UNCLASSIFIED

AD NUMBER

AD458325

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; DEC 1964. Other requests shall be referred to NMinistry of Aviation, Farnborough Hants, United Kingdom.

AUTHORITY

MOA notice, 15 Jun 1966

THIS PAGE IS UNCLASSIFIED

64087

DECEMBER

1964

ROYAL AIRCRAFT ESTABLISHMENT

TECHNICAL REPORT No. 64087

TECHNIQUES FOR MAKING VISUAL OBSERVATIONS OF EARTH SATELLITES

by

D. G. King-Hele

MINISTRY OF AVIATION
FARNBOROUGH HANTS

U.D.C. No. 522.6 : 535.834 : 629.195 : 521.3

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report No. 64087

December 1964

TECHNIQUES FOR MAKING VISUAL OBSERVATIONS OF EARTH SATELLITES

by

D. G. King-Hele

1. Satellites, Earth, artificial.

SUMMARY

This paper describes methods for observing Earth satellites in a quick and simple manner, with binoculars and stop-watch: an accuracy of about 0·1 sec in time and 0·05° in direction can be achieved. The uses of the observations for orbital determination and other purposes are outlined.

Departmental Reference: Space 82

CONTENTS

"And people without the reflector, with their opera glasses, will be able to see sufficiently well"

E. E. Hale, The Brick Moon (1871)[1]

1 INTRODUCTION

The simplest and cheapest way of observing an artificial Earth satellite is to watch it as it crosses the night sky, noting its position and the time at the moment when it crosses the line between two conveniently-placed stars. Naked-eye observations cannot be recommended because few satellites are bright enough to see; but with quite modest optical aid, such as 7 × 50 binoculars, it is possible to observe all near-Earth satellites with cross-sectional area greater than 1 square metre, and also many smaller satellites. If the chosen reference stars are not more than $\frac{1}{2}^{\circ}$ apart, the observations should have a directional accuracy of $0{\cdot}05^{\circ}$ or better. Timing is done by starting a stop-watch at the moment of observation and stopping it within a few minutes against a time-standard. At best the timing accuracy is about 0·1 sec.

This paper describes the observational methods I have come to adopt while making over 2000 visual observations in the past 7 years on about 150 different satellites (listed in the Appendix). The uses of such observations are also indicated. All observers should heed Pope's dictum,

To observations which ourselves we make,
We grow more partial for th' observer's sake[2];

so I must emphasize that other observers will have developed different methods, possibly better than mine. But the method described here is quick and reliable, and requires only the simplest equipment. The method is outlined in sections 2-4 and various arguable points are discussed in section 5. The uses of the observations are summarized in section 6.

2 PREDICTIONS OF SATELLITE TRACK OVER THE EARTH

The first requirement in satellite observing is a prediction of the time at which the satellite will be visible, its track over the Earth's surface and its height.

The British prediction centre is at the Radio Research Station, Slough, which at present makes predictions for some 40-50 selected satellites and sends them to regular observers in Britain and some European countries. Predictions are also made by various United States centres, notably the Spadats/Spacetrack center of NORAD and the Smithsonian Astrophysical Observatory. These predictions are received at a few establishments in Britain and, for some satellites, serve as the basis for Radio Research Station's predictions. Although all these types of predictions give similar information, the format adopted by R.R.S., Slough is perhaps the easiest for an observer using an instrument with a wide field of view (4° or more).

The predictions provided for a particular satellite by R.R.S. Slough consist of a transparent track diagram, which is placed over a map, the orientation of the track diagram being specified in a prediction sheet. See Ref.3 for further details. Fig.1 shows a section of the R.R.S. prediction sheet for the satellite Polyot 1 (1963-43A) during early October 1964. For each day the time at apex (point of maximum latitude north) and the longitude at apex are given for all transits which pass near Britain. (For a polar satellite the times and longitudes at which the satellite crosses latitude 50°N are given, instead of apex times and longitudes.) The most suitable transit for observation on, say, 2 October is that at 19 h 01 m U.T., because this is the first transit after the end of nautical twilight (which occurs at 18 h 48 m U.T. on 2 October at latitude 51°N) and the satellite passes near the observing station (Farnham, Surrey). Fig.2 shows the track diagram for Polyot 1 superposed on the map, the zero-line of the track diagram being rotated to the appropriate longitude, $44{\cdot}1^{\circ}$W. Also drawn on the map is a radial grid centred at the observing station with a 10° interval in azimuth and distances every 100 km.

Fig.2 indicates the track of the satellite over the Earth; Fig.1 gives the time at apex (19 h 01 m), the heights at points near apex, and the longitude at which the satellite enters eclipse (about 46° E of apex, i.e. at longitude 2°E).

This particular transit was chosen as an illustration not because it is a 'copybook example', but because it usefully brings out several of the difficulties likely to be encountered.

3 THE SATELLITE'S PATH AMONG THE STARS

Over small arcs, 30° or less, the path of the satellite among the stars is usually almost a straight line. Thus, if we aim at an accuracy of about $\frac{1}{2}^{\circ}$ to 1° in the predicted track - as is appropriate if the instrument used by the observer has a field of view of about 5° - it is only necessary to calculate the satellite's position among the stars at two points on its track, and then to join the two points with a straight line in the Star Atlas.

It is usually convenient to choose the two points at azimuths 30° apart and to observe the satellite in the neighbourhood of its point of nearest approach to the observing station. Sometimes, when the satellite passes nearly overhead, a wider spread of azimuth is needed; and sometimes it may be prudent not to observe near the point of nearest approach, e.g. if the satellite is in eclipse there, or passes near a gibbous moon.

For the transit shown in Fig.2, I chose to calculate the satellite's position at azimuths 270° (i.e. due west) and 240° (though, since the satellite passes so close, 270° and 210° would be just as good). The ground distances to the satellite track at these azimuths are seen to be about 180 and 130 km respectively. Fig.1 shows that the height of the satellite at 50°N going south is about 345 km; so the angles of elevation above the horizon are from Fig.3, about 60° and 68° respectively. From Fig.2 the time at which the satellite passes azimuth 270° is 7 minutes after apex, i.e. at 19 h 08 m. I find it convenient to write these details on a 5" × 3" record card, as shown below:

Time	sat	az	elev
19.08	Pol.1	270	60
		240	68

It is sometimes also useful to record the distance and height of the satellite.

The next step is to convert the azimuth and elevation to right ascension and declination. This can be done either with a star globe or with tables. If the azimuths are confined to 0, 30°, 60°, ... 330°, the tables prepared by the British Astronomical Association[4] are suitable; for any particular latitude the complete tables can be printed on one sheet, as in Fig.4, which is for 51·2° latitude. The equations on which the tables are based are given in Refs.3 and 4.

A convenient procedure for using the tables is as follows. The sidereal time at 0 h U.T. on the day of the observation (it is 0 h 43 m for October 2) is read from a current almanac, e.g. Whitaker's Almanack or the Astronomical Ephemeris (pp 10-17), and added to the time of the observation (19 h 08 m), giving 19 h 51 m. This value is then corrected to obtain local sidereal time by adding 3 minutes (19/24 of the 4-minute increase in sidereal time which occurs every 24 hours), and subtracting 4μ minutes, where μ is the observer's longitude west in degrees. (For Farnham $4\mu = 3{\cdot}3$, so the correction is usually ignored.) This gives the local sidereal time and hence the right ascension of the stars due south at the time of the observation. To obtain the right ascension of the satellite, the appropriate entry in the column labelled h (hour angle) in Fig.4 must be subtracted if the satellite is in the west, or added if it is in the east. In our example the first azimuth is 270°, i.e. to the west, and the elevation 60°. Thus from Fig.4, in which A indicates the altitude or elevation, the right ascension of the satellite at the first observation point is 19 h 51 m - 2 h 51 m = 17 h 00 m, and the declination 42°. Similarly we find the values for the second observation point by looking up azimuth 240° and elevation 68°. The full entry on the record card is then:

Time	sat	az	elev	R.A.	dec	S.T.	00.43
19.08	Pol.1	270	60	17.00	42	19.51	
		240	68	18.15	37		

The headings are omitted in practice, and entries for all other satellites to be observed that night are made on the same card. The 00.43, the sidereal time at 0 h, applies to all the satellites.

The right ascensions and declinations obtained above are then plotted in fairly soft pencil in a star atlas (Norton's Star Atlas[5] is ideal for the purpose), and joined by a freehand line, as in Fig.5. Since the points, marked by squares, are rather close together, the track has been extended beyond them.

The complete process described above - setting the track diagram, selecting two azimuths, calculating elevations, converting to right ascension and declination, and plotting in the atlas - can be accomplished in about 5 minutes.

4 MAKING THE OBSERVATIONS

4.1 Usual procedure for observing

When the predicted track of the satellite has been plotted in the star atlas, a quick glance shows which groups of stars can best be used as reference stars. A line of 3 or 4 stars of fourth, fifth or sixth magnitude at intervals of about $\frac{1}{2}°$, running perpendicular to the satellite's track, forms an ideal reference system; but any reasonably close group bright enough to have some of its stars shown in Norton's Atlas will serve.

The detailed methods of observation are inevitably subject to personal idiosyncracies, and any account of them exposes the observer to ridicule. Since these details are however, just what new observers want to know, I shall describe my own practice, in all its comic detail. About two minutes before the satellite is due (or more if the predictions are suspected to be in error), I don my overcoat, with a stop-watch and pencil in the right pocket and an auxiliary stop-watch and torch in the left pocket, hang 7 × 50 binoculars round my neck, seize Norton's Star Atlas, using the record card as a bookmark indicating the right star map, and, after plunging the western side of the house into darkness, go out into the back garden. I normally observe from a deck chair, which I carry to the most suitable point for observing and set at the lowest notch. I glance at the satellite's expected track drawn in the atlas (it is useful to seal up all pages in the atlas except the maps), and look up at the reference stars through the binoculars. I begin to sweep the field of view of the binoculars back along the satellite's track, with the aim of spotting the satellite about 5-10° before it reaches the first group of reference stars. The binoculars are held with one hand and supported by some fingers of the other hand, the remaining fingers being used to hold a stop-watch. If the satellite is not seen immediately, I usually sweep back and forth over about 10-20° of track: this helps to relieve fatigue of eyes and arms, and sometimes results in seeing the satellite when it has somehow slipped past, perhaps because it was going through a faint phase within the field of view.

Once the satellite is seen (on clear nights the success rate should be about 90% for well-predicted and reasonably bright satellites), I sweep the field of view to and fro between the satellite and the reference stars, to make sure it is approaching them as expected. If not, a new group must be rapidly chosen. I start the stop-watch as the satellite passes the line between two stars in the chosen reference group, at the same time estimating the position in the form "7/10 of the way up from the first to the second star". Continuing to follow the satellite with the binoculars, I take a second observation between two other stars (either preselected or not), stopping the subsidiary hand of the split-action stop-watch. Since the hands go round twice a minute, it is best to take the second observation within about 30 seconds of the first, to avoid misreading the stop-watch. Otherwise it is necessary to shine the torch on the stop-watch, thereby usually losing the satellite. I also estimate the stellar magnitude of the satellite by comparing it with the stars it passes; and, if its brightness is fluctuating regularly, I use the auxiliary split-action stop-watch to obtain the period of fluctuation by timing 5 and 10 fluctuations (if they are fairly rapid). The second stop-watch also comes into play if two satellites have to be observed in quick succession, or if another satellite is seen by chance.

I then mark the observed positions on Norton's Star Atlas, go indoors, telephone the Post Office Speaking Clock and stop the main hand of the stop-watch at the time signal. This is normally done about 3 minutes after making the first observation, i.e. within 5 minutes of going out to observe. On first hearing the Speaking Clock time announcement, for time t_o, say, I write down a time t_o + 20 seconds, estimate the position of the moving hand of the stop-watch at the six 'pips' $t_o - 2$, $t_o - 1$, t_o, $t_o + 8$, $t_o + 9$, and $t_o + 10$ seconds, and stop the watch at $t_o + 20$, the time already written down. The tenths-of-a-second reading should be within 1 tenth of a second of that estimated visually at the earlier sets of pips. If not, the error quoted should be increased appropriately. Finally, I listen to the next time announcement by the Speaking Clock, to confirm that the time written down was correct.

