THE DIAMETER OF 88 THISBE FROM ITS OCCULTATION OF SAO 187124

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Abstract

The 7 October 1981 occultation of SAO 187124 by 88 Thisbe was observed at twelve sites. The occultation observations, together with information about the asteroid's light curve, gives a mean diameter for Thisbe of 232 $\pm$ 10 km. This value is 10 percent larger than the previously published radiometric diameter of Thisbe.

Introduction

On 7 October 1981, the asteroid 88 Thisbe occulted SAO 187124, a 9th-magnitude star in Sagittarius. This occultation, originally predicted by Taylor (1981), was observed in the United States at twelve sites between Wisconsin and Utah. In this paper we discuss the observations and derive the diameter of Thisbe.

Observations

Taylor's (1981) prediction of the 7 October occultation, based solely on the catalog position of the star and the published ephemeris of Thisbe, gave a ground track falling across western Canada. However, plates taken on 27 September 1981 with the 0.5-m Carnegie Double Astrograph on Mt. Hamilton yielded a more southerly track stretching from southern California to the Great Lakes (see Fig. 1a). An additional plate taken with the same telescope on 4 October 1981 gave a similar ground track (Fig. 1b), as did plates taken with the 1.55-m Astrometric Reflector at the Flagstaff Station of the U. S. Naval Observatory on 6 October 1981 (Fig. 1c). The plates from Mt. Hamilton were measured relative to a reference frame defined by stars chosen from the Perth 70 catalog. The USNO plates were measured relative to a network of fainter stars whose positions were determined from the Mt. Hamilton plates. It is evident from inspection of Fig. 1 that the three predicted ground tracks agree to within approximately one-half the width of the track. The corresponding uncertainty in the predicted geocentric angular separation of the star and asteroid at closest approach is only 0.07 arcsec.

At the time of the occultation, Thisbe was expected to have a visual magnitude of 11.8, while SAO 187124 is nearly three magnitudes brighter. Consequently, the change in brightness of the merged star-asteroid image at immersion and emersion would be large, making this occultation easily detectable by visual observers. Assuming a diameter for Thisbe of 214 km as given in the TRIAD file (Bowell, Gehrels, and Zellner 1979), the maximum duration of the occultation was expected to be 9.9 seconds. Thisbe's shadow would move along the ground track from west to east.

The occultation of SAO 187124 was observed at the first twelve sites listed in Table I. The coordinates and altitudes of the sites are given in columns 3, 4, and 5. The observed times of immersion and emersion are noted in columns 6 and 7 along with the observers' estimates of the uncertainty in the absolute timing in column 8. Names of the observers are given in the footnotes to the table. The observations at Circleville, Utah; Otter Creek Reservoir, Utah; and Eau Claire, Wisconsin, were made photoelectrically. All others were visual.

Telescopes used for these observations ranged from the 0.6-m reflector at Sommers-Bausch Observatory to relatively small portable instruments. The photoelectric observations from Circleville and Otter Creek Reservoir were made with 0.35-m Celestron telescopes especially equipped for use at remote sites. Figure 2 shows a tracing of the occultation light curve recorded with one of these systems near Otter Creek Reservoir. In addition to the real-time strip chart display shown in Fig. 2, the data are recorded on magnetic tape for later digitization at high time resolution. The times listed in Table I for Otter Creek and Circleville were determined from the digital data. The photoelectric observations at Eau Claire were also made with a 0.35-m Celestron telescope. Pulse counting electronics giving 50 m sec integrations with 0.5 m sec dead time between integrations were used.

Analysis

The basic method of analysis employed in this paper has been discussed in detail by Wasserman et al. (1979) and Millis and Elliot (1979). In essence, each observed time of immersion or emersion defines a point on the limb of the asteroid. The asteroid's apparent limb profile is then represented by a circle or, if the data warrant, an ellipse fitted by least squares to all the observational points. In this way the effective diameter of the face of the asteroid seen at the time of the occultation can be derived. The occultation result can then be combined with information about the asteroid's brightness variation with rotation and aspect to give the best possible estimate of its overall mean diameter.

