High resolution imaging of mutual events of the Jovian satellites during the 2014/2015 apparition

John Sussenbach & Willem Kivits

During the 2014/2015 Jupiter apparition several mutual occultations and eclipses of the Galilean satellites took place. These mutual events occur every 5.93 years. A number of the events were recorded using 14-inch [355mm] or larger telescopes and different types of cameras. Processing programs like *Registax 6.1* or *Autostakkert2!* struggle to grade, align and stack the tiny images of the Jovian satellites. To obtain high resolution images different processing procedures were employed to optimise the quality of the images, including hand selection and the use of master frames. Several occultations and eclipses were recorded at high resolution. In several eclipses the umbra and penumbra could be successfully distinguished. An interesting phenomenon was observed near the date of opposition, *viz.* the simultaneous occultation and eclipse of Ganymede by Callisto on 2015 February 7, one day after opposition.

Introduction

Jupiter is a favourite object for planetary observers. Even with small telescopes many details can be seen on this giant among the planets, such as the dark North and South Equatorial Belts, many minor atmospheric features and, of course, the famous Great Red Spot. Another interesting feature of the Jovian system is the perpetual dance of the four large satellites Io, Europa, Ganymede and Callisto. From time to time transits of the satellites and their shadows over the globe of Jupiter can be observed (Figures 1 and 2). These phenomena make the Jovian system one of the most fascinating in the solar system.

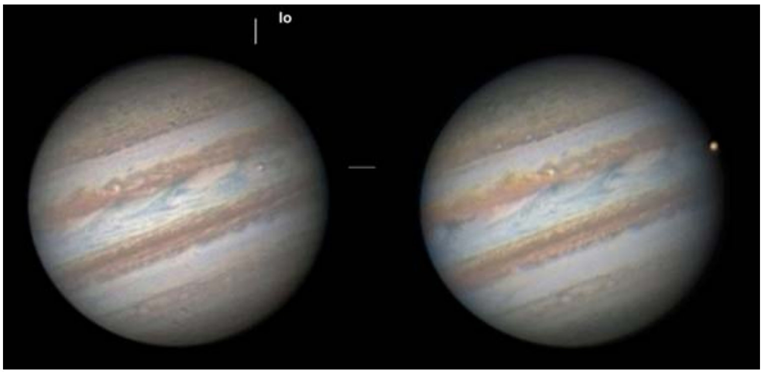

Figure 1. Transit of Io on 2014 November 25 (*Left:* 03:31 UT; *Right:* 04:00 UT). North is up in all images.

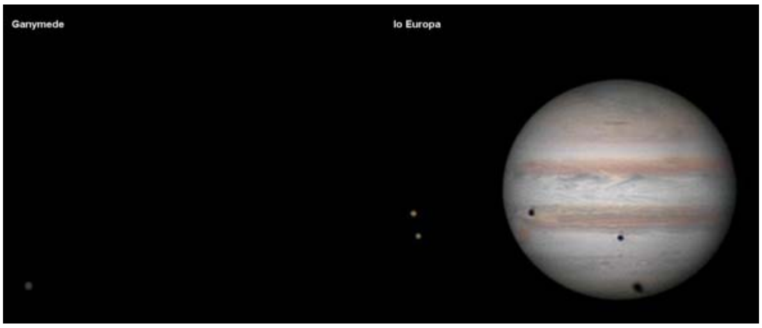

Figure 2. Triple shadow transit of Ganymede, Io and Europa on 2013 October 12.

Jupiter rotates around the Sun in nearly 12 Earth-years. Every 5.93 years the Sun and Earth pass through the Jovian equatorial plane (Figure 3). This causes some phenomena of particular interest, *viz.* mutual occultations and eclipses of the big Jovian satellites.

The *Institut de Mécanique Céleste et de Calcul des Ephémérides* (ICCME) has through the years collected observational data about these events.[1] The emphasis was on the photometric aspects. In recent years with the development of digital astropho-

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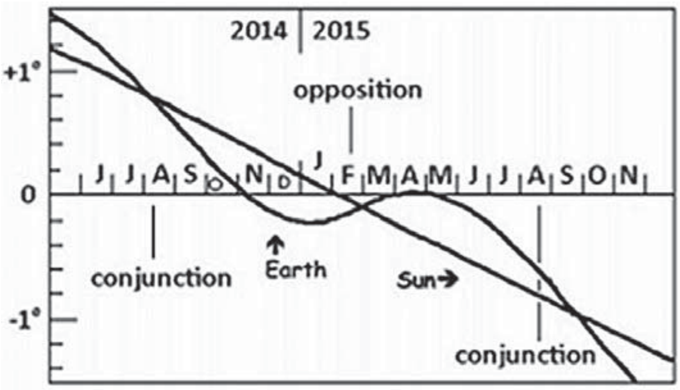

Figure 3. Jovicentric declination of the Earth and the Sun in 2014/2015.[5]

tography, amateurs such as Damian Peach, Christopher Go, Leo Aerts & Willem Kivits have successfully detected details on the tiny disks of the Galilean moons (see for instance the website of the ALPO Japan).[2] Marc Delcroix has posted a collection of resolved videos of these events from various observers.[3] Observations and photometry of these events have been used to check the orbits of the satellites.[4]

The most recent period that mutual events occurred was in 2014/2015. From the Netherlands Jupiter stood high in the sky and moved through Leo and Cancer. This was very favourable for imaging the events. The next opportunity will be in 2021. This passage will be rather unfavourable for us living in the Netherlands and the UK, because then Jupiter is low above the horizon in Capricorn and Sagittarius.

