

# Analysing 50 Lunar Eclipses

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## Abstract

The first attempt at observing a total lunar eclipse was made in 1972 January 30 with Peter Raw the then President of the Canberra Astronomical Society. Since that time another 49 eclipses have been analysed for crater timings leading to the evaluation of the oblateness of the Earth's shadow. Many local and overseas observers have contributed during the 32 years of the project with crater timings and images of these 50 lunar eclipses. This paper gives some of the history of the crater timing and lunar imaging analysis project together with the findings.

## Introduction

The aim of the project was to obtain data points on the perimeter of an ellipse by computing their coordinates referred to the umbra centre. The program used up to six umbra edge and mid-contacts with features timed during observation of a large number of craters for each lunar eclipse.

As the Astronomical Ephemeris uses an approximate value for the oblateness of the atmosphere of the Earth based on a geoid value of 1 in 298.257, these lunar eclipse timings enabled an observed value of oblateness to be determined.

### Observing Method

Prediction of mid-crater timing immersions and emersions in and out of the umbra were made available to each observer prior to the eclipse to encourage recognition of named features to be practiced prior to each eclipse. Initially, an observer's report form was provided with the predictions for return of crater timings for analysis. Also requested was that timing of three immersions should be made, that of first contact with the edge of each feature, its centre and second contact with the trailing edge. Additionally, three emersions should be timed if possible, that of third contact with the emerging edge of the feature, its centre or mid-timing and fourth contact with the umbra as the feature emerged fully from the umbra. Features such as mountains and bright spots on the lunar surface could be reported as mid-timings only and each primary contact of the edge of the Moon and umbra should be timed.

Timings should be accurate (synchronised with VNG or WWV short wave radio signals) and to 0.1 of a second if possible. The definition of the umbra edge is difficult as there is a gradual fading from the dark umbra to the white of the full Moon and effort must be made to continually judge the maximum rate of change in the density of the umbra edge for consistent observations.

### Analysis Method

A series of computer programs was prepared in Microsoft Basic to carry out accurate predictions of crater timings, to find the circumstances of each lunar eclipse, to reduce crater timings to give percent umbral enlargement and the mean error of each observer's data set. Many data files were prepared for these analysis programs for lunar and solar ephemerides for each eclipse, crater location and size and statistical data necessary to find observational accuracy and acceptability for the umbral oblateness estimates.

Earlier work done by Jean Meeus<sup>2</sup>, mathematical development for the single crater timing analysis by David Herald<sup>3</sup> and best-fit ellipse mathematics by the late Wilm Nijenhuis<sup>4</sup> were included in the analysis programs.

### Observations

Over the 32 years of the project crater timing observations have provided a large amount of data for the umbral enlargement and for the very sensitive estimate of umbral oblateness. See **Table 1** for a summary of the crater timings and **Table 2** for a summary of the mean observed oblateness.

