Size and shape of the umbra during a lunar eclipse

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Introduction

During a lunar eclipse, the Moon passes through the shadow of the Earth. The times of start and end of eclipse can be predicted geometrically, as can the times when the umbral shadow is expected to cross certain features on the Moon. In practice however it is found that the observed times deviate from the predicted times. The principal reason for these deviations, and others, is due to the fact that the Earth possesses an atmosphere. Variations also occur in the darkness, colour, size and shape of the umbra, which differ from eclipse to eclipse. In this paper we will describe the nature and measurement of the size and shape of the umbra, while a later paper will discuss darkness and colour. Results of the Total Lunar Eclipse Program to date are discussed, with particular reference to the two eclipses of 2003.

The Total Lunar Eclipse Program

In 1974 Byron Soulsby started the Total Lunar Eclipse Program as part of the activities of the Canberra Astronomical Society (Soulsby 1981, 1990). ASSA members started to contribute observations to this program in 1979, with results obtained during the total lunar eclipse of March 13 that year. Though serious lunar eclipse observations started earlier (see, for example, Cooper 1978), this was the first time that we had cooperated with the Australians. Since then observations have been made on several lunar eclipses, which have been reduced by Soulsby. New observers are encouraged to participate, and small telescopes are adequate to make these important observations to determine the size and flattening of the Earth's shadow, and to improve future lunar eclipse time predictions.

Predicted times of eclipse

During a lunar eclipse the Sun, Earth and Moon are aligned in space, such that the Earth's shadow is projected onto the Moon. The shadow consists of two cones formed by the interior and exterior tangents to the Sun and Earth, as shown in Figure 1. The interior cone represents the portion of the shadow where an observer on the Moon would see all of the Sun obscured. This is the umbral shadow, or umbra. The outer cone represents the portion of the shadow where an observer on the Moon would see the Sun partially eclipsed by the Earth. This is the penumbral shadow, or penumbra.

The path of the Moon through the Earth's shadow can be predicted quite accurately. These predictions result in a set of times called the circumstances of eclipse (Figure 2).

Since these predictions are made using rectangular coordinates, the contact times of the umbra with features on the Moon (craters, ridges, peaks, bright spots) can similarly be predicted. For these features, first and second contacts refer to the times of contact of the umbra with the leading and trailing edges of the feature. These are the immersion times of the features. Third and fourth contact refer to the two times as

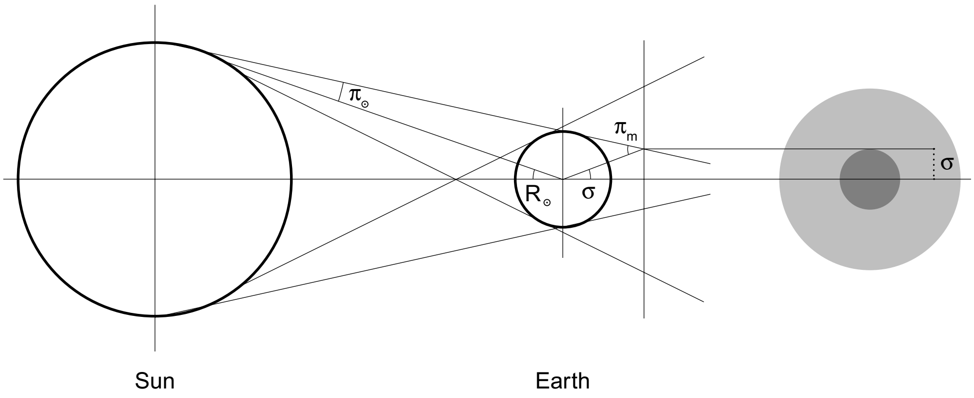

Figure 1. Earth's shadow during a lunar eclipse.

