NBS

Technical Note No. 184

LUNAR OCCULTATIONS OF TWO DISCRETE RADIO SOURCES IN 1963–1964

JOHN A. EDDY

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS
Technical Note 184
Issued October 11, 1963

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For sale by the Superintendent of Documents, U. S. Government Printing Office
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PRICE 20 CENTS

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LUNAR OCCULTATIONS OF TWO DISCRETE RADIO SOURCES IN 1963 - 1964

John A. Eddy

The bright, extended radio sources Taurus A. and IC443 lie close to the ecliptic and are occulted by the moon about every $8\frac{1}{2}$ years, providing rare opportunities to study their angular brightness distribution with very high resolution. The nature of the next series of occultations of these sources, which will occur for observers at Boulder during the period from November 1963 through August 1964, is discussed.

I. INTRODUCTION

Eight years ago Bakulin and Shklovski [1955] published a reminder to radio astronomers that lunar occultations of two major radio sources were due to occur at different times over the earth in the year to come. The sources were Taurus A (Crab Nebula) and IC443, a galactic nebula in Gemini; they are the only extended radio sources of significant flux density that lie near the ecliptic. The period of recurrence of these events, fixed by the ecliptic latitude of the source, is eight to nine years. The last series were observed in Europe and Australia in October and November 1955 and in January 1956. They will recur in North America throughout the period from winter 1963 through summer 1964.

II. IMPORTANCE OF LUNAR OCCULTATIONS

There are three principal reasons for observing the lunar occultation of radio sources. First, an estimate of the electron density of the lunar atmosphere can be obtained from accurate comparison of the predicted times of occultation of radio source behind the moon [Link and Neuzil, 1954]. The presence of a lunar atmosphere will cause refraction of the radio waves received from the occulted source during the times of emersion and immersion and will thus cause the observed period of obscuration to be somewhat less than that expected in the absence of refraction. In this way Elsmore and Whitfield [1955] and Elsmore [1958] observed occultations of IC443 and Taurus A to derive an upper limit for the density of the lunar atmosphere of about 10^{-13} that of the atmosphere of the earth.

The second reason for observing a lunar occultation is to determine the precise position of the occulted source. From the known ephemerides of the moon, the time of occultation of a source can be translated directly into a very precise position of right ascension and declination. Since the accurate determination of the positions of radio sources is a major problem in the present techniques of radio astronomy, this method is of unique value. It is, of course, rather limited since only sources that lie within the path of the moon are available. Furthermore, most occultations give information on only the right ascension of the source; information on declination is afforded only in the case of a grazing occultation by the upper or lower limb of the lunar disk. Hazard [1961] has determined the right ascension of the source 3C212 to within 5" of arc by this method and more recently [Bolton, 1963] has fixed the position of the distant source 3C273 to within about 1".

Finally, occultations permit the study of the angular structure or brightness distribution of occulted sources with unusually high resolution. The method involved is precisely that employed in the study of solar eclipses: the disk of the moon acts as a screen that progressively isolates the emission from incremental areas of the source. For most sources observed at the higher frequencies in the radio case, the moon is a more intense emitter than the occulted source, but this does not exclude the method provided the emission from the occulted source is within the range of detection of the radio receiver. Resolution is limited only by the Fresnel diffraction pattern at the lunar limb and by the time and intensity resolution of the radiometer. Recently, Scheuer [1962] has shown that the Fresnel diffraction limitation (about 18" of arc at 100 Mc/s and 6" at 1000 Mc/s) may be overcome by analytical reduction, so that the strip distribution of the occulted source may in practice be completely recovered from the diffraction records. The angular distribution of brightness across the Crab Nebula was studied by this method during the 1955-56 occultation by Costain, Elsmore, and Whitfield [1956]; Boischot, Blum, and LeRoux [1956]; Tuominen and Karras [1957]; and Seeger and Westerhout [1957]. The last occultation of IC443 was observed by Elsmore and Whitfield [1955] and by Rishbeth [1956], whose reconstruction of its angular distribution confirmed the tentative identification of the source that had been proposed by Baldwin and Dewhirst [1954]. Other sources whose angular distributions have been studied by lunar occultations are Kepler's Star [Rishbeth and Little, 1957; Talen, 1963], Jupiter, and 3C273 [Bolton, 1963]. The method again is limited to objects that lie near the ecliptic and whose flux densities are within the sensitivity range of the radiometer employed. It seems a particularly happy circumstance that the rather strong and interesting sources Taurus A and IC443 are included in these conditions.

