TIMING THE ECLIPSES OF JUPITER'S GALILEAN SATELLITES

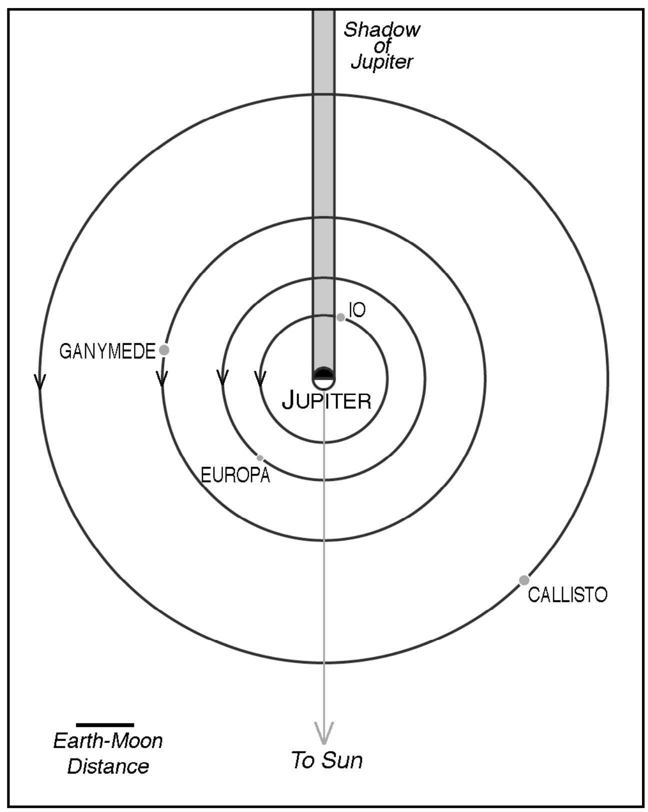
By: John E. Westfall, A.L.P.O. Assistant Jupiter Coordinator, Galilean Satellites
P.O. Box 2447, Antioch, CA 94531-2447, U.S.A. (E-mail: johnwestfall@comcast.net)

BACKGROUND INFORMATION

The four major ("Galilean") satellites of Jupiter form a miniature Solar System, whose "years" are measured in days. Astronomers have monitored the motions of these worlds from Galileo's time to the present to improve their orbital models and to study the effects of tides on the movements of Io and Europa. (In order outward from Jupiter, the Galileans are Io, Europa, Ganymede, and Callisto.) The most accurate ways to measure the positions of these moons are by photographic astrometry with large telescopes and by CCD photometry of the eclipses of these bodies by the shadow of Jupiter. The A.L.P.O. program, however, preserves continuity with almost four centuries of visual timings of these eclipses, investigating the sources of error in making visual timings. The "standard" to which we have compared our timings is the "E-2" ephemeris developed by Dr. Jay Lieske of the Jet Propulsion Laboratory.

The A.L.P.O. began a program of visually timing Galilean satellite eclipses in 1975, and to date (January 2006) has gathered about ten thousand such timings by observers throughout the world.

An eclipse immersion of Io is shown to the right, with the satellites moving counterclockwise as seen from the north. An eclipse begins with the satellite's ingress disappearance and ends with its egress reappearance. When visible, eclipse events are to the celestial west of the planet before opposition, and to the celestial east afterward. Note that an eclipse immersion or emersion may be invisible because Jupiter gets in the way, particularly near the dates of opposition or conjunction with the Sun. For example, only disappearances of Io are visible before opposition, and only reappearances after that date. Except for brief periods near quadrature (and near perihelion), the same is true also for Europa. On the other hand, both disappearance and reappearance can often be seen within a few hours of each other for Ganymede or Callisto. Callisto has eclipses only half the time—for three-year periods separated by three years; its latest eclipse period began in September 2001 and ends in September 2004.



