The Scale of the Solar System: Re-enacting the Transit of Venus Observations 5 - 6 June 2012

Craig ROBERTS, Australia and Matthew COOPER, Australia

Key words: Transit of Venus, timing, history, re-enactment

SUMMARY

The sighting of Australia by Captain Cook in 1770 was preceded by one of the most important scientific expeditions of the time; to measure the distance between the Earth and the Sun (an astronomical unit - AU) and so compute the scale of the solar system. This was achieved by measuring the time taken for Venus to transit across the face of the Sun for different locations on Earth and uses the parallax effect to compute 1 AU. The Transit of Venus is an astronomical event that occurs in a cyclic manner repeating every 243 years. Transits occur in pairs separated by eight years with large gaps either side of 112.5 years and 105.5 years which repeat sequentially. The last Transit of Venus occurred on 8 June 2004 and the next will occur on 5-6 June 2012.

A brief historical account of previous measuring campaigns which have occurred in 1761, 1769, 1874 and 1882 will be discussed. Surveyors have traditionally been involved in these measuring campaigns however nowadays modern techniques such as space-probe to planet radar distance measurements are used to compute the Earth- Sun separation.

An overview of the mathematics used to compute the Earth-Sun scale from time measurements of the transit will be presented. The accuracy of timing is a major determinant in the resultant distance measurement. A new method using video linked to a centralized timing system will be presented and it is hoped this will improve the quality of timing to a fraction of a second. Some information about the 2012 transit will be given and FIG delegates from those countries from which the next transit will be visible will be invited to participate in a re-enactment measuring campaign of the Transit of Venus on 5-6 June 2012.

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1. INTRODUCTION

On the 5 - 6th of June 2012, Venus will pass in front of the Sun in an event known as the transit of Venus. During the event, Venus will appear as a tiny dot on the face of the Sun (ingress), slowly moving across it before finally exiting from the face of the Sun (egress) about 6 hours later.

The transit of Venus is historically important as a method of determining the scale of the solar system. Transit observations allow the distance from Earth to Sun to be calculated – the fundamental unit for determining distances within the solar system. This distance is the Astronomical Unit, or AU. Throughout the 18th century many scientists travelled the globe to take observations of the transits of Venus, perhaps most notably explorer James Cook in 1769 who observed the transit in Tahiti, before discovering Australia and New Zealand.

Although there are far better ways to accurately derive the Astronomical Unit today, such as radar measurements to nearby planets (Sheehan & Westfall, 2004), the transit of Venus is a very rare event and presents a great opportunity to re-enact these original observations and use this as an opportunity to promote the surveying profession to the wider community.

Additionally with modern equipment and processing methods it is anticipated that a more accurate estimate of the Astronomical Unit would result. Digital image and video capture technology is now available, and integration with optical viewing devices such as telescopes and theodolites / total stations could provide a means of accurately timing stages of the transit of Venus, leading to a better quality observation, lasting evidence of the event and a better estimate of the Astronomical Unit.

The transit will not be visible in all parts of the Earth in 2012. Only a select few countries will experience the entire duration of the transit. For an observer in Sydney, ingress will begin at 8:16 AM local time on the 6th of June, with the transit lasting 6 hours 44 minutes and ending at 2:44PM local time (van Roode, 2009). Therefore to avoid the possibility of cloudy weather precluding observations, this paper hopes to attract FIG member organisations or institutions to simultaneously observe the transit from the locations around the world shaded white in Figure 1.