TABLE I.

Summary of Lunar Occultation Observations

Source	Occultation	Location	f Mc/s	λ	Equipment	Purpose	Reference
IC443	26 Apr. 55	Cambridge	81 38	3.7 m 7.9 m	Interferometer	Lunar Atmosphere Angular distrib.	Elsmore and Whitfield (1955)
IC443	8 Oct. 55	Fleurs	86	3.5 m	Mills Cross	Angular distrib.	Rishbeth (1956)
Taurus A	3 Nov. 55 30 Nov. 55	Dwingeloo	400	75 cm	82' Parabola	Angular distrib.	Seeger and Westerhout (1957)
Taurus A	30 Nov. 55 24 Jan. 56	Helsinki	81	3.7 m	Phase-Switching Interferometer	Diameter	Tuominen and Karras (1957)
Taurus A	30 Nov. 55 24 Jan. 56	Cambridge	81 38	3.7 m 7.9 m	Phase-Switching Interferometer	Lunar Atmos. Angular distrib.	Costain, Elsmore, & Whitfield (1956) Elsmore (1957)(1958)
Taurus A	24 Jan. 56	France	169 900	1.77m 33 cm	?	Angular distrib.	Boischot, Blum, Ginat, LeRoux (1956)
Kepler's Star	12 Sept. 56	Fleurs	86	3.5 m	Mills Cross	Angular size	Rishbeth & Little (1957)
Kepler's Star	(1962)	Portage Lake	800	37 cm	85' Parabola	Angular distrib.	Talen (1963)
3C212	8 Dec. 60	Jodrell	237	1.27m	250' Parabola	Position	Hazard (1961)
3C273	22 Aug. 62	Parks	400	75 cm	210' Parabola	Position, Angular distrib.	Bolton (1963)
Jupiter	5 Mar. 62 1 Apr. 62	Parks	400	75 cm	210' Parabola	Angular size	Bolton (1963)

Table I summarizes some previous observations of lunar occultations which have been reported in the radio astronomy literature.

III. OCCULTATIONS OF TAURUS A AND IC443 IN 1963-1964

It was stated in Section I that the occultations of Taurus A and IC443 recur in a period of eight to nine years, with the next occultation season beginning late in 1963. The explanation for this cycle of recurrence is given simply by the relation of the orbit of the moon to the ecliptic. The angle of inclination of the lunar orbit to the ecliptic is $5^{\circ}\ 9'$, so that the area of the sky traversed by the moon is a band $10^{\circ}\ 18'$ wide centered on the ecliptic. Within this band the position and shape of the apparent lunar orbit continually changes, following a major cycle of about 19 years that is fixed by the period of the regression of nodes. The interval between occultations of sources within the lunar band is thus determined by the 19 year cycle and the particular ecliptic latitude of the source. Thus Taurus A and IC443, found within about 1° of the ecliptic, are occulted about every half period, or every eight or nine years. The geometry of an occultation is, however, much different on alternate half-cycles. Figure 1 shows the path of the moon during the times of an occultation of IC443 in January 1956 and a half-cycle later in March 1964. The lunar band about the ecliptic is shown as a shaded area.

Figure 1 is constructed from geocentric coordinates taken from the American Ephemeris. Because of the significant horizontal parallax of the moon (about 1°) an exact calculation of a lunar occultation must be corrected for the geographic position of the observer, i.e., topocentric coordinates must be obtained.

