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VARIATION OF THE SOLAR DIAMETER FROM SOLAR ECLIPSE OBSERVATIONS, 1715–1991

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Abstract. The diameter of the Sun may be measured at the time of a solar eclipse. We have performed an exhaustive search of the astronomical literature to find all existing observations of solar eclipses suitable for this purpose. We have also taken new observations by new techniques. We have undertaken a project to reduce them systematically, and in an automated, self-consistent way. This will produce determinations of the solar radius at the times of solar eclipses from 1715 to the present. Re-reduction, using newer ephemerides, of observations made in 1984 shows that the component of the residuals caused by the ephemeris is substantially reduced. This paper summarizes the research plan, outlines the detailed astronomical features included in the calculations, and presents the results available.

1. Introduction

The question of whether or not the solar diameter is constant had been neglected for many years until early 1979, when Sofia, O'Keefe *et al.* noted that the solar constant could undergo variations if the solar diameter changed. Later that year, Eddy and Boornazian (1979) reported an apparent significant change over a few centuries, based upon analysis of a long series of meridian observations taken at Greenwich. Following the work of Smith and Messina (1981), this conclusion was shown to be unwarranted because systematic effects in the observations had not been treated correctly. By that time, however, the suggestion had inspired other lines of investigation.

Observations of a solar eclipse from the edges of its predicted path, taken to improve the parameters used in the calculation, were first attempted in 1715. Newcomb noted in 1870 that while the idea was good in concept, the execution was practically impossible at that time because of the effects of the rough limb of the Moon on contact times. It was not until 1963 that the terrain of the apparent limb of the Moon was known well enough to allow the effects to be calculated with useable accuracy.

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Late in 1979, Sofia, Dunham, and Fiala reported that, in effect, a solar eclipse could be observed in the same way as a grazing occultation of a point-source star. Observers station themselves along the predicted edges of the track of the umbra at a solar eclipse. The observations consist of timings of the formation and disappearance of individual Baily's Beads. Each timing is actually a measurement of the direction in space of a point on the apparent limb of the Sun. It is compared to a predicted sequence of Bead phenomena based on the calculated limb of the Moon for that instant as seen from each site, and identification made with a known limb feature (mountain peak or valley). As long as the position of each observing site is known to an accuracy within 50 feet, the only adjustable parameters in the calculation that affect the predicted times are the apparent diameter of the Sun, and the Sun's position relative to the Moon. Observations of the times of bead phenomena can be analyzed for these parameters. Timings from both edges of the predicted path are required in order to separate the effects of a change in the width of the path from a shift in its longitude.

Several reviews have evaluated and compared the various methods used for monitoring the solar diameter (Wittmann and Debarbat, 1990; Ribes, 1990; Ribes *et al.*, 1991). In general, the method we employ has been noted as being very accurate, but then set aside because the frequency of measurement is so low. Each eclipse observed provides a single measurement of the solar diameter, hence under the very best of conditions no more than three per year can occur.

While it is true that measurement by means of eclipses will not detect fluctuations with periods less than a few years, it can provide very precise calibration points for comparison to other data bases. Furthermore, it is the only means of accurate calibration, comparable to the accuracy of modern methods, which can use observations extending back in time for several decades.

2. Objectives

In long-term studies of global climate variation, it would be extremely valuable to identify a proxy indicator of variation of solar energy production, tied to an identifiable physical condition. Measurements of such a quantity could then be correlated to measurements of the solar constant over a period of decades to centuries. Variation of the diameter may be such a proxy (Sofia *et al.* 1991).

The solar ephemeris being used for predictions at the time we started was still based on Newcomb's theory of the Sun, and was suspected to be less accurate than that represented by DE200. Thus, accurate measurements of the relative position of the Sun and Moon would help check the accuracy of the ephemerides, the reference system, and the eclipse prediction procedure.

The precision and accuracy of the observations depends upon Watts' limb profile data (Watts, 1963). These observations also serve to evaluate the consistency of those data.