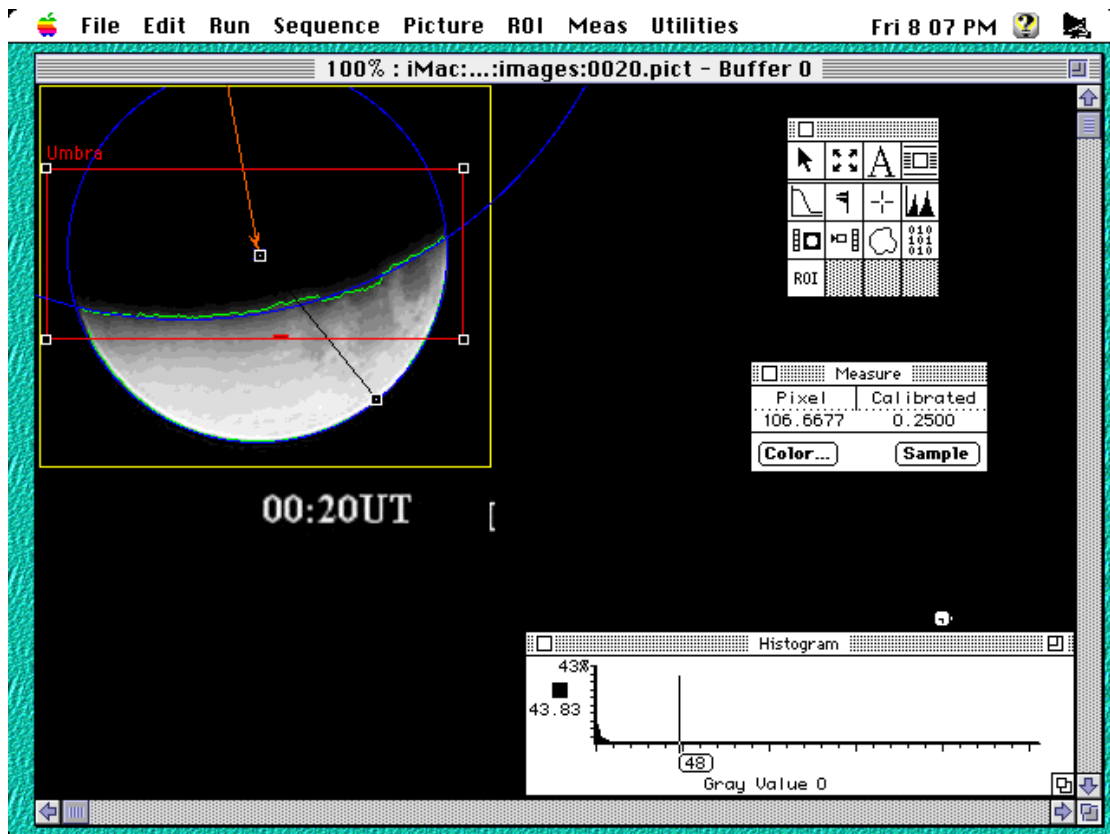
### Web Casts

In 1997 September 16 images were transmitted live for my first web cast over the Internet (See <http://jump.to/lunar-eclipse>). This was one of the first web casts made and the response was tremendous with the clouded out Athens Observatory using my animation of images<sup>5</sup>.

In 1998 March 13 it was found that imaging of the penumbra was possible, so from that date any penumbral lunar eclipses visible in Australia were observed. Others<sup>6</sup> attempted this as well and interesting images were obtained.

### Image Analysis

Imaging of lunar eclipses presents a challenge in regard to exposure, brightness and contrast of the Moon and the umbra. A video camera was used successfully to capture images to up-load for web casts and to provide images for measurements of the size of the umbra during eclipses. A MASS *QuickImage 24* frame grabber with a Macintosh IICI computer captured the images and another program, *Image Analyst* was used to measure the radius of a best-fit circle of the imaged umbra calibrated to the known semi-diameter of the Moon. A full image of the Moon was required to achieve this as shown in the following image:



The video camera used was an analogue unit so a frame grabber was required to copy the images in PICT format for measurement as illustrated above. The measured umbral semi-diameter was consistently below the value expected and this was thought to be due to its projection onto the curved surface of the Moon and possibly, due to change in size during the eclipse.

A software program was written to study this change in geometry with the imaged umbra compared to topocentric calculations made for each observing site. Overseas observers provided many images for this comparative study. **Table 3** lists some of the results obtained.

### Findings

**Umbral Enlargement** - The purpose of the program was to find the enlargement of the umbra from a large number of lunar eclipses based on many individual observer's crater timings. It was found that 7,850 immersion timings gave an umbral enlargement of 2.21 % with a mean error of 0.15 %. These were more consistent than emersion timings as the feature could be observed and timed before the beginning of the umbral immersion. Emersion timings were inherently more difficult as the feature was not revealed before it emerged from the dark umbral shadow. A mean value of 2.10 % enlargement with a mean error of 0.17 % resulted from 4,199 emersion timings. It can be seen from the mean errors in **Table 1**, that the accuracy of each event reflects this difference in observing the features.

The actual value of umbral enlargement varied for each eclipse, but overall the %E values are within a narrow range particularly for experienced observers. The table gives mean values for all observers only, but where some observers have timed a large number of features for each eclipse, they achieved a very low error of the mean.

**Umbral Oblateness** - From the large number of crater timings (a total of 12,049 timings are presented in **Table 1** in the range of  $0 < \%E < 4$ ) it was possible to obtain a meaningful sample of accurate timings for the very sensitive estimate of umbral oblateness.

These values were found to vary quite widely and are presented in **Table 2**, however the mean value of reciprocal oblateness for 4,356 immersion timings was 117.3 with a mean standard deviation of 0.04 and for 1,562 emersions it was 106.6 with a mean standard deviation of 0.05.

