The Lunar Observatories of Megalithic Man

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Summary

Surveys of a number of Megalithic lunar sites are given, with horizon profiles carefully determined. It is shown that these contain definite indicators of the rising and setting of the Moon at its solstices, to an accuracy limited only by uncertainties in atmospheric refraction. From the profiles the values of the inclination of the lunar orbit and of its small periodic perturbation are deduced and found to agree very closely with the values given by modern astronomers. The difficulties faced by the erectors are made clear and an attempt is made to explain how the accuracy may have been obtained. A discussion of a possible observing technique is given and it is shown how the sites would have helped with eclipse prediction.

Values of terrestrial and astronomical refraction are deduced from the sites themselves and shown to be rather larger than those assumed initially.

1. The mean inclination i of the Moon's orbit to the ecliptic has remained constant for hundreds, perhaps thousands, of years. It is, however, subject to a cyclical perturbation, herein called Δ, of amount about 9 minutes of arc with a period of exactly half an eclipse year. The line of nodes rotates once in about 18·6 years and so in this period the maximum declination, north or south, which the Moon can attain varies between the limits $\varepsilon + i \pm \Delta$ and $\varepsilon - i \pm \Delta$ where ε is the obliquity of the ecliptic (Fig. 22). The times when the declination attains these limiting values may be called the lunar solstices. In the sense that solstice means a standing still, the analogy with the Sun's solstices is not complete. At the Sun's solstices the solar declination attains a maximum. At the lunar solstice the monthly maximum in the declination itself attains a maximum. The conditions which obtain as the Moon passes through one of its solstices is best understood by looking at Fig. 1 which shows a

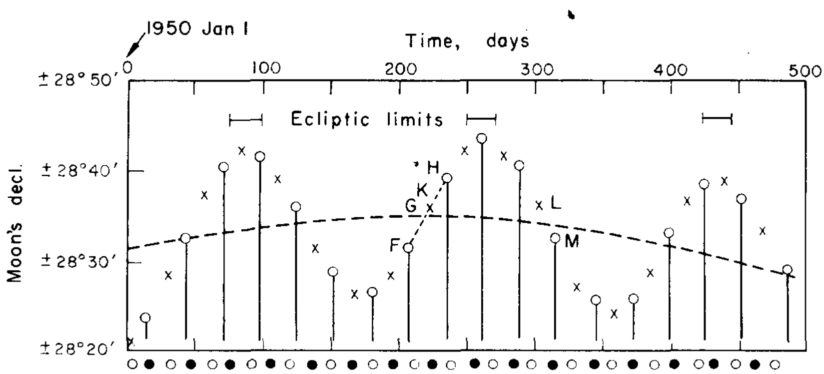


FIG. 1. Moon's declination at a recent lunar solstice. × monthly maximum positive declination; ○ monthly maximum negative declination; ⊢⊣ approximate ecliptic limits; ○ ● full and new Moon; M eclipse of the Moon; S eclipse of Sun; ---- top of 18·6-year cycle (see Fig. 22).

plot of the monthly declination maxima which occurred near the time of a recent lunar solstice. The 9′ ripple or perturbation is clearly seen superimposed on the smoother long period oscillation.

It has been shown elsewhere and will be shown here again that Megalithic man has left records in stone showing the value of the Sun's solstitial declination with an accuracy of 1′ or better, limited in fact only by the vagaries of refraction. His method of observation has been described in a previous paper in *Vistas in Astronomy* (Vol. 7) which will hereinafter be called Paper I. An examination of the site at Kintraw, to be described in section 5.2, provides a most convincing demonstration that this was the technique used. When the erectors used the same method to study the lunar solstice the 9′ ripple must have shown up clearly. It will be shown that they not only detected it but recorded it at several sites with surprising accuracy. In this they anticipated Tycho Brahe by more than 3000 years.

It will be seen from what has been said that the Moon's declination can be considered as consisting of three cyclical components. The fact that each of these components contains terms other than the main sinusoidal term affects the present discussion only indirectly.

The astronomical constants in which we are interested are

ε = obliquity of ecliptic = 23° 53′ 48″ at 1700 B.C. decreasing by about 40″ per century;

i = inclination of Moon's orbit to ecliptic = 5° 08′ 43′ constant mean value;

Δ = amplitude of main periodic term affecting i
= $0{\cdot}0748 \times {}^3/_8 \sin i = 8'.7$, period 173·31 days;

p = Moon's horizontal parallax, varies between 54′ and 61′ with a mean value of 57′.0;

s = Moon's semidiameter, varies between 14′ and 17′ with a mean value of 15′.5.

Δ has other small terms and so can be a little greater than the value given. It is one of the objects of this paper to show that there are many lunar sites in Britain capable of such accuracy that we can deduce from them mean values of i and Δ differing from the above by less than 1 minute of arc. A value of ε emerges as a by-product corresponding to a mean date of about 1700 B.C.

2. In Paper I it was shown that there are many sites in Britain where the stones erected by Megalithic man were intended to indicate the rising or setting points of the Moon at one or other its four solstices. In the present paper a study will be made of all sites visited by the author at the date of writing which appear to be capable of giving lunar declinations with an accuracy of a few minutes of arc. Several new sites have been discovered and several revisited and remeasured. When conditions permitted, the hill profile was measured by theodolite and referred astronomically to true north. It will be appreciated that the difficulties may be considerable. Having accomplished the long journey usually necessary one may find that the weather is unfavourable. One can, however, make sure that the local topography does not obstruct the view and one can make an approximate measurement of the height of the site referred to Ordnance-Datum. The distant hill horizon can afterwards be constructed by the sometimes laborious method of geodetic calculation based on the Ordnance Survey contours. If the contours represent the hill to ±10ft then at 7 miles distance the altitudes ought to be correct to ±1′, but this is only reliable with the large-scale maps. For long distances the uncertainty of the refraction to be used—it is the apparent altitude which is required—affects the accuracy just as it affects the reliability of a measured altitude. It follows that a brief discussion of refraction is necessary.

3. TERRESTRIAL AND ASTRONOMICAL REFRACTION

Consider a light ray from a celestial body S grazing a mountain top M and reaching an observer at O (Fig. 2). Astronomical refraction is the angle marked r and terrestrial refraction the angle $S'OM$. Any abnormal refraction increment between O and M will affect both but in different degree. For an increment in curvature $1/\sigma$ at a point x from M towards O the effect on astronomical refraction will be dx/σ but the effect on terrestrial refraction will be $x/L \times dx/\sigma$ where L is the distance of M from O. (See Ref. 1.)

When possible we measure the apparent altitude of M from O. This includes the terrestrial refraction existing at the time and so if conditions are normal we correct for astronomical refraction to obtain the true altitude of any celestial body when it appears to set on M. Strictly we ought to deduct the terrestrial refraction existing when the altitude was measured (daytime) and add that considered to exist when the body had been observed (night time). The astronomical refraction then to be deducted is night time refraction. Existing

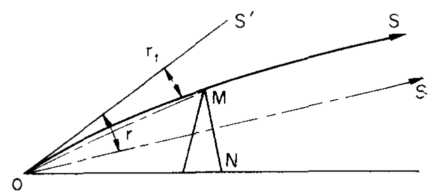


FIG. 2. Definition of the refractions.

tables of astronomical refraction are of necessity based on night observation or for low altitudes on observations of the setting Sun and as we shall see refraction at sunset has risen to near but not completely to its night time value.

When the apparent altitude is being obtained by calculation we ought to apply night refraction. The author has published(7) the results obtained from a long series of refraction measurements extending over several years. The altitudes of a number of hill and mountain peaks were measured in all possible conditions of temperature, weather, time of day, wind and cloud. The refraction obtained was expressed as

$$r = KLP/T^2$$

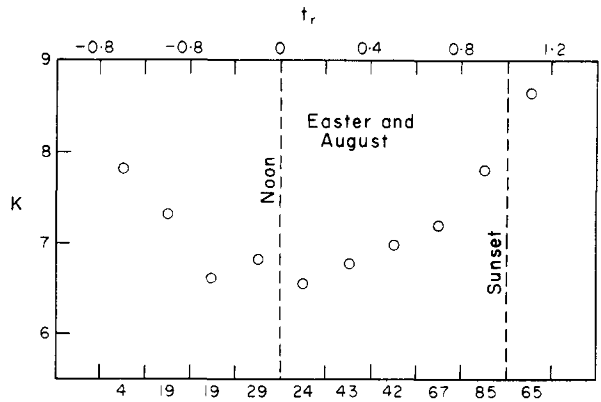
where r = refraction (seconds of arc);
P = barometric pressure (inches Hg);
T = temperature (°R) = °F + 460;
L = distance (feet);
K = refraction constant.

For details of the analysis of the results reference must be made to the original paper. Here we are concerned only with the mean values of K. The raw results uncorrected for the effects of wind and temperature gradient were very scattered. Values of K ranged from 5 to 13, but when means were taken for various times of day (expressed as a fraction of the interval from noon to sunset) a very definite result emerged (Fig. 3). The refraction appears to be a at minimum in the early afternoon and rises with increasing rate as sunset approaches. When darkness made further observation impossible the refraction was still rising. Fortunately some 90 measurements were also made to two distant lighthouses from shortly before dark to midnight and also before dawn. The values of K so obtained were scattered from $7^1/_2$ to 15 and showed a mean of nearly 11. There did not appear to be any significant fall towards midnight. With a clear sky overhead refraction tends to be high and so it is proposed to take for the preliminary reductions in this paper an arbitrary value of 12.

With $K = 12$, $T = 510°R$ and $P = 30$ in. we obtain a refraction value of 7·3 sec/mile. In view of the uncertainty of this value it will be sufficiently accurate to use a mean local curvature of the surface of the spheroid lowering the altitude of a point by 26″ per mile. Since refraction raises the altitude by 7.″3 per mile the total effect is a lowering by about 18.″7 or 0.′31 per mile. Thus the apparent altitude in minutes of arc of a point at distance D miles is

$$(3438/5280)\, H/D - 0{\cdot}31\, D$$

where H is the amount in feet by which the point is above the observer.



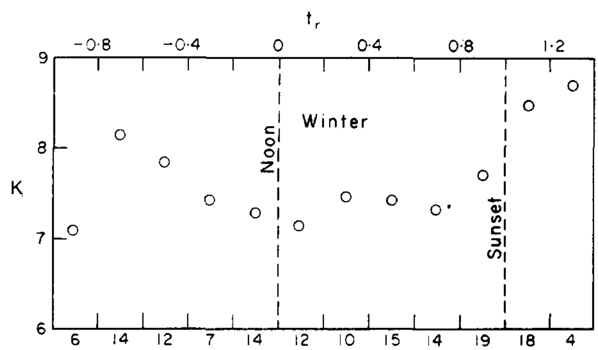


FIG. 3. Effect of time of day on refraction. t_0, time of the observation; t_n, time of local apparent noon; t_s, time of Sunset; $t_r = (t_0 - t_n)/(t_s - t_n)$. Each ringed point is the mean of n observations where n is the number written below the ring.