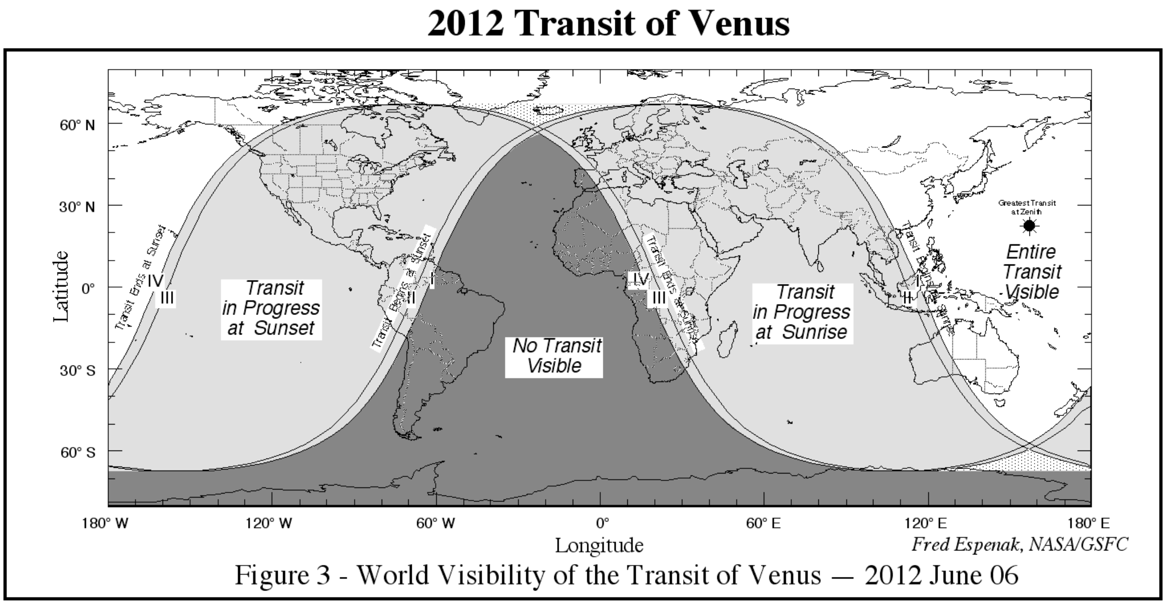


Figure 1 - Visibility of transit (NASA, 2009a)

This paper will seek to explain the transit of Venus and set out the basic computations and geometry for deriving a measure of the Astronomical Unit from timing measurements and make a call for partners in preparation for the event in June 2012.

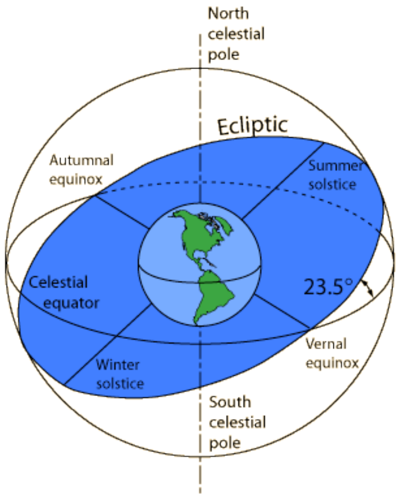
2. THE TRANSIT OF VENUS

2.1 The transit of Venus explained

The Earth orbits around the Sun in an ellipse, with the Sun at one of its foci. The orbit of the Earth forms a plane, with the Sun lying in the middle, known as the Earth's orbital plane. The ecliptic is the apparent path the Sun takes around the Earth in a year, relative to an observer on Earth. The ecliptic is not parallel to the direction of Earth's rotation (equator), but it is inclined by 23.5°, which is the cause of seasons. Figure 2 shows the ecliptic.

The ecliptic plane is the same as the Earth's orbital plane, and is used as a reference plane to compare the orbits of other planets.

Venus' orbit is inclined (by 3.39°) relative to the ecliptic, resulting in it crossing Earth's ecliptic twice in each complete orbit around the Sun. The two points it crosses are known as the ascending node (Venus moves up) and the descending node (Venus moves back down). These are insignificant events, except when Earth is aligned with one of the nodes and the Sun, at the same moment as Venus. When this happens Venus passes between Earth and the Sun, resulting in a planetary eclipse of the Sun. This event is known as the transit of Venus.



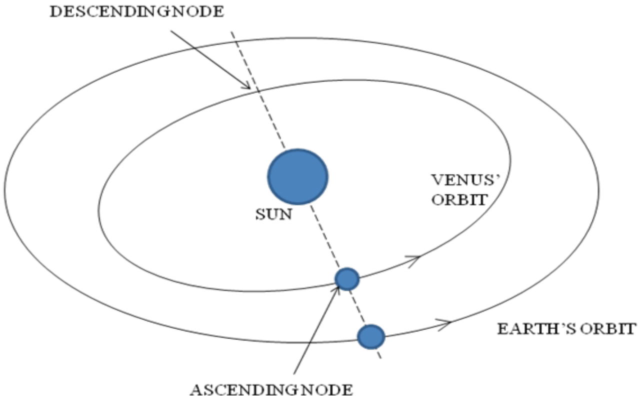


Figure 2 (left) – The Ecliptic (Hyperphysics, 2006), & Figure 3 (right) – Ascending and descending nodes of Venus' orbit relative to Earth's orbit