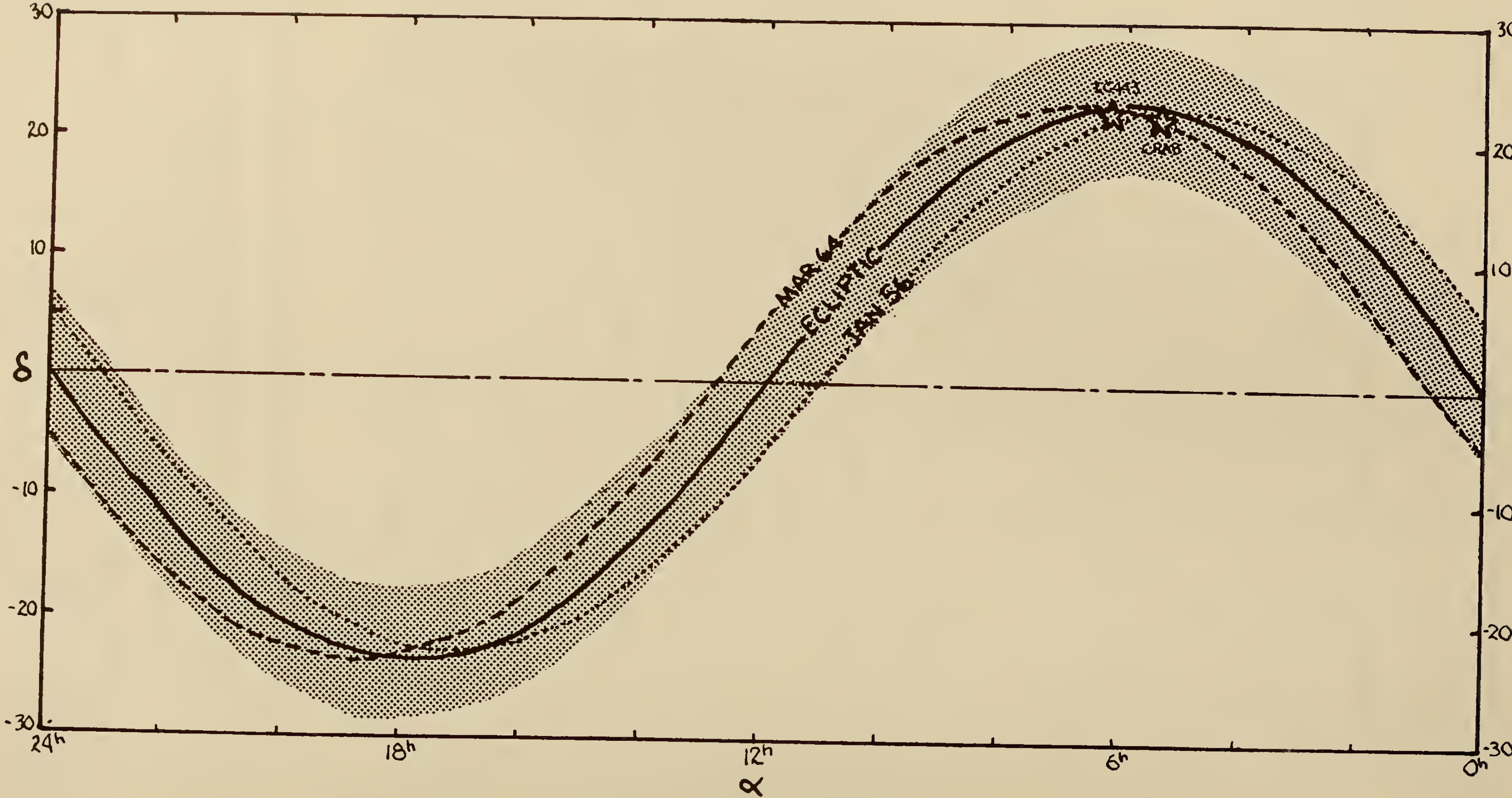

Figure 1. Path of the moon in right ascension and declination during lunations in January 1956 and March 1964 in which the radio source IC443 is occulted.

