Accuracy of Solar Radius Determinations from Solar Eclipse Observations, and Comparison with SOHO Data

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Solar Irradiance and Radius Variations

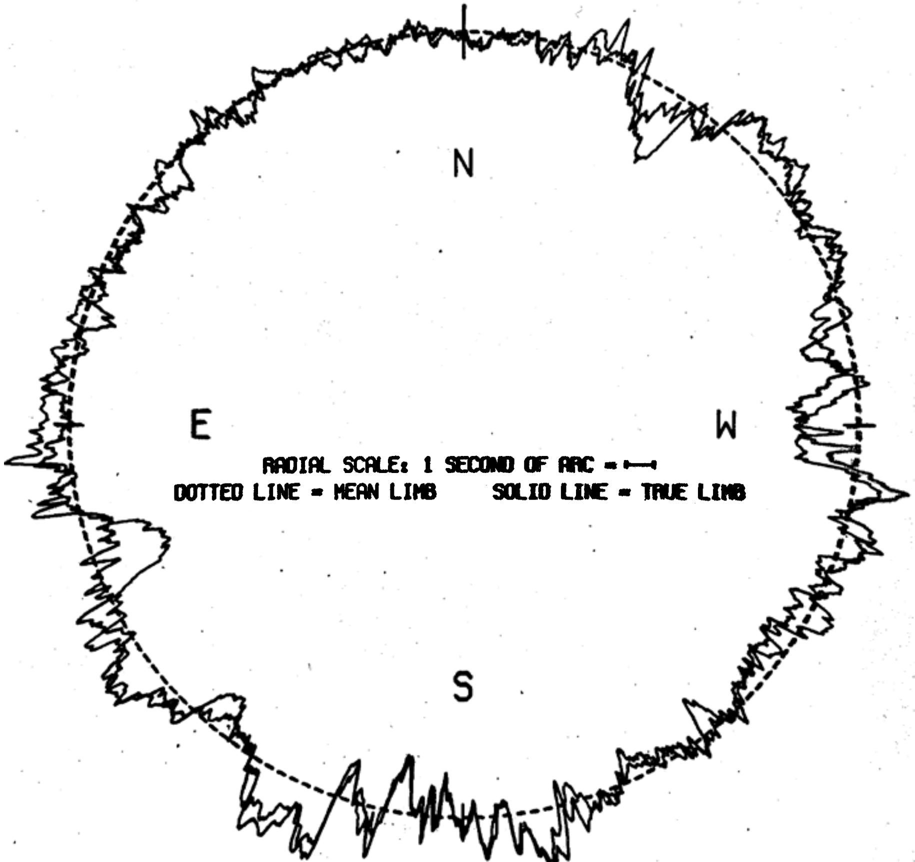
- Since 1978, a series of Active Cavity Radiometers has gathered precise total solar irradiance data, but global climate trends of interest occur over longer time spans.
- Over yearly and decadal time scales, Sofia and Li demonstrated that total solar irradiance correlates with the solar radius – *Science*, **204**, p. 1306, 1979.
- Observations of total and annular solar eclipses can provide the most accurate ground-based determinations of the solar radius, since the geometry of the fast-moving shadow is set in space; consequently, atmospheric seeing has only a small secondary effect on the observations.
- Solar Eclipses have been timed since 1715, so the hope is that observations of both current and past solar eclipses can be used to establish variations in the solar radius, and also in the total solar irradiance (via the Sofia/Li relation), over time scales of a few centuries.

Past Work on Solar Radius Variations from Eclipses

- Interest in solar eclipses increased in the early 1980's when comparison of observations of the February 26, 1979 eclipse, well-observed in North America, showed that the solar radius was about 0.4″ smaller then than during eclipses observed in 1715 (Dunham et al., *Science*, **210**, pp. 1243-1243, 1980) and in 1925 (Sofia et al., *Nature*, **304**, pp. 522-526, 1983).
- Timings of the eclipse duration (2nd and 3rd contacts), and of other Baily's bead phenomena near the limits of total and annular eclipses, were found to give the best accuracy – see the next panel.
- Members of the International Occultation Timing Association (IOTA) and others began traveling to the edges of eclipse paths to time Baily's bead phenomena, first visually by viewing a projected image of the Sun but since 1983 mostly by video recording the eclipse to obtain a more complete record of the phenomena.
- Solar radius values determined from observations of nine eclipses were published in 1994 (Fiala, Dunham, and Sofia, *Solar Physics*, **152**, pp. 97-104).
- Since the edge of the Sun is not perfectly sharp but has a steep gradient, and different filters have been used in the observations, questions about the accuracy of the observations have been raised that are addressed with the current study.

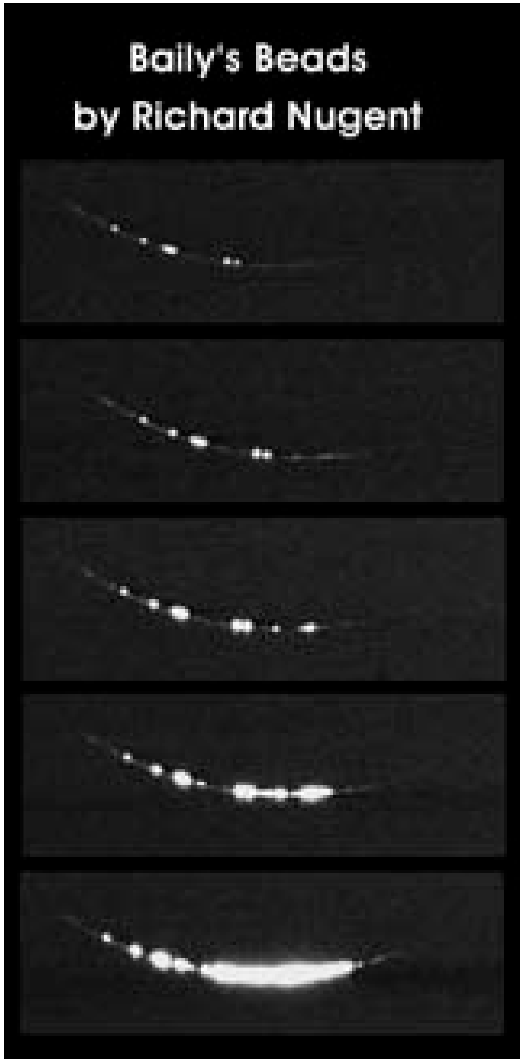
Why Observations near the Path Edges are better than those near the Center

- The Moon is very close to the ecliptic (hence its name) during a solar eclipse, so the latitude libration is near zero.
- The longitude libration can have any value during an eclipse.
- Consequently, the same lunar features cause bead events near the lunar poles, while different ones cause them near the center.
- For observations near the eclipse path limits, this reduces the effect of the typical ±0.2″ error of the profile data from Watts' charts (U. S. Naval Obs. Pub. #17, 1963) that were used for the profiles to the right.
- Some of the polar profile has been refined by observations of lunar grazing occultations of stars observed by IOTA members since 1962.
- Central eclipse timings might be used after the Lunar Reconnaissance Orbiter maps the Moon accurately and comprehensively.