The observation of mutual occultations and eclipses is hampered by the small diameter of the four large Jovian moons. Even during opposition the largest moon Ganymede (5268km) has an apparent diameter of only 1.68 arcseconds, while the smallest of the four, Europa (3122km), has an apparent diameter of about 1 arcsecond. Under non-optimal conditions a telescope with a diameter of 25cm is a minimum instrument to study these phenomena in detail. During the last apparition with mutual events, in 2009, the first resolved time-lapse videos of mutual phenomena were collected.[4] Because of the variable and unstable weather conditions in the Low Countries the authors have combined their observations of the 2014/2015 apparition to obtain as much data as possible.

The purpose of our observations was to investigate to what extent details of these mutual phenomena can be recorded with medium-sized telescopes, and in particular to what extent the penumbra and umbra can be distinguished during mutual eclipses. Special attention was paid to the unique situation around opposition, when occultations and eclipses might occur simultaneously. A preliminary report was published in Dutch in *Occultus* magazine.[6] Detailed information on the mutual events of 2014/2015 and useful information is found in a report of the Jupiter Section of the BAA.[7]

Figure 4. *Left:* Willem Kivits with his 20-inch (50.8cm) Newtonian telescope; *Above:* John Sussenbach and his C14 (35.5cm) Schmidt–Cassegrain telescope.

Methods

Instruments

Willem Kivits (Siebengewald, The Netherlands) used a Celestron C14 35.5cm Schmidt–Cassegrain telescope and a 20-inch (50.8cm) f/4 Newtonian telescope. John Sussenbach (Houten, The Netherlands) also used a Celestron C14 SCT (Figure 4).

There is normally not much difference in resolution between a C14 SCT and a 12 to 20-inch (30.5 to 50.8cm) Newtonian. Often, the seeing is the limiting factor and the maximum theoretical resolution is not achieved. Experience has shown that a 10-inch (25.4cm) telescope is about the minimum size required to make detailed images of the satellites.

Video cameras for planetary photography must be able to record many frames per second and have a high sensitivity. We used a QHY5LII (CMOS camera with 3.75×3.75 microns pixels resolution) and a DMK618 mono camera (containing the Sony ICX618 chip with 5.6×5.6 microns pixels). To minimise the effects of atmospheric turbulence we used 610nm (red) and 685nm (infrared) pass filters.

Recording and processing images

In general, images were recorded as AVI files and the focal ratio of the telescopes was usually between f/25 and f/40, depending on the weather conditions and the optical system employed. We recorded short movies of 1–2 minutes each at a frame rate of 60–100 frames per second, depending on the satellite recorded and the weather conditions. Callisto is much less bright than the other three satellites.

For processing the recorded AVIs the programs *Autostakkert2!*[8] (author Emil Kraaikamp) and *Registax 6.1*[9] (author Cor Berrevoets) were most often used. These programs automatically select the frames with the highest quality and then position and stack the best images. Although these programs in general work well on planets, they have more difficulty handling very small and faint objects.

When processing the AVI files the best results are obtained when the objects are well centred. Therefore, the recorded movies were first processed using the *PIPP* program.[10] This program selects the best images, centres the object and creates a new AVI of well-centred images. These new AVIs make it easier for the stacking software (*Autostakkert2!* or *Registax 6.1*) to select and position the best frames.

To improve the processing of AVIs of the mutual events of the Jovian moons we also used another procedure. Using the *PIPP* program the AVI files were converted into individual frames (BMP or TIFF format). These individual frames were enlarged in Adobe

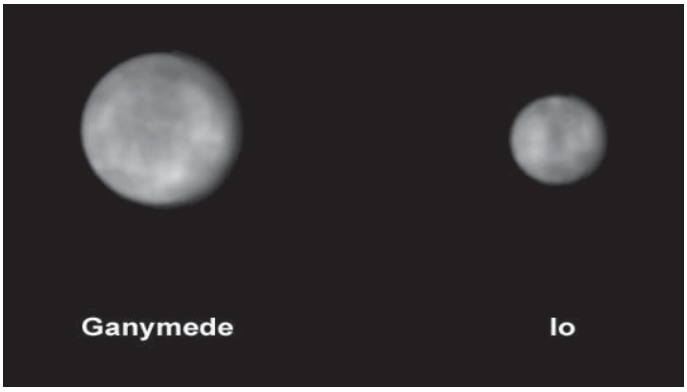

Figure 5. Master frames of Ganymede and Io.

