Project Jupiter

Prepared for

AAAA Member
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Prepared by

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Abstract

This Project Jupiter document describes the methods used by the American Association of Amateur Astronomers (AAAA) using observations of any of Jupiter's moons to derive their orbital period. From that derived orbital period, computations of the mass of Jupiter, the pull of gravity, and the escape velocity on Jupiter are accomplished. The methods used in Project Jupiter are general and to any planet with a moon. The methods outlined in the report are such that the AAAA members could use their existing equipment for this project and still attain reasonable results. One section of the report is devoted to a presentation based on the observations of the four primary moons of Jupiter by AAAA member Eugene Lanning. That section also compares their results with NASA data values for the orbital period, mass of Jupiter, etc. A suggested press release for a local newspaper is also provided.

The image of Jupiter on the cover page is courtesy of AAAA member Charlie Warren of Texas. Used by permission. Jupiter and three of its moons (Right to left are the moons Europa, Io and Ganymede. Callisto is not on the image.). CCD Image taken February 2, 2002.

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Project Jupiter

I. Purpose

Project Jupiter has five sub-goals, each of which is worthy of the effort involved in completing this project, and each within the reach of American Association of Amateur Astronomers (“AAAA”, a.k.a. “Quad-A”) members.

A. Develop observer’s observing & logging skills

In completing this project the observer will need to schedule a series of observing sessions, and keep a reasonable (but not burdensome) record of the observations at location(s) of their choice. The scheduling will promote regular observing sessions. All of the methods used in this project will require that the observer keep records of what is observed, and develop good estimating of the spacings between objects.

B. Determine orbit period & compare to reference data

The orbit period of a satellite of Jupiter will be determined from the observer’s observation data. Their data will be processed remotely, using a method that will yield the best estimate of the orbital period. The orbital period will then be compared with available reference data from NASA and the percent difference to the observer’s results will be provided. The comparison is intended to promote critical thinking of how the observations could be changed to improve results.

C. Promote Quad-A & Observer

Quad-A is a unique association of amateur astronomers. Members have differing skills, differing interests, each observes from a differing location, and each utilizes differing equipment. That diversity provides a rich Quad-A resource. The Quad-A members are linked together via e-mail and a quarterly newsletter. The dispersion of the observing sites and skills is a rich asset, as Quad-A members freely help other members. Project Jupiter is, in part, to promote Quad-A and the success of the local observer. This is accomplished by creating a press release of the individual member’s participation in Project Jupiter.

D. Determine mass of Jupiter & compare to reference data.

In Project Jupiter Kepler’s third law is utilized to determine the mass of the planet with which the satellite is orbiting. The observer’s data will be used to "weigh" Jupiter. A minimum of non-measured data is used in attaining this goal, illustrating the depth of information that can be derived from a set of observational data.

E. To expand personal horizons of Quad-A members.

By participating in Project Jupiter, many members will perform a project that may stretch their capabilities as previously envisioned. This is expected to lead to participation other challenging Quad-A projects.

F. The observer data will be used to determining other Jupiter characteristics

Additional horizons of Project Jupiter include determining the force of gravity on Jupiter, and the escape velocity[1] on Jupiter.

II. Background

A. Who first observed

"Probably the most significant contribution that Galileo Galilei made to science was the discovery of the four satellites around Jupiter that are now named in his honor. Galileo first observed the moons of Jupiter on January 7, 1610 through a homemade telescope. He originally thought he saw three stars near Jupiter, strung out in a line through the planet[2]. The next evening, these stars seemed to have moved the wrong way, which caught his attention. Galileo continued to observe the stars and Jupiter for the next week. On January 11, a fourth star (which would later turn out to be Ganymede) appeared. After a week, Galileo had observed that the four stars never left the vicinity of Jupiter and appeared to be carried along with the planet, and that they changed their position with respect to each other and Jupiter. Finally, Galileo determined that what he was observing were not stars, but planetary bodies that were in orbit around Jupiter. This discovery provided evidence in support of the Copernican

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1 Escape Velocity is that velocity that an object needs to reach parabolic or hyperbolic orbit around its primary, which permits it to escape to infinity.

2 See Attachment E, taken from http://www.jpl.nasa.gov/galileo/ganymede/discovery.html, by Ron Baalke

system and showed that everything did not revolve around the Earth. "[3]

Galileo originally called the Jupiter's moons the "Medicean planets", after the Medici family and referred to the individual moons numerically as I, II, III and IV. Galileo's naming system would be used for a couple of centuries. It wouldn't be until the mid-1800's that the names of the Galilean moons, Io, Europa, Ganymede and Callisto, would be officially adopted, and only after it became very apparent that naming moons by number would be very confusing as new additional moons were being discovered. [4]

B. Number

Jupiter is typically listed as having twelve moons, although 27 have been discovered[5]. Four of the moons are easily detected in most telescopes, and will be the moons observed in Project Jupiter. The next eight are of magnitude 13 through 19, needing a telescope of greater than 10 inches of aperture to detect the moons visually.

Detailed information about all of the moons of Jupiter is available at http://nssdc.gsfc.nasa.gov/planetary/factsheet/joviansatfact.html

III. Orbits

It has been shown by others that orbiting bodies follow an elliptical shaped (not egg shaped) orbit about the more massive body. In the early era of astronomy it was thought that the orbits were circular, as that was regarded as being more "perfect". Indeed, as a first approximation the orbits are very nearly circular – with a few exceptions. The circular approximation is sufficient for the purposes of the work accomplished in Project Jupiter because of the limitations of separation measuring equipment available to most amateurs.

In the vastness of space, there is no "up" or "down", or preferred direction. As such

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3 Taken from http://www.jpl.nasa.gov/galileo/ganymede/discovery.html, by Ron Baalke

4 Source: http://www.jpl.nasa.gov/galileo/ganymede/discovery.html, by Ron Baalke.

5 Some sources report 39, perhaps a number that will yet increase. All of the newly discovered satellites are small and not observable by amateurs.

the plane of the orbit of bodies may be at any angle to the observer. In double star work that is especially true, so the observed orbits may be viewed as if an observer were perpendicular to the orbit, nearly in the plane of the orbit, or in between those positions. The differing perspective distorts the perceived shape of the elliptical orbit. Fortunately for Project Jupiter the plane of the orbits of Jupiter's moons are such that the orbit characteristics may be determined with relative ease.

IV. Period Determinations

A. Why

The orbital period of a satellite/moon or planet is a fundamental parameter that is used to describe the relation of one object to another. The orbit period is a quantifiable parameter that may be precisely transmitted to others.

B. Predictions of positions

Because the orbital period may be determined with a high degree of accuracy – how much accuracy is dependent on the skill of the observer, the amount of time devoted to the task and the quality and type of equipment available – future positions of the object observed may be made with good confidence. This predictive capability is expected to be examined in a future AAAA project, to derive interesting conclusions.

C. The Period and its Relation to the Mass of the Planet

When the period of an orbiting body is known, then Kepler's Third Law (more later) and Newton's Law of Gravitation may be combined to enable one to calculate the mass of the body being orbited. Part of Project Jupiter is to perform those calculations.

D. What about other Planets?

While Project Jupiter is designed around the planet Jupiter, the technique is general to orbiting bodies[6]. Its application to any planet that has a satellite (including Earth) will yield corresponding information about the planet being orbited. The application to some planets may be limited by the ability of the telescope to resolve the satellite-planet spacing, or be constrained by the limiting magnitude of the telescope system in use.

V. Methods for Period Determination

Three methods are outlined in this section, the third of which will be used in Project Jupiter.

A. Occultation Method

One method to determine the orbital period of a satellite, if it is regularly disappearing behind a object (being hidden, occulted) is to measure the time interval between the occultations. While this is possible to do, and will be used as a method in a future Quad-A project, it will not be used in this Project Jupiter. The reason that it will not be used here is that it requires that the observer be observing at the exact time of the occultation, there is no latitude in the time of the observation. Also, if clouds should obscure viewing in that particular part of the sky when the occultation is to occur, then the observation timing has to be restarted.

Further problems consist of the magnitude difference between the satellite and the planet disk. When the magnitude difference is large, then the timing becomes subject to the judgment of the observer as to when the satellite was occulted.

An additional nuance is that the satellite will disappear when either it disappears behind the planet, or when it enters the shadow of the planet. Unfortunately the position of the shadow of the planet changes with time. Alternatively, one could time the reappearances. Timing the re-appearance is complicated because it is more difficult to time and detect the

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6 The model does have to be significantly upgraded to be used on moons whose orbits are significantly inclined to the Earth's orbit, i.e., those moons that do not orbit nearly in the plane of the ecliptic.

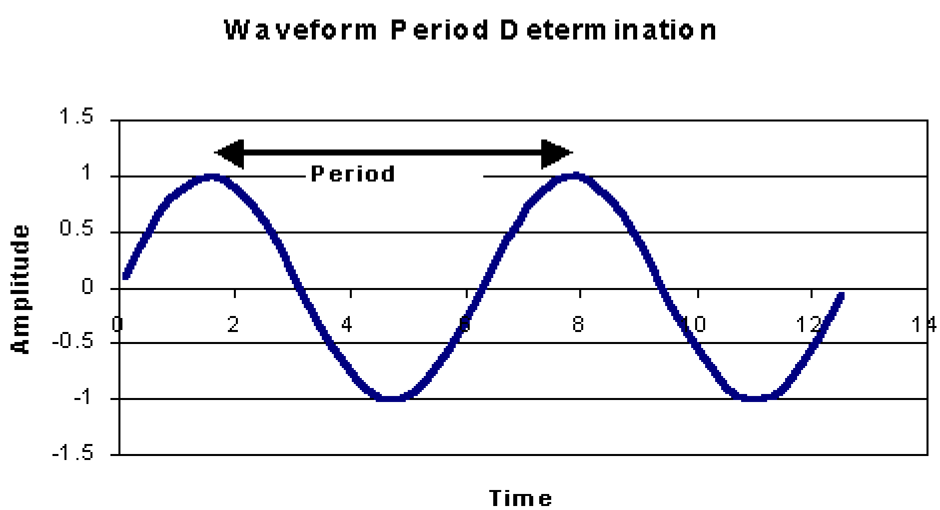
reappearance of the satellite from behind the planet without reference to external data sources and it is not an easy task to master.

The problem of accurate and repeatable timings is further compounded when the planet is one of the gas giants, as the planet lacks a sharply defined edge[7].

Because Quad-A members do not have the luxury of spending hours at the eyepiece to catch the exact occultation time, because of the magnitude differences in Jupiter and the satellites, and because Jupiter is a gas giant planet, the timings of the occulations will not be used in this project.

B. Maximum Extent Method

One definition of the period of a sinusoidal wave form is that the period is the time between successive peaks (or valleys), as illustrated below. The Maximum Extent Method is the application of this concept by estimating the period when the satellite is at its maximum extent (at its peak distance) from the planet.



By monitoring the motion of the satellite, and noting successive points at which the satellite is at its maximum extent from the planet, a person could

[7] For the gaseous planets, the diameter of the planet is defined where the atmospheric pressure is equal to 1 atmosphere.

infer an orbital period. This method has limited accuracy when the orbit of the satellite is nearly in the plane of the observation. As the satellite approaches its maximum extent the transverse (left-to-right or left-to-right) motion slows because the satellite motion at that time is mostly radial (away or towards the observer). The slow transverse motion makes it difficult to determine the time at which the true maximum occurs. The radial motion is not detectable in the typical amateur astronomer's equipment.

Because it would be difficult to determine when the maximum distance from Jupiter occurs for the satellite that the observer selects, this method has more uncertainty in determining the orbital period, and will not be used in Project Jupiter.

C. Fitting of Data Method

A statistical/mathematical term "Fitting of Data" means seeking the best formula that will reproduce the experimental (observed) data. If the data and the formula answers are reasonably close (one rarely gets a perfect agreement), then a person makes the assertion that the formula correctly represents the data, and the formula may be used for other related uses. The Quad-A member observation data is forwarded for the fitting of the data by an EXCEL spreadsheet created for Project Jupiter. Of primary of interest will be the orbit period, a value that the spreadsheet is designed to determine.

The process of finding the best formula, and hence the period, works best if there are a sufficient data so that the chance variations in the data are averaged out, i.e., when there is sufficient data to make observational or measurement errors not a major factor. For Project Jupiter the requested number of data points (observations) is from 8 to 20, for statistical reasons that will not be elaborated on here.

The process of fitting data to equations works best if there is at least one pattern in the data is provided for analysis. For Project Jupiter, that means that preferentially that data from at least one complete orbit of the moon selected for observing is supplied for analysis. Selecting the interior moons of Jupiter may not be the most advantageous, even though they complete their orbit sooner. The orbit time is smaller, but the data is harder to measure (the percentage error in the observation data will be larger). Observations over additional orbits will, however, offset the larger percentage of observational error.

The fitting of data method was selected for its ease in application with a wide variety of observer equipment. Also, the method was selected because the method can be refined in other Quad-A projects in experiments to determine other orbit parameters.

VI. Kepler's Third Law

Project Jupiter will be using an enhanced version of Kepler's Third Law, an enhancement that considers Newton's Law of Gravitation.

A. Who was Kepler?

Johannes Kepler was a German mathematician and astronomer that lived from 1571 to 1630. At the time Kepler was alive, Newton's Law of Gravitation was not yet discovered[8], so Kepler's Third Law is expressed as a proportion rather than an equation.

B. The Laws of Kepler

Based on his observations, Kepler developed three revolutionary thoughts. Thoughts that have withstood the test of time and scientific scrutiny to rise to the classification of a "Law". His Laws, paraphrased, are:

1. <u>#1: The shape of a planetary orbit is an ellipse.</u> The same hold true for the orbital shape of a moon about a planet. For ellipses, there are two "centers" (called foci) rather than just one center as for a circle. The more massive of the objects being orbited is located at one of the foci.
2. <u>#2: A line connecting the planet and the sun sweeps over equal areas in equal time periods.</u> Again, the same is Law applies for a moon orbiting a planet.
3. <u>#3: The square of the siderial period[9] of a planet is proportional to the cube of the semi-major axis distance the planet is from the sun.</u> Again, this Law holds for any moon orbiting a planet.

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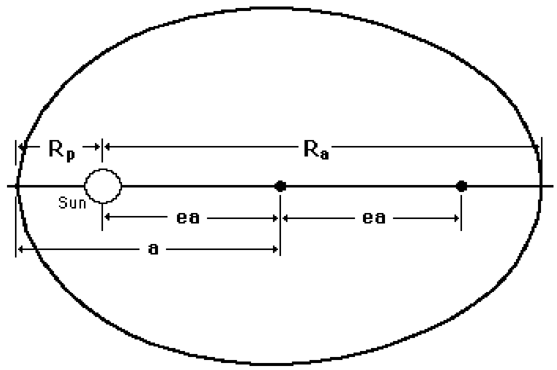
[8] Newton's laws were formulated around 1666, and published in 1687.

[9] Siderial period is the time it takes to make one complete orbit as seen from the surface of the body being orbited.



In the exaggerated diagram above, the semi-major axis length is labeled as 'a'. Because of the mass of the sun, the difference between distance a and distance R_p is actually small.

C. Examining Law #3

Law #3 is the Law that enables us to "weigh" Jupiter in Project Jupiter, when combined with the Law of Gravitation. For the mathematically inclined, the mathematics are in presented Attachment D. Attachment D is the solution for a circular orbit, an approximation that does not contribute too much uncertainty for Project Jupiter.

Normally an observation series like Project Jupiter is done in a college-level astronomy course. One exciting strength of Quad-A is that its members share expertise freely. This writeup is one such example of shared expertise that is intended to allow all Quad-A members to participate in this project, as the member need not personally fuss with the attendant mathematics.

VII. Observing Suggestions

A. When to observe

The first Quad-A application of Project Jupiter is anticipated to be the Fall of 2002. At that time Jupiter is well situated in the southern sky early in the morning, and is high enough that even observers that leave for work early in the morning can make a brief observation.

Project Jupiter may be performed at any time when Jupiter is suitable for viewing over 3 weeks or more. Project Jupiter is not date sensitive, and the Fall of 2002 is simply the first application of the Project.

B. How Often to Make Observations

Better estimates of the orbital period are attained with more observational data. The observer is encouraged to not only observe when the moon of Jupiter is at its maximum separation, but also to obtain data for the smaller separations. For the more widely separated moons (longer orbital period moons) each observer needs to make their observations over at least one orbit, preferably more orbits. For the outer moons, the observational dates may also be more widely spaced, providing flexibility for the observer.

Observation guidance:

1. Generally try to make around 12 observations, more if possible, but cover at least one complete orbit (as judged by when it reaches the maximum separations – resist the temptation to look up the orbital period in a book! After all, this project is to find things for ourselves, not look up information!).

   The observations may be terminated before 12 to 18 sets are obtained if the intermediate results produce an accuracy in determining the mass of Jupiter that is acceptable to the observer.

2. The observing sessions do not have to be on consecutive days. Even when days are planned to be skipped, a skipped observing session due to clouds[10] does not present a hindrance. The same applies to personal affairs that may preclude observing on a given day.

3. The observing sessions need not be equally spaced in time. The program that processes the observing data compensates for skipped days, irregular observation times of day, and so on.

4. Make sure your data is for the same moon. As the moon of your choice for project Jupiter nears Jupiter, its identity may be confused with the other moons. It may be easier to measure and record separations for all of the moons of Jupiter, or to start the observation sessions when the selected moon is at its maximum separation. It is permissible to submit data for more than one of Jupiter's moons for this Project Jupiter, but separate out the observation data for the

[10] Record show that Galileo's observations of Jupiter's moons on January 14, 1610 were not made because it was cloudy. Clouds just do not respect anybody!

different moons.

