The 2004 transit of Venus observed from the Open University Observatory

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The purpose of this report is to compare the accuracies of five different techniques for determining contact times. Recordings and measurements of the transit were taken through four instruments, the Open University's Meade LX200 for accurate timing of the third contact, and a Meade ETX 105 for coverage of the whole transit. Both were recorded on digital videotape. In addition, images were recorded on a webcam on a 100mm telescope and visual estimates were made with an ETX125. Analysis of the LX200 tapes gave an accuracy of ±5 seconds for the time of contact. Methods are compared in the Conclusions. Several other telescopes were used on campus for public displays of the event. There was minimal black drop.

1 Meade LX200

The telescope is a standard 40cm LX200 on an equatorial mount, on a free standing pillar in a floating dome.

Recording the transit

The aim was to record data permitting as accurate as possible a timing of the third contact. The 40cm telescope was stopped down to an 80mm glass solar neutral density (ND) filter, as available from Broadhurst Clarkson & Fuller (BCF), offset from the central secondary mirror, in a simple mask with two windows, one of which was blanked off (Figure 1).

The focal length of the LX200 is 4000mm working at f/50. A video eyepiece (640×480 pixels) fed the image to a digital tape recorder. The disk of Venus filled about a fifth of the frame.

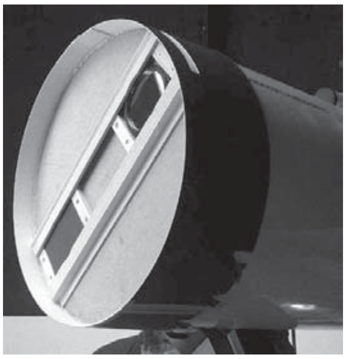

Figure 1. LX200 telescope with mask and filter.

The tape was later transcribed to DVD, with a time code on every frame. Its first section contains images of a clock which shows that the zero of the time code was at 11h 48m 26s UT (accurate to ±0.5 seconds which was adequate for the purpose of the transit), thus allowing conversion of all the time code to UT. The DVD recording allows time resolution of the image to 1/50 second (looking at half frames) which is unnecessarily fine for the transit itself, but has allowed analysis of the seeing and image jitter. This proved to be an added bonus, as it gave clues to the different causes of the jitter.

Measurements

Measurements have been made on a sequence of images before and slightly after the third contact, with the actual contact time deduced by interpolation. This method was chosen in order to avoid the effects of black drop optical distortions which have reportedly plagued past measurements[1] but in the event little distortion was seen. Interpolation is in any case far more accurate and reliable than a single snap judgement of the timing of the contact as it occurs.

There is considerable (several arcseconds) jittering of the image due to various causes. This is for the most part translation (i.e. bodily movement) of the whole image, and so does not hamper or degrade the measurement of the contact, provided one looks at individual frames, which are effectively frozen by the 40ms exposure time of the video eyepiece. The weather was essentially perfect during the transit, apart from a gusty breeze which sprang up near third contact and was annoying to exposed telescopes but not for the LX200 in its dome.

Analysis of LX200 data

Contact timing

Ideally one would like to be able to mark, on each frame, the position at which the contact will occur, and measure the distance from that point to the (nearest point on the) limb of Venus. That distance would then decrease linearly with time. However there is no way of identifying that point; the only measurement that can be made is of the gap between the limb of Venus and the limb of the Sun, which is always along a radius from the centre of the Sun's disk. This radial distance does not vary linearly with time, although fortunately the departure from linearity is small within a few minutes of the contacts. Assuming that Venus follows a straight trajectory across the Sun the equation for the gap length is

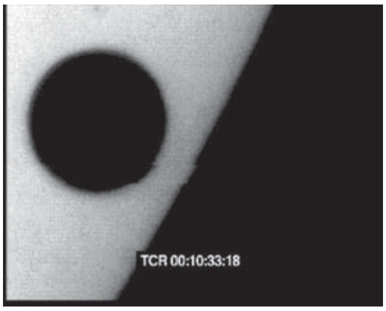

Figure 2. Image through the LX200. The time code format is hours:minutes:seconds: frame number.

$$\text{Gap} = z = R_S - R_V - \sqrt{(R_S^2\cos^2\theta + v^2 t^2)} \qquad [1]$$

where R_S = the radius of the Sun, θ = the half-angle subtended by the transit path at the centre of the Sun, v = the speed of Venus across the Sun, R_V = the radius of Venus, and t = the elapsed time from the centre of the transit. v and θ are to be found from the fitting; they are not predicted values.

