# Minor Planet Astrometry

## At Mabee Observatory

By

Luke Schmidt

Natural Sciences Seminar

Bethel College

2003

Project Advisor:  Tracy Tuttle
Academic Advisor:  Richard Zerger

# Table of Contents

I. Abstract:

The academic year of 2002-2003 is the inaugural year of the Mabee Observatory.  The goal of this project is to determine the observational limits of the observatory.  This will be done using minor planet astrometry to determine what level of precision can be reached when measuring the position of an astronomical body, as well as the magnitude limit of the observatory in its current configuration.  In order to accomplish this it will be necessary to understand the theory behind astrometry, CCD imaging and image processing.  The Mabee Observatory Meade LX200GPS telescope, SBIG CCD camera, along with software and asteroid databases provided by project CLEA of Gettysburg College in Pennsylvania and the Lowell Observatory of Flagstaff Arizona, will be used to obtain time series images of asteroids.  The images will be stacked and compared to show the asteroid moving across the stationary star field.  From this the asteroid's position and magnitude can be determined.  Asteroid observations were made with the goal of producing results of sufficient quality for submission to the Minor Planet Center.  Upon receipt of good observations the Minor Planet Center will use them to refine existing asteroid orbits and will issue Mabee Observatory an observatory code, marking it as a permanent observing location capable of producing precise and accurate results.  This is done in hopes that the feasibility of future projects can be calculated and recommendations for new equipment to expand and augment the current capabilities of the observatory can be made.

II. Introduction:

In a field as ancient as astronomy, only recently has the study of asteroids emerged from its childhood. This is due in large part to the progress of imaging and measurement technology. The first asteroid, Ceres was discovered by an Italian monk, Giuseppe Piazzi on January 1, 1801[1]. With the help of other astronomers and the math of Karl Friedrich Gauss, the orbit for this new type of object was calculated. It was found to exist in an orbit predicted by the Titius-Bode[2] relationship for planetary distances. However, soon after this discovery, the second asteroid Pallas was discovered and astronomers hypothesized that the planet in that orbit had broken apart. With the advent of larger telescopes and the use of photography the number of asteroid discoveries per year increased. However, in order to keep track of the asteroids, their positions had to be accurately determined using micrometers to measure their celestial coordinates on the photographic glass plates and then calculate their orbits so that ephemerides[3] could be generated. The greatest leap in minor planet discoveries occurred with the advent of the charged coupled device (CCD) and computers. These two tools allowed for many images to be quickly taken and the positions of the asteroids calculated almost instantaneously. Determining an asteroids position and orbit went from taking many hours to several seconds. Now, large automated telescopes log observations for both old and newly discovered asteroids at unprecedented rates. Over two hundred thousand asteroids are known today, this extremely large number and a limited amount of observing time available on large professional telescopes makes the participation of amateur astronomers a necessity in gathering information on all of these asteroids.

The availability of this type of research to amateur astronomers has happened only recently with the advent of high quality commercially produced CCD cameras and telescopes.

With these two tools and a home computer it is possible to produce results with a precision of 0.1 seconds of arc, this is approximately the angular diameter of a dime at a distance of 20 miles[4]. The need for accurate positional information and the wide range of apparent magnitudes makes minor planet astrometry the perfect tool for determining the observational limits of an observatory.

The academic year of 2002-2003 is the inaugural year of the Mabee Observatory. The goal of this project is to determine the observational limits of the observatory using minor planet astrometry and to understand the theory behind astrometry, CCD imaging and image processing. This is done in hopes that the feasibility of future projects can be calculated and recommendations for new equipment to expand and augment the current capabilities of the observatory can be made. Using software and asteroid databases provided by project CLEA of Gettysburg College in Pennsylvania and the Lowell Observatory of Flagstaff Arizona, asteroid observations were made with the goal of producing results of sufficient quality for submission to the Minor Planet Center. Upon receipt of good observations the Minor Planet Center will use them to refine existing ephemerides and will issue Mabee Observatory an observatory code, marking it as an observatory capable of producing precise and accurate results.