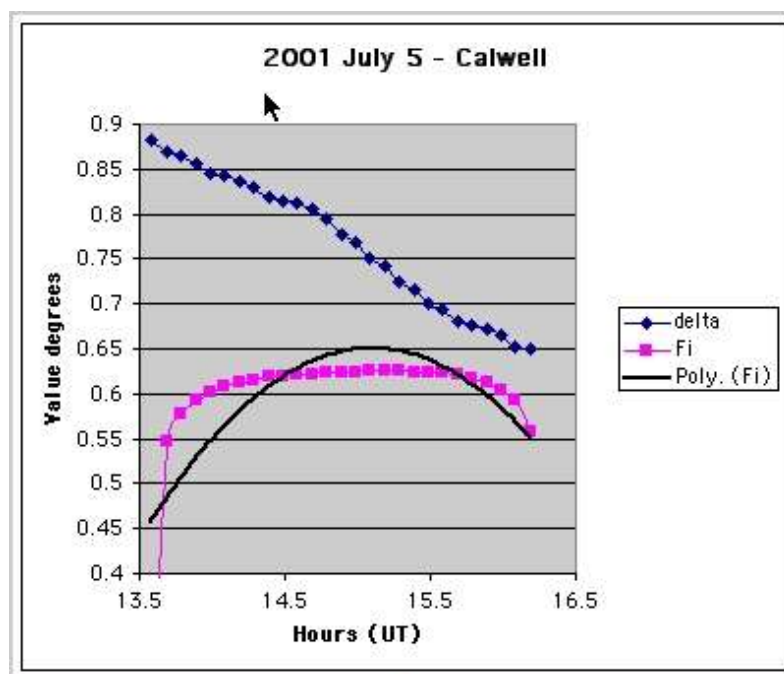
The height of the upper atmosphere of the Earth  $H$ , can be found from these oblateness values, where %E is the enlargement of the umbra,  $R_p$  is the polar semi-diameter of the upper atmosphere,  $R_e$  is the equatorial semi-diameter of the upper atmosphere and  $F_i$  is the observed reciprocal umbral oblateness, where the values of the Earth's radii are from the BAA Handbook<sup>7</sup> 2001, as follows;

$$\begin{aligned}
 H &= R_e(1 + \%E/100) - R_p(1 + \%E((1 - 1/F_i)/100)) \\
 &= R_e(1 + 2.0/100) - R_p(1 + 2.0(1 - 1/117.3)/100) \\
 &= R_e(1.02) - R_p(1.0198) \\
 &= 6378.140(1.02) - 6356.755(1.0198) \\
 &= 22.9 \text{ km}
 \end{aligned}$$

**Improved Lunar Eclipse Ephemeris** - An earlier mean observed oblateness value of 1/102 was incorporated into an improved lunar eclipse ephemeris<sup>8</sup> (ILEE) to compute the time of primary contacts for lunar eclipses. The program for eclipse circumstances included these time differences for each primary contact for comparison after each lunar eclipse.

**Measurements of the Umbra** - while it is conceded that the variation in the measurements of the imaged umbral semi-diameter as presented in **Table 3** could be questioned, the results speak for themselves, in as much that there is a consistency in the values which are all well below the expected umbral semi-diameter  $F_2$ . At first contact with the Moon the measured umbral size is lowest due to the greatest curvature of the Moon's surface, the size slowly increases at second contact as this curvature decreases, is greatest at mid-eclipse, and decreases near third contact when the Moon begins to emerge from the umbra and again where the curvature increases it has a low value at fourth contact.

Measurements taken indicate a slow increase in umbral size to mid-eclipse followed by a similar decrease to fourth contact. A computer program was written to find the expected measured semi-diameter of the umbra throughout any lunar eclipse with allowance for topocentric effects for the site of the observer. Computed values for the eclipse of 2001 July 5 for my then site in Calwell, Australia are shown in the following graph where the change in geometry of the umbra can be seen, where  $F_i$  is the measured semi-diameter of the umbra,  $\delta$  is the slant angle to the umbra edge and Poly. ( $F_i$ ) is the sixth order best fit polynomial to the  $F_i$  values



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Mean values of measurements made of the size of the umbra from seven eclipses were found to be 0.42 degrees at first contact, 0.61 at second contact, 0.57 at mid-eclipse, 0.52 at third contact and 0.47 at fourth contact. These measured values should be compared with the expected mean umbral semi-diameter of 0.73 degrees as given in Table 3.

### **Conclusions**

A large number of crater timing observations have yielded observed umbral enlargement within the narrow range of 2.10 % for emersion timings to 2.20 % for immersion timings, both very near the classical value of 2 %.