The precision of the observations depends on the detection system used. While it is necessary to have a system which functions in the same wavelengths as the human eye, sensitivity and recordability are important, and we have experimented with a variety of detectors for comparative evaluation. At the same time, we intercompare observing techniques in order to better evaluate the archival observations.

3. Implementation

When we began our current investigation in 1979, one of the guiding principles was to encourage as many people to observe as possible. It was also a requirement that the method used be comparable to the visual observations used in the past, and if possible, provide a record for remeasurement.

To this end, we used equipment that, while providing the necessary precision of observation, would be relatively inexpensive, very portable, and self-contained. For our first expeditions, use was made of 8-mm movie film and audio tape recorders. Subsequently, video cameras of increasing sensitivity were employed, progressing from vidicon to CCD.

The task of obtaining precise positions has progressed from using small scale topographic maps to using inexpensive, portable GPS receivers.

Time signals were obtained from standard radio broadcasts, and corrected for ΔT (variations in the Earth's rotation) with data from the U.S. Naval Observatory's Earth Orientation Division of the Time Service Department.

4. Current Status

Up to the current time, reduction of such observations has remained tedious, and still requires many hours of playing tapes over and over, identifying lunar features, distinguishing beads, and deciding the instants at which various phenomena occurred. Many videotapes of several eclipses remain unanalyzed for this reason. Although the capability of digitizing images has existed for several years, an affordable means of storing a sufficient quantity simultaneously, rectifying the orientation, and synchronizing the time signals from the sound track has remained unsolved. Table I lists the available data still to be analyzed.

Several advances in data and techniques promise to speed up the analysis as well as improve the accuracy. We have now integrated the DE200/LE200 ephemerides into our software, and JPL has extended the range of those ephemerides back to 1600. This provides a consistency which was previously uncertain.

5. Future Plans

Graphics capabilities now exist for direct comparison of the video records to predicted bead phenomena. We have already implemented a system that allows generation of the predicted patterns onto transparencies at the same scale as the video image. The predicted pattern can be laid directly over the video screen, and the tape stepped frame by frame until a match is reached. The problems remaining with that are that the video image still suffers from "blooming," because the filters were not quite correct; and the time signal is an estimate from a superimposed digital timer coordinated to the sound track by eye-and-ear estimation. This technique was used to re-analyze the data from 1984 (Section 6). A new workstation is available that has the capability of reading in several frames at once and displaying on the same screen not only several images but also the associated sound track, so that the time ticks are visual traces. The images can be enhanced to reduce the bloom. Predicted profiles for each frame can be displayed alongside as well.

We have collected 208 contact timings from central line stations for 59 eclipses over the years 1806–1979. We suspect that these are less accurate than timings from the edge, because the limb features in the central limb regions change dramatically from eclipse to eclipse. However, two developments may make these observations worth examination if the positions of the observers can be determined with sufficient accuracy and the Watts' data verified through independent means. First, improved lunar limb data may be generated from lunar orbiters with laser ranging equipment, such as the Clementine mission (Fisk, 1993; Dunham and Farquhar, 1993). Second, the precision becoming available with the new graphics methods may overcome the uncertainties of identification.

We feel that it is time for a comprehensive re-examination and re-reduction into one solution of all the eclipses listed in Table II. This will form the basis for adding in the reductions for eclipses listed in Table I.

6. Results

This method of using observations of eclipses has been applied for 9 eclipses (Table II). Each eclipse was treated independently. The result for 1715 (Dunham *et al.*, 1980) depends critically on the location of one of the three observers, and new information has been found (Morrison, Stephenson, and Parkinson, 1988). The result for 1987 (Wan *et al.*, 1990) was calculated with our old software system.