The author has published[6] the results of some measurements of astronomical refraction made with Prof. A. N. Black by observing the Sun repeatedly as it sank to an apparent altitude of —20′ and vanished into the sea. It was shown that there was no catastrophic effect as the last ray vanished. The refraction remained near to values obtained by extrapolation of published tables. Any set of measurements of this kind is, however, dependent on the weather conditions existing at the time and also to a great extent on the local terrain. It was shown[7] that the part of the ray near the ground close to the observer is affected to a height of about 50 ft by the temperature gradient measured at ground level and to a height of 300 to 500 ft by the wind strength. The longer the length of the part of the ray near the ground the greter is the effect. It follows that the only reliable method whereby we can find the mean refraction at a site for a low ray is to make an investigation on the spot or at a similar site. In the absence of information of this kind we shall in this paper use the values in Table 1 bearing in mind how unreliable they are at very low and negative angles of altitude.

Table 1. Astronomical Refraction (Minutes of arc at temperature $T = 50°F$)

app. altitude	$-\frac{1}{2}°$	$0°$	$+\frac{1}{2}°$	$1°$	$1\frac{1}{2}$	$2°$	$3°$
Refraction (r)	40.0	34·4	28·8	24·5	21·1	18·4	14·4
dr/dT	—	−0·11	−0·09	−0·07	−0·06	−0·05	−0·04

An examination of the data for the lunar sites presented in this paper shows that these are best explained by using slightly higher values for both astronomical and terrestrial refraction than those given above (see section 7.1).

Dip or the apparent angle of depression of the sea horizon is given by $\sqrt{\{2H/R - 2H/\varrho\}}$ where ϱ is the radius of curvature of the light path, R that of the Earth and H is the height of the observer above sea level. The above value of refraction makes $1/\varrho = 2 \times 7{\cdot}3$ sec/mile and so we have the dip in minutes of arc as $0{\cdot}90\sqrt{H}$, H being in feet. This is lower than the value usually quoted because we have used a high value of refraction.

4. In Paper I we were concerned with a list of observed declinations which were solar, stellar and lunar. To be able to recognize the lunar lines it was convenient to apply the effect of lunar parallax to $\pm(\varepsilon \pm i)$ so that a direct comparison could be made with the listed observed values. Here, since we are dealing almost exclusively with lunar lines, we use the more conventional method of correcting each observed altitude for refraction and parallax before computing the declination. (This must be kept in mind when comparing any lunar declination with that listed in Paper I.) We are then in a position to equate the declination to one of the values of

$$\pm\varepsilon \pm i \pm s \pm \Delta$$

There is no evidence that the erectors of the sites ever made use of the centre of the Moon's disc so we need not use the case with $s = 0$. There is, however, a good deal of evidence that they often used a mean maximum with $\Delta = 0$.

We deal in this paper with lines capable of giving the declination with an accuracy of a few minutes of arc and so an outlier unless distant or an alignment unless long cannot alone suffice. The kind of line we seek is an indicated distant well defined mark such as a mountain peak or notch, the indication being by outlier, alignment or slab. We have seen in Paper I and shall see again here that the erectors knew how to make excellent use of the most accurate of all namely the grazing of a mountain shoulder by the upper or lower limb where upper and lower refer to declination and not to altitude. It will be seen that at several places both the rising and setting moon were observed (see also Paper I, Fig. 39). So if the rising mark is indicated we are prepared to look for and to accept an unindicated setting mark. From the erectors point of view there would be no necessity to indicate both marks. When they saw the Moon rising on an indicated mark they would know that a few hours later it would at setting, itself show the setting mark. In thinking of these things we must bear in mind that 18 years had elapsed since the previous observations and so perhaps a new generation of observers was at work.

4.1. *Parallax and Semidiameter*

We can apply only mean values of these quantities. Suppose that on a particular night when the erectors observed the Moon it was nearer the Earth than its mean distance. The parallax would be large but as we apply the mean our calculated declination will be algebraically too small whether the Moon was being observed in the north or in the south. If the lower limb is being used the effect of the enlarged semidiameter will produce an error of the same sign. But if the upper limb is used a partial cancellation takes place and this, at the accuracy to which we are working, might be appreciable.

The astronomical definition of mean semidiameter is the semidiameter when the Moon is at a distance equal to the semi-major axis of the orbital ellipse. Dr. Roy points out that this is also the time mean of the semidiameter for the orbit as a whole. The same remark also applies to mean parallax.

5. The sites

In the following pages details will be found of those sites for which, at the date of writing, the author has sufficient information to allow the declinations to be deduced with an accuracy of a few minutes of arc. The nature of the indicator at each site is described or shown in the figure. Hill profiles for most of the sites are shown in the directions indicated. The profiles are nearly all drawn with an exaggerated vertical scale. This has been done because the Moon's apparent path makes such a small angle with the horizon that, in calculating the declination, altitude is more important than azimuth. Points marked A and B on the profiles are used to obtain the declination for the subsequent analysis. Points unmarked or marked C have not been so used. All angles of altitude shown on the figures are apparent altitudes. Azimuths are from north clockwise.

5.1. *Fowlis Wester, P1/10, Fig.* 4

A short way north of the village of Fowlis Wester, near Crieff, there is a site with two ellipses both having properties found in Megalithic ellipses. (2) The line joining the ellipses gives the small positive declination known to indicate the equinoxial Sun. With no correction for semidiameter the declinations shown are $+0^\circ 3$ for the rising Sun and $+0^\circ\!.4$ for the setting Sun.

The large outlier M stands on the major axis (produced) of the eastern ellipse. The outlier is so arranged that, viewed from the ellipse centre, all of the hill Creag na Criche showing on the distant horizon, is hidden except the point A. This point shows the exact declination of the upper limb of the Moon rising in its most northerly *mean* position The details were determined astronomically and were checked on a second visit considered necessary because of the obvious importance of the site. There is a very large boulder N some 450 ft to the east. From the boulder an observer would see the Moon at its extreme north declination $(\varepsilon + i + \Delta)$ rising on the same point A (See inset, Fig. 4). There is, however, no apparent indication and this line has not been used in the analysis. The other ellipse is ruinous, but its axis probably showed the Moon's setting position. The exact point may have been formerly marked on the relatively near high horizon which exists, in this direction. A line for $\delta = \varepsilon$ has not yet been found, but it may be there.

5.2. *Kintraw, A2/5, Figs.* 5, 6 *and* 7

On the steep hillside above Kintraw Farm there is a small plateau beside the road running up to the pass to the east from the head of Loch Craignish. Here there is a site which is in some respects unique. The midwinter Sun having set behind Ben Shiantaidh in Jura would reappear momentarily in the notch between the two mountains (Fig. 7), the same group the Paps of Jura, as was used from Ballochroy for the summer solstitial Sun (Paper I, Fig. 9). But because of a ridge immediately south of the site the phenomenon would not have been visible from ground level. From the top of the original cairn all the Paps of Jura would have been in sight. On a recent visit I decided that the best method of checking the sight line was to get round the impassable gorge which forms the northern boundary of the plateau, and climb the steep hillside which rises from the gorge. Having got into the correct position with the menhir lined up on the Paps we found ourselves on a little platform cut into the *very* steep hillside. My granddaughter immediately pointed out the large stone

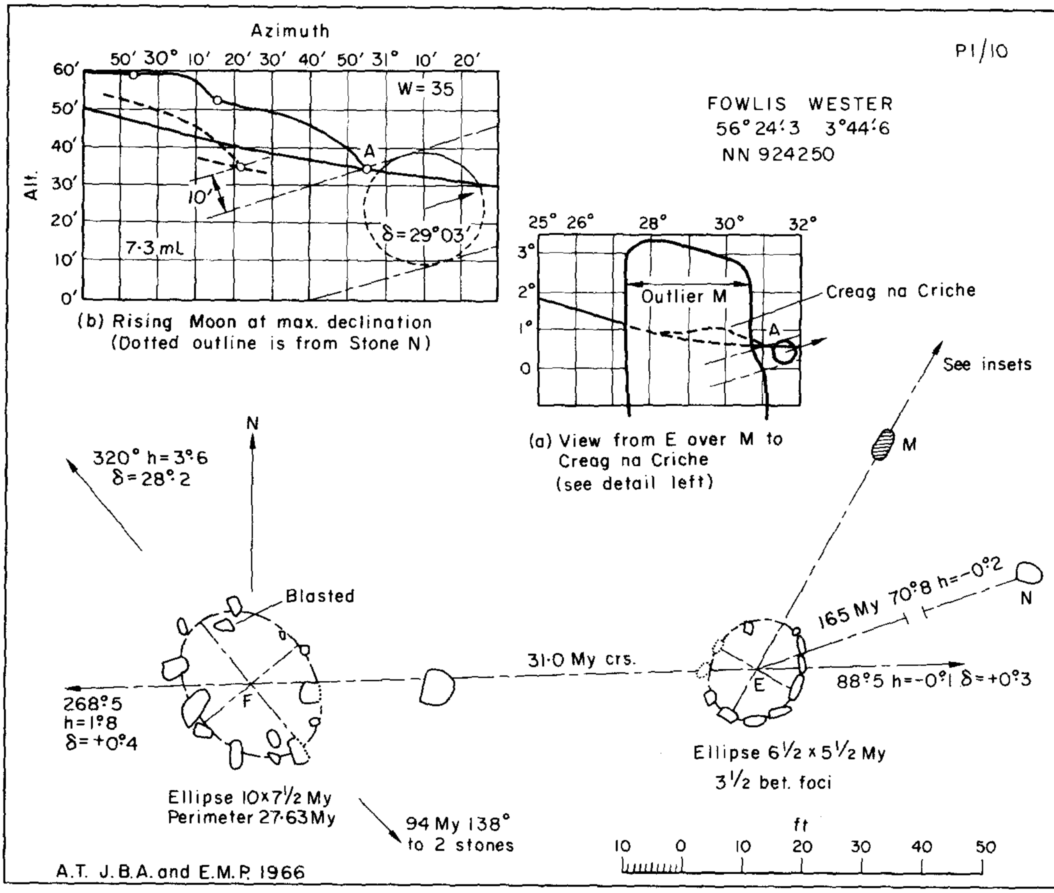


FIG. 4. Fowlis Wester, P1/10.