III. Theory:

In modern astronomy computers are arguably just as important as telescopes in gathering, organizing and analyzing information. Some modern analysis and modeling would be impossible without the aid of computers. However, one must be careful to understand the inner workings of the computer tools used for analysis. Otherwise the computer becomes a magic box and results may be found erroneously due to a misunderstanding of the software algorithms.

What follows is an outline of the steps necessary to accurately measure an asteroids position from an image. This procedure is a summary of an article[5] and a book[6] by Jeremy Tatum of the University of Victoria. Astrometry that was once done manually using glass photographic plates and micrometers is now done with computers, but the principle is the same and the same corrections and care must be used to obtain accurate and precise results.

The first necessary step is to measure the x and y coordinates of the object in the image being measured. This is very easy with an image from a CCD camera because the coordinate system has already been laid out. The pixels of the CCD form a grid and each pixel can count as a step in the x or y direction. However, due to atmospheric distortion a star or asteroid as it may be, usually takes up multiple pixels. The centroid of the star must be found. The centroid is the pixel that most accurately represents the stars true position in the image, generally, the brightest pixel will give a good estimation, but what if we want more accuracy than that?

The CLEA software used to measure the images uses the following procedure to find the centroid[7]. The star in question is searched for the brightest pixel. This pixel is used as the center for further calculations. A weighted pixel average is found for all of the pixels in an eight pixel radius around the center. The computer determines low and high image cutoffs, counts lower are given the value of 0 and those higher are given a value of 1000. The counts within the high and low range are given proportional weights between 0 and 1000. The weights are cubed and applied to the (x, y) pixels, then the x and y averages are taken. Project CLEA has found this method to give repeatable results.

The right ascension and declination of the (x, y) coordinates must be known. This is usually the coordinates of the center of the field, in other words, the coordinates that were given to the telescope to tell it where to point to find the asteroid.

Reference stars must be found in the field of the image. For each star the right ascension and declination must be known (α, δ), the proper motions in α and δ, $(\mu_\alpha, \mu_\delta)$, and the x and y coordinates of these stars. Additionally, the time of mid-exposure to the nearest second, the local sidereal time of the observation and the latitude of the observatory must be known.

The first corrections to the image are now ready to be applied. Proper motion corrections must be calculated for all of the reference stars. Proper motion is the slow shift in a star position on the celestial sphere due to motion of the star. Star catalogues are listed as belonging to a certain epoch, such as 1950.0 or 2000.0, the star catalogue contains star positions for that particular year and corrections must be made for each year after or before the epoch. This correction applies to the right ascension and declination of the reference stars.

An exact focal length must be determined next. Roughly, the telescopes focal length is the same for all images, but focus changes from image to image and night to night due to temperature changes and shifting of equipment. To determine the focal length to the nearest millimeter the formula:

$$f = \frac{S}{\theta} \tag{1}$$

Is used, where $f$ is the focal length, S is the distance between the stars in the image, in pixels, mm etc., and theta is the angular distance between the two stars in the sky. The focal length can be determined from any pair of stars, but it is best to find the focal length for all combinations of reference stars and take the average. This also serves as a good check for accuracy of the star positions. If the (x, y) coordinates were not measured correctly, the focal length will be off from the other two star combinations.

Once the focal length is determined the coordinates need to be converted to standard coordinates, $(\xi, \eta)$ for each star. This correction is necessary because the coordinate axes of the

image may not be exactly aligned parallel to the right ascension and declination axes. Also, the image is a flat representation of the spherical celestial sphere. The relationship of the standard coordinates to the coordinates of the reference stars in right ascension and declination is as follows:

$$\xi = \frac{\sin(\alpha - A)}{\sin D \tan \delta + \cos D \cos(\alpha - A)} \tag{2}$$

$$\eta = \frac{\tan \delta - \tan D \cos(\alpha - A)}{\tan D \tan \delta + \cos(\alpha - A)} \tag{3}$$

Where alpha and delta are the measured coordinates, A and D are the origin of the (x, y) axes and xi and êta are the standard coordinates.

