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Solar Radius Determination Using Baily Beads Observations of Annular Solar Eclipse on 15 January 2010 in Sri Lanka

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ABSTRACT

An attempt was made to determine the solar radius by using the data of Baily's beads observations carried out at the southern limit of the annular solar eclipse of 15th January, 2010 in Sri Lanka. A positive correction of 0.26"±0.18" to the solar radius was found and the standard solar radius was determined as 959.89±0.18 arcsec. Moreover, no strong correlation was found between the monthly sunspot number of the last 45 years and the variation of the Sun's radius during the same period.

1. INTRODUCTION

The accurate determination of the solar radius is very important to understand the variations of solar irradiance, effective temperature and magnetic field, and thereby the effect made on the Earth and the near space environment. Among the several techniques used to estimate the solar radius, the eclipse observation has been the preferred way during the past three decades.

The English astronomer Francis Baily was first noticed the Baily beads during the annular solar eclipse on 15th May 1836. The surface of the moon is not smooth as seen from the ground but a surface full of mountains and valleys. When the moon's limb sweeps the solar photosphere the light disappears and appears according to the lunar terrain. These light features are identified as Baily beads [1]. The timing of the appearance and disappearance of the Baily beads can be used to estimate the solar radius variation from its standard value with accuracy up to 0.01 arc seconds. The accuracy of the estimation of solar radius depends on the timing of beads and lunar limb profile which causes the Baily beads. The limb profile used in Occult 4 software is updated from Kaguya lunar explorer data which is the most accurate lunar limb profile.

The annular solar eclipse visible to Sri Lanka on 15 January 2010 (Saros 141) was the longest annularity with duration of 11minutes 8 seconds at its greatest. It is going to be the longest annular eclipse visible to Sri Lanka until the annular eclipse on 23rd December 3043 [2]. The greatest eclipse occurred at the middle of the Indian ocean at 07:06:33.1 UT when the central axis of the moon's shadow passed closest to the center of the Earth ($\gamma = 0.4$) with a magnitude of 0.919 [3].

2. INSTRUMENTS AND OBSERVATIONS

The solar eclipse was observed by two teams of the Arthur C Clarke Institute. One was located closer to the centerline and the other was at the southern limit.

2.1 Centerline Station

The centerline group was located closer to the Jaffna city (400 km from the capital city, Colombo) at geographical coordinates of 9^o 39′ 43.92" N and 80^o 0′ 47.88" E which is 14 km away from the centerline. The team was equipped with Celestron 2800 mm f/10 Schmidt-Cassegrain telescope with a Nikon Coolpix digital camera, where the image was transmitted to 32’’ Panasonic LCD Screen.

2.2 Southern Limit Station

The southern station was close to the town, Chilaw (70 km away from Colombo), geographical coordinates of 7^o 40’6.81’’ N and 79^o 49’ 50’’ E and an altitude of 4 m, is located 4 km inside from the south limit of the eclipse. The team was equipped with Vixen 720 mm f/9 refractor and Mead ETX 1250 mm f/13.8 reflector piggybacked on 12 inch LX200 Schmidt-Cassegrain which can track the sun. The Mead ETX was used for live web cast and the Vixen refractor was coupled with a Sony Handy Cam with a data transfer rate of 1/30 sec. The filter was a Baader AstroSolar filter with natural density 5. The UTC timings and the location were set by the Furuno GPS module (±15 m horizontal error) and the video camera time was synchronized to GPS at the beginning of the observation and again checked for time differences at the end of the observation. This procedure had to be performed because of the unavailability of a GPS time inserter in the video camera.

Although most of the eclipse phases were recorded, the relevant phases of the eclipse for this study, the beads observation, were recorded from 7:49:37 UT to 7:51:49 UT providing 3960 video frames. Even though a heavy tripod was used, the strong winds at the observation site affected to the video frames making the analysis difficult.