on the edge of the platform and the boulder on the south side of the gorge all arranged to form a line with the 12 ft menhir and the Paps. The platform is like a short length of narrow road and being about 20 ft above the level of the main site it provided exactly the kind of stance necessary for finding the day of the solstice. The observer stood at the west end until he saw the edge of the Sun in the notch. In the next few seconds he moved to his left till he cut off the last ray. He then marked his position. The night which showed the most westerly, position was, neglecting refraction changes, the solstice. About 1ft movement corresponds to 1″ declination so the site provided a very accurate instrument. We shall

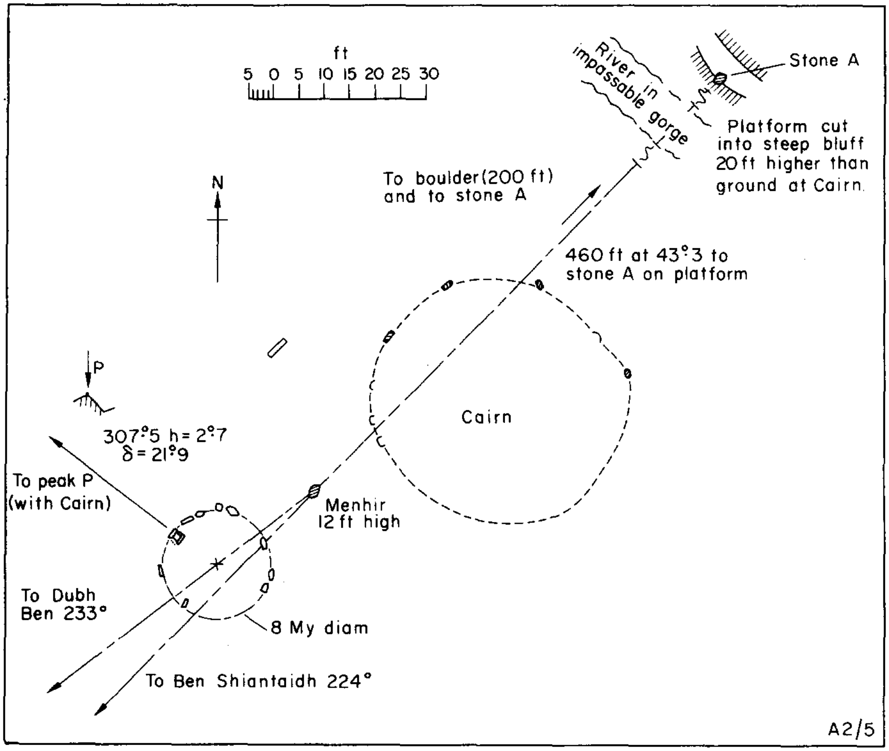


Fig. 5. Kintraw. 56° 11′ 17″, 5° 29′ 48″. NM 83010497. A2/5.

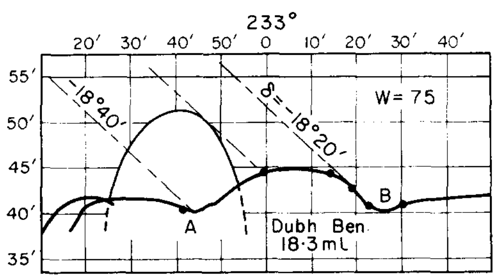


Fig. 6. Setting Moon with declination $-\varepsilon + i$ from Kintraw (Fig. 5).

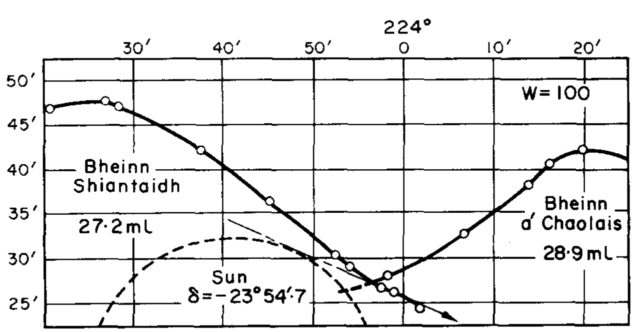


Fig. 7. Setting midwinter Sun from Kintraw.

see later that these solstitial lines, although accurately positioned by using the Sun with declination equal to ε, were used for observing the Moon in order to predict ~~the date of the~~ lunar solstice. This solstice would occur $4\frac{1}{2}$ years after the lunar declination maximum attained a value of ε (Fig. 22).

Comparing Kintraw with Ballochroy we see that the latter, because of the flatter slope of the foresight, allowed more time for the observer to adjust his position. Without the platform provided at Kintraw any attempt to move rapidly above the cliff while watching the Sun would have, sooner or later, resulted, in a serious fall. Today the platform is best approached by going down to the bridge and then climbing along above the right bank of the river.

The erectors chose the Kintraw plateau as the main position because it provided also very precise lunar sight lines. Some indication that it was so used is perhaps still to be found in the fact that the line from the menhir through the "circle" indicates the hill Dubh Ben also in Jura. This line is visible from the top of the cairn or from ground level. The outline shown in Fig. 6 was constructed from the contours on the 1 in O.S., but was checked and amplified by Sun/Theodolite observations from the site. It will be seen that we have the two limits 9′ on either side of $-(\varepsilon - i)$ defined correctly to within a minute or so. To find a spot in this difficult terrain which provided both types of line so accurately must have taken many decades of work. The accuracy with which the conditions are met is remarkable. There is little wonder that the erectors did not mind cutting the auxilliary platform and then perhaps raising the view point at the main site once the exact spot had been found by observations from the platform.

A small pocket in the circle, if it is a circle and not a despoiled cairn, was perhaps intended to indicate a notch in the horizon which now has a cairn at the top of the left-hand slope. This gave one of the calendar declinations (Paper I) and so would have fixed the position of the circle which would otherwise have been a more accurate indicator of Dubh Ben by being further from the menhir.

Altogether this site is so instructive that it must be considered as one of the most important of Megalithic man's many remarkable observatories.

5.3. *Escart, A4/1, Fig. 8*

Not far from Tarbert, Loch Fyne, on the south side of West Loch Tarbert there is an impressive alignment of five tall menhirs. The farmer points out that the two at the north end of the line point down the loch to where the Sun sets at midwinter, but the details have not been determined. If there is in fact a mark for the solstitial Sun then here again we have a dual purpose site but this time for the $-(\varepsilon + i)$ lunar solstice. A high wall now cuts the alignment in two so it is not possible to check that there is a clear sight line through the stones, but as is apparent on the survey this seems possible. The direction certainly points to Sheirdrim Hill, but even in winter, trees prevent direct verification. The line probably just grazes the bluff some 1000 ft from the stones. The outline shown was measured from the point where the line emerges, but circumstances did not allow of it being carried back to check on the stones. Thus the instrument position may have been slightly off the line affecting the azimuths by a few minutes of arc. The position of the stones must have been dictated by some second condition such as that suggested above.

5.4. *Callanish I, H1/1, Fig. 9*

The main site at Callanish has been described and surveyed by a number of writers (Paper I, p. 50). Recently Dr. Roy drew the authors attention to an important book by Col. Sir Henry James(5) which also contains a survey, albeit without accurate azimuths or altitudes. This work contains a number of classical extracts with a bearing on our present subject.

The long avenue to the north is formed by two of the most impressive alignments in Britain. Prof. Hawkins has pointed out that looking along the alignments to the South we see the setting point of the Moon in its most southerly position. Much more important, however, for our present study is the fact that the upper and lower limits of the 9′ perturbation are both shown, the values calculated from the profile being $-8'\!.0$ and $+7'\!.6$. The declination midway between the limits is $-29°\ 19'\!.2$. Deducting i and s gives $\varepsilon = 23°\ 54'\!.0$

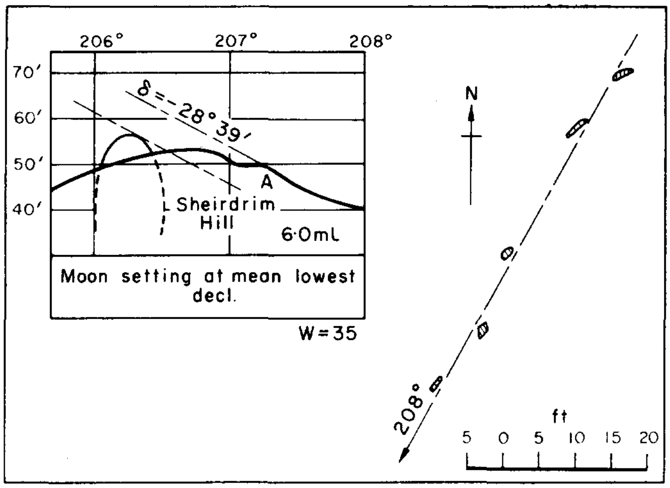


FIG. 8. Escart 55° 50′ 46″, 5° 26′ 26″. NR 8463466734. A4/1.

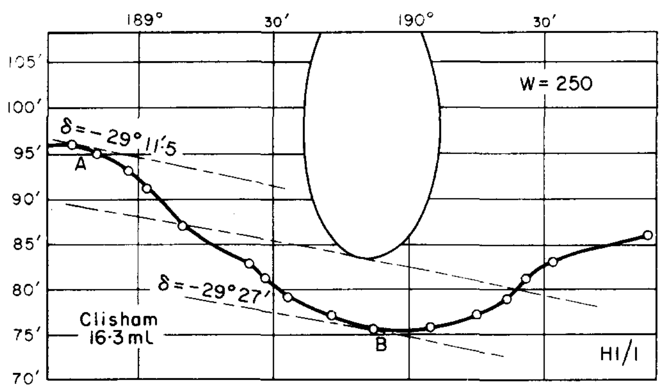


FIG. 9. Callanish I. H1/1. Moon at mean lowest declination.

which is the obliquity at 1900 B.C. The uncertainty is perhaps of the order ±100 years which still leaves the date not greatly different from that shown in Paper I (1800 B.C.) for the rising of Capella on the same alignments to the north or for the rising of Altair on the alignment which runs to the east. This, as has been shown elsewhere is by no means the only site at which a line serves a double purpose. The dual purpose perhaps explains why these two alignments were built so massively. A tremendous amount of experiment must have gone into finding a site which showed the declination limits so closely and at the same time allowed the line to show the Capella rising.

