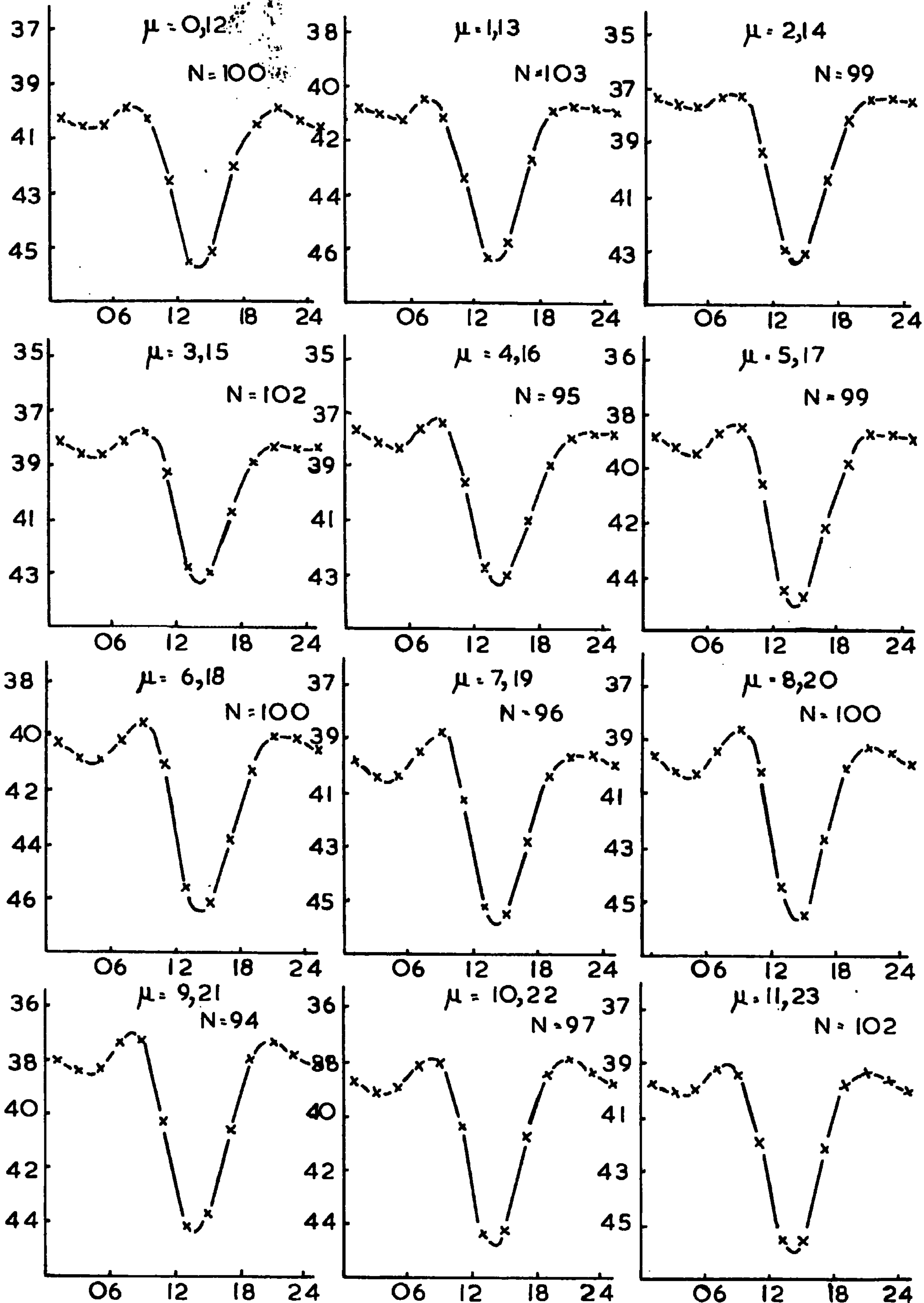
J SET

E SET

D SET

VERTICAL INTENSITY – GROUP II – ALL SEASONS

FIG. 39.



VERTICAL INTENSITY - GROUP II - J SET

FIG. 40.

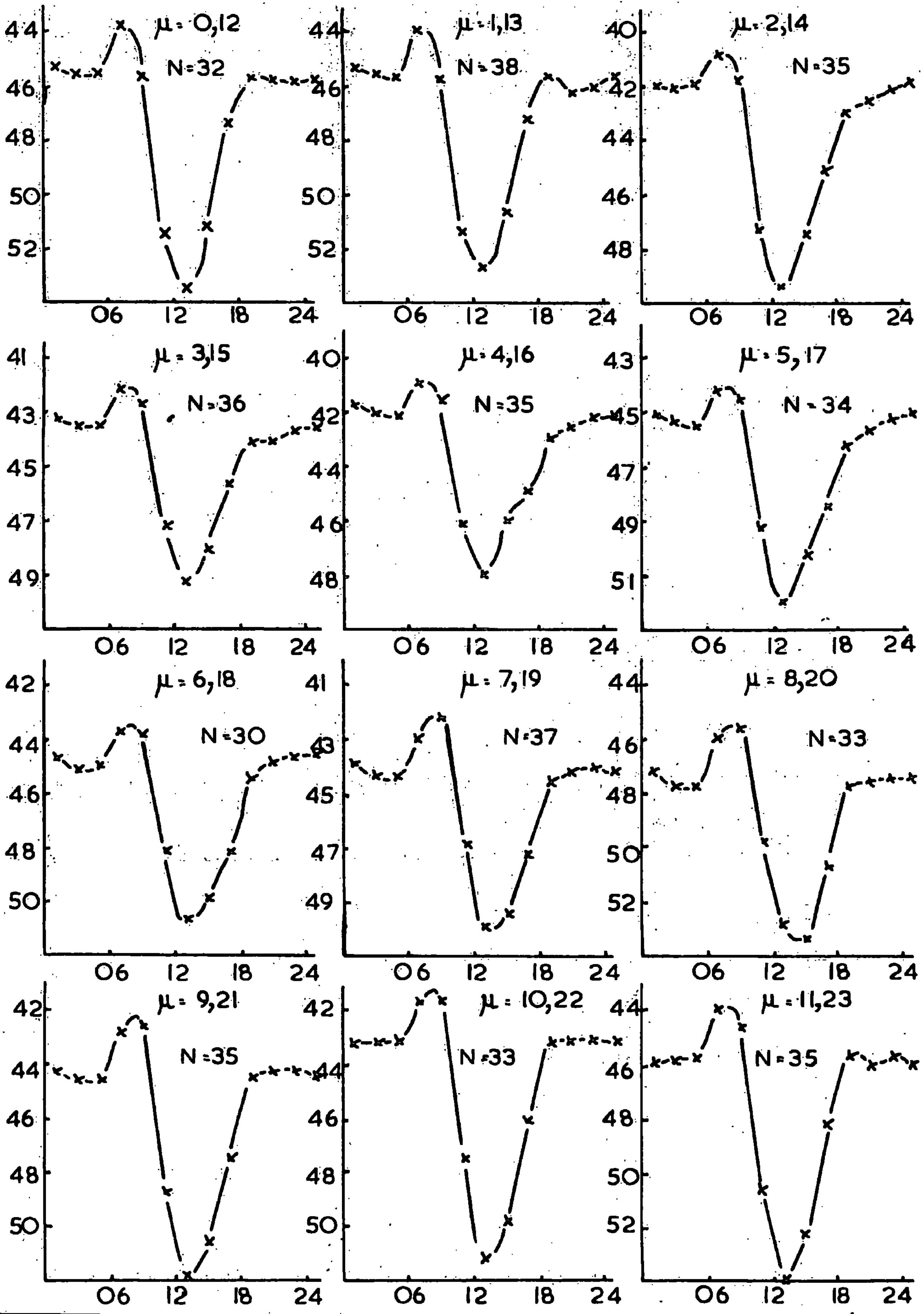
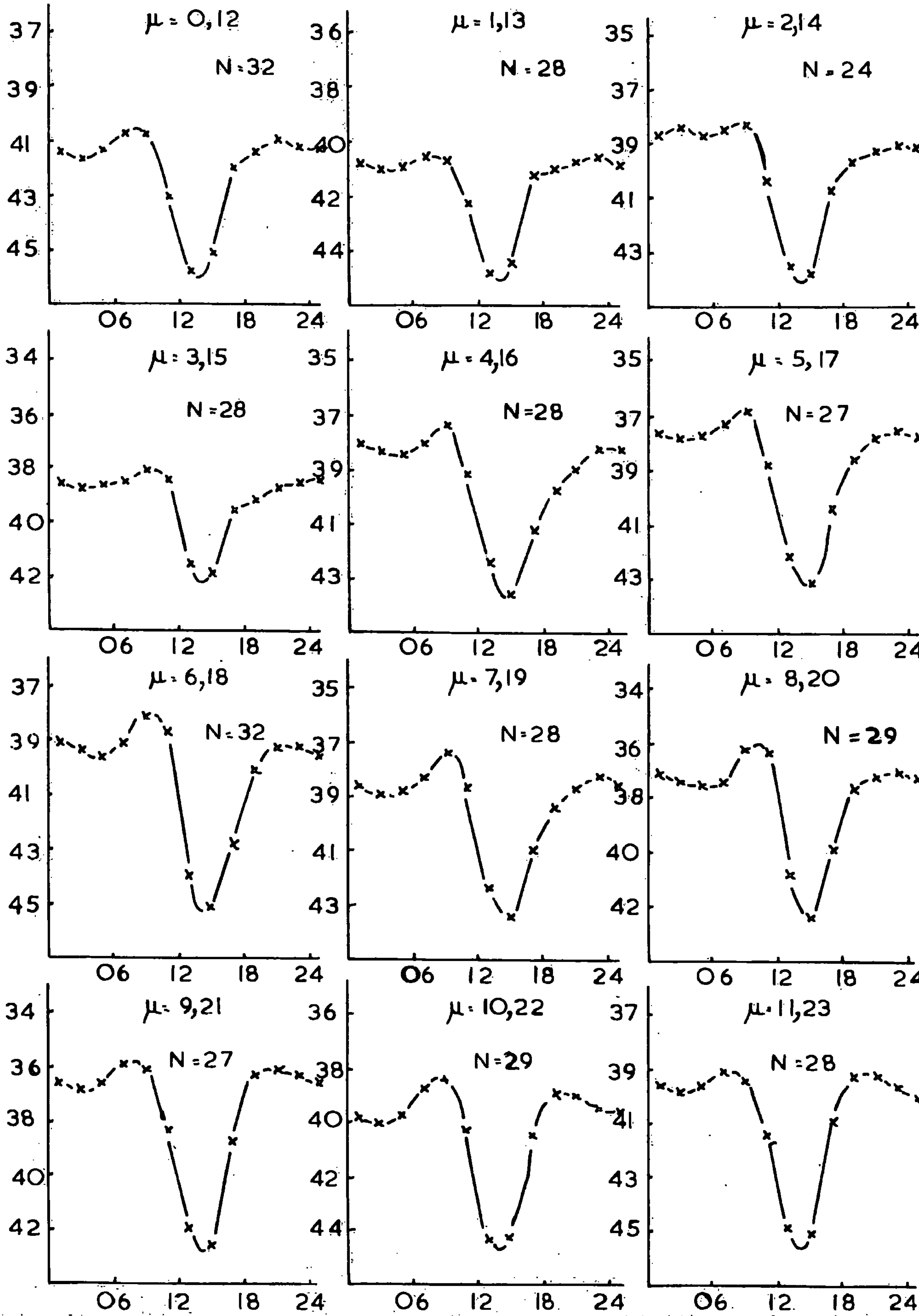


FIG. 41.

VERTICAL INTENSITY — GROUP II - E SET



VERTICAL INTENSITY – GROUP II – D SET

FIG. 42.

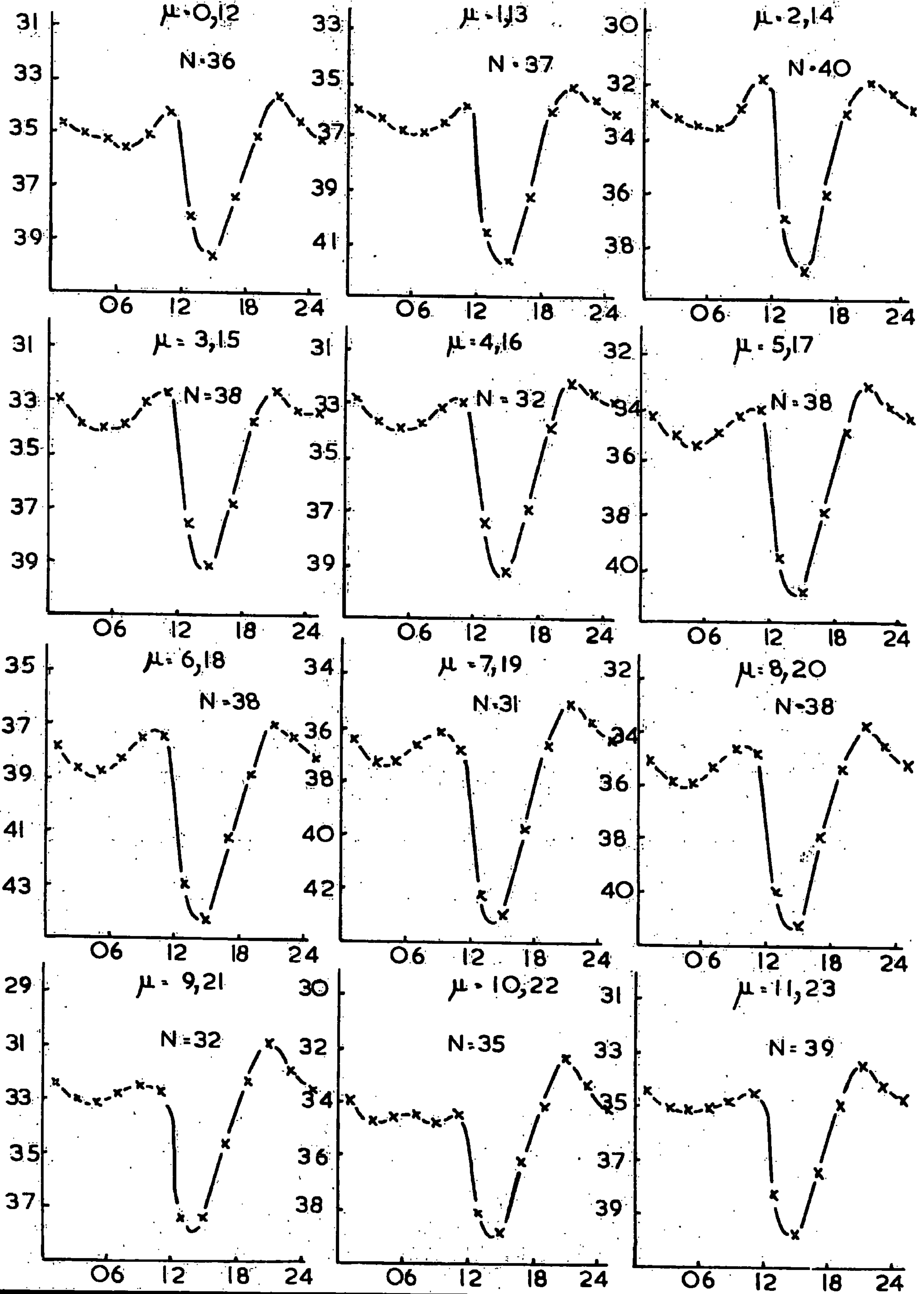


FIG. 43.

HORIZONTAL INTENSITY

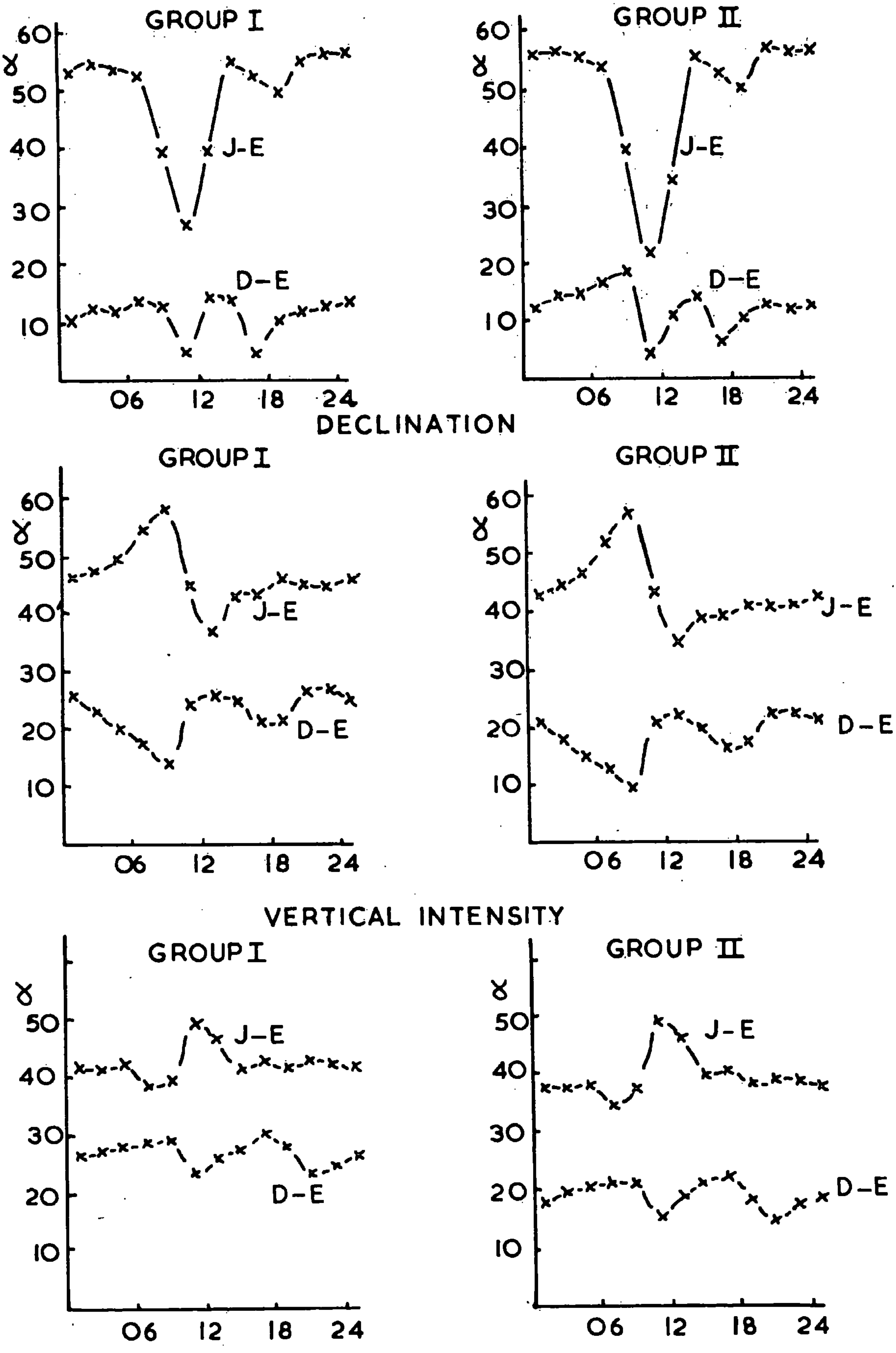


FIG. 44.

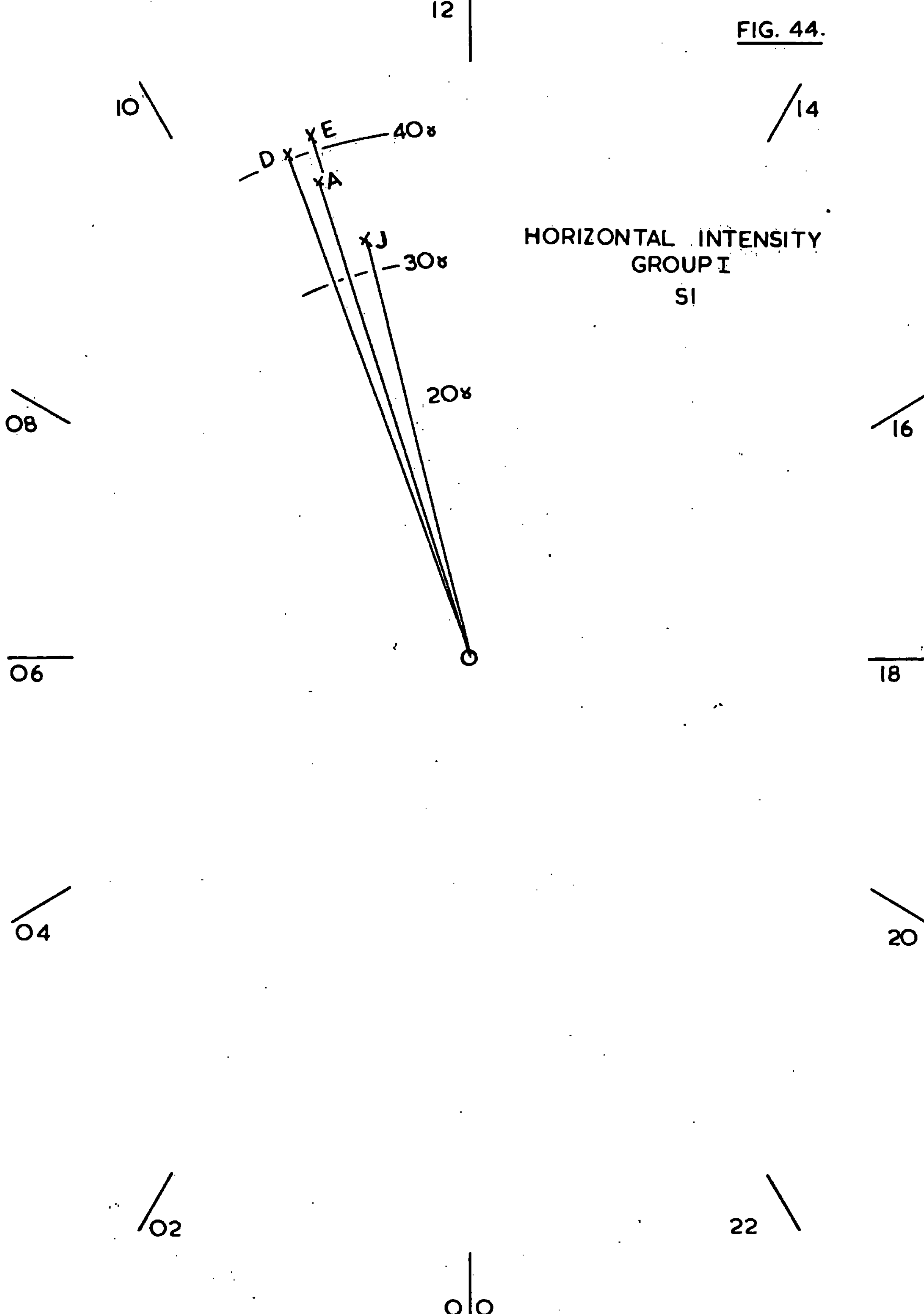
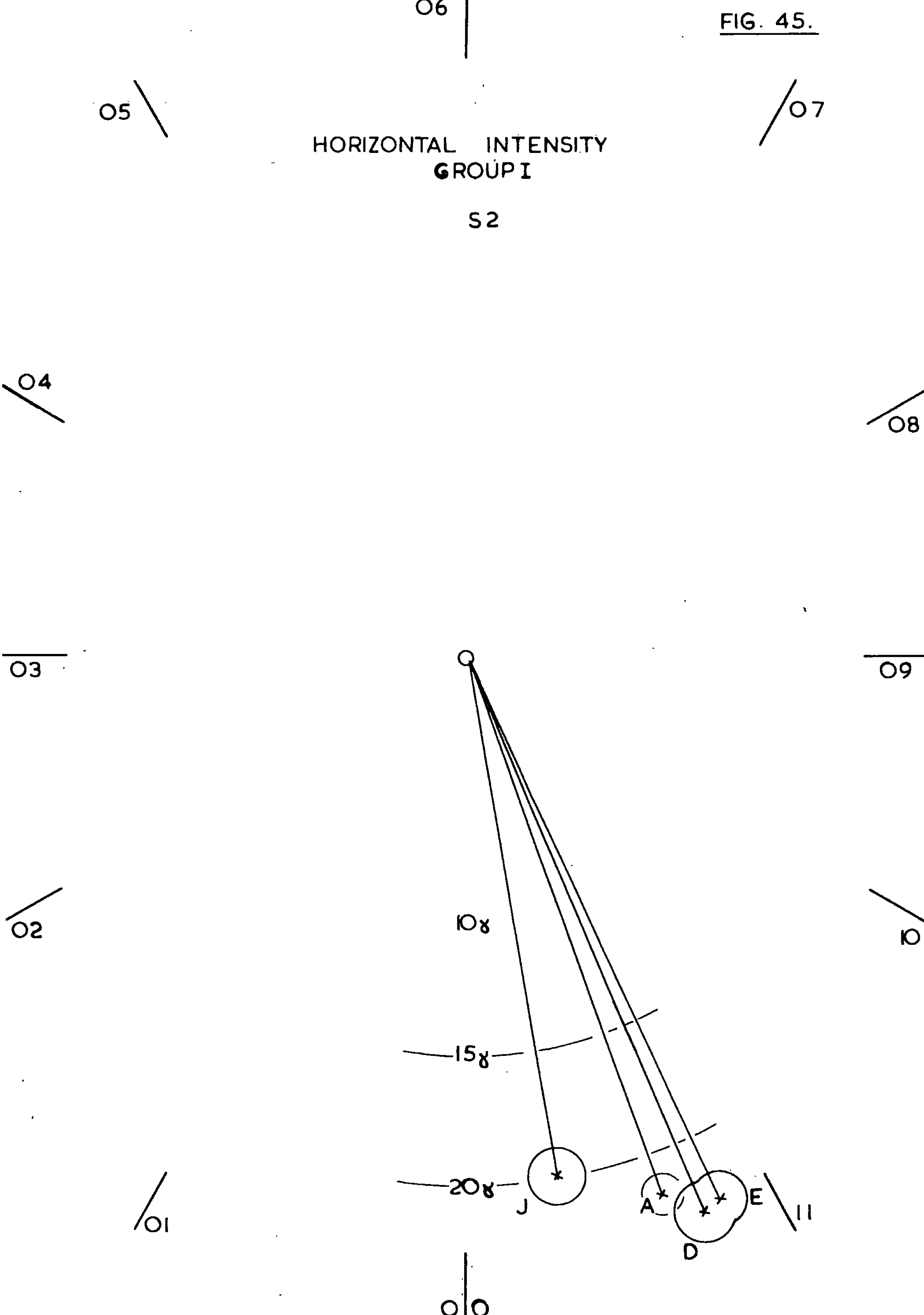

12
10
14
D
E
A
J
40γ
30γ
20γ
HORIZONTAL INTENSITY
GROUP I
S1
08
16
06
18
04
20
02
22
00

FIG. 45.



HORIZONTAL INTENSITY
GROUP I

S2

FIG. 46.

