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On the transit of Venus 2012: Method of computation for prediction of contact timings

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सार – सौर मंडल में शुक्र का मंडल पार करना एक अत्यंत अनोखी घटना है। यह परिघटना पिछली बार 8 जून 2004 को देखी गई थी। जिसे भारत के सभी भागों से देखा गया था। शुक्र के मंडल पार करने की अगली घटना 6 जून 2012 को होगी, हालॉकि पूरी घटना को भारत से देखा नहीं जा सकेगा। खगोल विज्ञान केन्द्र अपने वार्षिक प्रकाशन 'भारतीय खगोलीय पंचांग' में बुध और शुक्र के मंडल पार करने के आँकड़ों को प्रकाशित करता है। इस शोध पत्र में घटना के संपर्क समयों के परिकलन हेतु प्रणाली विज्ञान पर प्रलेख उपलब्ध कराने का प्रयास किया गया है। प्रणाली विज्ञान का उपयोग करते हुए 6 जून 2012 को शुक्र के मंडल पार करने की घटना के लिए भारत के प्रमुख स्थानों के भूकेन्द्रीय संपर्क समयों और स्थानीय संपर्क समयों का पूर्वानुमान लगाया गया है। इस प्रकार घटना के विभिन्न भूकेन्द्रीय चरणों से प्राप्त हुए परिणामों की तुलना नौ पंचांग कार्यालय संयुक्त राज्य अमेरिका की नौ वेधशाला और नासा द्वारा प्रकाशित किए गए पूर्वानुमानित समयों के साथ की गई है।

ABSTRACT. Transit of Venus over the solar disc is an extremely rare event. The phenomenon occurred last time on June 8, 2004 when the entire event was visible from all parts of India. Another Transit of Venus is going to occur on June 6, 2012, though the entire event will not be visible from India. The Positional Astronomy Centre publishes data on Transit of Mercury and Venus in its annual publication 'The Indian Astronomical Ephemeris'. In this paper an attempt has been made to provide documentation on the methodology for computation of contact timings of the event. Using the methodology, the geocentric contact timings and local contact timings for important places of India for the event of Transit of Venus of June 6, 2012 have been predicted. The result thus obtained for different geocentric phases of the event has been compared with the predicted timings published by The Nautical Almanac Office, United States Naval Observatory and NASA.

Key words – Transit, Inferior conjunction, Ecliptic, Node, Geocentric contact, Local contact

1. Introduction

The transit or passage of an inferior planet (Mercury and Venus) across the disc of the Sun takes place when the inferior planet in question is at inferior conjunction with respect to the Sun *i.e*., the geocentric longitude of the planet is the same as that of the Sun. If the orbit of the inferior planet was in the same plane as the orbit of the Earth, a transit would occur at every inferior conjunction. However, the orbits of the inferior planets are inclined to the ecliptic. Thus, an alignment of the Sun, planet and the Earth can only takes place along the line of nodes, where the plane of the orbit of the planet crosses that of the Earth.

The transit of Mercury or Venus across the Sun is a rare occurrence. Though, on an average 13 transits of Mercury take place in a century, the transit of Venus is extremely rare as the same occur in pairs with more than a century separating each pair.

Until June 8, 2004, no living person could see a transit of Venus as the last one before 2004 had occurred in the year 1882. The entire event of June 8, 2004 was visible from most of the places in Europe, Africa and Asia, including India. India is fortunate to see another transit, the second of the pair on June 6, 2012, though entire event will not be visible from India. The entire event of 2012 will be visible from north-west Canada, Alaska, eastern and northern Asia, New Zealand and eastern Australia. The beginning of 2012 event will not be visible from any place in India as the event will be in progress before sunrise. However, from time of sunrise of the date upto the end of the event will be visible from all parts of India. Though the entire event will not be visible from India, the ensuing transit of 2012 will still produce