5.5. *Callanish V, H 1/5, Fig. 10*

This site stands near the top of one of the many hills surrounding the main structure. Its stones are on the skyline from Callanish I with which it probably gives solar solstitial lines. But its main duty was as a lunar site. The sketch plan of the site made by my son Dr. A. S. Thom in 1953 shows that part of the alignment indicates. Ben Mhor 12·7 miles to the south. Prof. Hawkins at my suggestion visited the site recently and agrees that Ben Mhor is clearly indicated. The declination of the Moon's limb grazing the top with mean parallax is $-29° 20'.1$. This yields $\varepsilon = 23° 54'.9$ which differs by less than a minute from that given at Callanish I. Using the Moon grazing Sithean an Airgid in the same way and taking $\Delta = 9'$ gives $\varepsilon = 23° 53'.8$.

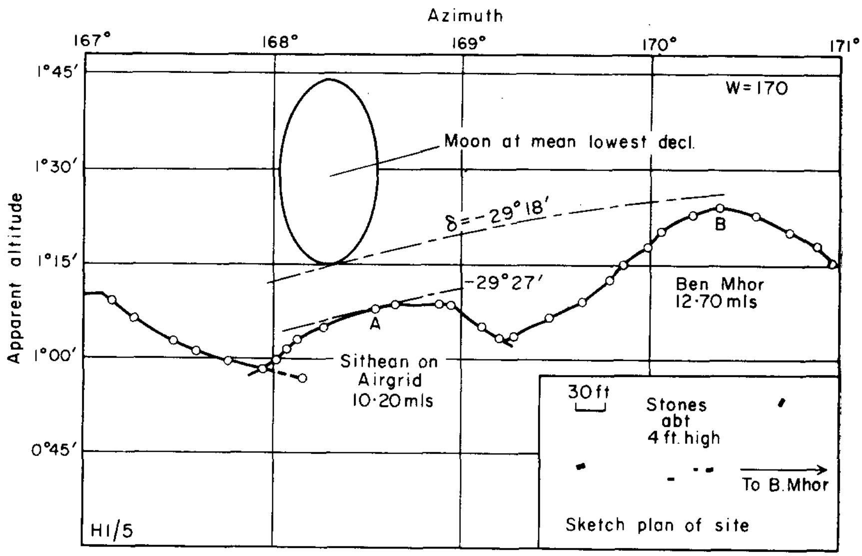


Fig. 10. Hills to south from Callanish V. 58° 10′ 13″.0, 6° 42′ 16″.3. NB 234299. H1/5.

The profile was constructed from the 6 in. O.S. which in this part of Lewis is contoured at 25 ft intervals. The hills are far enough away to permit geometrical accuracy without being so distant as to make refraction completely intractable. For these reasons the values deduced are considered as being amongst the most accurate presented in this paper.

It is suggested(2) that the continuation of the profile to the left showed the upper limit for the upper limb but, as Ben Mhor is the highest peak, here we shall restrict ourselves to the lines shown.

It is also shown(2) that Callanish V almost certainly had a lunar line to the north for the $(\varepsilon + i)$ case, but the profile is not accurately known.

5.6. *Stillaig, A10/5, Fig. 11*

This site lies on the east side of Loch Fyne near Skate Island. A plan of the site (in Paper I, Fig. 8) shows how the backsight *c* is orientated on the stone *a* behind which appears Cruach Brecain. A redetermination of the profile was attempted from the 1 in. O.S. and is given here, but it cannot be considered as being accurate by the standard which is now seen to be necessary for lunar sites.

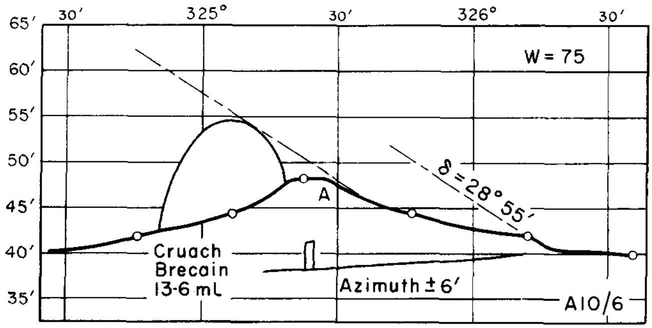


FIG. 11. Stillaig. Moon at mean lowest declination. 55° 51′.5, 5° 18′.0. NR 935678.

5.7. *Quinish, M1/3, Fig. 12*

This site is on the promontory forming the east side of Loch Cuan in the north of Mull. It is ruinous, but what remains indicates that the foresight was Carn Mhor, the highest hill visible to the south. The Sun did not show up when the profile was measured and an immenent gale made waiting impossible in the unsatisfactory anchorage provided by Loch

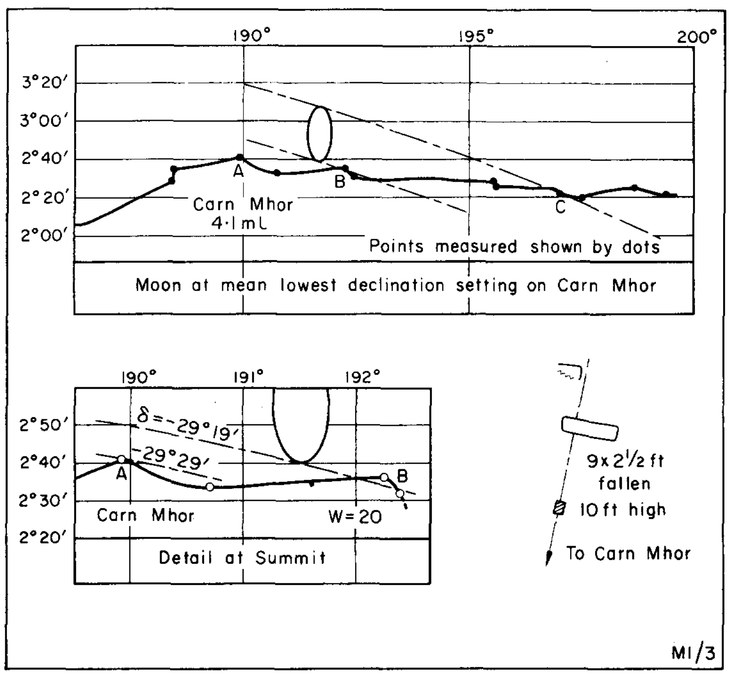


FIG. 12. Quinish, Mull. 56° 37′ 04″, 6° 13′ 04″. NM 4135855241.

Cuan. The lighthouse on the reefs to the north of Coll was used as a reference point. On request the Ordnance Survey provided the azimuth of the light (its position was uncertain) as 304° 50′. This permits us to be sure of the azimuths on the profile. The altitudes are to $\pm 1'$. It will be seen that Carn Mhor was undoubtedly considered by the erectors to give the absolute lowest declination. The notch *B* was probably used to give the mean lowest and *C* may have provided confirmation.

5.8. *Leacach an Tigh Chloiche, H3/11, Fig. 13*

A sketch plan of this important site will be found in Ref. 2, from which it will be seen that the indication of the lunar line is weak consisting of only a single slab. The declination limits are wider than we expect being 25′ instead of 18′ but the profile is not of high accuracy. Leacach an Tigh Chloiche itself forms a foresight for $\delta = \varepsilon$ from Sornach Coir Fhinn so here again we have the combination necessary for a complete lunar observatory.

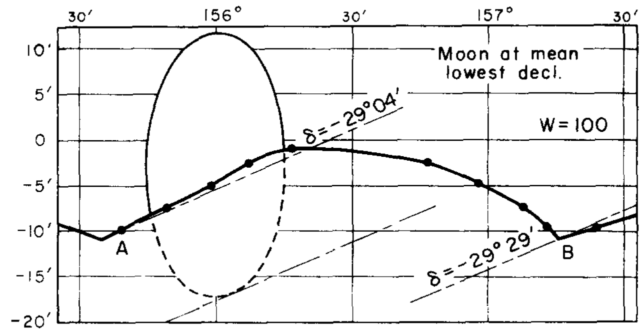


Fig. 13. Wiay Isd. from Leacach an Tigh Chloiche. 13·4 ml. 57° 34′ 38″, 7° 21′ 18″. NF 800669. H3/11.

5.9. *The standing stones of Lundin, P4/1, Fig. 14*

This site on the north shore of the Firth of Forth consists today of three menhirs. The two largest are about 14 ft high and being orientated on each other form an alignment which must be taken seriously. They are now slightly out of the vertical which makes it difficult

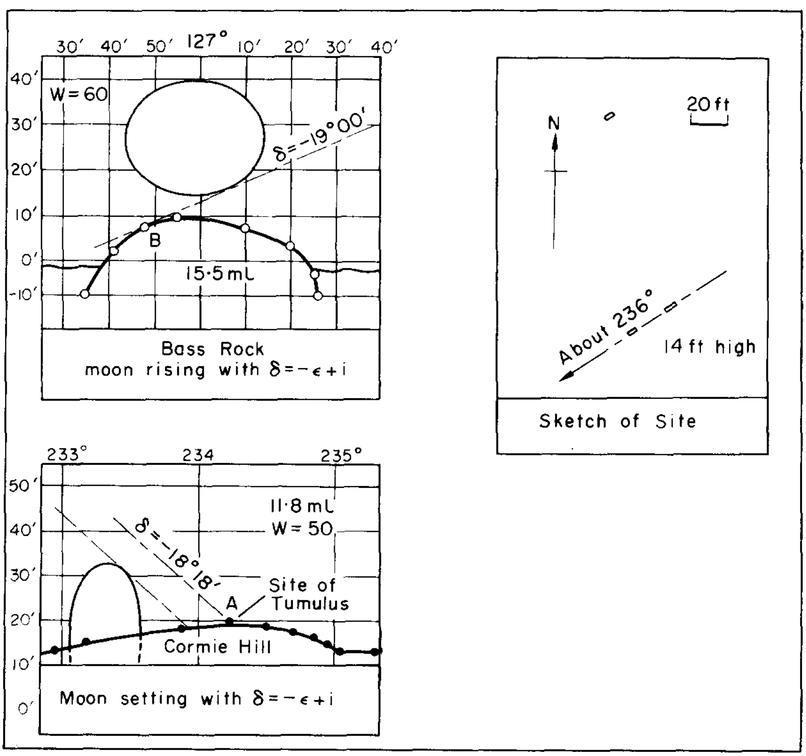


Fig. 14. Standing stones of Lundin. 56° 12′ 48″, 2° 57′ 36″. NO 4047502710. P4/1.

to determine the line accurately but it is within a degree or two of 236°. This line is now obscured by houses and trees, but the district is included in the new large-scale O.S. maps and these show that the line indicates Cormie Hill in Raith Park. A tower is shown and the map states that this is on the site of a tumulus. It will be seen on the constructed profile how the Moon with declination $-(\varepsilon - i)$ set on the hill. While this cannot be taken as an accurate line yet it shows that we are dealing with a lunar site and so we are not surprised at the accuracy with which that excellent foresight the Bass Rock far out in the Firth shows the rising position with the same declination. The points shown on the profile were by Sun/ theodolite technique in somewhat poor visibility and may be in error by $\pm 1'$.

