Bull. Astr. Soc. India (2013) **41**, 227–235

Transit of Venus on 2012 June 06: stray light estimation and restoration of Ca-K images of Twin Telescope from Kodaikanal Observatory

K. Prabhu[1], K. E. Rangarajan[1], B. Ravindra[1], K. Sankarasubramanian[2,1], R. Selvendran[3] and P. Kumaravel[3]

[1] *Indian Institute of Astrophysics, Bengaluru 560 034, India*
[2] *Space Astronomy Group, ISRO Satellite Centre, Bengaluru 560 034, India*
[3] *Indian Institute of Astrophysics, Kodaikanal, India*

Received 2013 March 01; accepted 2013 September 12

Abstract. Observations of the transit of Venus were made from the Kodaikanal Observatory on 2012 June 06 in Ca-K wavelengths. Only half of the event was visible from India. We utilized this unique opportunity to compute the contribution of the scattered light within the Twin Telescope optics at Kodaikanal. The instrumental and atmospheric scattered light are derived from the model point spread function which is a combination of four Gaussians with different widths and weights. The restoration procedure has significantly improved the rms contrast of the images. The rms contrast of the stray light corrected images are almost two fold larger than that those of the uncorrected images. The derived network element sizes matches well with previous observations.

Keywords : techniques: miscellaneous – atmospheric effects – telescopes – Solar system: general

1. Introduction

The large-sized solar telescopes can resolve the small-scale magnetic and convective features, yet the derived parameters of these features from the data can differ by an order of magnitude because of the stray light contamination in the data (e.g., (Louis et al. 2012)). The stray light is a combined effect of light scattering and image blurring. Both the effects can originate from the Earth's atmosphere as well as from the instrumentation aberrations. The final effect of the scattering is to broaden the point spread function (PSF) and reduce the contrast of the solar features in the image. The original intensity of the images can be obtained by deconvolving it with the known PSF of the instrument. The rare event such as the transit of inner planets across the solar disk can be used to compute the PSF of the instrument practically. Normally, we assume that the intensity of radiation coming from the night side (dark portion) of the planet is negligible compared to the solar intensity. If there is any detectable intensity in the image on the planet disk, that is due to the scattering of light originating from the Earth's atmosphere and the telescope. Using this information it is possible to compute quantitatively the scattering contribution to the contrast of the image.

In the past, several methods were used to remove the instrument and seeing induced degradations of the solar images (Brahde 1972; Hansen 1973; Albregtsen & Maltby 1981; Lawrence et al. 1985; Barducci et al. 1972; Martinez 1992; Walton & Preminger 1999; Criscuoli & Ermolli 2008; Deforest & Martens, & Wills-Davey 2009; Mathew, Zakharov & Solanki 2009) by taking advantage of astronomical events. The basic idea is to generate the model PSF and deconvolve it with the observations to retrieve the scatter free images.

The transit of Venus is a rare celestial event and in this paper we report the observations of this event from the Kodaikanal Observatory using the Twin Telescope (Singh & Ravindra 2012). We also used this event to quantify the scattered light in the Ca-K images during the transit of Venus which occurred on 2012 June 06. In Section 2, we briefly describe the telescope and observations of the transit of Venus. In Section 3, we elucidate the computation of model PSF of the system and image deconvolution. In Section 4, the results of our method on the enhancement in contrast are illustrated. The last Section ends with a discussion on the results.

2. Transit of Venus

Transit of Venus across the solar disk can occur during the months of either December or June in pairs, eight years apart. Again there will be long a gap of 105.5 or 121.5 years for the next transit to occur. In this century, the first Venus transit occurred on 2004 June 08. The transit of Venus which occurred on 2012 June 06 is the last one in this century. Unlike the transit of Venus that occurred during 2004, only half of the event was visible from India in 2012. In the past, the transit of Venus has been used to determine the solar parallax to find the Sun-Earth distance. But, in recent years the transit of Venus has been observed for understanding the black-drop effect (Ambastha, Ravindra & Gosain 2006; Pasachoff et al. 2004), co-aligning different telescopes (Wulser et al. 1998), determining the pixel resolution (Auchere & Artzner 2004). Apart from these, many researchers used it for removing the scatter light effect on the intensity of the images (e.g., (Maltby 1971; Mathew, Zakharov & Solanki 2009)).