4.2 What happened on the chosen transit of Polyot 1

In practice the procedure is not always so straightforward as described above. For the transit of Polyot 1 discussed in sections 2-3, the satellite happens to pass through a region rather empty of stars. Possible groups of reference stars are ringed in Fig.5, but are not entirely satisfactory. Also this was a close transit, so that some error in the predicted track can be expected, because of the difficulty in reading off distance accurately in Fig.2.

In fact Polyot 1 was first seen at the point A in Fig.5, nearly 2° lower than expected. The first group of reference stars was used, the first observation being at B, at right angles to the line from σ to 30 Herculis and at a distance 8/10 of the way between these two, as shown in Fig.5. It would have been better to obtain a position by interpolation rather than extrapolation, and the estimated error (s.d.) in this observation was 0·1° instead of the aimed-at 0·05°. The second observation was made at C, where the satellite appeared to coincide with the star θ Herculis. Coincidence with a fourth-magnitude star is rare; but most observations have some unusual features and this one was no exception. The error for this observation was recorded as 0·05°, but was probably less. The magnitude of the satellite was estimated as +4 to +5, varying every few seconds, but with no recognizable regularity, and was recorded as "4-5, varying".

The stop-watch was stopped at 20 h 10 m 50 s B.S.T., with the main hand reading 3 m 13·0 s and the subsidiary hand 16·0 sec. Thus the time of the first observation was 19 h 07 m 37·0 s (U.T.) and that of the second, 19 h 07 m 53·0 s. The timing of the observations and the stopping against the speaking clock felt right, so an error of 0·1 sec was recorded. (These times are incidentally within half a minute of those predicted, as is usually found for a fairly long-lived satellite: Polyot 1 is expected to last for about 10 years.)

It only remains to find the right ascension and declination of the satellite at the times of observation, by plotting the positions in a large star atlas. Bečvář's Atlas Eclipticalis and Atlas Borealis[6] are ideal for this purpose and have been supplied to selected observers by the British National Committee on Space Research. Using these atlases, with their excellent transparent overlays, the positions can normally be found in about 2 minutes. (It takes longer if the reference stars happen to be on different pages of the atlas.)

Fig.6 shows a section of the Atlas Borealis with the approximate track of Polyot 1 and the first observation marked by a triangle. Only about a quarter of the stars shown in Fig.6 were visible at the time, since seeing was not perfect that evening and nautical twilight had only just ended: still, it is obvious that fainter reference stars could have been chosen to improve the accuracy of the observation, if I had recovered more rapidly from the touch of confusion caused by first seeing the satellite 2° lower than expected.

Thus the report of these observations was as follows.

Observations of Polyot 1 (1963-43A)

From Farnham, England. Station 2265 in COSPAR World List

Date	Time U.T.	Error	Right asc.	Dec	Pos. error	Magnitude
1964 Oct 2	19.07.37.0	0·1	16 h 29·1 m	41·20°	0·1°	4-5 varying
	19.07.53.0	0·1	17 h 54·5 m	37·25°	0·05°	

R.A. and Dec are for epoch 1950·0. Errors are estimated s.d.

The right ascension and declination for the second observation could be improved by looking up θ Herculis in the star catalogue[7], which gives R.A. = 17 h 54·53 m, Dec = 37·256°. This refinement is worthwhile for a slow-moving satellite, but probably not for Polyot 1.

4.3 Conclusion

The description given above is a record of my most usual practice: but there are many possible variations, some of which will be discussed in section 5, and I do not claim that my practice is the best.

It will be noticed that the time taken for two observations of a satellite is about 15 minutes - 5 minutes preparing, 5 minutes going out to observe, and 5 minutes in obtaining the time and reducing the observations to right ascension and declination. If the weather has prevented observation on previous evenings, the process may take rather longer because the satellites to be observed must be chosen, and the accuracy of the predictions is less certain, so that a greater margin of error must be allowed.

5 DISCUSSION OF OBSERVATIONAL METHOD

5.1 Accuracy

The main limitation on the accuracy of visual observations is the timing error. It is believed that with a typical close satellite, moving relative to the observer at a rate of between $\frac{1}{2}$ and 1 deg/sec, a good observer can achieve an accuracy of 0·1 sec (standard deviation) if he uses an accurate 1/10th-second stop-watch, does not let it run for more than a few minutes, stops it against an accurate standard, and is conscious of having started and stopped it at the right moments. This belief is confirmed by some recent NASA tests[8] using stars crossing hairlines: errors of between 0·04 and 0·08 sec were recorded for apparent angular velocities greater than 0·5 deg/sec*. The best methods of timing, and their accuracy, need to be investigated more fully however.

With an angular velocity of 0·5 to 1 deg/sec, a satellite travels between 0·05° and 0·1° in 0·1 sec, and there seems little to be gained in seeking directional accuracy better than about 0·05°. This conclusion is subject to some qualification, however, since the error in timing leads to an along-track error, and it may still be useful to obtain better cross-track accuracy, so as to define the orbital plane more precisely.

Distant satellites, such as Midas-type satellites in circular orbits at 3600 km height, travel much more slowly, often at about 0·1 deg/sec, so that the directional error corresponding to a timing error of 0·1 sec is only about 0·01°. For these satellites it therefore seems logical to strive for a directional accuracy better than 0·05°. However it is rather doubtful whether any visual observations are of useful accuracy for long-lived satellites in distant stable orbits (see section 6).

Generally, therefore, it seems best to aim at an accuracy of 0·1 sec in time and 0·05° in direction, though better directional accuracy is always acceptable if it can easily be achieved, e.g. when a satellite coincides with a star, or if the observer is keen to achieve better accuracy. There is one situation in which an accuracy better than 0·05° should always be sought: this is when a satellite with a low perigee, short life and high-eccentricity orbit is observed near apogee, where it is slow-moving (e.g. Star-rad, 1962 βK, with an initial apogee height of 5500 km and perigee height of 200 km).

---

* The apparent angular velocity of nearly all observable satellites exceeds 0·5 deg/sec if an instrument with a magnification greater than about 5 is used.

5.2 Prediction of satellite track and choice of observation points

The procedure described in sections 2 and 3 is adequate if the observer has an instrument with a wide field of view and receives predictions of the geographical position and height of the satellite. If the field of view is narrow, less than 3°, a more accurate procedure is probably advisable, and tables soon to be issued by the British Astronomical Association will help to eliminate some of the inaccuracies in the graphical method.

Some observers are fortunate enough to be able to use computer programmes in which the input is the orbital elements of the satellite and the output is the coordinates of the satellite in right ascension and declination. Such a programme has been developed by R.R.S., Slough, and is used to give 'look data' to selected observers for a few satellites. This method bypasses the procedures described in sections 2 and 3, and the track among the stars can be plotted immediately. The computer programme has the advantages of better accuracy and better reliability, in the sense that, if a satellite is observed at the right time and place on one night, its predicted track and time for the next night are virtually certain to be correct; use of the computer programme is, however, more costly, cannot take account of timing corrections received only an hour or two before observing, and takes longer than the graphical method (especially if the latter is used only on fine nights, in England about 1 in 4, while the computer method is used to calculate tracks for every night).

Whatever the procedure used, there are a few possible difficulties worth mentioning. Normally it is best to look for the satellite before it reaches the point of nearest approach: then the observations can be made early and unhurriedly, and any remaining time can be devoted to noting variations in brightness, etc.

There are frequent exceptions to this rule, however. It is often wise to observe a satellite near the point where it is highest in the sky. This is the best procedure when the atmosphere is hazy, and even on a clear night it has the advantage that the satellite appears to be travelling horizontally, thus making it easier to sweep the field of view along the track. Very faint satellites are also best observed near the highest point of their path, or sometimes where the phase angle with respect to the Sun is greatest. If the Sun is to the north-west, for example, a faint satellite coming almost overhead from N.W. to S.E. is often most easily seen as it departs towards the south-east, provided it is not in eclipse. This is particularly true if the north-western sky is still bright.

If the satellite goes into the Earth's shadow during a transit it should be observed at least 20° to the sunward side of the eclipse line, if possible, since the predicted eclipse point may be slightly in error and the satellite may begin to fade before the eclipse point, especially if it is travelling nearly parallel to the shadow line.

Some observers prefer to calculate 3 points on the track rather than 2: this takes more time, but gives better accuracy, often reveals major arithmetical errors in calculating one of the points and allows for the possibility that the points may be on different pages in Norton's Star Atlas. This last difficulty does not often arise, since the Atlas has generous overlaps.

5.3 Making the observations (with binoculars)

I shall first assume that the observations are made with binoculars, leaving discussion of the choice of instrument until section 5.4. Probably the most suitable binoculars for general use are 7 × 50 or 8 × 60, with a field of view of about 5° and a limiting magnitude of about +8 for fairly fast satellites. For fainter satellites, 11 × 80 binoculars with a field of view of about 4° can be recommended.

Finding the satellite and making the observations are two distinct processes. If the predictions are good, the method of sweeping 5° or 10° back along the expected track is satisfactory. But the most valuable observations are often those of poorly-predicted satellites: then it is necessary to begin looking perhaps 5 minutes before the satellite is predicted to appear. Because of the Earth's rotation the satellite's track lies about 1° further east in longitude (i.e. 70 km at latitude 51°N) if it is 4 minutes early, 2° further east if it is 8 minutes early, and so on. If the satellite is bright and visibility is good, the effect of this shift in longitude on the satellite's apparent track can be minimized by observing it when it is only 10–20° above the horizon. If the satellite is due to pass nearly overhead north to south, at 200 km height, a 4-minute error in its predicted time will alter its maximum elevation by about 20°; but if it is observed 500 km to the east a timing error of −4 min only changes the elevation from 19° to 16°, i.e. within the field of view, if one looks slightly below the predicted position before the predicted time and slightly above it thereafter (or vice-versa if the satellite is in the west). In these conditions it is also often useful to make occasional rapid sweeps over a wide arc, 45° or more. If the satellite has to be observed high in the sky, a zig-zag scan to increase the field of view to 10° is advisable.

For satellites at heights of several thousand kilometres, the change in elevation due to errors in the predicted time is partly compensated by the apparent motion of the stars, i.e. the track relative to the stars changes less than might be expected. For example, a polar satellite passing overhead at 4000 km height will change its elevation by $1{\cdot}6^\circ$ if it is 4 minutes late, while the stars overhead change by $0{\cdot}6^\circ$ in the same direction during the same time interval, at 51° latitude.

If, as so often happens, the sky is partly covered with fast-moving clouds, it is best to try to define the satellite's path across the sky by noting its track relative to any bright stars that become visible and then to sweep to and fro along this track. It is useful to observe from a position where some obstacle cuts off vision of the sky at more than 10° below the expected track, so that one is not tempted to look low just because the sky is clear there.

If the satellite is known to be visible to the naked eye, it is often best to search with the naked eye, especially if timing is at all doubtful, and then transfer to binoculars when the satellite has been seen.

If the satellite is known to be faint and at the limits of visibility, it can sometimes be picked up by scanning back and forth along the track at approximately the satellite's expected speed. This introduces a sporting element, by increasing the chance of seeing the satellite on a forward sweep, but decreasing the chance of seeing it if it crosses during the backward half of the sweep.

If the satellite is visible only in bright flashes at long or irregular intervals, it is best to sweep quickly and widely to and fro along the expected track through an arc of perhaps 30°.

Staring at a fixed star-field for more than about 2 minutes does not seem to be a very efficient method of searching. Movement seems to keep the eye more alert and gives it the practice in coping with moving objects which it will need when the satellite appears. Otherwise the entry of a fast-moving satellite into a static picture can be rather traumatic, with consequent degradation in accuracy.

5.4 Choice of instrument for observing

Visual observations of long-lifetime satellites in stable and easily-predictable orbits are not usually accurate enough to be of much value in orbital determinations, though they may be useful in maintaining an ephemeris or for assessing rotational behaviour. If it is accepted that the main value of visual observations is in determining the orbits of satellites of fairly short life (see section 6), the instrument used for observing should have a fairly wide field of view, 5° or more if possible, to allow a margin of error of $\pm 2^\circ$ or more on the predicted track. Such an error can occur through errors in the predicted times, as explained in section 5.3, or through errors in calculating the track among the stars, especially if the transit is a close one (see sections 3 and 4.2).