Photoshop using the Batch option. In Photoshop a twofold brightness enhancement was then applied to obtain better raw material for the stacking programs. The new, enlarged frames were stacked automatically using *Autostakkert2!* or *Registax 6.1*.

Another, more laborious procedure to obtain the best frames is employing manual selection followed by stacking with *Autostakkert2!* This procedure delivers a better result than the automatic procedures. More details on the satellite surfaces are visible and also an improved image of the shadow transits is obtained.

Since the occultations and eclipses of Jupiter's moons often proceed very quickly, the number of frames that can be recorded is limited. In one minute, the moons move noticeably, so longer exposure and stacking frames should be avoided, because this leads to smearing and ultimately fewer details.

Optimisation of image quality

Here is a typical example of the details of the processing procedure, an occultation of Io by Europa. This event takes fewer than 4 minutes from first contact to last, so the number of frames is limited. To obtain a smooth animation the total number obtained in 4 minutes at 60–100 frames per second (about 15,000–24,000 frames) was split up in blocks of 500 frames each (5–8 sec.). If necessary the best frames were hand-selected, otherwise a fixed percentage of the frames was used. This yields a few dozen stacks at short intervals.

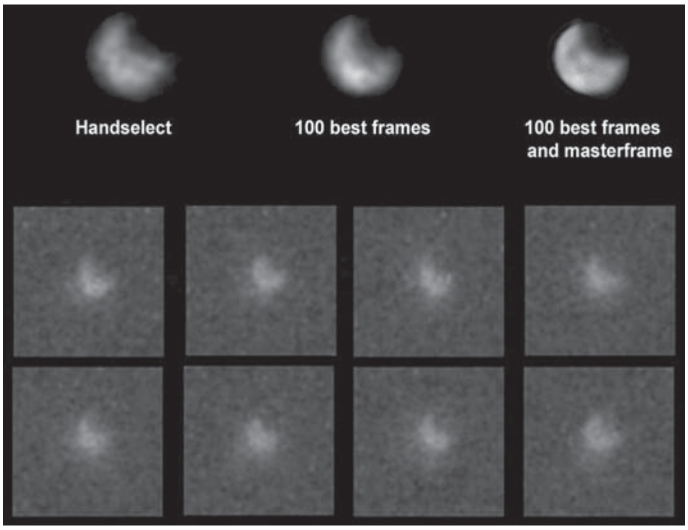

Figure 6. Example of the selection of the best frames recorded during the partial eclipse of Callisto by Ganymede on 2014 Nov 25. The bottom rows show examples of single raw frames. Note the presence of considerable noise. After a slight blur procedure we hand-selected the best images *(top left)*. Next, the best 100 images were combined *(top middle)*. Finally, this image was combined with 35% of a master frame *(top right)*.

Processing of these stacks sometimes yields noisy images. To obtain smoother images two different procedures were used.

The first procedure is to stack three adjacent frames and use these stacks for further processing. So, frames 1, 2 and 3 are combined yielding a new frame 2, subsequently frames 2, 3 and 4 are combined to yield a new frame 3, *etcetera*. This reduces the noise by a factor of three without detectable smearing effects.

The second procedure to improve the signal/noise ratio is to use so-called masterframes.

For this procedure many tens of thousands of frames are captured just before and after the mutual event. Subsequently, the best frames are combined and processed, yielding final images of high resolution and with very little noise (Figure 5). These master frames are then combined at a certain percentage with the images obtained during the mutual event. The percentage of master frames is kept as low as possible to maintain the natural look of the images. In most cases only 25–35% is used as an overlay. The master frames are carefully positioned in *Photoshop* or *Registax* on top of the mutual event frames and eventually the two layers are combined (Figure 6).

Results

Occultations

The first type of mutual events that can be distinguished is the mutual occultations of the Galilean satellites. At the beginning of the period of mutual events interesting close conjunctions sometimes occur, as described in the next paragraph. In addition two examples of occultations will be presented.

Close conjunction of Ganymede and Europa, 2015 Jan 1

On 2015 Jan 1 a close conjunction of Ganymede and Europa took place. The minimum distance of only 0.03" was reached at 01h 26.4UT. Despite poor seeing the close passage was easily visible, as shown in Figure 7. The difference in size and brightness of the two satellites is striking. Note the details visible on the disk of Ganymede.

Figure 7. Close conjunction of Ganymede & Europa, 2015 Jan 1.

Partial occultation of Io by Europa, 2015 Jan 7

On 2015 Jan 7 a partial occultation of Io by Europa occurred. The weather conditions were very unfavourable. The seeing was mediocre, but most disturbing were the clouds during the occultation. The first 7 minutes occurred under clear conditions, but after that the satellites were only seen occasionally, due to scattered patches of cloud. This reduced the qualityof the images.