The result for 1984 (Fiala *et al.*, 1985, shown as 1984[a] in Table II) has just been done anew (Table II, 1984[b]). The original 51 observations were re-reduced with the new ephemerides. In the original reduction, plots to identify limb features were linear, as shown in Figure 1. A new configuration plot

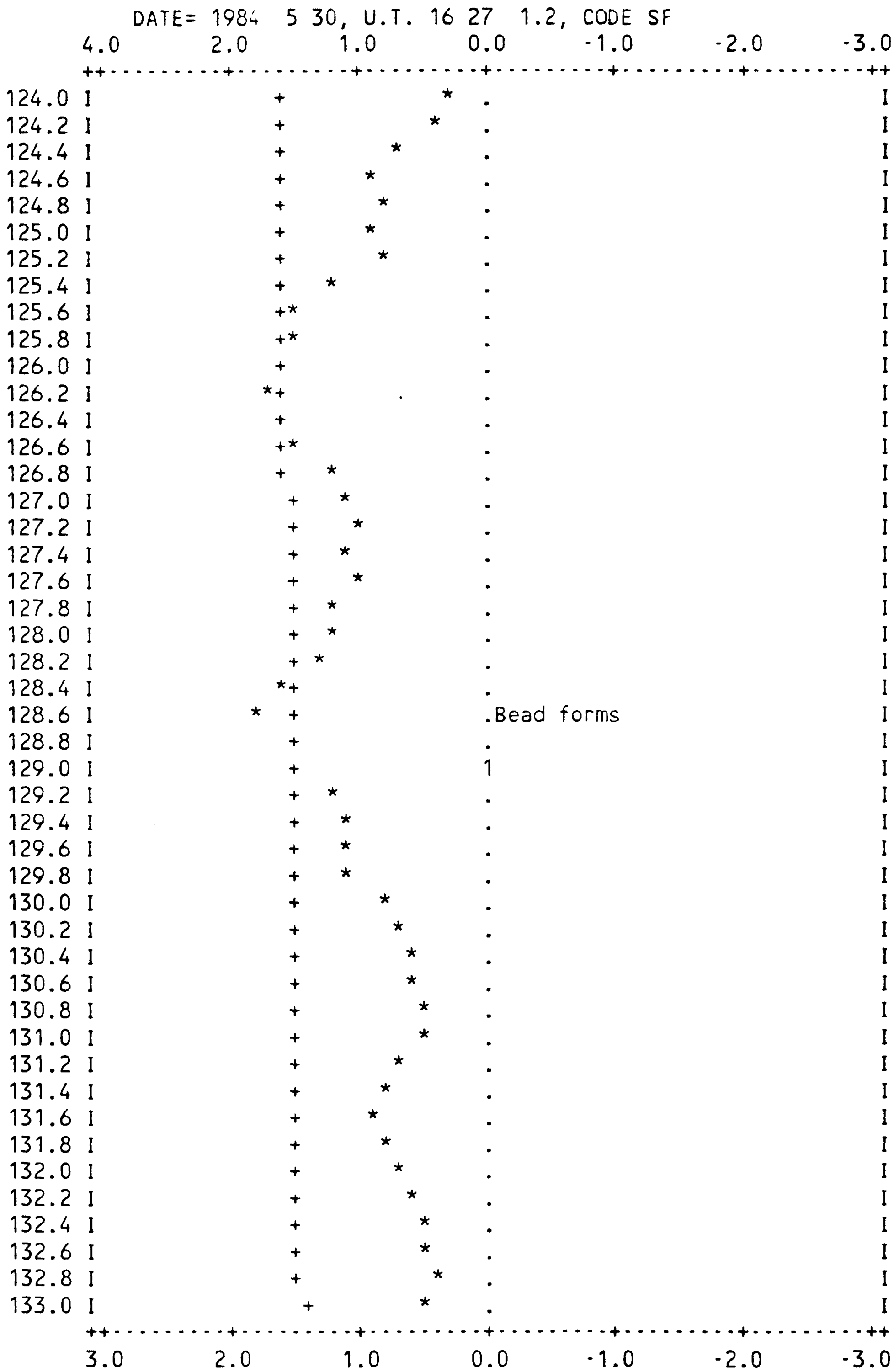

Fig. 1. Line profile of portion of limb. Watts angle vs. residual in seconds of arc. Angle measured from north to east. +++++ = solar limb, **** = lunar limb, ... = Watts mean datum.