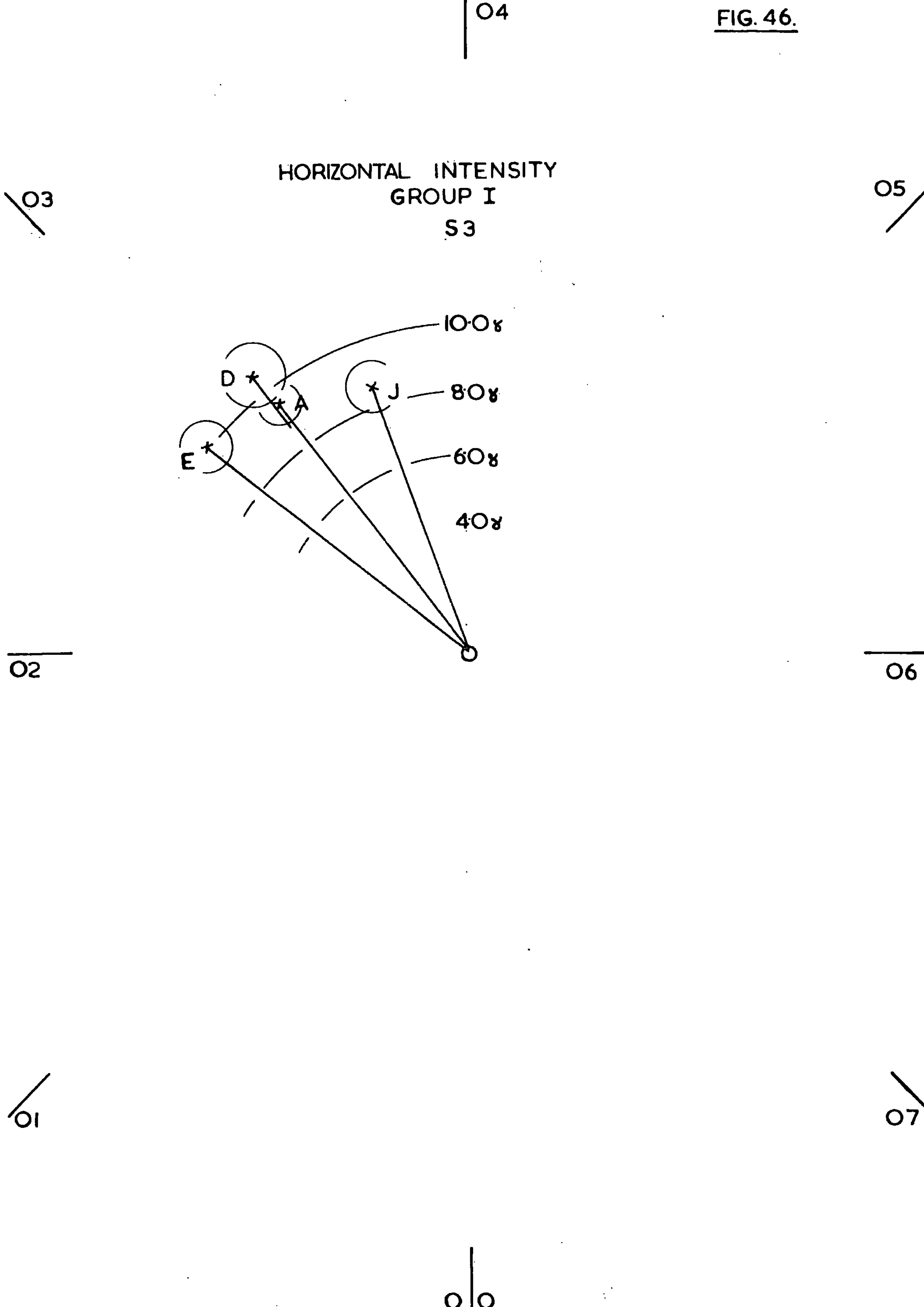

O4
HORIZONTAL INTENSITY
GROUP I
S3
O3
O5
10·0γ
D
A
J
8·0γ
E
6·0γ
4·0γ
O
O2
O6
O1
O7
O
O

FIG. 47.

HORIZONTAL INTENSITY
GROUP I

S4

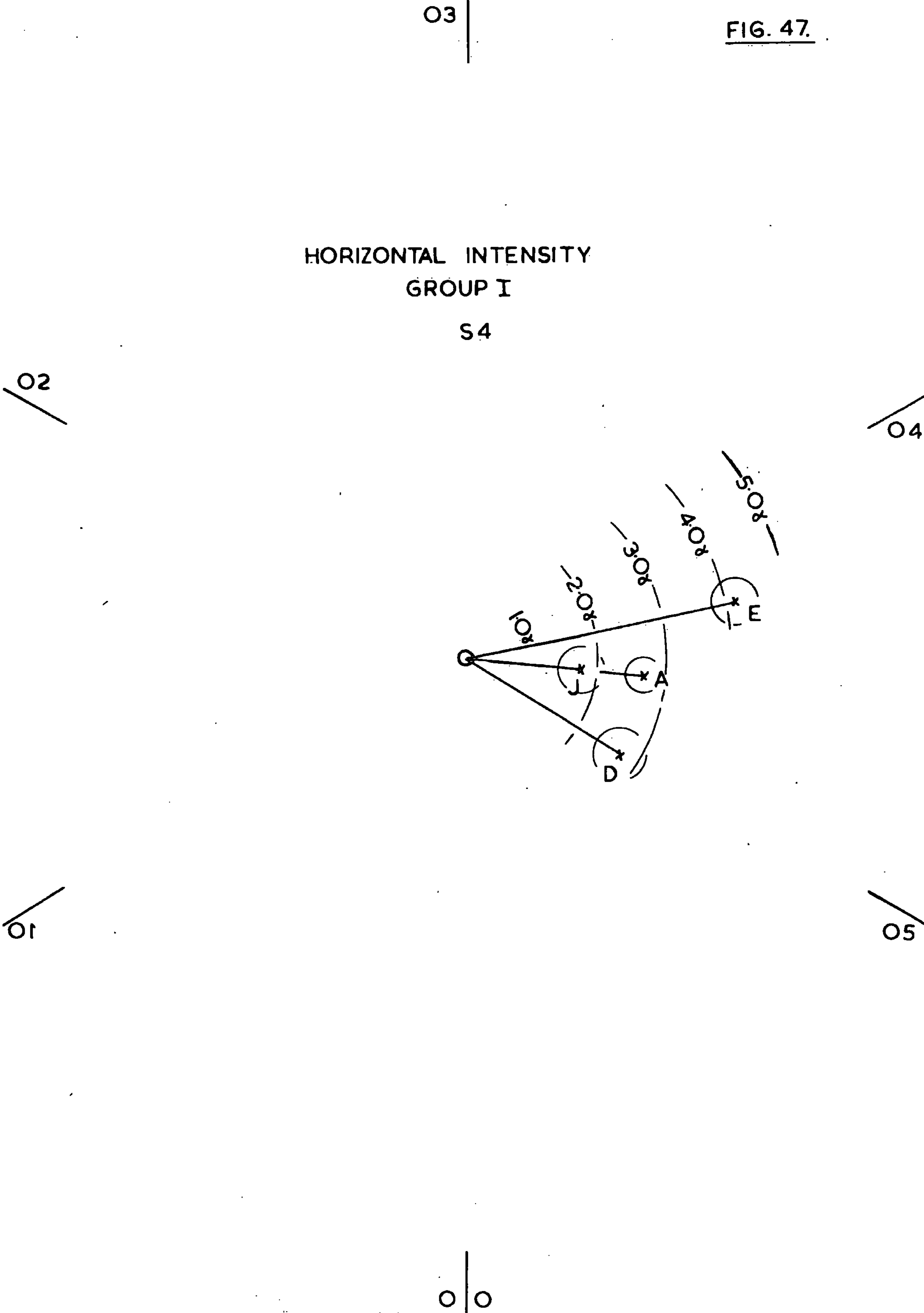


FIG 48

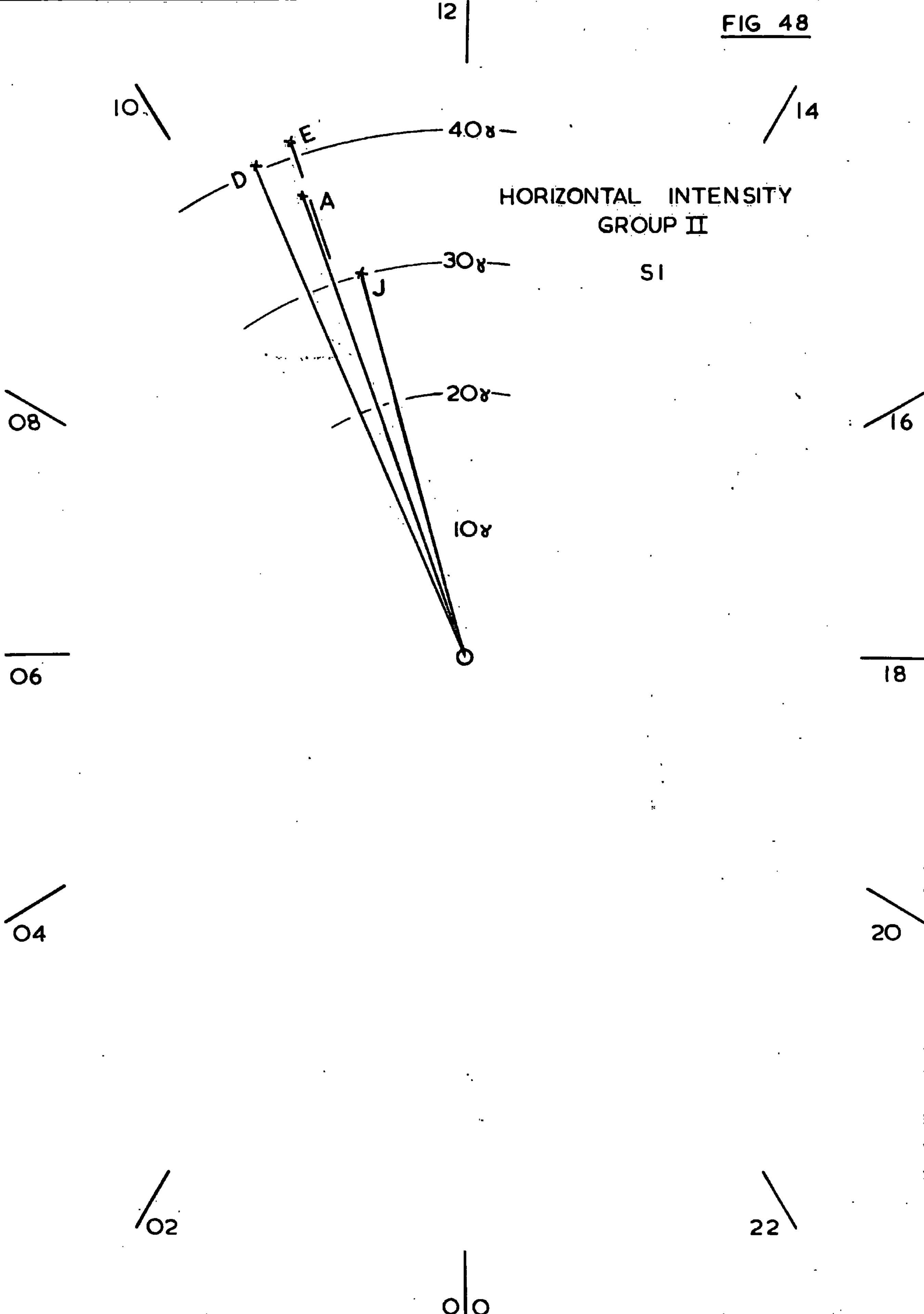
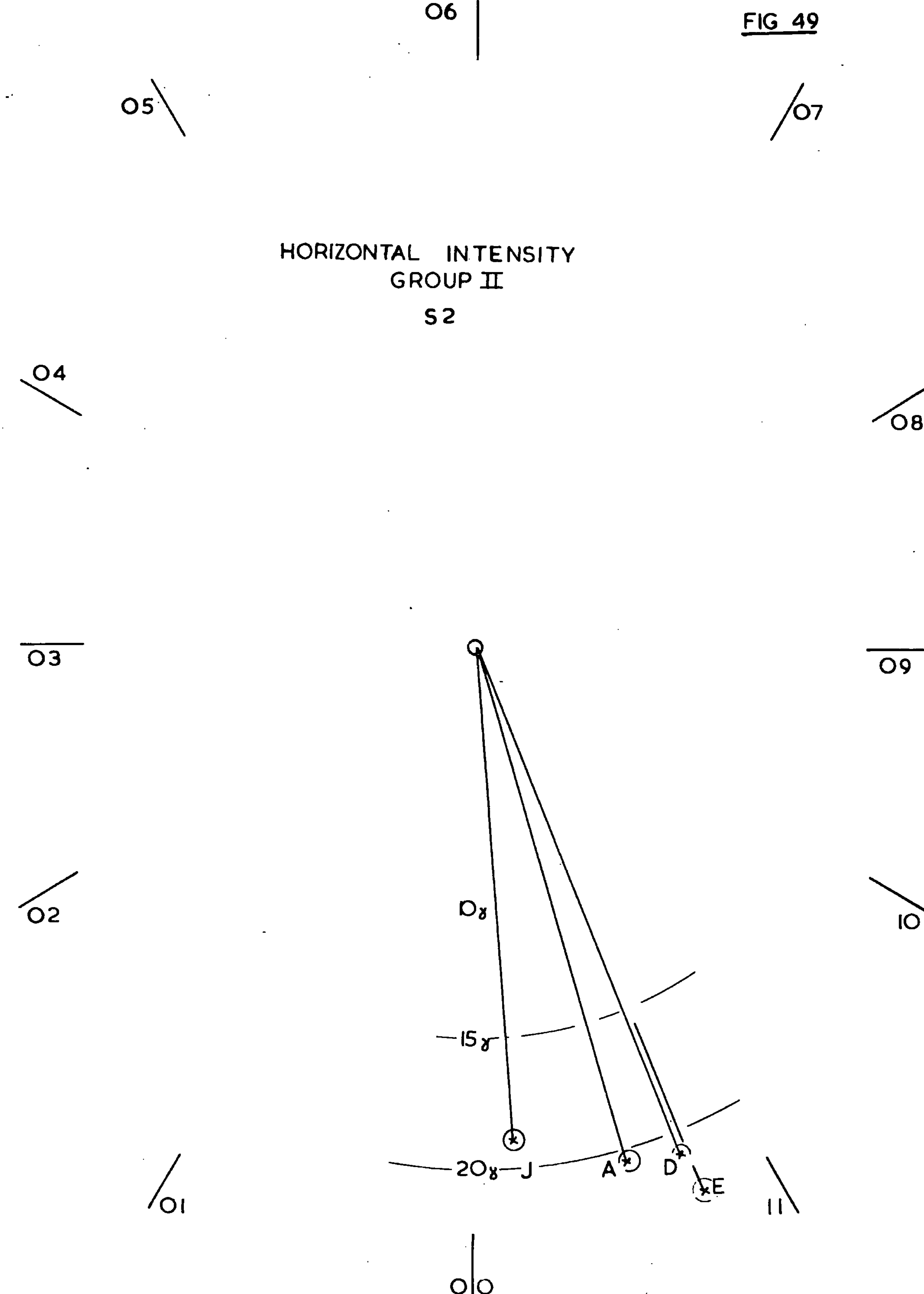
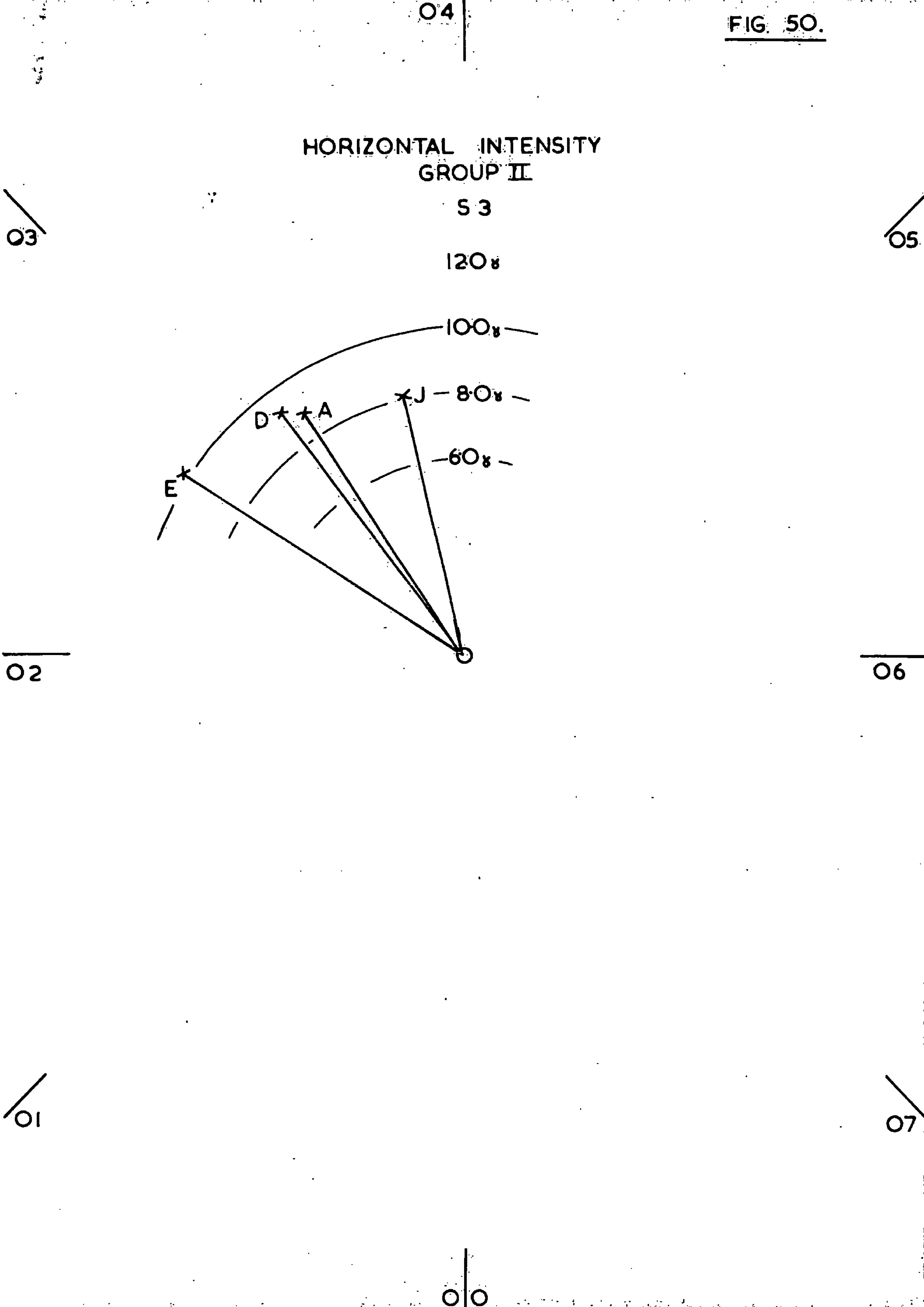

12
10
14
E
40γ
D
A
HORIZONTAL INTENSITY
GROUP II
30γ
J
S1
20γ
08
16
10γ
06
18
04
20
02
22
00

FIG 49



HORIZONTAL INTENSITY
GROUP II
S2

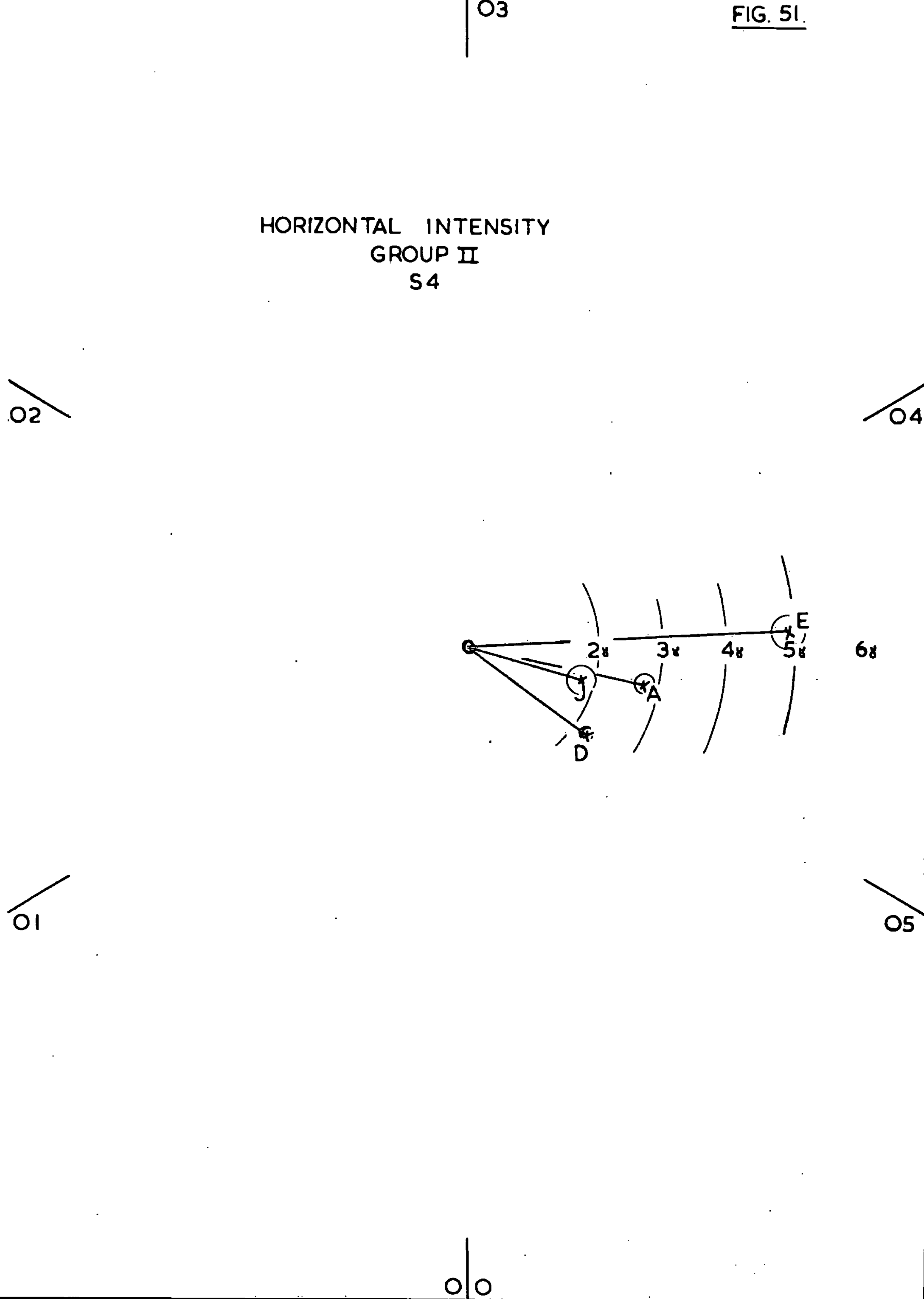
FIG. 50.



HORIZONTAL INTENSITY
GROUP II

S 3

FIG. 51.



HORIZONTAL INTENSITY
GROUP II
S4

FIG. 52.

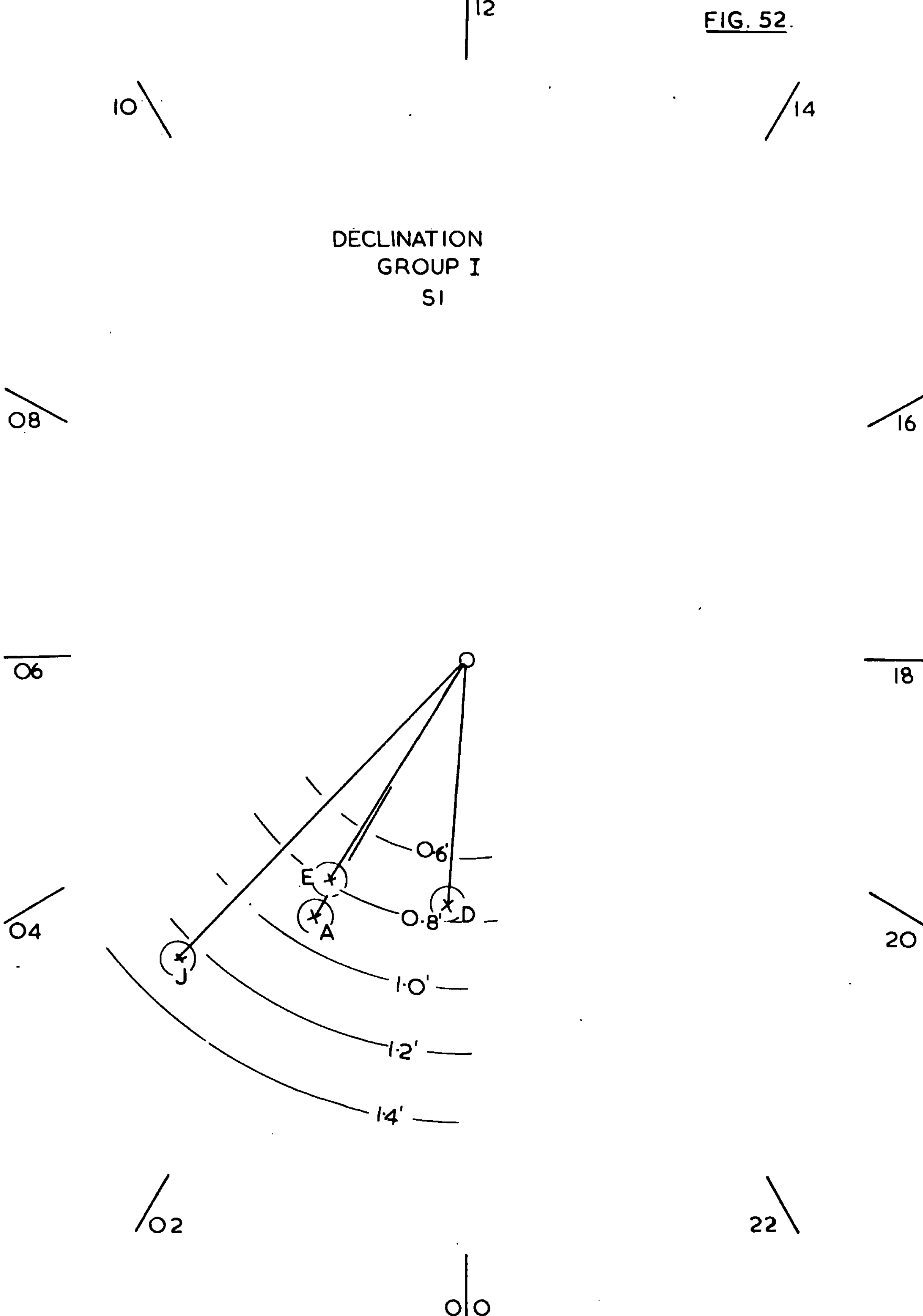

12
10
14
DECLINATION
GROUP I
S1
08
16
06
18
E
0·6'
D
0·8'
A
J
04
20
1·0'
1·2'
1·4'
02
22
00

FIG. 53.