How should one measure the gap? Our first attempt was using a ruler on a flat TV screen. However the thickness of the glass is a serious limitation and the image of the limb is inevitably blurred. The second attempt solved these problems by using a grid superimposed on each image. The third stage was to use a digital projector, which gives a sharper/larger image than the TV/computer screen, and to make a pair of transparent templates with sections of the limbs drawn on them. The size of the projected image was adjusted to fit these to fit the limbs (fitting by eye is adequate since the accuracy of the final result does not depend on this fitting). The two templates could be moved apart, for each frame, to the distance which fitted both limbs simultaneously. This 'animated template' exploits the excellent power of the eye/brain in fitting a line, and was the final method adopted (Table 1 and Figure 3). For each selected frame the reproducibility of repeated measurements with this technique was about 0.5mm. The zero was well defined (i.e. better than 0.5mm) because it is the position in which the lines (not the images) overlap. Time codes from the recording were used (unconverted to UT) to avoid subjectively biasing the final answer.

A different approach would be a computer fit to the line, either by taking several points on the limbs and using a best fit program, or by using the posterise filter in *Photoshop*.[2] The latter instantly gives a beautifully sharp contour map rendition of the line, but leads to the question of which contour one should choose? We did not attempt to use *Registax*[2] because of the danger of selecting images that look nice, rather than a random/representative set of images. Seeing affects both position and clarity of images, so there is therefore a danger of bias, which would need to be explored. Calibrated tests would be needed to decide which of these is the optimal method. It would also be possible to extract many more independent measurements from the tape.

The graph of the distance from the solar limb versus time is shown in Figure 3, together with a linear fit using *Matlab*.[2] The time zero on this graph is 10h 59m 0s UT, and the fitted line cuts the time axis at 314 seconds, which gives a measured time for the 3rd contact of 11h 4m 14s UT, compared to the predicted time of 11h 4m 8s. The crucial result is the calculated error on the intercept on the time axis. The purely statistical error from the fit is ±3 seconds.

However, there are some signs that there are a few seconds of unexplained systematic error. First, although the fit is good (i.e. most measurements are within the estimated 0.5mm errors) we found a difficulty with the details of the fitting. As will be illustrated in Section 2 below, Equation 1 implies that the fitted line should curve very slightly downwards. The second order term given by a quadratic fit to our data is small, but it is positive (i.e. upwards). It is possible that this is due to some slight black drop effect.[1] Secondly, the result is about 6 seconds later than the predicted value quoted, for example, by Espenak[3] from the formulae given by Jean Meeus[4] for London (after a small correction for the distance between London and Milton Keynes). We conclude that the interpolation method is capable of accuracies of a few seconds, even in an urban site, but there is more work to do to identify systematic errors.

Putting this into an historical context, Halley set an almost unachievable target of 1 second accuracy. Our 6 sec. uncertainty corresponds to about ~1% uncertainty on the astronomical unit. This accuracy is broadly comparable to the consensus of all the results for the 1874 transit (see summary of all results by Hughes in ref.9).