Now the standard coordinates differ from the (x, y) coordinates by only a translation and rotation, so they are linearly related. This relation is given by:

$$\xi - x = ax + by + c \tag{4}$$

$$\eta - y = dx + ey + f \tag{5}$$

The constants a, b, c, d, e, and f are called the plate constants, a name coming from a time when all astronomical images were taken on glass photographic plates. Each reference star has a pair of equations (eq. 4 and 5), so if we assume that we are using three stars, (the minimum necessary for coordinate determination) we will have six equations and six constants. This makes it possible to solve for the plate constants giving the standard coordinates of the reference stars.

Once the plate constants have been found, the right ascension and declination of the asteroid can be determined from the following equations.

$$\tan(\alpha_o - A) = \frac{\xi_o}{\cos D - \eta_o \sin D} \tag{6}$$

$$\tan \delta_o = \frac{(\eta_o \cos D + \sin D)\sin(\alpha_o - A)}{\xi_o} \tag{7}$$

Where $\xi_o$ and $\eta_o$ are the standard coordinates of the asteroid calculated from the plate constants equations, (4) and (5). The final right ascension and declination coordinates of the asteroid are $\alpha_o$ and $\delta_o$. By using more than three reference stars more accurate results can be obtained and errors in measurement of the reference stars are easier to detect. Using more than three stars creates a problem, the plate constant equations have a total of six unknowns, if more than three stars are used then the number of equations to be solved will outnumber the unknowns. For example, six stars would generate twelve equations and only six unknowns. This means that the best values for the plate constants must be determined using another method. In the field of astrometry, the standard method used is the Principle of Least Squares.

IV. Principle of Least Squares:

In least squares analysis a set of observations is made with the goal of determining a set of unknowns, in this case the plate constants. Due to small errors in measurement, equipment flaws and other sources of error a perfect fit to these observations is impossible. So the fundamental principle is that the most probable values are those which make the sum of the

squares of the residual errors a minimum[8]. The use of least squares is only necessary when the measurements are at the limit of the measuring precision of the system. Small inconsistencies in measurement are only noticed at high precision. Measuring the distance between two objects using a stick one foot long, rounded to the nearest foot, may always produce the same result. However if that stick is further incremented into fine markings, say 64 lines per inch, each measurement of the distance may result in a slightly different reading. Because the distances that are used in astronomy are so large, a small error in measuring a position can translate to a large error later on when determining an orbit.

When using least squares it is important to note that it only deals with random error. Systematic errors must be identified and corrected by the observer. For example, a marksman who places all of his shots in a small cluster, but whose sight is off so far that the cluster is far from the bulls-eye will not benefit from least squares. The application of least squares to the cluster of shots will find the center of the group of shots, but will tell nothing about the distance of this center from the true value, or the bulls-eye[9]. It is also important to note that the least squares method is most effective when a sufficient pool of measurements is analyzed. Using least squares analysis on two data points is not going to produce a better measure than a simple average. This method is based on the idea that the number of observations is large enough to determine the errors to which the observations are liable[10].

The plate constant equations are linear in nature, what follows is an example of the method of least squares for a straight line taken from Kreyszig's Advanced Engineering Mathematics[11]. For this example the following equation for a line will be used.