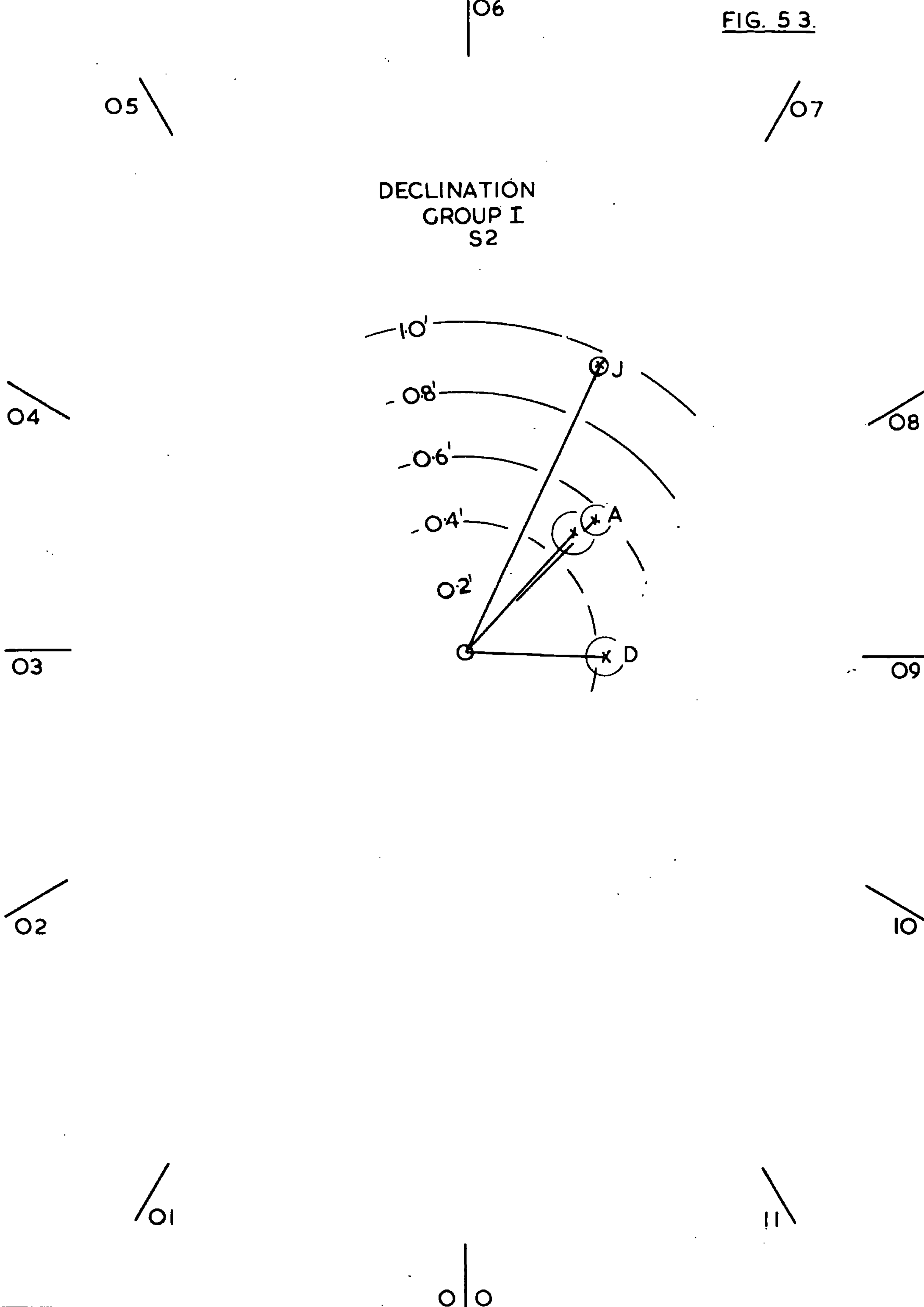

06
05
07
DECLINATION
GROUP I
S2
1·0'
J
0·8'
04
08
0·6'
0·4'
A
0·2'
03
D
09
02
10
01
11
0
0

FIG 54

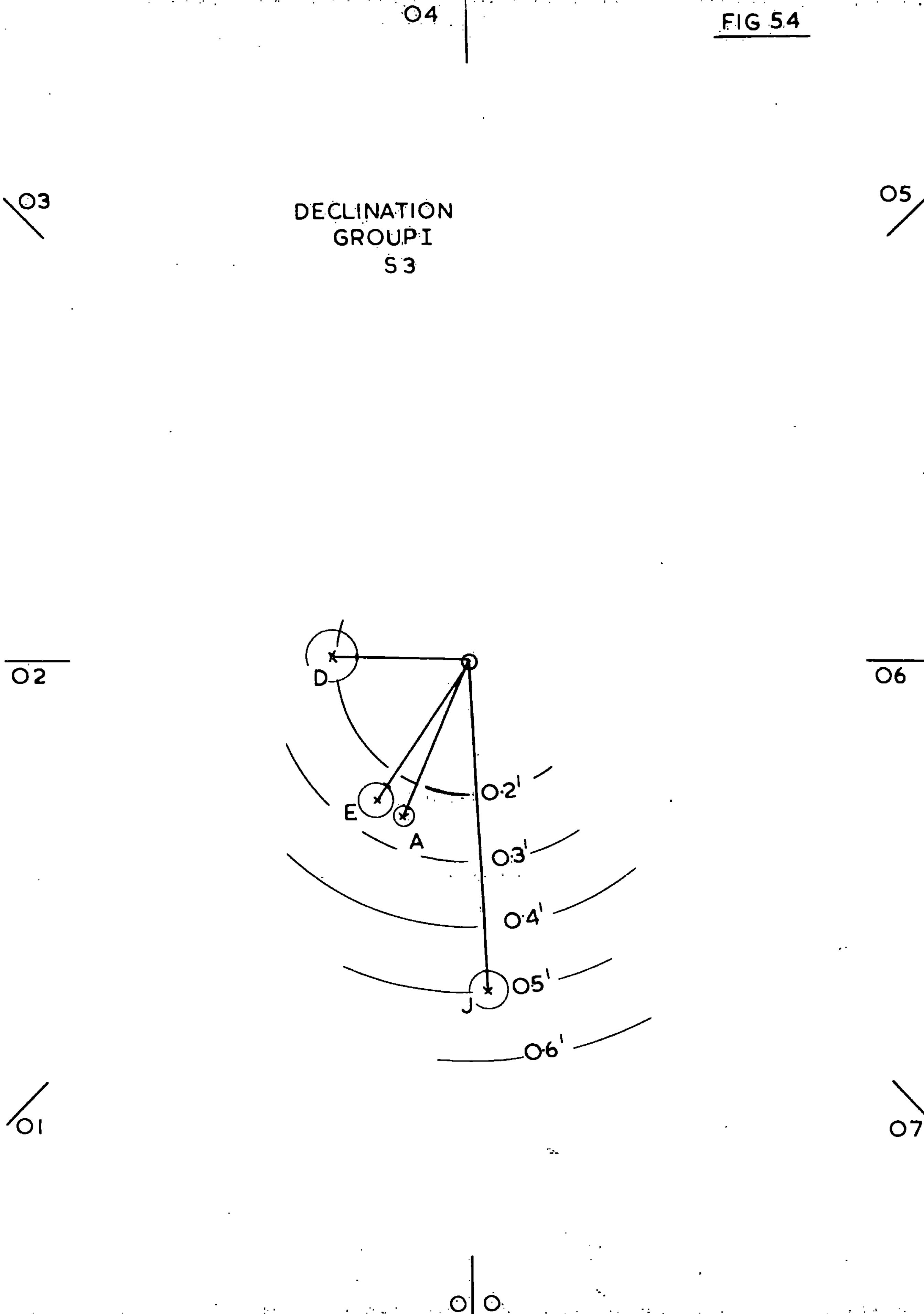


FIG. 55.

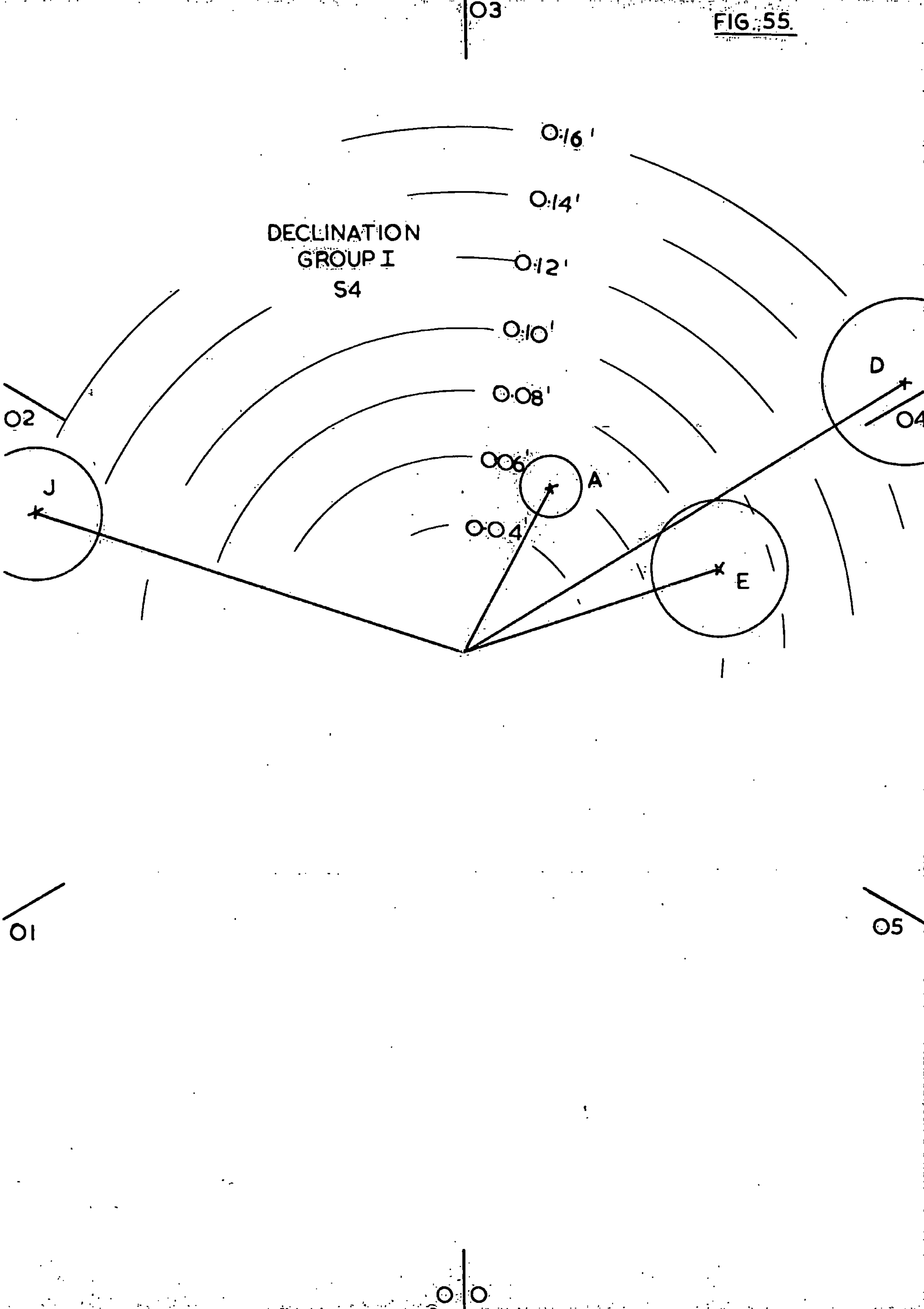

O3
O·16'
O·14'
DECLINATION
GROUP I
S4
O·12'
O·10'
O·08'
O2
D
O4
O·06'
A
J
O·04'
E
O1
O5
O O

FIG. 56.

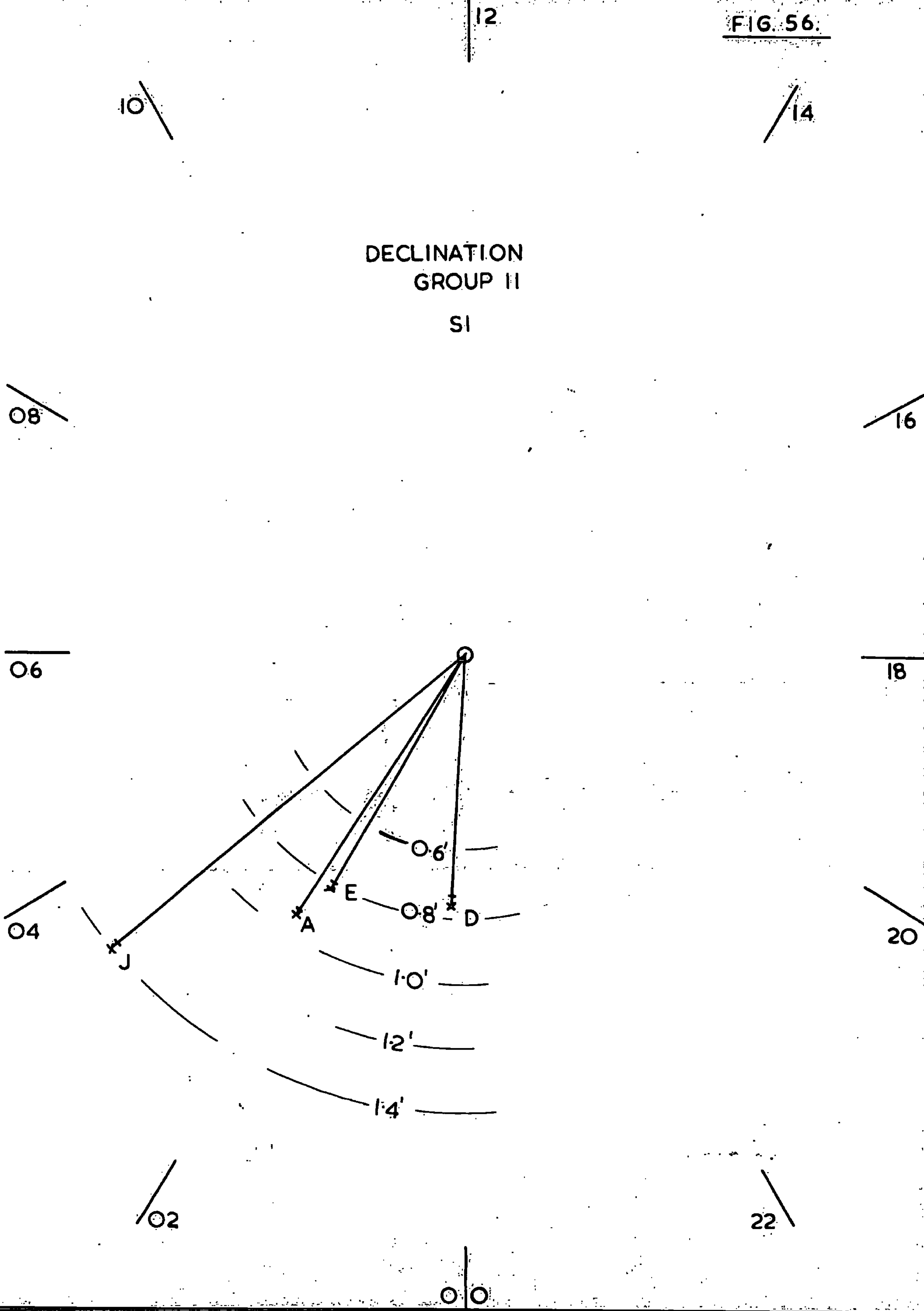

DECLINATION
GROUP II
S1
12
10
14
08
16
06
18
04
20
02
22
00
0·6′
0·8′
1·0′
1·2′
1·4′
J
A
E
D

FIG. 57.

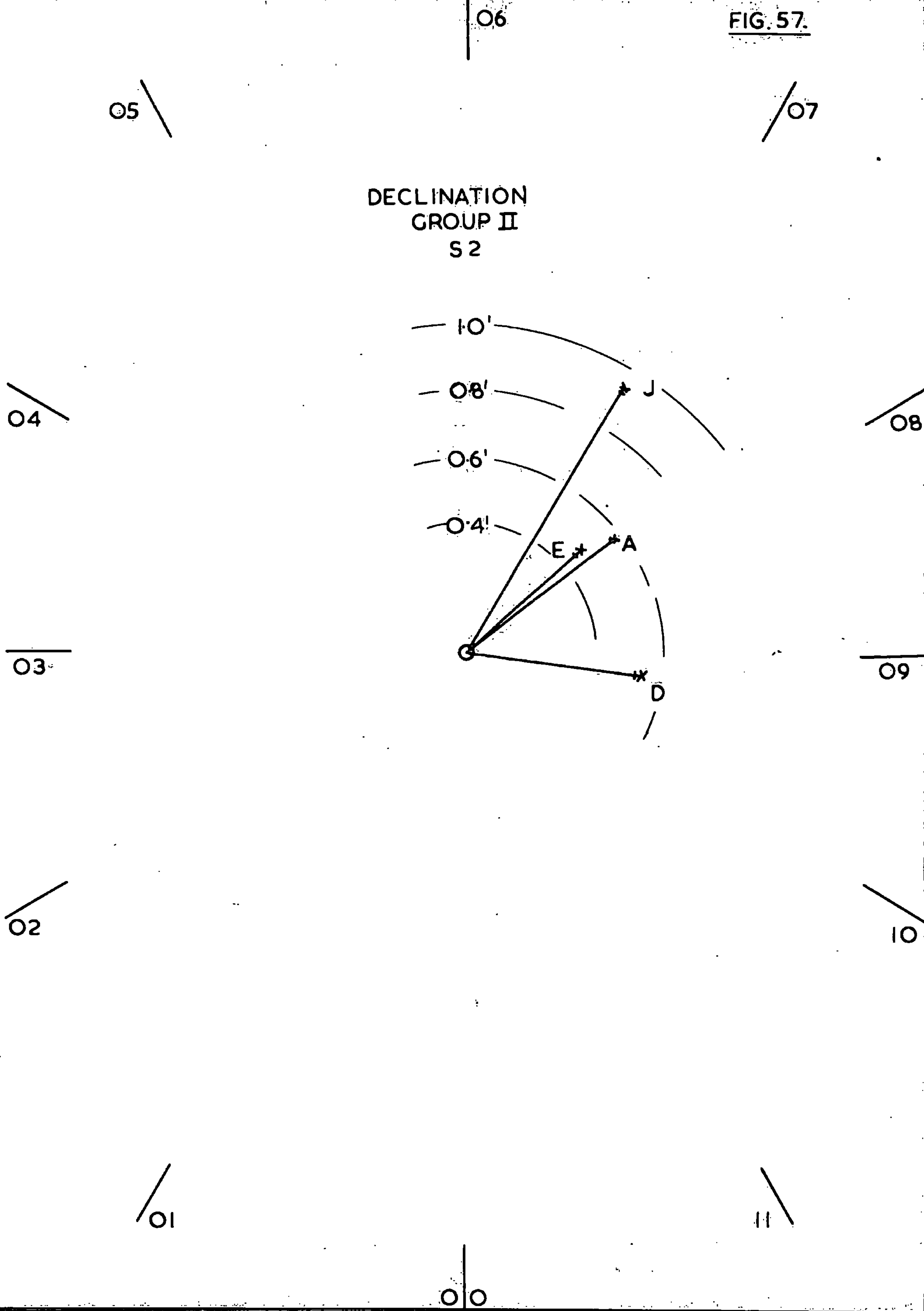

06
05
07
DECLINATION
GROUP II
S 2
1·0'
0·8'
0·6'
0·4'
J
E
A
D
04
08
03
09
02
10
01
11
00

FIG. 58.

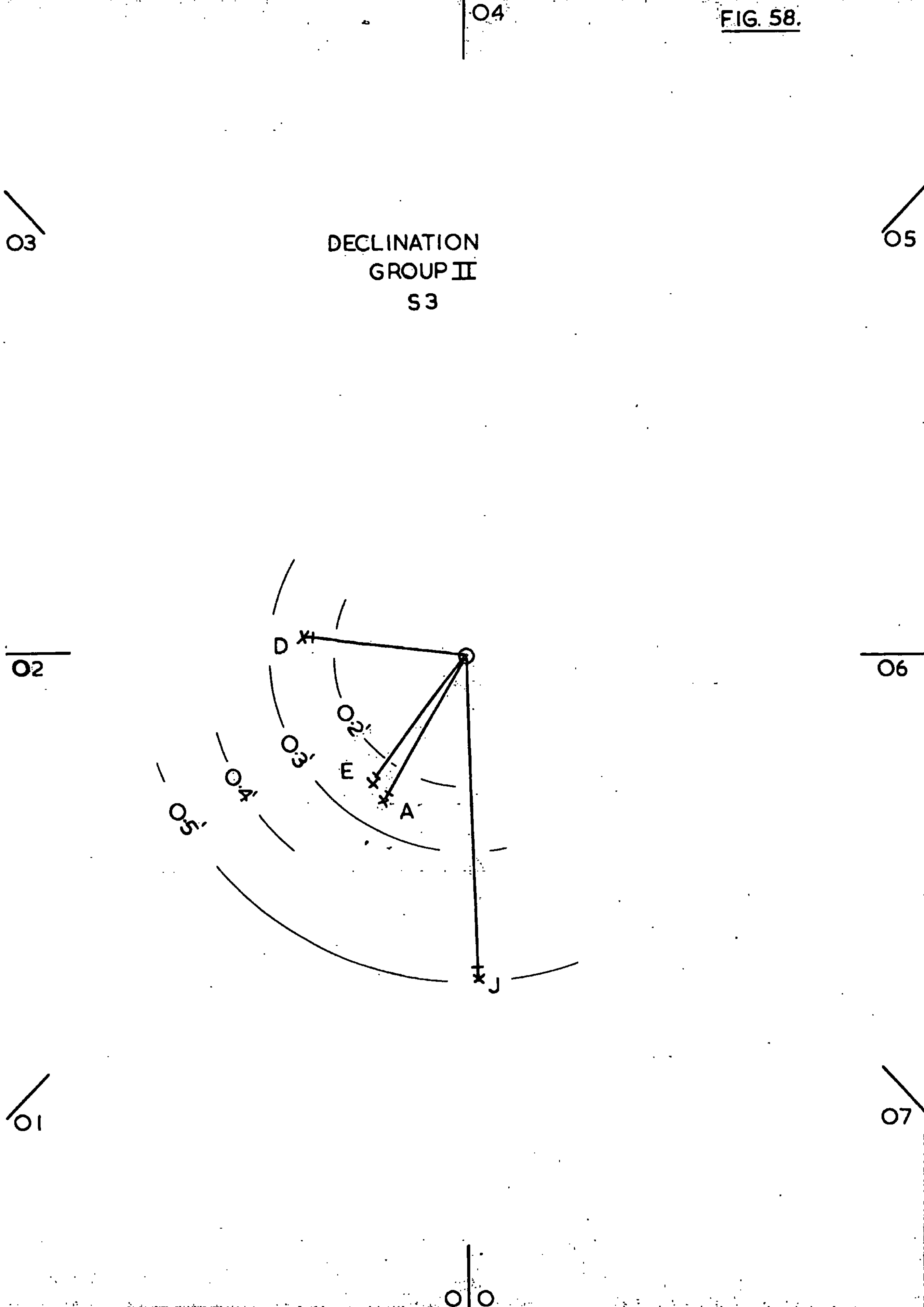


FIG. 59.

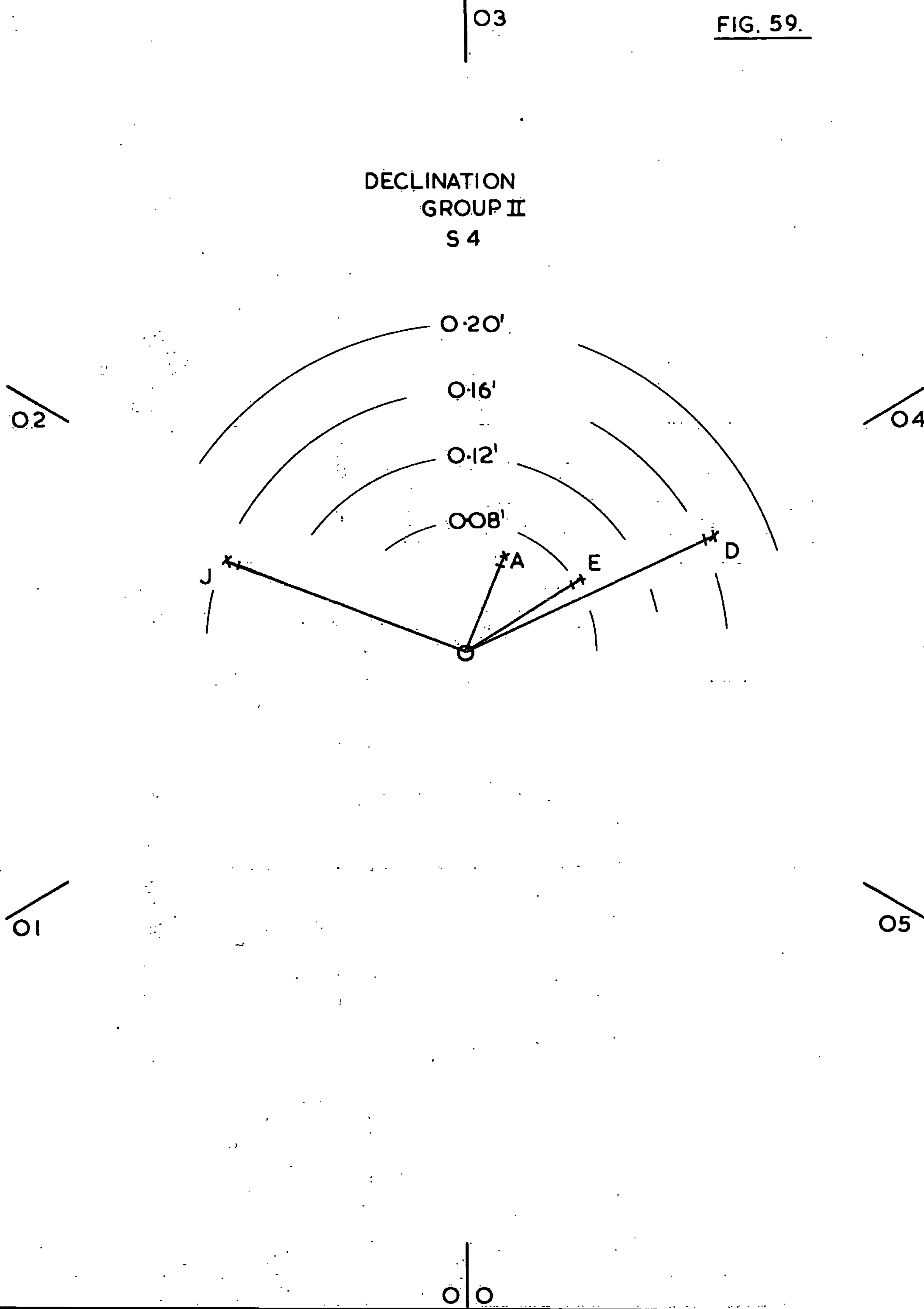
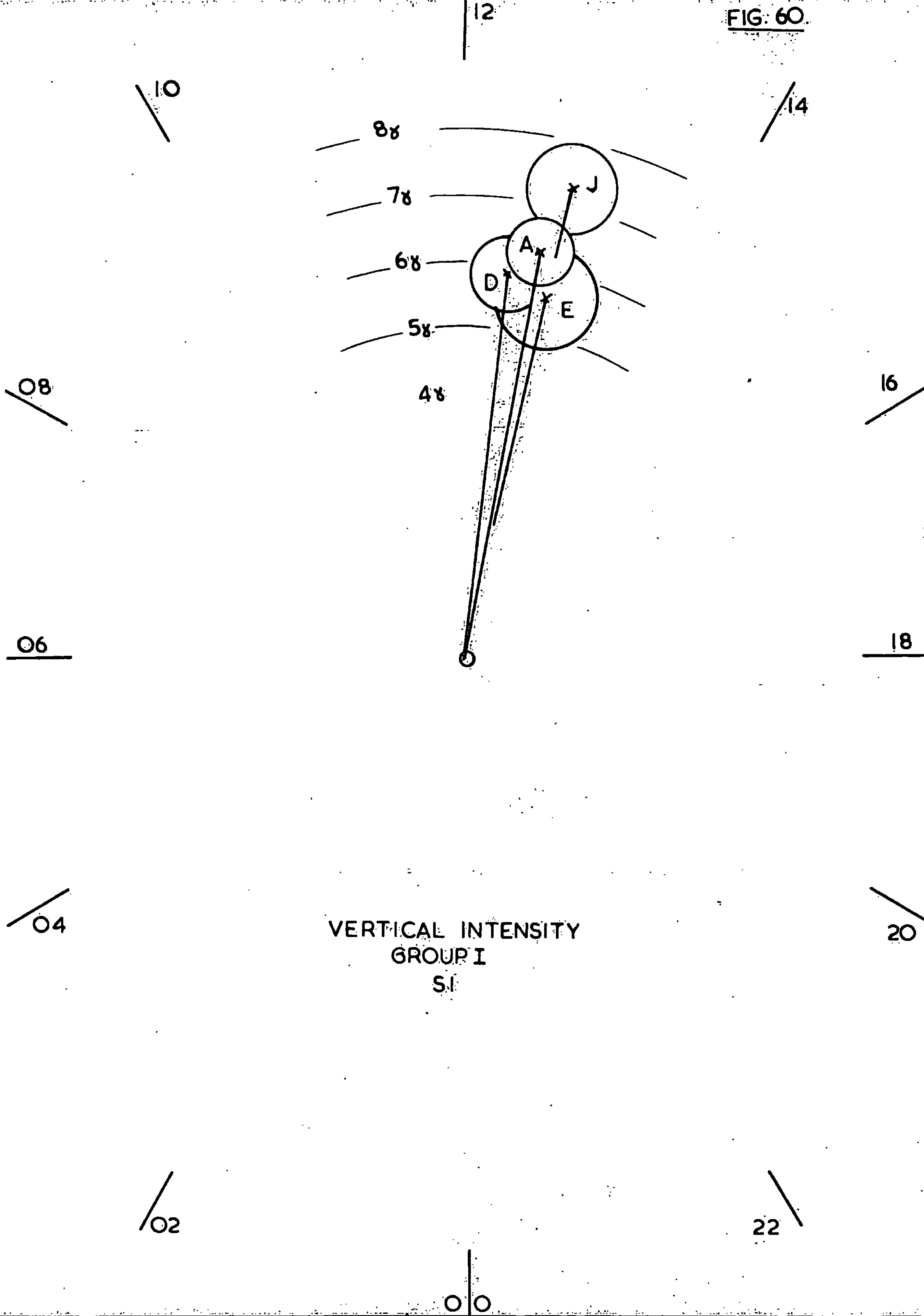


FIG. 60.