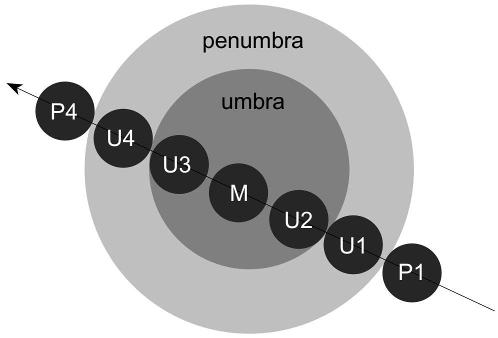

Figure 2. Circumstances of a lunar eclipse. P1 = first contact of Moon with edge of penumbral shadow; U1 = first contact with umbra, start of partial eclipse; U2 = second contact with umbra, start of total eclipse; M = time of mid eclipse; U3 = third contact with umbra, end of total eclipse; U4 = fourth contact with umbra, end of partial eclipse; P4 = fourth contact with penumbral shadow.

the umbra uncovers the features after mid eclipse. These times are the emersion times of the features.

Deviations of the umbra from prediction

It has long been known that the four contact times of the umbra with the Moon, and the immersion and emersion of features with the umbra do not occur at the exact predicted times. In the early 18th century the French astronomer Pierre Lahire (*Tabulae Astronomicae,* 1707) determined that the umbra was larger than predicted, and measured the extent of the enlargement as about 1/41 (2.4%). The enlargement was studied theoretically by Hepperger and Seeliger in the latter 1800s. In 1838 Maedler published a method to measure the enlargement of the umbra by observing the times of entry and exit of craters to and from the umbra, determining the radius of the umbra from the chords joining the two times. By averaging several craters the mean radius was compared to the predicted radius to give the percent enlargement. Nowadays a modified method is used where selenographic coordinates for lunar features are converted to rectangular coordinates. The formulae are complex and do not form part of this paper but may be visualised as follows.

Reference to Figure 1 shows that the predicted radius of the umbra, σ , is given by:

$$\sigma = \pi_{\odot} + \pi_{m} - R_{\odot} \quad (1)$$

while the observed radius of the umbra is shown in Figure 3 as σ_o. The percent enlargement of the umbra, S, is then derived from:

$$S = 100(\sigma_o - \sigma) / \sigma \quad (2)$$

The value of σ_o can be determined by observation of the four umbral contact times and the immersion and emersion times of craters to and from the umbra. The determination is made more accurate given large data sets, and as many observers as possible are encouraged to submit data.

In addition to the enlargement of the umbra, the actual shape of the umbra changes from eclipse to eclipse. In theory, the umbra is not spherical, but slightly flattened due to the fact that the Earth itself is flattened by a factor (f) of 1/298.3. This oblateness was discovered by Legentil in 1755 (Soulsby 1981). The predicted umbral oblateness is given by:

$$O_c = \frac{f^{-1}(\pi_{\odot} + \pi_m)}{(\pi_{\odot} + \pi_m + R_{\odot})} \quad (3)$$

Given sufficient crater timings made over a wide range of lunar latitudes, it is possible to construct the shape of the observed umbra. A best-fit curve through these points as shown in Figure 4 can then be used to derive the actual oblateness O_o of the umbra.

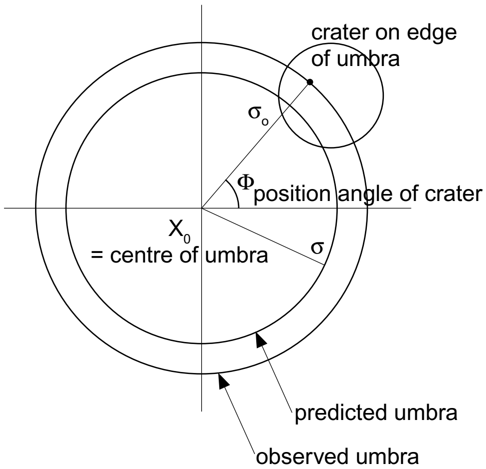

Figure 3. Measurement of umbral enlargement

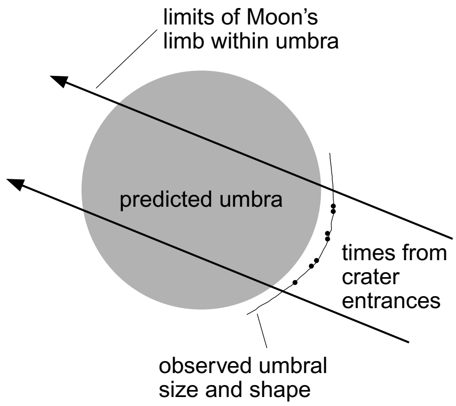

Figure 4. Determination of the shape of the umbra (diagram exaggerated for clarity)