A large number of crater timings has yielded a mean umbral oblateness value of 1/117.3 from immersion crater timings and 1/106.6 from emersion timings where both values are approximately one third of Earth's geoid value or flattening, of 1/298.257. The values obtained were incorporated into an improved lunar eclipse ephemeris to provide more exact prediction of primary contact times of lunar eclipses.

A small number of eclipses gave measurements of images of the umbra, which show low values and change in the umbral geometry, suggesting that variations in umbral size may occur during a lunar eclipse.

It was found that imaging of the penumbra is possible and reasonable processed images were obtained from several penumbral eclipses.

### **References**

- 1**     **Astronomical Ephemeris Explanatory Supplement, 1961, Section E pp 257-262**
- 2**     **Jean Meeus, Sky and Telescope, April 1979 pp 333**
- 3**     **David Herald, Canberra Astronomical Society, February 1982**
- 4**     **Wilm Nijenhuis, private communication**
- 5**     **Athens National Observatory, Dr Ioannis Bellas – Institute's Home Page**
- 6**     **Bengt Ask, Images of the penumbral eclipse of 1998 March 13 (use link  
[http://www.df.lth.se/~bengt/lunar\\_980313.shtml](http://www.df.lth.se/~bengt/lunar_980313.shtml))**
- 7**     **The Handbook of the British Astronomical Association, 2001**
- 8**     **Journal of the BAA, volume 100, number 6, 1990 pp 293-305**

Table 1 - Summary of crater timings

(I) = immersions, (E) = emersions

Date Sequence	Eclipse Type	No	(I) (E)	%E	Mean error +/-	Participating Countries
1972 Jan 30 0	Total	0	(I)	-	-	Australia
		0	(E)	-	-	
1974 Nov 29 1	Total	64	(I)	1.7410	0.0975	Australia
		23	(E)	2.2921	0.6680	
1978 Mar 24 2	Total	386	(I)	2.1966	0.1371	Australia, South Africa
		64	(E)	2.1471	0.2289	
1978 Sep 16 3	Total	689	(I)	1.9906	0.1188	Australia
		57	(E)	2.0246	0.1401	
1979 Mar 13 4	Partial	50	(I)	2.2303	0.1350	South Africa
		0	(E)			
1979 Sep 6 5	Total	206	(I)	1.9591	0.1511	Australia, NZ, USA
		265	(E)	1.8620	0.1281	
1981 Jul 17 6	Partial	86	(I)	2.1073	0.2328	South Africa, Brazil
		0	(E)			
1982 Jan 9 7	Total	359	(I)	2.1047	0.1556	Australia
		1	(E)	2.2044	-	
1982 Jul 6 8	Partial	65	(I)	2.0953	0.3286	Australia, NZ, Brazil
		289	(E)	2.1825	0.1594	
1982 Dec 30 9	Total	45	(I)	1.8291	0.1372	Australia, NZ
		88	(E)	1.7717	0.1083	
1983 Jun 25 10	Partial	99	(I)	2.0283	0.1340	Australia, NZ
		62	(E)	2.1500	0.1901	
1985 May 4 11	Total	576	(I)	2.0363	0.1636	Australia, Brazil, NZ, South Africa, Philippines, Spain, Austria
		202	(E)	1.9069	0.1197	
1985 Oct 28 12	Total	291	(I)	2.4873	0.1538	Australia, Italy, South Africa, NZ, Zimbabwe, UK, Cyprus, Singapore
		84	(E)	1.9198	0.2609	
1986 Apr 24 13	Total	683	(I)	2.0062	0.0875	Australia, Italy, NZ
		435	(E)	2.1028	0.1529	
1986 Oct 17 14	Total	462	(I)	2.1488	0.1777	Australia, Italy, NZ, Brazil, Austria, UK, Netherlands, South Africa, Belgium, Spain
		273	(E)	2.1313	0.1368	
1988 Mar 3 15	Partial	5	(I)	2.6725	0.0294	Australia, NZ, USA, Italy, UK
		5	(E)	2.0610	0.0252	
1988 Aug 27 16	Partial	44	(I)	2.2655	0.2176	Australia, NZ
		75	(E)	1.9514	0.0995	
1989 Feb 20 17	Total	334	(I)	2.2425	0.0846	Australia, NZ
		239	(E)	2.0021	0.0902	
1989 Aug 17 18	Total	357	(I)	2.1589	0.1450	Australia, Italy, Brazil, Netherlands, Spain, South Africa, Portugal, UK, Belgium, Austria
		83	(E)	1.8820	0.2906	
1990 Feb 9 19	Total	247	(I)	2.1511	0.1688	Brazil, Belgium, Italy, Netherlands
		184	(E)	2.3116	0.0970	
1990 Aug 6 20	Partial	59	(I)	2.5023	0.1714	Australia
		48	(E)	2.0630	0.1387	
1991 Dec 21 21	Partial	0	(I)	Clouded out		Australia
		0	(E)			
1992 Jun 15 22	Partial	86	(I)	2.2488	0.1447	NZ, Brazil
		76	(E)	1.9470	0.1870	
1992 Dec 9 23	Total	116	(I)	2.2998	0.1681	UK, Brazil, Portugal, Spain
		40	(E)	2.4117	0.2380	