Two Lunar Profiles from Watts superimposed, both lat. Libration 0 but with long. librations +1.0° and –5.0°

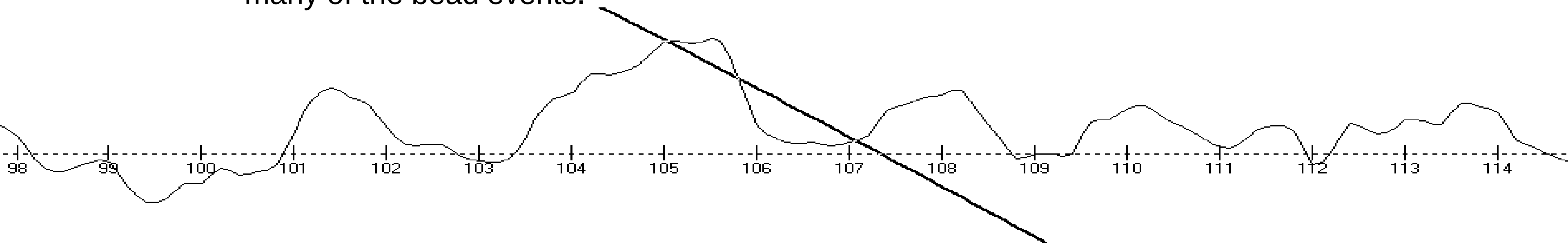
Video Recording of Baily's Beads, Curaçao, Feb. 26, 1998



- © Richard Nugent; recorded using a 4-inch Meade ETX and Thousand Oaks solar filter.
- 18:13:56 UT
- 18:14:00 UT
- 18:14:10 UT
- 18:14:12 UT
- 18:14:18 UT

Analyzing the Video Records

- The digital tape clock times were calibrated with UTC using time signals or GPS time stamps.
- A video time inserter that triggers from WWV minute tones, designed and built by Peter Manly, with results improved with a VTACT unit designed and built by Tom Campbell, Jr., was used to insert UTC displays on VHS video tapes.
- The tapes were then advanced slowly a frame at a time to establish the UTC of the recorded Baily Bead phenomena to an accuracy of about 0.1 second.
- Using the Baily's Bead module of the WinOccult program by D. Herald, downloaded from the main IOTA Web site at http://www.lunar-occultations.com/iota, the lunar feature (angle measured from the projection of the Moon's axis of rotation, called "Watts angle" or WA) was identified for each timing using the program's profile display (example below). The display is calculated for the time of the observed bead event.
- The height of the Sun's limb (the diagonal line below) above the lunar mean limb (the horizontal dashed line) at the bottom of the lunar valley (for D and R events), and the height of the Moon's limb at that angle, were entered into a spread sheet (see next panel) that calculated their difference (residual).
- Solrad, Dunham's DOS FORTRAN program, was used to calculate corrections to the Moon's center relative to that of the Sun, and the solar radius, using the residuals from many of the bead events.



Spreadsheet, Baily's Bead Times from Dunham's Video of the August 11, 1999 solar eclipse

UT, 10h	Event	Sun	Moon	WA	Residual
30:53.0	DA	-1.14	-1.14	32.1	0.00
30:46.8	DC	-1.02	-0.93	41.2	-0.09
30;46.8	DD	-1.33	-1.19	42.8	-0.14
30:26.9	DE	-0.90	-1.14	67.3	0.24
30:22.5	DF	-0.43	-0.19	70.9	-0.24
30:06.9	DG	0.05	-0.32	85.0	0.37
30:05.0	DH	-0.24	-0.48	87.2	0.24
30:00.8	DI	-0.10	-0.22	90.3	0.12
29:49.4	DJ	-0.73	-0.70	99.5	-0.03
31:48.0	RA	0.01	0.46	312.5	-0.45
31:48.2	RB	-0.25	0.42	310.7	-0.67
31:48.7	RC	-0.56	0.12	308.8	-0.68
31:53.0	RE	0.16	0.62	305.0	-0.46
31:53.2	RF	-0.25	0.09	302.8	-0.34
31:54.9	RG	-0.01	0.29	301.4	-0.30
31:55.3	RH	-0.10	0.08	300.4	-0.18
31:57.2	RI	-0.08	0.17	297.8	-0.25
31:57.2	RJ	-0.76	-0.45	295.1	-0.31
32:04.9	RK	-1.12	-1.32	283.7	0.20
32:08.9	RL	-1.08	-1.07	280.3	-0.01

"Event" is just an identifier, with the initial "D" for bead disappearance and "R" for bead reappearance. The "Sun" and "Moon" columns give the predicted height, in arc seconds, of the edge of the Sun and of the Moon above the lunar mean limb at the observed UT time. "WA" is Watts angle measured from the Moon's rotation axis in degrees. Residual is the difference, Sun height – Moon height. Only half of the bead events from this video tape that were analyzed are listed here.