The first step in timing a Galilean satellite eclipse is to know when and where it will occur. If the event is a disappearance, one needs to be able to identify the correct satellite before it disappears. In a reappearance, one needs to know where, in relation to Jupiter, the satellite will reappear. Some publications with this information are The *Astronomical Almanac*, the *BAA Handbook*, the *RASC Handbook*, and on the web at http://skyandtelescope.com under Observing>Celestial Objects>Planets.

Satellite	Diameter km	Distance from Jupiter: Kilometers	Distance from Jupiter: Jupiter Radii	Distance from Jupiter: Apparent arc-sec.	Orbital Period days	Orbital Velocity km/sec.	Penum. Width km	Ingress/ Egress Duration minutes	Eclipse Duration minutes	Stellar Magnitude
Io	3643	421,800	5.90	138	1.769	17.33	754	4.2-4.5	128-138	+5.0
Europa	3130	671,100	9.39	220	3.551	13.74	1200	5.2-6.4	135-174	+5.3
Ganymede	5268	1,070,400	14.97	351	7.155	10.88	1915	10.9-18.2	126-220	+4.6
Callisto	4806	1,882,700	26.33	618	16.689	8.21	3367	16.8-134.8	0-290	+5.6

(The satellites' apparent distances from Jupiter and stellar magnitudes are for mean opposition distance.)

Besides satellites being eclipsed by the shadow of Jupiter, satellite *occultations* occur when they pass behind Jupiter. They can also pass in front of the planet, causing *transits*. Finally, their shadows can fall upon Jupiter, creating *shadow transits*. Sadly, these forms of event cannot be timed as accurately as eclipses.

The Galilean satellites and their eclipses differ from each other in several ways, as shown in the table above. First, the eclipses of the Ganymede and Callisto are much more leisurely than those of Io and Europa, due to the larger diameters and slower velocities of the outer moons. Second, the differences in the immersion/emersion durations are also affected by the width of Jupiter's penumbral shadow. Indeed, Callisto can undergo partial eclipses, which can take several hours. For a given phase angle, outer satellite eclipse events will be appear farther from Jupiter than the events of the inner two moons, and thus glare from Jupiter is less of a hindrance when timing outer satellite eclipses than is the case with the inner.

Our observing program's schedule is determined by Jupiter's apparitions, which last from conjunction to conjunction, a period of about 13 Earth months. Please submit your timing reports shortly after the end of each apparition, rather than by terrestrial calendar year. We analyze timings by apparition, and publish reports on each apparition's timings in the *Journal, A.L.P.O*.

Some information about the next few Jovian apparitions is in the table below, which shows that the period before opposition is just as long as the period after. In order to obtain equal coverage of all forms of eclipses for all four satellites, it is important that observers try to make as many timings before opposition as they do after. Note that eclipse events occur near the glare of Jupiter's disk near the dates of opposition and conjunction. Events are farthest from Jupiter, and least affected by glare, near quadrature, when Jupiter is approximately 90˚ from the Sun. When Jupiter has a northerly declination, observers in the Earth's Northern Hemisphere are favored; when the opposite, those in the Southern Hemisphere.

Jupiter's seasons are indicated because the durations of eclipses are shortest near the solstices and longest near the equinoxes; the opposite is true for the durations of immersion and emersion. Callisto is eclipsed only for three-year periods centered on the equinoxes. Also, near the equinoxes the Earth and the Sun pass through the orbital planes of the satellites, which allows satellite mutual events to occur; when the satellites occult and eclipse each other.

Apparition	Date of Initial Conjunction	Opposition Data: Date	Opposition Data: Distance to Earth A.U.	Opposition Data: Declination	Opposition Data: Apparent Diameter arc-sec.	Jovian Seasonal Events (Northern-Hemisphere)
2003-2004	2003 Aug 22	2004 Mar 04	4.43	8° N	44.5	
2004-2005	2004 Sep 21	2005 Apr 03	4.46	4° S	44.2	
2005-2006	2005 Oct 22	2006 May 04	4.41	15° S	44.6	Winter Solstice (2006 JUN 17)
2006-2007	2006 Nov 21	2007 Jun 05	4.30	22° S	45.8	
2007-2009	2007 Dec 23	2008 Jul 09	4.16	22° S	47.3	
2009-2010	2009 Jan 24	2009 Aug 14	4.03	15° S	48.9	Spring Equinox (2009 Jun 22)
2010-2011	2010 Feb 28	2010 Sep 21	3.95	2° S	49.8	