A second requirement for the instrument is that it should allow easy tracking, for three reasons:

(1) The observer should be able to follow the satellite and choose new reference stars if it does not pass as expected through the group originally chosen.

(2) Two observations should be made rather than one, in order to reduce random errors of observation and to check that the direction of the track is the same as predicted, thereby greatly reducing the possibilities of (a) wrong star identification and (b) tracking the wrong satellite.

(3) It is useful to follow the satellite after the last observation, to note variations in brightness, or to settle doubts about identification: if the object goes into eclipse, for example, it is unlikely to be an aircraft.

All these requirements suggest that the eye should look in the same direction as the axis of the instrument, and that the field should not be inverted, or, even worse, rotated through an angle which varies with the elevation. Light, hand-held binoculars are preferable to inverting telescopes.

In partly cloudy weather, or when it is too bright to see many stars, binoculars are best for making 'guessed scans' along the track using knowledge of azimuth and elevation. On the other hand, a telescope is useful in a different way in cloudy conditions: for it can be set on a star near the satellite's predicted track at a time when that star happens to be visible; and if the sky happens to clear as the satellite passes that star, a satisfactory single observation can be obtained.

A third requirement is that the observation should be reliable: therefore the stars must be readily identifiable. Again a wide field of view helps, and rotation of the image is bound to be deleterious.

A fourth requirement is that the instrument can be quickly and easily used. Hand-held binoculars are preferable to a telescope which has to be carried out and set up beforehand.

A fifth requirement is that the instrument should allow observation of faint satellites. If this requirement is carried to its logical conclusion, one finishes up with a large telescope, which fails to satisfy the first four requirements. Obviously a compromise is called for. Hand-held binoculars satisfy the first four requirements and are also more efficient in that they utilize both the observer's eyes instead of one; but at present no light-weight binoculars with an aperture greater than about 80 mm are available, and, although this allows most satellites which are of interest to be observed, at least on close transits, a greater light-grasp is often desirable. Large telescopes will therefore continue to be used for observing faint satellites.

A sixth requirement is for accuracy. There is not much to choose between the possible instruments: a telescope fixed to a stand is however more stable than a hand-held instrument, at least in calm weather, and may allow slightly better accuracy.

5.5 Siting of the observing station

It might be thought that the ideal observing station would be one with a view down to the horizon in all directions, and with no terrestrial light-sources within many miles - a small island in mid ocean, perhaps. But if the instrument used is completely mobile, as with binoculars, it is useful to have screens, preferably of dense evergreen trees, to block out moonlight. Cypress trees are probably among the best for absorbing light, and a screen running from west to east is most useful for excluding moonlight if observations are made in the evenings. If the observer is within a few miles of the lights of a town, some part of the observing area should have its horizon completely screened up to about 30° elevation, so as to exclude light from near the horizon and to allow high-elevation satellites to be observed from a dark environment.

Observing stations should, if possible, not be situated down-wind of a large city. An east wind lasting more than a day or two usually brings London smoke over Farnham and worsens seeing by at least one magnitude, as compared with conditions in the more usual airstream, from the south-west.

In England a hill-top situation is usually better than a valley, both for seeing down to the horizon and avoiding low mists. But the situation should not be too exposed, otherwise winter winds will degrade accuracy by shaking the binoculars or telescope, bringing tears to the eyes and freezing the fingers.

The final and most important requirement, clear skies over the observing station, cannot be reliably met in Britain.

5.6 Reference stars

The best procedure, if it is possible, is to choose two close stars which lie perpendicular to the satellite's track and to note the time and position as the satellite passes between them, as in Fig.7(a). The stars should ideally be within $\frac{1}{2}^{\circ}$ of each other, of similar magnitude and not too different in magnitude from the satellite. An equally good observation is the coincidence of the satellite with a star, though this cannot be planned beforehand.

In practice this ideal procedure often fails, because the satellite does not exactly follow the predicted track. The observer must then decide whether to use reference stars from the group chosen beforehand or whether to choose new and perhaps faint ones which may not be readily identifiable later in the Star Atlas. The first alternative is safer, though less accurate.

If the satellite passes between two reference stars A and B distant d from each other, and at right angles to the line between them, as in Fig.7(a), it should be possible to estimate the fractional distance between the stars accurate to about d/20 at best or d/10 at worst, so that if the stars are $\frac{1}{2}^{\circ}$ apart, the accuracy (s.d.) should be better than $0{\cdot}05^{\circ}$. If the satellite S passes outside the pair of reference stars, as in Fig.7(b), extrapolation - say "3d/10 beyond" - is necessary: this is likely to be less accurate, with an error of perhaps d/10 for distances up to d/2 beyond the star and larger errors at greater distances. If the line between the reference stars is at an oblique angle to the track, as in 7(c), it may be best to make the observation when $A\hat{B}S$ is a right angle. There are many other possibilities for particular circumstances: if the satellite is visible only in discrete flashes, for example, it is often necessary to memorize its position relative to two stars and then draw the shape of the triangle immediately, at the side of the Star Atlas. If the situation is as in Fig.7(d), for example, the observer would note that ABS is approximately an equilateral triangle and that S is slightly to the left of AC and about halfway between A and C.

6 THE USES OF VISUAL OBSERVATIONS

6.1 For prediction

Visual observations are particularly useful at the beginning and end of a satellite's life, as a means of correcting predictions, which are likely to be in error either because the orbit is not well known (beginning of the life) or because the orbit is changing from hour to hour (end of the life). Since high-precision cameras normally require accurate predictions, the visual observations fulfil an essential purpose in allowing the predictions to be improved.

6.2 Observing re-entry

A satellite may re-enter the atmosphere anywhere in the world at latitudes less than its orbital inclination, and can only be properly tracked if numerous observers are in action. The behaviour of a satellite during re-entry is interesting in itself, and tracking during re-entry can lead to the recovery of fragments, as with Sputnik 4. If the satellite is tracked during re-entry and observed a few revolutions before, the changes in the orbit during its last few revolutions can be found, and this in turn can yield useful information on properties of the atmosphere below 200 km.

6.3 Identification of satellites

The United States Air Force keeps track of all known objects in space using radar detection methods, and in recent years has been making the essential part of this information public, so that for each launching an international designation is now satisfactorily allocated, and, for many satellites, orbits accurate enough for prediction purposes become available. When a satellite divides into several pieces, however, the size or function of the pieces is often unknown: this information can often be deduced from their visual appearance. If, for example, an Agena rocket ejects a small capsule, it is easy to decide which is which from their relative brightness. Similarly rockets of the Cosmos satellites have had characteristic rapid fluctuations in brightness with a period between $\frac{1}{2}$ and 1 sec and a magnitude of +1 or +2 on close transits: the rockets can therefore be distinguished from the instrumented satellites, which vary much less in brightness. An experienced observer can often make a good guess at the type of satellite he has seen, merely from its visual appearance, track and speed. Such identification is very useful in keeping records of satellites launched[9].

6.4 Variations in brightness

The brightness of a satellite and its fluctuations can be used to estimate the satellite's size and shape[10], if, as often happens, these have not been revealed. The satellite's mass can then also be found approximately from the rate of change of orbital period and a knowledge of air density.

Knowledge that the brightness does not vary can be useful: for example, although the weight and size of the Cosmos satellites have not been revealed, they do not fluctuate much in brightness, and so their effective cross-sectional areas are unlikely to vary greatly. Consequently any large variations in the rates of change of their orbital periods can plausibly be ascribed to changes in air density rather than changes in cross-sectional area.

The period of fluctuation in brightness is a useful guide to the rotational motion of a satellite and for some satellites the changes in this period reveal variations in air density or impulses suffered by the satellite, e.g. due to collision with meteorites. Some work has been done on this subject[11], but it remains relatively undeveloped.

6.5 Determination of orbits from observations

The main use of observations is to determine orbits, for the changes in orbits reveal (1) the properties of the upper atmosphere in the neighbourhood of perigee and (2) the Earth's gravitational field (see Refs.12 and 13 for reviews).

For studies of the gravitational field it is probable that in future only very accurate long-life orbits will be used, determined from precision-camera or Doppler observations: there seems little virtue in using less accurate orbits sampling the same gravitational field; nor is there much virtue in using low and short-lived orbits, except possibly that these are more sensitive to the higher harmonics in the gravitational field.

For studies of the upper atmosphere, however, the situation is quite different. Upper-air density varies with solar activity, between day and night, annually, semi-annually, and with height; it is safe to say that almost every satellite makes in the neighbourhood of its perigee a traverse of the atmosphere which is unique in its particular combination of these many variables. Every time a satellite decays without being properly observed, some information about the upper atmosphere has been lost. Visual observations are most useful for satellites with lifetimes of less than 20 years, but can yield some information about the upper atmosphere with satellites having lifetimes of up to about 100 years.

Various properties of the upper atmosphere can be determined from the changes in satellite orbits. First and most important, the air density at a height a little above the perigee height of the satellite can be evaluated[14] from the rate of decrease of period. Ref.15 is a recent example, which gives further references. If the satellite is low, with a rapidly changing period, rather inaccurate observations are still useful: if, for example, the observations are accurate to 1 second in time, the orbital period for a particular day can be found accurate to about 1 part in 40000 and its rate of change can be quite well determined. When values of density are plotted against height y, the slope of the curve gives the 'density scale height' $H = -\rho/(d\rho/dy)$, and from H values of temperature/(molecular weight) can be found.

The second orbital change which reveals properties of the atmosphere is the decrease in the perigee height below its initial value, which to a first approximation is equal to $\frac{1}{2} H \ell n\ (e_o/e)$, if the eccentricity e is between 0·02 and 0·2, where e_o is the initial eccentricity. If e_o, e and the decrease in perigee height are known, H can be found. An accuracy of 1 km or better in perigee height is desirable. This method is used in Ref.16.

The third relevant orbital change is in the inclination i of the orbit to the equator. The rotation of the atmosphere subjects the satellite to a small lateral force, which causes the inclination to decrease slightly (if $i < 90°$). The decrease, Δi, is proportional to the rotational speed of the atmosphere at heights near that of perigee, and this speed can be determined if Δi is known[17]. Δi is usually of order 0·1°, so that an accuracy of 0·01° or better in i is required.

Visual observations of the type described in this paper can yield orbits as accurate as are required for all three types of atmospheric study, if the observations are sufficiently numerous and well distributed. For example, the orbit of Transit 1B (1960 γ 2) has been determined[18] from visual observations in the period 2-10 June 1962 with an accuracy of 0·6 km in perigee height and 0·0017° in orbital inclination.

7 CONCLUSION

This paper describes quick and simple methods for making visual observations accurate enough to be useful in determining the orbits of satellites with lifetimes less than about 20 years. For many satellites these techniques will remain adequate in the future, but there will also be a demand for more accurate visual observations, for which it may be necessary to adopt more sophisticated methods than those given here.

ACKNOWLEDGMENT

I am grateful to Mr. G.E. Taylor of the Royal Greenwich Observatory, Herstmonceux, for valuable comments on the text of this paper.

Appendix

SATELLITES OBSERVED FROM FARNHAM (1958-64)

The satellites listed in Table 1 (page 21) have been observed with 7 × 50 binoculars. The first column gives the name and international designation. The second column indicates the lifetime, actual or estimated. (Normally short-lifetime satellites have been given priority in observing.) Column 3 gives N, the number of transits observed: normally two observations per transit were made, so the number of observations is about twice the number of transits. Column 4 gives the size in metres of the satellite, length and diameter for a cylinder, and diameter for a spherical or near-spherical satellite. A question mark after the values indicates that both are doubtful. Column 5 gives the stellar magnitude on a close transit: obviously the satellite is fainter when at low elevation or at apogee (if the orbit is appreciably eccentric). The symbol f indicates fluctuation in brightness between the magnitudes given; "st" indicates 'steady', i.e. constant brightness. The period of fluctuation P is only approximate, since most satellites rotate more slowly as time goes on. This whole column should be regarded as only a rough guide: for a more comprehensive picture, see Ref.19.

Table 1

SATELLITES OBSERVED FROM FARNHAM, 1958-64, WITH NUMBER OF TRANSITS OBSERVED, N.