2.2 History of the Transit of Venus

Transits of Venus were first predicted by Johannes Kepler in the early 17th century, as a result of his revolutionary work on determining the elliptical orbits of the planets about the Sun. The first transit of Venus to be scientifically observed was the transit of 1639, which Jeremiah Horrocks predicted after refining Kepler's work in planetary orbits (Sheehan & Westfall, 2004). Horrocks observed this transit using a telescope to project the image of the Sun onto a piece of paper, outlining the image of the Sun and marking the position of Venus at intervals. He and accomplice William Crabtree were the only people in the world to observe this transit (Ibid, 2004). He made an estimation of the Astronomical Unit from this, but his estimation was based on assumptions on the size of Venus (Ibid, 2004).

Early in the 18th century, Edmund Halley proposed a method of calculating the distance from Earth to Sun using transits of Mercury or Venus. His method was to observe a parallax shift of the Sun between two locations on Earth. Halley's method required the duration of a transit be recorded from the moment Venus enters onto the Sun's disk to the moment it leaves. Such observations were to take place at two locations where the entire transit would be visible, separated by as large a distance as possible to obtain maximum parallax.

Later, Joseph-Nicolas Delisle proposed a variation on this method that didn't require the entire duration of the transit to be timed. Delisle's version required only ingress (entry) or egress (exit) of Venus to be observed at a pair of stations, and recording the absolute time (in Greenwich or Paris time) of the event at each station (Sheehan & Westfall, 2004).

The transits of 1761 and 1769 were observed by many people, in different locations around the world. The 1769 transit is the one observed notably by Captain James Cook in Tahiti (assisted by astronomer Charles Green), which was successfully performed before they proceeded on to discover Australia and New Zealand (Howse, 1990). They used Delisle's method to observe the transit to calculate the AU (Sheehan & Westfall, 2004). Accurate time had to be determined of ingress or egress, plus latitude and longitude of the observing location. A Shelton astronomical regulator clock was used to determine time of the event, and this clock had to be checked daily against local noon (Howse, 1990). Latitude was determined by observing the Sun and stars with the quadrant, while longitude was determined by observing lunar distances with a Hadley sextant.

Cook and Green both noticed a "halo" around the edge of Venus as it made its way onto the Sun. This they called the penumbra, and the result of it was that they both missed the exact timing of the first contact of Venus with the Sun. For the second contact, however, they agreed exactly on its timing. They differed by 6 seconds for the time of the 3rd contact, while the fourth contact was difficult to time (because of the penumbra), with no time recorded in Cook's notes. Cook and Green were reportedly disappointed with their results, having undertaken the project with high expectations of accuracy. However, the results have since proven to be much better than they believed, according to Lomb (2004).

The 1874 transit was observed in Australia in various locations around NSW to overcome cloudy conditions or missed observations. However by 1882, transit observations were no longer used to calculate the Earth-Sun distance, since alternative methods had been discovered to calculate the Astronomical Unit (Sheehan & Westfall, 2004).

Table 1 shows the transits of Venus that have occurred since 1631, and those that will occur in the next century.

Date of transit	Ascending (A) or Descending (D) node	Duration since last transit (years and months)
6 December 1631	A	
4 December 1639	A	8 yrs
6 June 1761	D	121 yrs 6 months
3 June 1769	D	8 yrs
9 December 1874	A	105 yrs 6 months
6 December 1882	A	8 yrs
8 June 2004	D	121 yrs 6 months
5 June 2012	D	8 yrs
11 December 2117	A	105 yrs 6 months
8 December 2125	A	8 yrs

Table 1 – List of transits and their intervals (Sellars, 2001)

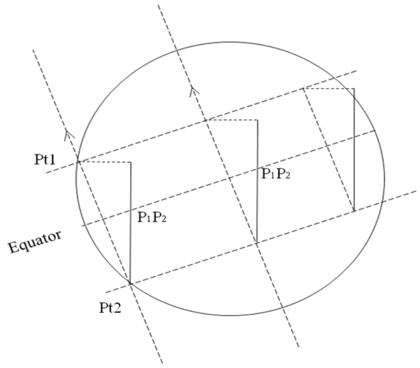
This table shows a regular pattern (122.5 yrs – 8 yrs – 105.5 yrs – 8 yrs – 122.5 yrs……), with transits occurring in 8 year pairs, with the transits in each pair occurring upon either an ascending or descending node in Venus' orbit.