5. Transits in front of the planet reveal the different surface brightnesses of the satellites themselves: Callisto and Ganymede very dark, Io a faint grey, and Europa usually invisible against the bright clouds. Therefore, visual recordings of a satellite in transit, while possible, are not likely.

VIII. Data Gathering Methods

The participating Quad-A observer may select any of the methods described in this section, as data from any all of them may be directly input into the Excel program for analysis. It is the observer's choice, but once a method is selected, it should be used for all of the Project Jupiter data for that moon.

A. Jupiter Diameter (JD) Method

1. Basics

This method uses apparent size of Jupiter as the unit of measure. While the apparent size of Jupiter does change appreciably over the course of a month of observations, the satellite separations vary in proportion, so the JD method is suitable for a rough unit of measure. It has been reported that Kepler used this measure in his efforts to determine the orbital periods of Jupiter's satellites.

2. Estimating Spacings

The observer may want to practice estimating distances (suggested practice sessions with mock data prepared beforehand[11]). Another helpful hint is to use a higher power eyepiece. The ratio of Jupiter's diameter to the moon spacing is relatively low (below about 1:15), in a region wherein the mind can more easily estimate the separation.

The Quad-A observer using the JD method may have varying degrees of success in estimating the separations. Inaccuracies are expected, but the goal here is to improve your observing skills, not to expect perfection. The fitting of the observed separations (See Section IX) will tend to help smooth out the inaccuracies.

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[11] Six practice examples, and the solutions, are provided in Attachment F.

Mr. C. Warren, a Quad-A member, contributed a useful idea for Project Jupiter. Mr. Warren found a piece of stiff plastic screening material with a wide and even weave. He made a little tube of cardboard, and applied the plastic weave to the top of the tube with tape. He then placed that over his eyepiece. It worked quite well on top[12] of the eyepiece, as his Nagler™ has good eye-relief with an adjustable sleeve. He selected an eyepiece focal length such that Jupiter nearly filled one mesh square, making the estimates of the moon spacings simply a matter of counting the mesh lines. He did find that the plastic weave itself was a little heavy (about ⅛ JD), so he needed some minor repositioning of the mesh to ensure each moon was visible. No one asserts that this measuring-by-mesh method is precise[13], but may be an improvement over unaided estimates of the JD spacings.

3. Need to use same eyepiece & scope

Because the separation of the satellite in any given observation is to be compared to other observations, there is a need to have consistent estimates from one observation to the next. The focal length of the eyepiece directly influences the FOV (as do other parameters that vary between eyepieces). Better orbital period estimates are obtained with observations from the same telescope and eyepiece combination.

4. Eyepiece Selection

Use higher power eyepieces, as they generally reduce the field of view (FOV) so that the proportionality of the satellite separation to the FOV is small. This makes the estimating of the moon separation as easy as possible. Details of the planet surface features, while interesting, are not needed for this project. Select an eyepiece that as that enables the maximum separation to be still in the FOV during subsequent observations without having to change eyepieces.

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[12] Experiments with placing the mesh near the focal plane, inside of the eyepiece, determined that the mesh was too magnified to be useful there.

[13] Because the mesh is not in the focal plane, the user needs to be careful that unwanted parallax is not introduced into the measurements.

Observers using a telescope lacking tracking capabilities will need to use a lower power eyepiece. That enables Jupiter and it's selected satellite remain in the FOV long enough to enable the observer to make a reasonably estimate of the JD value to be logged (It is harder to make a good estimate when the object moves more rapidly through the FOV.).

The apparent separation of the satellites from Jupiter will vary considerably over about six months (See Attachment G). Because of this the appropriate eyepiece (selected for FOV) for subsequent uses of Project Jupiter (not measures during a set of observations) may change.

5. Data Logging

During each observing session estimate the separation, in units of Jupiter Diameters (JD), of the selected moon from the center of Jupiter. Avoid the tendency to "smooth" the data at this stage. If on observation #2 the separation is 4 JD, on observation #3 it is 6 JD, and on observation #4 it is 5 JD (went back down), that is OK. Report what you observed, not what you think the separation should be! For each observation, record the separation measurement (in JD) on the data sheet (Attachment A). Note that when the moon is emerging (or disappearing behind) Jupiter that the spacing is 0.5 JD

B. Sketch Method

1. Basics

During each observing session the user makes a sketch on paper of the positions of the Moons as seen in the eyepiece. Later the separation on the sketch is measured and is then used as one data point in the Jupiter Project data analysis. This method requires no special equipment, but more observations than normal (try to get around 20) are recommended so that the inherit inaccuracies in any sketch may mitigated by the abundance of data.

2. Eyepiece Selection

Because the separation of the satellite in any given observation is to be compared to other observations, there is a need to have a consistent FOV from one observation to the next. The focal length of the eyepiece directly influences the FOV (as do other parameters that vary between eyepieces). Consistency of the sketches is enhanced when the same telescope and eyepiece combination are used for all sketches.

3. Use a high power eyepiece for sketching.

The use of higher power eyepieces generally reduces the field of view (FOV). The smaller FOV reduces the proportionality of the satellite separation to the FOV, making the sketching as easy as possible. Details of the planet surface features, while interesting, are not needed for this project. Select an eyepiece that as that enables the maximum separation to be still in the FOV during subsequent observations without having to change eyepieces.

Observers using a telescope lacking tracking capabilities will need to use a lower power eyepiece. That enables Jupiter and it's selected satellite remain in the FOV long enough to make a reasonably proportioned sketch (it is harder to make a good sketch the faster the object moves through the FOV.).

4. Eyepiece FOV

It is helpful if the field of view (FOV) of your eyepiece is determined before the observing sessions begin. This is not a required step, but may aid the observer in estimating separations when the FOV is known.

To determine the FOV, select a star near the celestial equator (within ±5° of zero declination) and time the star as it crosses the diameter of the field of view. Multiply by 15 to convert that clock time into arc-seconds (or arc-minutes if timed in minutes).

5. Use same size sketch circles

Because this method will obtain the separation between the satellite and the center of Jupiter by placing a ruler on a sketch, each sketch should be similarly sized. That is, for a given eyepiece that has a FOV of say 30 arc-minutes, the sketches should consistently use the same scale for the FOV.

For ease of recording data, it is suggested (not required) that the observer use "The Astronomer's Journal, An Observing Log and Sketch Book", available from AAAA's own www.AstroMax.com. That Journal has a convenient and consistent method of recording field observations that encourages consistency and completeness of observations.

6. Advanced Eyepieces

It is helpful in making sketches if an observer has a reticle eyepiece (an eyepiece with a built-in scale). This is a help, not a necessary piece of equipment to the successful completion of Project Jupiter. The scale on the eyepiece need not be calibrated in order to make to scale sketched.

For those interested, both Meade Corporation (see www.Meade.com and look for the Astrometric eyepiece at about $150) and Celestron (see www.celestron.com and look for the Micro Guide Eyepiece #9471) make such eyepieces. Another option is to see if another member of your local astronomy club would be willing to loan you one for this project. As stated, these eyepieces are a sketching aid, not a requirement for the successful completion of Project Jupiter.

7. Data Preparation

Measure the separation of the selected Moon from the center of Jupiter on each of the sketches made. It is recommended that the familiar inches and fractions be avoided by measuring the separations on the sketch in mm. Avoid the tendency to "smooth" the data at this stage. If on observation #5 the separation is 5 mm, on observation #6 it is 8 mm, and on observation #7 it is 6mm (went back down), that is OK. Report the data as sketched. For each observation, record the separation measurement (in mm) on the data sheet (Attachment A).

C. CCD/Astrophotography Method

1. Accuracy

The basic techniques used here are the same as the Sketch Method, but with the inaccuracies of the hand sketching removed.

2. Basics

During each observing session the observer takes an astrophoto or CCD image(s) that contains the moons of Jupiter. Later the separation on the photo/image is measured and is then used as one data point in the Jupiter Project data analysis.

3. Camera lens / CCD equipment Selection

Because the separation of the satellite in any given observation is to be compared to other observations, there is a need to have a consistent FOV from one observation to the next. The observer needs to select equipment that as that enables the maximum separation of the moon to be still on the images made during subsequent observations[14] without having to change your equipment.

4. Magnitude Differences

Because the magnitude of Jupiter and its satellites varies considerably, it is recommend that one image be taken of Jupiter with its moons and a separate and lesser-exposed image of Jupiter be taken. To image the satellites adequately the image of Jupiter is over exposed and pixel bleeding makes the image of Jupiter larger than is really the case. This contributes to position uncertainties.

It should also noted that the magnitude of Callisto is nearly a full magnitude less than the other satellites. Thus, the image that contains Callisto may need a slightly longer exposure.

Particular challenges with Jupiter are the low-contrast image and the strong limb-darkening. Therefore, points to consider are:
-- Adding many short exposures can be better than taking single exposures.
-- CCD chips are most sensitive in the near-infrared, so an unfiltered image looks like a red-light image (with rather low contrast though potentially fine detail), and may suffer particularly from chromatic dispersion. Imagers are recommended to use an infrared exclusion filter.
-- Because of limb-darkening, some form of digital unsharp-masking is needed to bring out the limb. Most observers process their images to reduce limb-darkening and enhance contrast. Such image-

14 Attachment G shows that the arc-second size of the images can vary by around 10% during the course of the observations.

processing should be done judiciously with awareness of the artefacts that it can create; check that there are not conspicuous rings around satellite shadows, nor any saturated white areas in the image.

5. Image Scale

It is helpful if the field of view (FOV) of your equipment is determined before the observing sessions begin. This is not a required step, but enables fewer assumptions to be made in the processing of your data. A variety of techniques may be used here, including creating star trails on the images from a timed exposure with the drive turned off.

To determine the FOV, select a star near the celestial equator (within ±5° of zero declination) and make a timed exposure. Multiply the exposure time by 15 to convert that clock time into arc-seconds (or arc-minutes if timed in minutes), then divide by the trail length to obtain the number of arc-seconds per pixel on the CCD electronic image or per mm on astrophotos.

6. Data Preparation

Measure the separation of the selected Moon from the center of Jupiter on each of the images made. It is recommended that the familiar inches and fractions be avoided by measuring the separations on the images directly in pixels on the computer fro CCD images, before prints of the images are produced. Measuring in mm for astrophotos is recommended. Avoid the tendency to "smooth" the data at this stage. If on observation #5 the separation is 80 pixels, on observation #6 it is 95 pixels, and on observation #7 it is 90 pixels (went back down), that is OK. Report the data as imaged. For each observation, record the separation measurement (in pixels or mm) on a separate line on the data sheet (Attachment A).

D. Astrometric Eyepiece Method

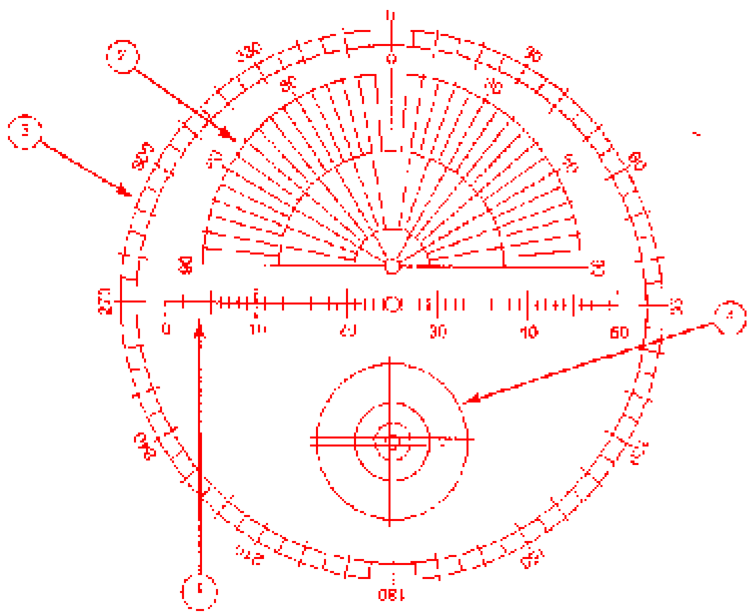
1. Accuracy

The basic techniques used here is the calibration of a reticle eyepiece to enhance the capability to measure separations that are normally only estimated.

2. Basics

The observer may use the Meade Corporation Astrometric eyepiece[15] or the Celestron Micro-Guide Eyepiece[16] to make the needed measurements. Rather than purchasing one of those eyepieces, see if another member of your local astronomy club would be willing to loan you one for this project.

The reticle markings in the Meade advanced eyepiece are:



Where ① is the linear scale that, when calibrated, is used to measure separations of objects, ② is the semicircular Position Angle Scale, ③ is the 360° Position Angle scale, and ④ is a Double Crossline/Concentric Circle area used for guiding.

During each observing session the observer takes measurements of the distance between moons of Jupiter and the center of the Jupiter image. Each measurement is then used as one data point in the Jupiter Project data analysis.

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15 See www.Meade.com and look for the Astrometric eyepiece, at about $150.

16 See www.celestron.com and look for the Micro Guide Eyepiece #9471

3. Equipment Selection

Because the separation of the satellite in any given observation is to be compared to other observations, there is a need to have a consistent calibration from one observation to the next. The observer needs to select equipment that as that enables the maximum separation of the moon to be still in the FOV during subsequent observations without having to change your equipment.

4. Reticle Scale

It is helpful if the field of the linear scale in your eyepiece is determined before the observing sessions begin. This is a required step before data submission to maximize the use of the calibrated eyepiece.

Provide the calibration ratio of the arc-seconds per Astro-Metric Unit (AMU) on the data sheet. Also, provide as a separate attachment the calibration effort (position of reference star & timings) for the eyepiece[17].

The use of a Barlow to make more accurate measurements when the Moons are close to Jupiter is encouraged.

5. Data Logging

Measure the separation of the selected Moon from the center of Jupiter on each on each observing session. It is recommended that the scale units be recorded, as that "raw" data will be multiplied by the scale factor within the EXCEL program. Avoid the tendency to "smooth" the raw data at this stage. If on observation #3 the separation is 15 reticle units, on observation #4 it is 14 units, and on observation #5 it is 16 units, that is OK. Report the data as measured. For each observation, record the separation measurement (in scale units) on a separate line on the data sheet (Attachment A).

---

[17] Mizar Consulting has generated a spreadsheet for this purpose. The spreadsheet evaluates the declinations and makes corrections, reviews the data for consistency, and produces a statistical analysis of the calibration effort. Contact Mizar Consulting to obtain a free copy.

Also, on one session, record on Attachment A the diameter of Jupiter, in reticle scale units.

If a Barlow lens is utilized for some observations, please annotate Attachment A with the additional magnification used.

IX. Data Processing

A. Remote processing of the observer data

One strong benefit of Quad-A is that members freely share the level of expertise that they posses. For this Project Jupiter an EXCEL spreadsheet was created to process observer's separation data. The EXCEL sheet is available on request[18] from Mizar Consulting.

B. Data Transmittal

Each observer transmits their separation data sheet(s) (filled out Attachment A) to Mizar Consulting by private e-mail, via the Quad-A group mail, or by postal service.

When four to five sets of separations are obtained, it may be beneficial to have a preliminary review of the data performed. The spreadsheet used has some capacity to predict Jovian moon positions, a capability that assists in moon identification in later observations.

C. Effects of Changes in the Distance to Jupiter

As the Earth and Jupiter move in their respective orbits (the orbits are indicated by circles) the apparent size of Jupiter changes with time. When Jupiter is at Opposition, its apparent size is larger than when it is at Conjunction. See the diagram on the next page for a visual representation.

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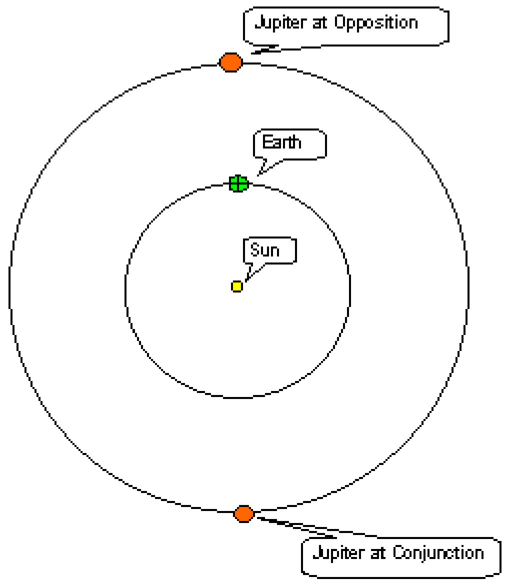
[18] At no cost, no obligation, and no additional solicitations or other mailings



For other than the measurements using the JD method, the EXCEL spreadsheet compensates for the changes in the apparent angular size of Jupiter (See Attachment G). Thus, the observed separations are normalized to a common Earth-Jupiter distance.

D. Effect of Planet Positions

During the observations, both Jupiter and Earth have orbital motion. The orbital motion not only changes the distance between the planets, but also the angle of viewing. As the angle between Earth and Jupiter changes the observer sees a different orientation of the orbit of the moon of Jupiter. At the beginning of the observations, for a moon at its maximum Eastward extent, let the position of the moon be 0°. The maximum Westward extent would then be 180°.

As the observations continue the angle between Earth and Jupiter changes by some amount, say 16°. Thus at the end of the observations the maximum extents are now 16° and 196° (each extent progressed by 16°). If an orbit period was equal to the observation time, then the moon would have begun at 0° and ended at 196° (more than 180°). If the orbit period were half the observation period, then the moon would have begun at 0° and ended at 188°. Thus while each orbit appears to have 180° between maximum extents, the true travel angle slightly different. The observed data is modified to account for this effect by the EXCEL spreadsheet.