	Satellite	Life	N	Size (m)	Magnitude and comments
1957 $\beta 1$	Sputnik 2	Nov 57 - Apr 58	15	20 × 3?	0. P = 2 min when varying
1958 $\delta 1$	Sputnik 3 rocket	May-Dec 58	16	20 × 3?	0-3 f. P = 9 sec
1958 $\delta 2$	Sputnik 3	May 58 - Apr 60	28	4 × 1·5	5. Brightness very variable
1959 $\varepsilon 2$	Discoverer 5 capsule	Aug 59 - Feb 61	1	0·6 × 0·9	7-8 f
1959 ζ	Discoverer 6	Aug - Oct 59	9	6 × 1·5	2. Usually steady
1959 $\iota 1$	Explorer 7	70 years	8	0·8 × 0·8	8 st. Much fainter now
1960 $\beta 2$	Tiros 1	60 years	9	0·5 × 1·1	8. Some rapid flashes mag.5
1960 $\beta 1$	Tiros 1 rocket	25 years	9	1·5 × 0·5	7-8 f. $P \simeq 1$ sec
1960 $\gamma 2$	Transit 1B	7 years	38	0·9	6 st. Slightly fainter now
1960 $\gamma 1$	Transit 1B rocket	Apr 60 - Aug 61	26	5·3 × 1·4	3-5 f. Sometimes steady
1960 $\varepsilon 1$	Sputnik 4	May 60 - Sep 62	36	6 × 1·6 ?	3 st. Sometimes variable
1960 $\varepsilon 2$	Sputnik 4 rocket	May - Jul 60	9	10 × 2?	2-5 f. $P \simeq 1\frac{1}{2}$ sec
1960 $\varepsilon 3$	Sputnik 4 cabin	5 years	68	5 × 2 ?	3 st. Sometimes variable
1960 $\varepsilon 6$	Sputnik 4 fragment	May - Sep 60	2	?	8 f. $P \simeq 1\frac{1}{2}$ sec
1960 $\varepsilon 7$	Sputnik 4 fragment	May - Sep 60	1	?	3
1960 $\eta 1$	Transit 2A	150 years	25	0·9	8 st.
1960 $\eta 3$	Transit 2A rocket	80 years	45	5 × 1·4	4-7 f. P = 3 sec in 1960
1960 θ	Discoverer 13	Aug - Nov 60	5	6 × 1·5	3-5 f
1960 $\iota 1$	Echo 1	7 years	113	30	0 st.
1960 $\lambda 2$	Sputnik 5 rocket	Aug - Sep 60	1	10 × 2?	3-4 f
1960 $\xi 1$	Explorer 8	60 years	5	0·8 × 0·8	8 st. Now fainter
1960 $\pi 1$	Tiros 2	60 years	4	0·5 × 1·1	8 st.

Table 1 (Contd.)

	Satellite	Life	N	Size (m)	Magnitude and comments
1960 π2	Tiros 2 rocket	30 years	10	1·5 × 0·5	7-8 f. P = 3 sec
1960 σ	Discoverer 18	Dec 60 – Apr 61	3	8 × 1·5	3-5 f
1961 α1	Samos 2	12 years	36	7 × 1·5	4 st.
1961 α2	Samos 2 nose-cap	10 years	3	?	8
1961 β3	Sputnik 7 fragment	Feb – Mar 61	1	?	1-6 f
1961 δ1	Explorer 9	Feb 61 – Apr 64	36	3·7	6 st.
1961 ε1	Discoverer 20	Feb 61 – Jul 62	14	8 × 1·5	2
1961 ζ	Discoverer 21	Feb 61 – Apr 62	11	8 × 1·5	2-5 f. P ≏ 10 sec
1961 λ1	Discoverer 23	Apr 61 – Apr 62	6	8 × 1·5	3-6 f. P = 6 sec
1961 ο1	Transit 4A	600 years	12	0·8 × 1·1	8 st.
1961 ο2	Injun 1	900 years	4	1 × 0·5	7-9 f. With flashes
1961 ο3	Transit 4A rocket remains	100 years?	10	?	6-8 f. Irregular
1961 ο6	Transit 4A rocket fragment	100 years?	1	?	7
1961 ο?	Fragments	100 years?	2	?	8
1961 π	Discoverer 26	Jul – Dec 61	1	8 × 1·5	3 st.
1961 ρ1	Tiros 3	100 years	1	0·5 × 1·1	8 st.
1961 ρ2	Tiros 3 rocket	50 years	9	1·5 × 0·5	7-8 f. P ≏ 5 sec
1961 σ1	Midas 3	100 000 years	28	9 × 1·5	7-8 f. P ≏ 1 min in 1961, 5 sec in 1964
1961 ω1	Discoverer 30	Sep – Dec 61	3	8 × 1·5	2 st. Sometimes variable
1961 αδ1	Midas 4	100 000 years	31	9 × 1·5	7. Mainly steady
1961 αε1	Discoverer 34	Nov 61 – Dec 62	18	8 × 1·5	2-5 fluct. slowly
1962 β1	Tiros 4	100 years	6	0·5 × 1·1	7 st. Flashes of mag 4.
1962 η1		Mar 62 – Jan 63	3	?	4 st. Sometimes variable

Table 1 (Contd.)

	Satellite	Life	N	Size (m)	Magnitude and comments
1962 $\eta 3$	(Agena rocket)	Mar - Nov 62	5	8? × 1·5	2-5 f. $P \simeq 10$ sec
1962 $\iota 1$	Cosmos 2	Apr 62 - Aug 63	12	1·8 × 1·2?	6 st.
1962 $\iota 2$	Cosmos 2 rocket	Apr - Oct 62	4	10 × 2?	2-6 f. $P \simeq \frac{1}{2}$ sec
1962 $\kappa 1$	Midas 5	100 000 years	25	9? × 1·5	6-8 f. $P = 12$ sec
1962 $\nu 1$	Cosmos 3	Apr - Oct 62	3	1·8 × 1·2?	6 st. Sometimes variable
1962 $\nu 2$	Cosmos 3 rocket	Apr - Aug 62	5	10 × 2?	2-4 f. Sometimes steady
1962 $o1$	Ariel 1	20 years	25	0·5 × 0·6	8. Some flashes of mag 4
1962 $o2$	Ariel 1 rocket	15 years	3	1·8 × 0·5	6-8 f. $P = 2\frac{1}{2}$ sec in 1962
1962 $\sigma 1$	(Agena rocket)	May 62 - Nov 63	18	8? × 1·5	2-5 f. $P = 7$ sec
1962 $\upsilon 1$	Cosmos 5	May 62 - May 63	1	1·8 × 1·2?	6 st.
1962 $\upsilon 2$	Cosmos 5 rocket	May - Dec 62	7	10 × 2?	2-5 f. $P = 0{\cdot}8$ sec
1962 $\omega 1$	(Agena rocket)	June 62 - Oct 63	12	8? × 1·5	2-4 f. Sometimes steady
1962 $\alpha\alpha 2$	Tiros 5 rocket	50 years	1	1·5 × 0·5	8-9 f. $P \simeq 5$ sec
1962 $\alpha\epsilon 1$	Telstar 1	10000 years	3	0·9	8 st.
1962 $\alpha\xi 1$	Cosmos 8	Aug 62 - Aug 63	8	1·8 × 1·2?	5 st.
1962 $\alpha\xi 2$	Cosmos 8 rocket	Aug - Dec 62	8	10 × 2?	2-5 f. $P = 0{\cdot}7$ sec
1962 $\alpha\upsilon$	(Agena rocket)	Sep 62 - Oct 64	9	8? × 1·5	2-4 f. $P \simeq 1/4$ min
1962 $\alpha\psi 1$	Tiros 6	50 years	4	0·6 × 1·1	8 st.
1962 $\alpha\psi 2$	Tiros 6 rocket	25 years	2	1·5 × 0·5	8
1962 $\beta\alpha 1$	Alouette	2000 years	15	0·9 × 1·1	8, with flashes of mag 4
1962 $\beta\alpha 2$	Alouette rocket	2000 years	22	6 × 1·5	3-6 f. $P = 13$ sec
1962 $\beta\theta 1$	Cosmos 11	Oct 62 - May 64	7	1·8 × 1·2?	6 st.
1962 $\beta\theta 2$	Cosmos 11 rocket	Oct 62 - Jun 63	2	10 × 2?	3-5 f

Table 1 (Contd.)

	Satellite	Life	N	Size (m)	Magnitude and comments
1962 βκ1	Star-rad	5 years	20	9 ? × 1·5	2–4 f. P = 3 sec in 1964
1962 βμ1	Anna 1B	5000 years	6	0·9 × 1·2	8 st.
1962 βμ2	Anna 1B rocket	2000 years	8	5 × 1·4	4–6 f.
1962 βξ3	Sputnik 24 rocket ?	Nov 62 – Jan 63	3	10 × 2 ?	2–3 f. P = 0·7 sec
1962 βτ6	Injun 3 rocket	6 years	2	6 ? × 1·5	2 st. Sometimes variable
1962 βχ1	Explorer 16	1000 years	12	1·9 × 0·6	8. Flashes of mag 4 every 3 sec
1962 βψ3	Transit 5A rocket	60 years	2	1·8 × 0·5	7
1963–03A	(Agena rocket)	7 years	18	8 ? × 1·5	3–5 f. P ≏ 2 sec in 1963
1963–05A		20 years	4	?	7–9 f. P ≏ 2 sec
1963–09A	Explorer 17	4 years	8	0·9	7 st
1963–10A	Cosmos 14	Apr – Aug 63	2	1·8 × 1·2 ?	3
1963–14A	Midas 6	100 000 years	3	9 ? × 1·5	8 st
1963–17A	Cosmos 17	2 years	12	1·8 × 1·2 ?	5
1963–17G	Cosmos 17 rocket	May 63 – Apr 64	5	10 × 2	2–4 f. P = 0·7 sec
1963–22A	Transit	50 years	1	1 ?	6
1963–24A	Tiros 7	50 years	1	0·6 × 1·1	8
1963–26A	Geophysics Research sat.	15 years	3	2·5 × 0·6	6–8 f. P = 3 sec
1963–27A	(Agena rocket)	7 years	14	8 ? × 1·5	2–4 f. P ≏ 2 sec in 1963
1963–30A	Midas 7	100 000 years	3	9 ? × 1·5	7 st.
1963–30D	(Balloon satellite)	5 years	12	2·4 ?	8 st.
1963–33A	Cosmos 19	Aug 63 – Mar 64	2	1·8 × 1·2 ?	6
1963–33B	Cosmos 19 rocket	Aug – Dec 63	4	10 × 2 ?	3–5 f. P ≏ 4 sec
1963–38A	(Ablestar rocket)	1000 years	5	5 × 1·4	5 st.
1963–38B		1000 years	2	?	8
1963–38C	(Radiation satellite)	1000 years	1	?	8

Table 1 (Contd.)

	Satellite	Life	N	Size (m)	Magnitude and comments
1963–43A	Polyot 1	10 years	7	?	4–6 f. Irregular
1963–43B	Polyot 1 rocket	2 years	1	?	5
1963–43D	Polyot 1 fragment	2 years	1	?	4–7 f
1963–47A	Centaur 2	500 years	1	8·6 × 3	6 in flashes. P = 15 sec
1963–49A	(Ablestar rocket)	1000 years	1	5 × 1·4	6 in flashes
1963–53A	Explorer 19	4 years	11	3·6	3 st.
1963–54A	Tiros 8	60 years	2	0·6 × 1·1	7 in flashes
1964–01A	(Agena rocket)	1000 years	2	8 ? × 1·5	5 st.
1964–01D	SR5	1000 years	1	0·6	8
1964–01E		1000 years	1	?	7–8 f
1964–04A	Echo 2	20 years ?	4	41	–1 st.
1964–04B	Echo 2 rocket	5000 years	2	6 × 1·5	5–6 f
1964–04C	Echo 2 casing	1000 years ?	2	?	8
1964–04D	Echo 2 casing	1000 years ?	1	?	8
1964–06A	Elektron 1	200 years	1	3 × 2 ?	5
1964–06D	Elektron 2 rocket	10 years ?	1	10 × 2 ?	4–6 f. P = 0·8 sec
1964–10A	Cosmos 25	Feb–Nov 64	2	1·8 × 1·2 ?	5 st
1964–11A	(Agena rocket)	7 years	1	8 ? × 1·5	4
1964–13A	Cosmos 26	Mar – Sep 64	2	1·8 × 1·2 ?	5 st.
1964–13B	Cosmos 26 rocket	Mar – May 64	1	10 × 2 ?	2
1964–15A	Ariel 2	4 years	3	0·9 × 0·6	7. Flashes of mag 5
1964–15B	Ariel 2 rocket	3 years	2	1·5 × 0·5	6–9 f
1964–17A	Cosmos 28	4–12 Apr 64	2	9 × 3 ?	3 st.
1964–17B	Cosmos 28 rocket	Apr – May 64	6	10 × 2 ?	3–5, P $\simeq \frac{1}{2}$ sec

Table 1 (Contd.)