3. HALLEY'S METHOD TO DERIVE THE ASTRONOMICAL UNIT

Stern (2004) presents a simplified methodology to calculate the AU using basic geometry based on sample data from the 2004 transit. The last transit occurred on the 8th of June 2004, close to the solstice. The "observations" in this calculation are predicted observations only for that transit.

Observing locations:	Lat	Long
Cairo (1)	30° N	32° E
Durban (2)	30° S	31° E

The locations were chosen because they share (approximately) the same longitude, which means that each appears to rotate around the Earth at a similar velocity relative to Venus. Equal and opposite latitudes were chosen so that the distance between the two points, perpendicular to the plane of the ecliptic, remains at all times of the day (Figure 4).



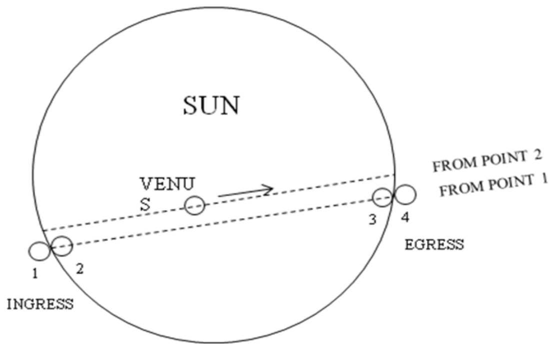


Figure 4 (left) – Distance between points 1 and 2 on the Earth with respect to the plane of the ecliptic & Figure 5 (right) – The path of the transit across the face of the Sun.

Observing the transit of Venus requires recording the times when Venus contacts the Sun. There are 4 contacts: numbered 1 to 4, the first called external ingress (Venus touches the outside of the Sun's disk), the second internal ingress (Venus now fully within the Sun's disk), the third internal egress (Venus touches inside of Sun's disk on the way out), and the fourth external egress (Venus touches outside of Sun's disk on way out) (Figure 5).

The length of time between these two contacts forms the basis of the calculations. This time is represented by an L value for each location. In this case, from Stern's data, L measured between the 2 contacts at each location was as follows:

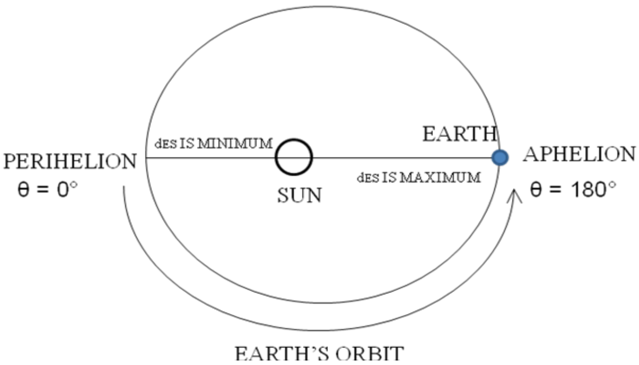
Cairo: 19,526 seconds
Durban: 20,055 seconds

Average L ($\bar{L}$) = 19,790.5 seconds L = 529 seconds

For the purpose of these calculations, the astronomical unit (AU) is the average distance from the Sun to the Earth. The distance between Earth and Sun varies because the orbit of Earth is elliptical (with the Sun at one of its foci), and the distance from the Sun varies according to the formula:

$$d_{ES} = AU\frac{(1-e^2)}{1+e\cos\theta} \qquad \text{(Equation 1)}$$

Where e is the eccentricity of the Earth's orbit, and θ is the angular position of the Earth in its orbit around the Sun, whereby 0° begins at the perihelion (see Figure 6). The distance from the Earth to the Sun d_{ES} at any point in its orbit is given by the formula shown in equation 1.