3. DATA ANALYSIS

3.1 Time Correction of the Baily Beads

Accurate determination of the solar radius highly depends on the identification of the exact timings of the appearing/disappearing of beads. Since the video provides 30 frames per second, the frame of appearing/disappearing bead can be determined up to 0.03 seconds of resolution. Since GPS time inserter was unavailable, the video camera time had to be used by synchronizing with the Furuno GPS time. Before the beginning of solar eclipse the video time was synchronized with GPS and the GPS time was recorded through the video camera. Both these timings were displayed in the same screen to observe any differences of the timings, such as electronic delays. This procedure was carried out again after the recording the solar eclipse.

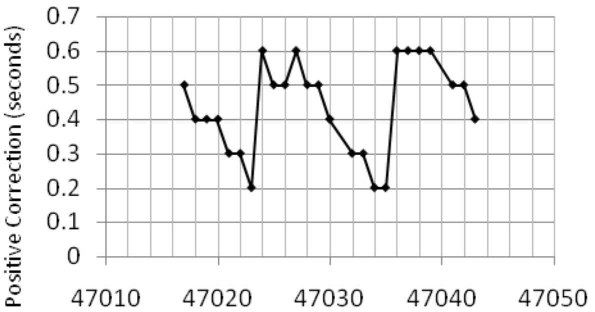

Fig. 1 Deviation of the video time from the GPS time for 40 seconds before the observation of the beads.

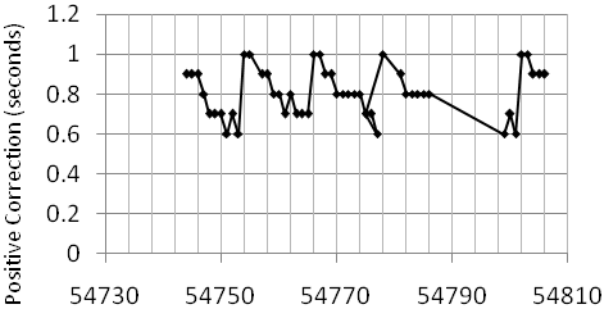

Fig. 2 Deviation of the video time from the GPS time for 80 seconds after the observation of the beads.

After careful analysis, two time anomalies were found in the video frames with the GPS time. The video time has a long term time delay as well as a short term time variation. The fig. 1 and 2 show the results of frame by frame analysis of the video time with the GPS time. The frame time is set in seconds by taking the initial point as midnight on 15th January 2010. A short term fluctuation of 0.4 seconds was observed in every 11 seconds (fig. 1). This may be due to some electronic delays in the video system. This anomaly continued in the frames recorded with the GPS after the solar eclipse (fig. 2). This variation occurred in 11 seconds which means 330 frames, giving an average value of positive error 0.001 per frame. Since it was able to determine the frame of appearing or disappearing within 5 frames of accuracy, the error due to this anomaly within five frames is 0.005, which is minute with the statistical error of the ΔR, 0.18 arcsec.

In the long term time anomaly, fig. 1 shows the minimum time delay with the GPS is 0.2 seconds which can be considered as the synchronizing error with the GPS at the beginning of the observation. After the observation it has increased up to a minimum value of 0.6 seconds (fig. 2) which means the video camera has an accumulated time delay of 0.4 seconds in 2.16 hours. The 3960 frames containing the Baily's beads was recorded within this time period and the correction was done by fitting a linear interpolation with frame timings and correction with the GPS. Hence a positive error of +0.25 seconds was applied for each bead in the appearing phase and a correction of +0.26 seconds applied for each bead in the disappearing phase.

3.2 Identification of the frames of appearing and disappearing beads

The Limovie (Ver.0.9.26) software was used to analyze the video frames one by one to find out the exact appearing/disappearing frame of the beads. There were 4 appearing and 4 disappearing beads identified in the video by matching with the simulated beads occurrence in the lunar terrain in Occult 4 software.