We have plotted in Fig. 3 the chords across Thisbe which one derives if the observed times of immersion and emersion in Table I are taken at face value. The solid lines represent photoelectric observations; the visual observations are indicated by dashed lines. Note that all the visually determined chords are displaced westward relative to the photoelectric chords. Displacements in this direction imply that the visual observers reported times which were systematically late relative to the photoelectric times, as would be expected if response time corrections were not made or were underestimated.

While the observed times of immersion and emersion reported by a visual observer are subject to significant systematic error, the elapsed interval between the two times--that is to say, the duration of the occultation--is determined much more accurately. Therefore, the visual chords in Fig. 3 are likely to have very nearly the correct lengths, but they are displaced laterally (i.e., in time) from their proper positions. Consequently, in our least-squares solution for the best-fitting circular limb profile of Thisbe, we have included the response times of individual visual observers as free parameters. This approach has the effect of allowing the visual chords to slide parallel to the photoelectric chords. Other free parameters in the solutions are the asteroid's diameter and corrections to the right ascension and declination of Thisbe. We have arbitrarily assumed that all positional error is in Thisbe's ephemeris. The resulting solution is illustrated in Fig. 4. All observations were given equal weight in the solutions. The best-fitting circular limb profile has a diameter of 221.8 ± 1.4 km, while the resulting corrections to right ascension and declination are -0.051 ± 0.00003 sec and -0.799 ± 0.0013 arcsec, respectively. The diagonal line across the bottom of the figure indicates the constraint placed on the solution by photoelectric observations at Erwin Fick Observatory near Boone, Iowa, which showed no occultation (Beavers 1981). Other negative photoelectric observations were recorded somewhat further south of the track at Lowell Observatory and Braeside Observatory in Flagstaff, Arizona, and at the Mt. Wilson Observatory (see Table I). To our knowledge, no observations, either photoelectric or visual, were made north of the track.

The response time corrections determined for each of the visual observers from the least-squares solution are listed in column 9 of Table I. They range from just over 2 seconds at Chamberlin Observatory, where clock error may have been a problem, to slightly less than 0.3 sec at Sommers-Bausch Observatory, where WWV time signals and the observers' responses were recorded simultaneously on an oscillographic recorder. Ignoring these two extreme cases and removing the personal equation corrections already applied to the Cheyenne and Cambridge observations, we obtain a mean response time of 1.1 seconds. While this value is larger than one might have expected, it is less than that determined from visual observations of the occultation of AG+0°1022 by Juno (Millis _et al._ 1981).

The last two columns of Table I contain the radial residuals (observed minus computed radius) for the solution shown in Figure 4. These values yield an rms residual per degree of freedom of 3.5 km, similar to the results obtained for other well-observed stellar occultations by asteroids (Wasserman et al. 1979; Millis et al. 1981).

The actual occultation track as determined from our analysis is shown in Fig. 5. Sites where the occultation was successfully observed are marked by filled circles; barred circles denote sites where photoelectric observations show that no occultation occurred. The predicted tracks shown in Fig. 1 depart from the actual track by no more than one-half the width of the track.

Discussion

Our analysis of the occultation observations has given a value of 221.8 $\pm$ 1 4 km for the diameter of that face of Thisbe seen at the time of the occultation. The quoted standard error, however, reflects only the formal uncertainty in fitting a circle through the shifted data points. The true uncertainty in the diameter is larger because of the effects of errors in the observed durations and because the true limb profile may depart from a circle.

The magnitude of the errors in the observed durations can be evaluated by comparing results from observers near the same chord. For the visual observers one finds in these instances a peak-to-peak scatter of about ± 0.25 sec, giving a mean chord length which is accurate to better than 2 percent. The photoelectric chords have significantly less uncertainty. Consequently, we estimate that the observational errors can be fully allowed for by increasing the quoted formal uncertainty by no more than a factor of two.