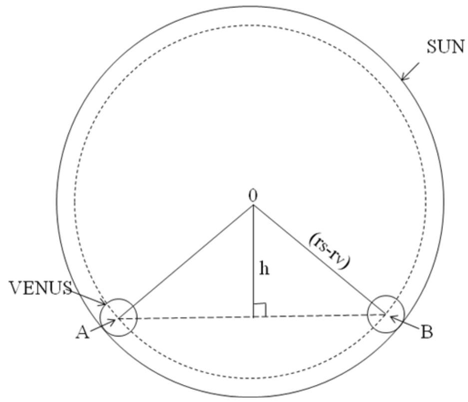


Figure 6 (left) – Elliptical revolution of Earth around the Sun, & Figure 7 (right) - Geometry of transit of Venus on the face of the Sun.

The Sun and Venus, as they appeared in the sky on Earth for this transit, have apparent diameters as follows (Stern, 2004):

Sun: 31.5 arc minutes (The apparent radius of the Sun (r_S) is 15.75')

Venus: 1 arc minute (The apparent radius of Venus (r_V) is 0.5')

According to Stern (2004), at each location a line can be drawn between the second and third points of contact (AB from figure 7) of the transit of Venus on the Sun. The line AB is a perpendicular distance h from the centre of the Sun (O)[1].

In this example, at Cairo, the transit of Venus follows the line A_1B_1, while at Durban, the transit follows the line A_2B_2 (see figure 9). At Durban, the distance h is slightly smaller than h at Cairo, because Venus, as it appears in the sky relative to the Sun at Durban, is slightly higher up (see figure 8).

[1] Note: Point A is the centre of Venus at the second point of contact with the Sun (internal ingress, when Venus' exterior just breaks contact with the inner edge of the Sun's disk). Point B is likewise the centre of Venus at the third point of contact with the Sun (internal egress). Hence the lines OA and OB have a length equal to the radius of the Sun minus the radius of Venus.

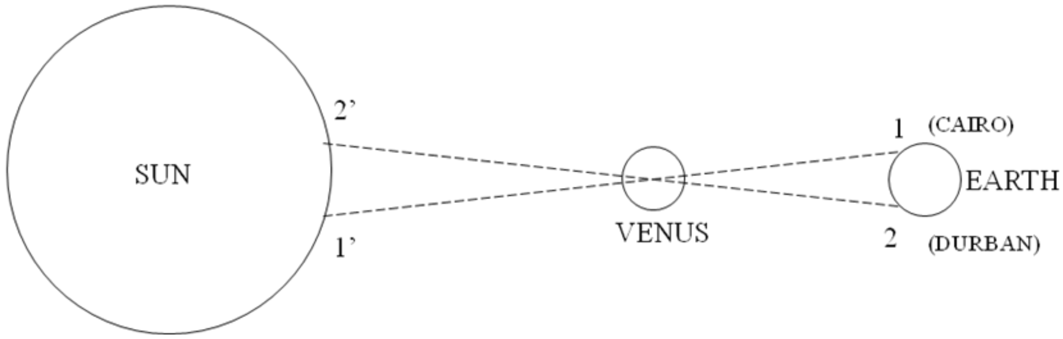


Figure 8 – Apparent line of sight of Venus on the face of the Sun from Earth

Thus there is a difference in *h* values (Δ*h*) between the two locations, represented by *D* (Stern, 2004) (Figure 9). This *D* is the apparent parallax shift of Venus relative to the Sun between Durban and Cairo, measured in minutes and seconds of arc.

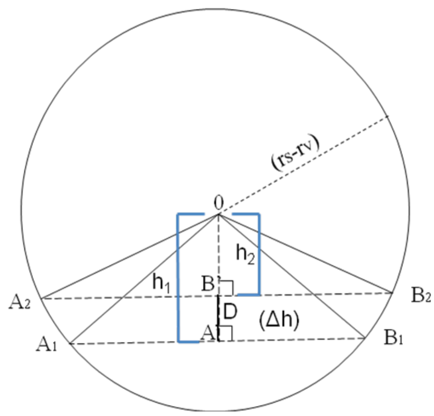


Figure 9 - Geometry of the trajectory of transit of Venus on the face of the Sun. (Note: D = difference between A' and B' in this diagram = Δh)

According to calculations by Heinz Blatter (2003), an approximation for the apparent velocity of Venus (ω_{VS}) relative to the Sun is

$$\omega_{VS} = 0.0672''/s$$

Using this value, and the durations recorded for the transit at each location, the apparent lengths A_1B_1 and A_2B_2 (Figure 9) can be calculated.

According to Blatter (2003), for each location:

$$l_{AB} = \omega_{VS} * L \qquad \text{(Equation 2)}$$

where *L* is the length of the transit (in seconds) at that location.