Table II lists the predicted occultations of Taurus A and IC443 during the 1963-64 season calculated for the geographic position 40°.148 N, 105°.231 W (the midpoint of the T-22 interferometer at Table Mesa, north of Boulder). The source coordinates (epoch 1964) used in the calculations were the following:

Taurus A	$5^h\ 32^m\ 19^s$	$+21°\ 59'.8$
IC443	$6^h\ 15^m\ 03^s$	$+22°\ 36'.0$

Taurus A (the Crab Nebula) is a source whose angular diameter is about 4' of arc; thus any occultation by the moon (angular diameter 31') is likely to be a total occultation. Occultations of this sort occur at Boulder on 13 May and 7 July 1964. IC443, on the other hand, is a more extended source whose radio diameter (about 45') is larger than that of the moon; thus an assortment of partial occultations is possible. The principal area of interest in IC443, at least at the longer wavelengths, is the north-following edge. Rishbeth [1956], in observing the partial occultation of the northern half of the nebula visible in Australia, noted that though only one tenth of the optical nebula was obscured, the 3.5m radio radiation was reduced by over one fifth, and concluded that the optical bright arch on the north-following edge is the source of strongest radio emission. Observations of an occultation of the sourthern part of the nebula visible in England [Elsmore and Whitfield,1955] seemed to bear this out, for an obscuration of a large part of the southern half resulted in little change in radio flux. The occultations to occur in the 1963-64 season present a nice opportunity to check these earlier results, since a rather complete range of IC443 occultations is predicted.

TABLE II

Predicted Occultations of Taurus A and IC443 at Table Mesa

Date	Zone Time	Source	Altitude	Azimuth	Comments
4 Nov. 63	2120-2200	IC443	16°	074°	Grazing occultation of southern fringe.
29 Dec. 63	1835-2015	IC443	34	088	Occultation of lower third of source.
22 Feb. 64	1250-1257	IC443	01	061	Grazing occultation of southern fringe at moonrise.
20 Mar. 64	1740-2040	IC443	67	225	Optimum occultation of northern (most intense) region of source.
13 May 64	1815-1915	Taurus A	28	276	Total occultation through central region moon.
14 May 64	0721-0900	IC443	10	068	Optimum occultation of northern region, shortly after moonrise.
7 July 64	1530-1630	Taurus A	19	283	Total occultation through central region of moon.
8 July 64	0407-0526	IC443	15	072	Occultation of northern third of source shortly after moonrise.
4 Aug. 64	1600-1645	IC443	01	300	Occultation of northern third at moonset.

The predictions given above were calculated on the 7090 computer using a program, RSL007, written by R. S. Lawrence. For a given span of time at a given geographic location, the program computes (1) the geocentric altitude (a) and azimuth (A) of the moon, (2) the topocentric altitude of the moon (a') using the formula

$$a' = a - \pi \cos a$$

where π = the interpolated equatorial horizontal parallax for the moon, and (3) the topocentric right ascension [$\alpha(a', A)$] and declination [δ (a', A)] of the moon. Asphericity of the earth is neglected. As an aid to observation, the program also calculates the altitude and azimuth of a given grid of points that describe the position of an occulted source. The program is sufficiently general to predict the lunar occultation of any fixed source at any geographic location on the earth. One of the predictions was checked by hand using the rigorous formulae given in section 2F of the Explanatory Supplement to the Ephemeris and was found to be accurate to within less than 0!5 of arc, indicating that the RSL007 predictions are satisfactory for predicting an occultation to within a few seconds of time. However, their use for data reduction purposes is not recommended. Completely precise predictions for individual occultations are probably best obtained from the Nautical Almanac Office; at least this has been the practice of previous observers [Rishbeth, 1956; Costain, Elsmore, and Whitfield, 1956]. Moreover, schedules of lunar occultations of a selected group of sources are furnished without charge on a routine basis by requesting this service from H. M. Nautical Almanac Office, Royal Greenwich Observatory.