VERTICAL INTENSITY
GROUP I
S1

FIG. 61.

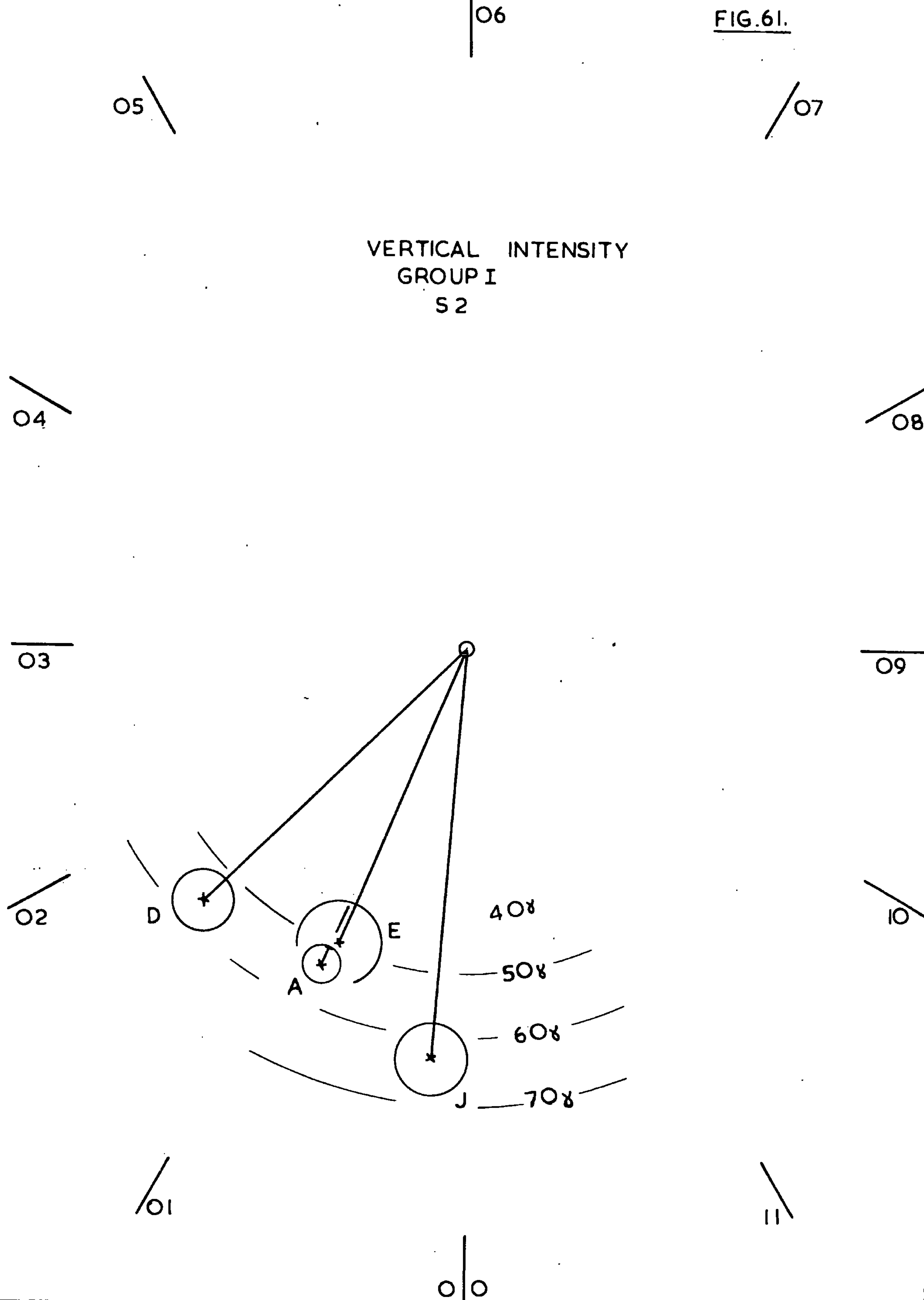
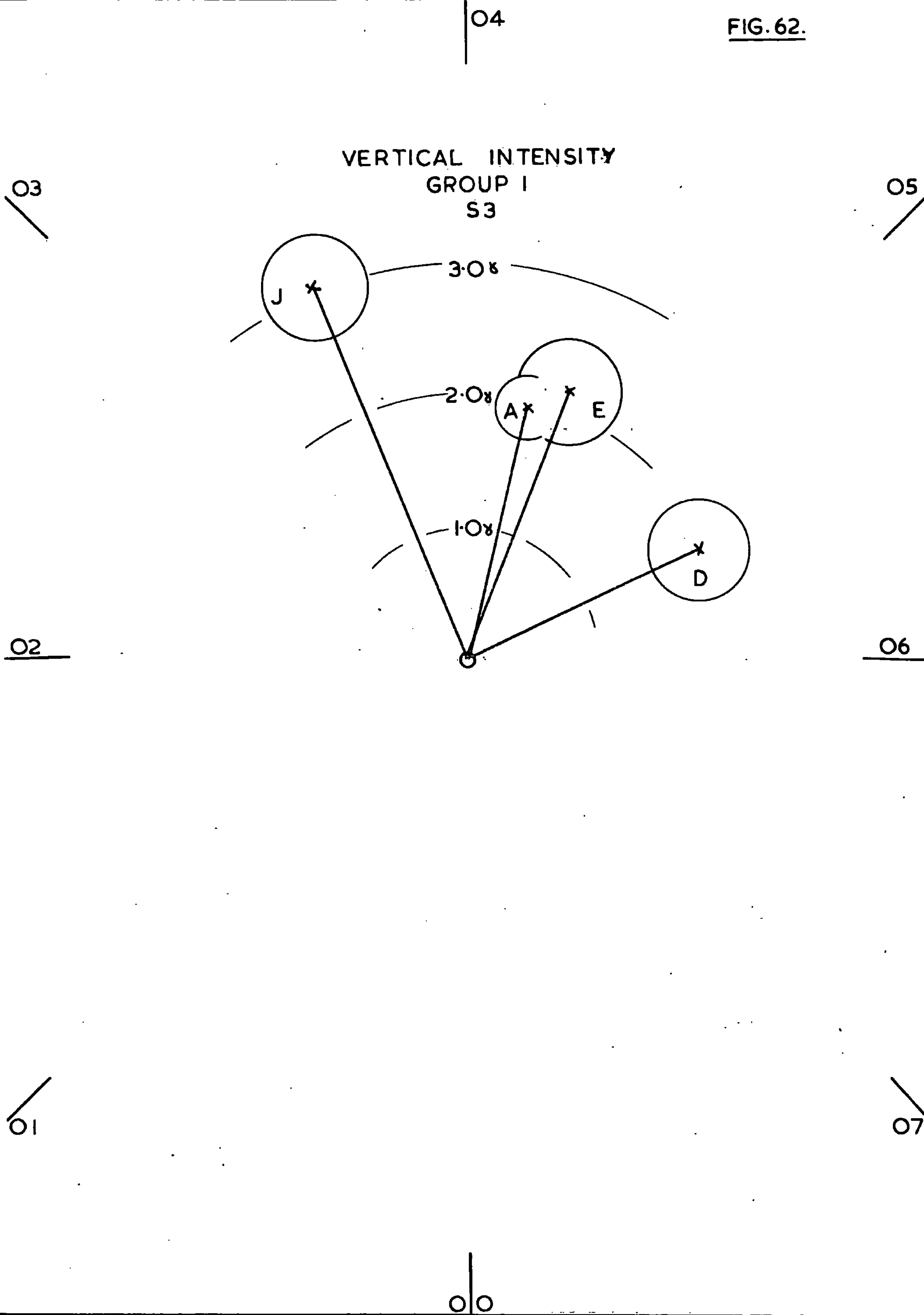

VERTICAL INTENSITY
GROUP I
S 2

FIG. 62.



VERTICAL INTENSITY
GROUP I
S3

FIG. 63.

VERTICAL INTENSITY
GROUP I

S 4

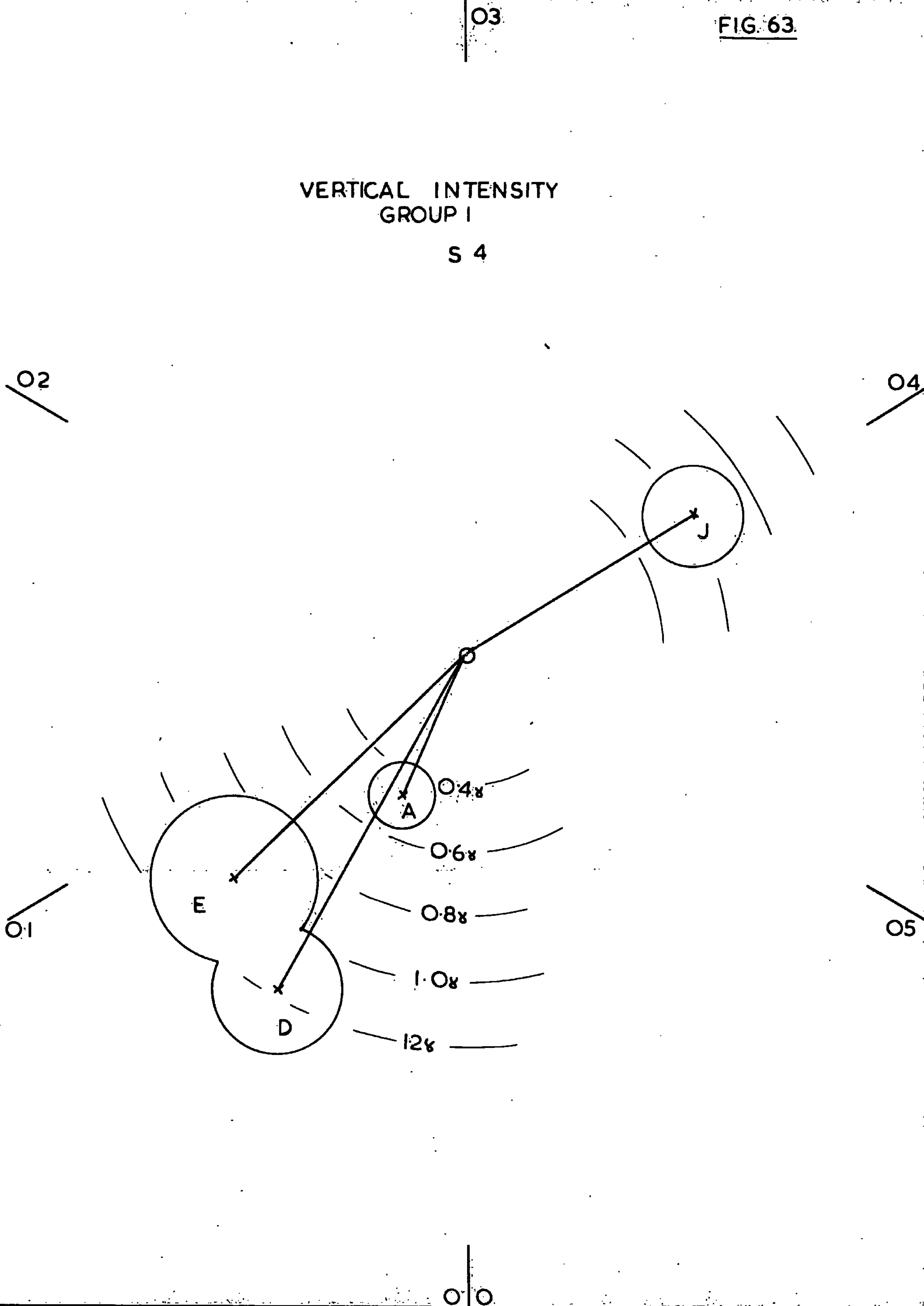
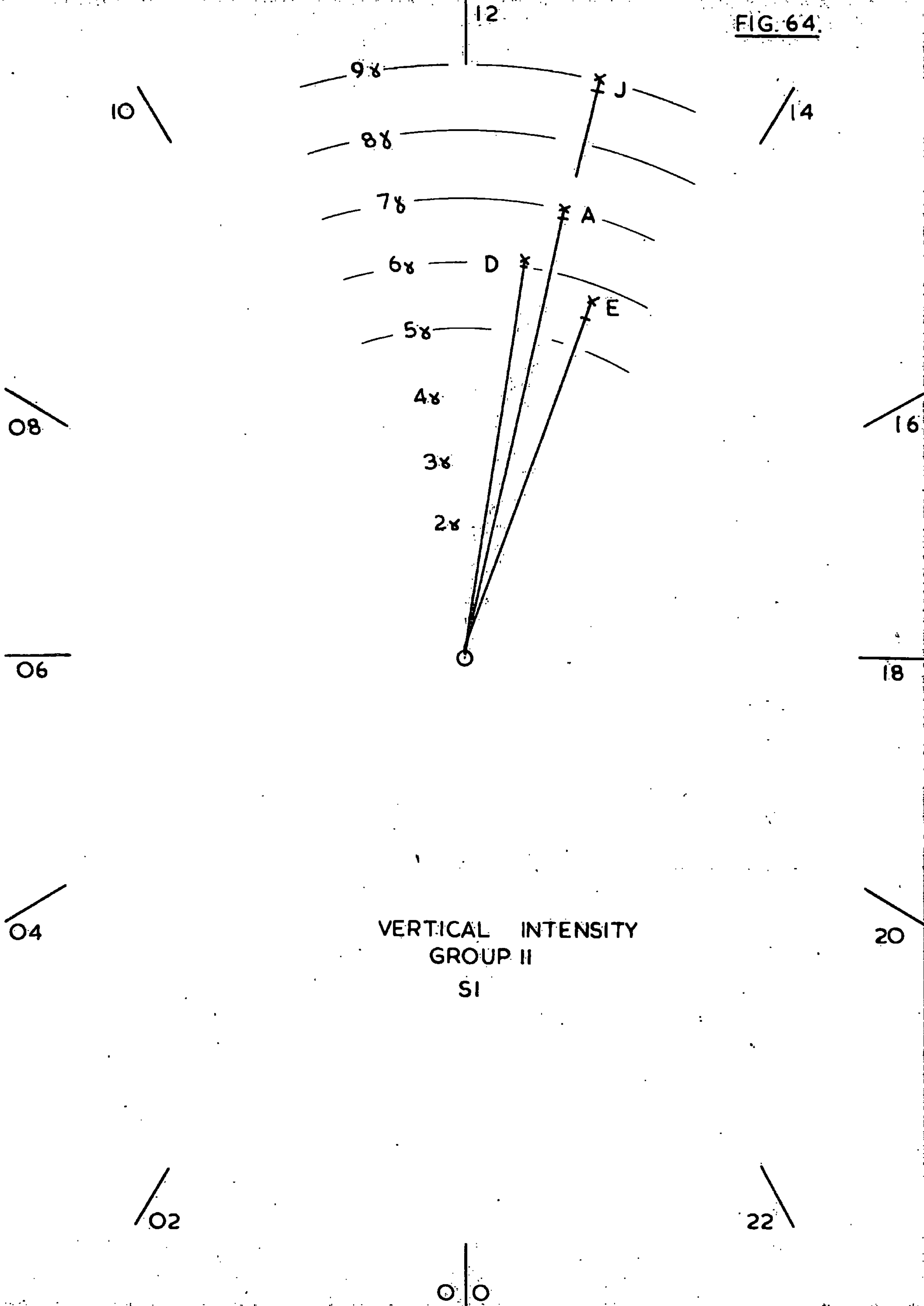
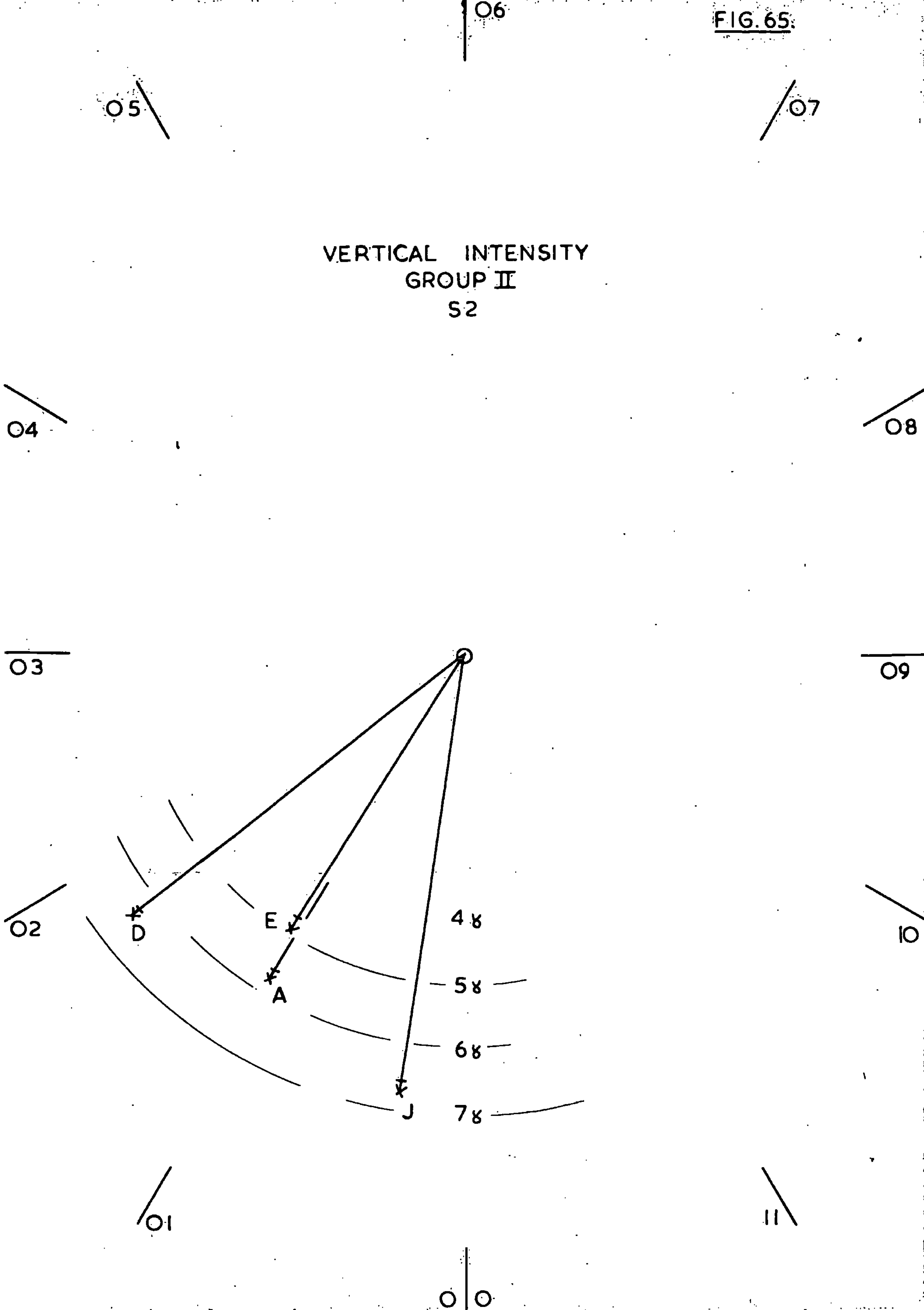


FIG. 64.



VERTICAL INTENSITY
GROUP II
S1

FIG. 65.



VERTICAL INTENSITY
GROUP II
S2

FIG. 66.

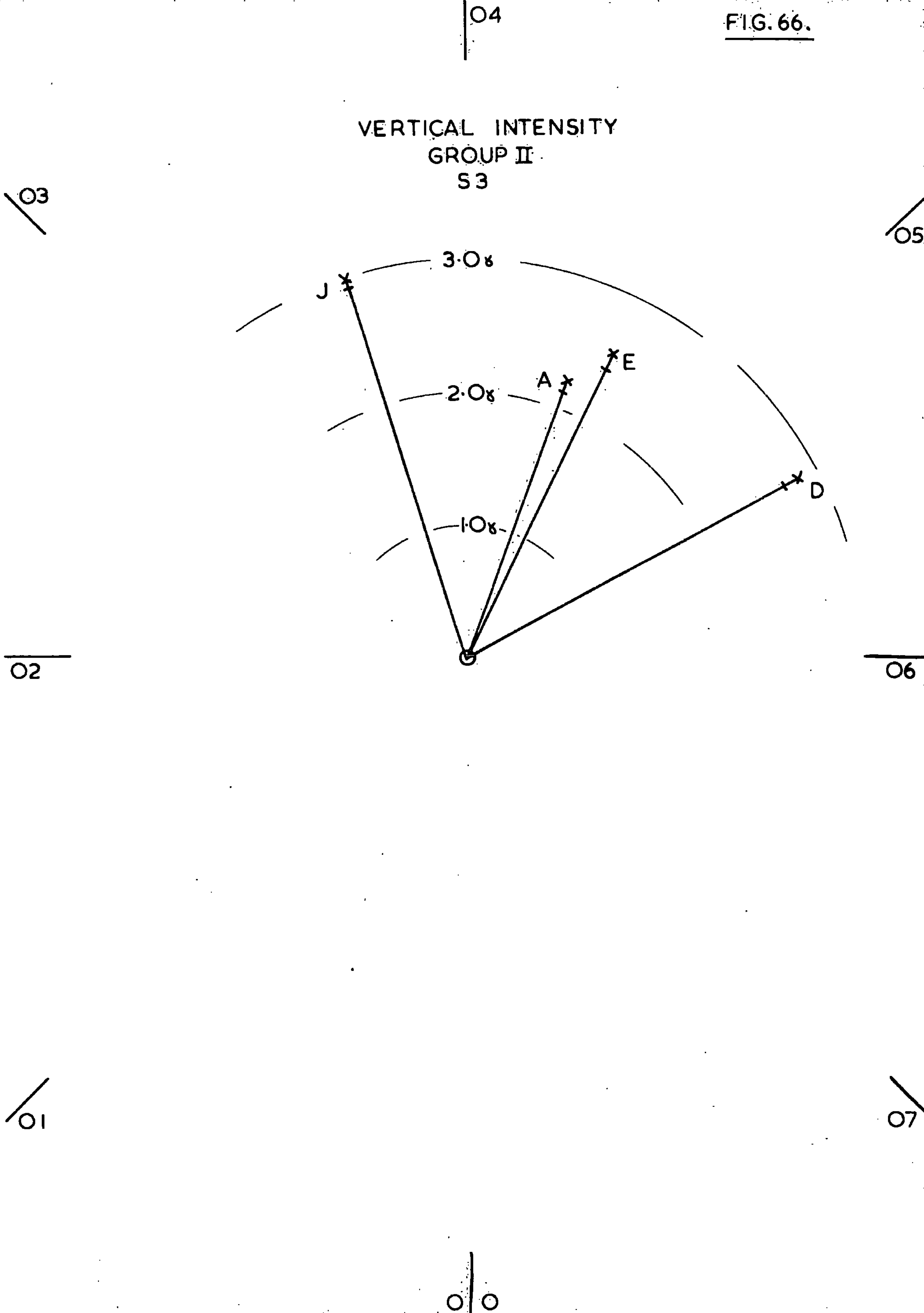

VERTICAL INTENSITY
GROUP II
S3

FIG. 67.

VERTICAL INTENSITY
GROUP II
S 4

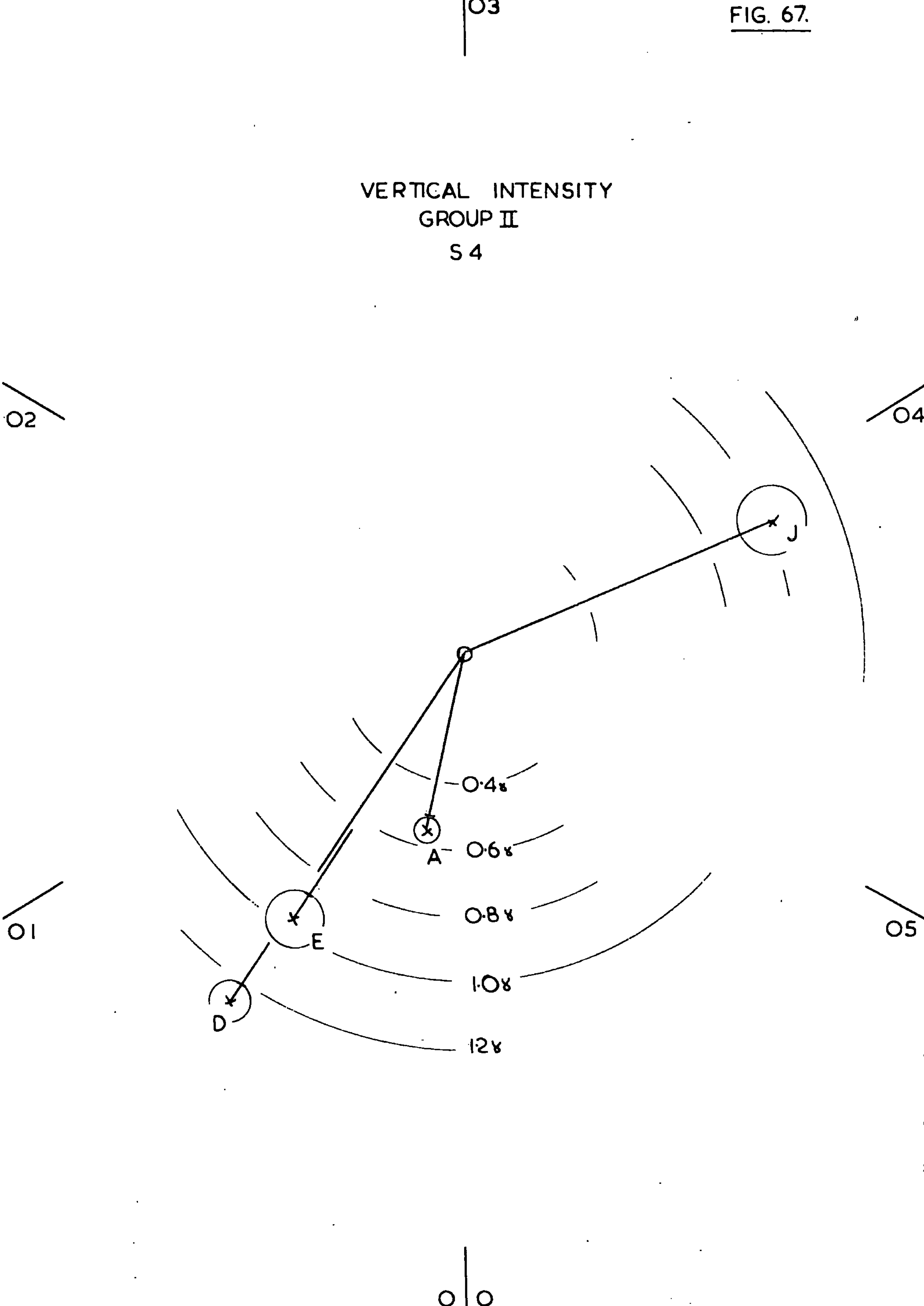


FIG. 68.