The perpendicular distance between the two trajectories Venus takes across the Sun is represented by the value *D*, the difference between the lengths *OA'* and *OB'* shown in figure 9. Blatter (2003) provides Equation 3 to compute D from the information obtained thus far.

$$D = l_{OA'} - l_{OB'} = \sqrt{(r_S - r_V)^2 - \left(\frac{l_{A_1B_1}}{2}\right)^2} - \sqrt{(r_S - r_V)^2 - \left(\frac{l_{A_2B_2}}{2}\right)^2} \qquad \text{(Equation 3)}$$

For this example $l_{A_1B_1} = 1312.5'' = 21.869'$, $l_{A_2B_2} = 1347.70'' = 22.461'$. Substituting the values for r_S and r_V into the formula above gives D = 0.3132'

Using some known data (given below) the distance P_1P_2 can be derived relative to the ecliptic.

Average radius of the spherical Earth (R_E) = 6371km,
Venus' orbital period (T_V) = 0.616 Earth years,
Eccentricity of Earth's orbit (*e*) = 0.01673,
Eccentricity of Venus' orbit = 0 (Venus' orbit has a very small eccentricity and is ignored).

This distance forms the baseline to compute the parallax of Venus and the Sun (Stern 2004). The angle subtended between points 1 and 2 (from the centre of the spherical Earth) is equal to, in this case, the latitude of Cairo minus the latitude of Durban (Figure 8). The chord between them is calculated by simple trigonometry:

$$\text{Chord } P_1P_2 = R_E \sin(lat(1)) - R_E \sin(lat(2)) \qquad \text{(Equation 4)}$$

Since the Earth is tilted 23.5° relative to the ecliptic, the chord between the points will be tilted by this angle as well. Since distance between points perpendicular to the ecliptic is required, the chord length is multiplied by cos(23.5º) giving:

$$\text{Dist } P_1P_2 = \text{chord } P_1P_2 * \cos(23.5^\circ) \qquad \text{(Equation 5)}$$

This perpendicular distance stays constant regardless of the rotation angle of the Earth at any time due to the symmetry of the chosen latitudes.

In this case, substituting the values lat(1) = 30°, lat(2) = -30°, R_E = 6371 km resolves

Chord P_1P_2 = 6371 km
Dist P_1P_2 = 5842.6 km

The aphelion occurs in early July, so at the time of the last transit (8th June 2004) θ is nearly equal to 180°. This could be computed accurately but for this purpose θ = 180° is assumed. Thus, substituting this value into equation 1 results in:

$$d_{ES} = 1.01673 \text{ AU} \qquad \text{(Equation 6)}$$

The orbital period of Venus is 0.616 Earth years (Stern 2004). From Kepler's Laws of planetary orbits, the period and orbital radius are related by the following formula:

$$T_V^2 \propto R_V^3 \qquad \text{(Equation 7)}$$

Since period is expressed in terms of Earth years and orbital radius in Astronomical Units, it becomes an equation:

$$T_V^2 = R_V^3 \qquad \text{(Equation 8)}$$

Substituting 0.616 yrs for T_V:

$$R_V\ (d_{VS}) = 0.724 \text{ AU} \qquad \text{(Equation 9)}$$

According to Stern (2004) the distance between Venus and the Earth (d_{EV}) is calculated by:

$$d_{EV} = d_{ES} - d_{EV} \qquad \text{(Equation 10)}$$

This gives: $d_{EV} = 1.01673 - 0.724 = 0.291$ AU

3.1 Parallax shift of the Sun

Parallax is a "Difference or change in the apparent position or direction of an object as seen from two different points" (Oxford English Dictionary 2nd Ed.). It is the parallax effect that is used to solve the distance of Venus from Earth, and thus calculate the astronomical unit.

Because the Sun is not infinitely far away, the location of its centre will shift slightly (with respect to distant stars) when viewed from two separate locations on Earth. This Solar parallax impacts on the parallax shift of Venus because the parallax of Venus is measured relative to the Sun. Figure 10 represents an exaggerated side-on view of a transit of Venus, at the time when Venus is in the middle of its transit between ingress and egress, and shows how the closeness of the Sun impacts on the observed parallax angle of Venus. (Assume Venus transits across the centre of the Sun relative to the centre of the Earth to simplify the concept).