E. Goodness of Fit

For Project Jupiter the best estimate of the orbital period, and other parameters, is determined mathematically from the observation data. Mathematically there are several measures that may be used to judge when the observed data is best reproduced by the computer. Prior tests have shown that the true elliptical orbit variation from an assumed circular orbit need not be considered for Project Jupiter.

Four measures of the Goodness of Fit used in the computer model are:

1. Standard Deviation

One measure of the fidelity of the data (how well it is trending) is the statistical measure called the Standard Deviation. The larger the Standard Deviation, the larger is the variation in the data being considered.

When the orbital period is being estimated, the observer's moon positions are subtracted from the position computed by the EXCEL program. As the EXCEL program inputs begin to match the observer's data the Standard Deviation value begins to drop. The value does not get to zero because of observational biases, errors, transcription mistakes, difficulty in estimating small separations, etc. The EXCEL program computes the Standard Deviation, so the Quad-A observer need not be concerned with the mathematics.

The concept here is that the statistical measure called the Standard Deviation is used as an indicator of when the orbital inputs best match the observed data. When a good match is found the Standard Deviation value reaches a minimum.

2. Correlation Coefficient

The Correlation Coefficient is a statistical comparison of two sets of data. The Correlation Coefficient ranges from -1 to +1, with ±1 representing the strongest (best) similarity measure ("correlation").

The observer's Project Jupiter separation data is compared with EXCEL generated data for a sinusoidal curve. When a computed "correlation coefficient" approaches 1.0 its is an indication that the computed separations are strongly matching the observed separations.

One of the EXCEL inputs for the sinusoidal formula is the orbital period, so a high correlation coefficient is one indicator that the orbital period input is the best estimate possible. As the Correlation Coefficient value approaches 1.0, it is also confirmation that the orbit is not strongly elliptical, validating an earlier assumption.

3. Least Squares

When two data sets are compared, one measure of their similarity is to examine the differences in the individual data values. By taking each value and multiplying it by itself ("squaring it") negative values do not cancel positive values, and the check becomes a sensitive check of the similarity of data sets. When the sum of the squared values is a minimum, the best agreement between the data sets has been determined.

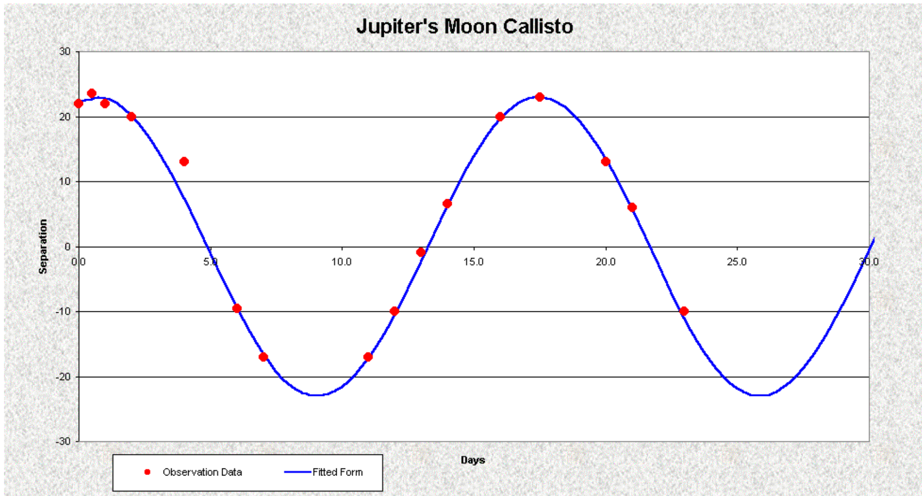
The EXCEL generated data is automatically subtracted from the observer's data, squared, and then summed. The program automatically displays the result so that the user can know when the minium value has been found. This provides added assurance that the best determination of the orbital period, based on the transmitted Quad-A observer's data, has been found.

4. Residuals

Residuals are the differences between what was observed and the mathematical representation of the process observed. Usually the residuals themselves do not have a pattern to then, they are randomly distributed. The Project Jupiter analysis makes reasonable graphical efforts to ensure that no residual biases impact the determined orbital period.

F. Processed Data

The observer's data is be processed into a graphical format, similar to the below image. The EXCEL program will be used to determine the orbit period rather than subjectively reading from the graph.



X. Observer's Data Results

A. Assumptions

1. A circular orbit adequately represents the true orbit for the selected moon of Jupiter.
2. The Meade Epoch2000™ planetarium type software program correctly provides the distance to Jupiter from the Earth (Geocentric distance) and the relative positions of the planets. Alternatively, for most observer data applications, the orbit mean- diameter for each of Jupiter's moons is obtained from NASA data.

B. Orbit Period Determined

The data supplied data by Eugene Lanning, replicated in Attachment A, was processed and is graphically shown in Attachment B. Excerpts from observation logs are provided as Attachment H.

Data obtained from the NASA website (http://nssdc.gsfc.nasa.gov/planetary/factsheet/joviansatfact.html) provided the reference data for accuracy determinations.

The results, by moon, are:

Moon	Orbit Period determined, days	Standard Deviation of data	Regression Coefficient	% Accuracy
Io	1.76950	0.65 AMUB	0.9974	100.0
Europa	3.55491	0.49 AMUB	0.9995	99.9
Ganymede	7.1593	0.56 AMUB	0.9998	99.9
Callisto	16.7355	0.62 AMUB	0.9998	99.7

The moon resonance parameters were also determined

Moon	Determined Resonance	Accuracy
Europa	2.009	-0.002
Ganymede	4.047	-0.003
Callisto	9.460	-0.026

Suspected data points:

> The third observation of Ganymede is different from the predictions by more than 2δ.
>
> The first and fourth observation of Europa is different from the predictions by more than 2δ.
>
> The first observation of Io is different from the predictions by more than 2δ.

The above cited data points are not conclusively erroneous, but are suspected as being abnormal – perhaps due to incorrect scale readings or drifting of the planet Jupiter from its reference position. Nevertheless, they were not excluded from the data analysis presented in this report.

C. The Weighing of Jupiter

CCD image courtesy of AAAA member Charlie Warren

The weighing of Jupiter is accomplished by using a variant of Kepler's Third Law that incorporates Isaac Newton's Law of Gravity. When the orbital period of a satellite is combined with an orbit diameter, then the mass of the planet being orbited may be calculated. The same EXCEL spreadsheet that estimated the orbital period performs these computations.

Eugene's data was used to estimate the orbital period of each of Jupiter's moons. Using NASA data for the orbital radii, the computed orbital periods yielded mass estimates for Jupiter as shown below:

Moon	Mass of Jupiter, Kg	$Kg_{Jupiter} / Kg_{Earth}$
Io	1.8976 E27	317.666
Europa	1.8946 E27	317.166
Ganymede	1.8950 E27	317.235
Callisto	1.8901 E27	316.405

The observed-weight-averaged-determined mass of Jupiter is 1.8952E27 Kg, or 317.264 times the mass of the Earth.

NASA often uses the mass of Jupiter, and their value (at http://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html) indicates a reference mass of $1{,}898.6 \times 10^{24}$ Kg (317.83 times the mass of the Earth). Thus the Eugene's data weight-averaged data is within 0.2% of the reference data.

The Astrometric calibration data supplied (Attachment I) enables the removal of one value obtained from NASA in the above analysis. The fitted-orbital parameter "Amplitude" (The orbital radius) was combined with the supplied arc-seconds per unit of measure to yield the radii of the orbit for each moon, in arc-seconds "ϕ". Using the distance to Jupiter the orbital size in Km was computed[19].

The orbital size determinations per the above description were:

Moon	Radii, Km	% Accuracy
Io	411,092	97.5
Europa	673,213	99.7
Ganymede	1,086,580	98.5
Callisto	1,905,924	98.8

The use of the computed orbital radius data and the computed orbital periods yielded mass estimates for Jupiter as shown below:

Moon	Mass of Jupiter, Kg	$Kg_{Jupiter} / Kg_{Earth}$
Io	1.7592 E27	294.501
Europa	1.9143 E27	320.458
Ganymede	1.9845 E27	332.211
Callisto	1.9600 E27	328.102

The observed-weight-averaged-determined mass of Jupiter is 1.8711 E27 Kg, or 313.236 times the mass of the Earth.

19 The formula is radius = distance * tan ϕ

NASA often uses the mass of Jupiter, and their value (at http://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html) indicates a reference mass of 1,898.6x10^{24} Kg (317.83 times the mass of the Earth). Thus the Eugene's data weight-averaged data is within 1.4% of the reference data. The Astrometric Eyepiece calibration has a standard deviation of 0.7% (Attachment I) and is a significant source of the above deviation.

D. Gravitational Force and Escape Velocity

The relative pull on objects on the "surface" of Jupiter[20] could be computed using the classic formula

$$F = \frac{GmM}{r^2}$$

Using NASA data for the diameter of the planet and Eugene's weight-average computed mass for Jupiter yields in the formula results in a weight[21] ratio of 2.47. This means that if an object on the Earth's surface weighs 1 lb, it will weigh 2.47 Lbs on the surface of Jupiter.

The computed weight ratio is within 4.6% of NASA's value (See http://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html) a ratio of 2.364 . NASA was contacted regarding the large bias. The large variation is because of NASA's treatment of Jupiter as a rotating body. Thus, the larger bias is not attributable to observer logging errors or to poor observing skills.

20 For the gaseous planets, the diameter of the planet is defined where the atmospheric pressure is equal to 1 atmosphere. Should a person be on the "surface", there is nothing there to support you!

21 The mass (Kilograms) of an object does not change on Jupiter, or on any other planet. Its weight (in pounds) does, however, change.

The Escape Velocity is that velocity such that an object may break free of the gravitational force. The escape velocity is found using the formula

$$escape \quad vel = \sqrt{\frac{2GM}{r}}$$

Using NASA data for the diameter of the planet and Eugene's computed mass for Jupiter in the above formula yields an escape velocity of 59.47 Km/Sec. The computed escape velocity is within 0.1% of the value used by NASA, namely 59.5 km/sec (see http://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html).

E. Predictive Capabilities

On October 15, 2002 Sky and Telescope issued a bulletin concerning an occultation of the moons of Io and Europa. The bulletin read "Its [Jupiter] moon Europa partially occults Io (another Jovian satellite) on the 17th (5:38 to 5:42 a.m. EDT)."

Predictions from the Project Jupiter spreadsheet, based on Eugene's observations, nearly nailed the time of this event. The orbital plane of the moons is nearly the same, but not exactly. The observations of Project Jupiter were intended to measure the mass of Jupiter, not exact moon occultations. Therefore the Project spreadsheet predicts separations but not occultations of one moon by another. The Project Jupiter spreadsheet predictor did predict the same separation for Io and Europa between 09:35 UT and 09:36 UT. At that time Io and Europa will be on the same side of Jupiter and have the same separation. Ganymede and Callisto will be on the opposite side, with Callisto being closer than Ganymede.

An observing session was used to monitor the occultation . The separation of the moons was recorded at 41, 19.5, and the pair at -13.5 AMUB. Pickering[22] (http://uk.geocities.com/dpeach_78/pickering.htm) =3 or 4 skies prevailed, skies unsuitable for accurate Astrometric measurements. Clouds

22 Two points are worth noting: 1) The Pickering scale is not intended for use with other apertures, but was specifically designed for a 5" objective. 2) Pickering intended that assessment of the seeing according to this scale should be carried out with a magnification of not less than x25 per inch on a test star of magnitude 1 or 2. Even a fairly small difference in aperture from the 5" norm makes this scale unsuitable.

in the area prevented plotting the closure of the separations, and by 09:42 UT observations were terminated.

F. Adequacy for determining c

The data was reviewed for the adequacy of determining the speed of light, analogous to the methods used by Romer. The difference between the NASA value for the orbit period and the observed orbit period was computed for each satellite, and then that difference per orbit was projected out for six months. If the accumulated difference was on the order of one or two minutes, then the data would be useful for determining the speed of light.

The "C Factor" (6 month accumulated orbit time difference) was

Moon	C Factor
Io	53.8 Min
Europa	4.6 Hrs
Ganymede	2.91 Hrs
Callisto	12.17 Hrs

The above C-Factor times are not adequate for determining the speed of light. Also, the formulation for the effects of the change in viewing angle are not developed enough to support the speed of light experiment.

XI. Other Contemporary Quad-A Results

A. Number Participants in Project Jupiter

In the initial Fall of 2002 Project Jupiter there were 6 AAAA members that participated in the project and submitted at least partial data as of the date of this report. Most members observed and logged the separations all of the moons of Jupiter, for a total of 50 Project Jupiter observation data sets.

B. Methods Utilized

The participants used a variety of techniques to estimate the separation of the moons from Jupiter. A breakdown by method is:

Method	Number of observation sets
JD Estimating	28
Sketching	3
CCD/Astrophotography	5
Astrometric Measurements	14

C. Results by method

The accuracy for which the orbital period is determined varies with the observing technique selected. The results for determining the orbital period, independent of the moon selected, is:

Method	Ave. % Difference
JD Estimating	0.8
Sketching	Indeterminate
CCD/Astrophotography	3.8
Astrometric Measurements	0.2

XII. Conclusions

AAAA members participated in a regular early-morning observing program named Project Jupiter in the Fall of 2002. During each session the separation between planet Jupiter and several of its Moons was recorded.

The observational data obtained by Eugene was entered into an EXCEL spreadsheet, determining the best estimate of the orbital periods:

1.76950 days for Jupiter's moon Io,
3.55491 days for Jupiter's moon Europa,
7.1593 days for Jupiter's moon Ganymede and
16.7355 days for Jupiter's moon Callisto .

The observational data was also used to calculate the mass of Jupiter as 1.8952E27 Kg, a value within 0.2% of available reference data. The weight of objects on Jupiter to within 4.6%, and the escape velocity on Jupiter to within 0.1%.

Although the results are better than expected, they are not useful in determining the speed of light as a separate Quad-A project.

Attachment C is a suggested press release highlighting Quad-A member Eugene Lanning's participation in Project Jupiter.

Project Jupiter

Attachment A: Data Sheet

Observer: Eugene Lanning (ealanni@alltel.net)

Observing Location Latitude: 40° 40' N Longitude: 95° 55' W

Telescope Brand: 8" Meade LX200 SCT (Nominal fl=1280mm)

Eyepiece: 12 mm fl

Astrometric Eyepiece (if used) Arc-Sec to AMU ratio: 6.42

CCD (if used) Arc-Sec to Pixel ratio: 0

Measuring System: AMUB (AMU, AMUB, mm, JD, or pixels)

Satellite Observed: Callisto

Observation	Observing at Date (GMT)	Observing at Time (GMT)	Jupiter Center to satellite spacing
1			
2	9/3/02	10:38	-56.0
3	9/5/02	11:10	-14.9
4	9/7/02	10:52	33.0
5	9/9/02	10:25	64.3
6	9/11/02	11:10	61.3
7	9/12/02	10:58	47.0
8	9/15/02	10:39	-24.6
9	9/17/02	10:30	-61.0
10	9/20/02	11:49	-55.5
11	9/21/02	10:41	-37.1
12	9/26/02	10:42	68.0
13	9/30/02	10:35	21.5
14	10/17/02	09:42	19.5
	Obs =	13	

Satellite Observed: Europa

Observation	Observing at Date (GMT)	Observing at Time (GMT)	Jupiter Center to satellite spacing
1	8/30/02	11:26	-24.0
2	9/3/02	10:38	-7.0
3	9/5/02	11:10	16.0
4	9/7/02	10:52	-20.0
5	9/9/02	10:25	24.3
6	9/11/02	11:10	-22.9
7	9/12/02	10:58	12.5
8	9/15/02	10:39	-11.0
9	9/20/02	11:49	21.0
10	9/21/02	10:41	-15.0
11	9/26/02	10:42	2.6
12	9/30/02	10:35	18.6
13	10/17/02	9:42	-13.5
14			
	Obs =	13	

Project Jupiter

Observation	Satellite Observed:		Ganymede
	Observing at		Jupiter Center to satellite spacing
	Date (GMT)	Time (GMT)	
1	8/30/02	11:26	-39.0
2	9/3/02	10:38	33.0
3	9/5/02	11:10	13.0
4	9/7/02	10:52	-37.0
5	9/11/02	11:10	38.1
6	9/12/02	10:58	19.5
7	9/15/02	10:39	-33.0
8	9/17/02	10:30	25.2
9	9/20/02	11:49	-9.0
10	9/21/02	10:41	-34.5
11	9/26/02	10:42	30.0
12	9/30/02	10:35	-18.0
13	10/17/02	09:42	41.0
	Obs =	13	

Observation	Satellite Observed:		Io
	Observing at		Jupiter Center to satellite spacing
	Date (GMT)	Time (GMT)	
1	8/30/02	11:26	9.3
2	9/3/02	10:38	-13.0
3	9/5/02	11:10	-2.5
4	9/7/02	10:52	8.0
5	9/9/02	10:25	15.3
6	9/11/02	11:10	12.2
7	9/12/02	10:58	-7.1
8	9/15/02	10:39	-9.0
9	9/17/02	10:30	-15.0
10	9/26/02	10:42	-14.1
11	9/30/02	10:35	6.9
12	10/17/02	09:42	-13.5
	Obs =	12	