	Satellite	Life	N	Size (m)	Magnitude and comments
1964-19B	Polyot 2	3 years	2	?	5
1964-26A	Transit	100 years	1	?	7
1964-28A	Cosmos 31	Jan - Oct 64	6	1·8 × 1·2 ?	5
1964-28B	Cosmos 31 rocket	Jun - Aug 64	3	10 × 2 ?	2-3 f
1964-30A	Starflash 1A	1 year	3	8? × 1·5	2 st.
1964-34A	Cosmos 34	1-9 Jul 64	3	9 × 3?	2 st.
1964-34B	Cosmos 34 rocket	1-15 Jul 64	1	10 × 2?	2-4 f
1964-35A	(Agena rocket)	7 years	2	8? × 1·5	3
1964-36B		6 months	1	?	6 in flashes
1964-38A	Elektron 3	200 years?	2	3 × 2 ?	4
1964-42A	Cosmos 36	7 months	3	1·8 × 1·2 ?	5-6 f
1964-42B	Cosmos 36 rocket	Jul - Dec 64	7	10 × 2 ?	2-3 f. P = 0·7 sec
1964-44A	Cosmos 37	14 - 22 Aug 64	1	9 × 3 ?	3 st.
1964-46C	Cosmos 40	Aug - Nov 64	1	?	6 in flashes
1964-46D	Cosmos 38 rocket	7 months	3	10 × 2 ?	2-4 f
1964-48A	Starflash 1B	6 months	1	8? × 1·5	2 st.
1964-50A	Cosmos 42	1 year	1	1·8 × 1·2?	5-7 f.
1964-50B	Cosmos 42 rocket	1 year	5	10 × 2?	5-7 f. P ≃ 1 sec
1964-51A	Explorer 20	1000 years	1	0·8 × 0·7	6 in flashes. P = 10 sec
1964-53A	Cosmos 44	50 years	2	1·8 × 1·2 ?	6 st.
1964-53B	Cosmos 44 rocket	50 years	3	10 × 2 ?	3-4 f. P = 0·7 sec
1964-55A	Cosmos 45	13-18 Sep 64	3	9 × 3 ?	3 st.
1964-55B	Cosmos 45 rocket	13-27 Sep 64	1	10 × 2?	1-3 f, P = 15 sec
1964-59B	Cosmos 46 rocket	Sep-Oct 64	2	10 × 2?	3-5 f, P = 1 sec

Table 1 (Contd.)

	Satellite	Life	N	Size (m)	Magnitude and comments
1964-63A	(Ablestar rocket)	1000 years	5	5 × 1·4	5 st.
1964-65B	Voskhod 1 rocket	12-20 Oct 64	4	10 × 2?	1-2 f. $P \simeq 2$ sec
1964-69A	Cosmos 49	14 months	3	1·8 × 1·2?	6 st.
1964-69B	Cosmos 49 rocket	5 months	2	10 × 2?	3-5 f. $P = 0{\cdot}8$ sec
1964-72A	(Agena rocket)	7 years	1	8? × 1·5	3-5 f
1964-76A	Explorer 24	5 years?	5	3·6	3 st.
1964-76B	Explorer 25	100 years	1	0·6	7-9 f
1964-76C	Explorer 24 rocket	100 years	2	1·5 × 0·5	8-9 f. $P = 4\frac{1}{2}$ sec
1964-80A	Cosmos 51	1 year	2	1·8 × 1·2?	5 st.
1964-80B	Cosmos 51 rocket	5 months	2	10 × 2?	2-4 f. $P = 0{\cdot}5$ sec

REFERENCES

No.	Author	Title, etc.
1	E.E. Hale	The Brick Moon and other stories. Little, Brown and Co. Boston, 1899. p.10
2	A. Pope	Moral Essays, Epistle I, lines 11-12 (1733)
3	D.G. King-Hele D.M.C. Walker	Methods for predicting the orbits of near Earth-satellites. Journ. Brit. Interplan. Soc., 17, 2-14 (1959) (Also R.A.E. Report GW 25, App.G.)
4	J. Heywood (Editor)	Artificial Earth Satellites. British Astronomical Association, 1961.
5	A.P. Norton	A Star Atlas and reference handbook, 14th edition. (Gall and Inglis, Edinburgh, 1959)
6	A. Bečvář	Atlas Eclipticalis, 1950.0; Atlas Borealis, 1950.0. Československé Akademie Věd, Prague (1958; 1962)
7	-	Apparent places of fundamental stars, 1950. (HMSO, London, 1949)
8	K.R. Garren, P.A. Gainer	Measurement of errors in manually recording transit times of stars and distant planets. NASA TN D-2433 (1964)
9	D.G. King-Hele E. Quinn	Table of the artificial earth satellites launched in 1957-63. R.A.E. Tech Note Space 56 (1964)
10	J.A. Pilkington	"Cosmos calculations" and "The 65-degree Cosmos satellites". Flight International, 12 Dec 1963, 977 and 1 October 1964, 605
11	P. Notni H. Oleak	Die rotation der traegerrakete von Sputnik 3. Veroeff. Sternwarte Babelsberg 13, 4 (1959) R.A.E. Translation No. 864 (1959)
12	D.G. King-Hele	The upper atmosphere: a review. R.A.E. Tech Note Space 50 (1963)

REFERENCES (Contd.)

No.	Author	Title, etc.
13	D.G. King-Hele	The shape of the earth. R.A.E. Tech Note Space 51 (1963) (J. Inst. Nav., 17, 1-16, 1964)
14	D.G. King-Hele	Theory of satellite orbits in an atmosphere (Butterworths, London, 1964) Ch. 7
15	D.G. King-Hele E. Quinn	The variation of upper-atmosphere density between sunspot maximum (1957-8) and minimum (1964). R.A.E. Tech Note Space 72 (1964)
16	D.G. King-Hele J.M. Hughes	Scale height in the upper atmosphere. R.A.E. Tech Note Space 4 (1962)
17	D.G. King-Hele	The rotational speed of the upper atmosphere. R.A.E. Tech Note Space 59 (1964) (Planet Space Sci., 12, 835-853, 1964)
18	R.H. Merson A.T. Sinclair	Orbital parameters of Transit 1B (1960 γ2) June 2-10, 1962. R.A.E. Tech Report 64036 (1964)
19	J.A. Pilkington	The visual appearance of artificial earth satellites. Planet. Space Sci. 12, 597-606 (1964)

D. S. I. R. RADIO RESEARCH STATION

SATELLITE PREDICTIONS

1963 43A POLYOT I SATELLITE

ISSUE No. II

Tn = TIME AT APEX G.M.T.
Ln = LONGITUDE OF APEX

REV NO	Tn HR MIN	Ln	REV NO	Tn HR MIN	Ln
1 OCT 1964					
4714	12 19.3	61.9 E	4715	14 1.7	36.0 E
4716	15 44.0	10.2 E	4717	17 26.4	15.7 W
4718	19 8.7	41.6 W			
2 OCT 1964					
4728	12 12.0	59.5 E	4729	13 54.4	33.6 E
4730	15 36.7	7.7 E	4731	17 19.0	18.2 W
4732	19 1.4	44.1 W			
3 OCT 1964					
4742	12 4.7	57.0 E	4743	13 47.0	31.1 E
4744	15 29.4	5.2 E	4745	17 11.7	20.6 W
4746	18 54.0	46.5 W			
4 OCT 1964					
4756	11 57.4	54.6 E	4757	13 39.7	28.7 E
4758	15 22.0	2.8 E	4759	17 4.4	23.1 W
4760	18 46.7	49.0 W			

HEIGHTS

LAT \ REV	4690	4760	
58.9 N	376	392	KM
	203	212	N.MLS
55 N	348	352	KM
	188	190	N.MLS
50 N	349	346	KM
	188	187	N.MLS
45 N	359	350	KM
	194	189	N.MLS