A photo report of this event is shown in Figure 8. The images were obtained by stacking the best 100 frames and followed by processing with *Photoshop*. The noise

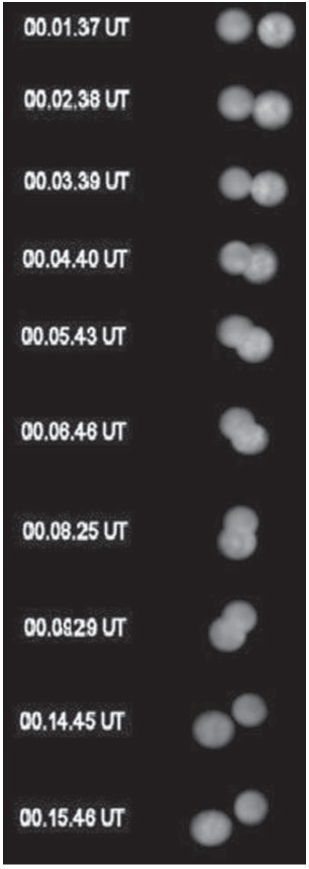

Figure 8. Partial occultation of Io by Europa, 2015 Jan 7. Master frames were used to improve the image quality.

level was reduced and subsequently the contrast was optimised. Master frames were obtained by processing the AVIs from the first 7 minutes of the observation session, when the occultation had not yet started. The raw stacks of the occultation were mixed for 35% with these master frames. The master frames of Io and Europa show distinct details. They demonstrate very well that with current telescopes and cameras detailed images can be obtained even from the Netherlands.

Io partially occults Ganymede, 2015 Feb 19

On 2015 Feb 19 a partial occultation of Ganymede by Io took place. Since the surface brightness of Io is much higher than that of Ganymede the progress of the occultation is easily seen (Figure 9). Maximum occultation was at 23:51UT. However, since Io is much smaller than Ganymede a large section of Ganymede remained uncovered.

Combined occultations and eclipses around opposition

Io occults and eclipses Ganymede, 2015 Feb 12

The 2015 opposition of Jupiter took place on Feb 6 at 19::00UT. In the period around the opposition date it is possible that an occul-

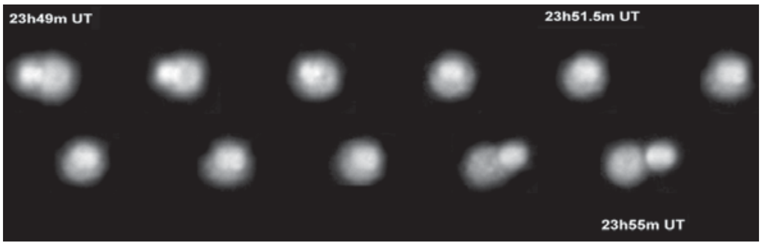

Figure 9. Partial occultation of Ganymede by Io, 2015 Feb 19.

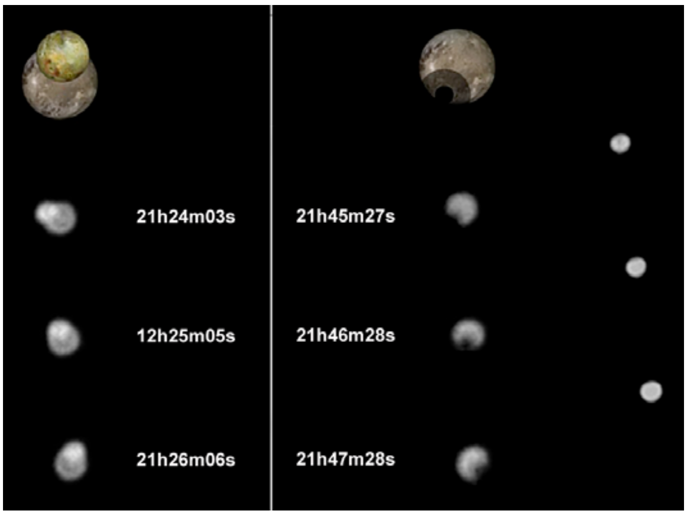

Figure 10. Io occults and eclipses Ganymede, 2015 Feb 12. *Top: WinJUPOS* simulations[11] at 21:26.4 UT *(left)* and 21:46.4 UT *(right).*

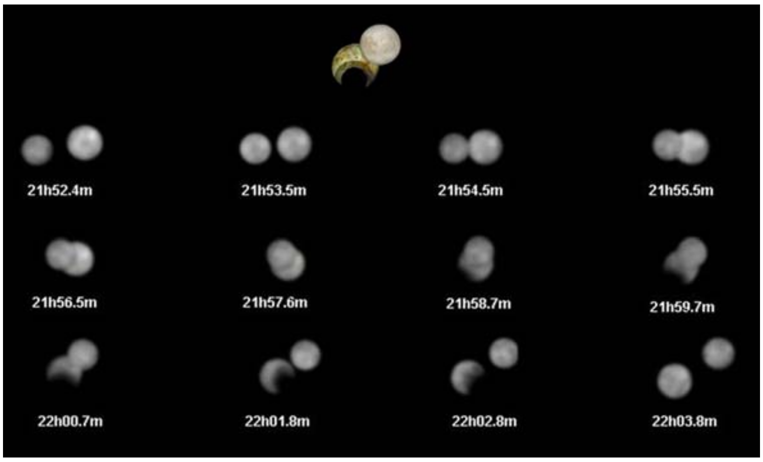

Figure 11. Europa occults and eclipses Ganymede, 2015 Feb 7 *(image J. Sussenbach). Top: WinJUPOS* simulation at 22:00.1 UT.

tation and an eclipse can take place during the same night. A good example of such an event was recorded on 2015 Feb 12 (Figure 10). It started with a partial occultation of Ganymede by Io. Maximum occultation occurred at 21:25UT.