Reasons for deviations in the umbra

Cassini (*Tables Astronomiques*, 1740) attributed the enlargement of the umbra to the effects of the Earth's atmosphere. In addition to the obscuration by the Earth's profile, sunlight is also modified by the atmosphere. The light path is both attenuated and refracted by the different layers in the atmosphere, with different wavelengths behaving differently. This fact accounts not only for the enlargement of the umbra but also the colour of the eclipsed Moon, with red predominant.

The atmosphere comprises five main layers:

1. Troposphere, extending to 10–15km, comprising most of Earth's weather. Light is attenuated by clouds, dusts and pollutants
2. Stratosphere, extending to around 50km. This layer contains aerosols from volcanoes, as well as some pollutants
3. Mesosphere, extends to 85km. Contains some aerosols and meteoric material.
4. Thermosphere, extends to 600km, and includes the layers at which most meteoric deflagration occurs.
5. Exosphere, outer layers merging with interplanetary space.

The effects of the lower three layers and partly the thermosphere cause an enlarged obscuration and refraction of the incident sunlight, and a concomitant enlargement of the umbra. At the same time it is noticed that since these layers are not solid, the edge of the umbral shadow is diffuse rather than sharp. Whether the diffusion of the umbral edge varies from eclipse to eclipse remains to be studied in detail.

It is likely that conditions in the troposphere, which extends a mere 0.24% of the Earth's radius, have a minimal effect on the variation, and that conditions in the stratosphere, mesosphere and lower thermosphere to 120km (1.88%) are more important. Link and Linkova (1954) have shown that higher umbral enlargements are demonstrated immediately following peaks from major meteor showers, when there is a larger concentration of meteoric dust in the upper atmosphere.

The enlargement of the umbra is probably related to the concentration of meteoric deflagration residues, volcanic aerosols, wavelength-specific absorbing molecules and the overall refractive index of the different atmospheric layers, and these conditions vary from eclipse to eclipse. Since these conditions are also not homogenous, it would explain why the shape of the umbra and its flattening deviate from that predicted. Lunar eclipse timings hence provide us with a unique method of measuring these effects.

Review of results of previous eclipses

Table 1 lists the lunar eclipses visible or partly visible from South Africa since 1978. Results of umbral enlargement derived from observations by Cooper are listed as well as global results analysed by Soulsby for each eclipse. These results include those of other ASSA members.

Table 1 indicates 22 lunar eclipses observable from South Africa since the start of the program. Reductions of ASSA data have been concluded for 9 of these eclipses, with a further 3 observed but not reduced. Of the remaining 10 eclipses, most were clouded out or the moon was too low for the portion of the eclipse visible. The September 1978 eclipse was missed due to the predicted event not being published in the ASSA *Handbook*.

The mean of the umbral enlargements for these 22 eclipses is 2.29% for the immersions and 2.10% for the emersions. The results of Cooper are generally in good agreement with the global measurements, with a mean error of 10%. This indicates partly the difficulty of estimating the exact edge of the umbra, and that the results could be improved if more observers contribute to the analysis.