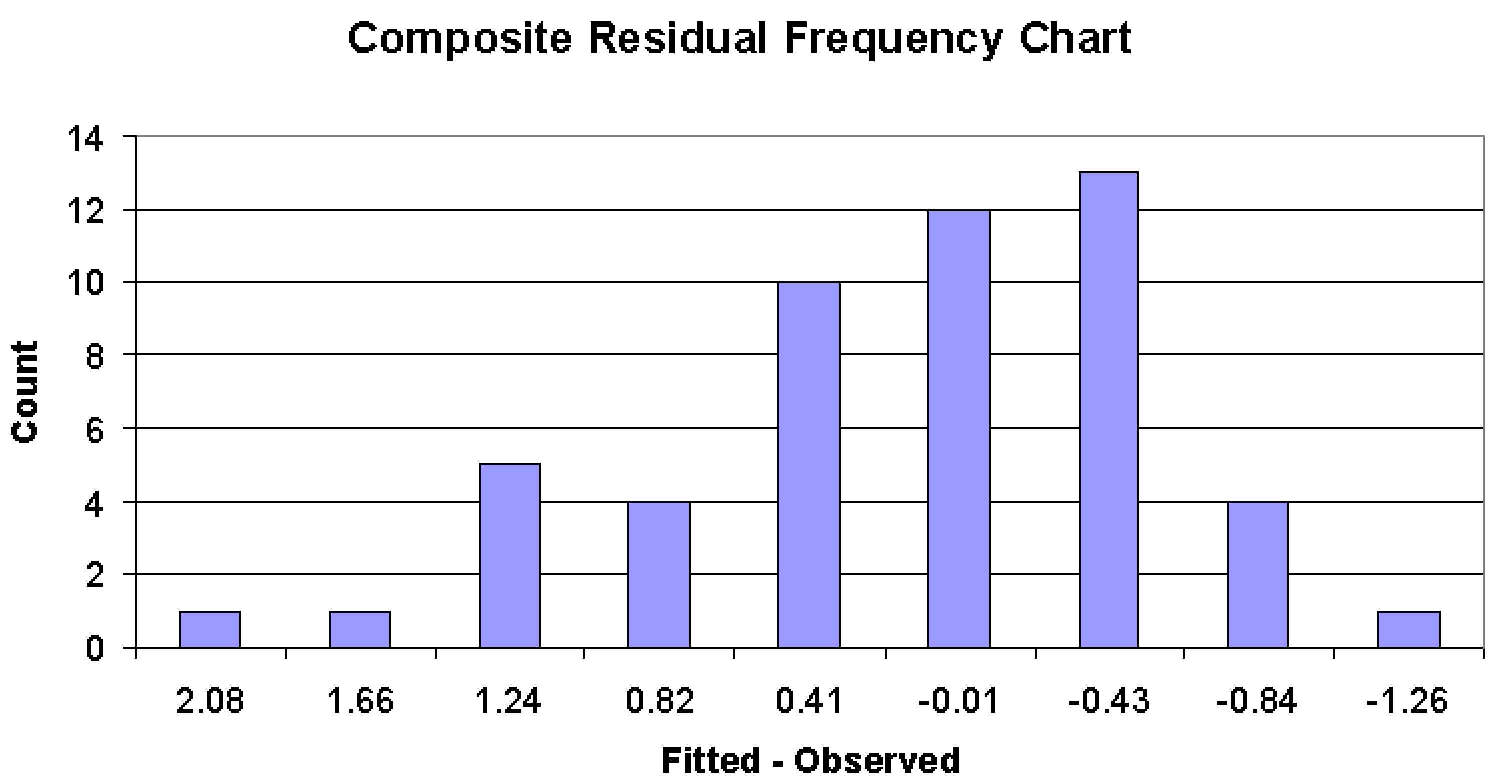
General notes:

A. There are 14 observing sessions in the above data.

B. With North up, westward positions are entered ***positive*** values.

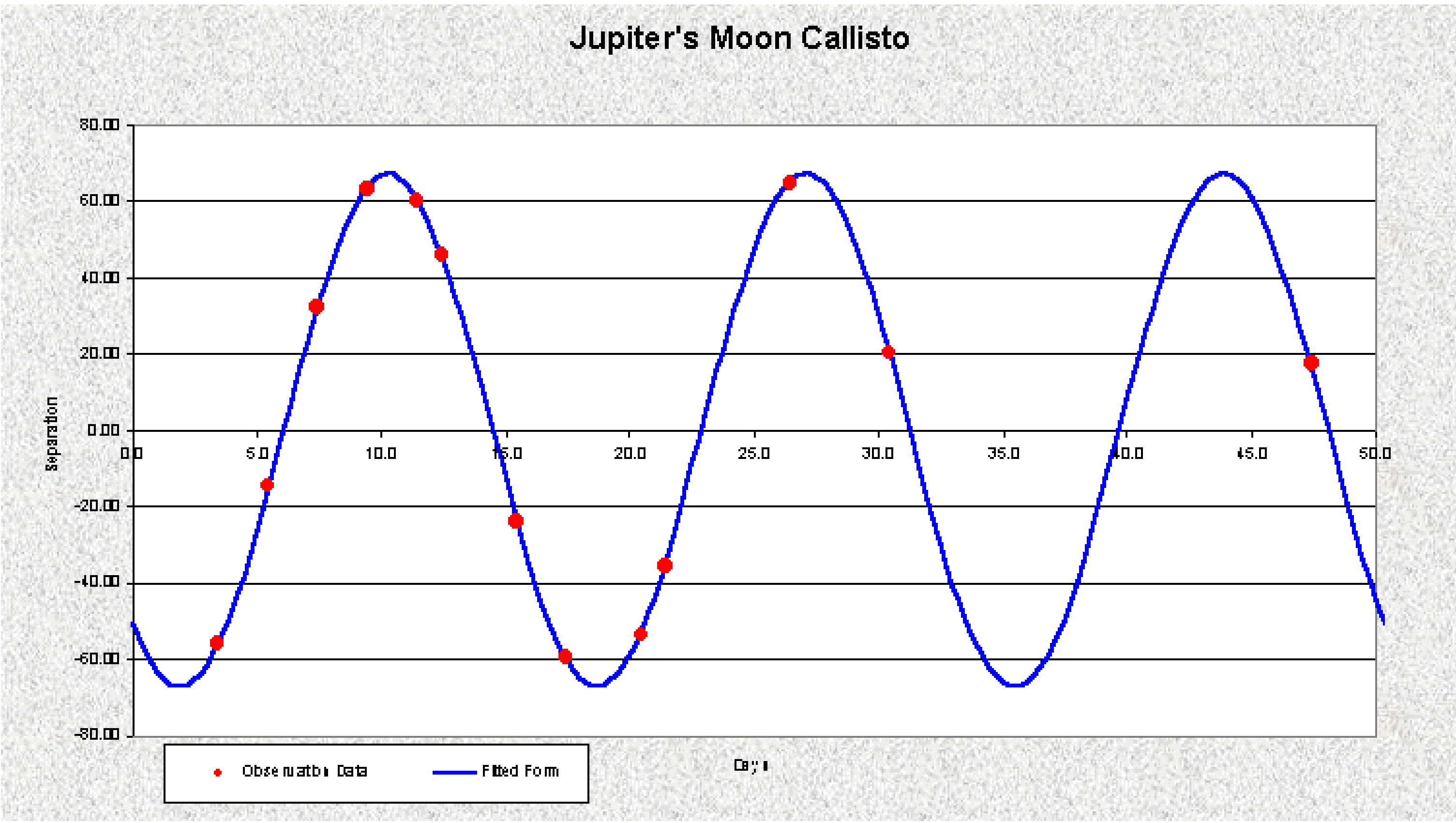
Attachment B: Processed Data Representation

The composite (all four moons) deviation of the observations from the determined respective orbit is:

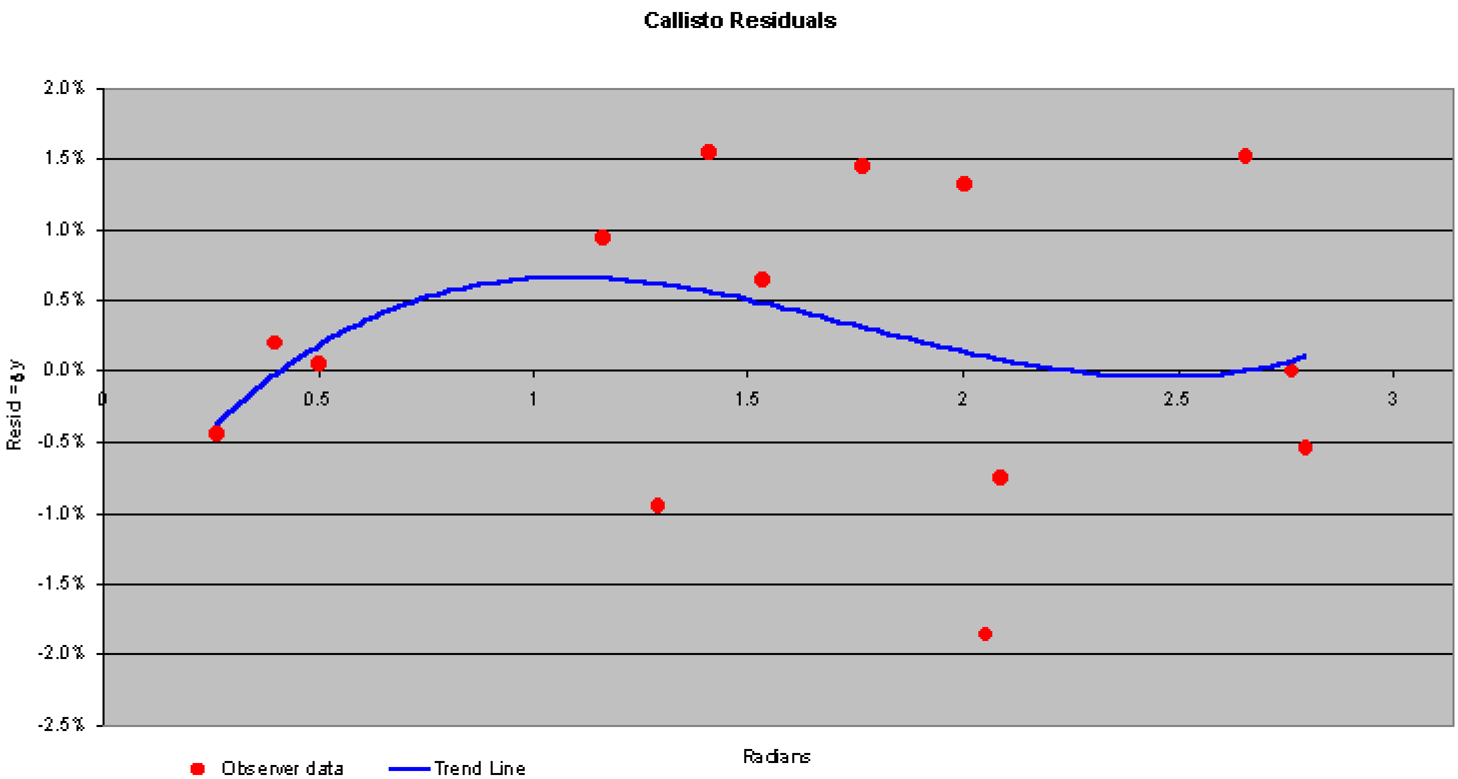


The trend is roughly normally distributed and is accepted.

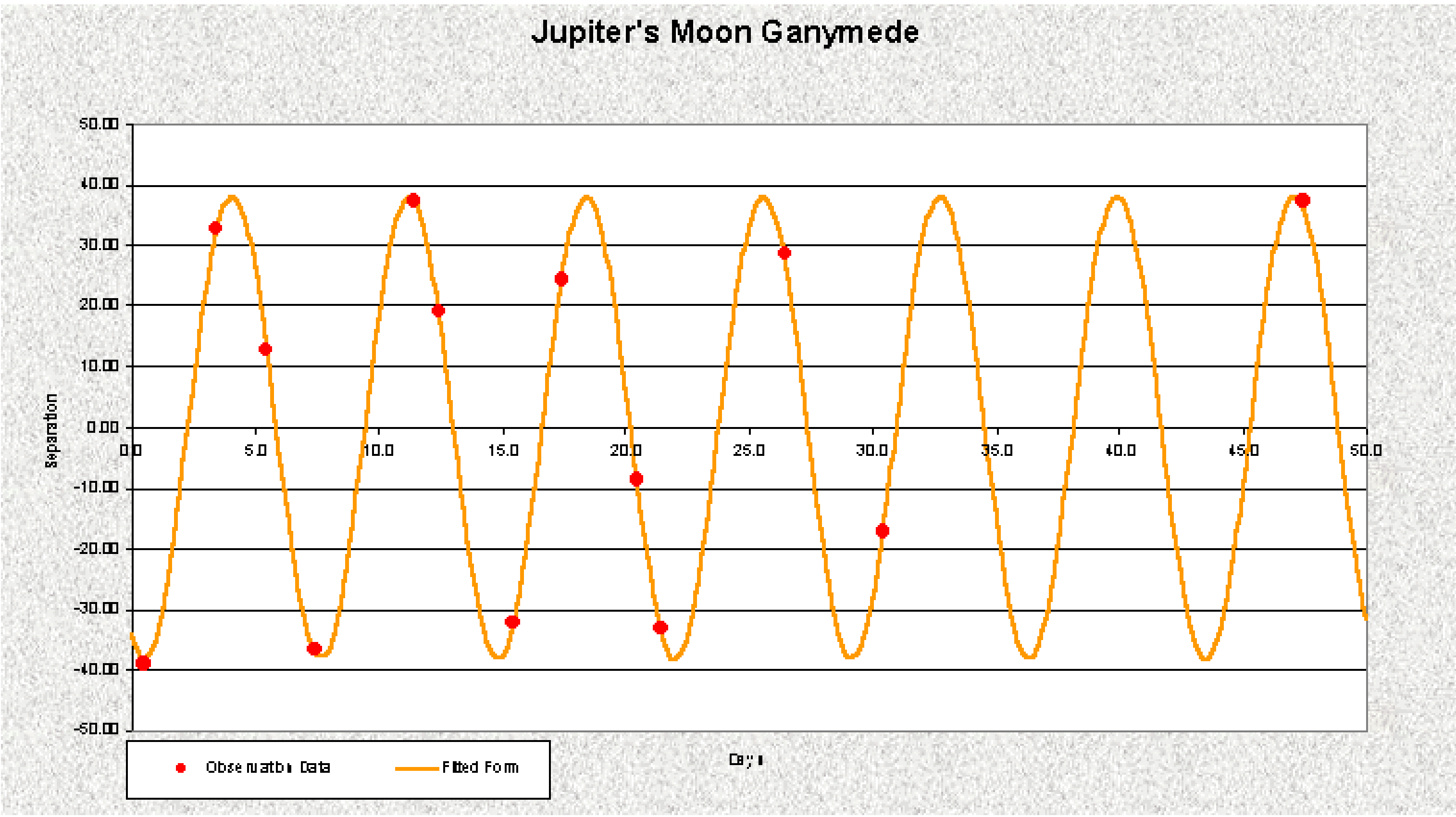
For the moon Callisto, the orbit was fitted to the observations as shown below.



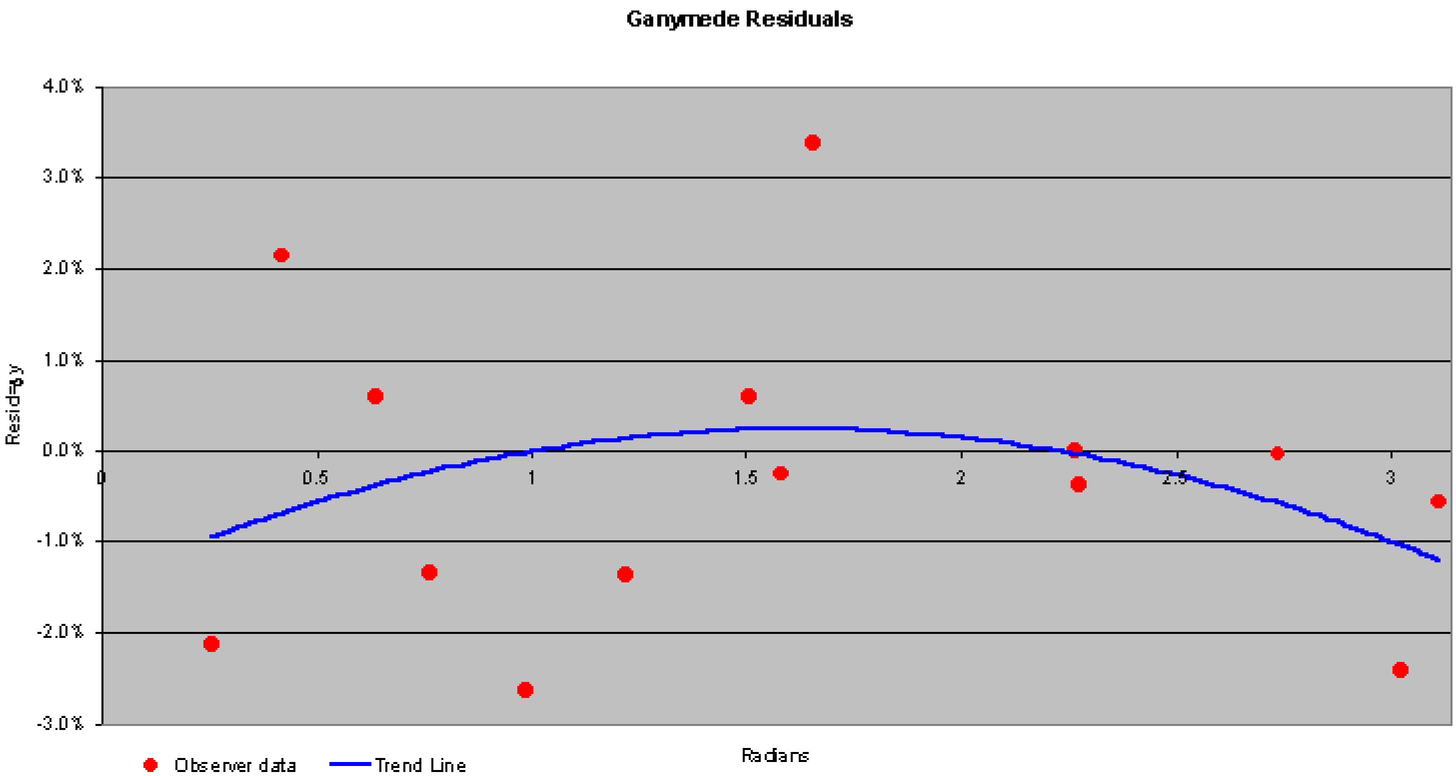
The Callisto residuals, in terms of percent of maximum extent and orbital position