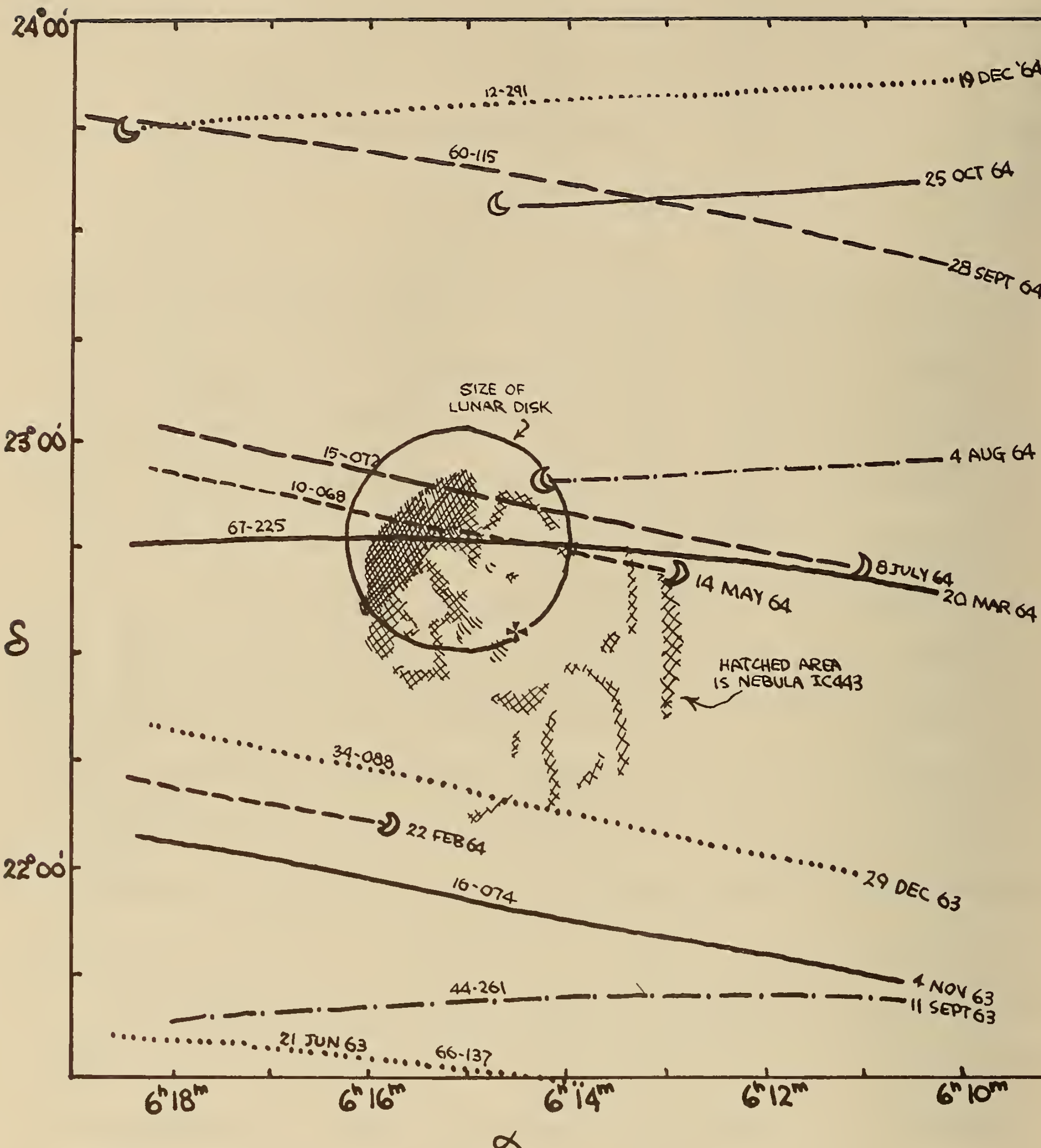

Figure 2. Path of the center of the moon at times of conjunction with the radio source IC443 as seen from Table Mesa from June 1963 through December 1964. The small lunar symbol denotes moonrise or moonset. Altitude and azimuth of the moon are given above each track for the time of closest approach to the radio source. Coordinates are topocentric right ascension and declination.