VISIBILITY

REV NO	ENTRY INTO ECLIPSE LAT	LONG WRT APEX
4620	56.1 N	25.2 E
4690	51.6 N	38.7 E
4760	42.9 N	53.0 E

Fig.1 Extract from predictions for Polyot 1

Fig.2

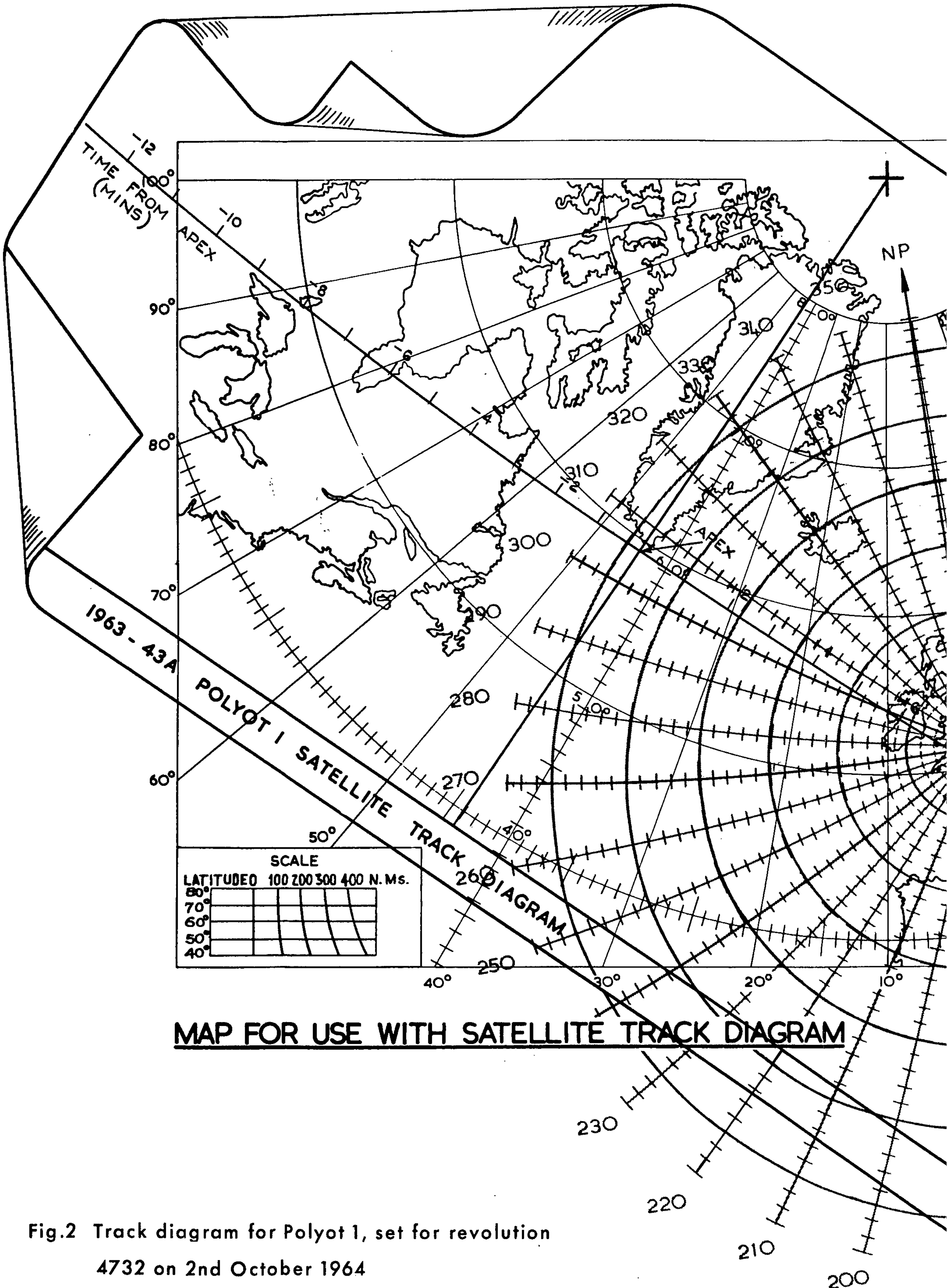
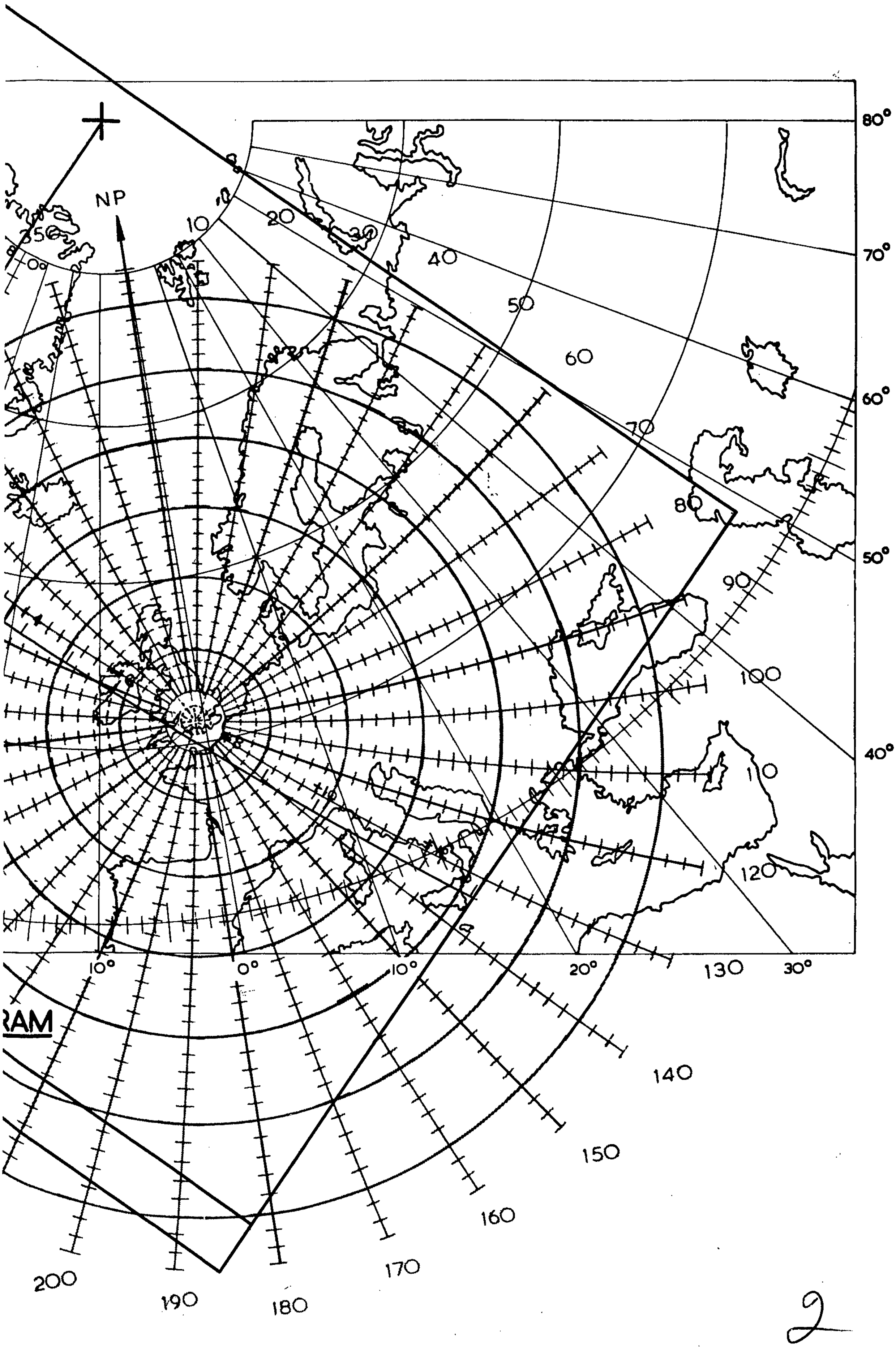


Fig.2 Track diagram for Polyot 1, set for revolution 4732 on 2nd October 1964


NP
80°
70°
60°
50°
40°
350
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
10°
0°
10°
20°
30°
RAM

S pA 1346

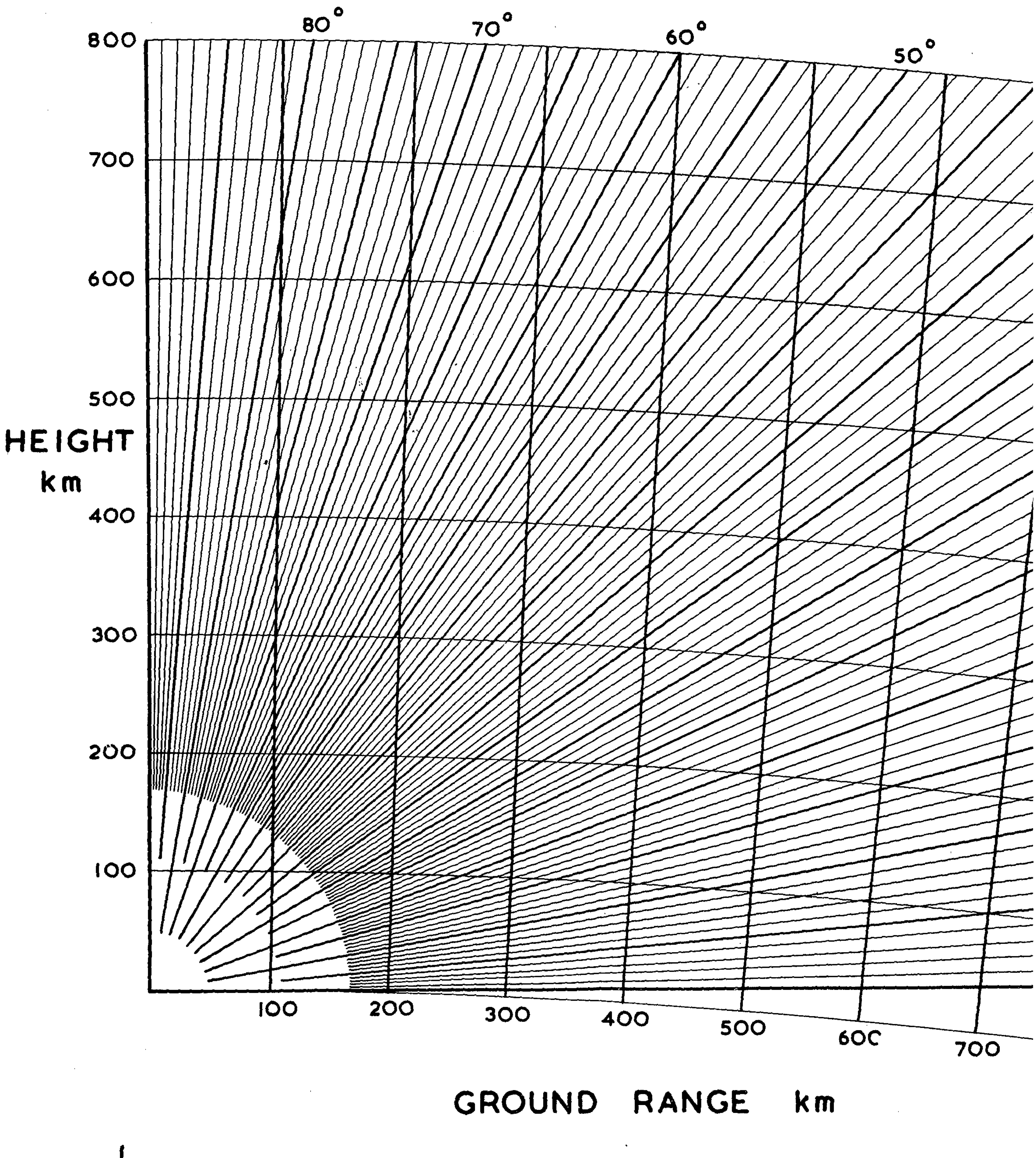
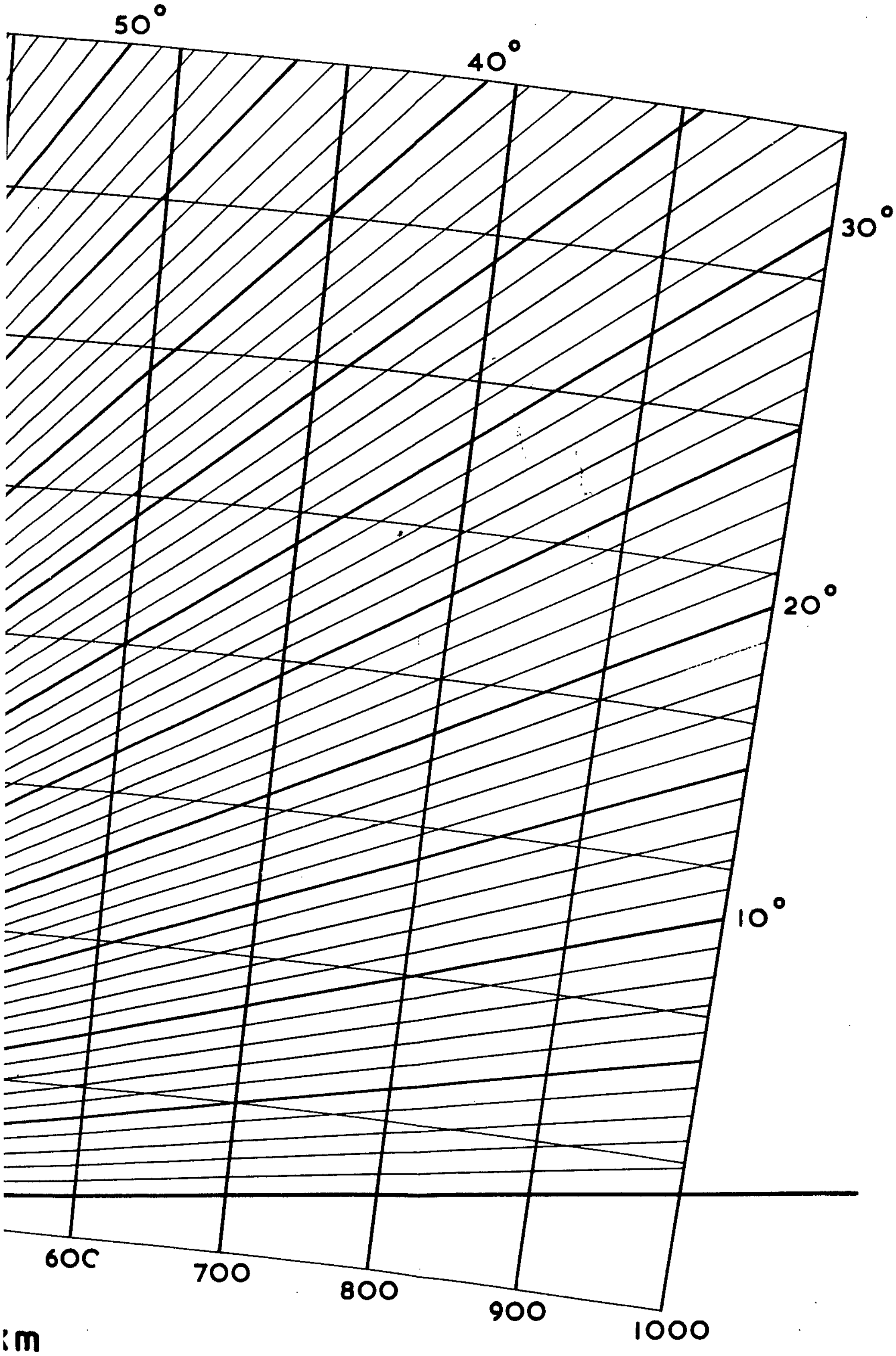