$$y = a + bx \qquad\qquad (8)$$

This is the equation of a line we want to fit through a given set of points, $(x_1, y_1)\ldots (x_i, y_i)$. The goal of least squares is for the square of the distance between the line and the point in question to be a minimum for all points. This distance is the vertical distance between the point and the line. Below in figure 1 a graphical representation of this is shown.
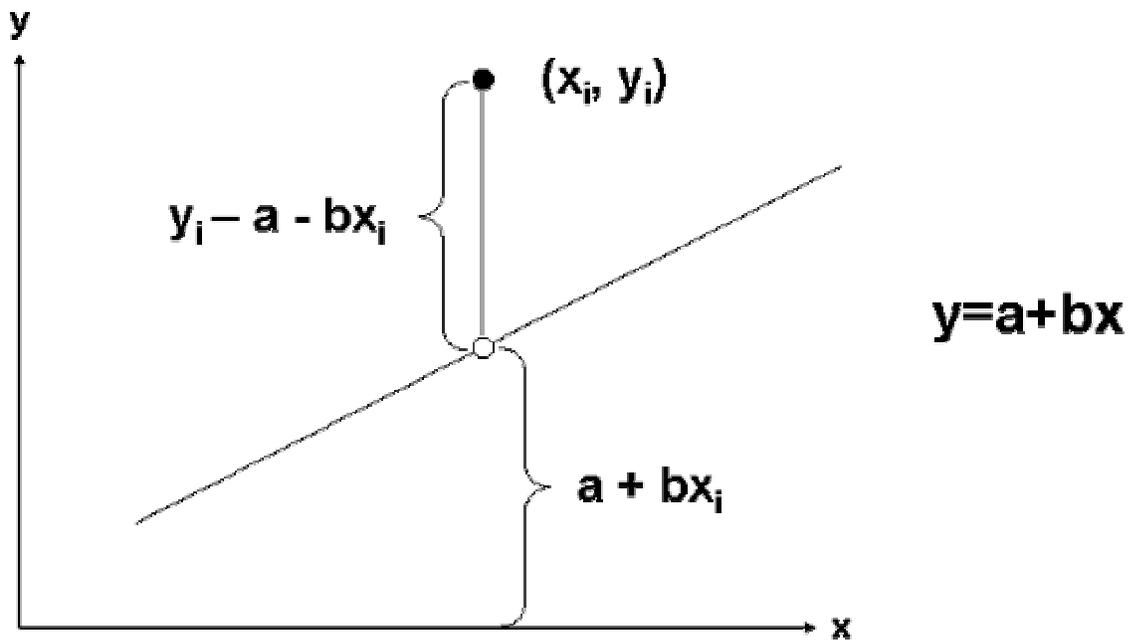


Figure 1

From this we can see that the distance from the point to the line is $y_i - a - bx_i$. This is the distance that needs to be squared and summed in the following manner.

$$q = \sum_{i=1}^{n}(y_i - a - bx_i)^2 \tag{9}$$

The distance must be squared; otherwise those points that are below the line will be a negative value and will cancel out positive distances in the summation. This could result in an apparent minimum value or in fact a negative value for the sum, which does not make sense. In order for equation 9 to be a minimum the following must be true.

$$\frac{\partial q}{\partial a} = -2\sum (y_i - a - bx_i) = 0 \tag{10}$$

$$\frac{\partial q}{\partial b} = -2\sum x_i (y_i - a - bx_i) = 0 \tag{11}$$

After the partials are taken and the sum distributed throughout the parenthesis one of the sums is moved to the right side of the equations. This produces a new set of linear equations that can be solved. These sets of equations are called the normal equations. The normal equations for the plate constants are found in a similar manner. The normal equations are solved for the plate constants and the plate constants can then be used to find the standard coordinates for the measured position of the asteroid. By using the method of least squares a much greater degree of accuracy can be achieved while only sacrificing a few seconds of calculation time on a computer.

V. Refraction and Aberration:

Two final corrections may also be necessary. The first, refraction correction is necessary due to the refraction of starlight as it passes through the atmosphere[12]. The star is displaced towards the zenith. This can amount to half a degree near the horizon. The important thing for astrometry is the differential refraction between the top and bottom of the detector. This correction is only necessary for those desiring sub-arcsecond resolution and large fields of view. With larger and larger CCD chips being made this is becoming increasingly important.