5.10. *Mid Clyth, N1/1, Fig. 15*

An analysis of the geometry and stone spacing of this site will be found in Ref. 3. Here we need only say that today it consists of three sectors arranged as shown in the inset in Fig. 15. There is definite trace of other lines to the east presumably now built into the

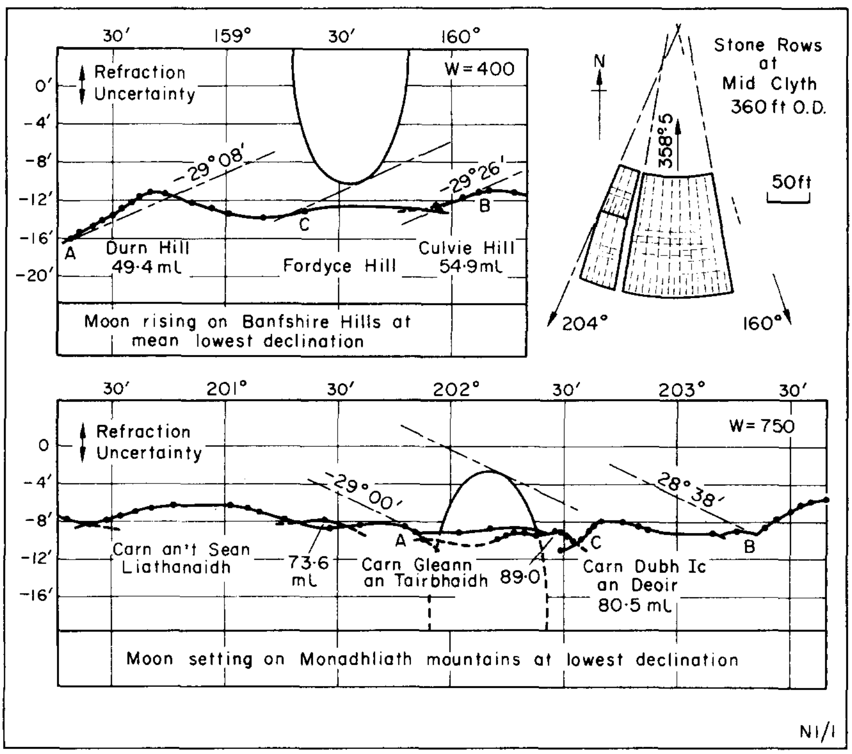


FIG. 15. Mid Clyth. 58° 19′.7, 3° 12′.3. ND 29523840. N1/1.

foundations of the track which passes close to this side. So perhaps the design was originally symmetrical about the meridian. If we consider the radiating lines as divisions on a protractor indicating azimuth then we see that where the main sector leaves off with its most westerly line the south-west sector takes over and where the south-west leaves off the north-west sector continuous. The last two lines of this sector contain the azimuth of the setting Moon in its most southerly position. Did the destroyed easterly sector extend to give the rising position? Almost certainly yes, since we find almost perfect foresights here. But why was it considered necessary to divide the visible arc of the Moon's path at lowest declination into 29 parts? Or, as is suggested[2], was the main sector intended for studying the gradual decrease in the arc which prior to 1750 B.C. Capella described below the horizon to the north? The mystery of the layout of this site and of others like it in Caithness is not yet unravelled but there can be no doubt that one of the purposes was lunar. The accuracy with which the lower declination limits are defined by two Banfshire hills is shown in Fig. 15. Once it was found that these hills hid the higher hills further inland the calculation of the profile was not difficult, but this cannot be said of the setting position. The difficulty here is the great depth of the Monadhliath Mountains. Dozens of peaks had to be plotted to make sure that the real skyline was being obtained. The great distances involved (70 to 90 miles) make it impossible to estimate the terrestrial refraction accurately. In fact changes in refraction at these distances can cause the hills behind, either to appear above the nearer hills or to vanish behind them. Never the less one is inclined to think that here again the usual limits are defined as indicated at A and B. Note that here as at Lundin Links the lower limb was used at rising and the upper at setting. But at this site it was probably necessary to use the upper limb at setting so that the small detail of these distant mountains would be seen silhouetted on the Moon's disc. It would be interesting if someone could get a photograph in really clear weather of the Monadhliath Mountains from Mid Clyth using a telephoto lens. It might allay the author's worry that after all he has missed one or other of the germane ridges.

5.11. *Glen Prosen, P3/1* (NO 349601)

A plan of this allignment will be found in Paper I, Fig. 20. On a second visit to check the azimuth no distant foresight could be detected and so the accuracy is limited to that which can be obtained from the alignment itself.

5.12. *Kingside Burn, G9/13* (NT 643642)

A plan will be found in Paper I, Fig. 10. The stones are rather smaller than shown so the azimuth determined from the alignment ought to be reasonably accurate. No distant foresight was noted.

5.13. *Parc-y-Meirw, W9/7, Fig. 16*

This is the most southerly of the reliable lunar sites known to the author. It is situated about 3 miles east of Fishguard and consists of a long line of 4 menhirs. After Paper I was published it occurred to the author that the Irish hills might show above the horizon on this alignment. Calculation based on the original O.S. of Ireland showed that in fact Mount Leinster is in sight but the large distances involved (over 90 miles) make the refraction very uncertain. The hill Croaghaun probably shows but the small hill to the right of Black Mount would be very low unless the refraction was higher than we are using (see section 7.1). This is not the place to discuss the possibility that the level of the sea was different in Megalithic times to what it is today (Ref. 10) but a 50 ft difference in level would at the height of the site (taken as 650 ft. O.D.) make a difference of only about 1′ in the dip of the horizon. The Moon with a declination of $(\varepsilon - i)$ appears to clear the spur by about 10′ so it is very probable that the erectors could see this hill.

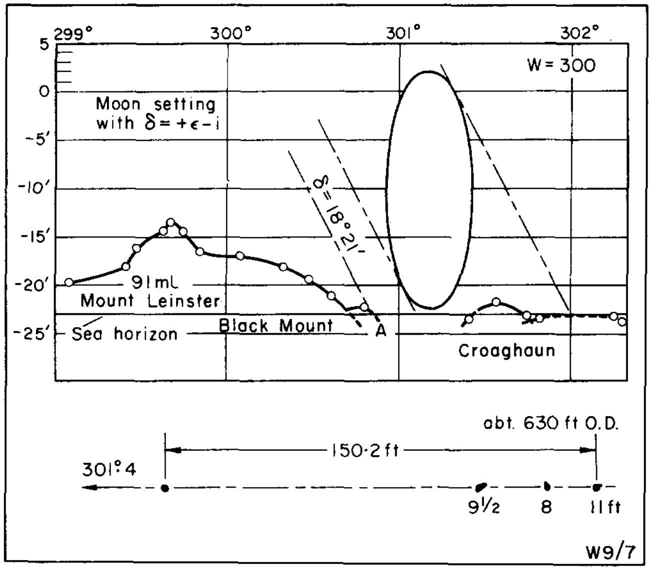


FIG. 16. Stones at Parc-y-Meirw. 51° 59′.2, 4° 54′.9. SM 999359. W9/7.

5.14. *Bunessan, M2/8*

All we have here is a flat-sided menhir with the long sides indicating a large rock standing on the skyline. The declination is 2′ higher than $\varepsilon + i + s + \Delta$ but this is hardly a reason for discarding the line.

5.15. *Blakelly Moss, L1/16, Fig. 17*

Some two miles south of Ennerdale Bridge in Cumberland there is a good circle of standing stones 54·5 ft or exactly 20 Megalithic yards in diameter. It stands close to the road on the east side but is not shown on the O.S. maps. When this circle was being surveyed there was no visible sun and the azimuths were referred to Screel Hill, 31 miles distant in Dumfriesshire, as being the only distant peak in sight. It turned out that the eastern escarpment (the obvious foresight and that used on the survey) shows the declination of the uper limb of the Moon at its mean solstice with such accuracy (±1′) that it is difficult to believe it is

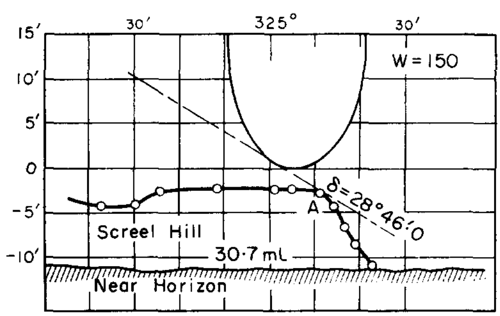


FIG. 17. Blakeley Moss. 54° 30′ 46″, 3° 27′ 11″.
NYOG 001402. L1/16. Moon at mean maximum declination.

by chance. In nearly all circles with outliers there is a stone in the ring on the *far* side exactly opposite the outlier. We find that the highest stone in this circle is exactly across the centre which is known accurately, from Screel Hill. The only possible place for an outlier indicating Screel Hill is the position now covered by the road so it seems possible that it has been removed. This is the only line included in the analysis which has such a weak indication that the site is lunar, but are we justified in neglecting it?

5.16. *Dervaig, M1/5, Paper I Fig. 7*

This important alignment was probably intended to show the solstitial Moon setting on the western and of Canna but verification at the site has not yet been possible. The O.S. does not show enough detail of the Canna shore and clifts and accordingly the line is not included in the analysis.

5.17. *Clachan an Diridh, P1/18*

These stones are now surrounded by a new forest. Two further attempts to measure the profile shown in Ref. 2 were not successful and accordingly this line is omitted. It seems to be a lunar site but the hill horizon is too near for dependence to be placed on a calculated profile until the larger-scale O.S. photogrametric survey includes this area.

6. An examination of the 17 sites described above shows that about 12 depend for their acceptance as lunar sites on alignments. It is remarkable that amongst these will be found about half of the most impressive alignments in Britain.