For a selected bead, frame by frame analysis was done for a suitable aperture which included the bead, and measures the intensity variation and plot against the frames (fig. 3). The distribution was approximated by fitting a polynomial or a spline function using MATLAB curve fitting tool. Subsequently, the variation of the first derivative (rate of change of intensity per frame) was obtained to see the sudden drops (for disappearing beads) or rises (for appearing beads) which can be considered as the disappearing or appearing frame of the bead (fig. 4). Furthermore the contour plots of the video frames in the vicinity of appearance/disappearance were obtained using MATLAB to ensure the appearing or disappearing frame determine by the intensity variation method.

In the counters, the intensity of the pixels is given in the z – axis with the gray scale range of 255 levels in two dimension frame and approximately one third of 255 is set as the cutoff to identify the appearing/disappearing frame. The frame determines by this method supports the frame determines by intensity variation method since the difference always lies within five frames. A combination of these two methods was taken to determine the exact frame of the appearing or disappearing bead.

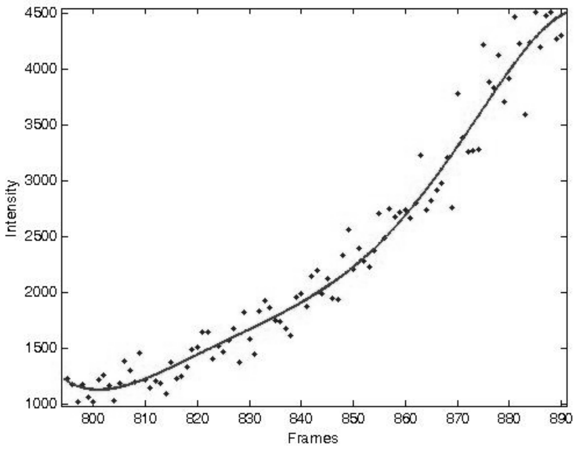

Fig. 3 Intensity of an appearing bead is plotted against the selected frames close to the appearances. A 5th degree polynomial is fitted with RMSE of 148.4

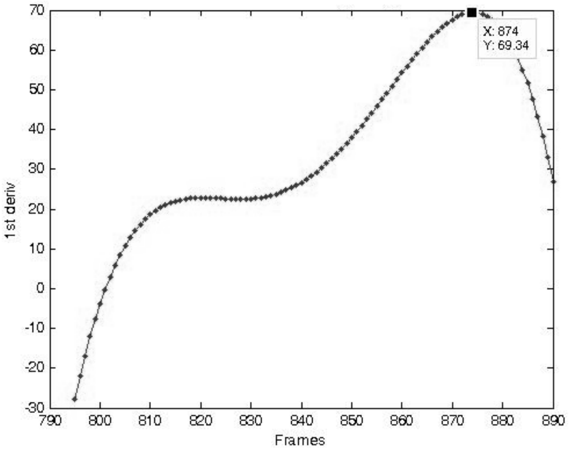

Fig. 4 The first derivative Vs frame is obtained to determine the frame of the appearance. The first derivative (The rate of change of intensity) is maximum at 874th frame which is considered

4. RESULTS

The standard angular solar radius at unit distance is 959.63 are seconds [4]. All eclipse data refer to this standard value to evaluate any radius changes. Initially the lunar valleys responsible for formation of Baily beads were identified using the bead simulation by Occult 4.0.8.6 package running with DE423/LE423 JPL ephemerides. The deviations of the moon's limb and sun's limb from the mean limb of the moon and the corresponding residual (Δh) for 8 beads were obtained as listed in the table 1. Both appearing and disappearing beads show a positive Δh which means the solar radius has to be bigger than the standard value (959.63 arcsec). The average of 8 beads yields the deviation of the solar radius $\Delta R = +0.26'' \pm 0.18''$.