About 15 min after the end of the occultation the shadow of Io reached Ganymede. Maximum eclipse was reached at 21:46.5UT. Note that the shadow shows an umbra as well as a penumbra.

Io occults and eclipses Ganymede simultaneously, 2015 Feb 7

The nearer we approach the date of opposition the higher the chance that simultaneous occultations and eclipses might occur. This was the case on 2015 Feb 7, one day after opposition, when a simultaneous occultation and eclipse of Ganymede by Io took place. Phenomena like these are rare, because they only occur near the date of opposition.

In Figure 11 images of the events are presented showing the approach of the two satellites. At 21:51.5 UT the two satellites touch each other and subsequently the occultation of Ganymede by Io starts. In the subsequent images the progress of the occultation is visible. The image of 21:58.7 UT shows that, while the occultation of Ganymede still continues, the shadow of Io has also reached Ganymede and eventually a simultaneous partial occultation and eclipse takes place at about 22:00.7 UT. Subsequently the occultation by Io finishes, while the eclipse still continues. At 22:03.8 UT the eclipse finishes also and from then on the distance between the two satellites gradually increases. In Houten (Sussenbach's location) the seeing conditions were quite good, whereas in Siebengewald some 90km away where Kivits lived, they were less favourable. Nevertheless even here it was possible to capture the combined occultation and eclipse (Figure 12).

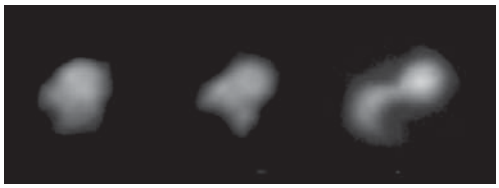

Figure 12. Occultation and eclipse of Ganymede by Io, 2015 Feb 7, midpoint 21:59 UT *(image W. Kivits).*

Eclipses

Partial eclipse of Callisto by Ganymede, 2014 Nov 25

On 2014 Nov 25 a partial eclipse of Callisto by the shadow of Ganymede took place. SER movies were recorded using exposure times of 1 minute at a frame rate of about 35 frames per second. The resulting files were processed as described above. The 100 best frames were stacked and slightly sharpened with *Photoshop CS2*.

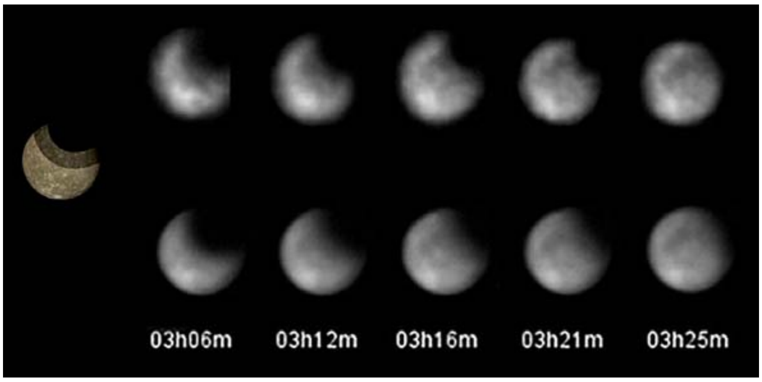

Figure 13. Progress of the partial eclipse of Callisto, 2014 Nov 25. *Top row:* For each frame the best 100 frames were stacked. *Bottom row:* Top row mixed with 50% master frames. Times are in UT. *WinJUPOS* simulation at 03:06 UT.

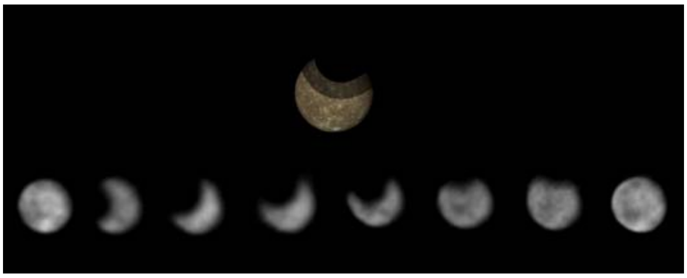

Figure 14. *Bottom:* Partial eclipse of Ganymede by Callisto, 2014 Nov 25 *(W. Kivits)*. *Top: WinJUPOS* simulation at 03:06 UT.

Subsequently, the contrast was increased. The result is shown in Figure 13. A remarkable amount of detail is visible on the small disk of Callisto, which is only about 1.5 arcseconds in size. The frames show a good reproducibility of the different details. This event was chosen to demonstrate the merits of hand selection of images.