In Fig. 18 will be found a histogram of $\pm\delta \mp \varepsilon \mp i$ with $\varepsilon = 23^\circ\!.90$ and $i = 5^\circ\!.145$. There is no definite evidence of any lines with semidiameter zero i.e. the limb was always used, but there is evidence that in 7 lines the mean maximum (in $\Delta = 0$) was used. Broadbent's analysis ([8]) for the examination of a quantum hypothesis might be applied. The analysis is intended to be used where there is a large number of nodal points. Here we have only three, but no other method of assigning a probability level to this example seems

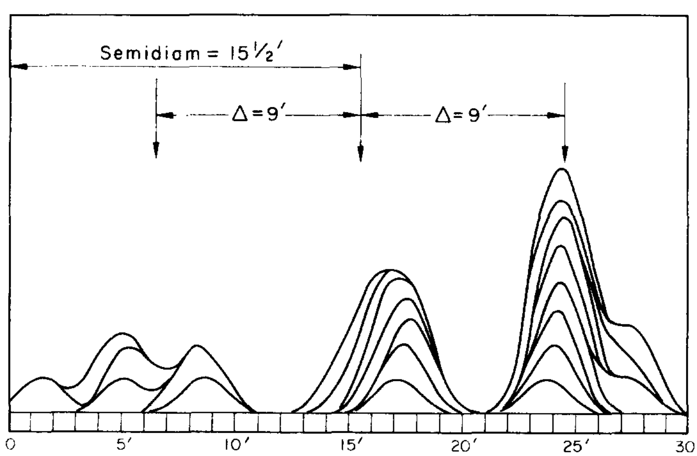


FIG. 18. Histogram of $\pm\ \delta \pm \varepsilon \pm i$.

to be available. Numbering the nodal points $-1, 0$ and $+1$ we find in Broadbent's notation, the quantum $2\delta = 9'.6$ and the position of the zero node $\beta = 15'.7$. The probability level is less than 0·5%. In our notation this means that $\Delta = 9'.6$ and semidiameter $= 15'.7$ and there is less than 1 chance in 200 of the values lying so near the nodel points by accident.

7. First Analysis

The 24 lines taken from the sites, shown or described, are given in Table 2. The 12 lines with the best indicators are given first so that these can, if considered necessary, he treated separately. It does not follow that the most accurate lines are confined to the first half of the table.

Table 2. Known Good Lines

Site	az	app. alt.	Decl.
A4/1 Escart	207° 17′	+49′	−28°.65
A10/6 Stillaig	325° 28	48′	+28°.76
H1/1 Callanish I	188° 45	95′.8	−29°.19
H1/1 Callanish I	189° 52	75′.8	−29°.45
H1/5 Callanish V	170° 18	84′.0	−29°.34
H1/5 Callanish V	168° 32	68′.0	−29°.45
M1/3 Quinish	189° 56	161′	−29°.46
G9/13 Kell Burn	129° 50	99′	−19°.06
P1/10 Fowlis Wester	30° 55	34′	+29°.32
P3/1 Glen Prosen	197° 57	118′	−28°.91
P4/1 Lundin	233° 15	+19′	−18°.30
Wa/1 Pare-y-Meirw	300° 49	−23′	+18°.35
A2/5 Kintraw	233° 16	+44′	−18°.34
A2/5 Kintraw	232° 44	+40′	−18°.67
H3/11 Leacach an	155° 39	−9′.5	−29°.07
H3/11 Tigh Chloiche	157° 17	−10′.5	−29°.48
L1/16 Blakeley Moss	325° 11	2′.5	+28°.77
M1/3 Quinish	192° 20	+154′	−29°.30
M2/8 Bunessan	330° 42	+12′	+29°.51
N1/1 Mid Clyth	158° 20	−15′.5	−29°.14
N1/1 Mid Clyth	160° 04	−11′.5	−29°.43
N1/1 Mid Clyth	201° 50	−9′.0	−28°.98
N1/1 Mid Clyth	203° 22	−9′.5	−28°.64
P4/1 Lundin	126° 49	+8′	−19°.00

The first 12 lines have better indicators than the last 12.

From the tabulated declinations we now proceed to deduce the most likely values of ε, i, Δ and s. Assuming that a line belongs to a lunar solstice then its declination is one of the values of

$$\delta = \pm\varepsilon \pm i \pm \Delta \pm s$$

where s is never zero but Δ may be zero. We can accordingly write the 24 observation equations given in Table 3. From these we form the 4 normal equations shown.

Table 3. Determination of ε, i, Δ and s

Observation Equations

A4/1	$-28°.65 =$	$-\varepsilon$	$-i$	$+\Delta$	$+s$
A10/6	$+28°.76 =$	$+\varepsilon$	$+i$		$-s$
H1/1	$-29°.19 =$	$-\varepsilon$	$-i$	$+\Delta$	$-s$
H1/1	$-29°.45 =$	$-\varepsilon$	$-i$	$-\Delta$	$-s$
H1/5	$-29°.34 =$	$-\varepsilon$	$-i$		$-s$
H1/5	$-29°.45 =$	$-\varepsilon$	$-i$	$-\Delta$	$-s$
M1/3	$-29°.46 =$	$-\varepsilon$	$-i$	$-\Delta$	$-s$
G9/13	$-19°.06 =$	$-\varepsilon$	$+i$		$-s$
P1/10	$+29°.32 =$	$+\varepsilon$	$+i$		$+s$
P3/1	$-28°.91 =$	$-\varepsilon$	$-i$	$-\Delta$	$+s$
P4/1	$-18°.30 =$	$-\varepsilon$	$+i$	$+\Delta$	$+s$
W9/7	$+18°.35 =$	$+\varepsilon$	$-i$	$-\Delta$	$-s$
A2/5	$-18°.34 =$	$-\varepsilon$	$+i$	$+\Delta$	$+s$
A2/5	$-18°.67 =$	$-\varepsilon$	$+i$	$-\Delta$	$+s$
H3/11	$-29°.07 =$	$-\varepsilon$	$-i$	$+\Delta$	$-s$
H3/11	$-29°.48 =$	$-\varepsilon$	$-i$	$-\Delta$	$-s$
L1/16	$+28°.77 =$	$+\varepsilon$	$+i$		$-s$
M1/3	$-29°.30 =$	$-\varepsilon$	$-i$		$-s$
M2/8	$+29°.51 =$	$+\varepsilon$	$+i$	$+\Delta$	$+s$
N1/1	$-29°.14 =$	$-\varepsilon$	$-i$	$+\Delta$	$-s$
N1/1	$-29°.43 =$	$-\varepsilon$	$-i$	$-\Delta$	$-s$
N1/1	$-28°.98 =$	$-\varepsilon$	$-i$	$-\Delta$	$+s$
N1/1	$-28°.64 =$	$-\varepsilon$	$-i$	$+\Delta$	$+s$
P4/1	$-19°.00 =$	$-\varepsilon$	$+i$		$-s$

Normal Equations

$636{\cdot}57 =$	24ε	$+12i$	$+\ \Delta$	$+\ 4s$
$413{\cdot}13 =$	12ε	$+24i$	$+\ 5\Delta$	$+\ 8s$
$53{\cdot}66 =$	ε	$+\ 5i$	$+17\Delta$	$+\ 5s$
$143{\cdot}83 =$	4ε	$+\ 8i$	$+\ 5\Delta$	$+24s$

Solving these we find

$$\begin{aligned} \varepsilon &= 23°\,54'\,09'' \\ i &= 5°\,08'\,30'' \\ \Delta &= 09'\,40'' \\ s &= 15'\,41'' \end{aligned}$$

These can be compared with the values given by astronomers (Section 1). The agreement is so good that it is necessary later to look into the explanation of how Megalithic man could have set out these lines so accurately.

A similar solution based on the 12 lines with the best indicators yields

$$\begin{aligned} \varepsilon &= 23°\,53'\,59'' \\ i &= 5°\,08'\,49'' \\ \Delta &= 08'\,00'' \\ s &= 16'\,56'' \end{aligned}$$

These values, based as they are on lines with indicators so good that no one is likely to question them, show that we are dealing with genuine lunar observatories. This gives added confidence that the other lines are also lunar.

7.1. *Second analysis*

When it is accepted that we are dealing with genuine lunar lines it is no longer necessary to have i, Δ and s unknowns. We can use the mean values of these quantities given by modern astronomy and proceed to make an attempt to deal with the greatest source of trouble in the whole investigation namely, refraction.

Since there are both north and south declinations it is possible to make astronomical refraction one of the unknowns and since there are lines of all lengths we can deal with terrestrial refraction in the same way. The method adopted is to assume that we add βD to terrestrial refraction and ϱr to astronomical refraction, where D is the length of the line in miles and r is the astronomical refraction already used (Table 1). β and ϱ are to be determined as those values which best fit the observed declinations in Table 2 retaining ε also as an unknown. The effect of adding βD is to increase the altitudes on the calculated profiles and the effect of adding ϱr to r is to decrease the final corrected true altitudes. The total effect on the declination in Table 2 is

$$+(\beta D - \varrho r)\, d\delta/dh$$

where h is the altitude. Algebraically this applies to both positive and negative declinations and so north declinations are numerically increased and south declinations numerically decreased. It is this which makes it possible to eliminate refraction in determining ε or to find its value. Each line which depends on a calculated profile gives an observation equation of the form

$$\varepsilon = \varepsilon_1 + \beta D d\delta/dh - \varrho r d\delta/dh$$

where $\varepsilon_1 = \delta \pm i \pm \Delta \pm S$; δ is from Table 2, and $i = 5°.145$, $\Delta = 0°.145$, $s = 0.°259$.

The necessary particulars are given in Table 4 for those lines which depend mainly on calculated profiles.

TABLE 4. DETERMINATION OF REFRACTION AND OBLIQUITY OF ECLIPTIC

Site	ε_1 deg	r min	D miles	$d\delta/dh$	$rd\delta/dh$ deg	$Dd\delta/dh$
A10/6	+23·874	26	14	0·93	0·4	13
H1/1	−23·931	20	16	0·99	0·3	15
H1/1	−23·901	23	16	0·99	0·4	16
H1/5	−23·936	22	13	0.98	0·4	13
H1/5	−23·901	23	10	0·98	0·4	10
P4/1	−23·849	30	12	0·88	0·4	11
W9/7	+23·899	38	90	0·84	0·5	76
A2/5	−23·889	27	18	0·87	0·4	16
A2/5	−23·929	27	18	0·87	0·4	16
H3/11	−23·811	36	13	0·97	0·6	13
H3/11	−23·931	36	13	0·97	0·5	12
L1/16	+23·884	35	35	0·91	0·5	28
N1/1	−23·861	37	49	0·96	0·6	47
N1/1	−23·881	36	55	0·96	0·6	53
N1/1	−23·949	36	90	0·96	0·6	86
N1/1	−23·899	36	90	0·96	0·6	86

The values of D and r have been rounded off to the nearest unit. As examples, working in degrees, the first two lines give the following observation equations

$$-\varepsilon + 23{\cdot}874 + 13\beta - 0{\cdot}4\varrho = 0$$
$$+\varepsilon - 23{\cdot}931 + 15\beta - 0{\cdot}3\varrho = 0$$

Omitting 23 from all 16 equations we find the normal equations

$$16\,\varepsilon - 14345 + 277\beta - 4{\cdot}8\varrho = 0$$
$$277\,\varepsilon - 252291 + 28235\beta - 271{\cdot}5\varrho = 0$$
$$-4{\cdot}8\,\varepsilon + 4318{\cdot}3 - 271{\cdot}5\beta + 3{\cdot}76\varrho = 0$$

from which $\varepsilon = 23°\,53'\,46''$
$\beta = 0{\cdot}00033$ deg/mile or $1{\cdot}2$ sec/mile
$\varrho = 0{\cdot}020$, i.e. 2% of r.