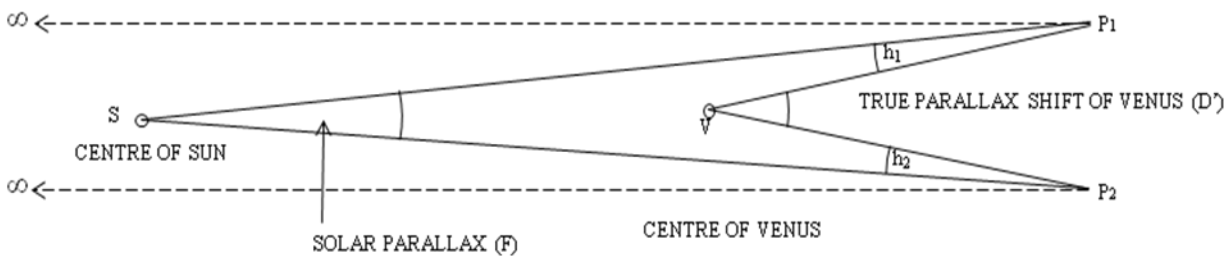


Figure 10 – Solar Parallax

From figure 10, at P_1 the angle α is equal to the angle h_1, or the line OA' as shown in figure 9. Likewise the angle β is equal to the angle h_2 at P_2. In figure 10, the centres of the Sun, Venus and the Earth all lie on the same plane (not usually the case with transits of Venus), so α and β are equal and opposite (in magnitude) angles. As shown previously, the parallax shift between the two locations of Venus relative to the Sun is D (Δh), which is equal to α – β. In this diagram the angles are opposite magnitudes (β is negative), therefore the angles sum to D.

At each point, the angle subtended between the centre of the Sun and the centre of Venus is smaller than the angle that would be subtended between some infinitely distant reference point (parallel to the ecliptic plane) and Venus. If the Sun were infinitely large and infinitely far away, it would not shift at all between the two observing locations and we could measure the true parallax shift of Venus between the two locations, relative to the Sun's centre. However, the Sun is actually close enough to Earth that Earth observers will experience a parallax effect when looking at it from two separate locations, just like Venus, only the parallax will be smaller.

To compute the correct parallax angle (*D'*), add the parallax of the Sun (*F*) to the parallax of Venus relative to the Sun (*D*) (Stern 2004). The equation for this is

$$D' = D + F \qquad \text{(Equation 11)}$$

Stern (2004) relates the value *F* to the distance P_1P_2 by looking at each value as a segment of a complete circle. The angle F can be expressed in minutes of arc, and there are 21,600 minutes in a full circle. The distance between P_1 and P_2 is a chord of a much larger circle, with a circumference of $2\pi d_{ES}X$, where d_{ES} is the distance between Earth and Sun at the time of the transit (due to elliptical orbit) (in Astronomical Units) and *X* is the number of kilometres in one astronomical unit. Since the parallax angle of the Sun is so small, the chord length between the two points is virtually identical to the arc length between them.

So, by observing Figure 11, it can be seen that the following is true:

$$\frac{F(in\ minutes\ of\ arc)}{21{,}600} = \frac{dist_{P_1P_2}}{2\pi d_{ES}X} \qquad \text{(Equation 12)}$$

Where d_{ES} = Radius of Earth's orbit at the time of transit, *X* = No. of km in one AU

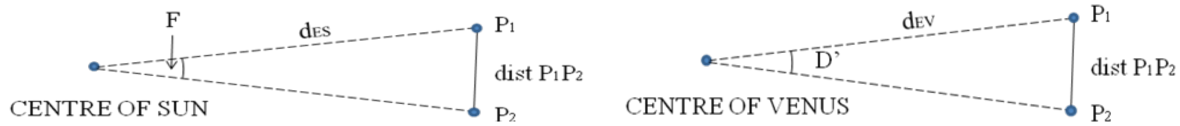


Figure 11(left) – parallax to the Sun & Figure 12 (right) – parallax to Venus

Rearranging equation 12 gives

$$X = \frac{21{,}600'}{2\pi d_{ES}} * \frac{d_{P_1P_2}}{F} \qquad \text{(Equation 13)}$$

Given the correct parallax angle of Venus (*D*'), the parallax angle between the two locations P_1 and P_2 can be represented diagrammatically, as shown in Figure 12.