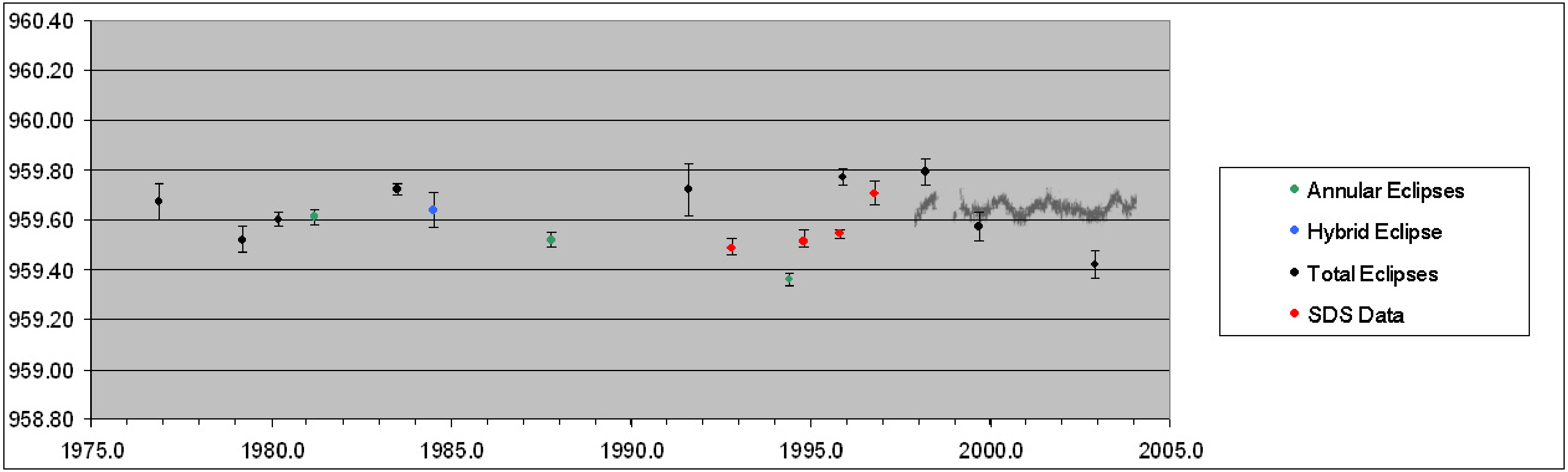
Solar Radius Determinations from Solar Eclipses

Year	Month	Day	Type	# Obs.	Method	ΔR⊙, "	σ, ±, "
1715	May	03	Total	3	visual	-0.5	0.2
1878	July	29	Total	12	visual	+0.55	0.15
1900	May	28	Total	8	visual	+0.12	0.09
1912	April	17	Hybrid	26	photoes	-0.29	0.22
1922	Sept.	21	Total	4	visual	+0.2	0.4
1925	Jan.	24	Total	11	visual	-0.21	0.17
1966	May	20	Hybrid	9	photoes	+0.03	0.05
1970	March	7	Total	4	visual & proj.	-0.05	0.12
1972	July	10	Total	14	visual & proj.	-0.02	0.61
1973	June	30	Total	7	visual & proj.	+0.4	0.2
1976	Oct.	23	Total	14	projection	-0.38	0.09
1979	Feb.	26	Total	21	visual & proj.	-0.05	0.08
1980	Feb.	16	Total	36	projection	-0.18	0.05
1981	Feb.	04	Annular	52	projection	-0.21	0.05
1983	June	11	Total	26	video & proj.	-0.10	0.08
1984	May	30	Hybrid	27	video	+0.13	0.07
1987	March	29	Hybrid	11	photoes	-0.19	0.08
1987	Sept.	23	Annular	44	video	+0.10	0.05
1988	March	18	Total	20	projection	-0.13	0.14
1991	July	11	Total	23	video	0.00	0.06
1994	May	10	Annular	75	video	-0.25	0.03
1995	Oct.	24	Total	25	video	+0.11	0.06
1998	Feb.	26	Total	44	video	+0.16	0.04
1999	Aug.	11	Total	19	video	-0.03	0.04
2002	Dec.	04	Total	13	video	-0.22	0.06
2005	Oct.	03	Annular	69	video	-0.06	0.03
2006	March	29	Total	105	video	+0.09	0.16

The radius correction, delta-R, is relative to the standard value at 1 A.U., 959.63 arc seconds. All have been reduced using David Herald's WinOccult program and analyzed with the Solrad programs. The Delta-R values are from 2-parameter solutions using bead events within 30° of the poles to use the better accuracy of the lunar polar profile as explained in panel #4.

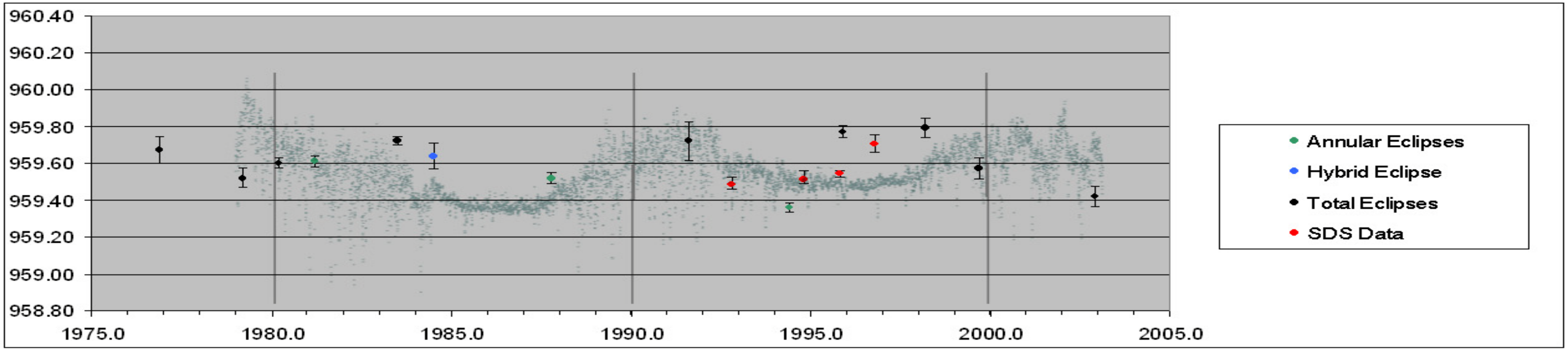
Solar Radius Determinations from Solar Eclipses Compared with SDS and SOHO Data

- The eclipse points with their formal solution error bars are plotted below.
- Four red dots are from the Solar Disk Sextant, from Sabatino Sofia.
- The gray curve is the “statistical thermal model correction” SOHO data from Fig. 13 of Kuhn, Bush, Emilio, and Scherrer, *Ap. J.*, **613**, p. 1249, 2004. Their “a priori thermal model correction” is about 0.2″ below the statistical thermal model data. SOHO was not designed to measure the solar radius; the application of large thermal effect corrections may have systematic errors.