Using all 24 lines gave

$\varepsilon = 23°\,54'\,22$
$\beta = 0{\cdot}00048$
$\varrho = 0{\cdot}040$

From these values it appears that the data from the profiles are best represented by increasing the astronomical refraction by 2 or 3% and increasing the value of terrestrial refraction from $7''\!.3$ to perhaps $8''\!.5$ per mile.

Perhaps we cannot yet altogether accept these values but with hindsight they are very much what we might have expected. The refraction in Table 1 is based largely on measurements at sunset and we have seen that terrestrial and therefore astronomical refraction tends to go on increasing after dark. The clear skies which seem to have existed throughout the period in which we are interested may have produced consistently high refraction at night by rapid cooling of the ground. Twice in August towards midnight with a clear sky and little wind the author has measured terrestrial refraction of about $9''\!.5$ per mile so it may well be that the reductions in Table 2 have been made with too low a refraction. It seems strange that we have to go to Megalithic observatories to obtain night time refraction at low altitudes—terrestrial and astronomical. It is to be hoped that someone suitably placed will make a series of observations of the setting Moon or of Sirius or Canopus to settle the matter, these being the only stars visible to low altitudes.

It will be seen that this 2nd analysis has not materially altered the value of ε, but a short investigation showed that it has slightly reduced its standard deviation to about $\pm 23''$.

7.2. *Effect of Summer and Winter Temperature*

A difficulty in assessing the true mean value of ε lies in the difference between summer and winter night temperature. A New Moon will interfere with observation and this will occur when the Moon is at a low declination in winter and at a high declination in summer. So there may have been relatively fewer observations when the Moon was at its solstice in the south during the winter than during the summer and similarly fewer observations when it was at its solstice in the north during the summer.

If we apply an estimated correction to allow for the higher winter and lower summer refraction we find that the effect is of the same sign for the numerical values of both north and south declinations. Thus the effect cannot be deduced from the measured declinations for lines of equal altitude in the way in which we have deduced mean refraction values. If any effect is actually present, it will have made our deduced value of ε slightly high.

8. Conditions Affecting Accuracy

The erectors were dealing with three cyclical declination components but all their information had to come from the monthly declination maxima. The only occasions on which they could observe an absolute maximum declination would be when the maxima of all three components occurred simultaneously with moonrise or moonset. As this is such a rare event we must look carefully at the conditions which would be actually encountered. For this purpose it will suffice to assume that near its own maximum each component behaves sinusoidally. Consider a component of amplitude g and period p. We wish to record the maximum but the observation is late by a time θ which is small compared with p. Then the error will be

$$E = g(1 - \cos 2\pi\theta/p) \text{ or } 2g \sin^2\pi\theta/p.$$

Since we seek an estimate only this can be written

$$E = 2g\pi^2\theta^2/p^2 \quad \text{or say } k\theta^2.$$

The values of k for the three components are

18·6 year component, $g = 5^\circ\!.15$, $k_1 = 0{\cdot}000132$
173·3 day component, $g = 9'$, $k_2 = 0{\cdot}0059$
27·32 day component, $g = (e \pm i)$, $k_3 = 47{\cdot}3$

These values of k give the error in minutes of arc when θ is in days. For the last component the worst case has been taken namely $g = 29^\circ$.

The mean values of the three periods have remained sensibly constant for thousands of years but individual values of the last period vary considerably. A complete investigation making allowance for these variations would probably demand a Monte Carlo method. Here we shall make a crude estimate using the mean. The above value of k, shows that 100 days after the maximum the first component has fallen only 1'.3 below its highest value and so *for the time being* we shall neglect its effect on the other two. Moonrise on a particular occasion could be $^1/_2$ day from the time of the monthly maximum with a consequent error of 12′, but we have seen that some sites were arranged for observing both moonrise and moonset and as, at the lunar solstices in these latitudes, the interval from rising to setting always differed definitely from 12 hours, either the rising time or the setting time would be nearer than 12 hours to the time of maximum declination. But let us consider what happened when there was a foresight for the rising Moon only. Assume that as usual the observer moved rapidly into the position showing grazing and marked the position with a stake. Suppose that the intervention of bad weather or of a new Moon allowed him to observe two successive maxima of the 3rd component, one before and one after the maximum of the 2nd component.

Put M = tropical mean lunar month = 27·3216 days,
D = Lunar day or mean interval between two successive lunar transits = 1·03505 days.

Then the conditions will bett as in Fig. 19 which shows declination plotted on time. The Moon rose at time marked A and after 1·035 days was observed to rise again at B. After a further 26 x D days, i.e. about a month later, it would again have approximately the same declination and would rise at time C, and a day later at D. The greatest error would occur if there were complete symmetry, i.e. if $x = M - x$ and $n = m$, where x, m and n are defined by the figure. Then we get $x = 13{\cdot}66$ days, $m = n = 0{\cdot}205$ days and the total error or the amount by which the declination at B and C falls below Q is, as shown on the figure

$$k_2x^2 + k_3m^2 \quad \text{or } 1.1 + 2'\!.0, \quad \text{i.e. } 3'\!.1.$$

Observations at A and D would have shown a much lower declination and would have been replaced by those made at B and C. It will be found that any other values of x and m will produce one value showing a smaller error than 3'.1. If it so happened that observations were made in a year when the above assumed unfavourable conditions obtained, then, due to the incommensurability of the periods the next solstice, 18·6 years later, would have been more favourable. Nevertheless it might well have taken a long time to establish the final backsight unless the erectors had used some means of allowing for the most troublesome of the three terms namely k_3m^2 above. As we shall see in later paragraphs there were

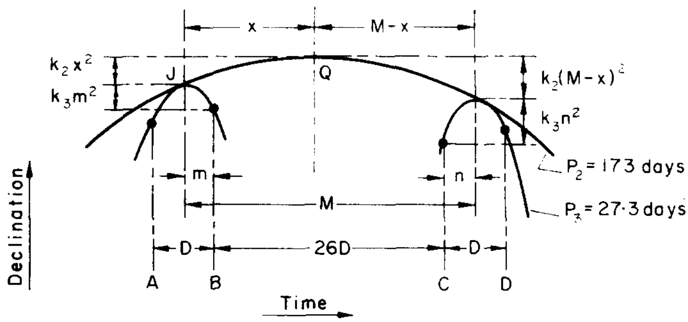


Fig. 19. Moon's declination near a lunar solstice. Two declination maxima are shown near a maximum of the 173-day cycle. (Not to scale).

methods available to them whereby they could have made approximate allowance for these terms. But there were continual fluctuations in the Moon's apparent position produced by variations in parallax, semidiameter and refraction. The observers could neither have explained these nor separated them out. If they always recorded the highest numerical positive and negative declinations the effect would be to leave us with too high a value of ε, but we have not yet enough evidence as to how they dealt with anomalies to form a definite opinion.

8.1. If all the work which Megalithic man directed to recording the conditions at the lunar solstices was intended to assist in eclipse prediction then we have to consider if he could have determined the period of the 2nd component which is exactly half an eclipse year. Godfray[11] in his Lunar Theory (1859) says: "Tycho Brahe further discovered that the inclination of the lunar orbit to the ecliptic was not a constant quantity of 5° as Hipparchus had supposed, but that it had a mean value of 5°8' and ranged through 9'30" on each side of this, the least inclination 4°58½' occurring when the node was in quadrature, and the greatest 5°17½' being attained when the node was in syzygy." We see in Fig. 1 how this works out. The eclipses occur only when the declination is near one of the maximum points of the 173- day cycle, i.e. when the node of the lunar orbit is in opposition or conjunction. Using an observatory such as we have been discussing the erectors would have noticed this relation when the Moon was near one of its solstices ($\varepsilon + i$). But throughout part of the 9 years which elapsed before the next solstice ($\varepsilon - i$), the ripple would not have been apparent. Could they have obtained at one solstice a sufficiently accurate value of the period to carry them through to the next? Once they had done this, they would be able to improve their estimate of the period to any desired extent. Assuming there was a method of determining the day of the maximum there is still a difficulty. The 18·6 year component distorts the ripple so that its maxima are brought together by over 2%. To show this write

$$\delta = \varepsilon + i \cos 2\pi(b + t)/p_1 + \Delta \cos 2\pi t/p_2$$

where (see Fig. 20] $p_1 = 18{\cdot}61$ years, $p_2 = 173$ days, $\Delta = 9'$ and we measure t from the maximum of the undisturbed ripple. Having differentiated to find the maximum of the combination we can replace sines by angles and so find

$$t_{\max} = -ibp_2^2/\Delta p_1^2$$

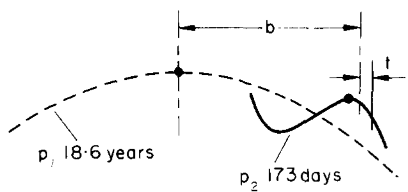


FIG. 20. Displacement of the maximum of the second component.

as the displacement of the maximum. Numerically this gives $t_{\max} = -0{\cdot}022b$. Thus it does not matter how many waves we include at one solstice the period will appear too short by about 1 part in 40. It is true that the period between the minima will be too long by the same amount so that the mean will be correct. But this method seems too difficult.

There are, however, 7 lines recording the value of $\varepsilon \pm i$ exactly, i.e. the point G in Fig. 1. Figure 18 shows how accurately this position ($\Delta = 0$) was recorded. It must be remembered that the values shown contain errors due to faulty measurement on the authors part and discrepancies produced by the fact that we have brought together lines which may have been erected at different times, i.e. with different values of ε. The method used to obtain the high accuracy which these lines must originally have possessed was probably to interpolate on the ground the position midway between the stake positions showing the observers stance for the maximum and minimum points of the 9′ ripple at the lunar solstice. Lines so established for the mean would give a better method of estimating the period of the 173 day component, but looking at Fig. 1 we see that there were still difficulties, one of these being interpolation.

8.2. *Possible Observing Technique*

There are really two separate problems. How were the positions of the backsights established and how were they used?