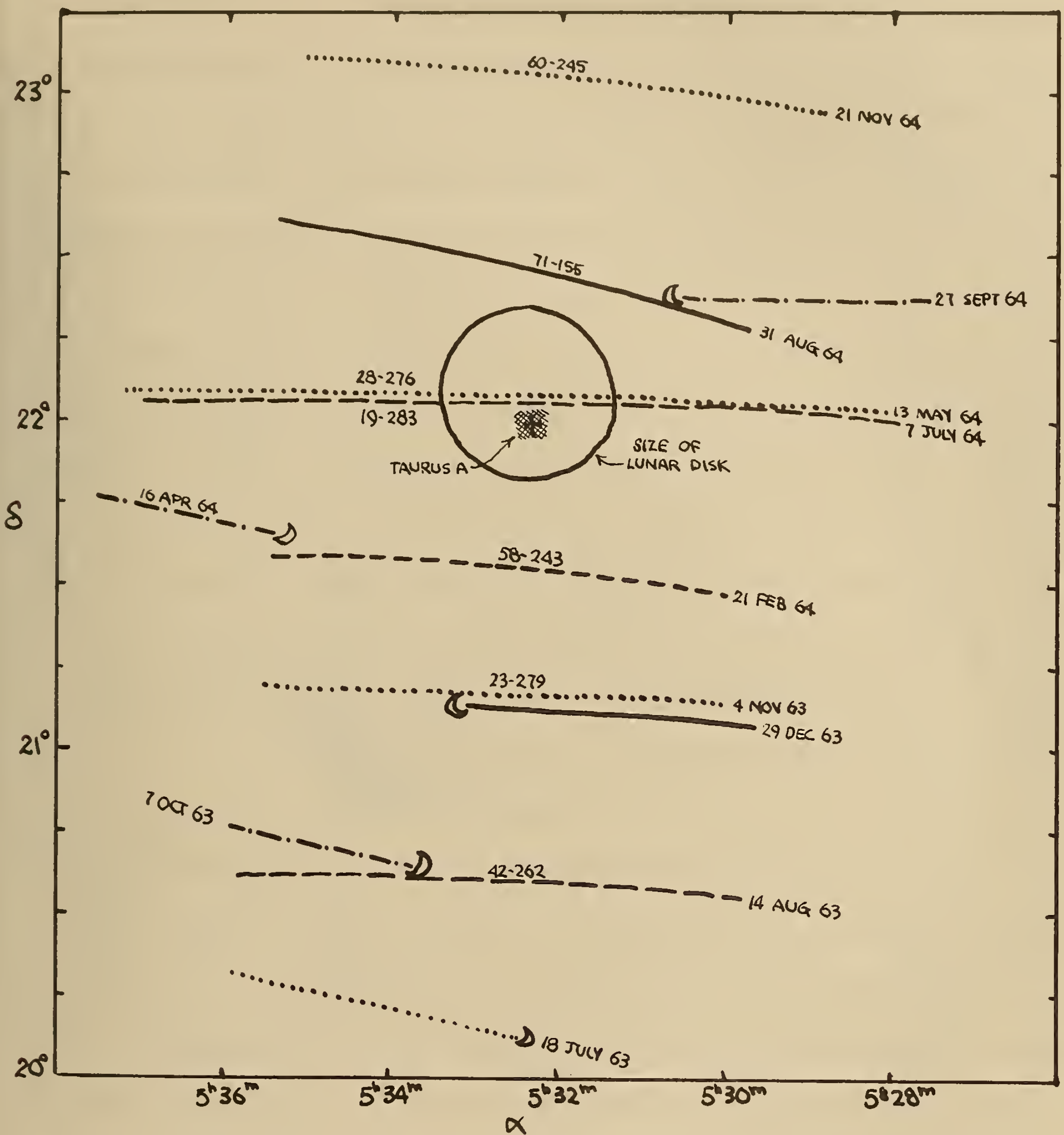

Figure 3. Path of the center of the moon at times of conjunction with the radio source Taurus A as seen from Table Mesa from July 1963 through November 1964. The small lunar symbol denotes moonrise or moonset. Altitude and azimuth of the moon are given above each track for the time of closest approach to the radio source. Coordinates are topocentric right ascension and declination.