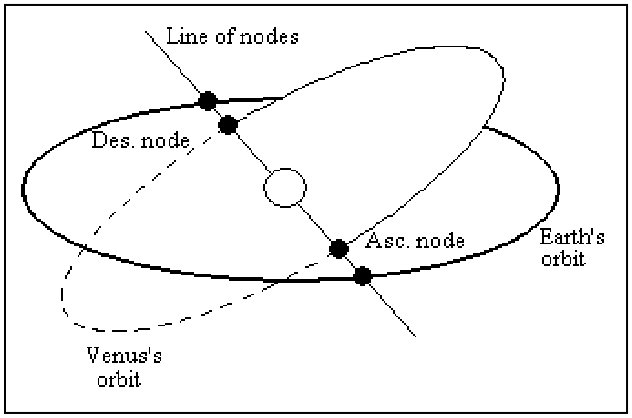

Fig. 1. Alignment of the Sun, Venus and Earth along the line of nodes

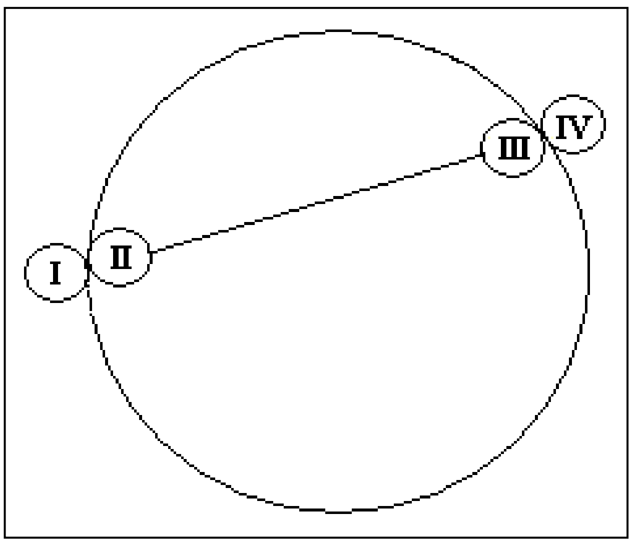

Fig. 2. Four contacts during passage of Venus over the Sun's disc

great interest to scientists, amateur astronomers and students for viewing and capturing the event.

Few experiments can be carried out from the event of Venus transit by amateurs and students like estimation of speed of Venus, measurement of diameter of Venus (Shylaja, 2004). Earth-Sun distance can also be measured using the event (through the distance to the Sun and planets can now be measured accurately using radar) (Rathnasree *et al*., 2004).

Scientist can track the changing of Solar Irradiance that takes place during a transit. This provides a great practice to test observing methods, strategies and techniques for the scientists to find planets outside our solar system *i.e*., extra solar planets by detecting the changing light from the host stars which helps in identifying a planet moving in front of the Star (G. Schneider *et al*., 2006).

For viewing and capturing the event and for all above purposes, the most important thing is to know the contact timings of the event. Due to parallax, the times of the contacts vary according to the observer's location. In this paper an attempt has been made to present the methodology for computation of the contact timings and following the methodology, the timings for geocentric contacts and local contact timings for different cities of India for June 6, 2012 event have been predicted. The same methodology is also applicable for computing contact timings for transit of Mercury.

Brief details of the methodology for computation of contact timings (geocentric and local) are described in section 2. This methodology has been adapted from the Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac (1961). In section 3, the details of input data used and computational methods are described. In section 4, the results on predicted geocentric contact timings and local contact timings for important stations in India for transit of Venus of June 6, 2012 have been shown. Concluding remarks are given in section 5.

2. Data and methodology

Transit of Venus across the Sun's disk should occur when both the Earth and Venus come simultaneously sufficiently close to the node of the Venus orbit (Fig. 1). The range is approximately $\pm\,\theta$:

$\theta = r_s\,(1/r-1/R)(1-T_e/T_p)$ cosec i, where R, r are the radii vectors and T_e, T_p are the actual daily motions of the Earth and planet respectively, i is the inclination of the planet's orbit and r_s is the Sun's semi-diameter in AU.

The approx. dates at which transits of Venus can occur, the corresponding value of θ and the frequency of occurrence over 100 years is as follows.

Node	*Date*	θ	*frequency*
Des.	7 June	41'	0.6
Asc.	9 Dec.	37'	0.6

The transits of Venus have occurred at intervals of 8, 121½, 8, 105½ and 8 years. The last one had occurred on Dec. 8, 1882 and after 121½ years on June 8, 2004 and the next one is going to occur after 8 years on June 6, 2012.

There are four different stages of this phenomenon. The initial stage is known as first external contact, *i.e.*, exterior ingress and is denoted by I. Then the planet moves across the Sun and in due course it reaches the second stage first internal contact *i.e.*, interior ingress and is denoted by II. From this point the planet advances