Solar Radius Determinations from Solar Eclipses and SDS Compared with ACRIM Data

- The eclipse points and Solar Disk Sextant data are plotted like on the previous panel.
- The gray curve in the background is ACRIM data (total solar irrandiance, NOT radius, so the radius scale on the left has no meaning for these data) from http://earthobservatory.nasa.gov/Study/VariableSun/variable2.html



Accuracy of the Video Observations of the Total Solar Eclipse of February 26, 1998

	3-Parameter solutions with all data								
N1	#	N2	#	S1	#	S2	#	DR	ERROR
DD	20	PR	51	RN	21	WW	25	-0.04	0.0355
DD	20	-	-	RN	21	-	-	0.24	0.0257
-	-	PR	51	RN	21	-	-	0.00	0.0337
DD	20	-	-	-	-	WW	25	-0.06	0.0452
-	-	PR	51	-	-	WW	25	-0.22	0.0291
	2-Parameter solutions with polar data								
N1	#	N2	#	S1	#	S2	#	DR	ERROR
DD	15	PR	18	RN	11	WW	04	0.16	0.0542
DD	15	-	-	RN	11	-	-	0.26	0.0360
-	-	PR	18	RN	11	-	-	0.20	0.0349
DD	15	-	-	-	-	WW	04	0.00	0.0494
-	-	PR	18	-	-	WW	04	-0.07	0.0418

The radius determinations were calculated in two stages, first a solution solving for corrections to the ecliptic longitude and latitude of the Moon's center relative to the Sun's center, and the solar radius. The longitude correction from this first solution was then fixed in a second solution that used only bead events within 30° of the poles and found corrections only to the latitude and radius. There were two video recordings made at each limit (N1, N2 and S1, S2) with observer's initials in the table followed by the number of bead timings. The first line in the two tables includes all observers; the results for different combinations of single observers at each limit follow. The first line of the 2nd (2-parameter) table was used in the table in panel 9. Although the formal error for each result is rather small, the differences between results for different combinations of observers show that the true error is larger, about ±0.15″, apparently reflecting different levels of the Sun detected by different scope/filter/camera combinations.

All of the New 2-Parameter Solutions

MM	DD	YYYY	DR	ERROR	DD	ERROR	N1	#	N2	#	S1	#	S2	#	S3	#
12	04	2002	-0.08	0.0949	-0.04	0.1012	DD	05	WD	01	RV	08	-	-	-	-
			-0.21	0.0543	-0.19	0.0581	DD	05	-	-	RV	08	-	-	-	-
			0.38	0.0936	0.43	0.0981	-	-	WD	01	RV	08	-	-	-	-
08	11	1999	-0.06	0.0598	-0.01	0.0672	DD	03	-	-	RN	16	-	-	-	-
02	26	1998	0.16	0.0542	-0.53	0.0566	DD	15	UA	18	RN	11	WW	04	-	-
			0.26	0.0360	-0.44	0.0373	DD	15	-	-	RN	11	-	-	-	-
			0.20	0.0349	-0.48	0.0369	-	-	UA	18	RN	11	-	-	-	-
			0.00	0.0494	-0.15	0.0513	DD	15	-	-	-	-	WW	04	-	-
			-0.07	0.0418	-0.20	0.0446	-	-	UA	18	-	-	WW	04	-	-
10	24	1995	0.11	0.1088	0.27	0.1199	WW	03	-	-	RN	10	DD	06	-	-
			0.08	0.0826	0.44	0.0947	WW	03	-	-	RN	10	-	-	-	-
			0.14	0.0316	-0.03	0.0377	WW	03	-	-	-	-	DD	06	-	-
05	10	1994	-0.27	0.0239	0.02	0.0251	SF	14	-	-	KW	26	-	-	-	-
07	11	1991	0.09	0.1035	-0.06	0.1075	WB	01	-	-	DD	28	HB	01	GR	03
			0.10	0.0774	-0.07	0.0798	WB	01	-	-	DD	28	-	-	-	-
			-0.19	0.1722	0.17	0.1826	WB	01	-	-	-	-	-	-	GR	03
			-0.16	0.2104	0.13	0.2260	WB	01	-	-	-	-	HB	01	GR	03

The first 3 columns give the date (month, day, year), followed by the values in arc seconds for corrections to the solar radius (DR) and ecliptic latitude (DD). Observer initials and number of polar bead events used are in the following columns, as described in the last panel. 1998 was the first year that high-resolution video records were obtained by 2 observers at each limit, allowing the comparisons shown in the previous panel.

Comparison of Eclipse Radius Determinations from High- and Low-Resolution Videos

- Several observers from Germany, members of the European Section of IOTA, travelled to Mexico to observe the July 31, 1991 eclipse from locations near the path edges. They used telephoto lenses and video cameras that gave low-resolution images of the whole Sun. Reinhold Buechner analyzed the few bead events recorded by each for inclusion in the table in the previous panel.

- The comparison of HB and GR with DD’s high-resolution video recording using a 5-inch telescope also near the southern limit of the 1991 eclipse showed a difference of almost 0.3″ in the radius, with the low-resolution systems detecting a lower (brighter) level of the Sun.

- **By September 21, this presentation will be available at http://iota.jhuapl.edu/eclipse.htm**

Comparison of Eclipse Radius Determinations from Direct Visual and Filtered Video Methods

- David Dunham’s son William made a direct camcorder recording of the Sun near the northern limit of the December 2002 eclipse while David recorded it using a filtered 4-inch telescope. The camcorder recording seemed to capture the direct visual view of the eclipse. When the same southern-limit observations (by R. Venable) were used to analyze bead times from the two records, the results differed by almost 0.6″ as shown in the table. But the camcorder had only one polar bead event so this result is not very reliable. Nevertheless, it shows that direct visual observers probably time the eclipse inner contacts (last bead to disappear and first to reappear) at rather higher levels in the Sun than the filtered video recordings.
- Since early observations like those in 1925 and 1715 were visual, this may explain why the solar radius for those eclipses was determined to be about half an arc second greater than it was at modern eclipses.
- However, the northern limit in 1925 was determined by seeing a brief flash spectrum at an observatory, not a direct visual observation, and there is a large uncertainty in the position of the northern-limit observer of the 1715 eclipse.
- There were no videos of the 1979 eclipse; some of those observations were direct visual, like the old eclipses, but others were with visual observation of an image projected by small telescopes, a technique that has not been calibrated relative to, for example, high-res. video, but Dunham, who has used both, believes they have similar sensitivities.
- David Herald video recorded the 2002 eclipse near the southern limit with a medium-resolution system; it will be useful to see how that compares with the results of Roger Venable’s higher-resolution video observations.

Conclusions, Future Work, Acknowledgments

- Due to the gradient at the Sun's edge and different filtration used to record Baily's beads and time the contacts, the true accuracy of solar radius determinations from past eclipses seems to be about $\pm 0.2''$.
- Observers watching an eclipse directly without filters are likely to time the contacts at a much higher level of the Sun than telescopic observers using filters, possibly explaining the larger radius of the Sun determined from the 1925 and 1715 eclipses relative to the radius determined from the recent eclipses.
- Some of the results might be improved by identifying specific lunar features that cause the same bead events at different eclipses, and use just those for the polar radius determinations.
- Some eclipses observed near the path edges before 1979 have not been analyzed.
- Standard (that is, the same) equipment should be used as much as possible for future eclipses; Richard Nugent's compact 4-inch telescope with Thousand Oaks solar filter gives good results and is recommended for use by others. More comparisons with visual observations, both direct and of images projected with small telescopes, are needed to better calibrate historical eclipse results with those determined from video recordings.
- Dunham, Fiala, and Warren thank the National Science Foundation for its support of their travel to India to record the October 1995 eclipse. We are indebted to all others who used their own resources to obtain these data.
- The new analyses presented here were supported by NASA Grant NNG04GM60G.