In the Methods section above on optimisation of images we described how by using master frames the quality of the final images can be improved. For each time point the best 100 hand selected frames were stacked, yielding the top row of Figure 13. 50% of the images were then combined with a master frame, as shown in Figure 13 bottom row. This shows clearly that the use of the master frames has very little effect on the pattern of the details, but the signal/noise ratio has improved considerably. Interestingly, in this series the expected penumbra is hardly noticeable. Apparently it is so dark, that under these conditions the penumbra can hardly be distinguished from the umbra.

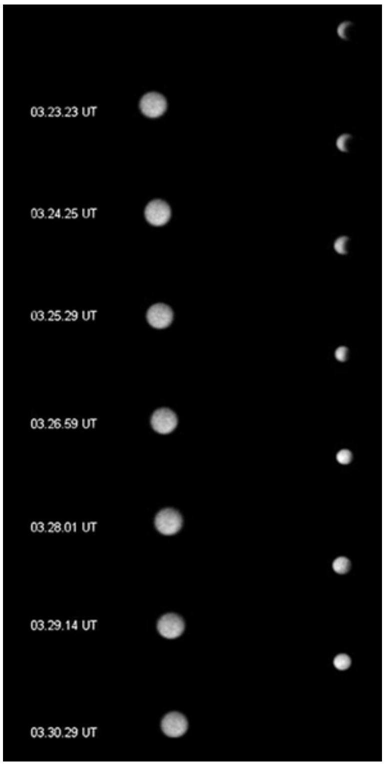

Figure 15. Partial eclipse of Io by Ganymede, 2014 Dec 21 (*J. Sussenbach & W. Kivits*). After stacking, 30% masterframes were used.

Another representation of the eclipse of 2014 Nov 25 is shown in Figure 14. Kivits started his recording a bit earlier so that a larger portion of the eclipse was recorded. The orientation is slightly different in Figures 13 and 14 because of the azimuthal mount used by Kivits. Note the bright spot (*Osiris* region) near the South Pole, that in Figure 14 is located at 6 o'clock, whereas in Figure 13 it is located at about 7 o'clock.

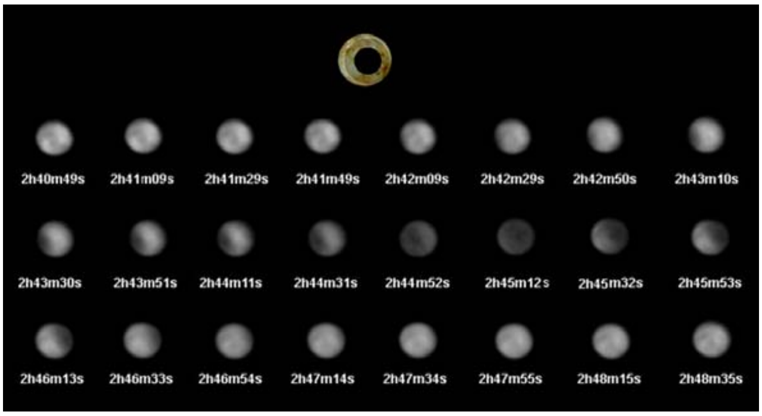

Figure 16. Europa eclipses Io, 2015 Feb 22. *Top: WinJUPOS* simulation at 02:45.2 UT.

Partial eclipse of Io by Ganymede, 2014 Dec 21

On 2014 Dec 21 a partial eclipse of Io by the shadow of Ganymede took place. At the beginning of the eclipse it was so cloudy that no recordings could be made. Only the second part ofthe eclipse was recorded (Figure 15). This time the best 100 frames of each SER movie were stacked and then blended with 30% of a master frame.

The seeing was worse than on 2014 Nov 25. Therefore, it was not possible to detect many details on the satellite surfaces. Here too, the penumbra was indistinguishable from the umbra.

Europa eclipses Io, 2015 Feb 22

On 2015 Feb 22 an almost total eclipse of Io by Europa took place. Europa is smaller than Io and so is its shadow. Therefore, a total