FIG. 3 SATELLITE GRID

Fig. 3



2

E GRID

Fig. 4

Lat 51.2   Az = 30 or 330

A	h	Dec	A	h	Dec
0	9 34	32.9			
1	9 32	33.8	46	6 12	69.6
2	9 30	34.7	47	6 01	70.1
3	9 28	35.6	48	5 50	70.4
4	9 26	36.6	49	5 39	70.8
5	9 24	37.5	50	5 27	71.1
6	9 22	38.4	51	5 15	71.3
7	9 20	39.3	52	5 03	71.5
8	9 18	40.2	53	4 50	71.6
9	9 16	41.1	54	4 38	71.7
10	9 14	42.0	55	4 25	71.7
11	9 12	43.0	56	4 12	71.7
12	9 09	43.9	57	4 00	71.7
13	9 07	44.8	58	3 47	71.5
14	9 04	45.6	59	3 35	71.4
15	9 02	46.5	60	3 23	71.1
16	8 59	47.4	61	3 11	70.9
17	8 56	48.3	62	2 59	70.5
18	8 53	49.2	63	2 48	70.2
19	8 50	50.1	64	2 37	69.8
20	8 47	50.9	65	2 27	69.3
21	8 44	51.8	66	2 17	68.9
22	8 41	52.7	67	2 08	68.3
23	8 37	53.5	68	1 59	67.8
24	8 34	54.4	69	1 50	67.2
25	8 30	55.2	70	1 42	66.6
26	8 26	56.0	71	1 34	66.0
27	8 22	56.9	72	1 27	65.4
28	8 17	57.7	73	1 20	64.7
29	8 13	58.5	74	1 13	64.0
30	8 08	59.3	75	1 07	63.3
31	8 03	60.1	76	1 01	62.6
32	7 58	60.8	77	0 55	61.8
33	7 53	61.6	78	0 50	61.1
34	7 47	62.3	79	0 44	60.3
35	7 41	63.1	80	0 39	59.5
36	7 35	63.8	81	0 35	58.7
37	7 28	64.5	82	0 30	57.9
38	7 21	65.2	83	0 26	57.1
39	7 14	65.8	84	0 22	56.3
40	7 06	66.4	85	0 18	55.5
41	6 58	67.0	86	0 14	54.6
42	6 50	67.6	87	0 10	53.8
43	6 41	68.2	88	0 07	52.9
44	6 32	68.7	89	0 03	52.1
45	6 22	69.2	90	0 00	51.2

Az = 60 or 300

A	h	Dec	A	h	Dec
0	7 37	18.3			
1	7 34	19.1	46	4 53	51.1
2	7 32	19.9	47	4 48	51.6
3	7 30	20.7	48	4 42	52.1
4	7 27	21.5	49	4 36	52.5
5	7 25	22.3	50	4 30	53.0
6	7 22	23.1	51	4 24	53.4
7	7 19	24.0	52	4 18	53.8
8	7 17	24.8	53	4 12	54.2
9	7 14	25.6	54	4 05	54.6
10	7 12	26.4	55	3 59	54.9
11	7 09	27.1	56	3 52	55.2
12	7 06	27.9	57	3 46	55.5
13	7 03	28.7	58	3 39	55.8
14	7 00	29.5	59	3 32	56.0
15	6 57	30.3	60	3 25	56.3
16	6 54	31.1	61	3 18	56.5
17	6 51	31.8	62	3 11	56.6
18	6 48	32.6	63	3 04	56.8
19	6 45	33.4	64	2 56	56.9
20	6 42	34.1	65	2 49	57.0
21	6 39	34.9	66	2 42	57.1
22	6 36	35.6	67	2 34	57.1
23	6 32	36.4	68	2 27	57.1
24	6 29	37.1	69	2 19	57.1
25	6 26	37.8	70	2 12	57.1
26	6 22	38.6	71	2 05	57.0
27	6 19	39.3	72	1 58	56.9
28	6 15	40.0	73	1 50	56.8
29	6 11	40.7	74	1 43	56.7
30	6 07	41.4	75	1 36	56.5
31	6 03	42.1	76	1 29	56.3
32	5 59	42.7	77	1 22	56.1
33	5 55	43.4	78	1 15	55.8
34	5 51	44.1	79	1 08	55.6
35	5 47	44.7	80	1 01	55.3
36	5 43	45.4	81	0 55	55.0
37	5 38	46.0	82	0 48	54.6
38	5 34	46.6	83	0 42	54.3
39	5 29	47.2	84	0 35	53.9
40	5 24	47.8	85	0 29	53.5
41	5 19	48.4	86	0 23	53.1
42	5 14	49.0	87	0 17	52.6
43	5 09	49.5	88	0 11	52.2
44	5 04	50.1	89	0 06	51.7
45	4 59	50.6	90	0 00	51.2

Az = 90 or 270

A	h	Dec	A	h
0	6 00	0.0		
1	5 57	0.8	46	3 4
2	5 55	1.6	47	3 4
3	5 52	2.3	48	3 4
4	5 50	3.1	49	3 3
5	5 47	3.9	50	3 3
6	5 45	4.7	51	3 2
7	5 42	5.5	52	3 2
8	5 40	6.2	53	3 2
9	5 37	7.0	54	3 1
10	5 35	7.8	55	3 1
11	5 32	8.6	56	3 0
12	5 30	9.3	57	3 0
13	5 27	10.1	58	3 0
14	5 25	10.9	59	2 5
15	5 22	11.6	60	2 5
16	5 19	12.4	61	2 4
17	5 17	13.2	62	2 4
18	5 14	13.9	63	2 3
19	5 12	14.7	64	2 3
20	5 09	15.5	65	2 2
21	5 06	16.2	66	2 2
22	5 03	17.0	67	2 1
23	5 00	17.7	68	2 1
24	4 58	18.5	69	2 0
25	4 55	19.2	70	2 0
26	4 52	20.0	71	1 5
27	4 49	20.7	72	1 5
28	4 46	21.5	73	1 4
29	4 43	22.2	74	1 3
30	4 40	22.9	75	1 3
31	4 37	23.7	76	1 2
32	4 34	24.4	77	1 2
33	4 31	25.1	78	1 1
34	4 28	25.8	79	1 0
35	4 25	26.6	80	1 0
36	4 22	27.3	81	0 5
37	4 19	28.0	82	0 5
38	4 16	28.7	83	0 4
39	4 12	29.4	84	0 3
40	4 09	30.1	85	0 3
41	4 06	30.7	86	0 26
42	4 02	31.4	87	0 1
43	3 59	32.1	88	0 1
44	3 55	32.8	89	0 06
45	3 52	33.4	90	0 00

Fig.4 Tables for converting azimuth and elevation (A) to right

: 90 or 270

A	h	Dec
46	3 48	34.1
47	3 44	34.7
48	3 41	35.4
49	3 37	36.0
50	3 33	36.7
51	3 29	37.3
52	3 25	37.9
53	3 21	38.5
54	3 17	39.1
55	3 13	39.7
56	3 08	40.2
57	3 04	40.8
58	3 00	41.4
59	2 55	41.9
60	2 51	42.4
61	2 46	43.0
62	2 41	43.5
63	2 36	44.0
64	2 32	44.5
65	2 27	44.9
66	2 22	45.4
67	2 16	45.8
68	2 11	46.3
69	2 06	46.7
70	2 01	47.1
71	1 55	47.5
72	1 50	47.8
73	1 44	48.2
74	1 38	48.5
75	1 33	48.8
76	1 27	49.1
77	1 21	49.4
78	1 15	49.7
79	1 09	49.9
80	1 03	50.1
81	0 57	50.3
82	0 51	50.5
83	0 44	50.7
84	0 38	50.8
85	0 32	50.9
86	0 26	51.0
87	0 19	51.1
88	0 13	51.2
89	0 06	51.2
90	0 00	51.2

Az = 120 or 240

A	h	Dec	A	h	Dec
0	4 23	-18.3			
1	4 31	-17.4	46	2 39	20.1
2	4 18	-16.6	47	2 37	20.9
3	4 16	-15.8	48	2 34	21.7
4	4 14	-15.0	49	2 32	22.5
5	4 11	-14.1	50	2 29	23.3
6	4 09	-13.3	51	2 27	24.1
7	4 07	-12.5	52	2 24	24.9
8	4 04	-11.6	53	2 21	25.7
9	4 02	-10.8	54	2 19	26.5
10	4 00	-10.0	55	2 16	27.3
11	3 58	-9.1	56	2 13	28.1
12	3 56	-8.3	57	2 10	28.9
13	3 53	-7.5	58	2 08	29.7
14	3 51	-6.6	59	2 05	30.4
15	3 49	-5.8	60	2 02	31.2
16	3 47	-5.0	61	1 54	32.0
17	3 44	-4.1	62	1 56	32.8
18	3 42	-3.3	63	1 52	33.5
19	3 40	-2.4	64	1 49	34.3
20	3 38	-1.6	65	1 46	35.0
21	3 36	-0.8	66	1 43	35.8
22	3 34	0.1	67	1 40	36.5
23	3 32	0.9	68	1 36	37.2
24	3 29	1.8	69	1 33	38.0
25	3 27	2.6	70	1 29	38.7
26	3 25	3.4	71	1 26	39.4
27	3 23	4.3	72	1 22	40.1
28	3 21	5.1	73	1 18	40.8
29	3 18	6.0	74	1 14	41.5
30	3 16	6.8	75	1 10	42.2
31	3 14	7.6	76	1 06	42.9
32	3 12	8.5	77	1 02	43.5
33	3 10	9.3	78	0 58	44.2
34	3 07	10.1	79	0 54	44.8
35	3 05	11.0	80	0 50	45.5
36	3 03	11.8	81	0 45	46.1
37	3 01	12.6	82	0 40	46.7
38	2 58	13.5	83	0 36	47.3
39	2 56	14.3	84	0 31	47.9
40	2 54	15.1	85	0 26	48.5
41	2 51	16.0	86	0 21	49.1
42	2 49	16.8	87	0 16	49.6
43	2 47	17.6	88	0 11	50.2
44	2 44	18.4	89	0 06	50.7
45	2 42	19.2	90	0 00	51.2

Az = 150 or 210

A	h	Dec	A	h	Dec
0	2 26	-32.9			
1	2 24	-31.9	46	1 23	10.6
2	2 23	-31.0	47	1 22	11.5
3	2 21	-30.1	48	1 20	12.5
4	2 19	-29.1	49	1 19	13.4
5	2 18	-28.2	50	1 18	14.4
6	2 16	-27.3	51	1 16	15.3
7	2 14	-26.3	52	1 15	16.3
8	2 13	-25.4	53	1 13	17.2
9	2 11	-24.5	54	1 12	18.2
10	2 10	-23.5	55	1 11	19.1
11	2 08	-22.6	56	1 09	20.0
12	2 07	-21.6	57	1 08	21.0
13	2 06	-20.7	58	1 06	21.9
14	2 04	-19.8	59	1 05	22.9
15	2 03	-18.8	60	1 03	23.8
16	2 01	-17.9	61	1 02	24.7
17	2 00	-16.9	62	1 00	25.7
18	1 59	-16.0	63	0 59	26.6
19	1 57	-15.0	64	0 57	27.6
20	1 56	-14.1	65	0 56	28.5
21	1 55	-13.1	66	0 54	29.4
22	1 53	-12.2	67	0 52	30.4
23	1 52	-11.2	68	0 51	31.3
24	1 51	-10.3	69	0 49	32.2
25	1 49	-9.3	70	0 47	33.1
26	1 48	-8.4	71	0 45	34.1
27	1 47	-7.5	72	0 44	35.0
28	1 46	-6.5	73	0 42	35.9
29	1 44	-5.6	74	0 40	36.8
30	1 43	-4.6	75	0 38	37.8
31	1 42	-3.7	76	0 36	38.7
32	1 40	-2.7	77	0 34	39.6
33	1 39	-1.8	78	0 31	40.5
34	1 38	-0.8	79	0 29	41.4
35	1 37	0.1	80	0 27	42.3
36	1 36	1.1	81	0 25	43.2
37	1 34	2.0	82	0 22	44.1
38	1 33	3.0	83	0 20	45.0
39	1 32	3.9	84	0 17	45.9
40	1 30	4.9	85	0 15	46.8
41	1 29	5.8	86	0 12	47.7
42	1 28	6.8	87	0 09	48.6
43	1 27	7.7	88	0 06	49.5
44	1 25	8.7	89	0 03	50.3
45	1 24	9.6	90	0 00	51.2