The more serious source of error, and one that is difficult to evaluate precisely, is the possibility that the true limb profile departs markedly from a circle. Observational coverage of Thisbe's southern hemisphere was quite limited during the 7 October occultation. Obviously, the existence of large limb irregularities in that region cannot be ruled out. We do note that in the region well covered by the observations (see Fig. 4), limb irregularities have scales of only a few kilometers comparable to those seen on other well-observed large asteroids (Wasserman *et al*. 1979; Millis *et al*. 1981).

Another possibility to be considered is that the limb profile may be elliptical rather than circular. We have not presented a fit of an ellipse to the data because, in our opinion, the data do not have sufficient coverage of the asteroid to distinguish meaningfully between an ellipse and a circle. If one does fit an ellipse, however, the observations from Cheyenne and Cambridge near the northern edge of the track and the negative result from Erwin Fick Observatory constrain the effective diameter ($\sqrt{ab}$) of the ellipse to fall within 3 percent of the diameter derived from the circular solution.

As has been mentioned earlier, the diameter derived from the occultation pertains only to the face of Thisbe seen at the time of the occultation. In order to derive an overall mean diameter, one must assess the variation in the asteroid's apparent cross-section with rotation and aspect by inspection of the object's light curve. In the case of Thisbe, the available data are limited. Schober, Scaltriti, and Zappàla (1979) from observations on four nights in 1977 found the brightness of Thisbe to vary with a period of $6^{h}.0422$ and a full amplitude of 0.19 mag. Photometry by J. W. Young at Table Mountain Observatory on 23 October 1981 is consistent with these values, although a full cycle of the light curve was not covered (Harris 1981). Young's observations, combined with the period measured by Schober, Scaltriti, and Zappala, indicate that the 7 October occultation occurred near the time of minimum light and, therefore, minimum cross-sectional area. At maximum brightness, assuming a light curve amplitude of 0.19 mag, one would expect the effective diameter of Thisbe to be approximately 9 percent larger than the value determined from the occultation. The mean diameter will be near the average of these two. Accordingly, we adopt 232 ± 10 km as the occultation diameter of Thisbe where the error has been estimated conservatively to allow for the various sources of uncertainty discussed above. This value for Thisbe's diameter is 10 percent larger than the radiometric diameter quoted by Morrison and Zellner (1979).

No secondary occultations attributable to possible satellites of Thisbe were reported during the 7 October

1981 event.

We thank the staff of the Flagstaff Station of the U. S. Naval Observatory for taking plates used in refining the predictions for this occultation. The Lick Observatory astrograph plates were taken by E. Harlan. D. Dunham kindly provided an accurate ephemeris for Thisbe and transmitted visual timings by several members of the International Occultation Timing Association (IOTA). We thank S. Schultz, L. Allred, and J. Fox for permission to use their unpublished observations. This research was supported at Lowell Observatory by NASA Grant NSG-7603 and at Lick Observatory by NSF Grant AST 79-09098. The Lowell computing facility, used in this work, was obtained with generous grants from the Digital Equipment Corporation and the National Science Foundation and with further help from Mrs. R. L. Putnam, the Perkin Fund, the National Aeronautics and Space Administration, and the U. S. Naval Observatory.

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TABLE I. Observations of the 7 October 1981 Occultation of SAO 187124 by 88 Thisbe.