Table 1. Results of lunar eclipse measurements 1978 – 2003

Date	Mag (a)	TM (b)	% umbral enlargement (%E) (c)	(d)	(e)	(f)	Notes
1978 03 24	1.46	18:23	(16)	—	2.76	2.00	
1978 09 16	1.33	21:04	—	—	2.63	1.61	Not observed
1979 03 13	0.86	23:08	1.78	—	2.64	—	
1981 07 17	0.55	06:47	1.88	—	2.11	—	
1982 01 09	1.34	21:56	—	—	2.05	2.14	Observed but no times
1985 05 04	1.24	21:57	1.96	2.04	2.11	1.96	
1985 10 28	1.08	19:43	—	2.06	2.19	2.18	Cloud during most of eclipse
1986 10 17	1.25	21:18	2.16	—	2.15	2.13	
1989 08 17	1.60	05:09	1.97	1.45	2.14	1.86	
1990 02 09	1.08	21:11	(4)	(20)	2.15	2.31	Entrances mainly cloudy
1992 06 15	0.69	06:57	—	—	2.25	1.95	Author ill
1992 12 10	1.27	01:44	—	—	2.30	2.41	Clouded out
1994 05 25	0.25	05:30	—	—	2.89	2.87	Clouded out
1996 04 04	1.38	02:10	—	—	2.24	2.29	Clouded out
1996 09 27	1.24	04:54	—	—	2.27	1.99	Cloud just after 1C
1997 03 24	0.92	06:39	—	—	2.25	2.01	Author in Austria. Cloud after first contact
1997 09 16	1.20	20:47	(30)	(3)	2.13	1.95	Emersions tape recorder failed
2000 07 16	1.77	15:56	—	—	1.96	2.10	Eclipse ended just after moonrise
2001 01 09	1.20	22:20	2.29	1.78	2.18	1.98	
2001 07 05	0.50	16:55	—	—	2.68	2.55	Too low
2003 05 16	1.13	05:40	2.28	—	2.16	1.85	Too low for emersions
2003 11 09	1.02	03:18	2.54	2.12	2.19	1.93	

(a) Magnitude of the eclipse. (b) Time of maximum eclipse, SAST. (c) Percentage umbral enlargement, %E, from immersion times, by Cooper. (d) %E from emersion times, by Cooper. (e) %E from immersion times, global analysis by Soulsby. (f) %E from emersion times, global analysis by Soulsby. Figures in brackets in columns 4 & 5 are number of timings made but not submitted for reduction.

Observation of future eclipses

It is important to continue the measurements started in the 1970s to provide an ongoing series of measurements which can be used to measure long-term trends, provide correlation to the different variables thought to cause deviations in the umbral shadow, and to improve lunar eclipse predictions. Table 2 lists the upcoming lunar eclipses visible

Table 2. Upcoming lunar eclipses

Date	Mag (a)	TM (b)
2004 May 04	1.31	22:31
2004 October 28	1.31	05:04
2006 September 07	0.19	20:52
2007 March 04	1.24	01:21
2008 February 21	1.11	05:26
2008 August 16	0.81	23:10
2009 December 31	0.08	21:23
2011 June 15	1.71	22:13

(a) Magnitude of the eclipse. (b) SAST of maximum eclipse.

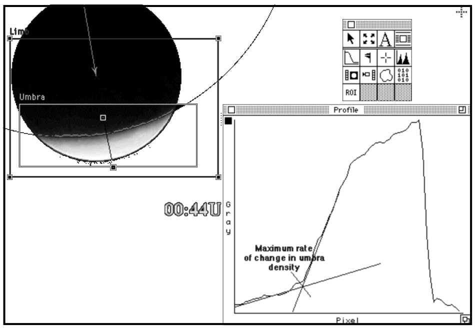

Figure 5. Analysis of the intensity of the umbra. The point of maximum rate of change in umbra density can be regarded as the 'edge' of the umbra. Graphic by Theodore Lunar Observatory.

from South Africa in the next decade. As many observers as possible are requested to make timings of the primary contacts and crater immersions and emersions, and to submit these for analysis.

These measurements can be made with a small telescope. The timing accuracy required is 0.1 minutes (6 sec). In addition to timing the primary contacts, the observer should select a number of features on the Moon which are easily identified and recognised, and time the moments when they enter or exit the umbra. The edge of the umbra is diffuse for reasons explained previously, and the observer should identify its edge as the point where the intensity gradient is at its maximum as shown in Figure 5. Observations are best made with a low power eyepiece. Time sources should be traceable to an acceptable standard.

Selenographic coordinates have been identified for around 7 500 lunar features. However, under the oblique lighting conditions of Full Moon, lists of certain features which stand out most prominently, and hence are easy to identify, should be consulted. Figure 6 (image by Mauritz Geyser) identifies features used most often by Cooper in the past. Figure 7 identifies 70 bright spot-like features based on the list of Antonin Rukl. Prospective observers are encouraged to use these features for timing purposes on upcoming eclipses.