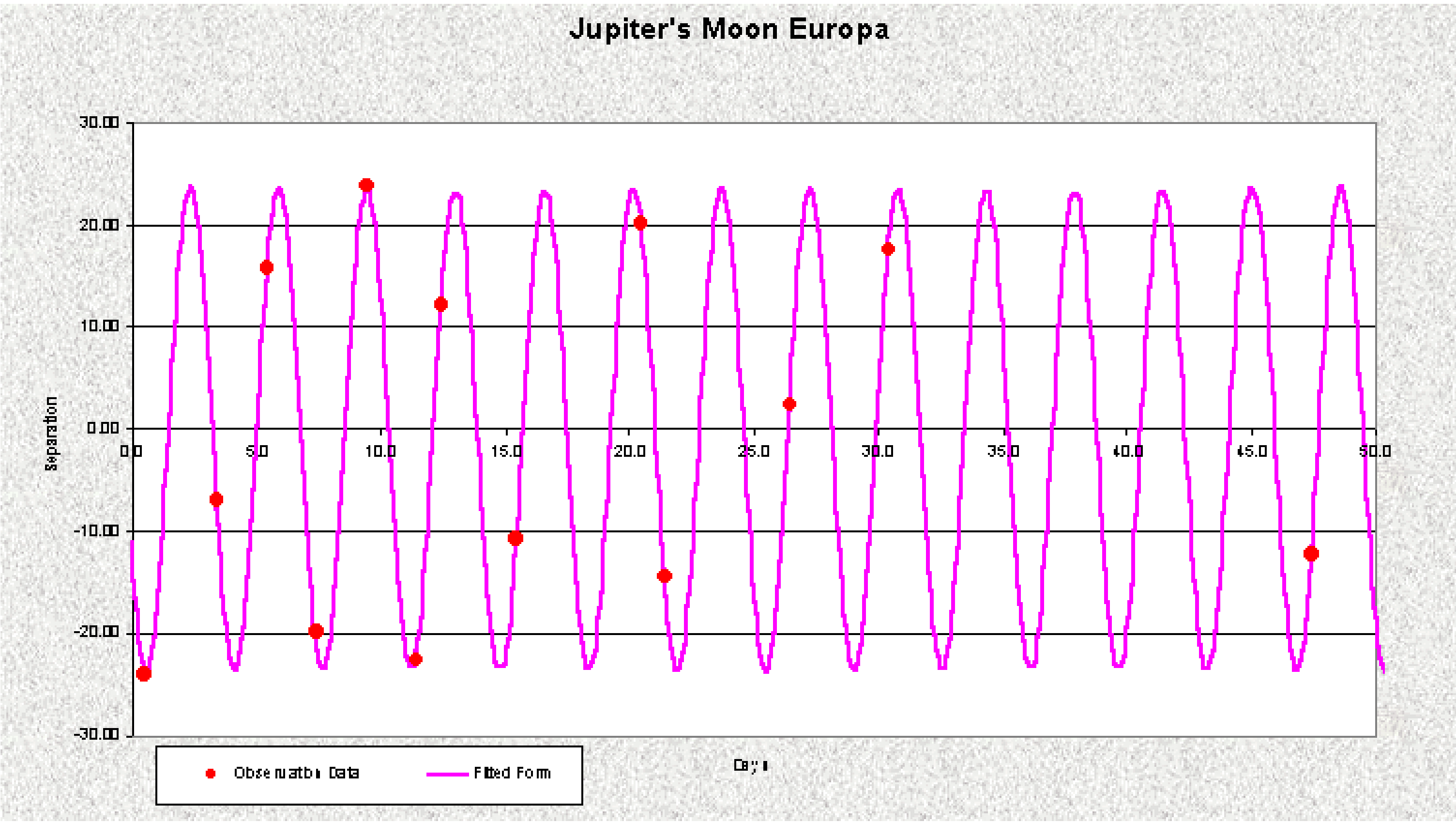
For the moon Ganymede the fitting was:



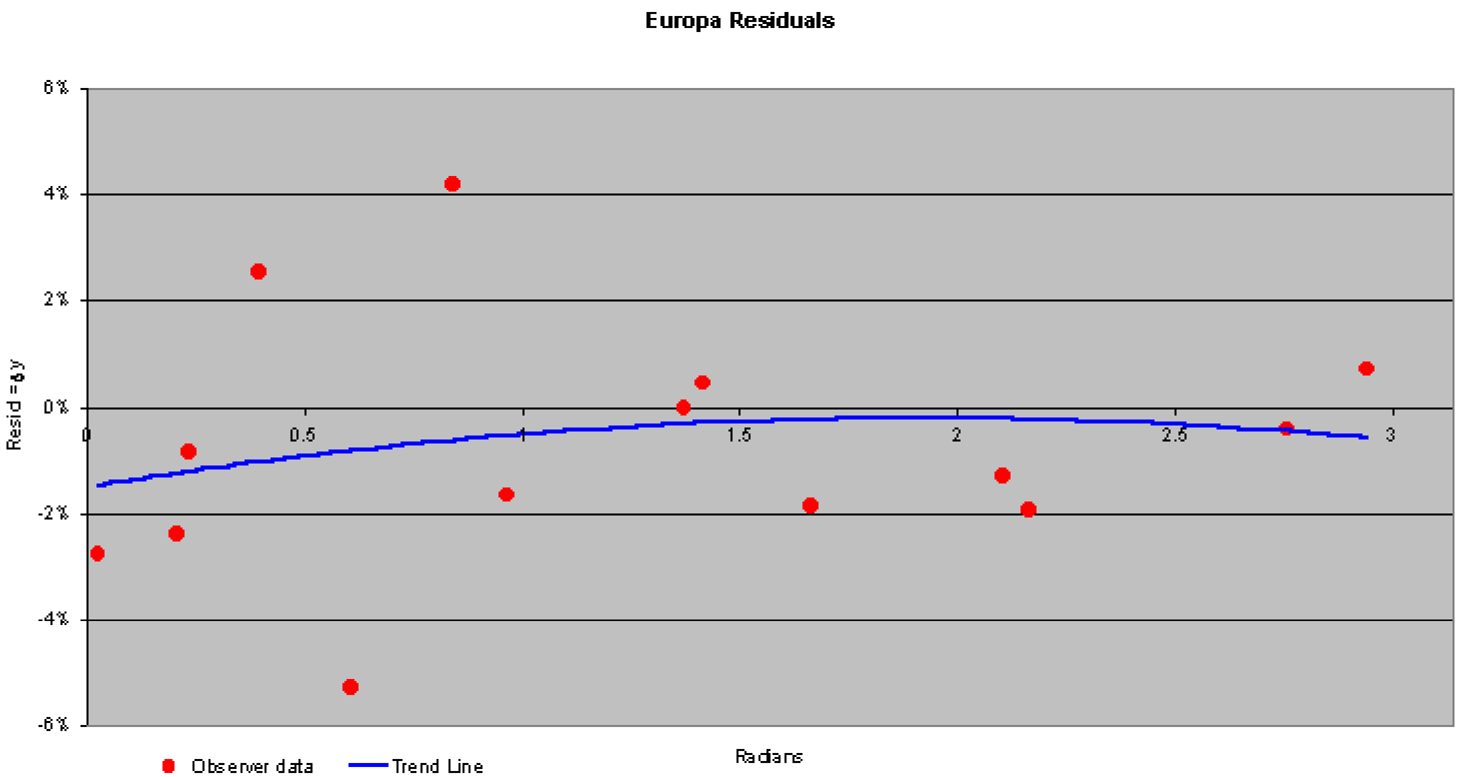
The Ganymede residuals, in terms of percent of maximum extent and orbital position



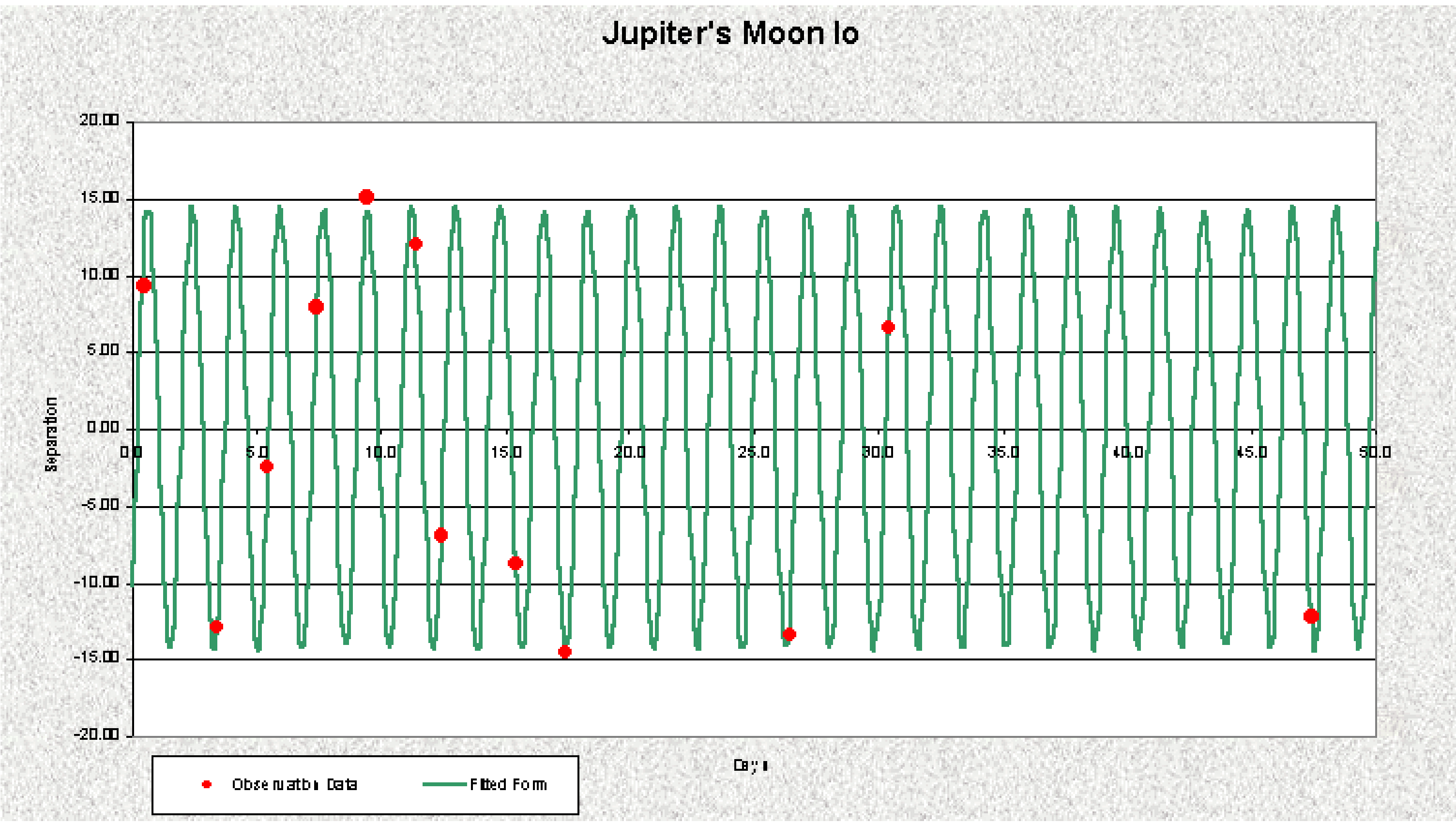
The fitting for Europa is:



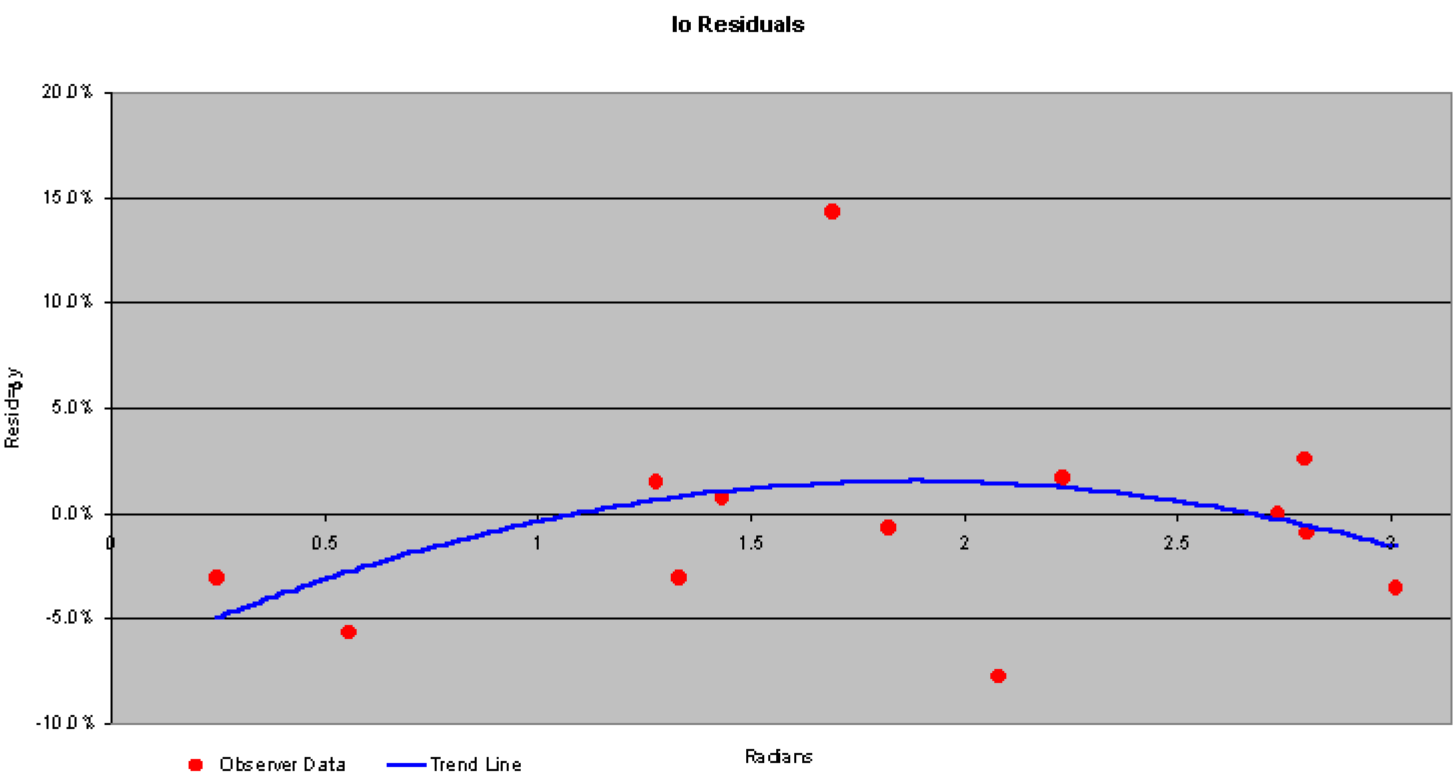
The Europa residuals, in terms of percent of maximum extent and orbital position



The fitting for Io was:



The Io residuals, in terms of percent of maximum extent and orbital position



Project Jupiter

Attachment C: Press Release

Local amateur astronomer Eugene Lanning has recently completed a very unusual observing project with his/her own telescope. One of the goals of Project Jupiter, an American Association of Amateur Astronomers (www.corvus.com) project was to determine the weight of the Planet Jupiter from a series of observations of the planet that were made in the early morning hours.

Eugene used his 8 inch diameter telescope and observational skills on Project Jupiter. Eugene has been interested in astronomy for over 40 years, and currently observes from Nebraska City. Eugene is a member of the American Association of Amateur Astronomers ("Quad-A"), an Internet-based club.

Data gathering sessions commenced when Jupiter was in the early morning sky. In each session Eugene measured the separation of each of the four largest moons of Jupiter using a special calibrated eyepiece in his telescope. Data from 14 separate Project Jupiter observation sessions was then analyzed by an Quad-A computer program. Based on Eugene's data, the weight of Jupiter was determined at nearly 4.18E27 Lbs (4.18 billion-billion-billion Lbs), about 317 times a much as the entire Earth weighs. That weight agrees within 0.2% to available NASA data, exceeding accuracy expectations for his observations.

Eugene says this Project Jupiter work was fun, and that observing Jupiter is now "like seeing an old friend, a real pleasure." Eugene said that his skills in making and recording observations, analysis, research, and leadership also benefitted from the Project.

Eugene plans to continuing with amateur astronomy, with particular interest in observations of multiple star systems and other Quad-A special projects.

This Fall ten other amateur astronomers from across the United States are also participating in the Quad-A sponsored Project Jupiter.