Since this transit was also observed from the spacecraft TRACE and ACRIM, which are of course unaffected by see-

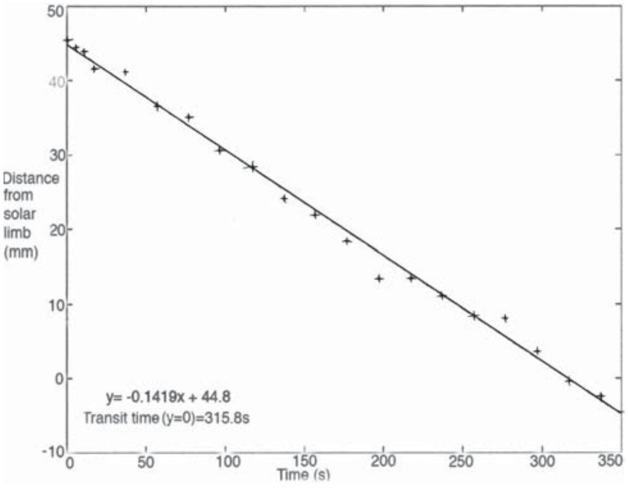

Figure 3. Linear fit to LX200 data.

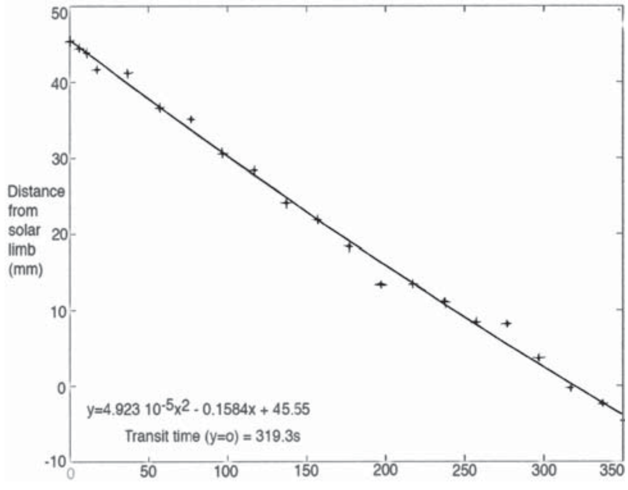

Figure 4. Quadratic fit to LX200 data.

Table 1. Gap between Venus and the Sun's limb in the projected image, as a function of time

sec	0.68	5.68	10.68	17	37	57	77	97	117	137	157
m m	45.4	44.4	43.9	41.6	41.1	36.6	35.1	30.6	28.4	24.1	21.9
sec	177	197	217	237.04	257	276.96	296	317	337	350	
m m	18.4	13.4	13.4	11.1	8.4	8.1	3.6	–0.4	–2.4	–4.6	

ing, it was the first time that the Earth's atmosphere could definitely be excluded as a source of black drop. Their images led Pasachoff *et al.*[5] to conclude that any remaining effects are explainable by limb darkening and the point spread function of the telescope, i.e. the atmospheres of Venus and the Sun did not give rise to distortion. The spacecraft GOES-12, SOHO and ACRIM also provided images.[6] High resolution mountain altitude images from the Swedish Solar telescope showed a clear aura beyond the limb. Many images from the AURA/GONG/NSF telescopes have also been published on their website.[7]

Study of image jitter

The displacement of the image due to seeing is called the 'image excursion'. We were interested in the sub-second variations of this excursion, which for brevity we call jitter.

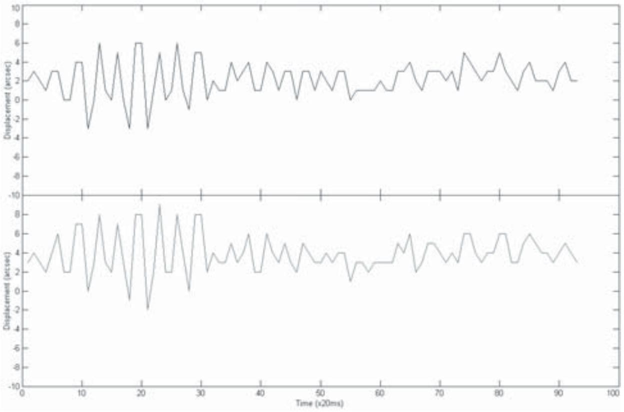

Figure 5. Jitter of the image from frame to frame. *Top:* horizontal jitter; *bottom:* vertical jitter.