3. Instrument and observations

On 2012 June 06, the transit of Venus event was observed from Kodaikanal observatory using the Twin Telescope. The specifications, optics and the design are described elaborately in Singh & Ravindra (2012). The transit was observed from 00:48 UT onwards, and during that time Venus

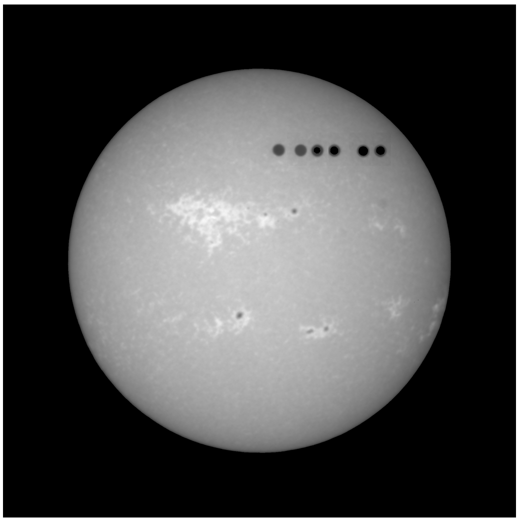

Figure 1. Composite of a number of selected images to show the transit path of Venus on 6^{th} June, 2012. Venus is seen as dark spots in the Northern portion of the Sun. In Ca-K images the white patches are the plage regions and dark patches are sunspots.

had crossed half of the solar disk. The month of June is normally the beginning of monsoon season at Kodaikanal, and there were passing clouds near the Sun during the entire transit period and whenever the cloud cleared up in small intervals of time, we could acquire a few good solar images during the transit. Fig. 1 shows the composite image of the Venus transit made using a number of available Ca-K images from the observations. Unlike the 2004 event, during 2012 Venus passed across the northern portion of the solar disk.

The obtained Ca-K data have been corrected for flat-fielding. The reduced solar image was arranged so that the disk center and the image center matches correctly and then the image was rotated in such a away that the solar north is in the upward direction. More details on the data reduction can be found in Singh & Ravindra (2012).

4. Model PSF and correction for stray light

In an ideal case the radiation coming from the night side of the planet disk should be zero. But, in our observations the intensity values of Venus disk is not zero. The intensity values on the Venus disk indicates the presence of stray light in the image. The normalised intensity profile obtained from the centre of the Venus disk is plotted in Fig. 2(a). Fig. shows that there is about 30% of stray light present in the images. The measured full width at half maximum of the profile is 55-arcsec which is a little smaller than the size of Venus during the transit across the solar disk.

In order to determine the contribution of stray light in the final image, radial profiles of

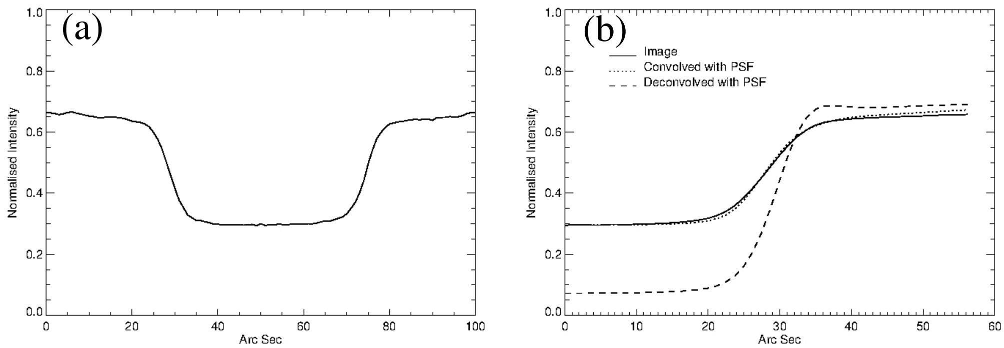

Figure 2. (a): The plot shows the normalized intensity values taken through the central disk of Venus, and clearly indicates the stray light contribution of about 30% due to the instrumental optical components and atmospheric seeing. (b): Plot shows the average radial profiles of observed image (continuous line), convolved with model PSF (dotted line), and deconvolved (dashed line) images.