Aberration is not referring to optical aberrations in lenses and mirrors. Instead it refers to the aberration of light due to the vector difference between the velocity of the earth through space and the velocity of light. Aberration causes the star to be displaced to the point on the celestial sphere that the earth is moving towards[13]. Once again the only important thing for

astrometry is the differential aberration. This turns out to be a much smaller effect than the differential refraction and is usually not necessary.

VI. CLEA Corrections:

The following corrections are performed by the CLEA software[14].

Displacement of origin – constant differences between measured and true coordinates.

Error of orientation – the rotation of the measurement coordinate system with respect to the true coordinate system.

Non-perpendicularity of axes – in case the measurement axes are not strictly orthogonal.

Scale errors – calculation of focal length across the plane to account for errors in scale, both in x and y directions.

Plate constants are determined using the least squares method. At least three comparison stars are required, but more are recommended.

**Putting Theory into Practice**

VII. Location:

All of the images and data that were used for this project were gathered at the Mabee Observatory located on the fourth floor of the Krehbiel Science Center. The observatory is located in North Newton Kansas at the following coordinates:

97º 20' 31.82" W Longitude

38º 04' 29.76" N Latitude

The ground level elevation is 1448.5 feet above sea level. The telescope sits in the dome on the fourth floor at an additional elevation of 50 feet for a total elevation of 1498.5 feet above sea level.

VIII. Telescope:

The Mabee Observatory Telescope is a Meade 16" LX200GPS Schmidt-Cassegrain Telescope. The design of a Schmidt-Cassegrain telescope employs a combination of mirrors and lenses to gather and focus light. Incoming light passes through a two sided aspheric correcting plate at the front of the telescope. In the LX200GPS this correcting plate is equipped with Meade's Ultra High Transmission Coatings or UHTC. These coatings increase light transmission by reducing the amount of light reflected by the glass upon impact and exit[15]. This light is then reflected off of the spherical primary mirror and back to a convex secondary mirror on the back side of the correcting plate. The light is then focused through a hole in the center of the primary mirror and passes into the eyepiece, or CCD camera[16]. A representation of this is pictured below in Figure 2.
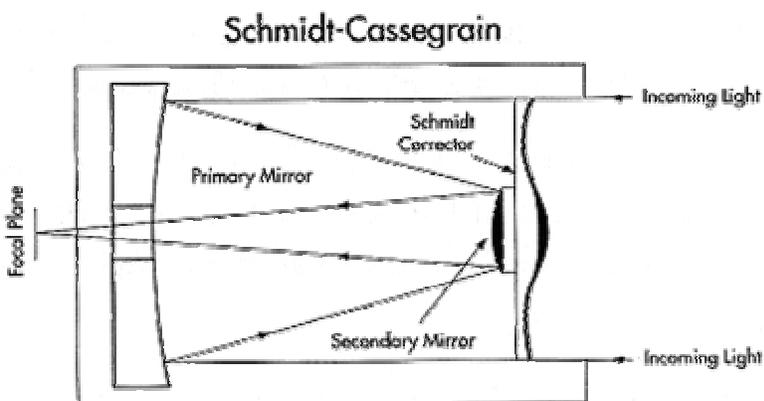


Figure 2

The Schmidt-Cassegrain design is a very efficient design.  Because the light path is bent so many times a very long focal length can be achieved in a relatively small telescope.  The focal length of the Meade 16" LX200GPS is 406.4cm but the length of the optical tube is only 83.82cm.  Without the folded light path design of a Schmidt-Cassegrain the telescope would have to be four meters long to achieve the same F/10 focal ratio.  The focal ratio is the focal length divided by the aperture, so in the case of the Meade 16" LX200GPS, the focal length is 406.4cm and the aperture is 40.64cm to give a ratio of:

$$\frac{406.4}{40.64} = 10 \tag{12}$$

Currently the focal ratio on the Mabee Observatory LX200GPS has been changed to F/3.3 from its factory F/10 setup by placing a focal reducer in the light path.  A focal reducer changes the effective focal length of the telescope while keeping the aperture the same.  The advantage of having a lower focal ratio is the wider field of view it offers.  The larger the focal ratio is, the smaller the field of view.  Because the exact location of the asteroids that are being imaged is not always known, a large field is advantageous because it increases the chances of successfully imaging the asteroid.