The sequences can be used to analyse the jitter to a resolution of 1/25 second. In fact one can look at half frames, which are separated by 1/50 second (every TV frame is actually two interleaved scans at half resolution). Both seeing and telescope vibration will contribute to the jitter. Seeing can cause distortion, or change in magnification, or displacement (it can also cause change in intensity, which is important, and recordable, in stellar observations, but not here).

A plot of the displacements shows rapid movements, with a suggestion of some periodicity at about 10Hz. 10Hz is way below the resonant frequency of the pillar, but is in the right frequency range for vibrations transmitted through ground from passing lorries, of which there is a plentiful supply on the M1 about 2km away. The occasional lorry passing on the campus definitely causes vibration. The distortion and magnification changes are some five times smaller (only about ±1 arcsecond, not shown) and can only be due to seeing. As a means of distinguishing between the two we measured the vertical and horizontal diameters of Venus, frame by frame, and calculated the product of the differences from the mean value. This method sidesteps the complications of the aspect ratio in video/TV. We took a negative product to correspond to distortion and a positive value to a change in magnification. The remaining question is what portion of the displacements is due to seeing? An arcsecond seems a low value for seeing on a hot summer morning. So far we have only measured about fifty frames, which is only 2 seconds worth, so this is an area for further study.

2 Meade ETX105 UHTC and camcorder

The aim was to record and time the whole transit. This means having a section of the limb of the Sun in frame at all times as a reference, which was impossible with the small field of view of the LX200. Two problems had to be solved: no tape lasts 6 hours, and the image provided by a camcorder alone is too small. We therefore used an ETX105 telescope, mounted on a #884 tripod (the standard tripod supplied with the ETX105), which has a hinged telescope platform providing an adjustable wedge facility for equatorial mounting. The latitude and longitude of the site (the Open University cricket field) as determined by a Garmin GPS12 were entered into the #497 Autostar. The telescope was powered with a 12volt 18AH emergency car boost start unit.

The camcorder – Sony TRV22E

Considerable adaptation was needed to make a domestic camcorder into an astronomical instrument.

The TRV22E is a palm-sized camcorder from Sony's 2003 range, and uses an NP-QM71 lithium ion battery of 20Wh capacity, capable of driving the unit for eight hours. It also has an interval mode which was used for the long period between 2nd and 3rd contacts. During interval mode, the camera's circuitry and viewfinder are both active making it essential that a high capacity battery is used. Crucially, there is no interruption to the time code, which is recorded on every frame. The camcorder's internal clock, set to UT, was synchronised to an MSF based radio clock. In addition, the clock was photographed both before and after the transit.

The TRV22E can also record still photos to a memory stick, and very conveniently, this can be done both live and during playback. This 'snapshot during playback' mode was used in the analysis of the results.

Remote microphone

During the transit, but especially near contact times, the camcorder recorded commentary from visual observations five metres away using the club's ETX125, which was fitted with a higher magnification eyepiece to allow better precision in viewing (the microphone also recorded the continual and not insignificant noise of the 125's motors). The purpose of this telescope was to record descriptions of the black

Figure 6. Image through ETX105 and camcorder.

drop effect, and the visual estimate of the moment of contact, which could then be timed against the camcorder's time code. It is very instructive to hear the observer trying to foresee the right moment.

The optical train

Solar filter

The solar filter was that supplied by BCF for the ETX105, and is a screw-in glass mounted type with the filter surfaces fully protected.

DigimaxT 40 eyepiece

The recently introduced DigimaxT 40 was used to mount the camcorder on the telescope's eyepiece socket. The advantage of the DigimaxT 40 is that various adapters (at both ends) allow fitting to different cameras, microscopes and telescopes, and that adjustment to the tube length is also provided. This feature allows optimal positioning of the camcorder so as to minimise vignetting, and maximise the field of view. The DigimaxT 40 weighs 225g, and moves the camcorder's centre of gravity about 15cm away from the eyepiece socket. The DigimaxT 40 has a relatively wide angle of view which can be narrowed by use of the zoom on the camcorder.

This gave sufficient magnification to make useful measurements of Venus, but of course this necessarily means that only part of the Sun's disk is in frame.