No.	Location	Longitude	Latitude	Altitude (meters)	Immersion	Emersion	Absolute timing uncertainty (sec)	Shift	Residuals (km) Immersion	Residuals (km) Emersion
1	Cheyenne, WY	$6^h59^m40^s.9$	41°12'24"	1980	$2^h01^m44^s.9$	$2^h01^m52^s.8$		$-0^s.99$	1.3	1.3
2	Cambridge, MN	6 12 34.06	45 33 01.6	286	2 02 17.7	2 02 25.6	0.2	-0.89	-0.8	-0.8
3	Minneapolis, MN	6 12 57.04	44 58 40	260	2 02 18	2 02 27.5		-1.27	-1.3	-1.3
4	St. Paul, MN	6 12 40.51	44 56 11.1	289	2 02 17.5	2 02 27.5		-0.74	2.3	2.3
5*	Circleville, UT	7 29 05.67	38 10 07.8	1853	2 01 16.94	2 01 27.30	0.02	-	4.1	0.9
6*	Otter Creek, UT	7 28 08.55	38 10 46.2	2146	2 01 17.88	2 01 28.24	0.02	-	3.4	0.2
7	Greely, CO	6 58 49.1	40 24 19	1460	2 01 46	2 01 56	0.5	-1.60	-1.9	-1.9
8	Mankato, MN	6 15 59.3	44 08 28.0	302	2 02 16.2	2 02 26.6		-0.81	0.7	0.7
9	Sommers-Bausch Observatory	7 01 02.93	40 00 13.0	1648	2 01 42.85	2 01 53.19		-0.29	-0.4	-0.4
10	Golden, CO	7 01 30.0	39 52 30.0	2725	2 01 43.3	2 01 53.2		-0.80	-5.4	-5.4
11*	Eau Claire, WI	6 05 59.84	44 47 44.4	268	2 02 21.91	2 02 32.36	0.1	-	-2.4	+4.0
12	Chamberlin Obs.	7 01 44.9	39 25 38	2678	2 01 44.5	2 01 55.0	1.0	-2.13	2.4	2.4
13	Erwin Fick Obs.	6 15 45.8	42 00 20.0	332	No Occultation					
14	Mt. Wilson Obs.	7 52 14.3	34 12 59.5	1742	No Occultation					
15	Braeside Obs.	7 26 39.6	35 12 40.5	2207	No Occultation					
16	Lowell Obs.	7 26 08.6	35 05 48.6	2200	No Occultation					

*Photometric observations

1 P. Maley, R. Peterson. Quoted times include personal equation correction of 0.3 sec. See *IAU Circular* No. 3652.
2 J. Fox. Quoted times include personal equation correction of 0.5 sec.
3 R. Fiedler.
4 S. Schultz, L. Allred.
5 N. White, R. Bertram.
6 R. Millis, R. Nye
7 R. Dietz, V. Barlock, C. Moncivais.
8 J. Pierce, S. Kipp.
9 D. Steel, C. McKay.
10 G. Emerson, See *IAU Circular* No. 3642
11 R. Elliott, W. Smethells, P. Price.
12 R. Everhart, E. M. Everhart. See *IAU Circular* 3652.
13 W. Beavers.
14 K. Horne, R. Gomer, A. Filippenko.
15 R. Fried.
16 R. Oliver.

FIGURE CAPTIONS

Figure 1. The predicted ground track of the 7 October 1981 occultation of SAO 187124 by 88 Thisbe based on (a) plates taken at Lick Observatory on 27 September 1981, (b) a plate taken at Lick on 4 October 1981, and (c) plates taken at the Flagstaff Station of the U. S. Naval Observatory on 6 October 1981.

Figure 2. The light curve of the 7 October 1981 occultation of SAO 187124 by 88 Thisbe observed near Otter Creek Reservoir in central Utah.

Figure 3. Chords across Thisbe, uncorrected for the response times of visual observers. Solid lines represent photoelectric observations; dashed lines are chords derived from visual observations. Table I lists the observing sites corresponding to the chords, beginning with the northernmost chord.

Figure 4. A circular limb profile fitted by least squares to the occultation observations. This solution yields a diameter for the face of Thisbe seen at the time of the occultation of 221.8 ± 1.4 km. The response times of

visual observers were included as free parameters in the least-squares solution. The diagonal line near the bottom of the figure represents the constraint placed on the solution by negative observations at Erwin Fick Observatory.

Figure 5. The actual ground track of the 7 October 1981 occultation as determined from the least-squares solution shown in Figure 4. Filled circles denote sites where the occultation was observed. The other symbols indicate sites where photoelectric observations showed no occultation.