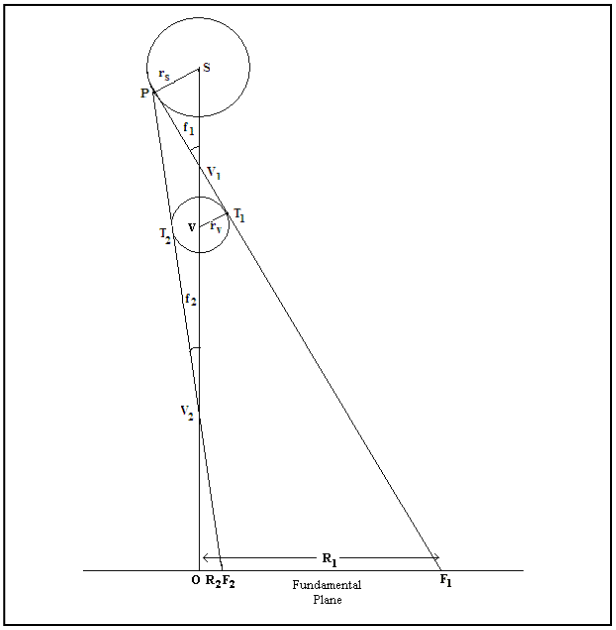

Fig. 3. Intersection of umbral and penumbral cones on fundamental plane

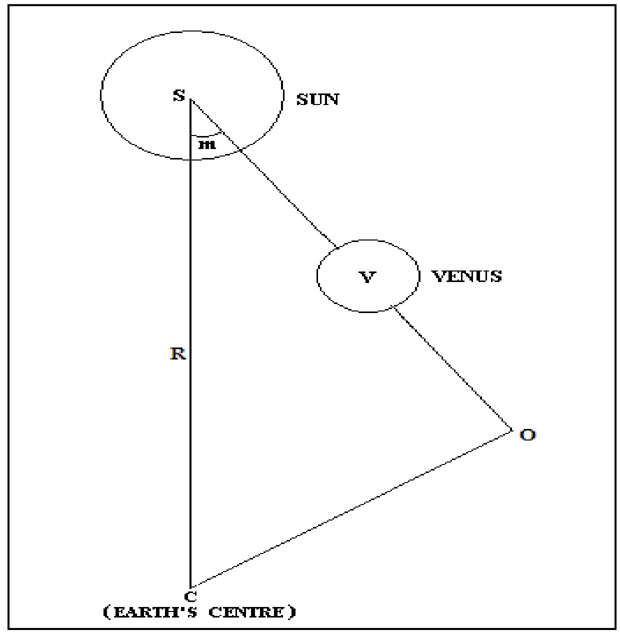

Fig. 4. Angular distance of the planet from the earth as seen from the Sun

across the Sun as a brilliant black disc and after the lapse of nearly six hours the planet reaches the third critical stage second internal contact, *i.e.*, interior egress and denoted by III. Finally the planet begins to pass off the Sun's disc and it arrives the stage IV known as exterior Egress. These four stages are shown diagrammatically in Fig. 2.

For computation of the phenomenon, the heliocentric method of Bessel's theory of Eclipse has been adapted. In this theory the *xy*-plane, which is perpendicular to the axis of the shadow and passes through the center of the Earth is considered as the fundamental plane. The interior and exterior common tangents to the Sun and Venus are involved for geometrical concepts for the prediction of the transit. Accordingly for the exterior contacts of the Ingress and Egress the interior tangents to the Sun and the planet generate a cone of penumbra, whose vertex lies in between the planet and the Sun. On the other hand, exterior tangents of the Sun and the planet generate a cone of umbra, whose vertex lies in between the planet and the Earth, which is used to calculate the interior contacts of Ingress and Egress of the Transit.

Let in Fig. 3, S, V be the centers of the Sun and Venus, r_s and r_v are the semi - diameter of them respectively. Then, the interior tangent PT_1 generates a cone of penumbra at vertex V_1 and the exterior tangent PT_2 generates a cone of umbra at vertex V_2. OF_1, OF_2 are the radii of the shadow projected on the fundamental plane. In Fig. 4, $\angle CSO = m$ be the angular distance of the planet from the Earth as seen from the center of the Sun. In Fig. 5, xy plane is the fundamental plane with *x*-axis parallel to the plane of the ecliptic, positive in the direction opposite to the motion of the of the Venus around the Sun; the *y*-axis is positive towards the north. *M* be the position angle, reckoned from the *y*-axis.

For computation of the geocentric and local contacts for transit of Venus the following parameters are required:

The heliocentric longitude (l_e), heliocentric latitude (b_e) and the radius vector (*R*) of the Earth.

The heliocentric longitude (l), heliocentric latitude (b) and radius vector (r) of Venus.

f_1, f_2 are the angles which are the generators of the penumbral and umbral cone.

R_1, R_2 are the radii of the penumbral and umbral shadow on the fundamental plane.

From Figs. 4 & 5, we have

$OC = R \sin m$ and $OS = R \cos m$

$x = R \sin m \sin M$

$y = R \sin m \cos M$

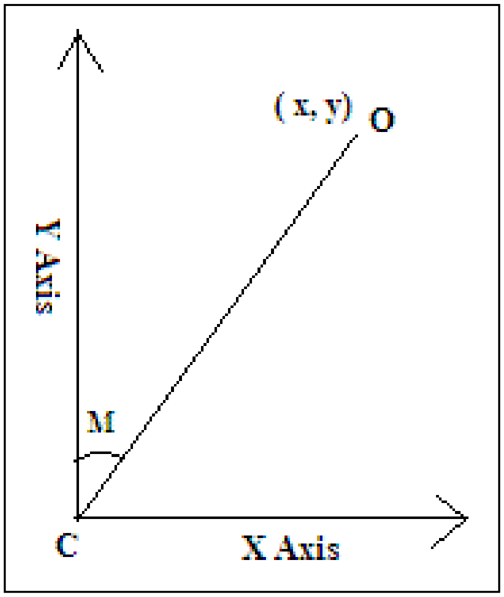

Fig. 5. Position angle, reckoned from *y*-axis, of the centre of the Earth with respect to the origin of coordinates