to right ascension and declination. Adapted from ref. 3

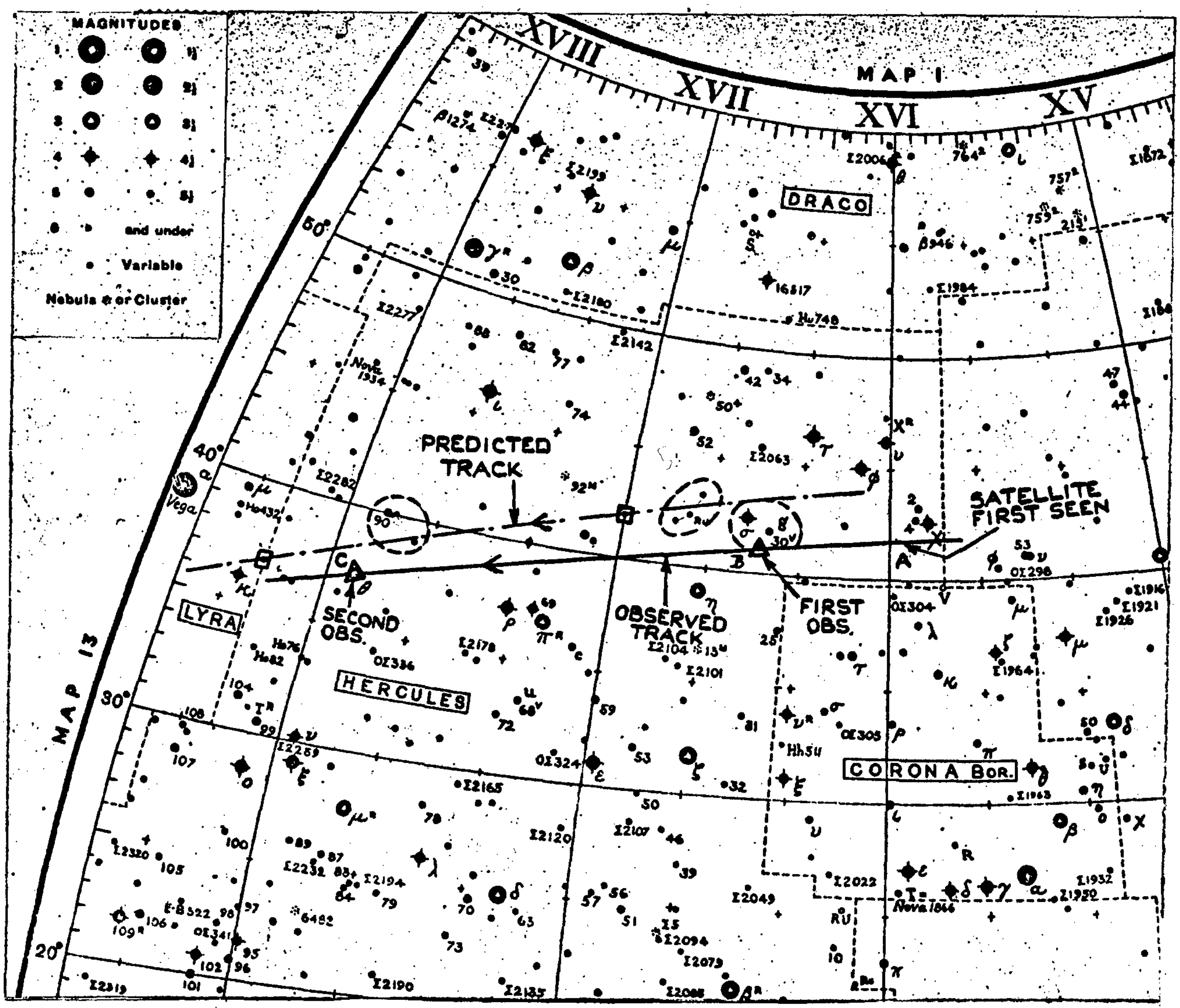


Fig.5 Predicted and observed tracks of Polyot 1 on 2nd October 1964, plotted in Norton's star atlas

Fig.6

Neg. No. 170113

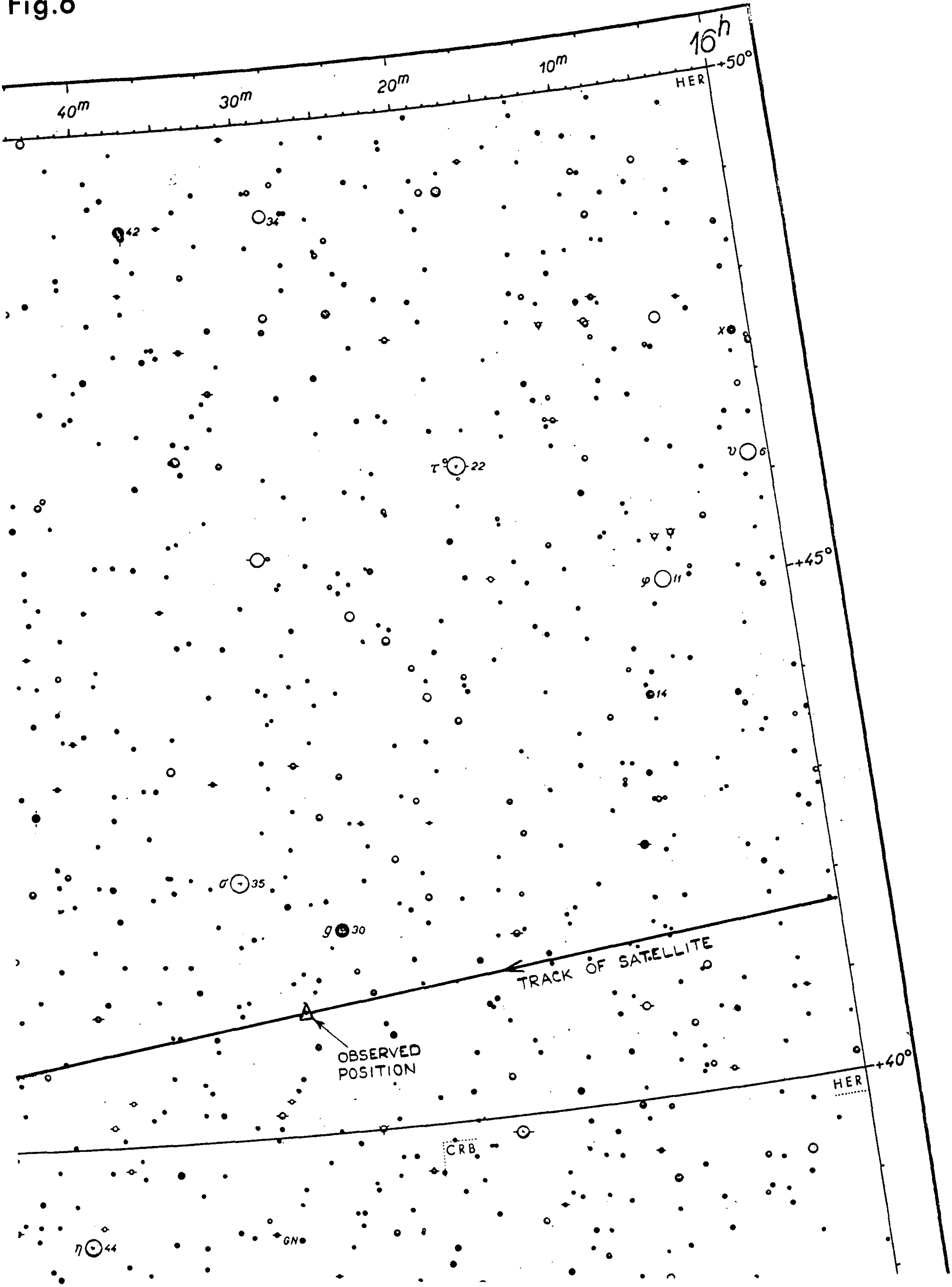
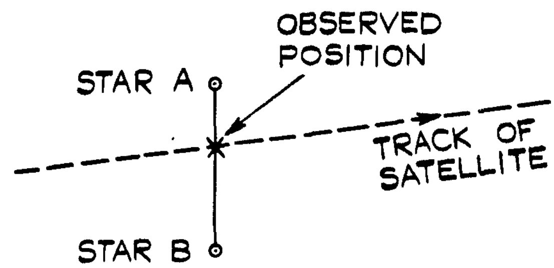
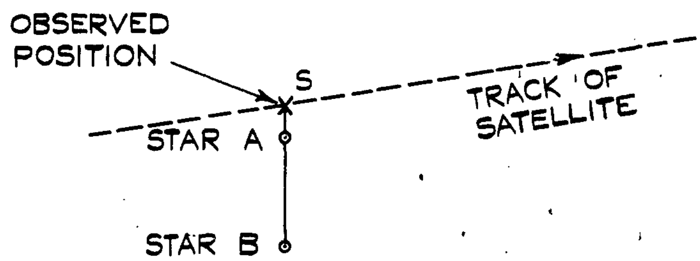


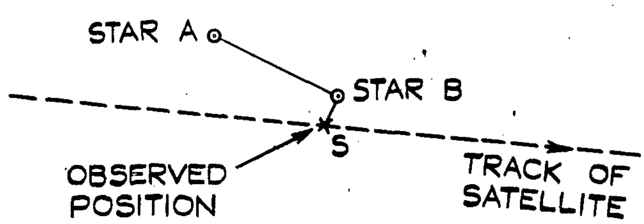
Fig.6 Apparent track of Polyot 1 on 2nd October 1964, plotted in the Atlas Borealis



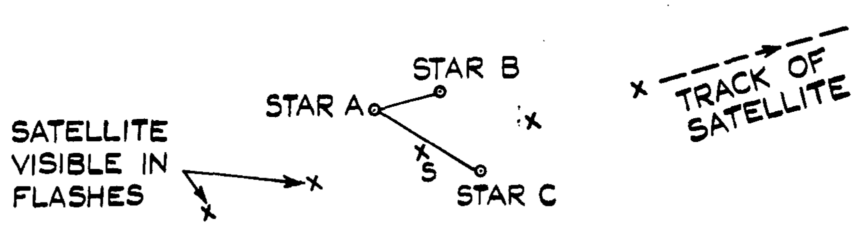
(a) NEAR - PERPENDICULAR PASSAGE
BETWEEN TWO STARS



(b) EXTRAPOLATION



(c) RIGHT - ANGLE TRIANGLE



(d) FLASHING SATELLITE. PATTERN
RELATIVE TO STARS

FIG. 7(a - d) POSSIBLE METHODS OF OBSERVATION
RELATIVE TO REFERENCE STARS

DETACHABLE ABSTRACT CARDS

King-Hele, D. G. 522.6 : 535.834 : 629.195 : 521.3

TECHNIQUES FOR MAKING VISUAL OBSERVATIONS OF EARTH SATELLITES

Royal Aircraft Establishment Technical Report 64087 December 1964

This paper describes methods for observing Earth satellites in a quick and simple manner, with binoculars and stop-watch: an accuracy of about 0.1 sec in time and 0.05° in direction can be achieved. The uses of the observations for orbital determination and other purposes are outlined.

King-Hele, D. G. 522.6 : 535.834 : 629.195 : 521.3

TECHNIQUES FOR MAKING VISUAL OBSERVATIONS OF EARTH SATELLITES

Royal Aircraft Establishment Technical Report 64087 December 1964

This paper describes methods for observing Earth satellites in a quick and simple manner, with binoculars and stop-watch: an accuracy of about 0.1 sec in time and 0.05° in direction can be achieved. The uses of the observations for orbital determination and other purposes are outlined.

King-Hele, D. G. 522.6 : 535.834 : 629.195 : 521.3

TECHNIQUES FOR MAKING VISUAL OBSERVATIONS OF EARTH SATELLITES

Royal Aircraft Establishment Technical Report 64087 December 1964

This paper describes methods for observing Earth satellites in a quick and simple manner, with binoculars and stop-watch: an accuracy of about 0.1 sec in time and 0.05° in direction can be achieved. The uses of the observations for orbital determination and other purposes are outlined.

King-Hele, D. G. 522.6 : 535.834 : 629.195 : 521.3

TECHNIQUES FOR MAKING VISUAL OBSERVATIONS OF EARTH SATELLITES

Royal Aircraft Establishment Technical Report 64087 December 1964

This paper describes methods for observing Earth satellites in a quick and simple manner, with binoculars and stop-watch: an accuracy of about 0.1 sec in time and 0.05° in direction can be achieved. The uses of the observations for orbital determination and other purposes are outlined.