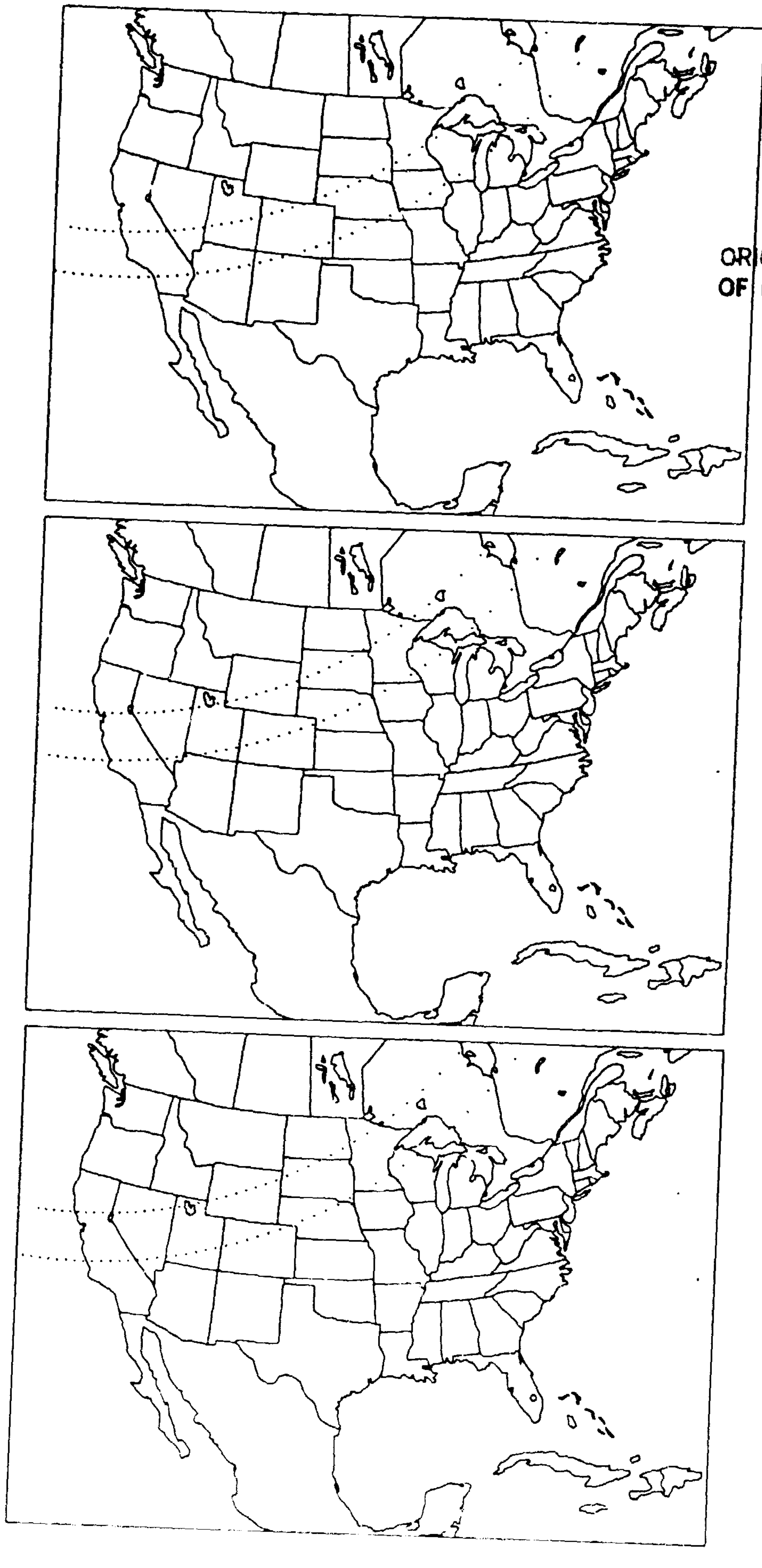

Figure 1.