Timings should be made to 1-second precision. Suitable time sources are GPS receivers, “Atomic” (radio-controlled) clocks, and U.S. National Institute of Standards and Technology time signals broadcast by WWV (Fort Collins, CO) and WWVH (Kauai, HI) at frequencies of 2.5, 5, 10,and 15 mHz (plus 20 mHz for WWV only), or can be heard by telephoning 900-410-TIME. The Canadian (Ottawa) CHU time signal frequencies are 3.330, 7.335, and 14.670 mHz, and the telephone number is 613-745-1576 (English) or 613-745-9426 (French). Other time signal transmitters currently operating are listed on the last page. If you prefer not to use radio signals when actually observing, it is sufficiently accurate to rely on a digital watch which is checked against a radio time signal within a few hours of the event. Don’t expect your observed time to agree with the predicted time; you are timing the beginning or the ending of an event, while the prediction is for the middle. Thus, Io and Europa typically reappear about 1-2 minutes “early” and disappear the same amount “late.” Ganymede’s time difference is more like 4-8 minutes, and can be up to about 15 minutes for Callisto.

Visual Timings

Making a visual timing of an eclipse of one of Jupiter’s satellites is very simple. In the case of an ingress, time the moment when the “last speck” of the satellite disappears. For an egress, time the reappearance of the “first speck.” You can do this with any good telescope over about 5 cm (2 in) aperture, although we recommend fairly high magnifications (the minimum is perhaps 60-80X) in order to clearly separate the satellite from Jupiter’s glare. An eyepiece occulting bar is also recommended, in order to block out the direct light of Jupiter. With high magnifications and eclipses well away from Jupiter’s limb, you also can place the planet just outside the field of view.

Enter and submit all your visual timings on the A.L.P.O. Galilean Satellite Eclipse Timing Report Form. This form need not actually used at the telescope, where you can use whatever method you find convenient as long as all the pertinent data are recorded. Many observers prefer to use a portable audio recorder, recording their voice comments along with a radio time signal. We recommend that you photocopy as many copies of the following form as you need. One reason why it is important to use this particular form is that detailed instructions are given in its lower portion.

Reducing Visual Timings

The program Coordinator reduces the timings. In a typical apparition, several hundred timings are submitted to the Coordinator. They are then organized into groups by satellite (1-4) and event type (reappearance or disappearance). He then finds the the time differences between the observed times of events (first or last speck) and the times of mid-event (ingress or egress) as predicted by the E-2 Ephemeris. He then makes a least-squares regression fit to the following formula, where the telescope aperture in centimeters is x, and the time difference is defined as $Dt = time_{observed} - time_{predicted}$: $Dt = A + B [1/x]$

The effect of aperture is usually statistically significant. Because this model incorporates aperture, timings made with a wide range of apertures may be combined. Coefficient A represents the predicted time difference for a theoretical “infinite” aperture (i.e., for 1/x = 0). The actual residual of each satellite is the mean of its disappearance and reappearance A-coefficients. As an example of this method’s accuracy, orbital 1-s uncertainties for the 1991-92 Apparition, the last analyzed in which Callisto was eclipsed, were ± 38 km for Io, ± 52 km for Europa, ± 88 km for Ganymede, and ± 161 km for Callisto. This analysis is done for every Jovian apparition and then is published in the *Journal, A.L.P.O.*

References

Lieske, J.B. (1981). "Catalog of Eclipses of Jupiter's Galilean Satellites, 1610-2000." *Astron. Astrophys. Supl. Ser.*, 44: 209-16 (May). [The full catalog is available on microfiche.]

Mallama, Anthony. (1991). "Light Curve Model for the Galilean Satellites During Jovian Eclipse." *Icarus*, 92: 324-31.