Comparison of new and earlier results for the solar diameter from eclipses

Month	Day	Year	Type	Obs.	new ΔR ″	Error ± ″	old ΔR ″	Error ± ″	Difference new - old ″
Mar.	29	2006	total	105	0.09	0.16			
Oct.	3	2005	annular	69	-0.06	0.03			
Dec.	4	2002	total	13	-0.22	0.06	-0.21	0.05	-0.01
Aug.	11	1999	total	19	-0.03	0.04	-0.06	0.06	0.03
Feb.	26	1998	total	44	0.16	0.04	0.16	0.05	0.00
Oct.	24	1995	total	25	0.11	0.06	0.14	0.03	-0.03
May	10	1994	annular	75	-0.25	0.03	-0.27	0.02	0.02
July	11	1991	total	23	0.00	0.06	0.09	0.10	-0.09
Mar.	18	1988	total	20	-0.13	0.14			
Sept.	23	1987	annular	44	0.10	0.05	-0.11	0.03	0.21
Mar.	29	1987	hybrid	11	-0.19	0.08			
May	30	1984	hybrid	27	0.13	0.07	0.09	0.04	0.04
June	11	1983	total	26	-0.10	0.08	0.09	0.02	-0.19
Feb.	4	1981	annular	52	-0.21	0.05	0.02	0.03	-0.23
Feb	16	1980	total	36	-0.18	0.05	-0.03	0.03	-0.15
Feb.	26	1979	total	21	-0.05	0.08	-0.11	0.05	0.06
Oct.	23	1976	total	14	-0.38	0.09	0.04	0.07	-0.42
June	30	1973	total	7	0.40	0.20			
July	10	1972	total	14	-0.02	0.61			
Mar.	7	1970	total	4	-0.05	0.12			
May	20	1966	hybrid	9	0.03	0.05			
Jan.	24	1925	total	11	-0.21	0.17	0.51	0.08	-0.72
Sept.	21	1922	total	4	0.20	0.40			
Apr.	17	1912	hybrid	26	-0.29	0.22			
May	28	1900	total	8	0.12	0.09			
July	29	1878	total	12	0.55	0.15			
May	3	1715	total	3	-0.50	0.20	0.48	0.20	-0.98

1715 eclipse, northern limit, Darrington, England

to the present astronomy department at Cambridge. For the town of Darrington, local telephone inquiry revealed that the old town was the western half of the present village, and being quite small, this was sufficient information. These locations were recovered from the Geodetic maps.

6.11

Figure 6.2

Halley's Critical Observations

Observer	Place	Lat	Lon	$2C_{obs}$	$3C_{obs}$	$\Delta T^{\dagger}$
Halley	Royal Society	51.516	359.892	9^m03^s	12^m26^s	-10.5[§]
Rev. Pound	Wanstead Essex	51.573	0.037	9 28	12 48	-11.3
Prof. Cotes	Cambridge U.	52.205	0.119	—	14 37	-13.6
	Mean of the above timed contacts					ΔT_t = -11.8 ±
	Darrington	53.664	358.736	"Point like Mars"		
	Bocton Kent	51.288	0.938	"Point like Star"		
	Cranbrook Kent	51.101	0.529	"Duration instant"		
	Geometric determination from the above					ΔT_g = - 8.8 ±

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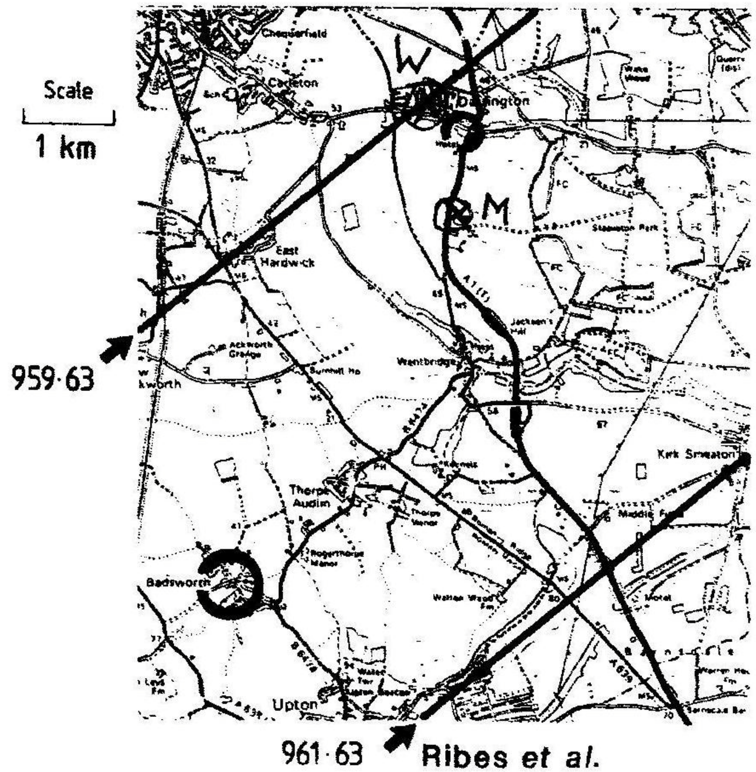

Fig. 4 The calculated northern limits of the path of totality of the 1715 eclipse in relation to Darrington and Badsworth. The limits have the same significance as in Fig. 3.

1715 eclipse, southern limit, Bocton, England

Golf Course, and shows clearly on the Geodetic Survey Map.

The observation attributed to Bocton, Kent, was transmitted to Halley by a fellow society secretary who passed through the village returning to Canterbury from Norton Court where he had presumably gone to be within the belt of totality. It is stated that the townspeople agreed that the eclipse had been not quite complete, "*a single point like a star remaining.*" The Bocton of 1715 was on the pilgrim's way to Canterbury, the same one noted in Chaucer, and at the location of the present Boughton Church Farm which appears on the Geodetic Map. I am indebted to the Reverend Schofield the vicar of Boughton Street for this crucial information.