Figures 2 and 3 show the positions of the center of the moon and the sources Taurus A and IC443 for the series of occultations and near-occultations that are in the visible hemisphere at Boulder from June 1963 through December 1964; they indicate the general march of the moon through these two sky regions throughout this period. Coordinates are topocentric right ascension and declination for the geographic position of Table Mesa. Pairs of numbers (e.g. 67-225) given alongside the tracks indicate the approximate altitude and azimuth of the center of the moon at closest approach to the occulted source. A lunar symbol at either end of a track indicates moonrise and moonset. Figure 4 compares the geocentric and topocentric coordinates of the path of the center of the moon for the IC443 occultation of 20 March 1964 to demonstrate the effect of the coordinate conversion. The occultation on this date occurs at a rather high altitude (about 67°); the conversion effect would be more severe for events at lower altitudes.

IV. SUMMARY

Lunar occultations of the radio sources Taurus A and IC443 will be observable at Boulder during late 1963 and early 1964 in step with a cycle of recurrence of about $8\frac{1}{2}$ years. Taurus A will be occulted on two occasions, both at elevations below 30° in the western sky. IC443, a more extended source, will undergo a series of very favorable partial occultations.

Figure 5 illustrates the onset and duration of the coming occultation season on a time scale that covers a period of about $1\frac{1}{2}$ years. The ordinate is an importance scale, obtained rather subjectively by weighting together (a) the fraction of the source that is occulted by