After transformation of co-ordinates of heliocentric system to fundamental plane co-ordinates we have

$$x = \mathrm{R}\cos be \sin(\mathrm{l}-\mathrm{l_e})$$

$$y = \mathrm{R}\,[\cos \mathrm{b} \sin \mathrm{b_e} - \sin \mathrm{b} \cos \mathrm{b_e} \cos(\mathrm{l}-\mathrm{l_e})]$$

Except the value of M all the angles of the above equations are small. The equation may be simplified as

$$\mathrm{m} \sin \mathrm{M} = \mathrm{l} - \mathrm{l_e} = v \qquad (1)$$

$$\mathrm{m} \cos \mathrm{M} = \mathrm{b_e} - \mathrm{b} = u \qquad (2)$$

From equations (1) and (2), we get

$$\mathrm{m}^2 = u^2 + v^2 \qquad (3)$$

If we denote prime for hourly variations,

$$v' = \mathrm{l}' - \mathrm{l}'_e = n \sin \mathrm{N} \qquad (4)$$

$$u' = \mathrm{b}'_e - \mathrm{b}' = n \cos \mathrm{N} \qquad (5)$$

$$\text{Thus, } n^2 = u'^2 + v'^2 \qquad (6)$$

From Fig. 3

$$\mathrm{f_1} = (\mathrm{r_s} + \mathrm{r_v}) / \mathrm{r} \text{ and } \mathrm{f_2} = (\mathrm{r_s} - \mathrm{r_v}) / \mathrm{r} \qquad (7)$$

$$\mathrm{OV_1} = \mathrm{OF_1} \cot \mathrm{f_1} = \mathrm{R_1} \cot \mathrm{f_1}$$

$$\mathrm{V_1S} = \mathrm{PS} \operatorname{cosec} \mathrm{f_1} = \mathrm{r_s} \operatorname{cosec} \mathrm{f_1}$$

Again OS = R cos m [From Fig. 4]

$\mathrm{OS} = \mathrm{OV_1} + \mathrm{V_1S}$ [From Fig. 3]

$$\mathrm{R} \cos \mathrm{m} = \mathrm{R_1} \cot \mathrm{f_1} + \mathrm{r_s} \operatorname{cosec} \mathrm{f_1}$$

$\mathrm{R} \cos \mathrm{m} \sin \mathrm{f_1} = \mathrm{R_1} \cos \mathrm{f_1} + \mathrm{r_s}$ [multiplying by $\sin \mathrm{f_1}$ on both sides]

$$\mathrm{R_1} = \mathrm{R} \cos \mathrm{m} \sec \mathrm{f_1} (\sin \mathrm{f_1} - \mathrm{r_s} / \mathrm{R} \cos \mathrm{m})$$

$\mathrm{R_1} = \mathrm{R} \cos \mathrm{m} \sec \mathrm{f_1} (\mathrm{f_1} - \mathrm{r_s} / \mathrm{R} \cos \mathrm{m})$ [for small value of $\mathrm{f_1}$]

Similarly the radius of the umbral shadow can be calculated as

$$\mathrm{R_2} = \mathrm{R} \cos \mathrm{m} \sec \mathrm{f_2} (\mathrm{f_2} - \mathrm{r_s} / \mathrm{R} \cos \mathrm{m})$$

If $\mathrm{L_1}$ and $\mathrm{L_2}$ are the penumbral and umbral shadow length in AU. Then

$$\mathrm{L_1} = \mathrm{R_1}/\mathrm{R} = \cos \mathrm{m} \sec \mathrm{f_1} (\mathrm{f_1} - \mathrm{r_s}/\mathrm{R} \cos \mathrm{m}) \qquad (8)$$

$$\mathrm{L_2} = \mathrm{R_2}/\mathrm{R} = \cos \mathrm{m} \sec \mathrm{f_2} (\mathrm{f_2} - \mathrm{r_s}/\mathrm{R} \cos \mathrm{m}) \qquad (9)$$

Geocentric contacts take place at the instants at which the distance R sin m = R m of the centre of the Earth from the origin is equal to $\mathrm{R_1}$ for exterior contacts or $\mathrm{R_2}$ for interior contacts, *i.e.*,

$\mathrm{R\,m} = \mathrm{R_1} \Rightarrow \mathrm{L_1} = \mathrm{R_1}/\mathrm{R} = \mathrm{m}$ for exterior contact [From equation (8)]

and $\mathrm{R\,m} = \mathrm{R_2} \Rightarrow \mathrm{L_2} = \mathrm{R_2}/\mathrm{R} = \mathrm{m}$ for interior contact [From equation (9)]