Attach photo

Attachment D: Weighing Jupiter, the Mathematics

Taken from Physics for Students of Science and Engineering, Combined Ed., John Wiley & Sons, D. Halliday and R. Resnick, 1965

Consider two spherical bodies of masses M and m moving in circular orbits under the influence of each other's gravitational attraction. The center of mass of this system of two bodies lies along the line joining them at a point C such that mr = MR. The large body of mass m moves in an orbit of constant radius R and the small body of mass m in an orbit of constant radius r, both having the same angular velocity. The gravitational force acting on each body must provide the necessary centripetal acceleration. The centripetal force is $m\varpi^2 r$, thus because of the equality mr=MR, we find

$$m\varpi^2 r = M\varpi^2 R$$

Balancing the centripetal and gravitational forces we get

$$\frac{GMm}{(R+r)^2} = m\varpi^2 r$$

If one body has a much greater mass than the other, the R is negligible compared to r. The above equation simplifies to

$$GM = \varpi^2 r^3$$

If the angular velocity is expressed in terms of the period of the revolution,

$$\varpi = 2\pi / T$$

Then the equation becomes

$$GM = \frac{4\pi^2 r^3}{T^2}$$

Re-arranging we have the form of Kepler's third law:

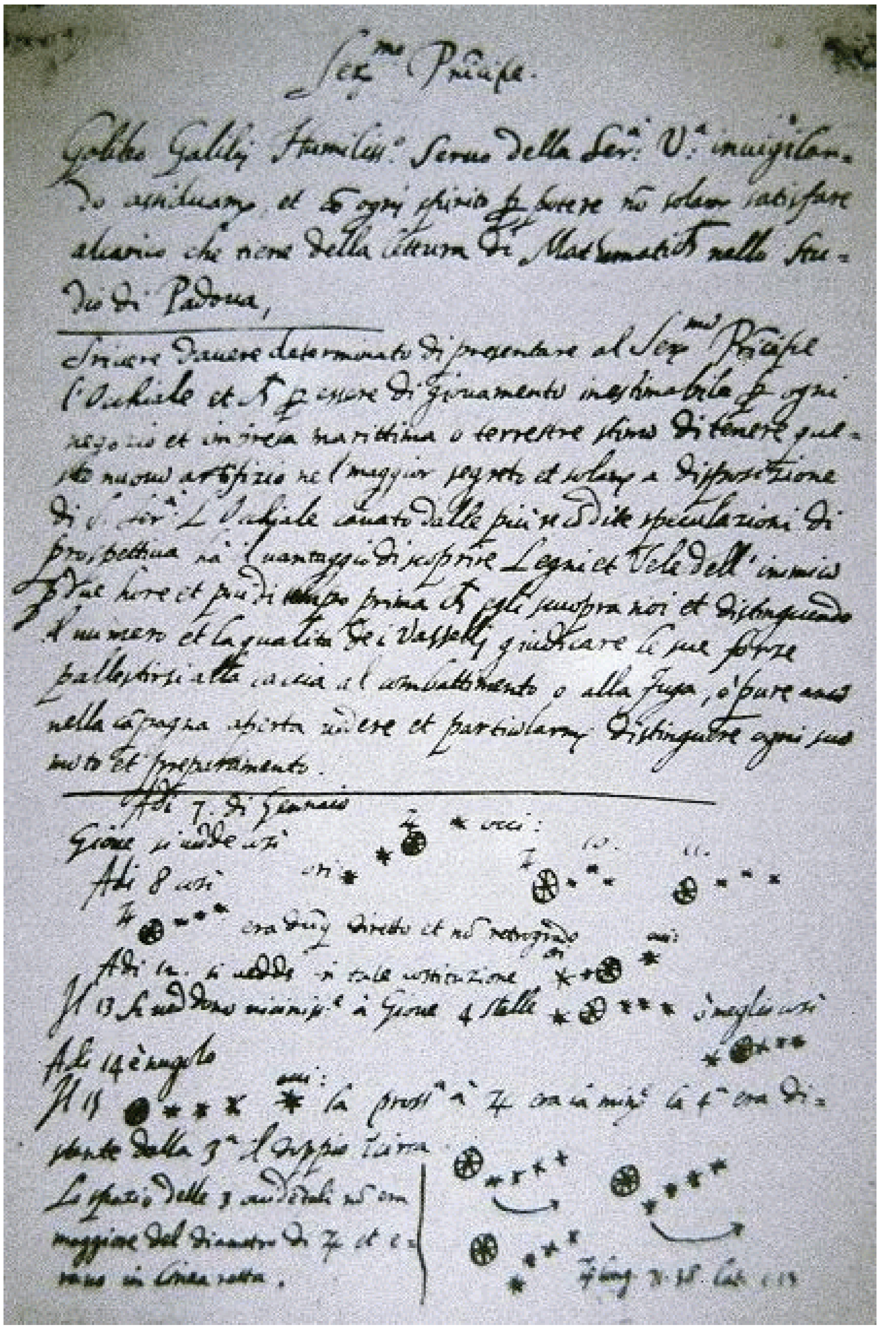
$$T^2 = \frac{4\pi^2}{GM} r^3$$

For Project Jupiter we now solve for M, the mass of Jupiter

$$M = \frac{4\pi^2}{GT^2} r^3$$

Attachment E: Galileo Galilei Discovers Jupiter's Moons

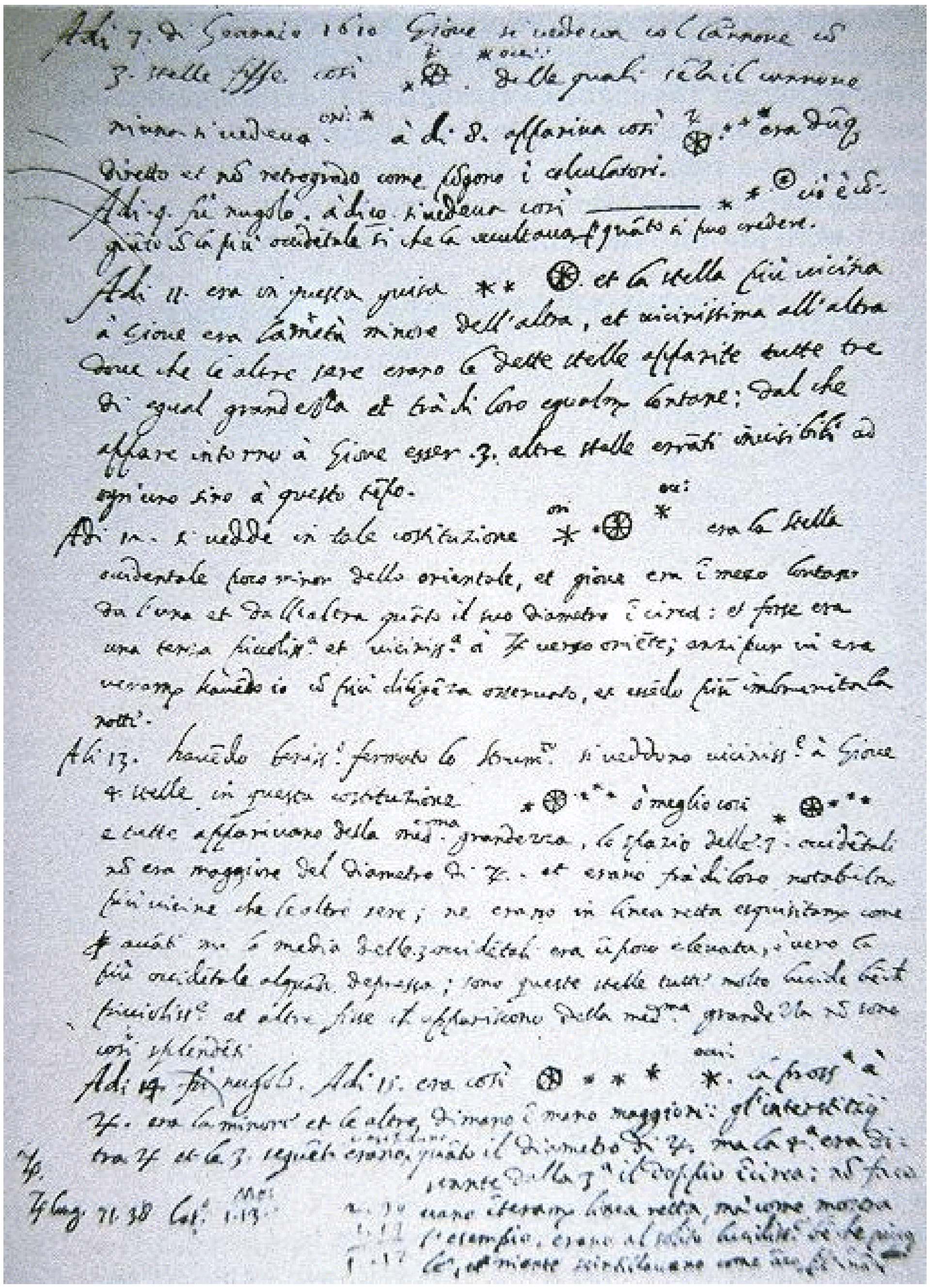
See Section II.A of this report for explanation.


Ser.mo Principe.

Galileo Galilei Humiliss.o Servo della Ser.tà V.a invigilando assiduamente, et con ogni spirito per potere non solamente satisfare al carico che tiene della lettura di Matematiche nello Studio di Padova,

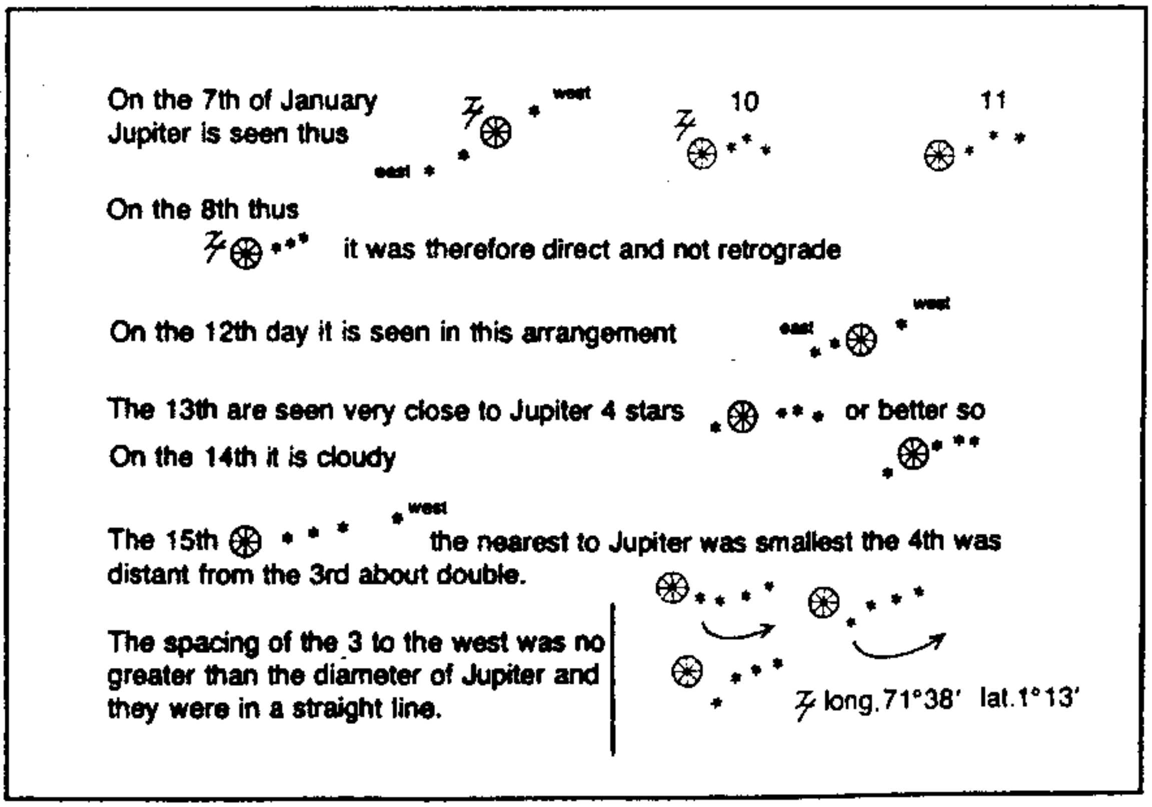
Inoltre d'havere determinato di presentare al Ser.mo Principe l'Occhiale et poter essere di giovamento inestimabile per ogni negozio et impresa marittima o terrestre stima di tenere questo nuovo artifizio nel maggior segreto et solamente a disposizione di V. Ser.tà L'Occhiale cavato dalle più recondite speculazioni di prospettiva ha il vantaggio di scoprire Legni et Vele dell'inimico due hore et più di tempo prima che egli scuopra noi et distinguendo il numero et la qualità de i Vasselli giudicare le sue forze pallestirsi alla caccia al combattimento o alla fuga, o pure ancora nella campagna aperta vedere et particolarmente distinguere ogni suo moto et preparamento.

Adì 7. di Gennaio
Giove si vedde così: ... così:
Adì 8 così ...
era dunque diretto et non retrogrado
Adì 12 si vedde in tale costituzione
Il 13 si veddono vicinissime a Giove 4 stelle ... o meglio così
Adì 14 è nugolo
Il 15 ... così: la prossima a Giove era la minore la 4a era distante dalla 3a il doppio in circa.
Lo spazio delle 3 occidentali non era maggiore del diametro di Giove et erano in linea retta.
long. 71 38 Lat. 1 13



Adì 7. di Gennaio 1610 Giove si vedeva col Cannone con 3. stelle fisse così * ⊕ * delle quali senza il cannone niuna si vedeva. ** * à dì 8. appariva così ⊕ * * * era dunque diretto et non retrogrado come vogliono i calculatori.
Adì 9. fu nugolo. Adì 10. si vedeva così * * ⊕ cioè congiunto con la più occidentale sì che la occultava per quanto si può credere.
Adì 11. era in questa guisa * * ⊕ et la stella più vicina à Giove era la metà minore dell'altra, et vicinissima all'altra dove che le altre sere erano le dette stelle apparite tutte tre di egual grandezza et trà di loro egualmente lontane; dal che appare intorno à Giove esser 3. altre stelle erranti invisibili ad ogn'uno sino à questo tempo.
Adì 12. si vedde in tale costituzione * ⊕ * era la stella occidentale poco minor della orientale, et Giove era in mezzo lontano dall'una et dall'altra quanto il suo diametro in circa: et forse era una terza piccolissima et vicinissima à ♃ verso oriente; anzi pur vi era veramente havendo io con più diligenza osservato, et essendo più imbrunita la notte.
Adì 13. havendo benissimo fermato lo strumento si veddono vicinissime à Giove 4. stelle in questa costituzione * ⊕ * * * ò meglio così ⊕ * * * * e tutte apparivano della medesima grandezza, lo spazio delle 3. occidentali non era maggiore del diametro di ♃. et erano fra di loro notabilmente più vicine che le altre sere; nè erano in linea retta esquisitamente come per avanti ma la media delle 3. occidentali era un poco elevata, overo la più occidentale alquanto depressa; sono queste stelle tutte molto lucide benchè piccolissime et altre fisse si appariscono della medesima grandezza non sono così splendenti.
Adì 14. fu nugolo. Adì 15. era così ⊕ * * * *. la prossima à ♃. era la minore et le altre di mano in mano maggiori: gl'intersitii tra ♃ et le 3. seguenti erano quanto il diametro di ♃. ma la 4a era distante dalla 3a il doppio in circa; [illegible] linea retta, ma come mostra l'esempio, erano al solito lucidissime benchè piccole, [illegible]
♃ long. 71.38 Lat. 1.13

Translation of previous pages



On the 7th of January Jupiter is seen thus

west

east

10

11

On the 8th thus

it was therefore direct and not retrograde

On the 12th day it is seen in this arrangement

east

west

The 13th are seen very close to Jupiter 4 stars

or better so

On the 14th it is cloudy

The 15th

west

the nearest to Jupiter was smallest the 4th was distant from the 3rd about double.

The spacing of the 3 to the west was no greater than the diameter of Jupiter and they were in a straight line.

♃ long. 71°38′ lat. 1°13′

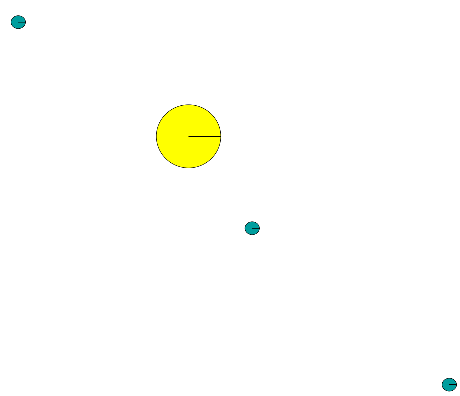
Attachment F: Practice JD estimating sessions.

Estimate the spacings for these Jupiter-moon separations. For this practice, do not use a ruler, as there will not be one in your view in the eyepiece. Create other practice views of your creation .