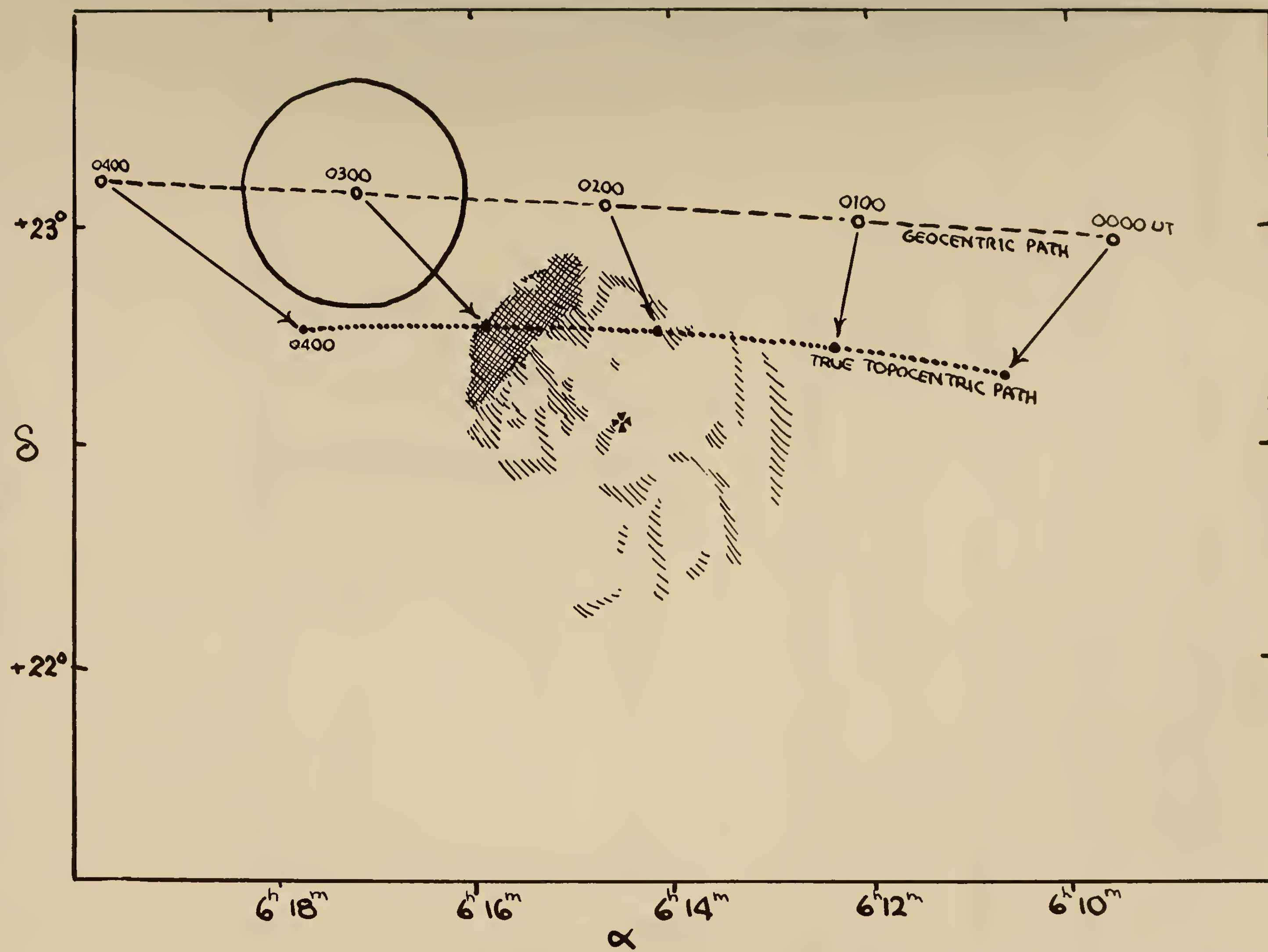

Figure 4. Path of the moon at the time of conjuction with IC443 on 20 March 1964, showing the comparison between the geocentric path (taken from the Ephemeris) and the actual topocentric path computed for the terrestrial coordinates of Table Mesa.

the moon, and (b) the observability of the particular occultation at Boulder. Thus, the optimum occultation of IC443 on 20 March 1964 is rated perfect at 1.0, while the partial occultation of the same source on 4 August 1964 that is interrupted by moonset is rated 0.1.

Observations of the Taurus A and IC443 occultations made during their last occurrence provided the first accurate determination of the angular extent of these two sources. The more favorable series of occultations coming up should be even more profitable, especially if observed on a variety of frequencies and at different polarizations. The opportunity will not come again in this decade.

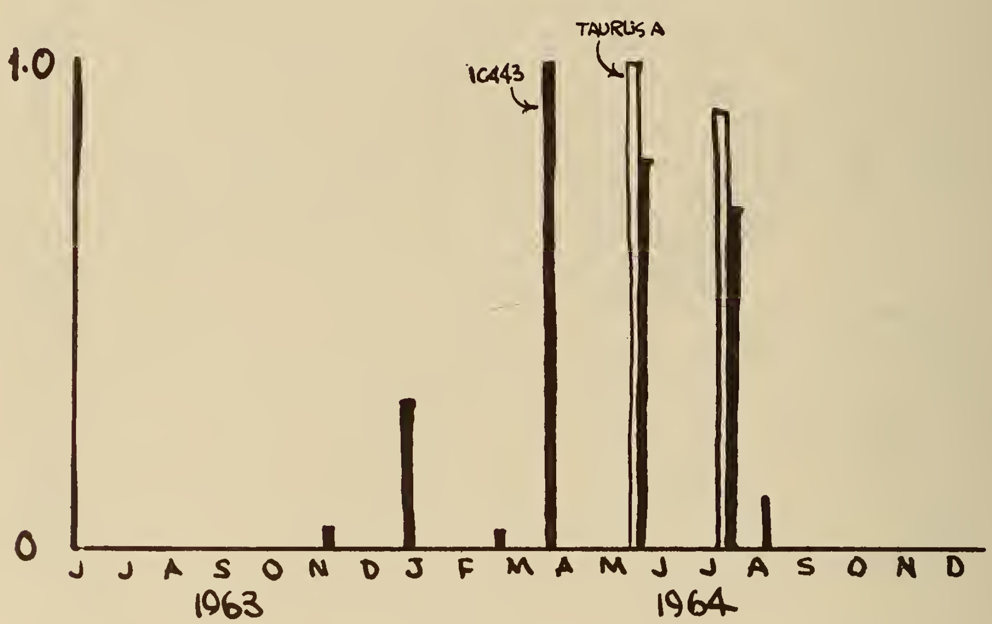

Figure 5. Graphical presentation of the data in Table 2, demonstrating the nature of the Occultation Season of 1963-1964. The ordinate is a scale of relative importance.

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