Table 1. Baily bead events for 15 January 2010 annular solar eclipse. A – appearing beads, D – disappearing beads. The limb heights and Δh were taken from Occult 4.0.8.6 software. WA – Watts angle

Bead No	Video Frame No.	WA	Occult Time UT	Observed Time UT	Positive Error with GPS (sec.)	Corrected Time UT (h:m:s)	Moon Limb (″)	Solar Limb (″)	Δh = (M-S) (″)
A_1	347	310.3	07:49:47.4	07:49:45.87	0.25	07:49:46.12	-0.07	-0.14	0.07
A_2	484	332.3	07:49:54.4	07:49:50.67	0.25	07:49:50.92	-1.22	-1.41	0.19
A_3	654	319.0	07:49:57.3	07:49:56.07	0.25	07:49:56.32	-0.37	-0.90	0.53
A_4	874	317.7	07:50:06.3	07:50:03.07	0.25	07:50:03.32	-0.10	-0.26	0.16
D_1	3854	338.6	07:51:39.0	07:51:43.17	0.26	07:51:43.43	-0.54	-0.90	0.36
D_2	3747	342.8	07:51:37.0	07:51:39.47	0.26	07:51:39.73	-0.55	-1.03	0.48
D_3	3668	346.2	07:51:36.2	07:51:37.00	0.26	07:51:37.26	-0.72	-0.79	0.07
D_4	3835	347.6	07:51:40.6	07:51:42.53	0.26	07:51:42.79	-0.75	-1.00	0.25

5. DISCUSSION

From the analysis of the annular solar eclipse 15th January 2010, the determination of solar radius is 959.89±0.18 arcsec, with a positive correction of 0.26 aresec to the standard value of 959.63 arcsec [4]. This observation was done at the beginning of the solar cycle 24 which is predicted to be maximum in 2013. Due to the limitation of the facilities we were able to handle only one observation site at south limit causing lesser number of beads (just 8 beads) in the range of 37.3 degrees in the North Pole limb of the moon. Though it is not statistically enough for high accuracy correction, the positivity of the correction provides a better understanding on how the solar radius varies from it standard value especially with the beginning of the solar cycles 24.
The corrections were done due to the uneven time updating on the video frames in the camera system. The updating time on the video frame was progressively delayed and observed to be 0.25 to 0.26 seconds at the duration of Baily beads. Apart from this correction, there is another inconsistency of updating the time in the video frame within every 11 seconds. The variation is not systematic enough to interpolate for the frames of beads.

Correction to the ΔR was done using the range 310.3 to 347.6 degrees in the lunar limb just covering the 37.3 degrees in the solar North Pole which provides only 8 beads for analysis. The number of beads directly affected to the accuracy of the ΔR but in this observation it was limited by the facilities available. The sign of the ΔR is stressed rather than the value of it because of the lesser number of beads observation. A large value, ΔR = +0.26 was observed meaning the sun expanded at the time of observation, compared to the negative values observed during the last observations in 2002 and 2006 [4][5].

An attempt was made to find out a correlation with monthly sunspot number with the ΔR for the observation from 1965 to 2010. The fig. 5 shows the variation of monthly sunspot number from 1965 to October 2010 and the continuous line is the best fit for the data points indicating

Table 2. Solar radius deviation from the standard value of 959.63‘’ at different solar observations from 1715 to 2010. This is taken from A. Kilcik, C. Sigismondi *et al.* 2009. The last observation, 15th January 2010 is from our results.