TABLE I
UNREDUCED OBSERVATIONAL MATERIAL

Archival data, observations from edge of path:

1869 August 8	Total	Eastern U.S.
1878 July 2	Total	Western U.S.
1922 September 21	Total	Australia.
1988 March 18	Total	Indonesia.

Videotapes, from edge of path:

1984 May 30	Annular	Eastern U.S., several
1984 Nov. 22	Total	Papua New Guinea.
1987 Sept. 23	Annular	China, two locations

TABLE II
RESULTS FROM SOLAR ECLIPSE OBSERVATIONS

Date	Eclipse Type	No. Obs	Correction to Solar Radius[1]	Correction to Lunar Ecliptic Long	Correction to Lunar Ecliptic Lat
			(All in seconds of arc)		
1715 May 3	Total	3	$+.48 \pm .2$		
1925 Jan. 24	Total	8	$+.51 \pm .08$		
1976 Oct. 23	Total	43	$+.04 \pm .07$	$+.65 \pm .10$	$-.45 \pm .09$
1979 Feb. 26	Total	47	$-.11 \pm .05$	$+.52 \pm .09$	$+.25 \pm .05$
1980 Feb. 16	Total	232	$-.03 \pm .03$	$+.32 \pm .03$	$+.07 \pm .04$
1981 Feb. 4	Annular	153	$-.02 \pm .03$	$+.02 \pm .05$	$-.02 \pm .04$
1983 June 11	Total	201	$+.09 \pm .02$	$+.65 \pm .03$	$-.19 \pm .02$
1984 May 30[2]	Annular	51	$+.23 \pm .04$	$+1.01 \pm .05$	$-.47 \pm .06$
1984 May 30[3]	Annular	51	$+.09 \pm .04$	$-.12 \pm .06$	$-.03 \pm .06$
1987 Sep. 23[4]	Annular	123	$-.11 \pm .03$	$+.57 \pm .09$	$+.02 \pm .02$

Notes.
1: Standard value 959.63 seconds of arc.
2: Old analysis, Dunham site (Fiala *et al.*, 1985).
3: New analysis, Dunham site, with LE200/DE200 ephemerides.
4: Shanghai Observatory expeditions to Funing and Tenchang, China (Wan *et al.*, 1989).

of the predicted appearance for each observation was prepared (Figure 2), and compared with the video tape. Figure 3, a digitized image of a video frame made several years ago, illustrates how imprecise the video image is by comparison to the prediction. About one-third of the identifications of limb features were changed. The result is quite different, but with nearly the same mean error as before. What is not shown is the great improvement in the residuals overall. The correction seems to have been shifted from the ephemeris to the solar diameter. This is consistent with the suspicion that the previously used solar ephemeris was indeed drifting in accuracy as