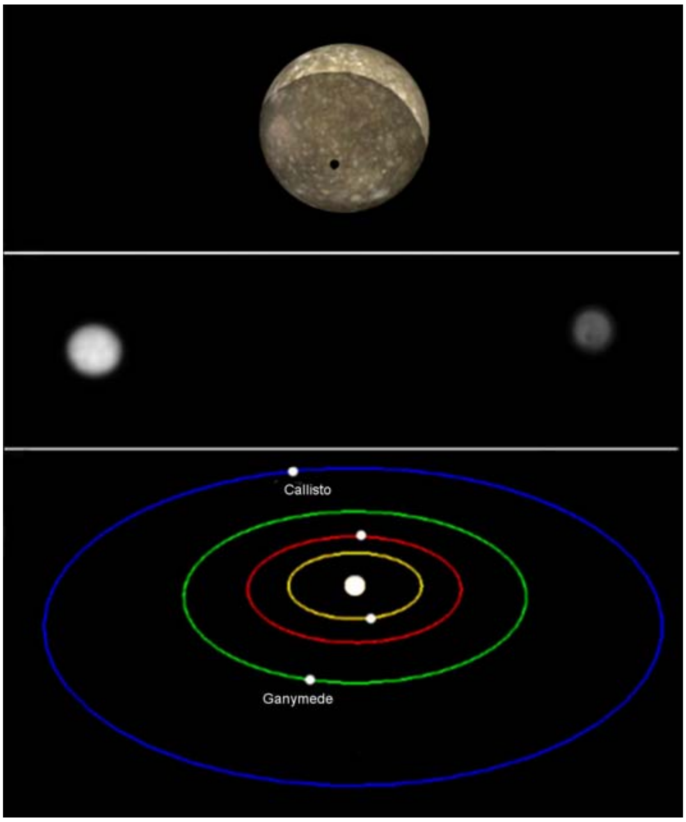

Figure 17. Ganymede eclipses Callisto, 2015 Feb 2. *Top:* simulation with *WinJUPOS*; *Middle:* the actual image and *Bottom:* the Jovian system on 2015 Feb 2.

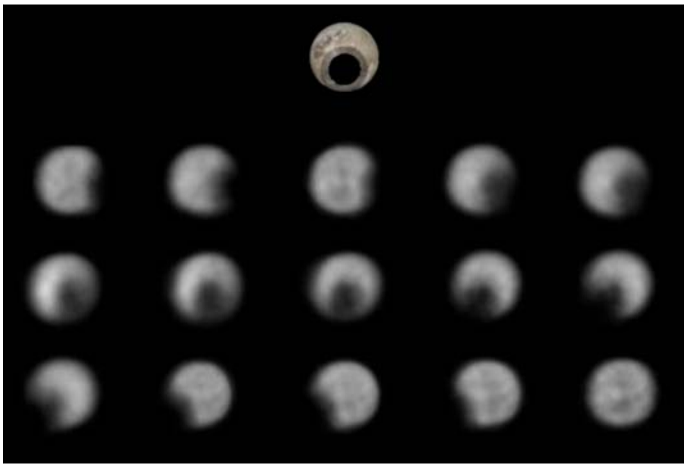

Figure 18. Io eclipses Ganymede, 2015 March 13. 35% master frames were used. *Top: WinJUPOS* simulation at 23:31.3 UT.

eclipse will never happen. However, this was a close call. Interestingly, the eclipse showed a large penumbra, illustrated in Figure 16, which is even more extended than the umbra. The maximum of the eclipse occurred at 02:44.9 UT. Imaging of this phase is extremely difficult due to the very faint image in that stage.

Ganymede eclipses Callisto, 2015 Feb 2

The relative sizes of the penumbra and umbra vary from eclipse to eclipse. It depends on the sizes of the satellites involved and their relative distances. An extreme example took place on 2015 Feb 2, when Ganymede eclipsed Callisto. As shown in Figure 17, Callisto is almost completely eclipsed by Ganymede. However, the contribution of the umbra is quite small as is also shown in the simulation using *WinJUPOS*.

The bottom diagram in Figure 17 shows the reason for this. Callisto and Ganymede are at opposite positions in their orbits and the distance amounts to almost 3 million kilometres. In the actual image, the umbra is slightly larger than expected and this is probably due to turbulence in the atmosphere, which leads to smearing of the image.

Io eclipses Ganymede, 2015 March 13

On 2015 March 13 Io eclipsed Ganymede. The full shadow of Io reached Ganymede, but due to the larger size of Ganymede this led to an annular eclipse (Figure 18). The penumbra was rather small. Note the details recorded on Ganymede.

Discussion

Imaging and processing of mutual events

During the 2014/2015 apparition we were able to capture about 30 different mutual eclipses and occultations. In this report we only show a number of representative examples. In the future we will present a more extensive study including photometric analysis. In this report we have focused on the high resolution imaging aspects of our observations.

The results presented in this paper unmistakably show that with medium-sized telescopes mutual events in the Jovian system can be recorded quite well at high definition. It is clear that the weather conditions play a paramount role in observing details on the Jovian moons. Simultaneous recording with more than one telescope, as described in this article, leads to better results.

In our studies we have used three different type of processing procedures, *viz.* 1) automatic processing with *Autostakkert 2!* or *Registax 6.1*; 2) hand selection of images followed by processing with these two programs and 3) the latter in combination with the use of master frames.

It is our experience that automatic processing of images of the Jovian satellites using the programs *Registax 6.1* or *Autostakkert2!* is often not satisfactory and will not yield the most detail from the recordings. Due to the small size of the objects these programs have difficulty in discriminating between background noise and the structural information in the satellite images themselves. Therefore automatic selection based on image quality is often not satisfactory with these programs and yields mediocre final results, which leads to a poor final image. In this communication we demonstrate that hand selection of images results in a more detailed and sharper final image. It is of course a tedious and time-consuming procedure, but it is certainly worth the effort.