#1

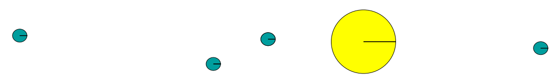
#2

#3

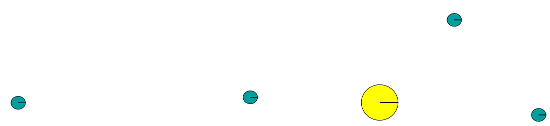


Project Jupiter

#4



#5



#6

Answers:

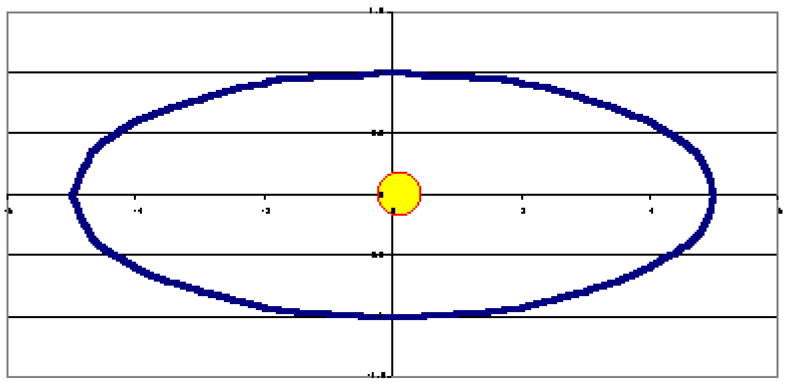
#1: -5.1, -0.28 (Ignore transiting moon's shadow at 0.25), 1.6, 28
#2: -5.7 -2.6, -1.9, 8.9
#3: -3.8, 1.5, 6.9, and unknown (one is being occulted). Always estimate the distances along the line created by the Moons through Jupiter, not just the right to left spacing.
#4 -6.4, -2.9, -1.7, 3.4
#5 -11.8, -4.2, 5.2, one either occulated or lost in the glare from Jupiter. Disregard the nearby star that is not in the plane of the moons! Did you get used to a given size for the planet and forget that in this case the apparent size of Jupiter changed?
#6 -2.4, 2.3, 10.0, one not shown

Attachment G: Earth-Jupiter Distance Effects

I. The effect

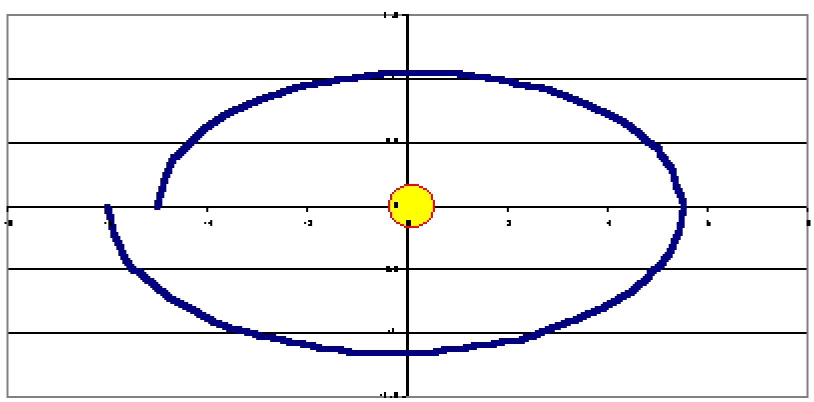
A. In common life, as one approaches an object it appears to get larger. The growth in the size of the object is in the apparent size, not in the actual size of the object.

B. In astronomical projects usually the effects of the changing distance to the orbiting body is lilliputian and the observed orbit is as expected:



Sometimes the effect is evident over a long period, but is not noticeable. If the observer frequently changes the eyepiece for a telescope, they do not notice the changed apparent size.

C. When the orbiting body is approaching at a significant rate, the orbit takes on the appearance of a spiral. We now plot the closed orbit (a stable orbit), shown above, differently because of the changing distance:



In studying the orbit of the observed spiral the effects of the changing distance have to be mathematically removed. Only then would the laws of the orbits relate to the data.

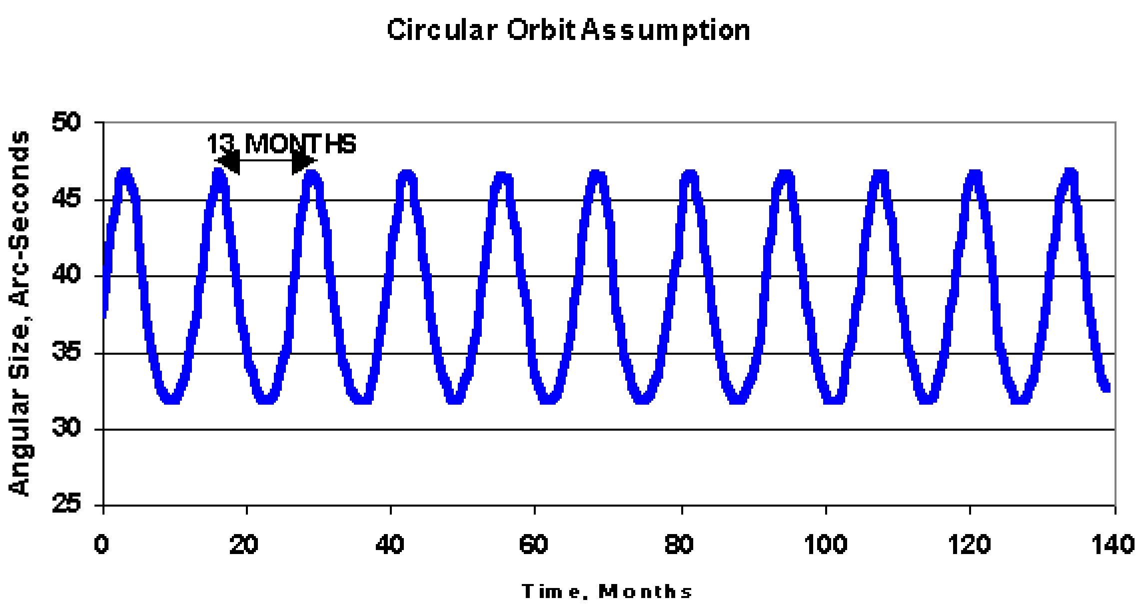
II. Effect is noticeable for Project Jupiter

A. Apparent size vs. time

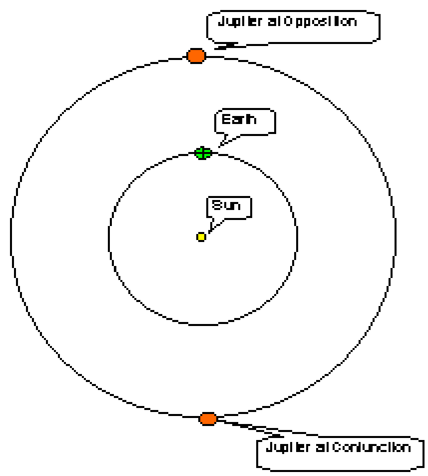
The apparent size of Jupiter will vary considerably over the time needed to collect the observations for Project Jupiter (typically about 30 days). The effect can reach 10% of the separation distances measured, so the effect of the changing distance needs allowed for in the computations.

1. The importance of the effect

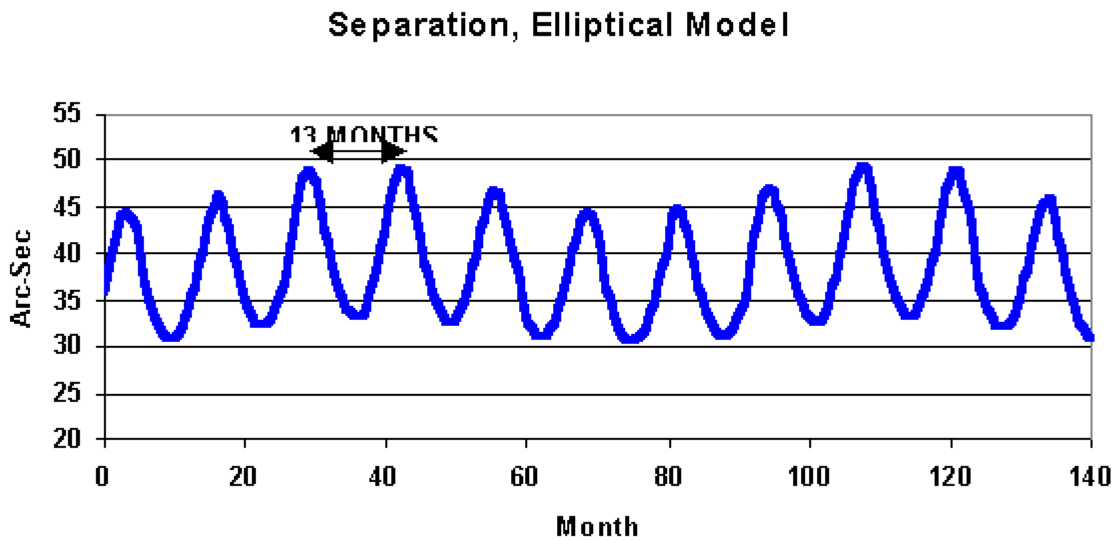
To estimate the importance of the apparent size change with time, Mizar Consulting created a mathematical model of the Earth and Jupiter, each traveling in a circular orbit. The change in the apparent size was computed to be:



2. Miscellaneous notes
   a. When the apparent size of Jupiter is a minimum, Jupiter is "lost in the glare" of the Sun and observing then is not recommended. The risk of a misaligned telescope causing permanent eye damage is too great.
   b. When the apparent size of Jupiter is at its maximum, we say that Jupiter is at "Opposition" (opposite from the direction to the sun).

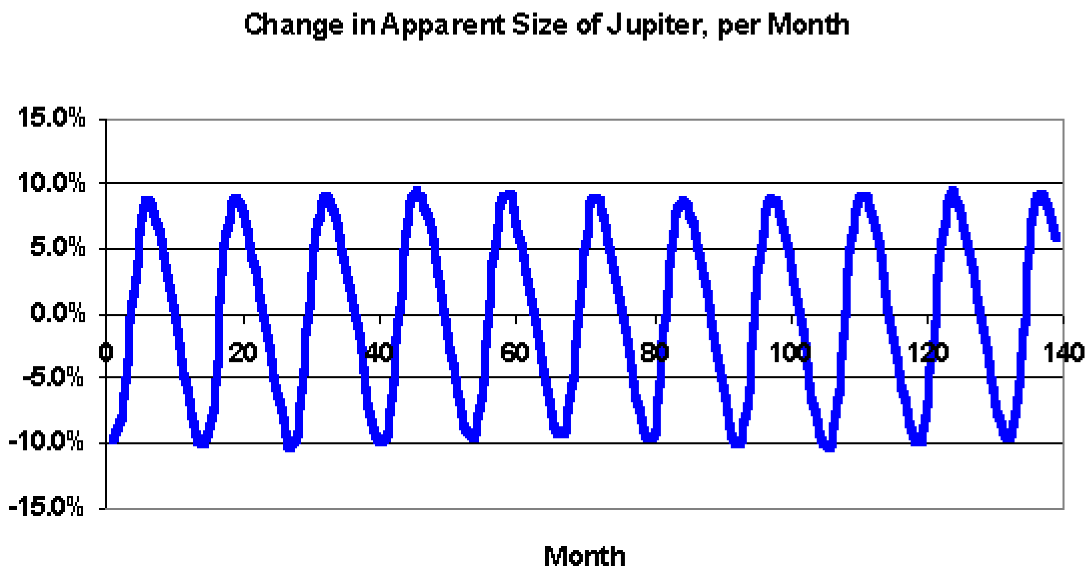


   c. The effect of refining the circular orbit model to explicitly model the elliptical orbits of the planets shows an interesting effect. The ellipticity of the orbits manifests itself as a 12-year pattern in the apparent size of Jupiter:



B. Percent change in apparent size with time

The change in the apparent size, over the typical 30-day-observation period for Project Jupiter can approach 10%.



C.

Impact of fitting the data

If we have not compensated the effect of the changing distance for, then the effect is that the amplitude of the moon's orbit size grows over time (or decreases if the Earth - Jupiter separation is increasing). In Project Jupiter we assume that all of the variation in the data, when compared to the trial fit orbit, is due to fitting differences. The changing distance introduces another variable, that if not compensated for, that will cause an incorrect orbit period to be determined. To extract the best information from the observer's data, least squares must include compensation for the changing distance in the determination of the orbit period.

III. Technique to remove effect

A. For each observation the geocentric distance to Jupiter is found using MEADE's Epoch 2000® software, a commercially-available planetarium type software package.

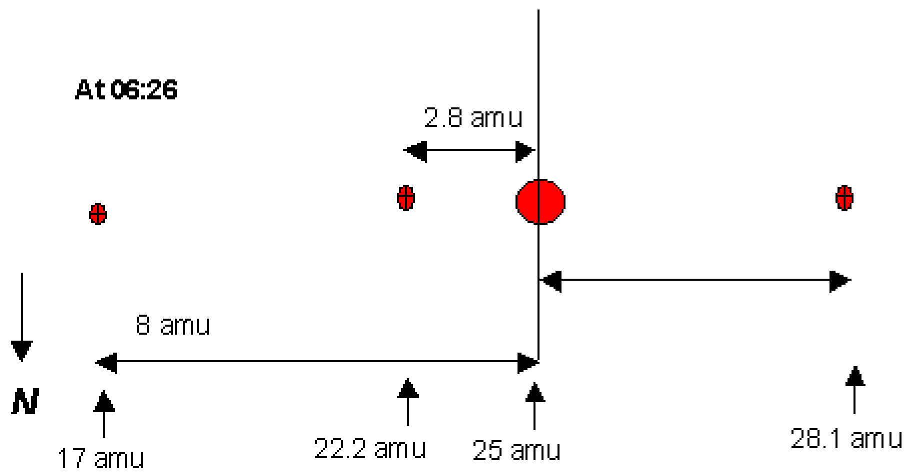
B. The observed separation is corrected linearly to a base date, the first observation date and time. The linear model is a sufficient approximation of the true tangent function because of the very small angular sizes involved.

C. When the JD measuring system is selected, the apparent size change in Jupiter matches the apparent size change for the separation of the moons from Jupiter. Thus, the JD observation method inherently corrects for the changing apparent size and they need no additional modeling.

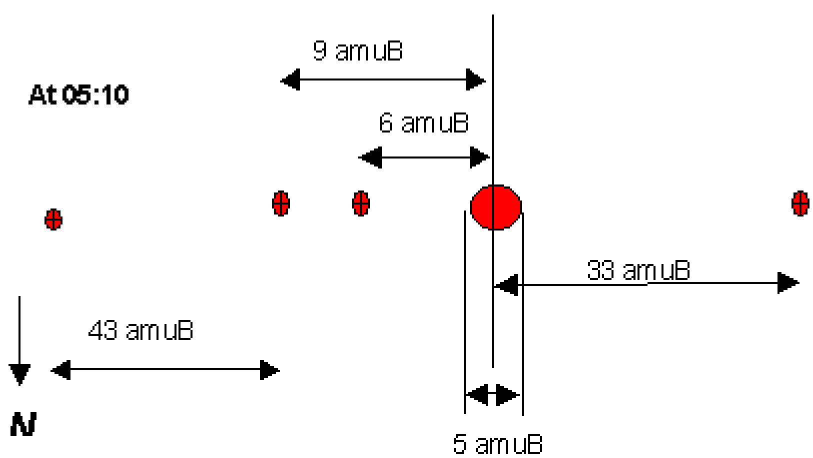
Attachment H: Raw Observation Data

The following diagrams are excerpted from the observation logs, and is included herein for completeness.

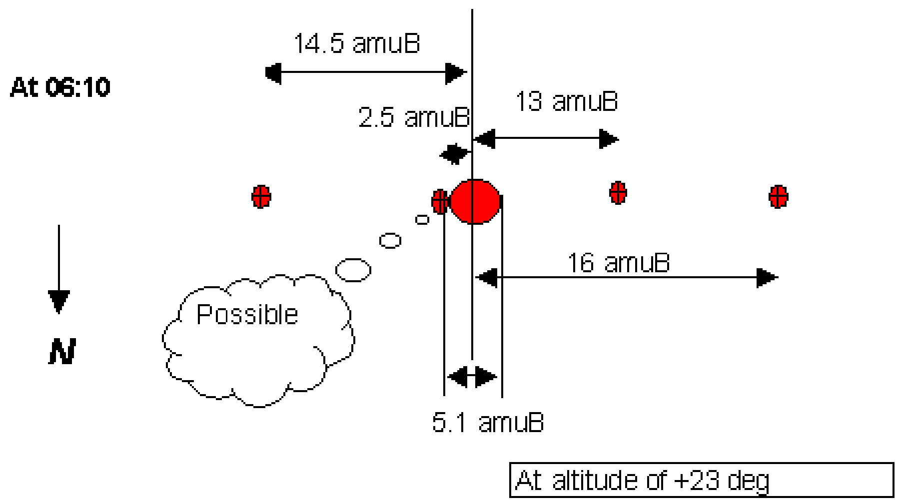
Aug. 30, 2002 (Session #13)



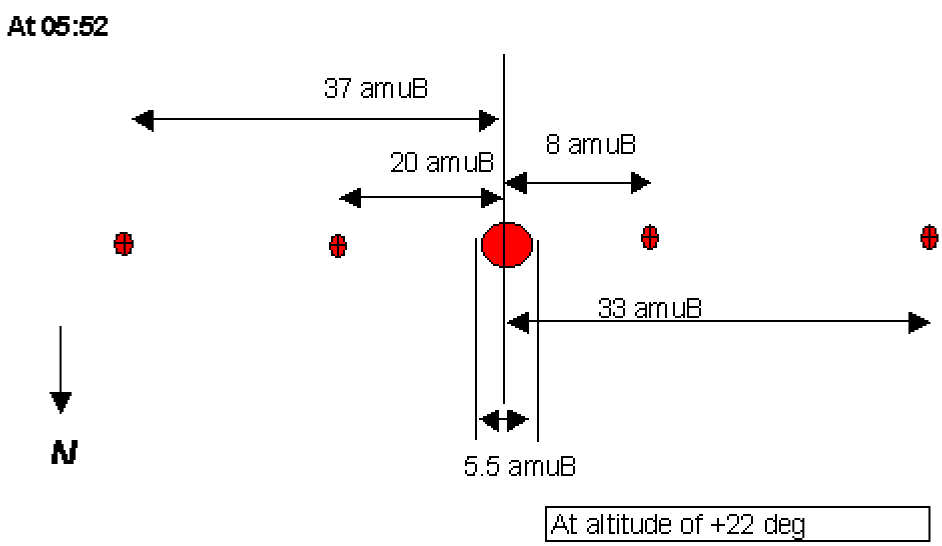
Sept. 3, 2002 (Session #14)