The observation attributed to Cranbrook in Kent was transmitted to Halley by Mr. William Tempest, but w

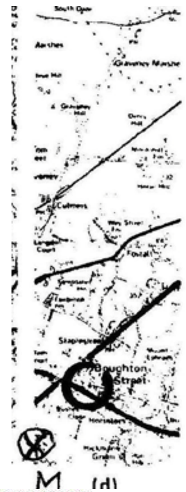

Fig. 3 The calculated southern limits of the path of totality of the 1715 eclipse in relation to Lewes (*a*), Wadhurst (*b*), Cranbrook (*c*) and Bocton (Boughton Street) (*d*). The limit using the current value of the Sun's semi-diameter is labelled 959.63 arc s. The limit using the early eighteenth century result of Ribes *et al.*[1] is labelled 961.63.

(Map center is at (WGS84 datum) Lat = 51.288171, Lon = 0.938043, which is 1812.504 Km from path center.)

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Estate agent's valuation:	Ask an Estate Agent for their opinion of the value your home for either sale or rental

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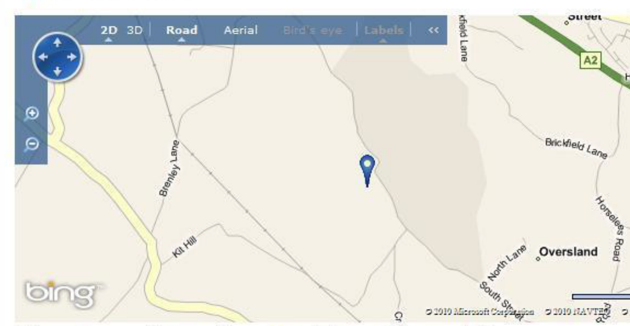
Approximate location



Nearby postcodes | Schools | Supermarkets | Petrol | (pin accuracy low)

Geometry of a lunar (grazing) occultation

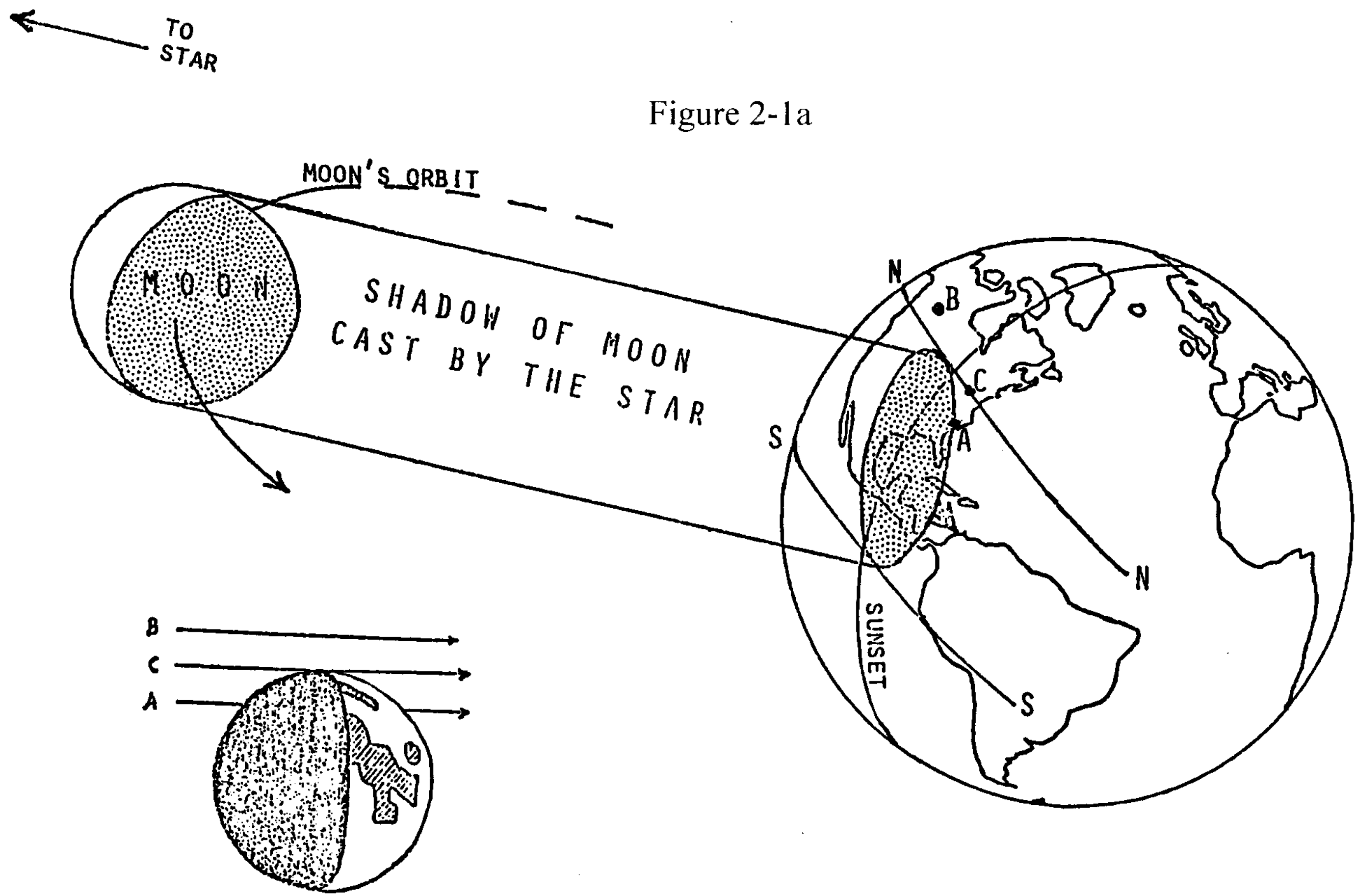
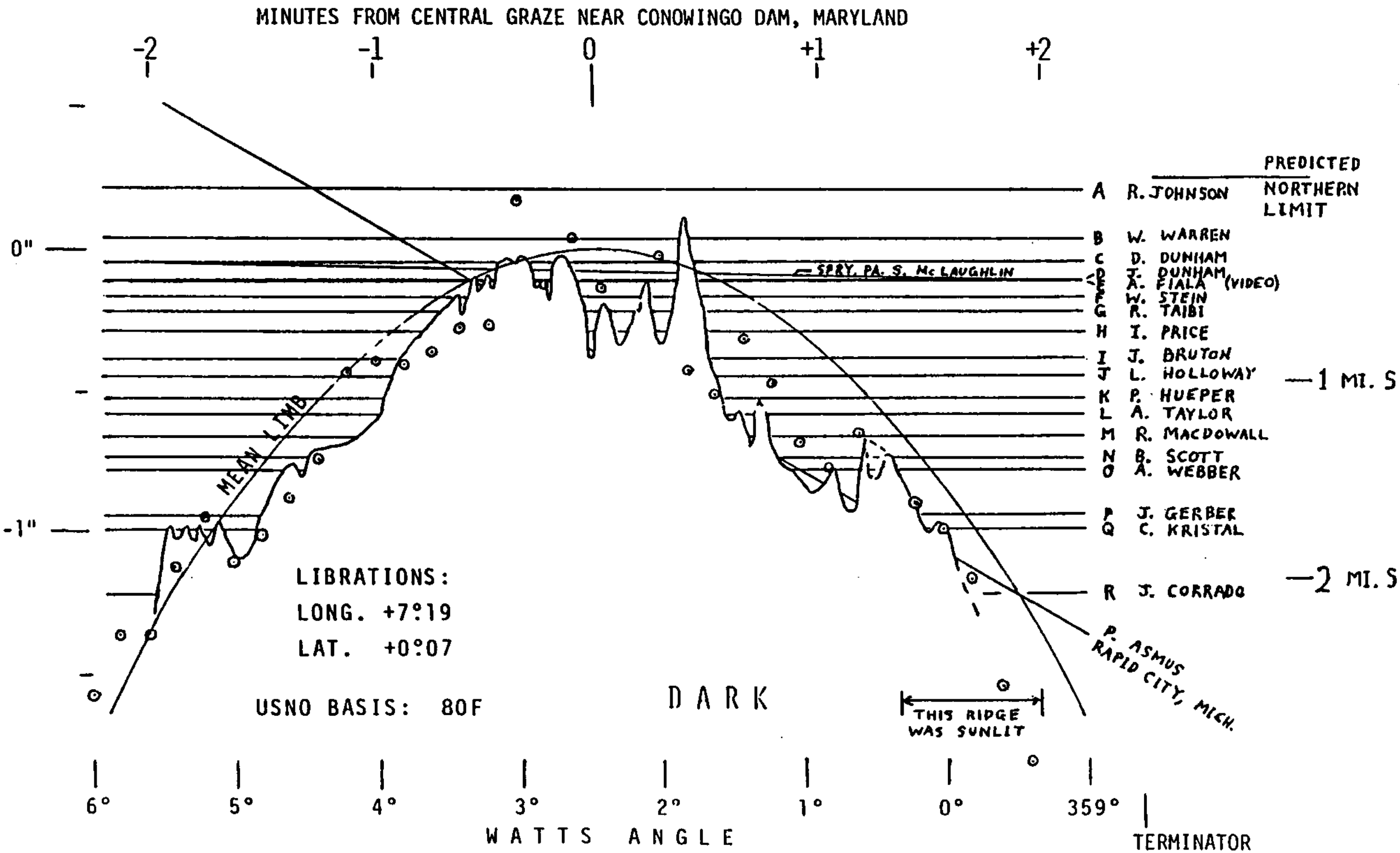