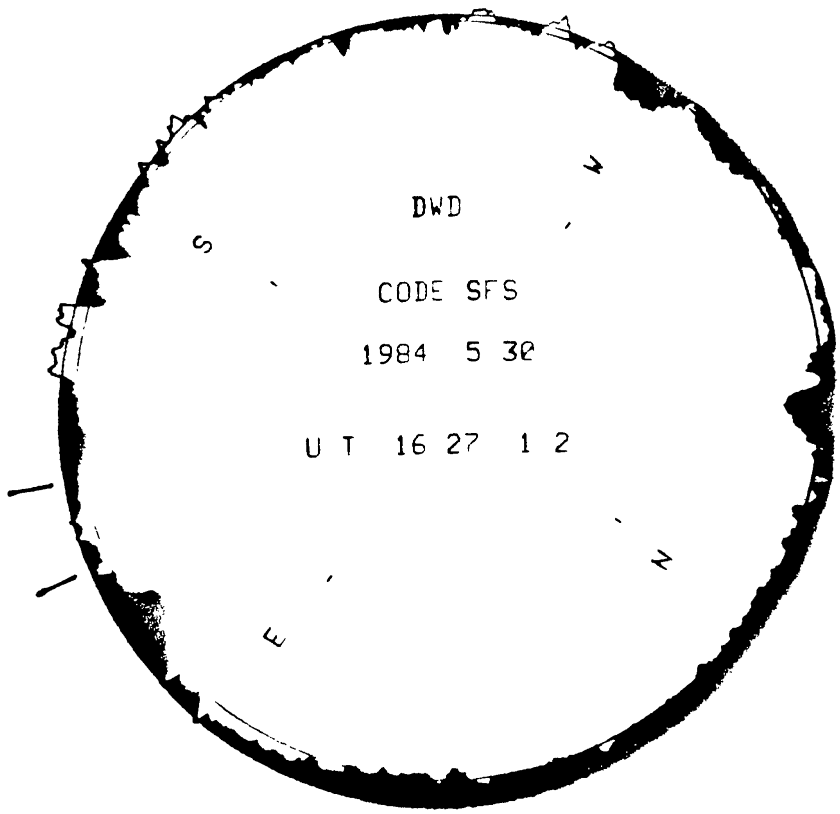

Fig. 2. Predicted profile for one observation. The region corresponding to Figure 1 is marked.

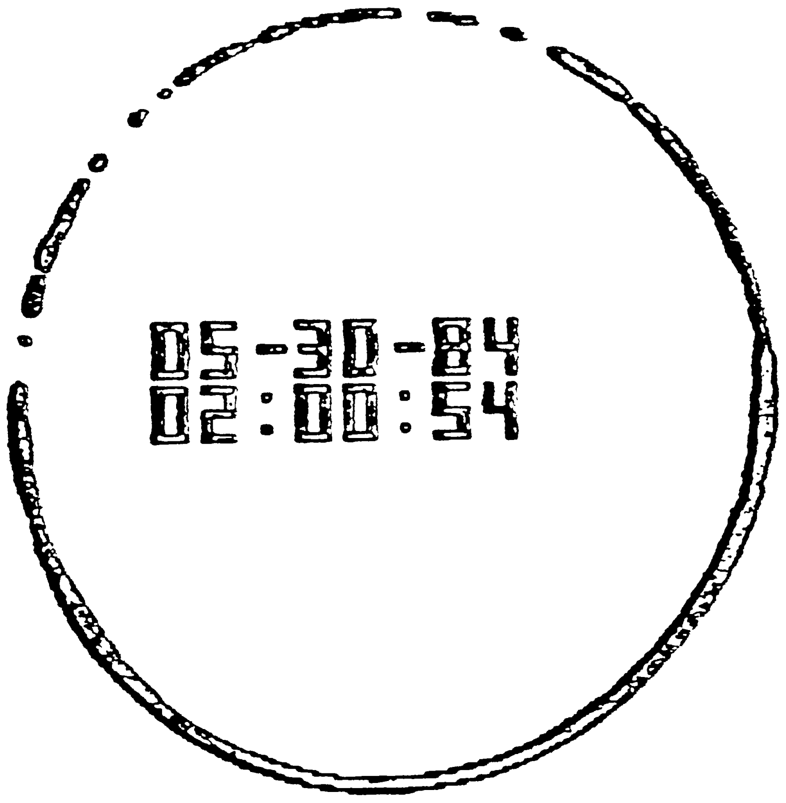

Fig. 3. A contour plot of a video image corresponding to Figure 2, in the same orientation.

time progressed from the epoch, and that made the correct identification of the limb features difficult. The effect of the errors in the ephemeris was probably magnified in this particular eclipse, it being unlike all the others in that many bead events were occurring nearly simultaneously around the complete limb of the Moon. Revisions in the values in Table II will probably not be as large for the other eclipses, but this result for the eclipse of 1984 really emphasizes the need to re-reduce those other data.

7. Acknowledgments

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