HORIZONTAL INTENSITY
GROUP I

L1

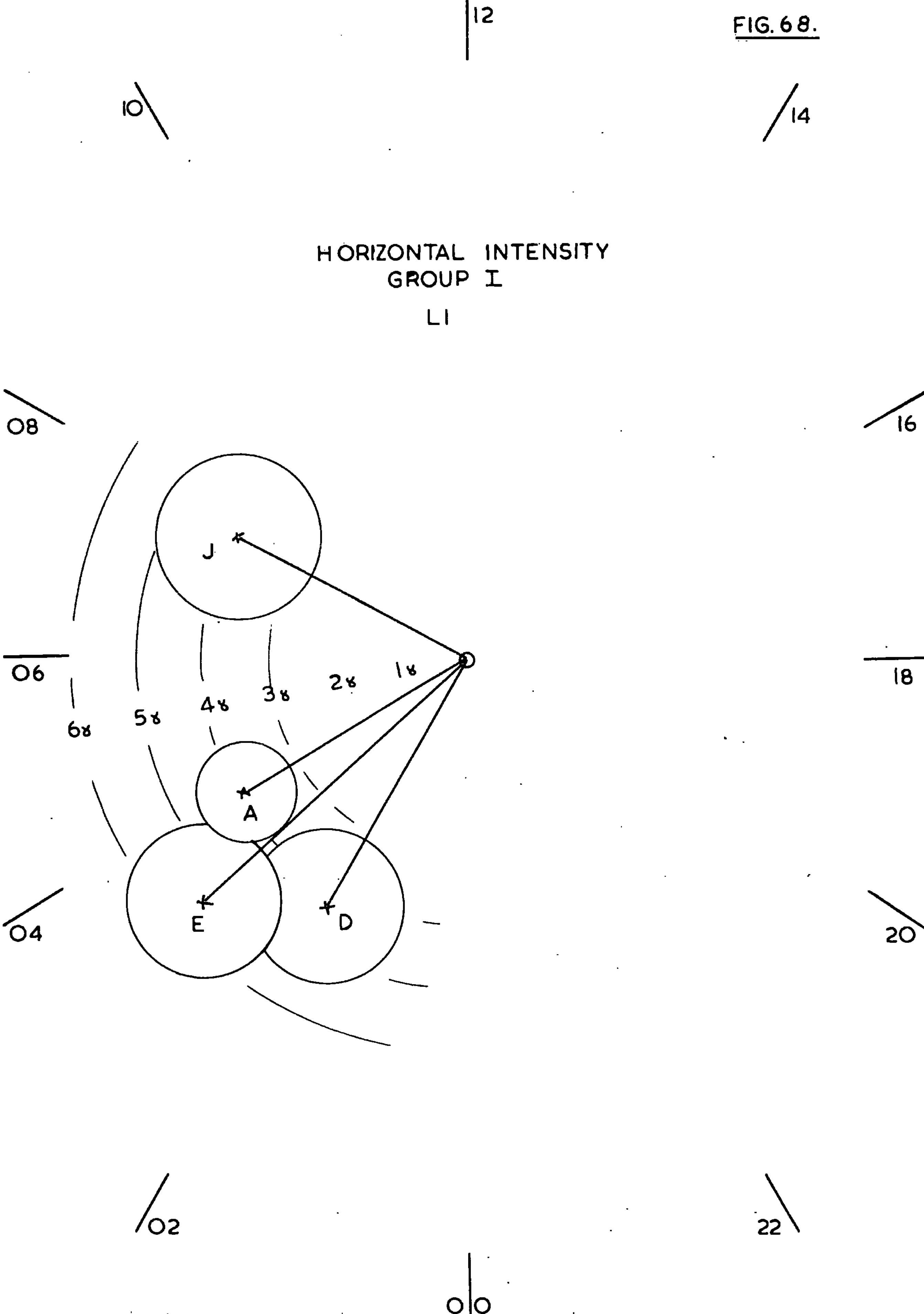


FIG. 69.

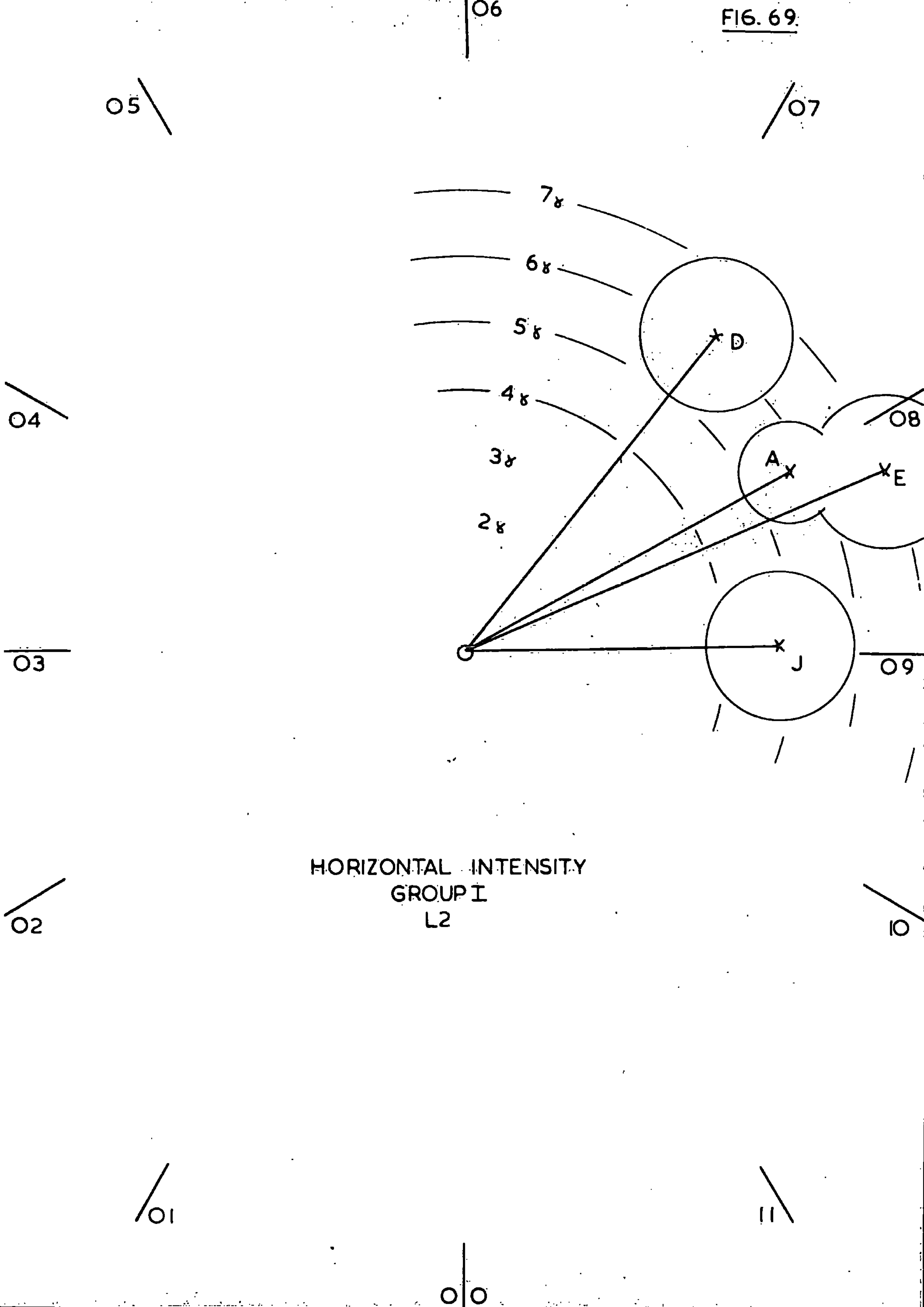

HORIZONTAL INTENSITY
GROUP I
L2

FIG. 70.

HORIZONTAL INTENSITY
GROUP I
L3

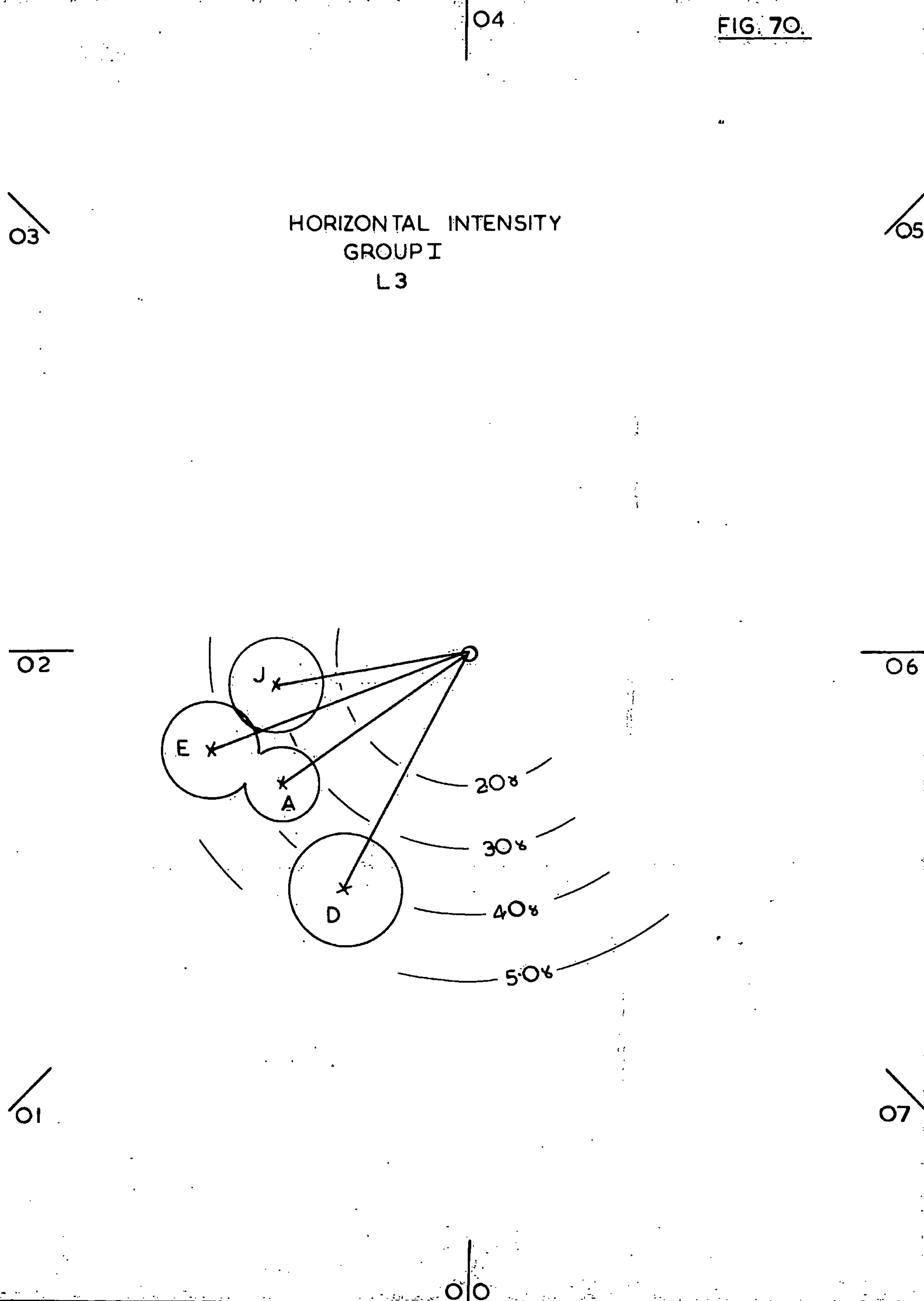


FIG. 71.

HORIZONTAL INTENSITY
GROUP I
L4

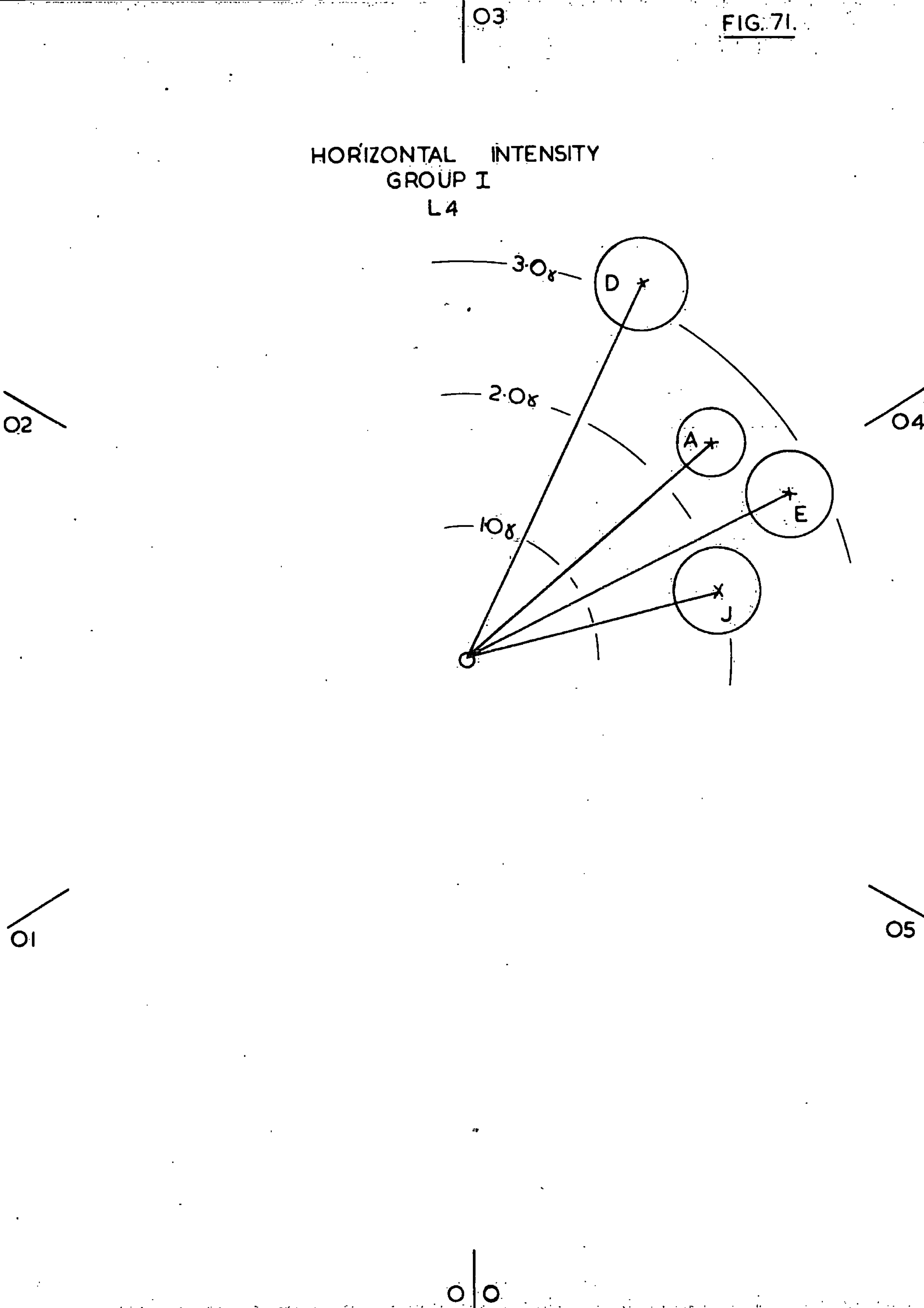


FIG. 72.

HORIZONTAL INTENSITY
GROUP II
L1

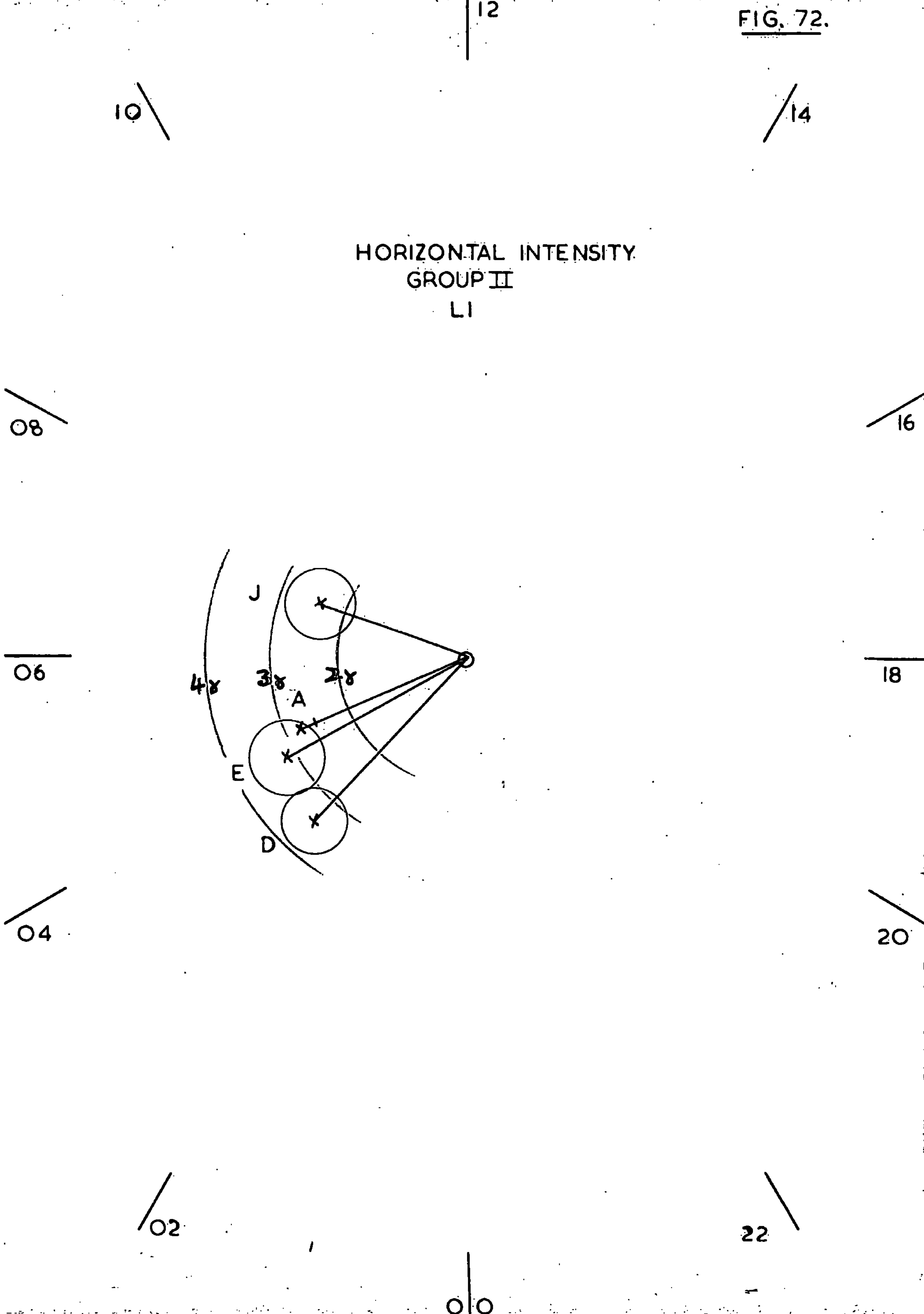
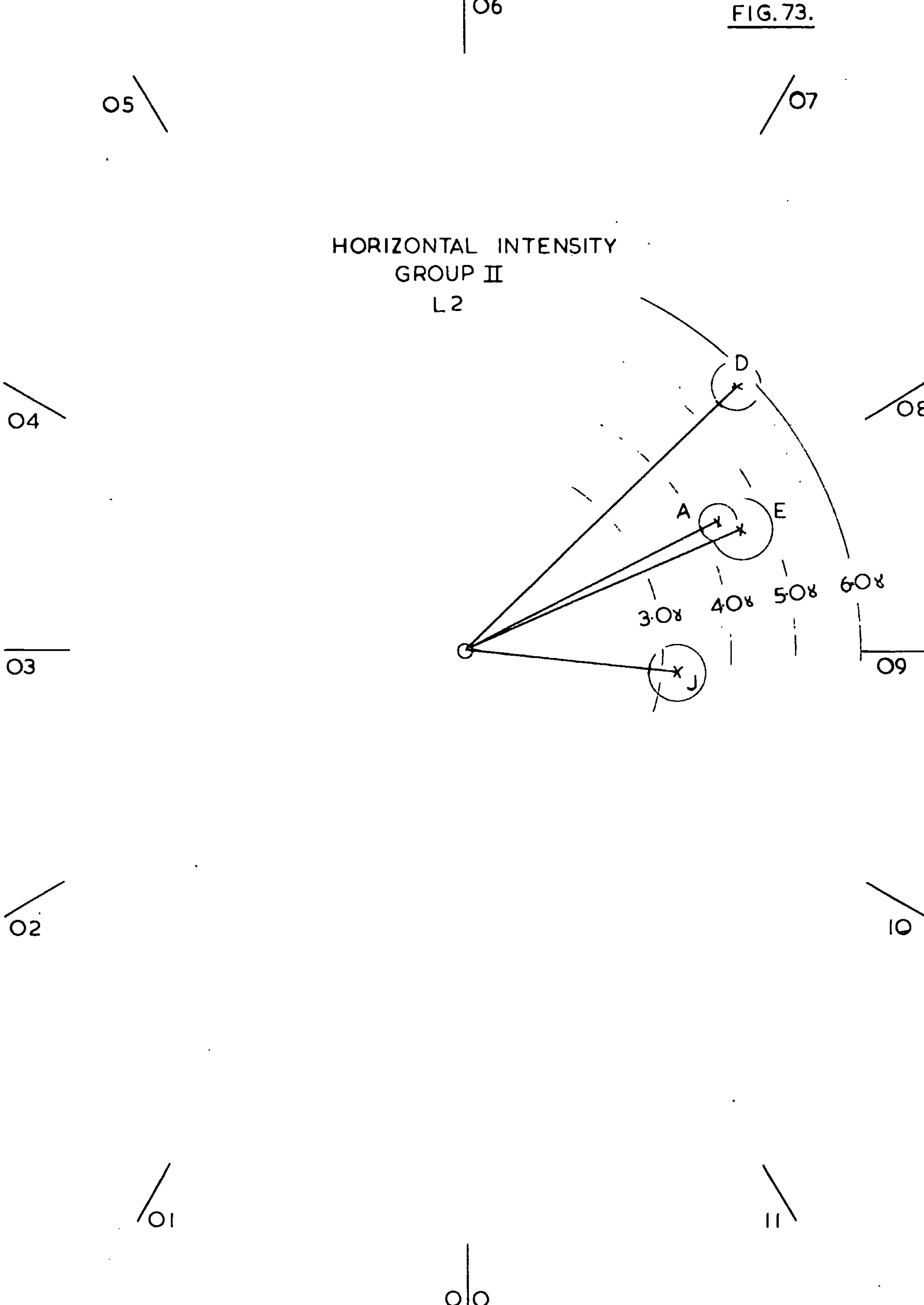


FIG. 73.



HORIZONTAL INTENSITY
GROUP II
L2

FIG. 74.

HORIZONTAL INTENSITY
GROUP II
L3

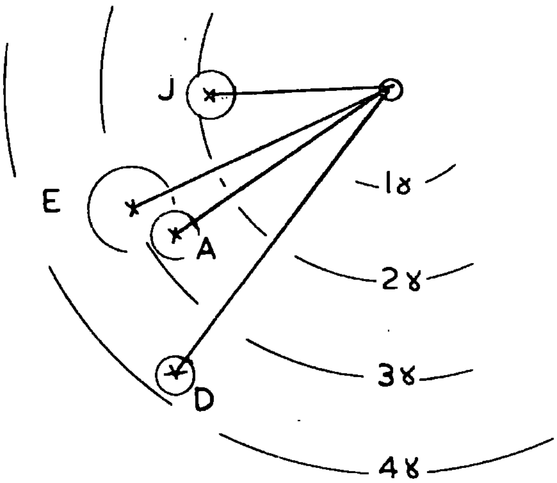


FIG. 75.