In addition to manual selection of the best frames, which is of course a very tedious procedure, we have introduced the use of so-called master frames. These are high resolution images of the moons obtained by capturing many thousands of frames of the individual moons briefly before and after a particular mutual event. The original image of a stage of an occultation or eclipse is merged with a fixed percentage of a master frame. It is obvious that careful positioning of the master frames is essential and that the creation of artefacts must be avoided. In the case of eclipses only those parts of the master frames can be used that do not coincide with the penumbra and umbra. This approach requires careful consideration.

Evaluation of the use of master frames and other processing techniques

As far as we know the procedures described here to improve the image quality have not been applied by other amateurs. In particular the use of master frames to improve the quality of the images has not been reported before.

It is interesting that nowadays amateurs use different techniques to improve the signal/noise ratio and to obtain high resolution images. For the last few years derotation of multiple images using *WinJUPOS* has become widely accepted to extend the application of images obtained a during a longer time span than the rotation of a planet normally allows. In general, the main part of the planet shows quite nice details, but the borders in particular sometimes show artefacts, due to the nature of this procedure.

Another method frequently employed to improve the resolution of images is the use of multiple alignment points in processing programs like *Registax 6.1* and *Autostakkert 2!*. Although these programs yield decent images it should be realised that they also introduce some minor artefacts. This can be seen when, for example, Jupiter images obtained with alignment points with various different sized alignment areas are combined in a single movie. You must not be surprised to see small bright details jumping a bit in the multi-alignment frame. The reason is that the edges of the alignment areas need to be stitched together, and this leads to some deformation in the stitched areas. However, as long as it stays within certain limits it is acceptable.

In this report we deal with the imaging of mutual events, that often proceed so rapidly that only a small number of frames can be combined without resulting in smearing. We have introduced the use of master frames to improve the signal/noise ratio and to enhance the resolution of the images. Merging the mutual event frames with master frames must be performed in an extremely careful and exact way. If that is done we have found that the images clearly demonstrate both an improvement in resolution of detail and a reduction in noise, without introducing disturbing artefacts.

In the case of eclipse images, merging near the shadow area should be avoided to prevent the introduction of artefacts. Furthermore, when the recordings of the events will be used for astrometric and photometric purposes the master frame procedure should not be applied. With these limitations and considerations in mind and describing precisely how images are obtained, in our opinion the use of master frames is a useful addition to the broad spectrum of processing techniques currently available.

Application of occultation and eclipse data for accurate position determination

In general, mutual occultations of Jovian moons can be recorded at high resolution and this offers an opportunity to time the start and end of an occultation. Careful review of the video images allows the times of contact points to be determined within an accuracy of 15–20 seconds. We are currently investigating whether photometric analysis of the videos might improve the accuracy of timing.

Imaging of eclipses is more difficult due to the presence of a penumbra and an umbra. Due to processing and contrast enhancement of the raw images, artefacts can easily be introduced leading to over or under representation of the penumbra. On the other hand, eclipses are often preferred for photometric timing, because the magnitude drop is usually greater than for occultations, so the midpoint can be determined more accurately. So, it depends on the specific nature of the mutual event, whether it is a useful event for measurement or not.

Photometric analysis of our videos is in progress and hopefully it might improve the timing of contact points and mid-points. Eventually, proper analysis and application of the data obtained with high resolution imaging of these events might be very useful to improve the calculation of the ephemerides of the Jovian system, as has already been demonstrated by Arlot *et al*.[4]

Structural details on the Galilean satellites

We have demonstrated that with medium-sized telescopes, several detailed surface features can be visualised, in particular on Ganymede and Io. It is interesting to compare albedo differences in our images and the maps provided by NASA/JPL. Using the *WinJUPOS* program we produced a simulation of Ganymede on 2015 January 1 (Figure 19). Several similarities can be detected, although there are also differences. It should be realised that the JPL image is based on a mosaic of partial images and that the two images were obtained at different wavelengths. We estimate that resolution of the details is of the order of 0.1 arcsecond.

Figure 19. *Left:* Details on Ganymede, 2015 Jan 1, 01:06 UT. *Right:* A *WinJUPOS* simulation using images from the Solar System Simulator.[12]

Finally, we anticipate that in the near future the possibilities for amateurs to produce high resolution images will continue to increase with, for example, cameras capturing 600 frames per second in different spectral windows, by reduction of seeing effects and preprocessing of images before stacking, etc. In the last few years, one of us (WK) has performed extensive studies on Jupiter's moons and found that about one hundred surface features are detectable on Ganymede, a few dozen on Io and Callisto and perhaps a dozen on Europa. Of course, this was under excellent conditions and using high resolution imaging. Also on the Internet fine images of the Jovian moons are available. There are four small worlds to image and to explore, and in addition, every six years there are these wonderful mutual events to enjoy.

Address (JSS): Meekrap-oord 3, 3991 VE Houten, The Netherlands *[john@jsussenbach.nl]*.

Editor's note: We regret to advise that co-author Willem Kivits passed away on 2016 February 23 at the age of 64. We extend our most sincere condolences to his family and colleagues.

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