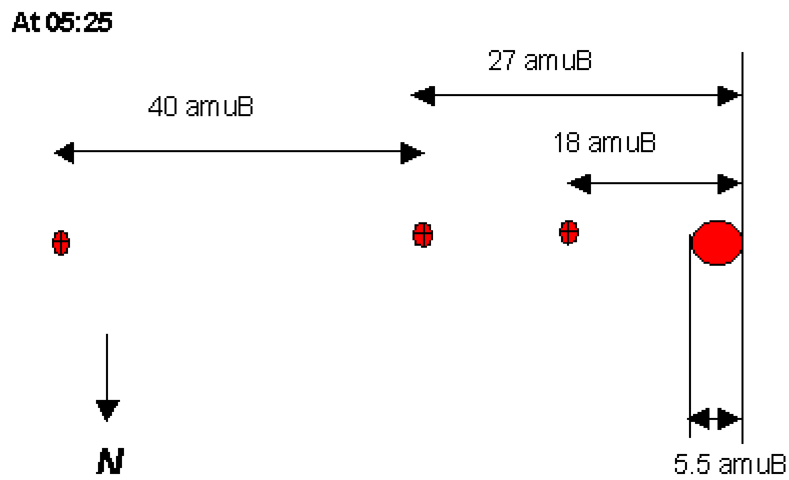
Sept. 5, 2002 (Session #15)



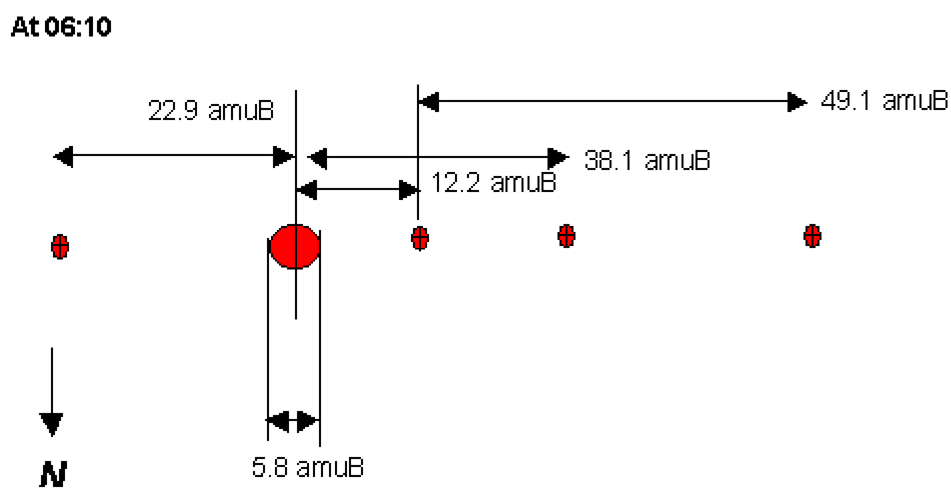
Sept. 7, 2002 (Session #16)



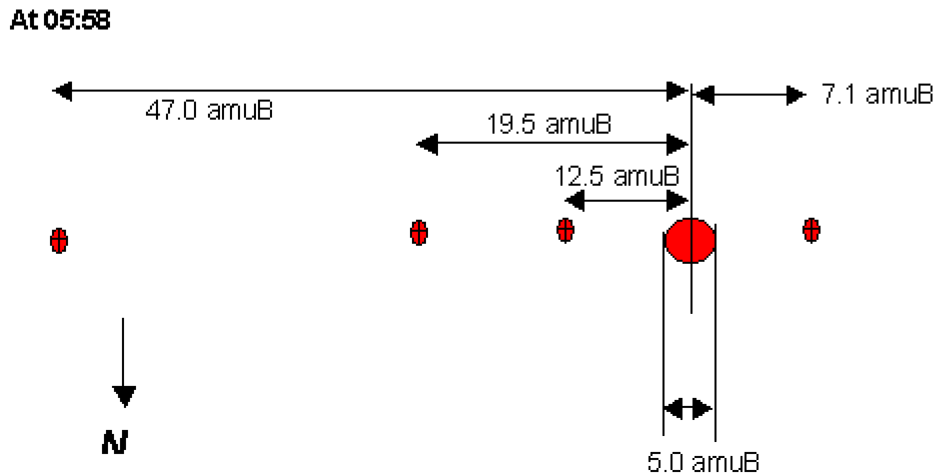
Sept. 9, 2002 (Session #17)



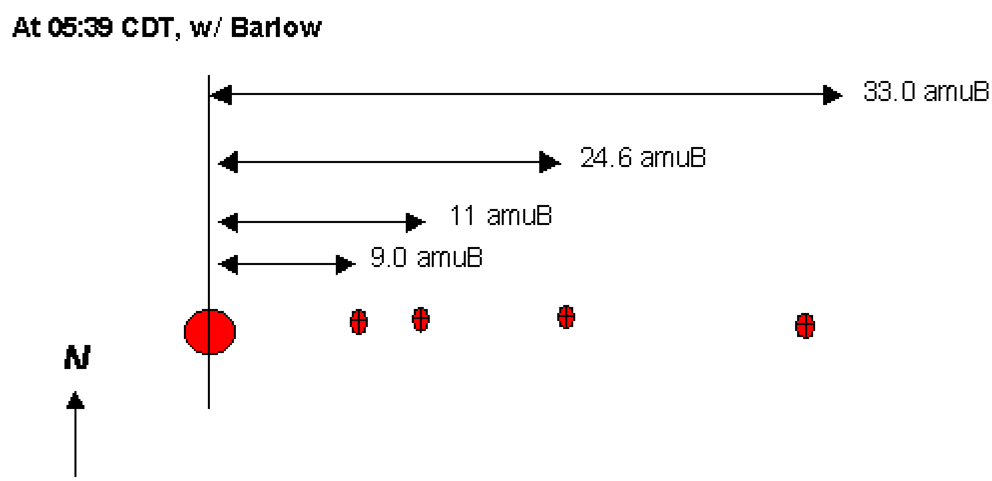
Sept. 11, 2002 (Session #18)



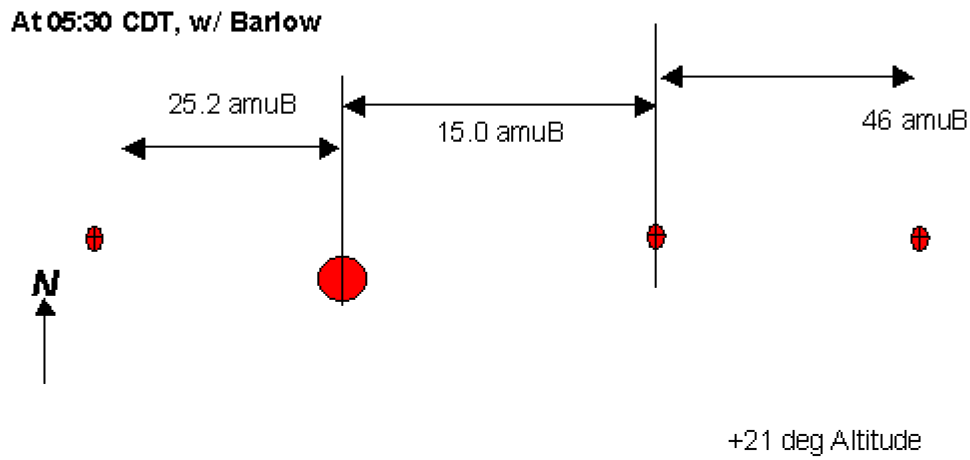
Sept. 12, 2002 (Session #19)



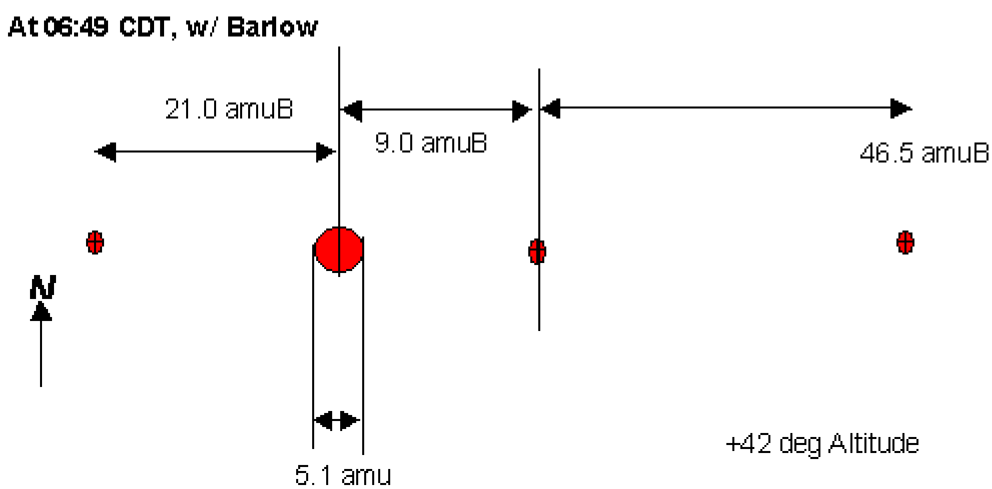
Sept. 15, 2002 (Session #20)



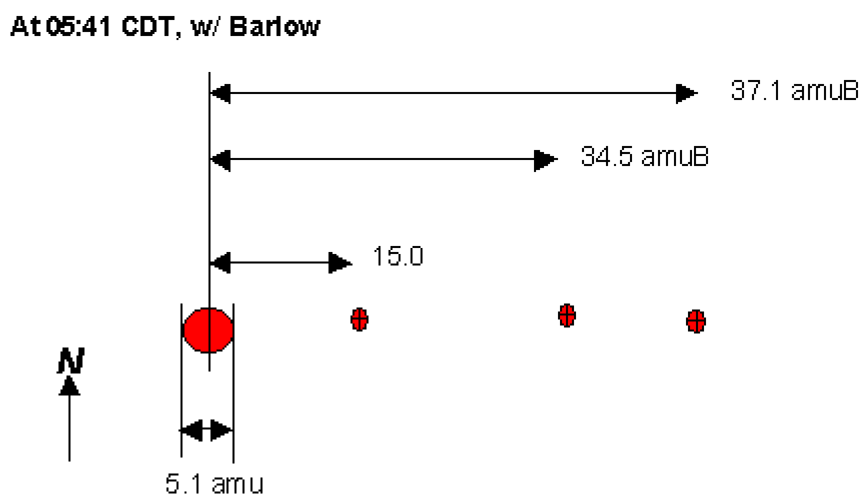
Sept. 17, 2002 (Session #21)



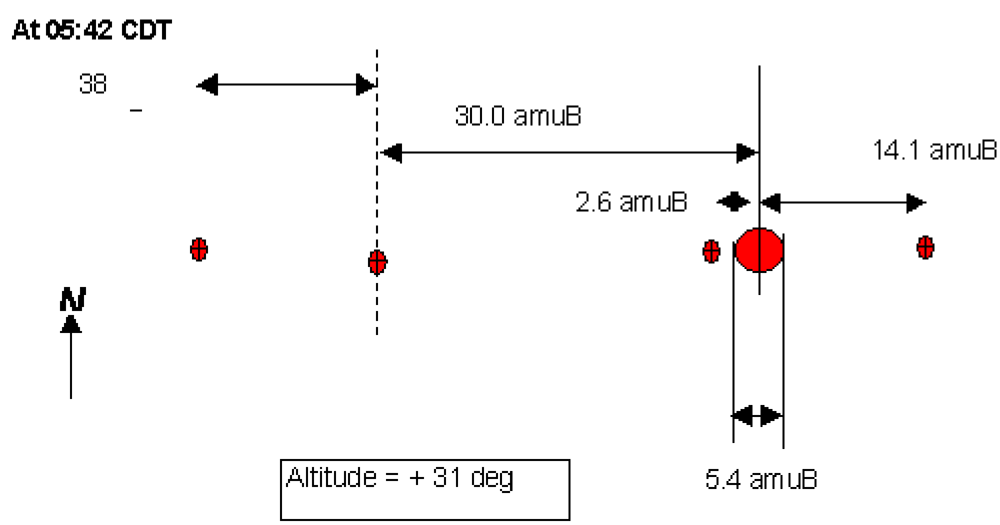
Sept. 20, 2002 (Session #22)



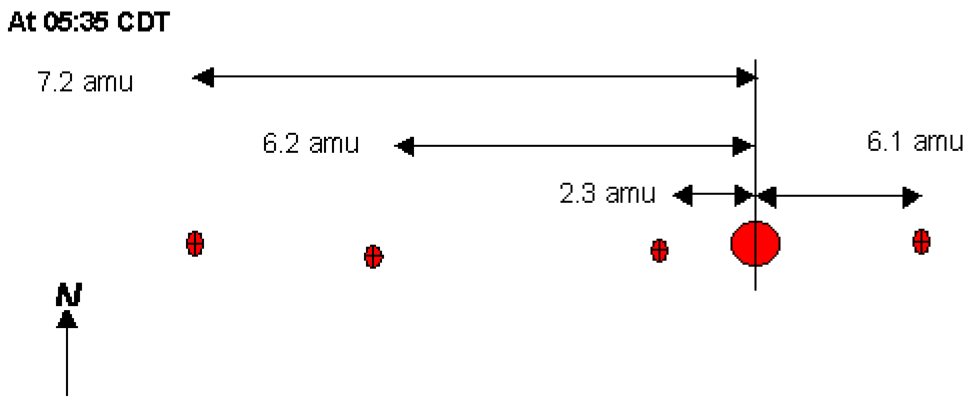
Sept. 21, 2002 (Session #23)



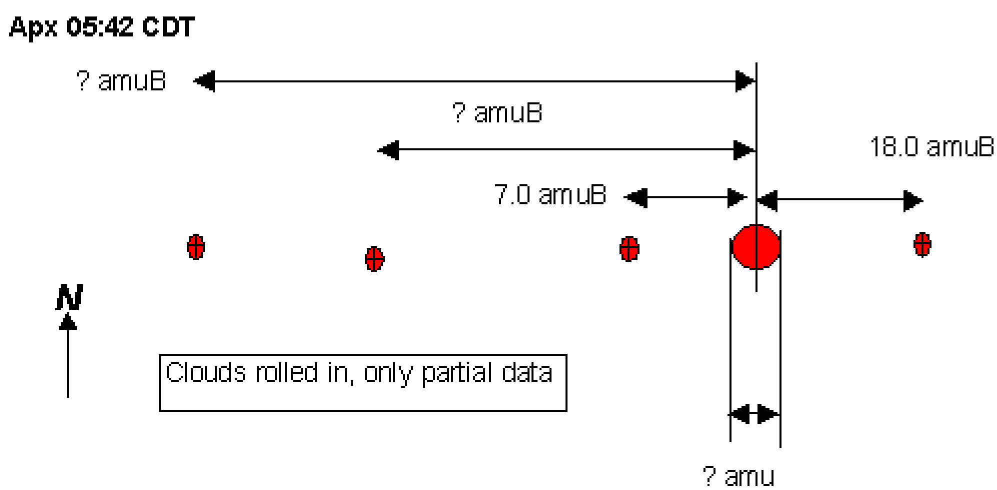
Sept. 26, 2002 (Session #24)



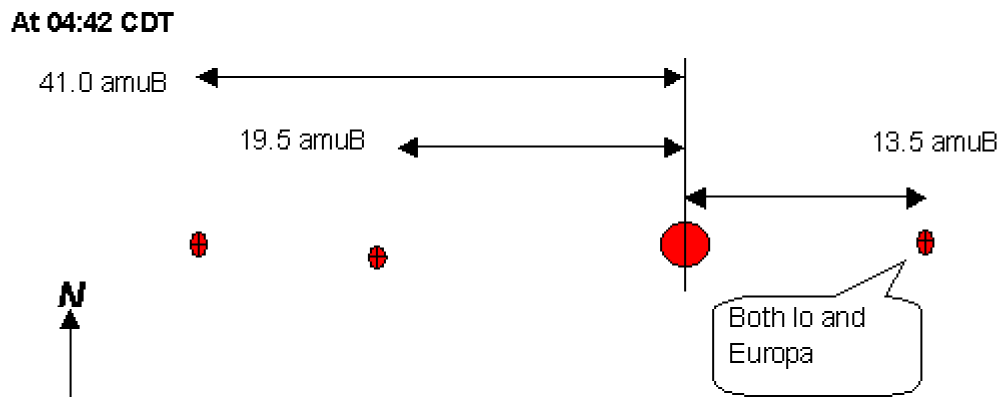
Sept. 30, 2002 (Session #25)



And also



Oct. 17, 2002 (Session #26)



**** End Attachment H ****

Attachment I: Astrometric Eyepiece Calibration Data

From observations on Sept 1, 2001 (Session #8)

Use the EAST key with GUIDE. Time Astrometric+ **3X Barlow** (before diagonal) on 0-50 scale NEAR 0 deg. Decl.				
@ RA 00Hr 18m 44 Sec, Dec +01deg, 38m, 38Sec. May have been SAO #109119 in Pisces. At 02:26 Local time.				
Meas. #1	0	Min	21.54	Sec
Meas. #2	0	Min	21.33	Sec
Meas. #3	0	Min	21.3	Sec
Meas. #4	0	Min	21.76	Sec
Meas. #5	0	Min	21.45	Sec
Meas. #6	0	Min	21.35	Sec
Meas. #7	0	Min	21.37	Sec
Meas. #8	0	Min	21.4	Sec
Meas. #9	0	Min	21.32	Sec
Meas. #10	0	Min	21.33	Sec
Ave. Time	0.00	Min	21.42	Sec
Std Dev of time:			0.14	Sec.
Std Dev of time:			0.7%	%
Scale 50	5	'	21	"
Scale 10	1	'	4	"
Scale 1	0	'	**6.42**	"
Scale 1 σ			**0.04**	**" Std Deviation**