Figure 2.

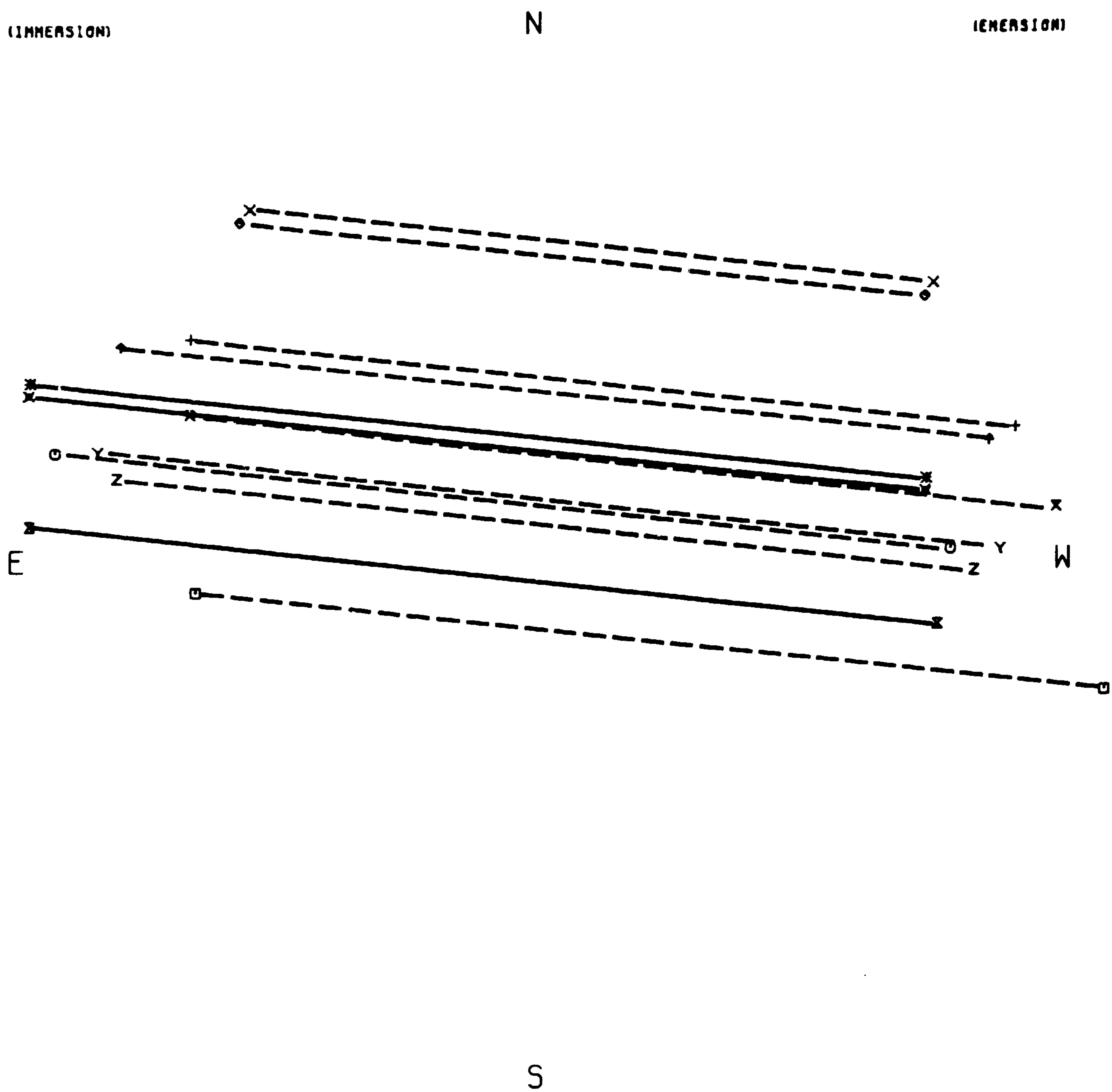

Figure 3.