intensity values are extracted at every 5° interval on the Venus disk. Then the average radial profile from 72 measurements is computed and plotted in Fig. 2(b) (continuous black line). The performance of an observing instrument can be quantified by the response of the system to a point source of light and is called the point spread function (PSF) of the image forming system. The operation of the image forming system is to perform a convolution of the object intensity distribution (O(x,y)) and the PSF ($\psi(x,y)$) of the image forming system (Goodman 1968) and is given by,

$$I(x,y) = \int_0^{\infty}\int_0^{\infty} \mathrm{O(x,y)}\psi(x,y)\mathrm{d}x\mathrm{d}y \tag{1}$$

where I(x,y) is the observed image.

Thus by deconvolving the PSF with I(x,y) we will obtain the true intensity distribution of the object in the image plane. This will be the case for space based observations, whereas if the telescope is ground based then PSF of the image forming system has the contribution from the Earth's atmosphere too. Hence, the PSF comprises of both the image forming system and the atmospheric seeing contributions. In order to examine the contribution from stray light in the image, the observed images are modified by making the intensity values of the Venus disk zero as will be the ideal case. This modified image is convolved with the combination of four Gaussians which we consider as the model PSF. Following Mathew, Zakharov & Solanki (2009), we generated two dimensional model PSF by summing the four Gaussians given by,

$$PSF = \sum_{i=1}^{4} W_i C_i exp(\frac{-(x+y)^2}{2b_i^2}) \tag{2}$$

where, b_i is the width of the Gaussian, W_i the weight of the i^{th} Gaussian, and C_i=1/2π $b_i{}^2$, the normalization constant. Table 1 lists the fitted values of weights and widths of four Gaussians

Table 1. Fitted parameters for the model PSF.

Gaussian	Width (arcsec)	Weight
1	1.3	2.0
2	2.0	5.0
3	4.0	7.0
4	45.0	14.5

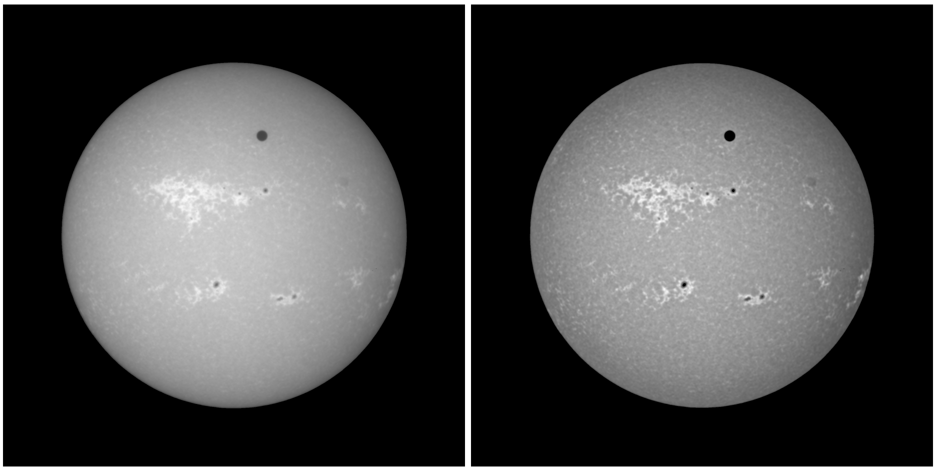

Figure 3. Sample images showing the normal flat fielded and co-aligned (left) and the restored (right) Ca-K images of Sun. The enhancement in the contrast is clearly visible in the restored image (right).

used as combination to get the model PSF. The profile obtained from the sum of two or more Gaussians with same weight and width will overlap on each other. But, for different width the generated Gaussian profiles are different. Then the added profile width becomes large and wings goes to zero fast. This is similar to the observed profile of Venus. Hence we used a linear combination of 4 Gaussians. In this combination, the first Gaussian represents the diffraction limited case of the telescope and the other three represent the scattered light contributions from the telescope and the Earth's atmosphere. We are assuming that the scattering by the atmosphere is a integrated one with all the contributions such as dust, air and water molecules. Since the signal integration time during the acquisition of the Ca-K images is more than the atmospheric correlation time (10–20 ms), one can assume that the atmospheric and instrumental distortions are uniform and radially symmetric over the focal plane of the telescope (Walton & Preminger 1999).