X4 ND Filter

During trials before the transit, it was found that keeping the camcorder aligned with the eyepiece was quite difficult, and that better results were obtained when the Sun was slightly obscured. A review of the camcorder's aperture readout showed that the aperture was stopping down to around f/14 when the Sun was shining in a clear sky. The camcorder's lens has a minimum focal length of 3.3mm, so the physical aperture at f/14 is around 0.25mm diameter. In this context, the fit of the DigimaxT 40 into the eyepiece socket is too loose (although suitable for normal use), in fact it was surprising that maintaining optical alignment to 0.25mm was possible at all.

The solution was to introduce a ×4 ND filter in the lower part of the DigimaxT 40 and open the aperture to around f/5.6. This coated filter was from the set provided with a Minolta RF 500mm f/8 catadioptric lens, and so was optimised for high quality telescope use. This setup worked well for most of the transit. However for the first half hour the camcorder was short of light and the early images turned out to be of significantly lower quality (see below).

Assembly, balance and equatorial mounting issues

It was decided early on that equatorial mode would be used so that images captured during the transit would not be rotated during the six hour period. This introduced complications with the mounting of the camcorder (on the upper eyepiece) in that in the early part of the transit, the camcorder would be seriously tilted (approximately 40° away from vertical) in an anticlockwise position (as viewed from behind the telescope). Later on, approaching the last contact, this tilt would be much smaller (approaching 5°), with the camcorder nearly vertical and reinforced the need for the ND filter mentioned above.

The alternative port on the rear of the optical tube assembly (OTA) is virtually unusable in the equatorial mode, as there is so little clearance, approximately 8mm, between this port and the telescope base during setup.

The balance weights and adapters supplied by BCF for the ETX proved insufficient to balance the DigimaxT 40 and camcorder (855g). The adapters were modified to take much longer screwed rods allowing static balance with a minimum of weight.

In addition to the balance weight modifications, a tie was added from the camcorder to a ring clamped around the ETX105 OTA. This helped to reduce the wobble introduced by the slop in the eyepiece mount, and helped direct the forces more normally into the eyepiece mount.

Results

Recording sequence

The camcorder was set to Spotlight AE (AE = Auto Exposure) mode (to help ensure that the Sun's brightest areas were not saturated) and was set to record in LP mode, which is good for about ninety minutes in normal filming mode.

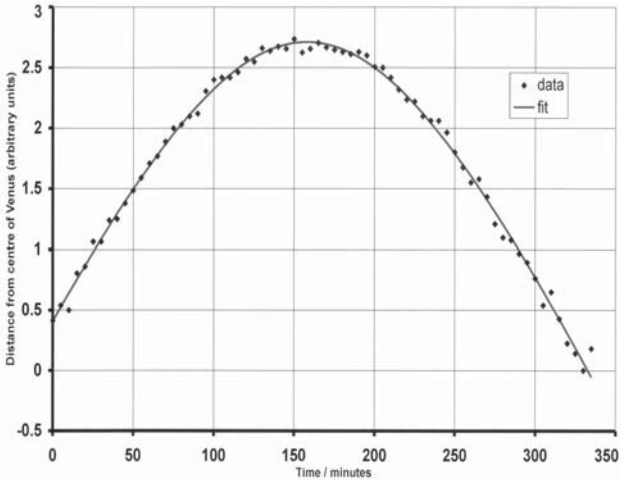

Figure 7. Fit of Eq.1 to camcorder measurements.

From just before 1st contact to just after 2nd contact, normal filming was done. During the period from just after 2nd contact to just before 3rd contact interval mode was used with two seconds of video being recorded every minute (1/30 normal rate) giving about three hundred short sequences. From just before 3rd contact to just after 4th contact, normal filming was done. Thus the total tape time was less than 90 minutes (about 65 minutes) with uninterrupted timing.

Due to use of the upper eyepiece port, the images were upright but laterally reversed, i.e. Venus appeared to travel across the lower part of the Sun from right to left.