Cooper (2009) details Stern's derivation arriving at an expression for X as:

$$X = \frac{21{,}600'}{2\pi d_{ES}} * d_{P_1P_2} \frac{\left(\frac{d_{ES}}{d_{EV}} - 1\right)}{D} \qquad \text{(Equation 14)}$$

So far, the following terms have been computed:

$d_{ES} = 1.01673$ AU
$d_{P_1P_2} = 5842.6$ km
$d_{EV} = 0.291$ AU
$D = 0.3132'$

Substituting these values into equation (Equation 14) gives $X = 157{,}302{,}177$ km.

The current accepted value for 1 AU is 149,597,870.691 km (NASA, 2009b).

The benefits of Stern's method of computing the AU are its simplicity, in contrast to Blatter's more complex calculations. Blatter's method accounts for pairs of observing locations that do not lie on the same meridian of longitude, or share the same latitude magnitude either side of the equator. Blatter states that for the Astronomical Unit to be determined to 1% accuracy, the duration of the transit must be determined to 0.02% (about 4 seconds). Likewise the apparent diameter of the Sun's disk should be determined to an accuracy of 0.1% for the above result.

4. THE 2012 RE-ENACTMENT OF THE TRANSIT OF VENUS OBSERVATIONS

Cooper (2009) details some hardware and methodology that would be suitable for a modern re-observation of the Transit of Venus. It is established that a video of the event would leave a lasting record and allow accurate timing of the ingress and egress times. Cooper (2009) details the problems with fitting a video to a total station or theodolite and ultimately recommends partnering with amateur astronomers who use astronomical telescopes with an accurate tracking and timing mechanism. Cooper (2009) gives a detailed explanation of a local amateur astronomers' equipment.

For 2012, it would be ideal to have collaboration between different observers around the world, with a common location to send observation data. This could be achieved by setting up a web site in which all observers of the 2012 transit can deposit videos of the transit, images, and any timing results collected. The web page should include a program to calculate the Astronomical Unit, or link to such a program. One example of an online site where a user can enter transit timing results and calculate a value for the Astronomical Unit is Steven van Roode's Online Parallax Calculator, found at http://www.transitofvenus.nl/parallax.html.

5. CONCLUDING REMARKS AND A CALL FOR PARTNERS

Observing the transit of Venus in 2012 will be of benefit to any student or professional with an interest in astronomy, as it will serve as a present-day spectacle showing how science has progressed since early astronomers used the transits of Venus to determine the scale of the solar system. It is also a terrific opportunity to raise the profile of the surveying profession to the wider community.

It is proposed to use video image capture through a telescope to provide a means of permanently recording the results of the transit. Post-processing of the event will enable the determination of the astronomical unit more accurately without fear of missing ingress or egress whilst still using the parallax method. Matching time through digital insertion of GPS time will provide timing quality superior to previous observations and hopefully produce a comparable result to the agreed value for the astronomical unit.

It is hoped that readers of this paper who are located in those regions of the world where the 2012 Transit of Venus will be visible, namely eastern Asia, Indonesia, New Zealand, Russia and Alaska as well as Australia, will embrace this project. The first author hopes to use this project in the wider media to raise the profile of the surveying profession.

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BIOGRAPHICAL NOTES

Craig Roberts is a Senior Lecturer in Surveying/ GPS/ Geodesy at the University of New South Wales, Sydney, Australia. He has lectured at RMIT University in Melbourne for two years. He graduated from the University of South Australia with a Bachelor of Surveying in 1988. He began his career as a private surveyor in Adelaide and has since worked as a Geodetic Engineer at UNAVCO, USA involved with GPS for geodynamic studies in Nepal, Ethiopia, Argentina and Indonesia. He worked as a scientific assistant at the GeoForschungsZentrum, Germany where his main focus was orbit determination and prediction for a number of geodetic research satellites. He completed his PhD thesis in March 2002 supervised by Prof. Chris Rizos. His current research interests involve leveraging CORS infrastructure for practical application to surveying and spatial information.

CONTACTS

Craig Roberts
School of Surveying and Spatial Information Systems
University of New South Wales
Sydney NSW 2052
AUSTRALIA

Tel. +61-2-9385 4464
Fax + 61-2-9311 2695
Email: c.roberts@unsw.edu.au
Web site: www.gmat.unsw.edu.au