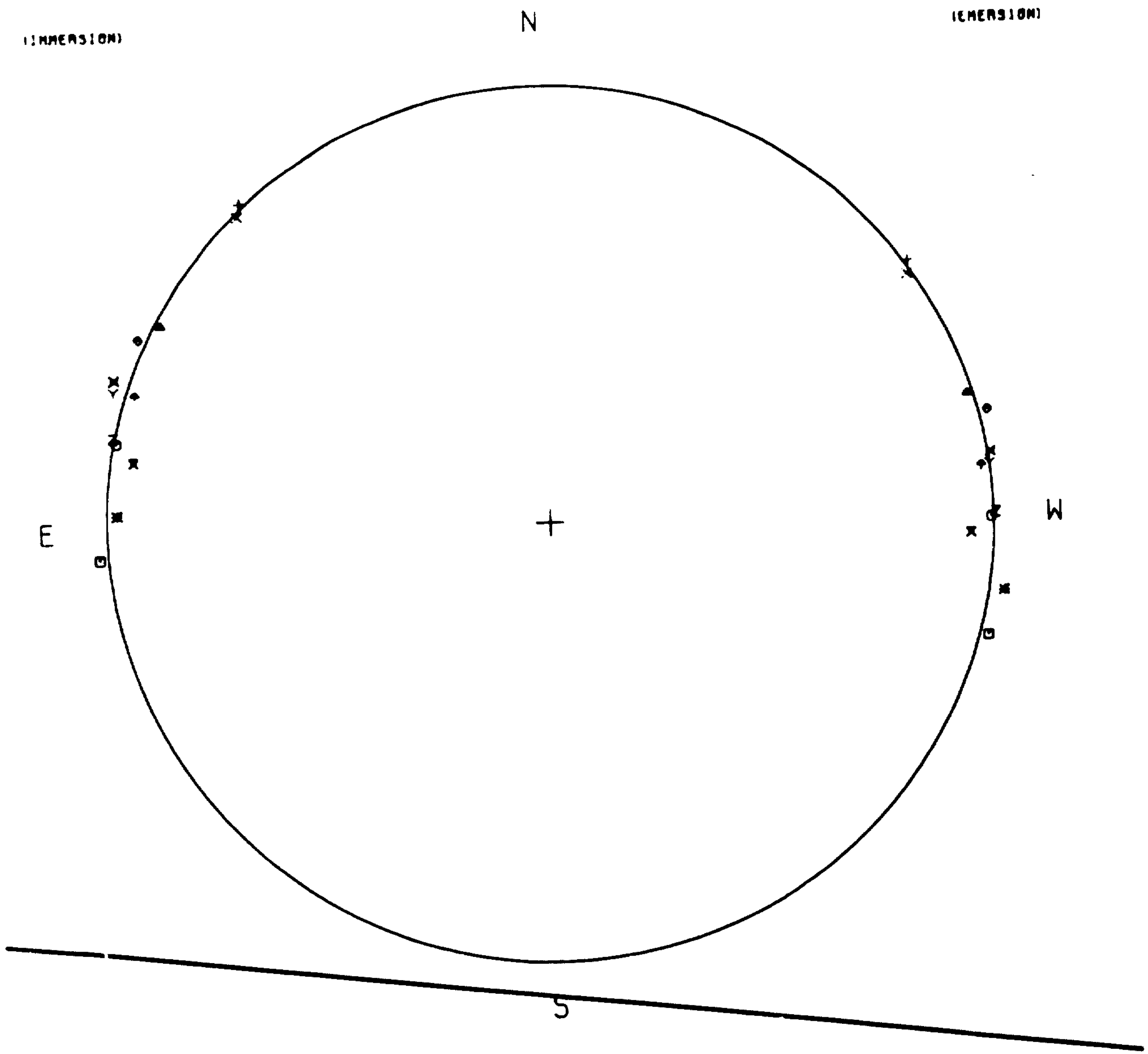

Figure 4.