2.1. *Geocentric contacts of transit*

Let T_0 be the assumed time for the contacts of transit. Let actual time of contact occurs at $T = T_0 + t$. At time T_0, let u_o, v_o, u_o', v_o' be the corresponding values of u, v, u', v' at T.

$$u = u_o + u_o' t$$

$$v = v_o + v_o' t$$

The shadow length L, at time T becomes

$$u^2 + v^2 = \mathrm{L}^2$$

$$(u_o + u_o' t)^2 + (v_o + v_o' t)^2 = \mathrm{L}^2$$

After rearranging, the above equation becomes

$$(u_o'^2 + v_o'^2)\, t^2 + 2\,(u_o\, u_o' + v_o\, v_o')t + [(u_o^2 + v_o^2) - L^2] = 0$$

$$\text{or } n_o^2 t^2 + 2(u_o\, u_o' + v_o\, v_o')t + [(u_o^{\,2} + v_o^2) - L^2] = 0$$

where $n_o^2 = u_o'^2 + v_o'^2$

By solving the quadratic equation we have

$$t = -\frac{uu_0' + v_0 v_0'}{n_0^2} \pm \frac{L}{n_0}\sqrt{1 - \left(\frac{u_0 v_0' - v_0 u_0'}{n_0 L}\right)^2}$$

$$\text{Let, } \frac{u_0 v_0' - v_0 u_0'}{n_0 L} = \sin\varphi \qquad (10)$$

$$\cos\varphi = \pm\sqrt{1 - \left(\frac{u_0 v_0' - v_0 u_0'}{n_0 L}\right)^2} \qquad (11)$$

$$t = \frac{L}{n_0}\cos\varphi - \left(\frac{uu_0' + v_0 v_0'}{n_0^2}\right) \qquad (12)$$

where $\cos\varphi$ is taken as negative for ingress and positive for egress.

For L = m we have the time of contacts.

2.2. *Local contacts of transit*

At a point on the Earth surface there is some deviation of time of contacts in respect of time of geocentric contacts. Let t $(= T_1 - T_c)$ be the deviation of time. Where T_c is time of geocentric contact and T_1 be the time of local contact.

Let the quantities u, v, u', v', m, n, L at time T_c change to corresponding values u_1, v_1, u_1', v_1', m_1, n_1, L_1 at time T_1 . The relation may be written as

$$u_1 = u + q \qquad u_1' = u' + q' \qquad q' = dq / dt$$

$$v_1 = v + p \qquad v_1' = v' + p' \qquad p' = dp / dt$$

$$m_1^2 = u_1^2 + v_1^2 \qquad n_1^2 = u_1'^2 + v_1'^2 \qquad L_1 = L + \omega$$

If β, λ are the observer's latitude and longitude of the observer's geocentric zenith, ρ is the geocentric distance and π_s is the horizontal parallax of the Sun at the time considered as per Newcomb the relations become

$$q = \rho \sin \pi_s \,\sin \beta$$

$$p = \rho \sin \pi_s \cos \beta \sin (l_e - \lambda)$$

$$\omega = \rho \sin \pi_s \sin r_s \cos \beta \cos (l_e - \lambda)$$

If τ be the local side real time, ϕ' be observer's geocentric latitude and ε is the obliquity of the ecliptic. The relation between (β, λ) and (ϕ', τ) becomes

$$\cos \beta \cos \lambda = \cos \phi' \cos \tau$$

$$\cos \beta \sin \lambda = \sin \phi' \sin \varepsilon + \cos \phi' \cos \varepsilon \sin \tau$$

$$\sin \beta = \sin \phi' \cos \varepsilon - \cos \phi' \sin \varepsilon \sin \tau$$

by solving the above equations we have the values of q, q', p, p', ω by the following expressions

$$q = \pi_s (\rho \sin \phi' \cos \varepsilon - \rho \cos \phi' \sin \varepsilon \sin \tau)$$

$q' = -\tau' \pi_s \rho \cos \phi' \sin \varepsilon \cos \tau$ (τ' is hourly variation of sidereal time)

$$p = \pi_s \rho \cos \beta \sin (l_e - \lambda)$$

$$= \pi_s \rho\, (- \sin \phi' \sin \varepsilon \cos l_e - \cos \phi' \cos \varepsilon \cos l_e \sin \tau + \cos \phi' \sin l_e \cos \tau)$$

$$p' = \pi_s \rho\, (l_e' \sin \phi' \sin \varepsilon \sin l_e + l_e' \cos \phi' \cos \varepsilon \sin l_e \sin \tau - \tau' \cos \phi' \cos \varepsilon \cos l_e \cos \tau + l_e' \cos \phi' \cos l_e \cos \tau - \tau' \cos \phi' \sin l_e \sin \tau)$$

$$\omega = \pi_s \rho \sin r_s \cos \beta \cos (l_e - \lambda)$$

$$= \pi_s \rho \sin r_s\, (\sin \phi' \sin \varepsilon \sin l_e + \cos \phi' \cos \varepsilon \sin l_e \sin \tau + \cos \phi' \cos l_e \cos \tau)$$