Snapshots

To simplify measurements, a series of snapshots was taken during playback of the transit between 2nd and 3rd contacts. The technique was to play the film back onto the TV with the camcorder's date and time data on display, and at the same time record to a VHS recorder. This indelibly associates the camcorder's internal clock time with the recorded images. The VHS tape was then rewound and replayed into the A/V input of the camcorder, and snapshots were taken by pressing the 'Photo' button. This is crucial because the time data, whilst present on the original MiniDV tape, was not otherwise available, with the video editing application used. Consequently this important association of image with time data is impossible without the record to VHS and subsequent playback stages (note that EXIF data recorded with the snapshots records the camcorder's clock time at which the snapshot was taken during the later playback, and for analysis purposes is therefore of no value here).

The initial set of snapshots was made at 5 minute intervals throughout the transit, and approximately seventy snapshots were taken. Each snapshot showed Venus silhouetted against the Sun's disk, with a portion of the limb in view.

Analysis

Each snapshot was examined in *Photoshop 5LE*, and the positions of the centre of Venus (X_V, Y_V) and that of the nearest Sun's edge (X_S, Y_S) noted against the graticules. This was easy and fairly precise for Venus as fortuitously, the cross indicating the graticule position just filled the image of Venus at the scale produced by the telescope. Matters were less precise when estimating and putting coordinates to the nearest edge of the Sun's limb. In one case due to temporary telescope misalignment, the nearest Sun's edge was not captured on video. However, enough of other parts of the Sun's disk were captured to allow generation of a circle in *Photoshop* which was the same size as the Sun's disk. This was then aligned with the visible parts of the disk, and the missing co-ordinates estimated.

The differences (X_S–X_V) and (Y_S–Y_V) were calculated from the *Photoshop* readout and plotted for each snapshot.

The fit of Equation 1 to the measurements is shown in Figure 7. A crucial point is that it is not necessary to calibrate these *Photoshop*/camcorder distances in absolute terms, because it is only the zero crossing time which is needed. Eq.1 was slightly re-arranged using four fitted parameters: the total duration T, the time from second contact t, the opening angle θ, and an overall scaling parameter. The radius of Venus term was removed since measurements were from the centre of Venus, whereas the LX200 measurements were of the gap between Venus and the Sun's limb.

The fitting yielded an estimated total duration T of 329 ± 1.5 minutes compared with the true value of 325 minutes. The missing early points (see above) degraded the accuracy of this method. The time of the 3rd contact time according to the fitted curve is 11h 7m i.e. 3 minutes late, a puzzling discrepancy since the fit to the curve is so good. This time can also be estimated visually by viewing the tape and this gave a time of 11h 3m 21s i.e. 43 seconds early. The recording of the independent visual observer's comments gave a value within 2 seconds of the predicted value, but this must be regarded as possibly fortuitous since the commentary alone allows no quantitative estimate of uncertainty, whereas being able to combine the visual and recorded data after the event gives much greater confidence in the significance of the results. The webcam data was treated differently.

3 100mm telescope and webcam

Data acquisition

A Philips ToUcam webcam was used (in conjunction with a Mogg eyepiece adaptor[8]) at prime focus on a 100mm reflector with a full aperture solar filter. Approximately one quarter of the full disk of the Sun was projected onto the CCD chip, and data were recorded for both third and fourth contacts.

A Dell Inspiron 8200 laptop was used with the Windows XP version of Philips VRecord to obtain an uncompressed avi file, sampled at one frame per second, for approximately twenty minutes. Each frame was exposed for 1/100 seconds before being written to the hard disk. Unfortunately, the hard disk of the laptop was unable to write all of the data recorded from the CCD due to buffer underruns. As a consequence of this, approximately one quarter of the data were lost during the data acquisition.

The data collected were further analysed using *Matlab*.[2] It was immediately obvious that the buffer underrun problem had severely affected the data for 4th contact. It was therefore decided that only the determination of the 3rd contact time would be considered, allowing for the rejection of three quarters of the remaining dataset.