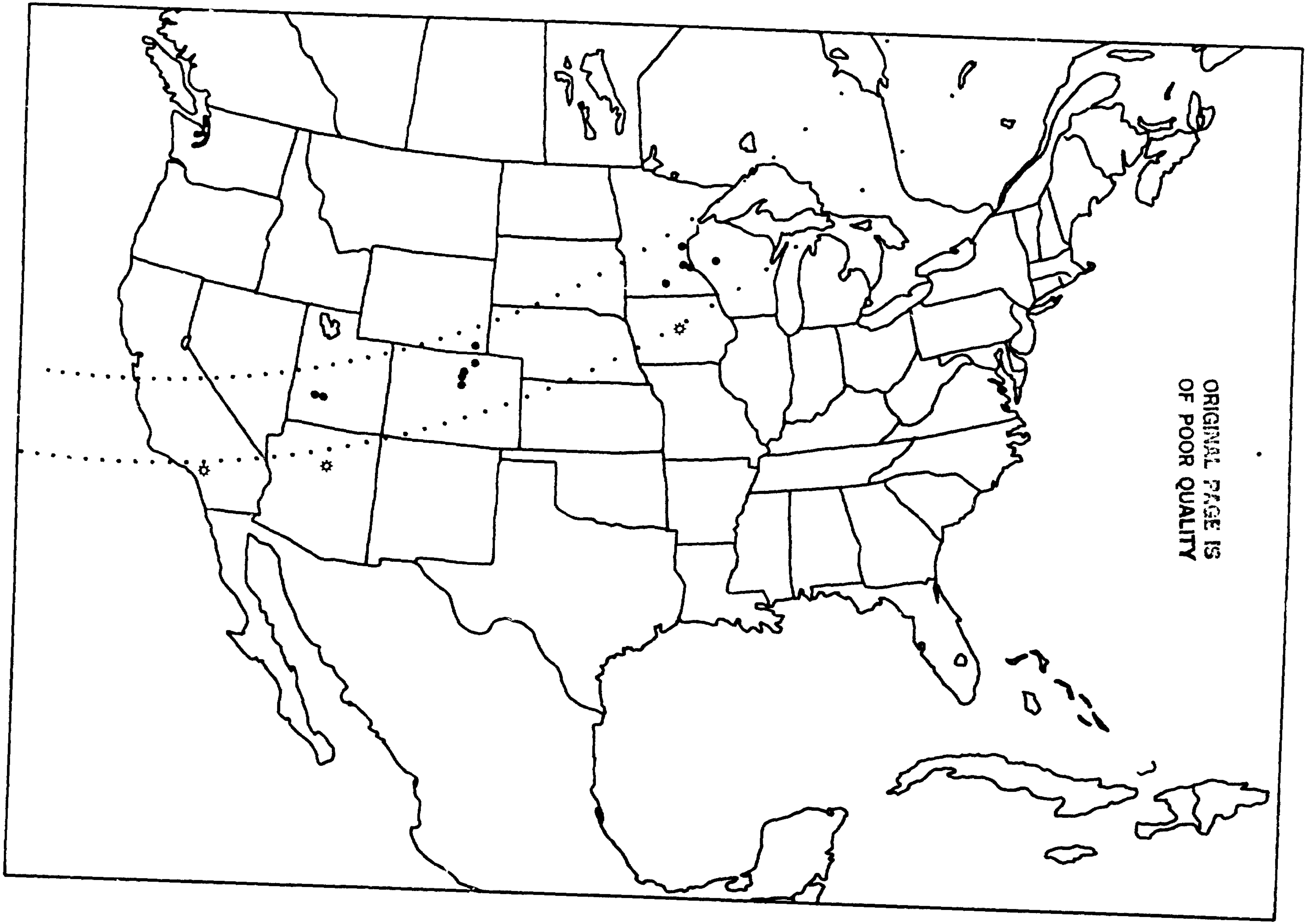

Figure 5.