We know that

$$v = l - l_e = m \sin M$$

$$u = b_e - b = m \cos M$$

$$v' = l' - l'_e = n \sin N$$

$$u' = b'_e - b' = n \cos N$$

$$uu' + vv' = mn\,(\cos M \cos N - \sin M \sin N)$$
$$= m\, n \cos (M - N)$$

TABLE 1

Input data on longitudes, latitudes and radius vectors of the Earth and Venus for different hours in Terrestrial Time (TT)

Day (June 2012) & hour in TT	l_e	b_e	R (AU)	l	b	r (AU)
$5^d\ 22^h$	920236".7	0	1.014722	919936".9	267".676	0.7260234
$5^d\ 23^h$	920380".2	0	1.014728	920175".1	235".4755	0.7260281
$6^d\ 4^h$	921097".7	0	1.014756	921365".6	182".876	0.7260518
$6^d\ 5^h$	921241".2	0	1.014762	921603".7	168".752	0.7260565

TABLE 2

Geocentric contact timings for Transit of Venus of June 6, 2012

	Computed value		USNO value	NASA value
	UT	IST	UT	UT
CONTACT –I (Ingress- Exterior Contact)	$5^d\ 22^h\ 9^m\ 39^s.9$	$6^d\ 3^h\ 39^m\ 39^s.9$	$5^d\ 22^h\ 9^m\ 41^s.8$	$5^d\ 22^h\ 10^m$
CONTACT-II (Ingress – Interior Contact)	$5^d\ 22^h\ 27^m\ 25^s.2$	$6^d\ 3^h\ 57^m\ 25^s.2$	$5^d\ 22^h\ 27^m\ 29^s.9$	$5^d\ 22^h\ 27^m$
CONTACT –III (Egress- Interior Contact)	$6^d\ 4^h\ 31^m\ 44^s.7$	$6^d\ 10^h\ 01^m\ 44^s.7$	$6^d\ 4^h\ 31^m\ 44^s.0$	$6^d\ 4^h\ 32^m$
CONTACT-IV (Egress – Exterior Contact)	$6^d\ 4^h\ 49^m\ 25^s.9$	$6^d\ 10^m\ 19^m\ 25^s.9$	$6^d\ 4^h\ 49^m\ 32^s.1$	$6^d\ 4^h\ 49^m$

Now for the local contact T_1, taking t as the correction time or the deviation time, components of umbral shadow length can be written as

$$L_1 \sin M_1 = L \sin M + p + v_1't$$

$$= L \sin M + p + (v' + p')t$$

$$= L \sin M + p + v't \qquad \text{[neglecting p't]}$$

$$= L \sin M + p + nt \sin N$$

Similarly,

$$L_1 \cos M_1 = L \cos M + q + nt \cos N$$

By solving the above two equations and omitting terms p^2, q^2, t^2, pt and qt

$$L_1^2 - L^2 = 2L\ [(p \sin M + q \cos M) + nt \cos (M - N)]$$

Putting the corresponding values of sin M, cos M, cos (M – N) in above equation

$$(L_1^2 - L^2)\ m = 2L\ [pv + qu + (uu' + vv')t]$$

$$(L_1 + L)\ (L_1 - L)m = 2L\ [pv + qu + (uu' + vv')t]$$

$$2L\ (L_1 - L)\ m = 2L\ [pv + qu + (uu' + vv')t]$$

[taking $L_1 \approx L$]

As before $(L_1 - L) = \omega$

$$t = \frac{m\omega - pv - qu}{uu' + vv'}$$

By putting the values of p, q and ω as calculated before, the value of t becomes

$$t = B\ \rho \sin \phi' + \rho \cos \phi'\ (C \sin \tau + D \cos \tau)$$

where

$$B = \frac{\pi_s}{uu' + vv'} (v \sin \varepsilon \cos l_e - u \cos \varepsilon + \mathrm{m} \sin r_s \sin \varepsilon \sin l_e) \quad (13)$$

$$C = \frac{\pi_s}{uu' + vv'} (v \cos \varepsilon \cos l_e - u \sin \varepsilon + \mathrm{m} \sin r_s \cos \varepsilon \sin l_e) \quad (14)$$

$$D = \frac{\pi_s}{uu' + vv'} (-v \sin l_e + \mathrm{m} \sin r_s \cos l_e) \quad (15)$$

Introducing the ephemeris sidereal time μ (= τ - λ) where λ is geographic longitude of the observer, the universal time of local contacts will be found from:

$$\text{U.T.} = \text{Tc} + \text{B}\,\rho \sin \phi' + \kappa\,\rho \cos \phi' \cos (\text{K}-\mu+\lambda) \quad (16)$$

Here $C = \kappa \sin K \qquad D = \kappa \cos K \quad (17)$

By using above formulae the predicted time of local contacts for four stages can be obtained.