We know from Kintraw and Ballochroy that the observer moved rapidly across the line of sight till he found the exact position for grazing. If he marked for the Moon the position for three successive nights, moving back a little each night he would find he had an arc set out on the ground. This arc could be used to show roughly the extreme position (see Fig, 19) From a study of Avebury(2) we know that the large radius arc there was probably set out by offsets from chords. No rope could be used to strike an arc of radius 750 Megalithic yards such as we find carefully set out at Avebury. The Avebury engineer would establish the ends and the centre of the arc by measuring along the radii. From his very extensive knowledge of practical geometry he would know that the versine (or sagitta) of a flat arc is reduced to one quarter of its length when the chord is halved. He could thus go on subdividing till he had as many points as he required. The same method could be applied to the three lunar stakes. These observers had set out many lunar sites probably experimenting at each for years and could have learned that at a given site with a given foresight the sagitta of the arc was always the same length (B_1, B_2, Fig. 21). With this knowledge it was, at a particular monthly maximum only necessary to establish two stakes A_1 and B_1, corresponding to A and B in Fig. 19. The sagitta ν was known, the arc $A_1 B_1$ could be roughly set out on the ground and so the extreme position J_1 could be found. This method, given flat ground, was certainly available. To find out if it was used needs much more field work. With certain exceptions to be mentioned later we see only the final position marked in stone. But at Mid Clyth perhaps we are looking at an elaborate backsight in the form of a sheet of stone

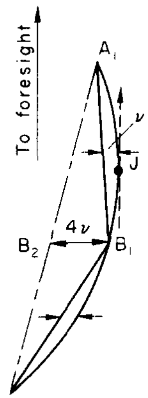


FIG. 21. Determination of maximum.

"graph paper". The stakes were perhaps placed on the grid on several successive nights and the necessary interpolations worked out at leisure. The north-west sector has the correct orientation and size for a foresight on Warehouse Hill two miles to the north-north-east and the solstitial Moon, $(\varepsilon + i)$, rose on this hill.

The above is, of course, speculative and even so still leaves us wondering how the erectors at Mid Clyth established that the foresights provided by Durn Hill and Culvie Hill gave such accuracy (Fig. 15). The necessary backsights must have ranged over a very much larger area than that enclosed by the stone rows. It may be of interest in this connection to mention that there is a very similar sector of stone rows at Ulbster not far from Mid Clyth. The hill altitudes at Ulbster are not known but this site may be another lunar observatory.[3]

8.3. *Flat Area Needed for the Backsights*

On each profile will be found approximate values of W the transverse movement in feet needed to produce a declination change of one minute of arc. This enables an estimate to be made of the space required for the interpolation operations which have been suggested as possible techniques.

Suppose we are finding the stake position for one of the monthly maximum declination points. If we adopt the method indicated in Fig. 21 the transverse movement required corresponds to perhaps 3′ declination difference. If Megalithic man did not use this method but depended simply on looking at solstice after solstice for the maximum the side movement would be of the same order. In either method there was at most sites sufficient space available. If it was desired to find the maximum of the 9′ ripple from two monthly maxima already established on the ground not much more space was necessary.

But what about those sites which were set up for the node of the 9′ wave, i.e. the point G in Fig. 1? To interpolate on the ground the date of G from the known dates of F and H needed a much wider space corresponding to perhaps 8 or 9 minutes of declination. It is perhaps significant that among the lunar observatories only at those which have a foresight for the node ($\Delta = 0$) do we find round the stones the wide space needed. Consider, for example, Lundin where the great stones are in the wide stretch of ground now used as a golf course. On the other hand sites like Callanish I, Escart and Kintraw have restricted side movement and at the same time have no foresight for the $\Delta = 0$ case.

We may ask how at sites with restricted side movement the initial determination of the permanent backsight was made. I think the answer is to be found in the relation between Callanish I and Callanish V. The latter as we have seen has accurate foresights for mean and maximum positions of the Moon at the lunar solstice. Since the two sites are intervisible it was easy to signal from V to I when the Moon was passing through one of the required positions.

9. Eclipse Prediction

An eclipse can happen only when the Sun and Moon are within a small distance of the nodes of the lunar orbit. This distance is known as the ecliptic limit. Its value for solar and lunar eclipses, total and partial, will be found in standard texts. On Fig. 1 these limits are indicated roughly in days stretching on each side of the date when the node was in syzygy, i.e. when the 9′ oscillation was at a maximum. A lunar eclipse will occur if a full Moon falls inside the limits shown. It is seen that at the third "danger period" shown on Fig. 1 the full Moon happened just outside the limit and so was not eclipsed. The eclipse limits for solar eclipses are wider than those for lunar eclipses.

To predict the danger periods Megalithic man had to know the date of one maximum and the period of the 9′ oscillation. Considering the effort he expended on lunar observatories it would be strange if he had not obtained a reasonably accurate knowledge of this period. He was also interested as we have seen in the node ($\Delta = 0$) of this oscillation and at Callanish V he had apparently established lines for this declination ($\varepsilon + i$) with the Moon in the north as well as in the south (see Fig. 10; and also fig. 11.4 in Ref. 2). Perhaps Mid Clyth and other sites had the same facilities. Without too elaborate interpolation he could use these sites to get an estimate of the date of this node, G in Fig. 1. Facing south he would see that the monthly maximum F was too early and then a fortnight later facing north he would see that K was a little late. He had another opportunity some months later at L and M. The date of the maximum was one quarter of 173 or 43 days after the estimated date of G or the same interval before the date estimated between L and M. There were obvious ways in which he could make sure he was dealing with a maximum sufficiently near to the top of the 18·6-year cycle.

The above procedure is a natural development of the method by which the Megalithic calendar was controlled, i.e. by pairing dates (see Paper I or Ref. 2). For the calendar one line, i.e. one declination fixed two epochs separated by 2, 4, 6 or 8 of what in Paper I we called "months". Here one declination fixed two dates separated by one quarter of an eclipse year.

Having determined the date of a maximum the observer was in a position to predict the danger periods till the next lunar solstice when presumably he checked by new observations. There were of course times when he could not observe, e.g. during bad weather or when one of the declination maxima happened to be too close to new Moon. To bridge these gaps he probably tried to get as accurate a value of the period as possible.

It may be that in the above we have not interpreted the evidence correctly but when we consider the complexity of sites like Mid Clyth, Ulbster, Fowlis Wester or Callanish even in their depleted condition it is certain that some kind of sophisticated technique was in use. The study of Megalithic man's calendar made in Ref. 2 shows that the actual time (the solstice) when the Sun attained its maximum declination was never as much as a day from the appropriate calendar epoch. But the calendar was not linked to the tropical year by solstitial observations. This was done at more easily determined dates, ideally at the equinoxes. It is reasonable to suppose that the same idea was extended to eclipse predic-

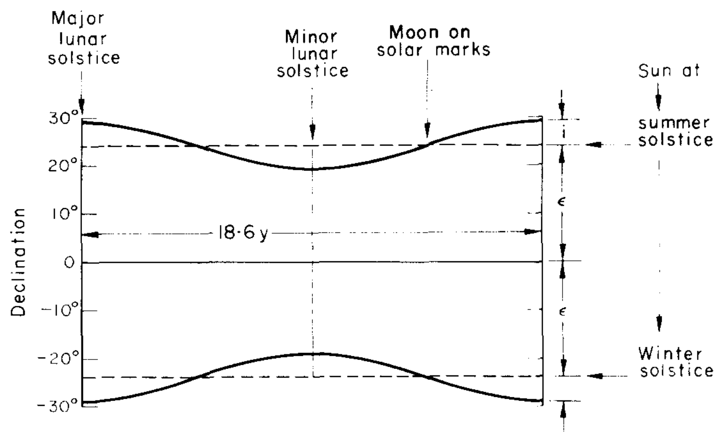


FIG. 22. Limits of lunar declination throughout one revolution of the nodes. The perturbation Δ is too small to show on this scale (see Fig. 1).

tion. Just as the date when the Sun had its maximum declination was linked (by the calendar) to the dates when the declination was near zero, so the date when the 9′ oscillation was a maximum was linked to the dates when it was zero.

Sites like Kintraw and Callanish were solar and lunar. If the builders obtained by their usual technique the date when the Moon at its monthly maximum was on one of the solar solstitial foresights its declination would be $\varepsilon \pm$ correction for parallax. By experience they would have known that a lunar solstice would follow after a definite interval which they could have determined. Its value would be the same for all similar sites apart from a small latitude correction.

Thus we have reason to believe that observations at the time when an oscillation passed through its node, made in order to determine its phase and in particular the date of its maximum, were used in three different cases

1. Sun at or near the equinoxes to phase the calendar and to give the exact date of its solstices.
2. Moon when $\Delta = 0$ to determine the date of the maximum and so the eclipse danger periods.
3. Moon on the Sun's solstitial marks to determine the date of the next lunar solstice i.e. the date when (2) should be observed.

We find that at several places there are contiguous sites for the accurate determination of all three. All are necessary for the object in view. The isolated examples of each which are scattered through the country are probably remnants of what were once complete sets.

It is possible that those solar observatories which at first sight appeared to be for the direct determination of the solstice were intended not for this at all but, although set up by using the Sun, were primarily for lunar observations.

Finally let it be said that a modern astronomer equipped with only stakes and string would have been able, using the sites we have described, to determine the date of the maximum of the 9′ ripple, i.e. the date of the middle of the danger period. Judging by what the erectors achieved with the limited means at their disposal they were by no means our inferiors in ability and ingenuity.

10. Conclusion

In Paper I and in Ref. 2 it has been shown that Megalithic man had developed a sophisticated calendar which was accurately linked to the tropical year. Here it has been shown that he had numerous lunar observatories throughout Britain which could provide the information necessary for the prediction of the danger periods for eclipses. Obviously these observatories were useless without the calendar and so we are not surprised to find at half a dozen places that the calendar and lunar sites are close together.

Judging by the very large menhirs which exist at many of the lunar sites the erectors attached great importance to these observatories. We are now in a position to appreciate what an enormous effort these people spent in getting accuracy. It behoves us to take the same care in measuring the sites and in analysing the results. It is very unlikely that one worker has succeeded in finding all the lunar observatories. There must be many yet to be discovered. Those already known and those found in the future must be accurately surveyed. It is no longer sufficient to work to a minute or so. A theodolite reading to 10″ must be used by a surveyor competant to make the necessary astronomical determinations of azimuth and altitude.

The larger alignments are to some extent legally protected but the outlying ancillary stones are vulnerable. Every boulder however insignificant in appearance ought to be recorded before the onslaught of our subsidized agriculture has removed it for ever. These positions may give further clues as to how the observatories were used.

Acknowledgements

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