The modified Venus image (whose values are zero) is convolved with model PSF obtained by varying the widths and weights of the four Gaussians iteratively to match the intensity values of the convolved image with the observed image. The good match is taken as the best PSF and is shown in Fig. 2(b) as dotted line. Once the best matching PSF is obtained, then by deconvolving the model PSF with the observed images one can obtain the stray light corrected images. Table 1 lists the values of widths and weights of four Gaussians. The smallest width represents the diffraction limited resolution of the imaging system in arcsec. The dashed line in Fig. 2(b) represents the intensity profile of the Venus disk obtained after deconvolving the observed image with the best model PSF.

Fig. 3 shows the Ca-K images before (left) and after (right) stray light correction. Clearly, the enhancement in the contrast is seen in the stray light corrected image. The Maximum Likelihood method is used to deconvolve the observed images which is available freely in the IDL Astrolib library (Richardson 1972; Lane 2004). In the scattered light corrected profile, the size of the Venus disk is 57.5 arcsec which is close to the size of 58.6 arcsec for that particular day. It is about 5% larger than the original image.

5. Results

5.1 Contrast analysis

Fig. 4 shows the comparison of sunspot and plage regions in the enlarged portion of small field-of-view in Fig. 3. We applied a threshold method to identify the plage regions. The identified plage regions are shown by contours. The comparison of two images shows that in the contrast enhanced image the plage area reduces. However, there is an inclusion of other small areas into the plage regions. In order to quantify the enhancement in the contrast of the restored images we choose Ca-K data from 2012 May 25 to 2012 June 15 for the analysis. We extracted a 64×64 pixel sub-region at the center of the solar image and computed the rms contrast for the small region which is plotted in Fig. 5(a). The best fit model PSF of 2012 June 06 was used to remove the stray light of all the images in this period. The rms contrast of the stray light corrected (continuous line) image is 1.2 to 1.8 times larger than the observed images (dotted line). Thus the procedure improves the contrast of the Ca-K images significantly.

5.2 Size of the network

In the contrast enhanced images the boundaries of plages and small-scale structures can be clearly demarked. Now, it is interesting to see how the network cell areas can vary in the stray light corrected image compared to the original image. To do that we first interpolated 2k×2k pixel image to 1k×1k pixel image, so the resolution reduces to $2.5''$ pixel^{-1}. Then a 64×64 pixel sub-region at the disk centre is used to determine the network cell sizes and about 12 network cells can be accommodated in this area. We used the auto-correlation technique to find the network cell size and network element size of the selected small region. The result is plotted in Fig. 5(b). In Fig. 5(b) the dashed curve represents the auto-correlation of the observed image and the continuous line represents the same for stray light corrected image. In the plot the central peak