Edge detection algorithm

A *Matlab* script was written to perform edge detection on the remaining image frames. During the transit across the solar disk, two edges due to the disk of Venus and the solar limb would be expected (Figure 8a). As the contact occurs, one edge would be expected as it is impossible to determine

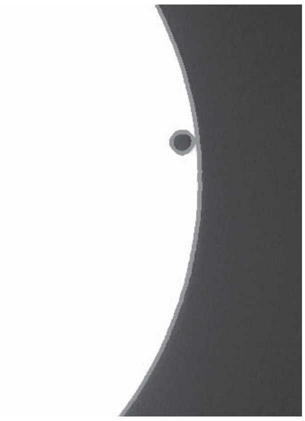

Figure 8a. *(left)* 1 second before 3rd contact. The two automatically detected edges are shown in grey.
Figure 8b. *(right)* 3rd contact with the single detected edge shown in grey.

the difference between sky background and the disk of Venus (Figure 8b). The computer was set up to inform the user when the number of detected edges within the images dropped to unity.

This algorithm gave the calculated time of 3rd contact as 11h 04m 07s ± 01s which is compatible with the actual time of 3rd contact. The standard error quoted was calculated by varying the parameter which determined the position of an edge, between the maximum and minimum values that gave two edges when the disk of Venus was transiting across the solar disk.

Conclusions

With all the instruments, the recordings allowed interpolation and careful subsequent investigation of the statistical errors, which is impossible with a one-off visual estimate. The automated method of determining the moment of contact gave a remarkably small random error of about 1 second, but is at the mercy of systematic errors. However the LX200 gave a series of measurements, which allowed interpolation and checks of internal accuracy. It also gave a suggestion of some systematic errors so we give priority to the LX200 measurements. Ideally we should get the best of both worlds by applying the automated method to the LX200 images.

However only the camcorder had a wide enough field of view and enough data storage to have a portion of the Sun's limb in view at all times, allowing the complete transit to be measured. In the absence of easily recordable sunspots within the relevant field of view, the other instruments had no valid reference point visible except within a few minutes of the contacts.

For the benefit of other observers we should reiterate our three errors. The first is that the extra ND4 filter spoilt the first twenty minutes of camcorder images, though it was necessary for the rest. The second is that inadequate buffering lost a crucial sequence of the 3rd contact webcam recording, and the third (of omission rather than commission) is that we have not yet found a way of calibrating the circularity of the Venus image to see if image distortion is a significant source of error. This is more difficult than it might appear since video pixels are not square.

Finally, there is room to further exploit automated image analysis as a tool.

Acknowledgments

To the members of the OUAC, many of whom spent several hours showing visitors the transit through the various telescopes, and all of whom were supportive of the project, and to the referee for the improvements resulting from his comments.

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2 The programs referred to are Adobe *Photoshop*, Microsoft *Excel*, Mathsoft *Matlab* and *Registax* (which is available as a free download from http://registax.astronomy.net)
3 http://sunearth.gsfc.nasa.gov/eclipse
4 Meeus J., *Astronomical Algorithms*, Atlantic Books, 1991, ISBN 0943396352
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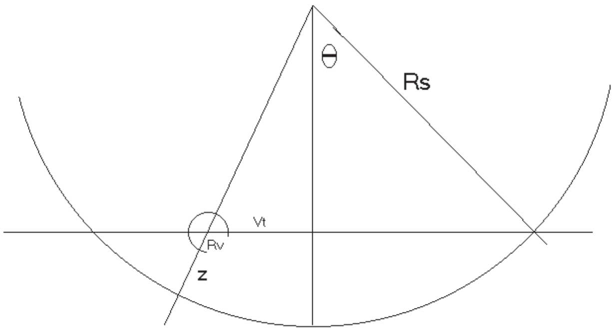
Appendix: the derivation of Eq.1



The length of the chord is (speed of Venus across face) × total transit time. We take t = time from centre of chord and, by Pythagoras' Theorem, get an expression for the distance from the centre of the Sun out along a radius to the centre of Venus. The gap between Venus and the limb of the Sun is then the radius of the Sun minus this distance, minus the radius of Venus, which is equation 1.

Received 2005 January 15; accepted 2005 March 30