Figure 2-1a

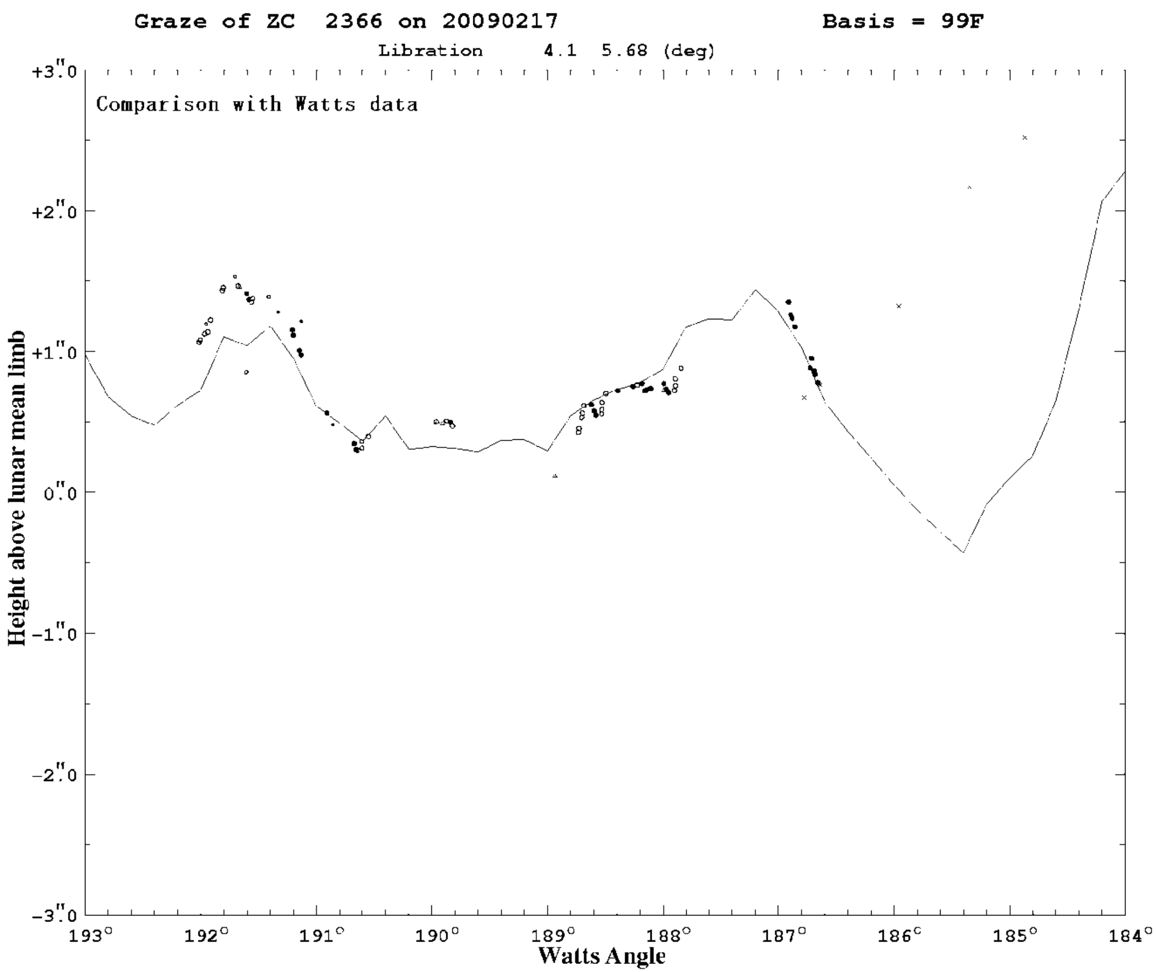
Figure 2-1b

Lunar Profile from Graze of delta Cancri – 1981 May 9-10



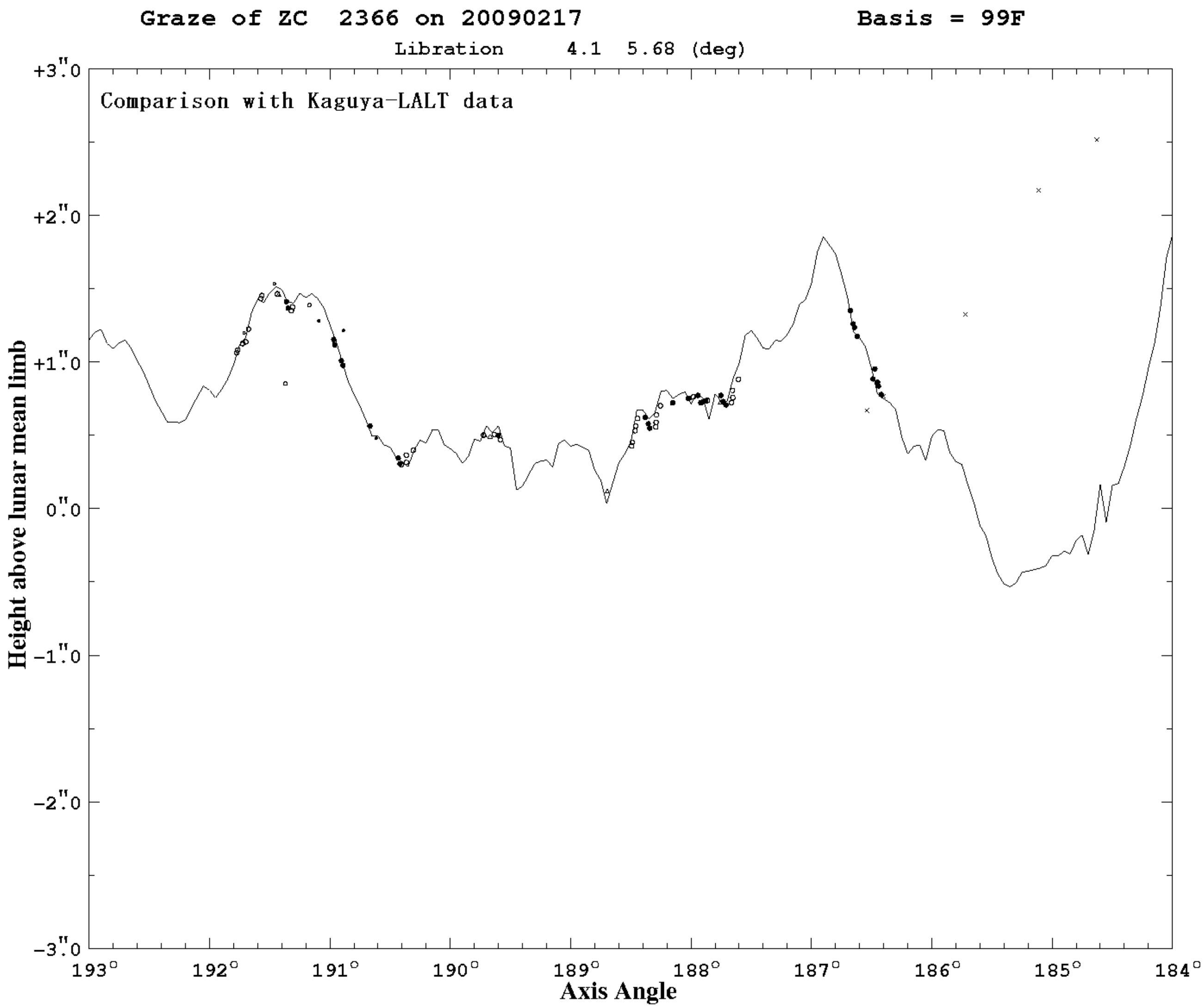
Circled dots are Watts' predicted limb corrections

Grazing occultation analyzed with Watts profile data



From a grazing occultation of Antares observed from Bardoc, Western Australia, on 2009 February 17

Grazing occultation analyzed with Kaguya profile data



Same Antares graze as shown in the previous slide

More Conclusions Future Work

- The SOHO folks, with an instrument that is not suited for the purpose, claim that they have found that the solar diameter does not change by more that a few mas over 15 years. To do that, they have ?corrected? the measurements for processes not calibrated or properly characterized with sizes several orders of magnitude larger than the claimed accuracy. If true, it would have profound implications on the physical origin of solar variability, and it would contradict calibrated measurements of the SDS, besides current eclipse results. We need to know the answer, and extensive work is going on in order to properly analyze the measurements of the calibrated data from the experiment SODISM on the PICARD satellite. We hope to settle this within a relatively short time,
- All of our previous studies (except for the 2010 eclipses) were done with Watts data for the lunar profile; they need to be re-analyzed with Kaguya data
- We need to make modern (and "ancient" visual) observations of future eclipses while Picard and SDS are making observations, to better establish the accuracy of solar diameter determinations from different types of eclipse observations.
- we should analyze the 1869 August eclipse observations that I've inherited from Alan Fiala, and possibly the 1803 eclipse in the n.e. USA could be useful.