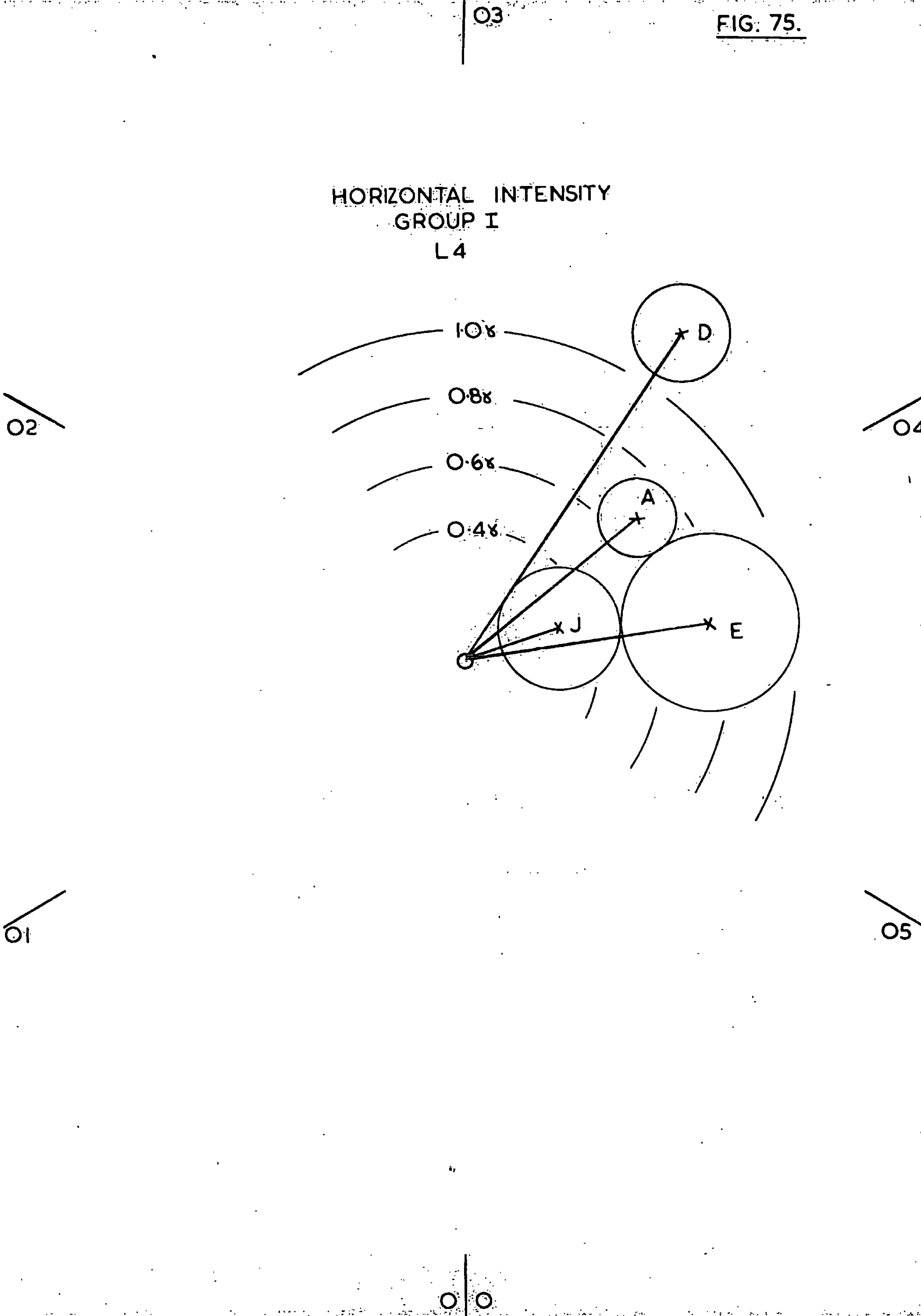

HORIZONTAL INTENSITY
GROUP I
L4

FIG 76

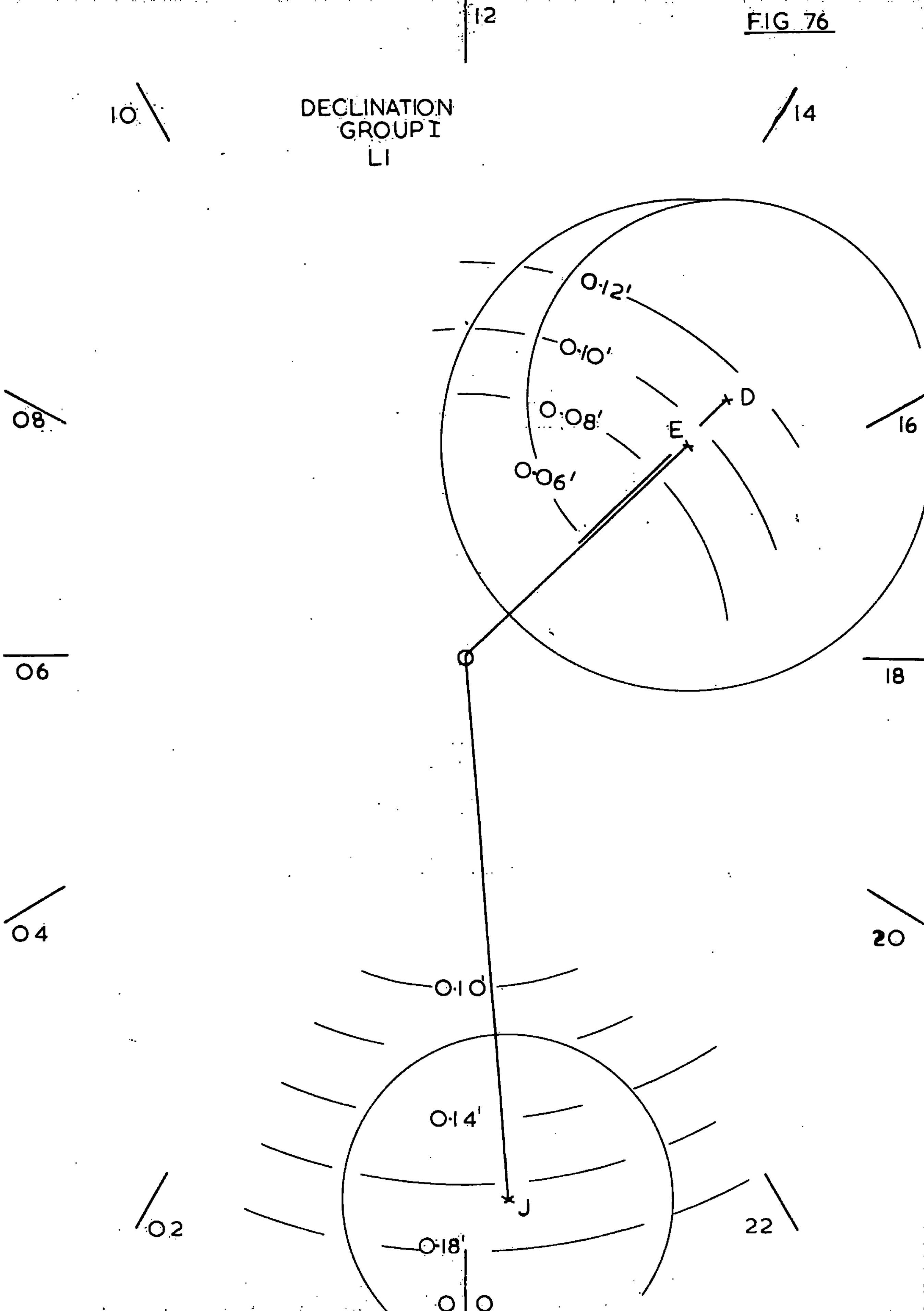

12
10
DECLINATION
GROUP I
L1
14
0·12'
0·10'
D
08
0·08'
E
16
0·06'
06
O
18
04
20
0·10'
0·14'
J
02
0·18'
22
00

FIG 77

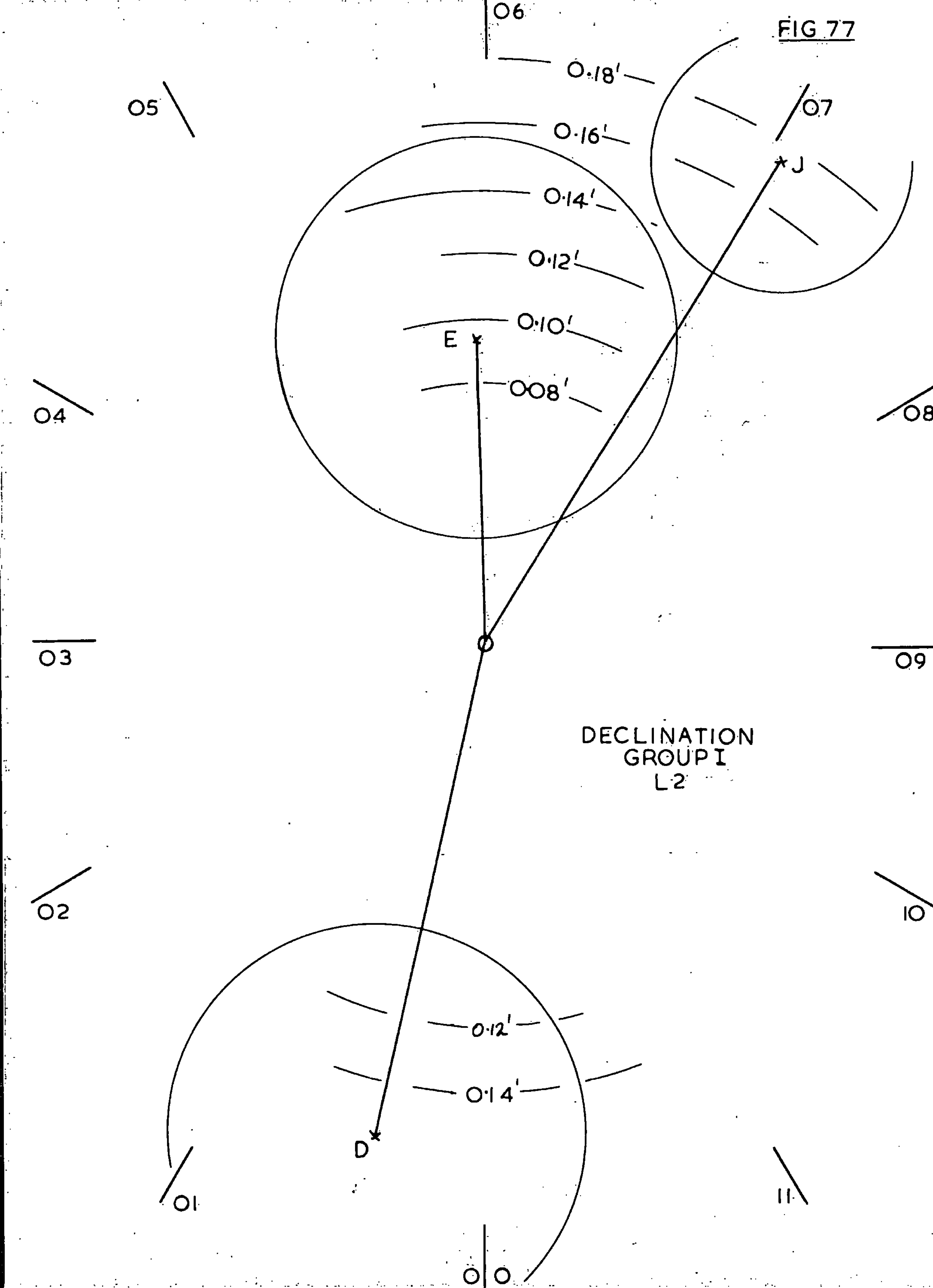

O6
O·18'
O5
O·16'
O7
J
O·14'
O·12'
O·10'
E
O08'
O4
O8
O
O3
O9
DECLINATION
GROUP I
L 2
O2
10
O·12'
O·14'
D
O1
11
O O

FIG. 78.

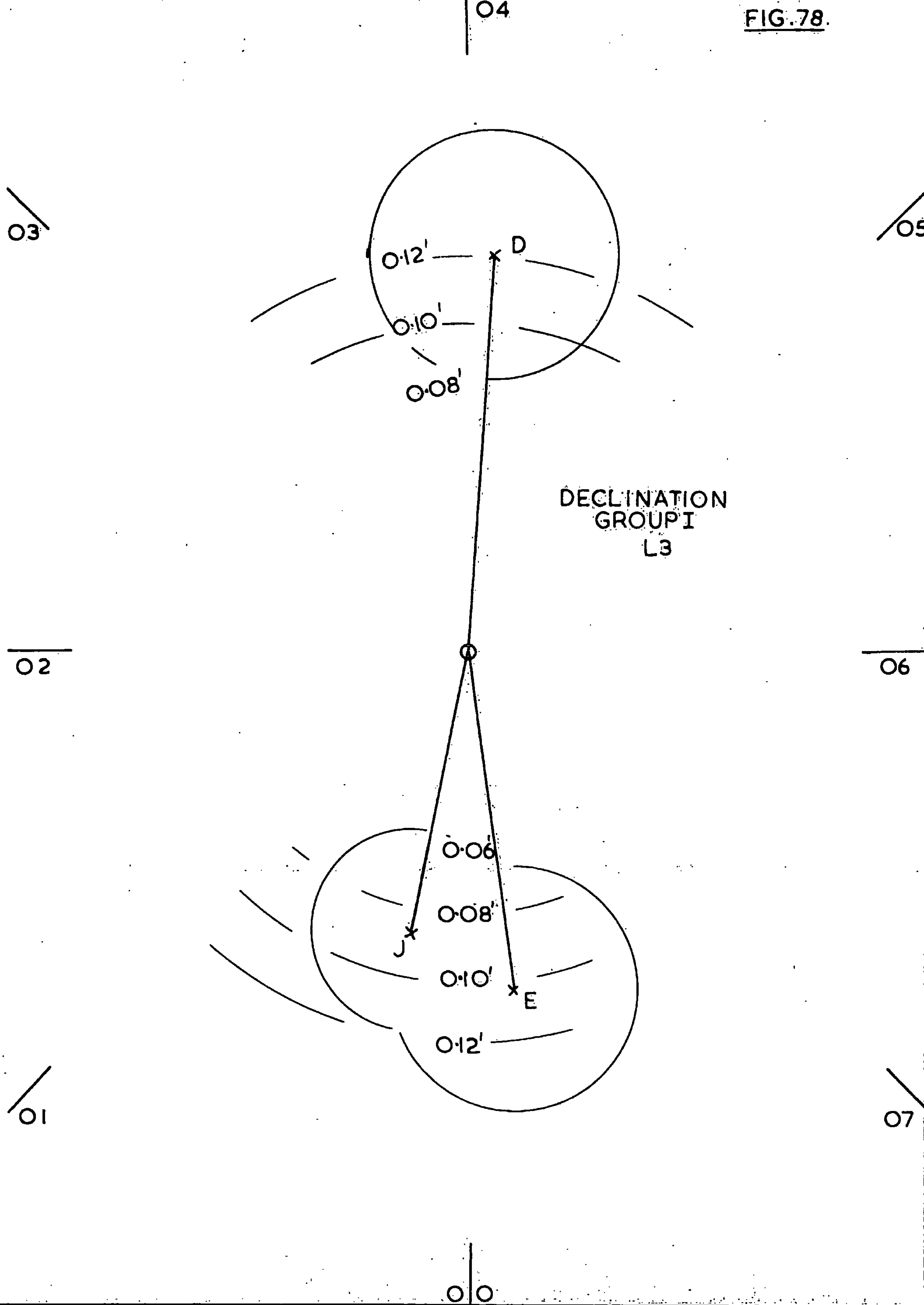

O4
O3
O5
O·12'
D
O·10'
O·08'
DECLINATION
GROUP I
L3
O2
O6
O·06'
O·08'
J
O·10'
E
O·12'
O1
O7
O O

FIG. 79.

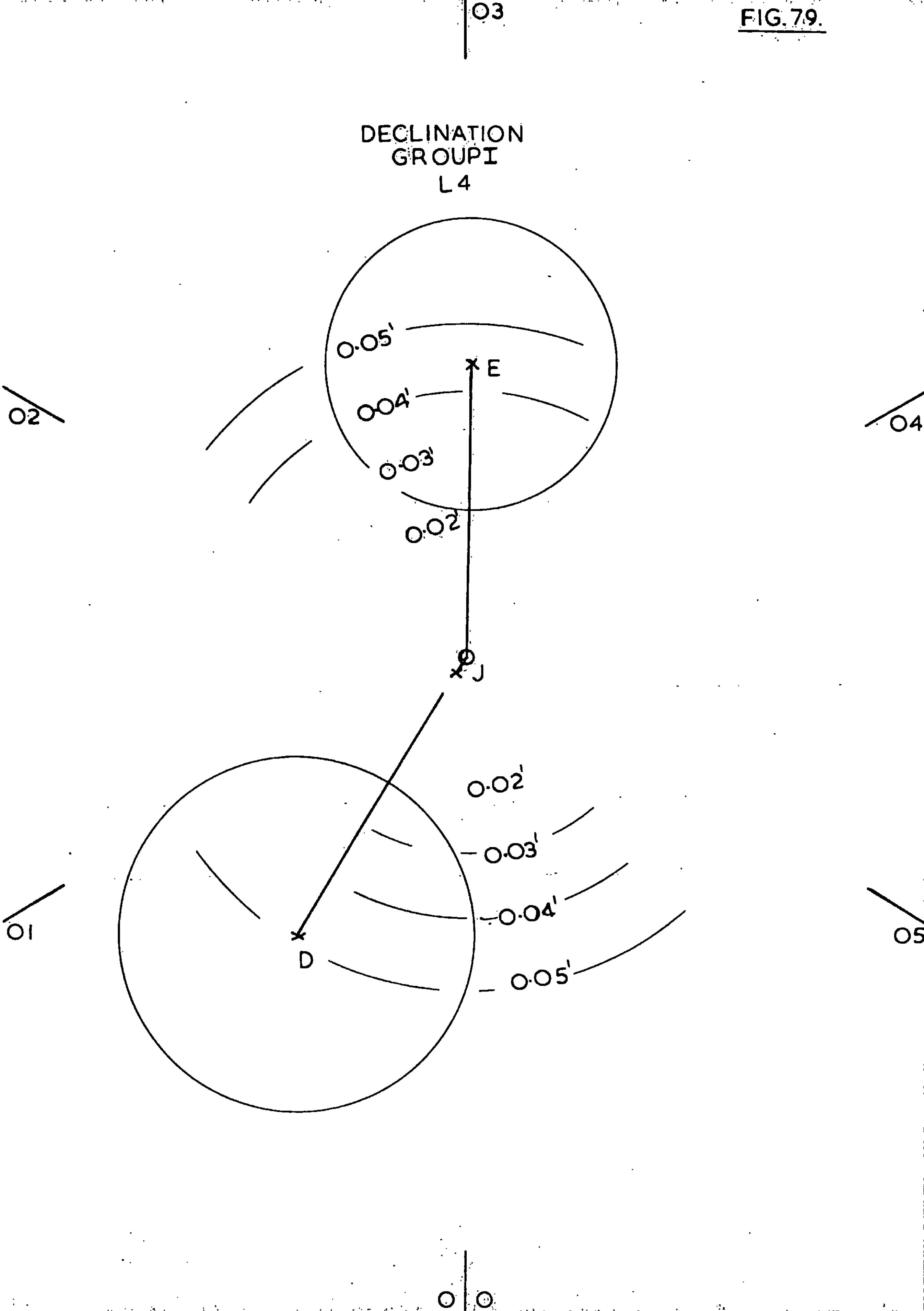

O3
DECLINATION
GROUP I
L4
0·05'
E
0·04'
0·03'
0·02'
O2
O4
J
0·02'
0·03'
0·04'
0·05'
D
O1
O5
O
O

FIG. 80.

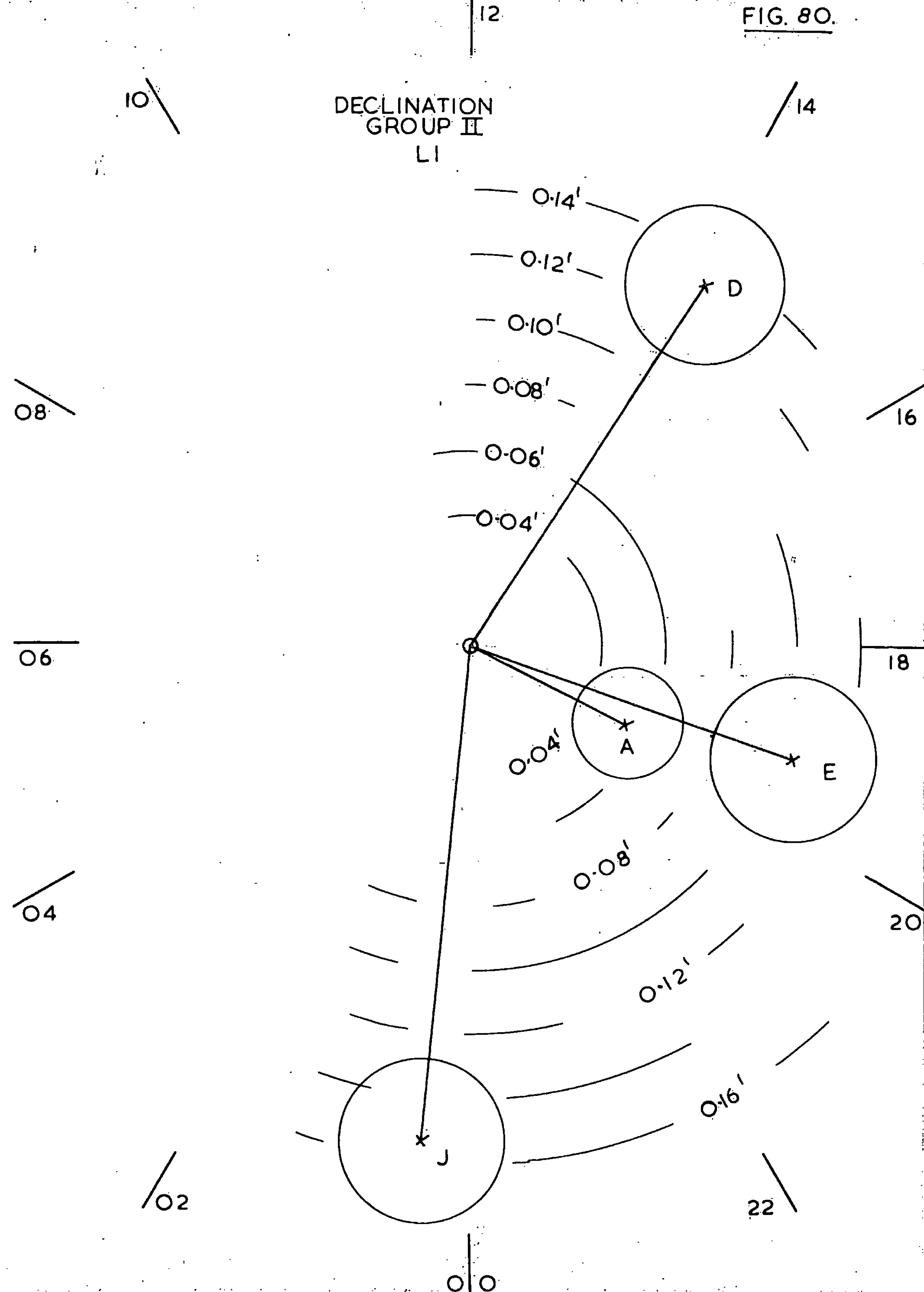

12
10
14
DECLINATION GROUP II
L1
0·14'
0·12'
0·10'
0·08'
0·06'
0·04'
D
08
16
06
18
A
E
0·04'
0·08'
04
20
0·12'
0·16'
J
02
22
0|0

FIG. 81.

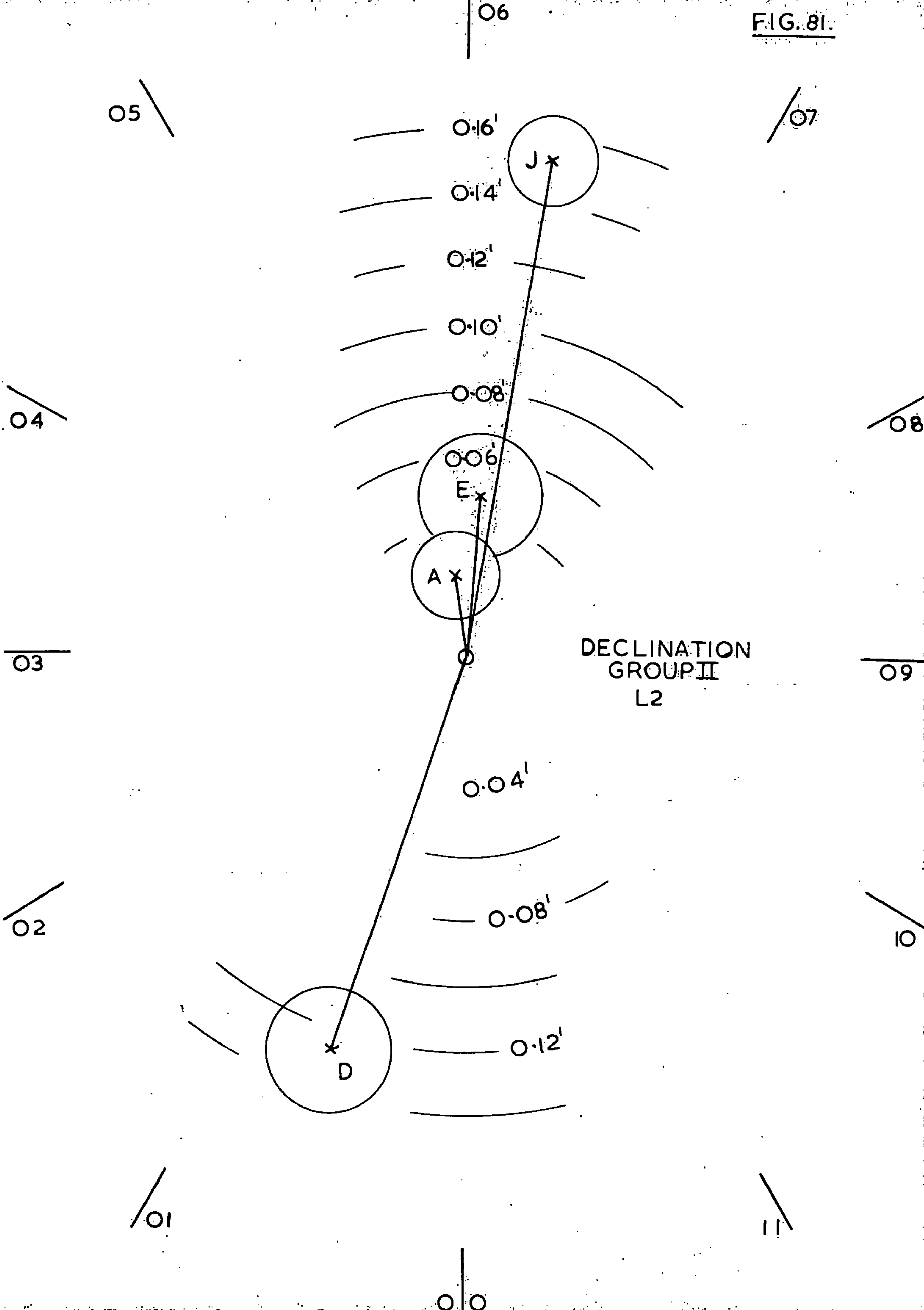

06
05
07
0·16'
J
0·14'
0·12'
0·10'
0·08'
04
08
0·06'
E
A
03
DECLINATION
GROUP II
L2
09
0·04'
0·08'
02
10
0·12'
D
01
11
00

FIG. 82.

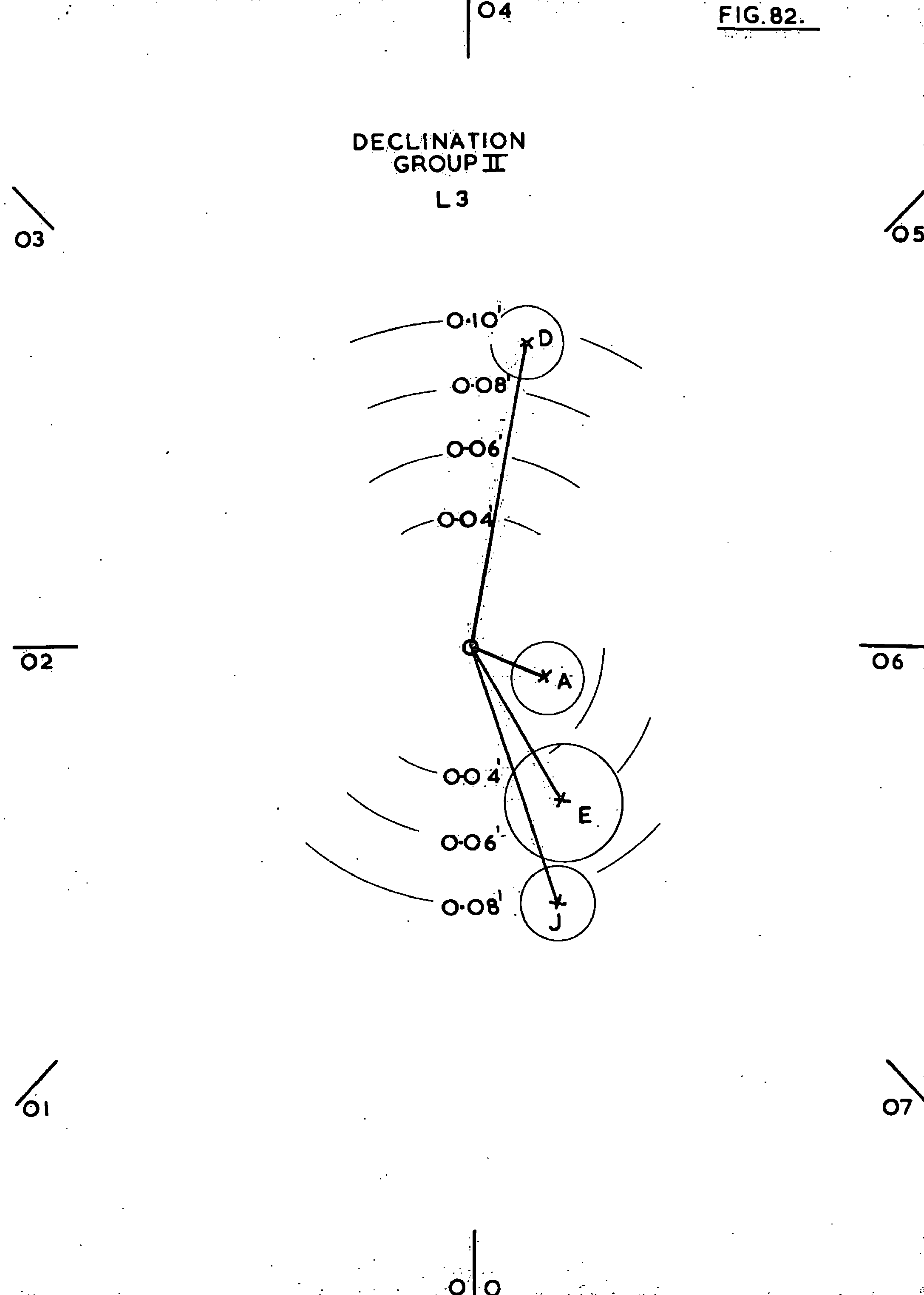

O4
DECLINATION
GROUP II
L3
O3
O5
0·10'
D
0·08'
0·06'
0·04'
O2
O6
A
0·04'
E
0·06'
0·08'
J
O1
O7
O O

FIG. 83.