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Table 1 continued

Date Sequence	Eclipse Type	No	(I) (E)	%E	Mean error +/-	Participating Countries
1993 Jun 4 24	Total	194	(I)	1.9025	0.1095	Australia
		129	(E)	2.0421	0.1582	
1993 Nov 29 25	Total	39	(I)	2.2812	0.1115	Brazil
		8	(E)	2.1041	0.2464	
1994 May 25 26	Partial	5	(I)	2.8899	0.2111	Brazil
		5	(E)	2.8709	0.1971	
1995 Apr 15 27	Partial	36	(I)	1.9147	0.1150	Australia
		42	(E)	2.2772	0.0542	
1996 Apr 4 28	Total	333	(I)	2.2382	0.1066	Netherlands, Brazil, Belgium, Spain
		303	(E)	2.2927	0.1130	
1996 Sep 27 29	Total	170	(I)	2.2734	0.1274	Italy, Belgium, Netherlands
		95	(E)	1.9912	0.1921	
1997 Mar 24 30	Partial	101	(I)	2.2535	0.1265	Italy, Brazil,
		90	(E)	2.0053	0.0986	
1997 Sep 16 31, WC 1	Total	328	(I)	2.1298	0.1100	Australia, Slovakia, Italy,
		212	(E)	1.9476	0.1420	
1998 Mar 13 32	Pen	Only images were analysed				Australia, France
1998 Aug 6 33	Pen	Only images were analysed				Australia
1998 Sep 6 34	Pen	Only images were analysed				Australia
1999 Jan 31 35, WC 2	Pen	Only images were analysed				Australia
1999 Jul 28 36, WC 3	Partial	25	(I)	2.3072	0.0994	Australia
		27	(E)	2.0066	0.0932	
2000 Jan 21 37, WC 4 (link)	Total	235	(I)	2.3349	0.1444	Australia, Brazil, South Africa, Italy
		65	(E)	1.7922	0.1974	
2000 Jul 16 38, WC 5	Total	233	(I)	1.9565	0.1272	Australia
		175	(E)	2.0980	0.1010	
2001 Jan 9 39	Total	221	(I)	2.1816	0.0894	Australia, Poland, South Africa
		94	(E)	1.9828	0.1369	
2001 Jul 5 40	Partial	9	(I)	2.6765	0.2839	Australia
		9	(E)	2.5488	0.3406	
2001 Dec 30 41	Pen	Only images were analysed				Australia
2002 May 26 42	Pen	Only images were analysed				Australia
2002 Jun 24 43	Pen	Only images were analysed				Australia
2002 Nov 20 44	Pen	Only images were analysed				Australia
2003 May 16 45	Total	163	(I)	2.0234	0.0986	South Africa, Brazil, Italy
		76	(E)	1.8993	0.0508	
2003 Nov 9 46	Total	254	(I)	2.1845	0.1168	South Africa, Brazil (includes 116 predictions)
		187	(E)	1.9282	0.1274	
2004 May 4 47	Total	49	(I)	1.9331	0.1866	South Africa, Brazil, UK
		46	(E)	1.9036	0.2197	

Table 1 continued						
Date Sequence	Eclipse Type	No	(I) (E)	%E	Mean error +/-	Participating Countries
2004 Oct 28 48	Total	141 38	(I) (E)	2.2338 1.8746	0.1530 0.1252	South Africa, Brazil, Austria, USA
2005 Apr 24 49	Pen	Only images were analysed				Australia
2005 Oct 17 <b>50</b>	Partial	A "Live" web-cast and an animation of 63 images was produced.				Australia
<b>Sum</b>		7850 4199	(I) (E)			
<b>Mean</b>			(I) (E)	2.203 2.099	0.147 0.165	