Mallama, Anthony, Halley M. Aelion and Celeste A. Mallama (2004). "Jovian Satellite Positions from Hubble Space Telescope Images." *Icarus*, 167: 321-29.

Mallama, Anthony, D. Collins, P. Nelson, J. Park and B. Krobusek (2000). "Precise Timings of Galilean Satellite Eclipses and Assessment of the E5 Ephemeris." *Icarus*, 147: 348-52.

Westfall, John E. (1983-84). "Galilean Satellite Eclipse Timings: 1975-82 Report." *J.A.L.P.O.*, 30: 45-53. (Oct.), 105-15 (Jan.), and 145-54 (Apr.).

________ (1986a). "Galilean Satellite Eclipse Timings: 1982/83 Report." *J.A.L.P.O.*, 31: 105-19 (Jan.).

________ (1986b). "Galilean Satellite Eclipse Timings: 1983/85 Report." *J.A.L.P.O.*, 31: 198-206 (July) and 249-58 (Nov.).

________ (1987). "Galilean Satellite Eclipse Timings: 1985/86 Report." *J.A.L.P.O.*, 32: 114-28 (Oct.).

________ (1988). "Galilean Satellite Eclipse Timings: 1986/87 Report." *J.A.L.P.O.*, 32: 245-57 (Oct.).

________ (1989). "Galilean Satellite Eclipse Timings: 1987/88 Report." *J.A.L.P.O.*, 33: 157-67 (Oct.).

________ (1991). "Galilean Satellite Eclipse Timings: The 1988/89 Apparition." *J.A.L.P.O.*, 35: 14-24 (Mar.).

________ (1992). "Galilean Satellite Eclipse Timings: The 1989/90 Apparition." *J.A.L.P.O.*, 36: 63-67 (July).

________ (1994). "Galilean Satellite Eclipse Timings: The 1990/91 Apparition." *J.A.L.P.O.*, 37: 154-64 (April).

________ (1996). "Galilean Satellite Eclipse Timings: The 1991/92 Apparition." *J.A.L.P.O.*, 39: 16-27 (June).

________ (1998). "Galilean Satellite Eclipse Timings: The 1992/93 Apparition." *J.A.L.P.O.*, 40: 14-25 (Jan.)

________ (1999). "Galilean Satellite Eclipse Timings: The 1993/94 Apparition." *J.A.L.P.O.*, 41: 24-35 (Jan.)

________ (2000). "Galilean Satellite Eclipse Timings: The 1994/95 Apparition." *J.A.L.P.O.*, 42: 74-82 (Apr.)

________ (2006). "Galilean Satellite Eclipse Timings: The 1995/97 Apparition." *(in press)*.

Selected Standard Frequency and Time Signal Stations

(Continuous broadcasts only. From Klaus Betke, 31 Aug 2005)

BPM (Shaanxi, China) 5.0, 10.0, 15.0 MHz
BSF (Chung-Li, Rep. of China) 5.0, 15.0 MHz
CHU (Ottawa, Canada) 3.330, 7.335, 14.670 MHz
DCF77 (Mainflingen, Germany) 77.5 KHz
France Inter (Allouis, France) 162.0 KHz
HBG (Prangins, Switzerland) 75.0 KHz
HD1OA (Guayaquil, Ecuador) 1.510 MHZ
JJY (Mt. Otakadoya & Mt. Hagane, Japan) 40.0, 60.0 KHz
MSF (Rugby, United Kingdom) 60.0 KHz
RBU (Moscow, Russia) 66.67 KHz
RWM (Moscow, Russia) 4.996, 9.996, 14.996 MHz
WWV (Ft. Collins, CO, USA) 2.5, 5.0, 10.0, 15.0, 20.0 MHz
WWVB (Fort Collins, CO, USA) 60.0 KHz
WWVH (Kekaha, HI, USA) 2.5, 5.0, 10.0, 15.0 MHz
YVTO (Caracas, Venezuela) 5.0 MHz