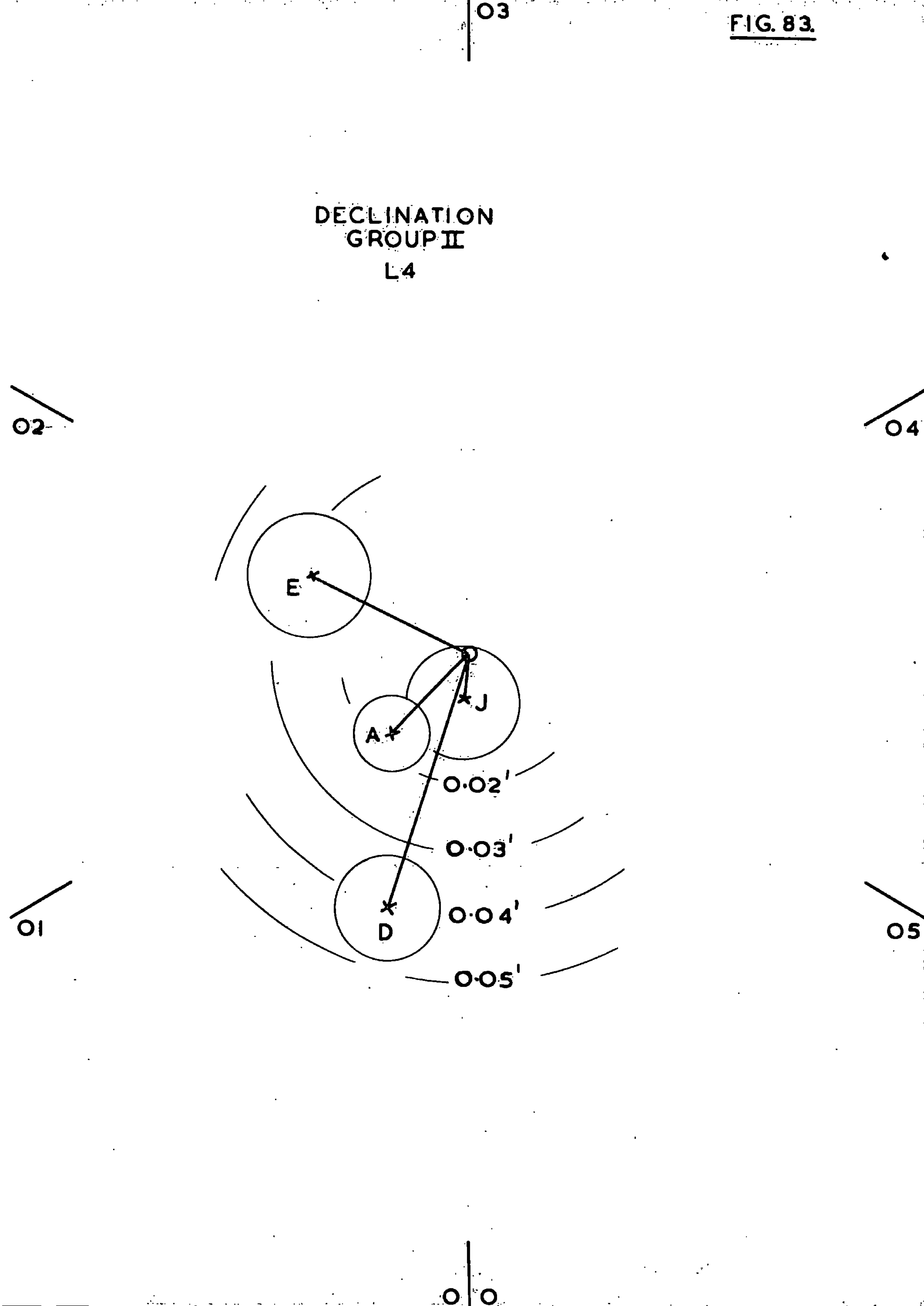
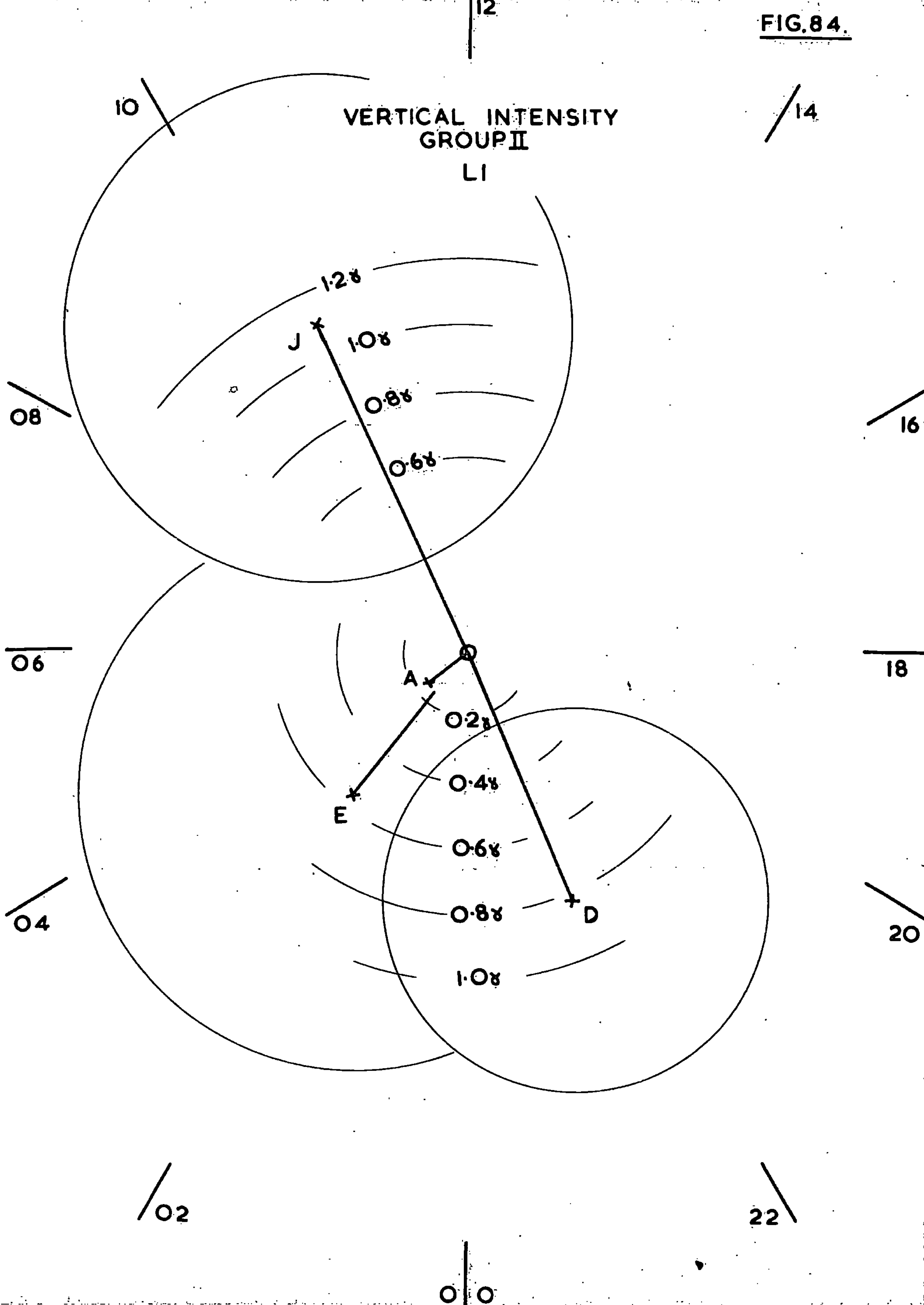
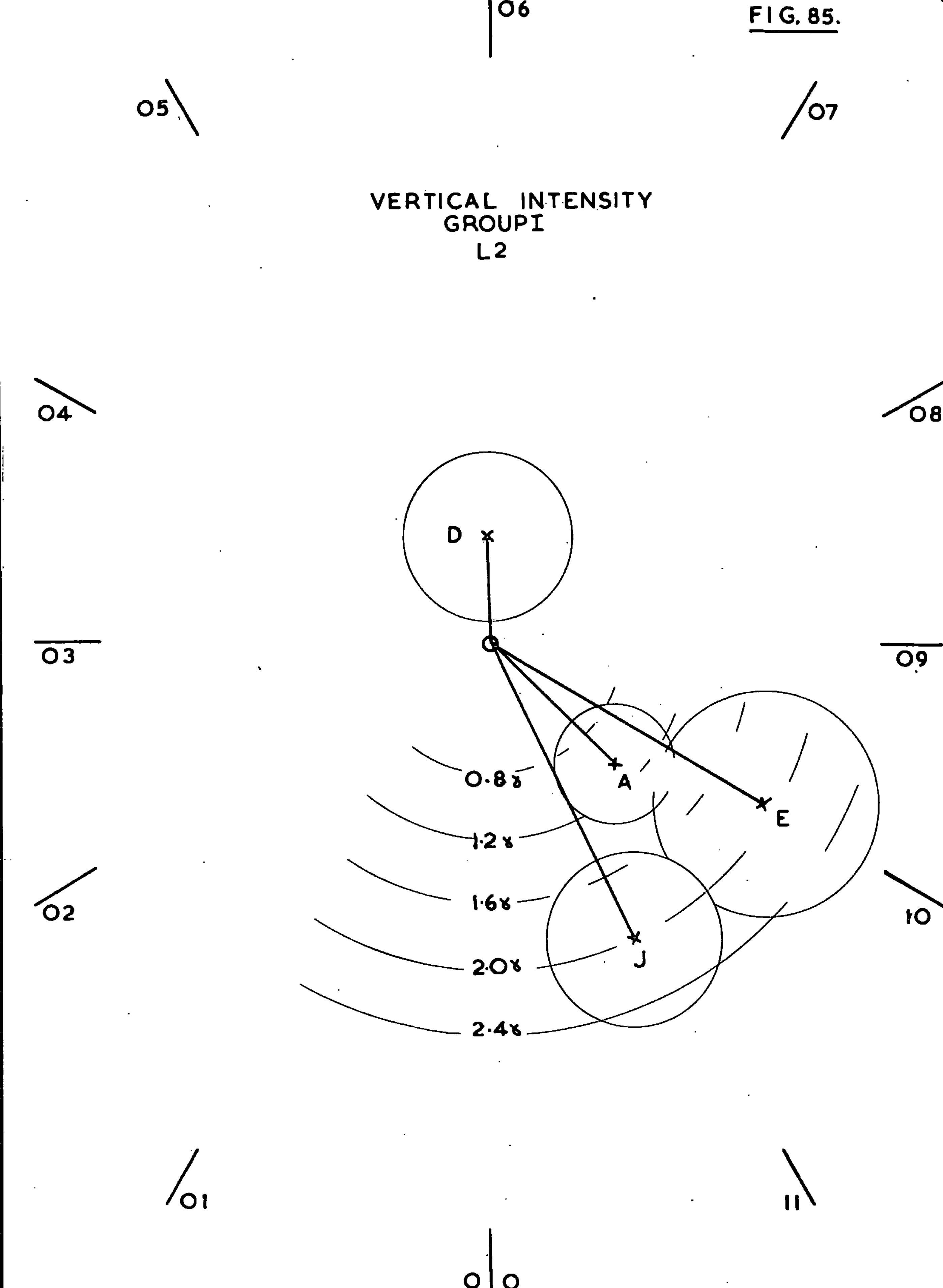


FIG. 84.



VERTICAL INTENSITY
GROUP II
L1

FIG. 85.



06
05
07
VERTICAL INTENSITY
GROUP I
L2
04
08
D
03
09
0.8γ
A
1.2γ
E
02
1.6γ
10
2.0γ
J
2.4γ
01
11
0
0

FIG. 86.

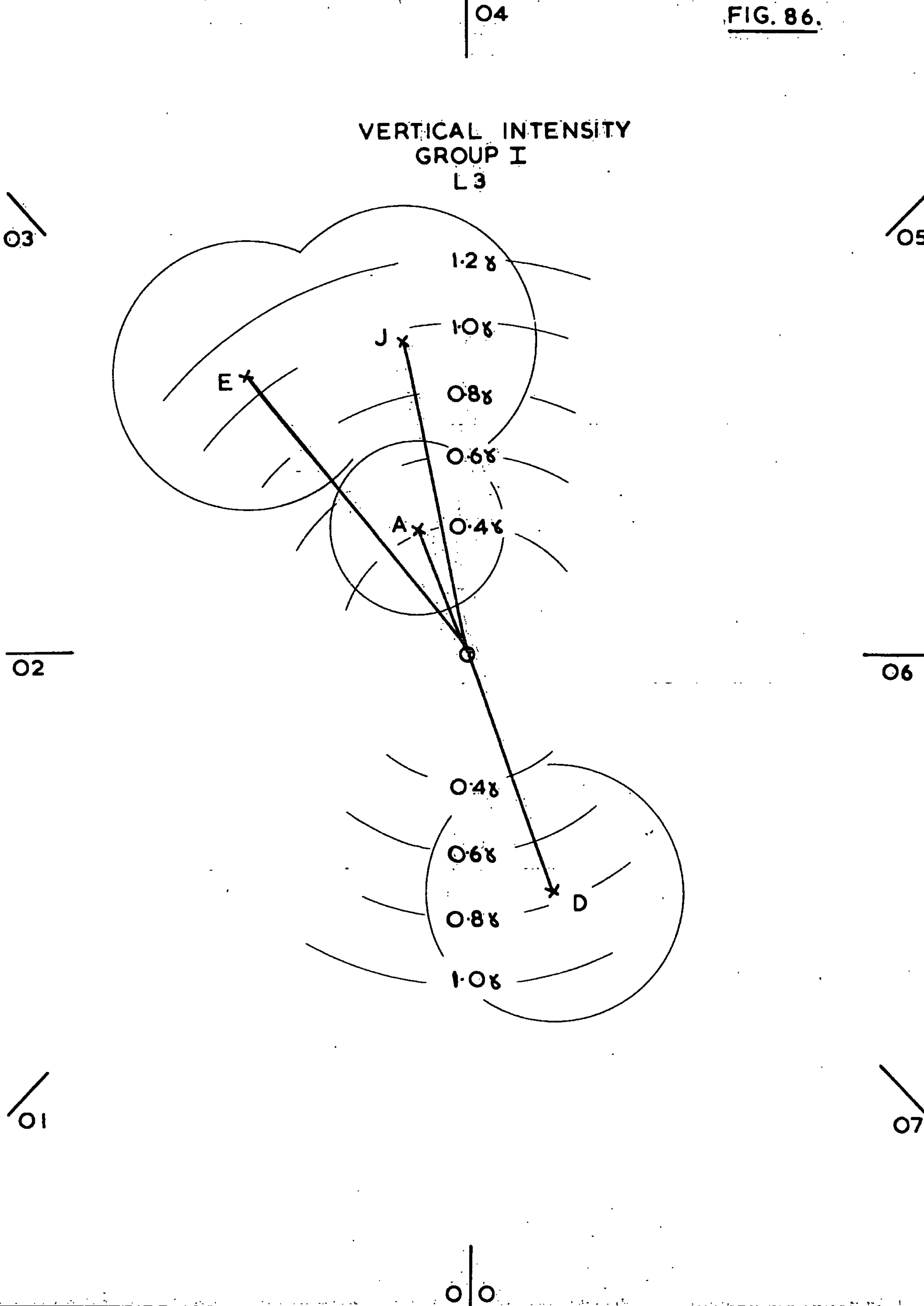
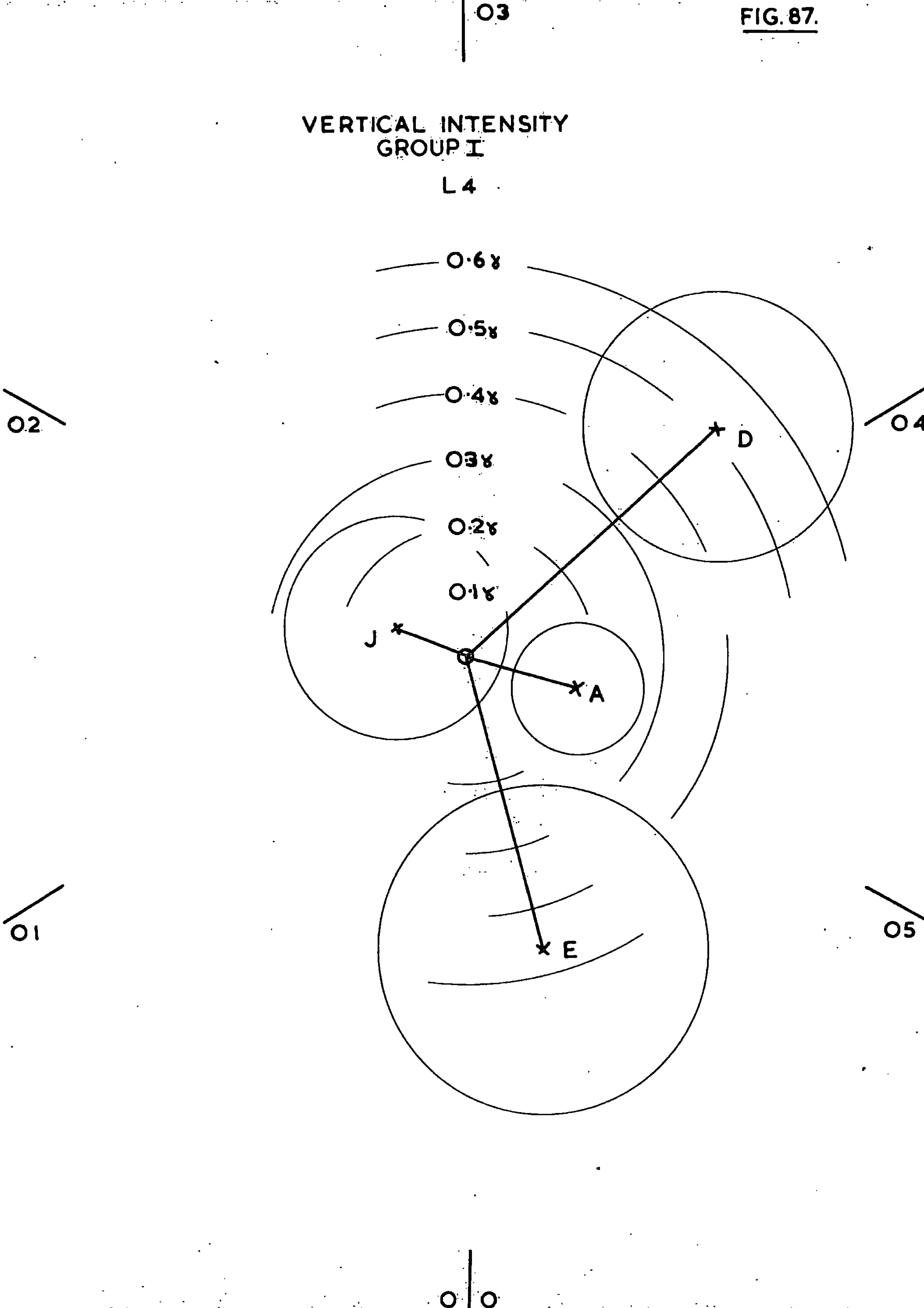

O4
VERTICAL INTENSITY
GROUP I
L3
O3
O5
1·2 γ
1·0γ
J
E
0·8γ
0·6γ
A
0·4γ
O2
O
O6
0·4γ
0·6γ
D
0·8γ
1·0γ
O1
O7
O
O

FIG. 87.



VERTICAL INTENSITY
GROUP I

L 4

FIG 88

VERTICAL INTENSITY
GROUP II
L1

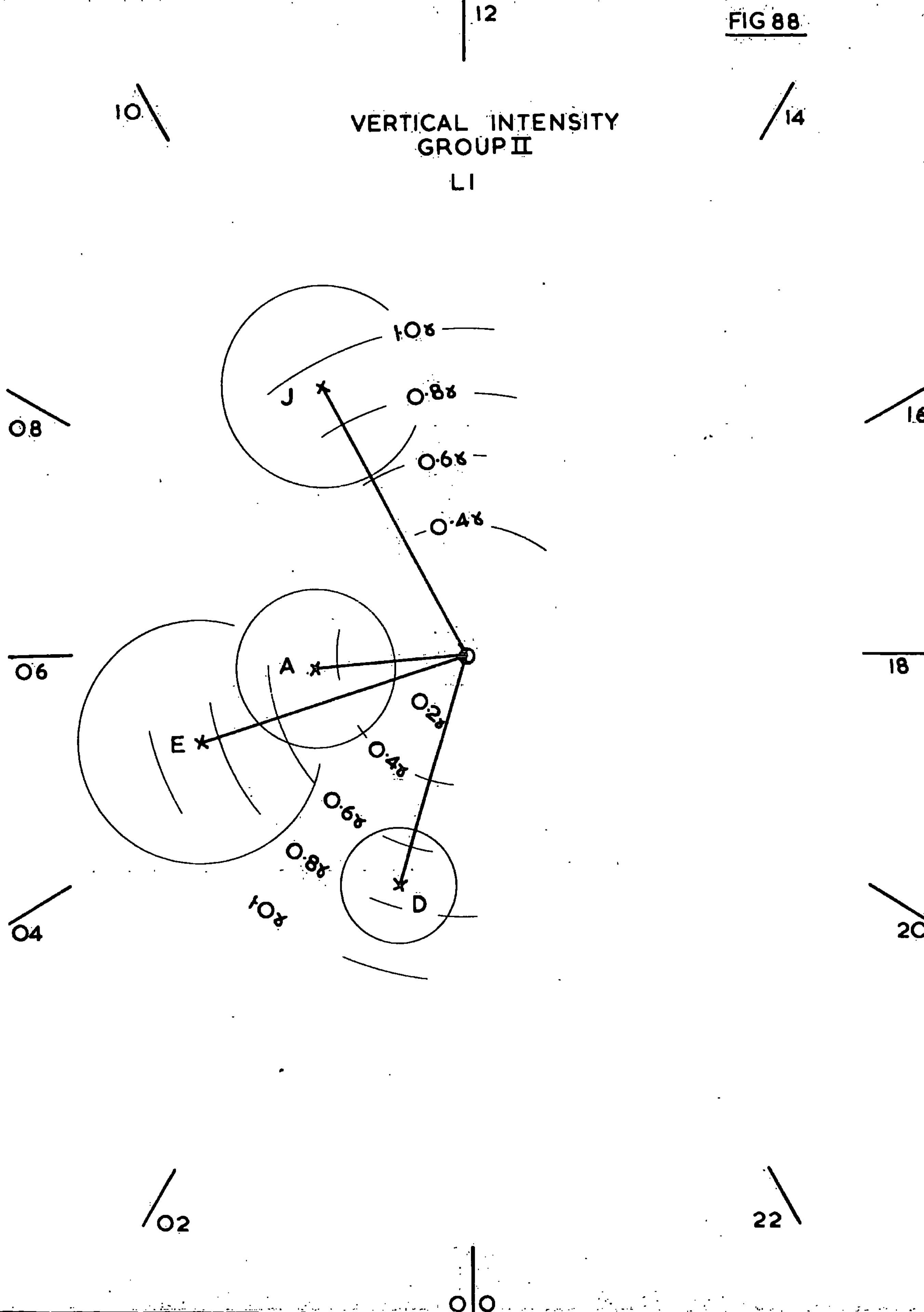
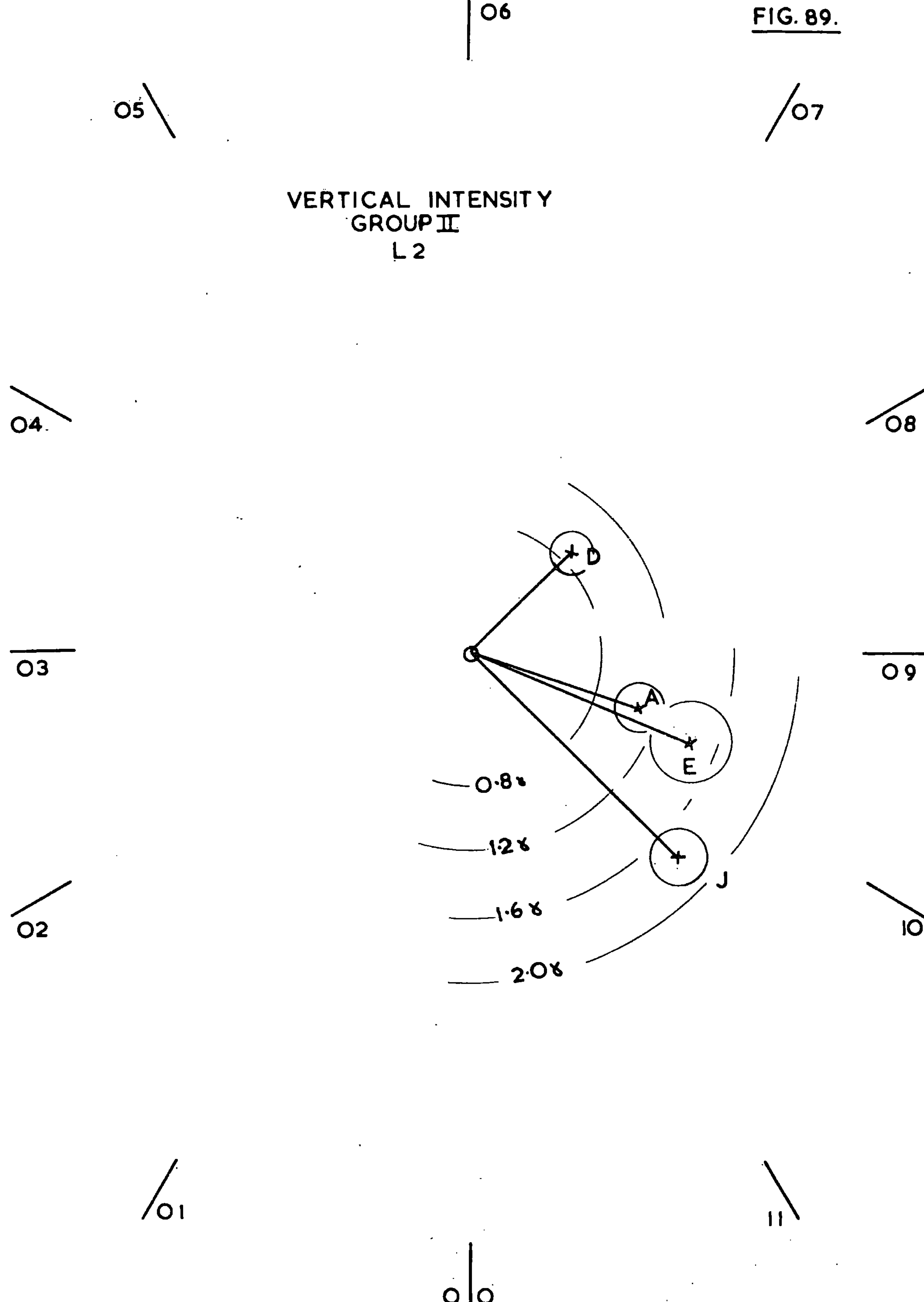


FIG. 89.



VERTICAL INTENSITY
GROUP II
L 2

FIG. 90.

VERTICAL INTENSITY
GROUP II
L3

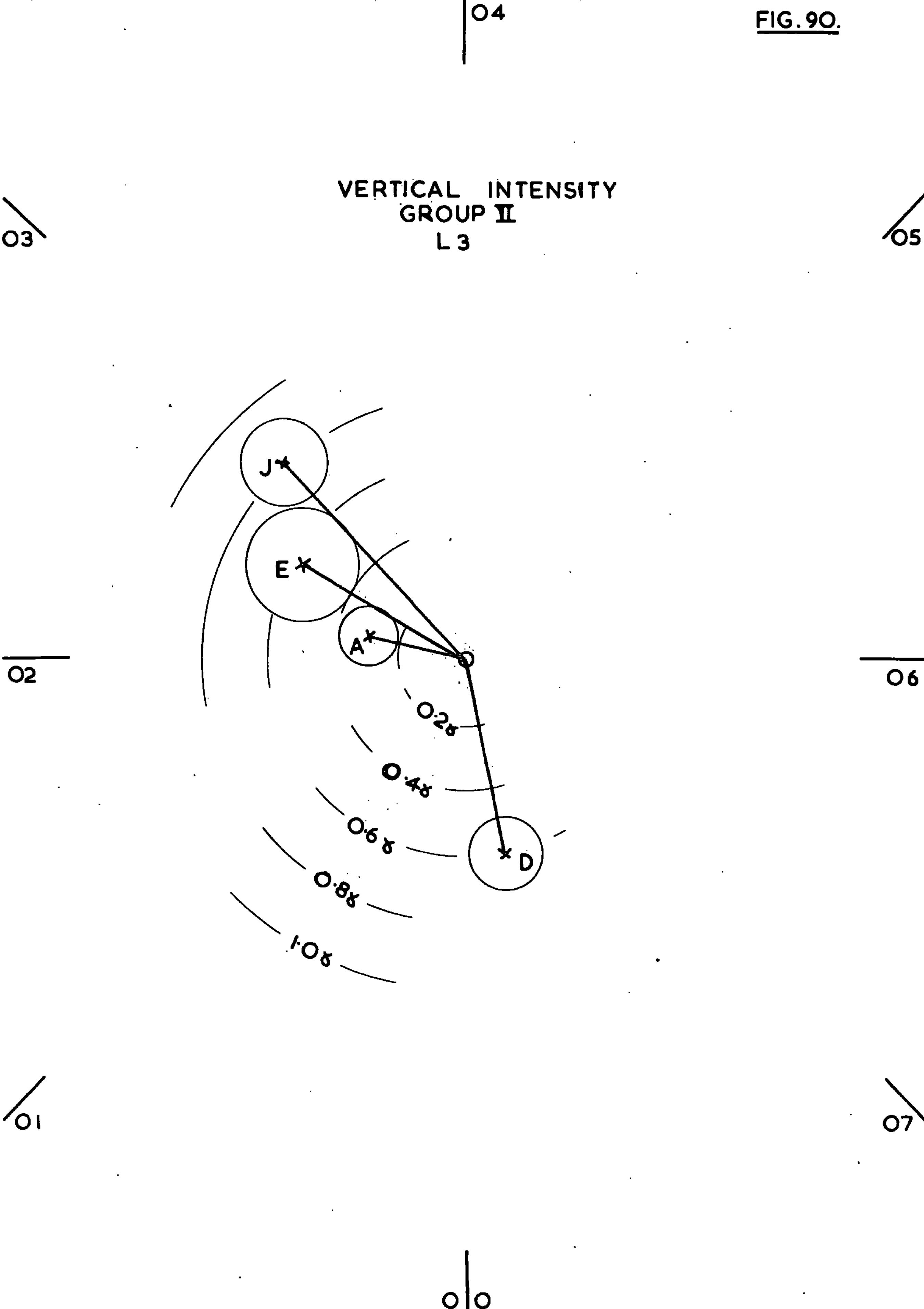


FIG. 91.