Conclusion

ASSA members have contributed useful measurements in the past to the Lunar Eclipse Program. This paper summarises the results of umbral measurements, and requests a greater contribution for future eclipses.

Acknowledgements

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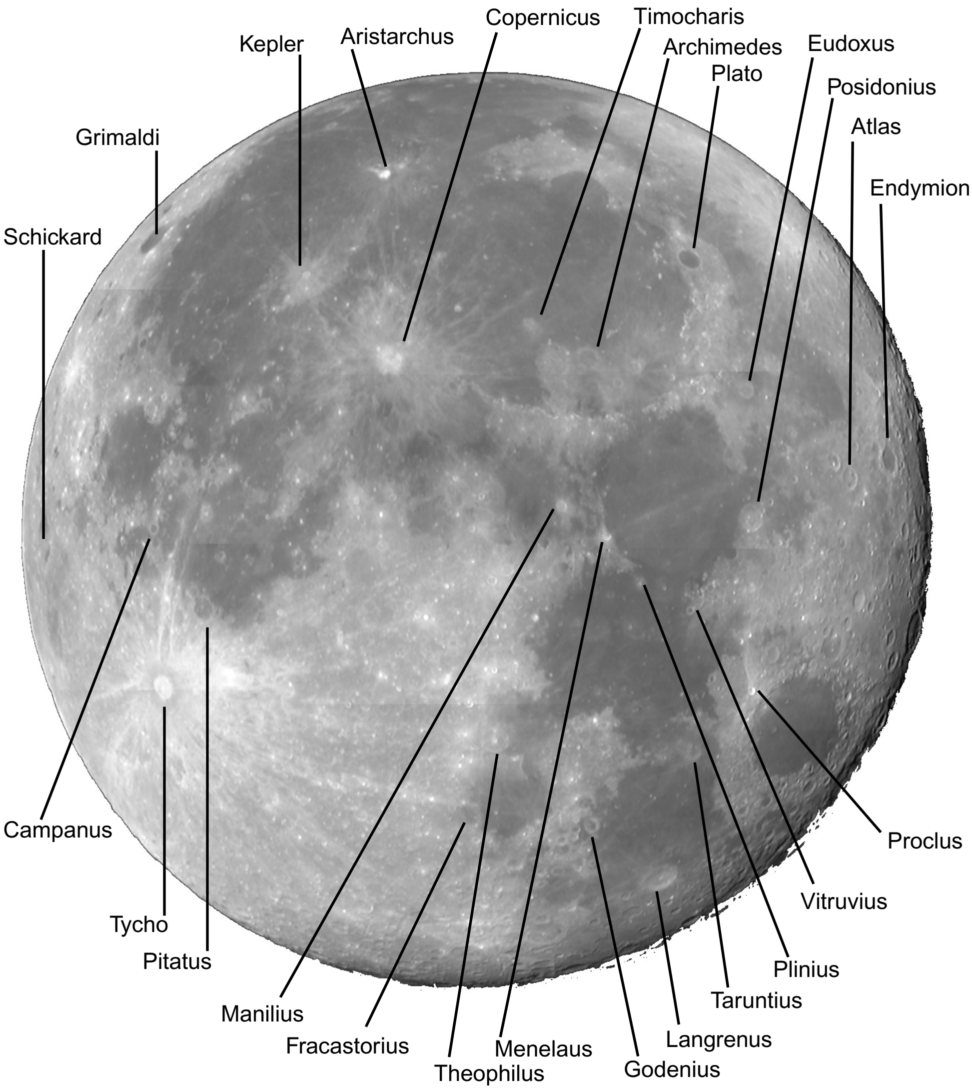

Figure 6. Prominent craters on the Full Moon. Lunar images by Mauritz Geyser.