**Legend for Table 1**

**Sequence** is the number of the eclipse in the Soulsby series

**No** is the number of crater timing observations statistically accepted for analysis

**Type** of eclipse either Total, Partial or Penumbral. For the latter no crater timings are possible

**%E** is the percent enlargement of the umbra, where  $0 < \%E < 4$  for the current analysis

**Mean Error** is the error of the mean, the standard deviation /  $(No)^{1/2}$

**Table 2 – Oblateness Estimates as 1/f**  
From acceptable crater timings with  $0 < \%E < 4$

Date	Immersion Timings			Emersion Timings		
	Number	Mean f	sd	Number	Mean f	sd
1974 Nov 29	70	266.6	0.01	23	95.7	0.06
1978 Mar 24	266	116.2	0.03	24	50.7	0.15
1978 Sep 16	532	67.9	0.04	11	83.9	0.01
1979 Mar 13	43	254.4	0.01	-		
1979 Sep 6	70	161.8	0.07	79	-	0.04
1981 Jul 17	23	93.8	0.01	-		
1982 Jan 9	236	133.8	0.03	-		
1982 Jul 6	47	-	0.04	233	30.5	0.02
1982 Dec 30	38	54.4	0.05	11	111.5	0.07
1983 Jun 25	92	156.6	0.01	14	52.9	0.09
1985 May 4	345	121.8	0.06	102	120.7	0.05
1985 Oct 28	107	134.3	0.09	38	134.7	0.03
1986 Apr 24	513	45.9	0.03	164	225.1	0.08
1986 Oct 17	303	84.4	0.03	124	165.5	0.04
1988 Aug 27	39	-	0.18	41	143.1	0.02
1989 Feb 20	185	180.5	0.05	67	73.1	0.04
1989 Aug 17	148	70.0	0.08	13	-	0.11
1992 Jun 15	40	68	0.11	17	106.5	0.01
1992 Dec 9	27	46.6	0.01	32	118.1	0.06
1993 Jun 4	132	95.5	0.03	7	219.2	0.02
1993 Nov 29	18	79.2	0.07	0		
1995 Apr 15	0			32	22.5	0.01
1996 Apr 4	230	45.1	0.03	154	111.2	0.06
1996 Sep 27	68	37.5	0.04	54	100.3	0.07
1997 Mar 24	42	80.4	0.06	11	54.5	0.08
1997 Sep 16	195	175.8	0.03	75	56.5	0.01
2000 Jan 21	133	135.6	0.03	0		
2000 Jul 16	214	97.7	0.02	175	65.4	0.01
2001 Jan 9	192	265.7	0.04	48	189	0.02
2003 Nov 9	35	163.6	0.03	105	120.8	0.04
2004 Oct 28	59	50.5	0.02	0		
<b>sum</b>	4356	3283.6	1.12	1562	2451.4	1.05
<b>mean</b>		117.27	0.04		106.58	0.05

**Legend for Table 2**

**Number** of crater timing observations statistically accepted for analysis

**Mean f** is the estimated reciprocal oblateness of the umbra

**sd** is the standard deviation

**Table 3 – Image Analysis of the Umbra**

Using \*. PICT images captured by a MASS *QuickImage 24* Frame Grabber  
and measured size in degrees with *Image Analyst*

Date	Measured $F_i$					$F_2$	$S_c$	Comments
	Near 1C	Near 2 C	Mid	Near 3 C	Near 4 C			
1995 Apr 15	0.41	-	0.60	-	0.45	0.753	0.271	partial
1996 Apr 4	0.52	-	0.65	-		0.698	0.259	partial
2001 Jan 9	-	0.72	-	0.58	0.52	0.767	0.274	total
2003 May 16	0.27	0.63	-	-	-	0.774	0.273	total
2003 Nov 9	0.40	0.60		0.60	0.40	0.646	0.241	total
2004 May 4	0.46	0.54	0.45	0.56	-	0.763	0.272	Total, digital images
2004 Oct 28	0.45	0.55	-	0.35	0.50	0.679	0.252	total
mean	0.42	0.61	0.57	0.52	0.47	0.73	0.26	

**Legend for Table 3**

**Measured  $F_i$**  is the umbral semi-diameter measured with *Image Analyst*©

**Near 1C** is the measured value near the time of first contact, etc

**$F_2$**  is the constant value of the expected umbral semi-diameter

**$S_c$**  is the semi-diameter of the Moon, used to calibrate measured images