VERTICAL INTENSITY
GROUP II
L 4

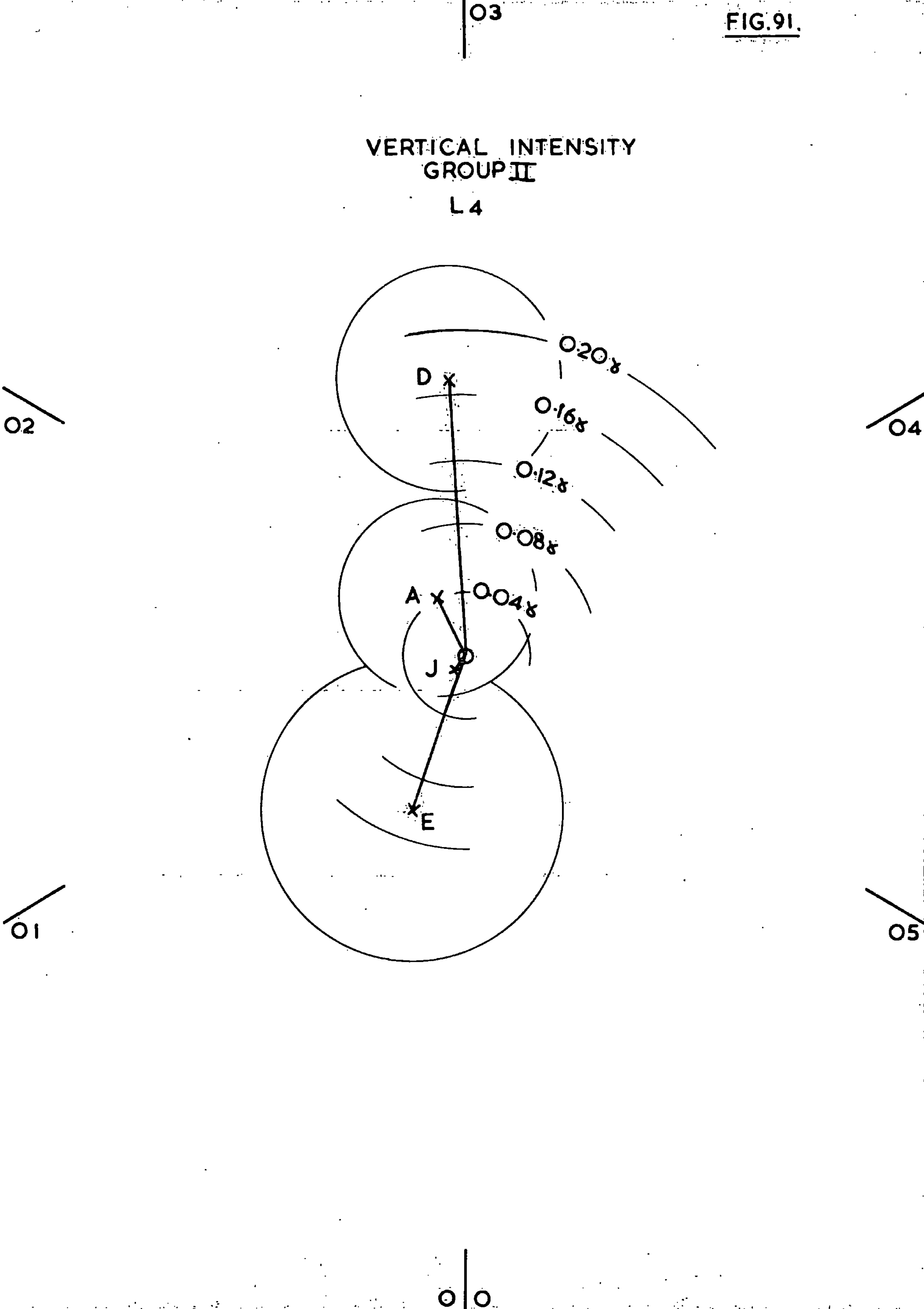
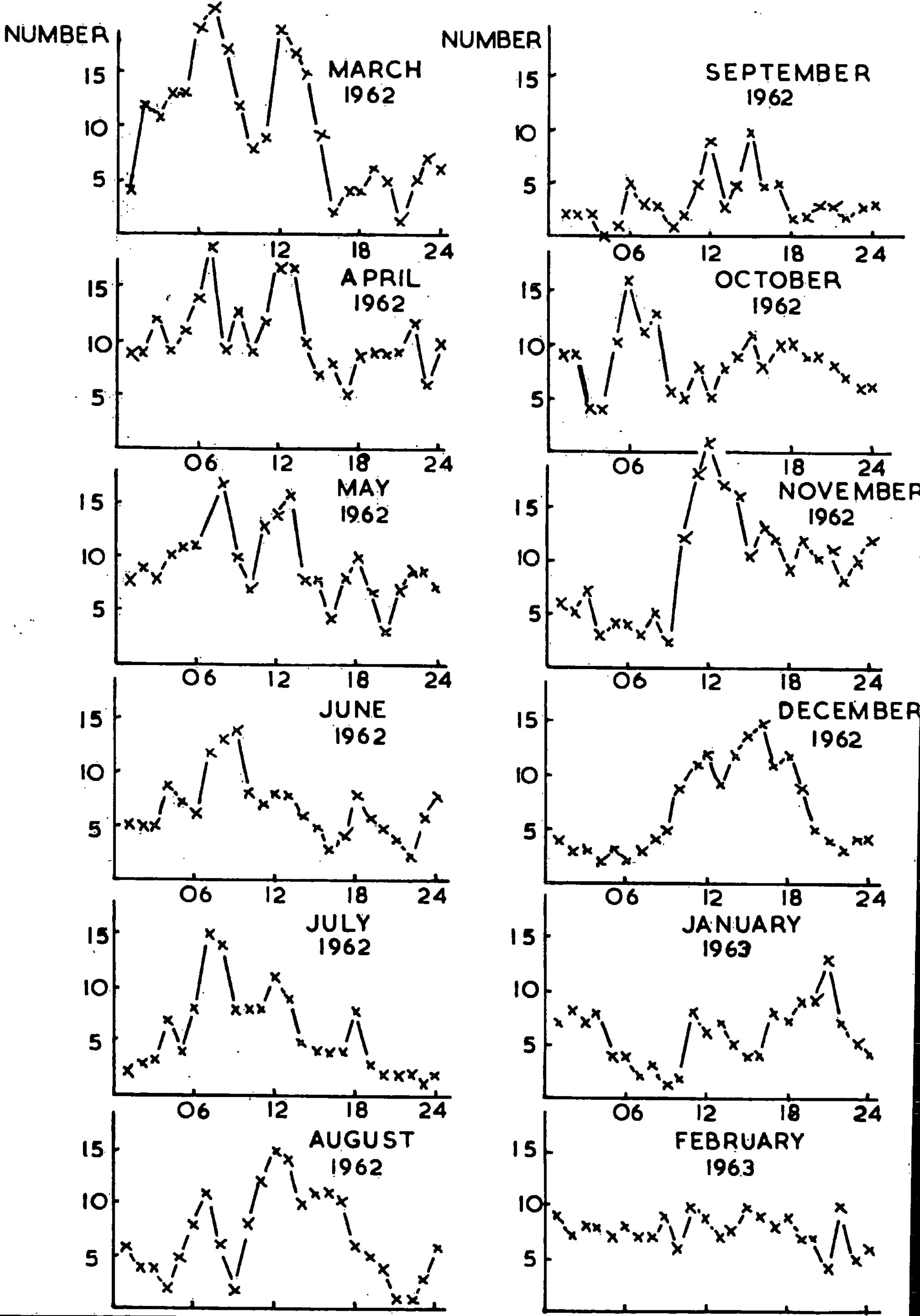


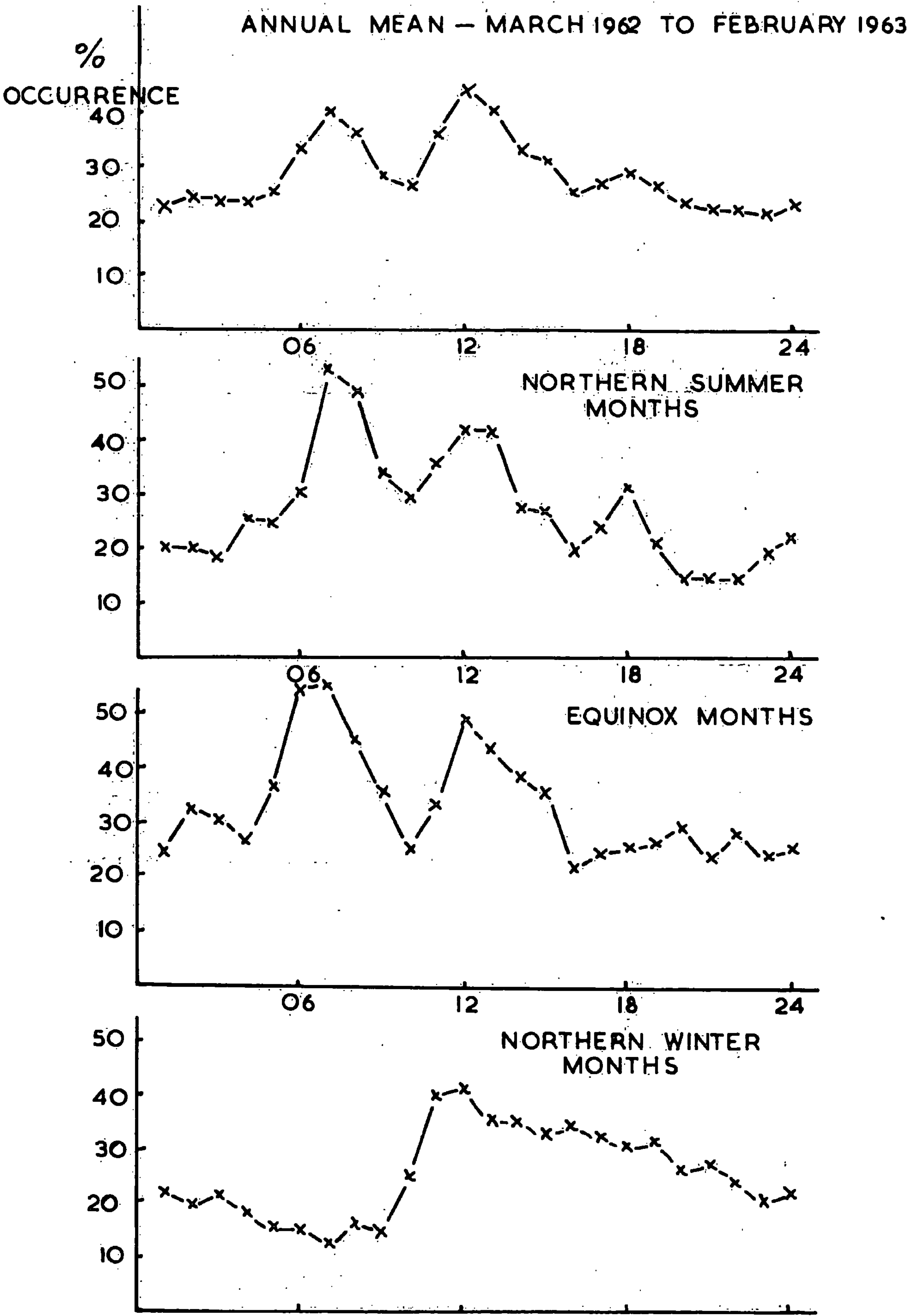
FIG.92

OCCURRENCE OF SHORT PERIOD VARIATIONS.

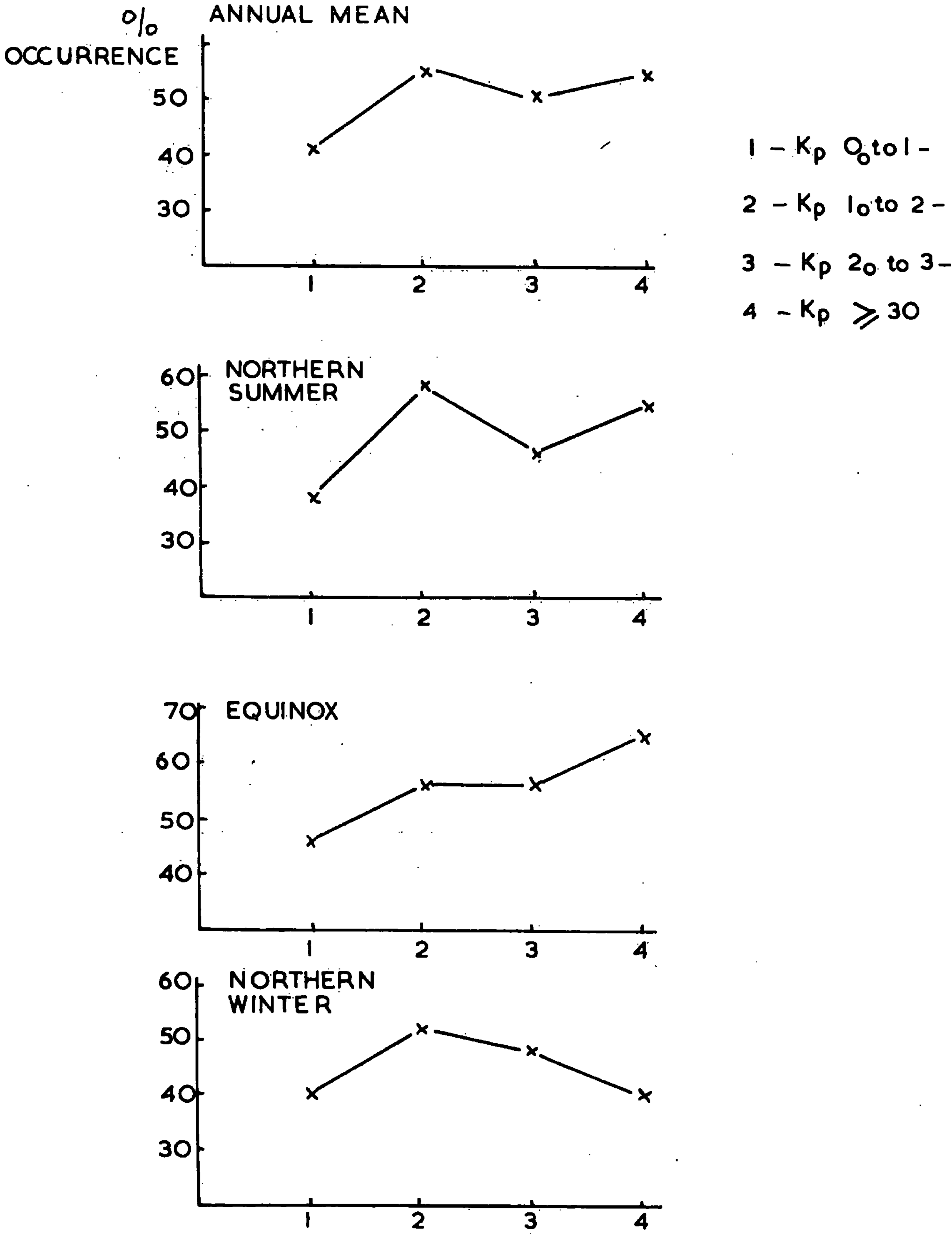


OCCURRENCE OF SHORT PERIOD VARIATIONS.

FIG. 93

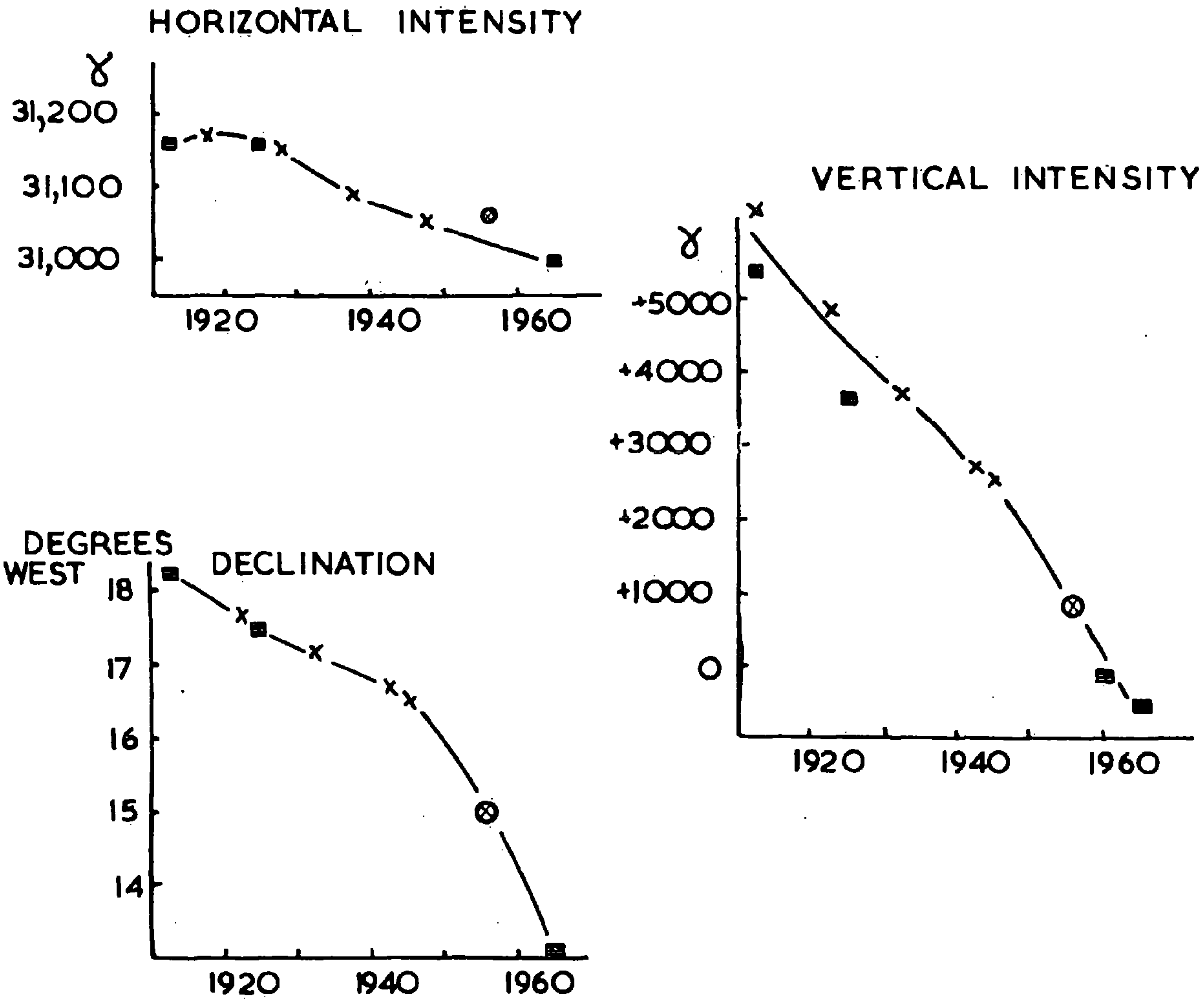


OCCURRENCE OF PULSATIONS WITH MAGNETIC ACTIVITY. FIG. 94.



SECULAR VARIATION IN SIERRA LEONE.

FIG. 95.



KEY

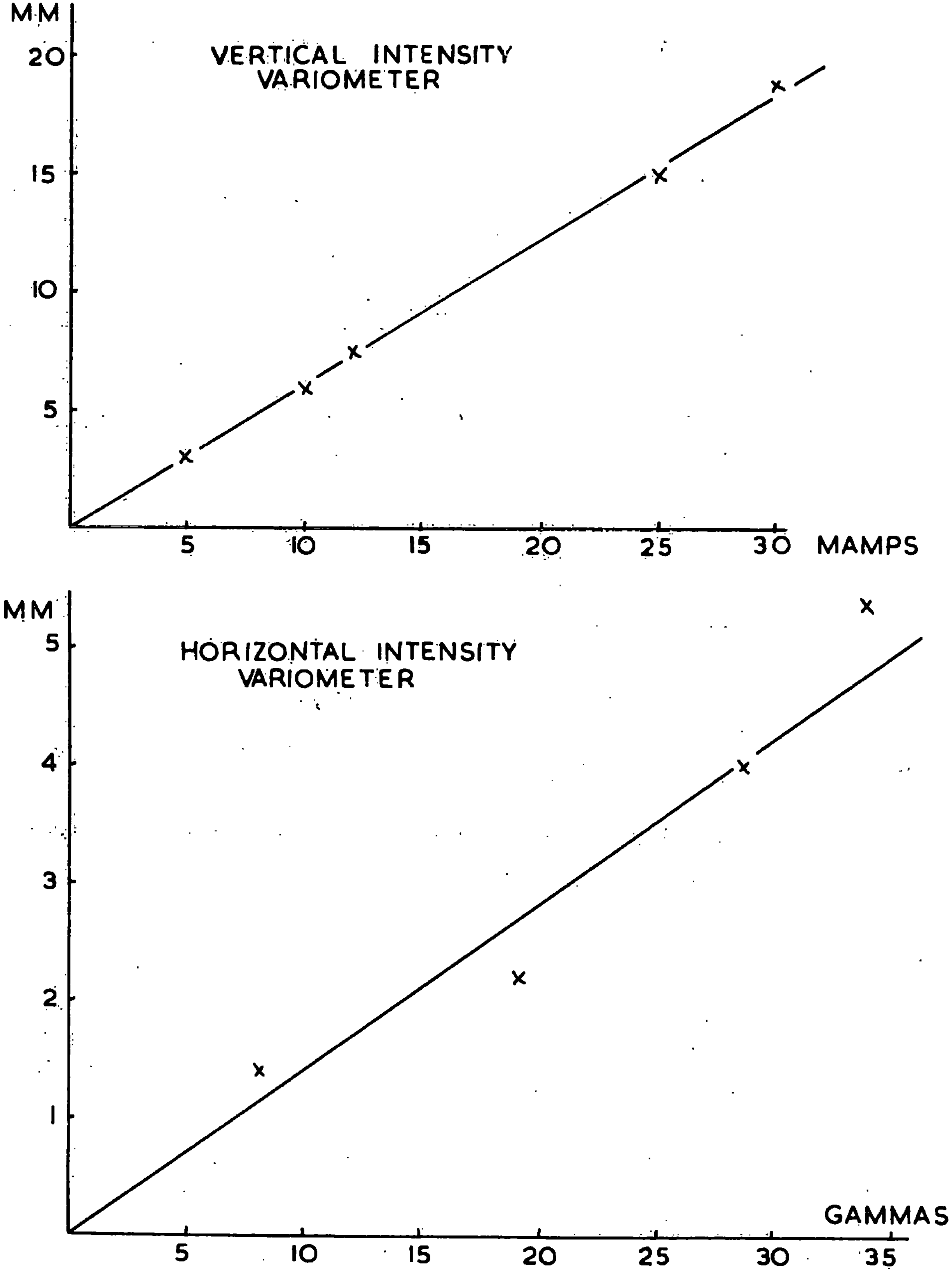
■ - OBSERVED VALUES, CARNEGIE SURVEYS& RIVERS

X – EXTRAPOLATED VALUES, VESTINE

⊗ - EXTRAPOLATED VALUES, FRENCH WEST AFRICA SURVEYS

CALIBRATION CURVES — ROKUPR

FIG. 96.



VERTICAL INTENSITY VARIOMETER

HORIZONTAL INTENSITY VARIOMETER

HORIZONTAL INTENSITY — 14th – 20th MARCH 1964

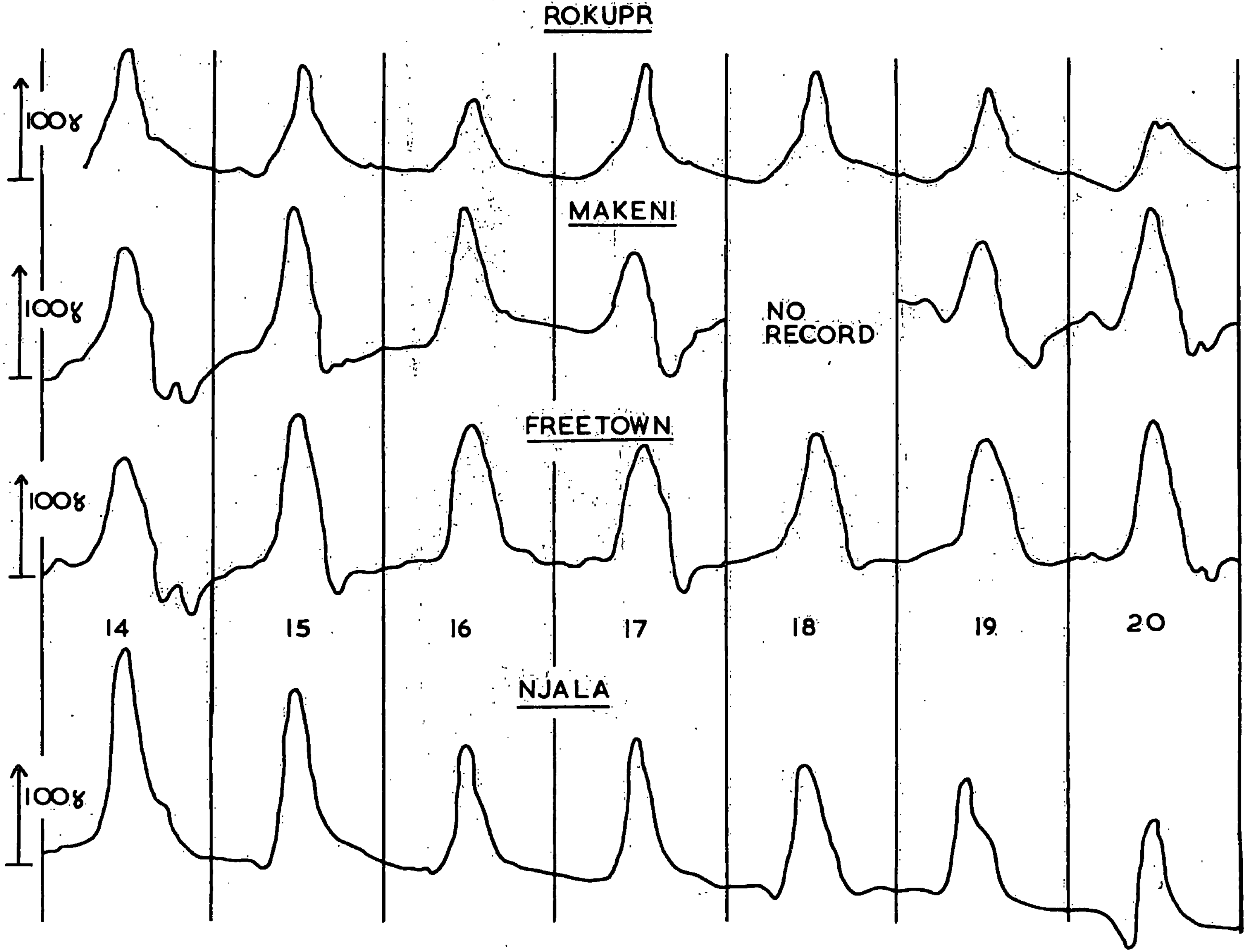


FIG. 97.