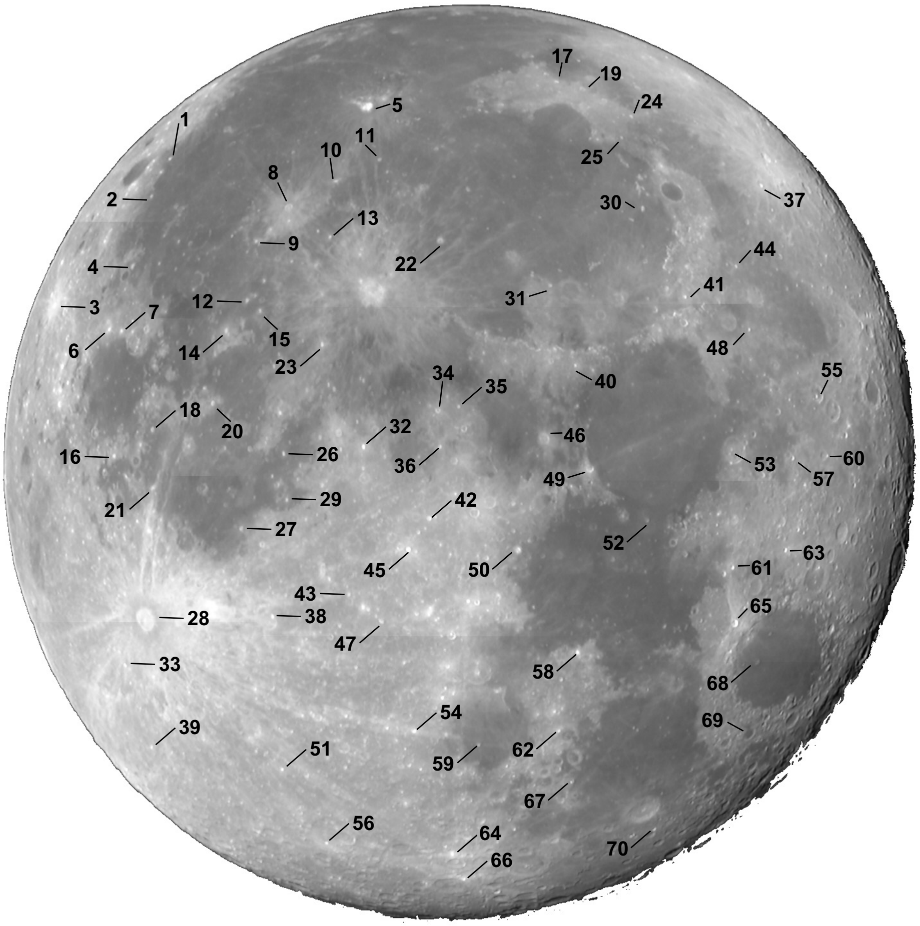

Figure 7. Bright spots on the Moon (from Antonin Rukl, 'Mondkarten für Finsternis und Bedeckungsbeobachter', Sternfreundeseminar, 1979)

1 Lohrmann A
2 Damoiseau E
3 Byrgius A
4 Billy
5 Aristarchus
6 Mersenius C
7 Gassendi alpha
8 Kepler
9 Encke B
10 Bessarion
11 Brayley
12 Lansberg D
13 Milichius
14 Euclides
15 Lansberg B
16 Dunthorne
17 Sharp A
18 Agatharchides A
19 Foucault
20 Darney
21 Kies A
22 Pytheas
23 Gambart A
24 La Condamine A
25 Maupertuis A
26 Guericke C
27 Birt
28 Tycho (c.peak)
29 Alpetragius B
30 Pico
31 Archimedes A
32 Mösting A
33 Maginus H
34 Bode
35 Bode A
36 Chladni
37 Epigenes A
38 Werner D
39 Zach delta (SE-Inner wall)
40 Aratus
41 Cassini C
42 Pickering
43 Airy A
44 Egede A
45 Hipparchus C
46 Manilius epsilon (central peak)
47 Abulfeda F
48 Eudoxus A
49 Menelaus
50 Dionysius
51 Nicolai A
52 Dawes
53 Posidonius A
54 Polybius A
55 Hercules G
56 Janssen K
57 Maury
58 Censorinus
59 Rosse
60 Cepheus A
61 Macrobius B
62 Gutenberg A
63 Tralles A
64 Stevinus A
65 Proclus
66 Furnerius A
67 Bellot
68 Picard
69 Firmicus
70 Langrenus M