Date	Eclipse type	Number of obs.	ΔR ["]
1966 May 20	Hybrid	20	– 0.22 ± 0.20
1970 Mar 7	Total	300	+0.11 ± 0.008
1973 June 30	Total	85	+0.21 ± 0.015
1976 Oct 25	Total	43	+0.04 ± 0.07
1979 Feb 26	Total	47	– 0.11 ± 0.05
1980 Feb 16	Total	232	– 0.03 ± 0.03
1980 Feb 16	Total	135	+ 0.21 ± 0.0012
1981 Feb 4	Annular	153	– 0.02 ± 0.03
1983 June 11	Total	201	+0.09 ± 0.02
1984 May 30	Hybrid	51	+0.29 ± 0.04
1984 May 30	Hybrid	51	+0.09 ± 0.04
1987 Sep 23	Annular	123	– 0.11 ± 0.03
1991 July 11	Total	59	+0.09 ± 0.10
1991 July 11	Total	300	+0.25 ± 0.008
1994 May 10	Annular	53	– 0.27 ± 0.02
1995 Oct 24	Total	92	+0.14 ± 0.03
1998 Feb 26	Total	76	+0.16 ± 0.05
1999 Aug 11	Total	58	– 0.06 ±0.06
2002 Dec 04	Total	58	– 0.21 ± 0.05
2006 Mar 29	Total	35	– 0.41 ± 0.04
2006 Sep 22	Annular	13	–0.06 ± 0.06
2010 Jan 15	Annular	8	+0.26 ±0.18

the 11 year solar cycle which can be used to predict the next solar maximum (solar cycle 24) in year 2013.

The result indicates there is no strong relation between the solar cycle and the ΔR except a tendency to inflate the solar radius with the peak of the solar activity during the periods of 1990 and 2000 which are the peaks of solar activity cycles 22 and 23 respectively. The present observation was done at the rising edge of the 24th solar cycle, giving a higher value of ΔR. The father observations should be carried out to investigate a firm correlation between ΔR and solar cycle.

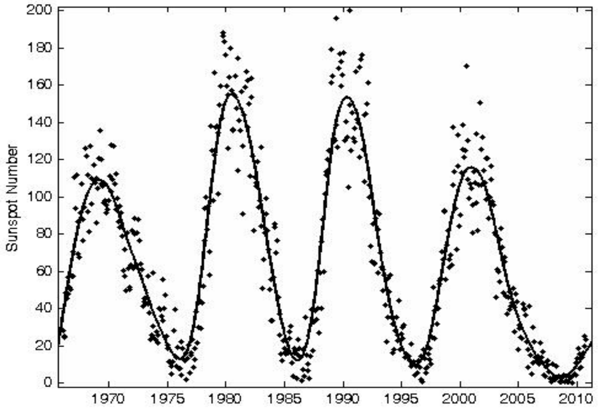

Fig. 5 Averaged monthly sunspot number (dots) variation during the period of 1965 to October 2010. The best fit is spline function with smoothing parameter 0.21 (continuous). The sunspot data is taken from Solar Influence Data Analysis Center.

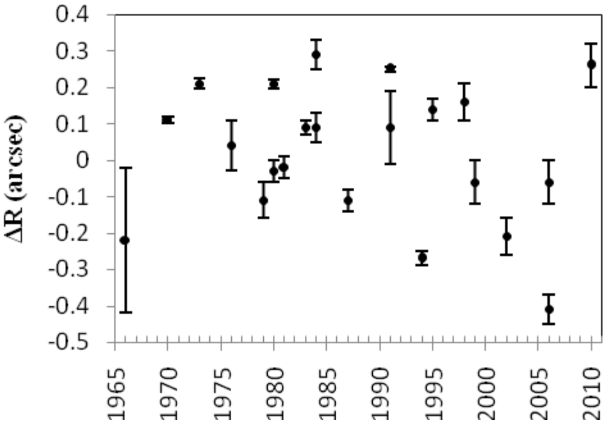

Fig. 6 Variation of the solar radius change in recent solar eclipses from 1965 to 2010. The data and corresponding error were taken from table 2. The last observation at 2010 is from this paper.

6. CONCLUSIONS

The solar radius was calculated by means of the annular solar eclipse viewed to Sri Lanka on 15th January 2010, and found to be 959.89±0.18 arcsec.

This is the first estimation in the beginning phase of 24th solar cycle and was import to determine that the sun expanded at the time of observation. There is no solid relationship between ΔR and number of sunspots except for some tendency for the sun to expand with the increase of sun's activity. Further observation should be made to increase the statistics of ΔR in order to investigate the correlations.

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