3. Input data and computational methods

For computation of the contact timings, the standard values of the following parameters have been taken as input:

Semi diameter of the Sun (r_s) = 959.63″

Semi diameter of the Venus (r_v) = 8.40″

Obliquity of the ecliptic (ε) = 23°.436

Horizontal parallax of the Sun (π_s) = 8.666″

Knowing the date of occurrence of the event, the data pertaining to heliocentric longitudes, heliocentric latitudes and radius vectors of the Earth and Venus for certain hours of the day of event have been obtained by running the software used for generation of the same data for the Indian Astronomical Ephemeris. The hours have been chosen arbitrarily. The input data used for different hours have been shown in Table 1.

For computation of geocentric contact timings, the arbitrary initial time chosen is T_0 (here 22^h *TT* of June 5, 2012) and the data on heliocentric longitudes, heliocentric latitudes and radius vectors of the Earth and Venus for the chosen time for June 5, 2012 are obtained. Same data for another hour (here 23^h *TT* of June 5, 2012) are obtained for finding hourly variations of the parameters. Using equations (1) to (12), value of t is computed. Again we consider the chosen time $T_0 = T_0 + t$, the data on heliocentric longitudes, heliocentric latitudes and radius vectors of the Earth and Venus for the time $T_0 + t$ are computed by interpolation method (using hourly data for 22^h *TT* and 23^h *TT*). Using the same data in equations (1) to (12), the value of t is computed again. The process is repeated and iteration is continued until $|L - m| < 10^{-5}$ and finally value of t gives the time of contact in UT for geocentric contact. Now if we use L_1 value from equation (8), time of contact – I is computed by considering negative value of cos φ and time of contact – IV is computed by considering positive value of cos φ in equation (11). Similarly, time of contact – II and time of contact – III are computed by using the value of L_2 from equation (9) and considering cos φ in equation (11) positive and negative respectively.

For computation of local contact timings of different places, the timings computed for different phases of geocentric contacts have been used. The data on heliocentric longitude of the Earth for the corresponding timings are obtained from input data by interpolation method. Using the values of heliocentric longitude of the Earth, the semi diameter of the Sun, obliquity of the ecliptic and horizontal parallax of the Sun in equations (13), (14) and (15), values of B, C and D are calculated. K and κ are calculated using equation (17). The sidereal time (τ) has been obtained from the software used for generation of data in Indian Astronomical Ephemeris. Using the above values in equation (16), the following equations for local contact timings in UT for four different phases are derived.

Contact I :

$$UT_1 = 5^d\, 22^h\, 09^m\, 39^s.9 - 275^s.959965\ \rho \sin \phi' + 283^s.372936\ \rho \cos \phi' \cos (-218°.317802 - \lambda)$$

Contact II :

$$UT_2 = 5^d\, 22^h\, 27^m\, 25^s.2 - 295^s.337135\ \rho \sin \phi' + 282^s.124638\ \rho \cos \phi' \cos (-220°.689777 - \lambda)$$

Contact III :

$$UT_3 = 6^d\, 04^h\, 31^m\, 44^s.7 + 139^s.0176234\ \rho \sin \phi' + 379^s.811089\ \rho \cos \phi' \cos (-347°.258489 - \lambda)$$

TABLE 3

Local circumstances for transit of Venus of June 6, 2012 computed for some important places in India in IST