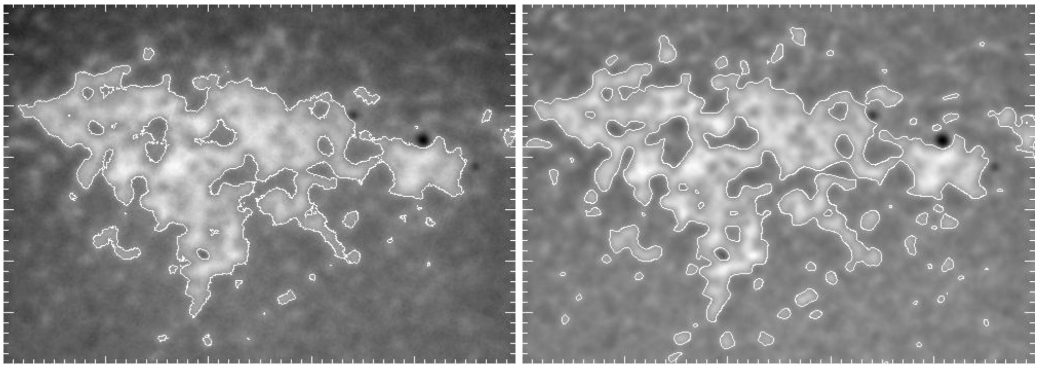

Figure 4. Sub-portions of 500×350 pixel image from Fig. 3 showing plages and sunspots of normal (left) and restored (right) images. Contour plots of same intensity values are overlaid on the images. The small-scale features have come up clearly in the restored images and it is contoured as well (right image).

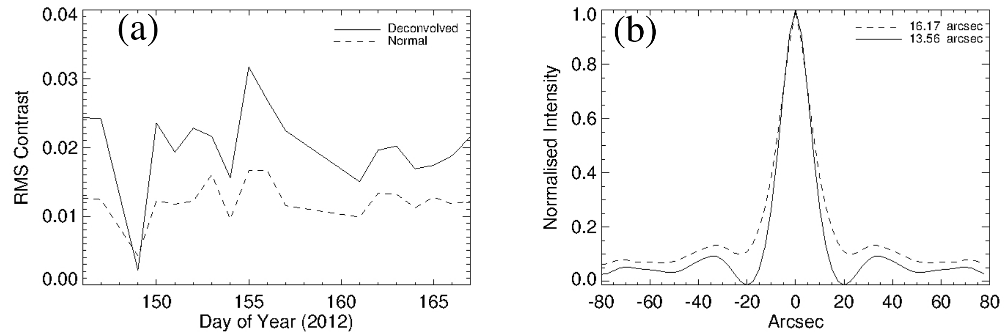

Figure 5. (a): The rms contrast computed at the center with 64×64 pixel sub-region of 1K×1K image. The dashed line shows the contrast of images with stray light and the solid line shows the contrast of the same region in the restored images. (b): The autocorrelation function of 64×64 sub-region of the 1K×1K solar image on the disk center. It is clear that the network element size (distance between the central maximum to the secondary maximum) is 33 arcsec for normal images (solid) and is 35 arcsec for restored images (dashed). FWHMs of the central peaks are indicated in the upper right corner of the figure.

has a highest correlation and later the correlation decreases with the distance. However, there is a repetition of the peak on both sides of the central peak. These small peaks indicate the repetition of the network cells in the image. The distance between the central peak and the peak of the secondary gives the size of the network cells and found to be 33 arcsec in the observed image and 35 arcsec in the stray light corrected image. In the stray light corrected image the boundaries of the network cells can be recognized with better contrast and hence the difference in the size of the network cells. By fitting a Gaussian we computed the FWHM of the profile. The FWHM indicates the size of the network elements which are the building blocks of the network cells. The obtained FWHM is 13.56 arcsec which is the average size of the network elements observed in the chromosphere (Ravindra & Venkatakrishnan 2003).

6. Summary and discussions

We report the observations of the transit of Venus from the Kodaikanal Observatory. The rare celestial event was utilized to compute the scattered light in the imaging system. We applied a linear combination of four Gaussians to obtain the best fit model PSF and subsequently restored the full-disk images of Ca-K which are affected by the scattered light due to the Earth's atmosphere and telescope. The last Venus transit of the century has been used to retrieve the PSF of the combined system. While the technique has been applied to the Ca-K images obtained from Twin Telescope at Kodaikanal, we see a large improvement in the image contrast. The network cells and the intra network boundaries can be identified clearly with the restored images. The plage region also exhibits a significant improvement in the contrast.