- Sabatino Sofia writes: The main objective is to try to determine the solar behavior as far back as possible, in order to establish the role of solar variability as a climate driver. Since we cannot measure the solar irradiance in the past, a particular aspect of the diameter study is its ability to be a proxy for the luminosity.
- Because of these objectives, the most important task of this study is to determine the solar diameter for as many of ancient solar eclipses, as far back as possible.
- Especially useful could be observations made near the edges of past solar eclipses, or of very small-magnitude solar eclipses (hybrid annular-total eclipses, like the one of April 1912).
- A search of old observatory archives, especially in Europe, could be productive for finding useful observations that we could analyze with modern techniques

French recommend recording the flash spectrum with a diffraction grating placed in front of the telescope

- The French astronomers criticized IOTA's approach of just video recording Baily's beads directly with filters since the brightness level of the beads when events are timed is poorly known.
- They prefer recording the flash spectrum, which was also done with photographic cinemagraphic cameras by Japanese astronomers at a few eclipses in the late 20th century; this way, the whole light curve at every point on the lunar limb within many degrees of the final contact point is recorded and can be better assessed (when the absorption lines in the spectrum turn to emission lines, marking the transition from the photosphere to the chromosphere).
- They note that the diffraction gratings are not a very expensive addition to the video setups that we use, and I agreed that we should encourage their use at future eclipses.