Stations	Ingress Exterior Contact (Contact-I)	Ingress Interior Contact (Contact-II)	Egress Interior Contact (Contact-III)	Egress Exterior Contact (Contact-IV)	Sun-rise time
	h m s	h m s	h m s	h m s	h m
Agartala	- - -	- - -	10 03 50	10 21 03	4 38
Ahmedabad	- - -	- - -	10 05 36	10 22 49	5 54
Aijwal	- - -	- - -	10 03 42	10 20 55	4 33
Allahabad	- - -	- - -	10 04 49	10 22 01	5 14
Amritsar	- - -	- - -	10 05 30	10 22 42	5 27
Bangalore	- - -	- - -	10 04 54	10 22 09	5 54
Bhopal	- - -	- - -	10 05 10	10 22 23	5 35
Bhubaneswar	- - -	- - -	10 04 18	10 21 31	5 08
Chandigarh	- - -	- - -	10 05 18	10 22 30	5 19
Chennai	- - -	- - -	10 04 38	10 21 53	5 43
Cochin	- - -	- - -	10 04 55	10 22 11	6 04
Cooch Behar	- - -	- - -	10 04 05	10 21 17	4 40
Darjeeling	- - -	- - -	10 04 13	10 21 25	4 42
Derhadun	- - -	- - -	10 05 12	10 22 24	5 16
Delhi	- - -	- - -	10 05 15	10 22 27	5 24
Dibrugarh	- - -	- - -	10 03 34	10 20 46	4 14
Gangtok	- - -	- - -	10 04 12	10 21 24	4 41
Guwahati	- - -	- - -	10 03 53	10 21 05	4 32
Gaya	- - -	- - -	10 04 30	10 21 42	5 03
Haridwar	- - -	- - -	10 05 11	10 22 23	5 16
Hyderabad	- - -	- - -	10 04 56	10 22 10	5 42
Imphal	- - -	- - -	10 03 37	10 20 50	4 27
Itanagar	- - -	- - -	10 03 43	10 20 55	4 22
Jaipur	- - -	- - -	10 05 22	10 22 35	5 35
Jammu	- - -	- - -	10 05 31	10 22 43	5 25
Kannyakumari	- - -	- - -	10 04 46	10 22 02	6 02
Kohima	- - -	- - -	10 03 36	10 20 48	4 22
Kolkata	- - -	- - -	10 04 05	10 21 18	4 52
Lucknow	- - -	- - -	10 04 55	10 22 07	5 14
Madurai	- - -	- - -	10 04 44	10 22 00	5 57
Mangalore	- - -	- - -	10 05 10	10 22 25	6 05
Mount Abu	- - -	- - -	10 05 36	10 22 49	5 51
Mumbai	- - -	- - -	10 05 30	10 22 44	6 03
Mysore	- - -	- - -	10 04 59	10 22 13	5 59
Nagpur	- - -	- - -	10 04 57	10 22 10	5 32

TABLE 3 (*Contd.*)

Stations	Ingress Exterior Contact (Contact-I)	Ingress Interior Contact (Contact-II)	Egress Interior Contact (Contact-III)	Egress Exterior Contact (Contact-IV)	Sun-rise time
	h m s	h m s	h m s	h m s	h m
Nashik	- - -	- - -	10 05 27	10 22 40	5 56
Panaji	- - -	- - -	10 05 22	10 22 37	6 03
Patna	- - -	- - -	10 04 28	10 21 41	4 59
Pondicherry	- - -	- - -	10 04 39	10 21 54	5 48
Pune	- - -	- - -	10 05 24	10 22 38	5 59
Port-Blair	- - -	- - -	10 03 18	10 20 33	4 56
Ranchi	- - -	- - -	10 04 24	10 21 37	5 03
Shillong	- - -	- - -	10 03 51	10 21 03	4 33
Shimla	- - -	- - -	10 05 17	10 22 29	5 18
Shilchar	- - -	- - -	10 03 44	10 20 56	4 31
Siliguri	- - -	- - -	10 04 12	10 21 24	4 44
Srinagar	- - -	- - -	10 05 31	10 22 43	5 21
Thiruvanantapuram	- - -	- - -	10 04 50	10 22 06	6 05
Udaipur	- - -	- - -	10 05 31	10 22 44	5 48
Ujjain	- - -	- - -	10 05 19	10 22 32	5 42
Vadodara	- - -	- - -	10 05 31	10 22 44	5 53
Varanasi	- - -	- - -	10 04 40	10 21 52	5 07

N.B. : "-- --" indicates the contact begins before the sun-rise time of the corresponding places

Contact IV :

$$UT_4 = 6^d\,04^h\,49^m\,25^s.9 + 120^s.405012\ \rho \sin\phi' + 373^s.492828\ \rho \cos\phi' \cos(-347°.258489 - \lambda)$$

Values of $\rho \sin\phi'$ and $\rho \cos\phi'$ are calculated separately. Putting the value of geographic longitude (λ) of the place, $\rho \sin\phi'$ and $\rho \cos\phi'$ in the above four equations, the four contact timings are calculated.

4. Results and discussion

The computed timings of different geocentric phases of the event of transit of Venus of June 6, 2012 is shown in Table 2. The timings of different geocentric phases of the event published in The Astronomical Phenomena for the year 2012 prepared jointly by The Nautical Almanac Office, United States Naval Observatory (USNO) and Her Majesty's Nautical Almanac Office, UK and the same timings shown in the Six Millennium Catalog of Venus Transit on NASA's official website (http://eclipse.gsfc.nasa.gov/transit/transit.html) are also given in Table 2. Contact timings of the event for some important places of India have been calculated and the same are shown in Table 3. For local contact, the timings of contact – I and contact – II for different places of India have not been shown in Table 3 as both the timings occur before sunrise time of respective places.

5. Conclusion

The above work has been undertaken recently with a view to compute the data indigenously on the forthcoming event of Transit of Venus for publication in the Indian Astronomical Ephemeris. It is found that the output obtained for different geocentric phases of the event by the methodology described above matches well with the data published by the USNO and NASA. Only very small variations in time second are found in the computed data when compared with the USNO value.

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