The chromospheric network cell sizes observed in Ca-K wavelength were studied by many researchers with different techniques (Hagenaar, Schrijver & Title 1973; Srikanth, Singh & Raju 2000; Berrili, Florio & Ermolli 1998; Berrili, Ermolli & Florio, Pietropaolo 1999). With the autocorrelation technique applied to the central portion of the image, we obtained network cell sizes of about 23.5 Mm for normal observation and 25.2 Mm for the restored images. These sizes closely compare with the commonly accepted chromospheric cell sizes. The network element size obtained from the corrected images is about 13.56 arcsec which is in good agreement with the study done by Ravindra & Venkatakrishnan (2003).

The image restoration techniques has important implications in the space-based instruments where the effects due to the Earth's atmospheric variation is absent and the stray light mainly originates from the instrument. The transit of inner planets provide a unique opportunity to compute the stray light contamination in the images. These events are very useful not only for space based observations, but also for the ground based observations of the Sun. Indian institute of Astrophysics is planning to put a 2-m class telescope for solar observations at high altitude place in Himalayas. The same procedure can be adopted to estimate and correct the stray light in the images obtained from this telescope (Hasan 2010) in the future.

References

Albregtsen F., Maltby P., 1981, Sol. Phys., 71, 269
Ambastha A., Ravindra B., Gosain S., 2006, Sol. Phys, 233, 171
Auchere F., Artzner G. E., 2004, Sol. Phys, 219, 217
Barducci A., Cavallini F., Ceppatelli G., Righini A., 1972, A&A, 240, 203
Berrili F., Florio A., Ermolli I., 1998, Sol. Phys., 180, 29
Berrili F., Ermolli I., Florio A., Pietropaolo E., 1999, A&A, 344, 965
Brahde R., 1972, Sol. Phys., 26, 318
Criscuoli S., Ermolli I., 2008, A&A, 484, 519

Deforest C. E., Martens P. C. H., Wills-Davey M. J., 2009, ApJ, 690, 1264
Goodman J. W., 1968, Introduction to Fourier Optics, McGraw-Hill, San Fransisco, California
Hagenaar H. J., Schrijver C. J., Title A. M, 1997, ApJ, 481, 988
Hansen T., 1973, Sol. Phys. 32, 505
Hasan S.S., 2010, in Andrei A., Kosovichev A., Rozelot J.-P., eds, IAU Symp. 264, Solar and Stellar Variability: Impact on Earth and Planets, Cambridge University Press, Cambridge, p. 499
Kosugi T., Matsuzaki K., Sakao T., et al., 2008, Sol. Phys., 243, 3
Lane R. G., 1996, 2004, J. Opt. Soc. Am., 13, 1992
Lawrence J. K., Chapman G. A., Herzog A. D., Shelton J. C., 1985, ApJ 292, 297
Louis R. E., Ravindra B., Mathew S. K., Bellot Rubio L. R., Raja Bayanna A., Venkatakrishnan P., 2012, ApJ, 755, 16
Maltby P., 1971, Sol. Phys., 18, 3
Martinez Pillet V., 1992, Sol. Phys. 140, 207
Mathew S. K., Martinez Pillet V., Solanki S. K., Krivova N. A., 2007, A&A, 465, 291
Mathew S. K., Zakharov V., Solanki S. K., 2009, A&A, 501, L19
Pasachoff J. M., Schneider G., Babcock B. A., Butts D. L., Gangestad J. W., Westbrook O. W., Cordova A. R., Gaydosh K., Seiradakis J. M., 2004, AAS DPS Meet., 36, 3901
Ravindra B., Venkatakrishnan P., 2003, Sol. Phys., 214, 267
Richardson W. H., 1972, J. Opt. Soc. Am., 62, 55
Scherrer P. H., et al., 1995, Sol. Phys., 162, 129
Schrijver C., Title A., Acton L., et al., 1996, BAAS, 28, 934
Singh J., Ravindra B., 2012, BASI, 40, 77
Srikanth R., Singh J., Raju K. P., 2000, ApJ, 534, 1008
Toner C. G., Jefferies S. M., Duvall T. L., 1997, ApJ, 478, 817
Walton S. R., Preminger, D. G., 1999, ApJ, 514, 959
Wulser J. P., Hudson H. S., Nishio M., Kosugi T., Masuda S., Morrison M., 1998, Sol. Phy, 180, 131