The telescope is mounted on a permanent equatorial pier.  This pier is made out of steel and is mounted to a concrete pillar that is isolated from the surrounding floor to reduce vibrations.   The equatorial pier is aligned with the north celestial pole so that objects may be tracked accurately across the sky.

IX. Polar Alignment:

It is necessary for the telescope to track very accurately across the sky for long exposure images.  This is why the telescope is set up in the equatorial position.  In an equatorial setup the axis of rotation in right ascension points directly at the north celestial pole when the telescope is in the northern hemisphere.  Because the celestial sphere rotates around the same axis, the declination of an object does not change as it moves across the sky and only the right ascension axis needs to rotate.  This method has several advantages over an altitude azimuth setup where the scopes left/right axis points directly to the zenith.  The first is that when tracking an object using a telescope set up in an altitude/azimuth setup both drives must be constantly changing to keep the object centered.  This results in an up and over stair stepping motion of the telescope.  This results in jerkier motion and errors in the images.  Also, in this setup the field seen by the telescope will rotate as the telescope tracks the object higher or lower in the sky.  This can be corrected for with an external field rotator, but is completely unnecessary when an equatorial pier is used to mount the telescope.  In order for the telescope to track correctly in a polar alignment the right ascension axis of rotation must be aligned parallel to the axis of the earth's rotation very precisely.  This was accomplished in the Mabee Observatory by first determining north, doing a rough alignment and then finally using the drift method of alignment as described in the Meade LX200GPS manual.

The cement pier where the telescope was going to be mounted was first prepared by determining the exact direction of north.  This was accomplished by a system of plum bobs.  The first bob was placed in the center of the northern edge of the pier; a second bob was placed at the rear.  The second bob was moved left and right until it was possible to sight through the strings of the bobs and have the strings line up so as to appear as a single string with the North Star

directly behind the string. Then a line was drawn between the tips of the plum bobs. This line points at the north celestial pole with enough accuracy that any further correction can be made by sliding the steel pier from side to side. The location of the three pier mounting bolts was marked and steel bolts were mounted with epoxy into the pier. The steel pier, custom built by Meade for 38 degrees north latitude was put in place. The pier was leveled by placing a nut and washer both above and below the base of the pier. This allowed the pier to be moved up and down by any of the three bolts and then the pier tightened down by sandwiching the pier base between the pairs of washers and nuts. After this was accomplished the rest of the telescope was mounted onto the pier.

The telescope was first rough aligned to the celestial pole. This was done by putting the right ascension setting circle on the telescope at 00 R.A. and the declination setting circles at 90º. This is called the polar home position. When in the polar home position the fork arms that hold the optical tube assembly are level and the optical tube is parallel to the right ascension axis of rotation. In this position, when correctly aligned, the telescope should be pointed directly at the celestial North Pole and the right ascension axis of rotation should be parallel to the earth's axis of rotation. The base is mounted on three bolts mounted into the floor and spaced equally around the circular base. A nut and washer were placed below the telescope pier and another washer and bolt above. By doing this the pier can be sandwiched between the washers and nuts. The bottom washer and nut are used to adjust the tilt of the pier. When proper position is found the top washer and nut can be tightened to keep the pier and telescope exactly aligned. Using the washers and nuts to adjust the telescope, the telescope and pier were moved so that the telescope was pointing at the north celestial pole. We used the North Star, Polaris, to determine when the telescope was pointing at the north celestial pole. When the North Star was in the center of the

field of view at high power the telescope had been rough aligned.  This was done visually, so it was not accurate enough for precise tracking. The drift method was employed at this point.
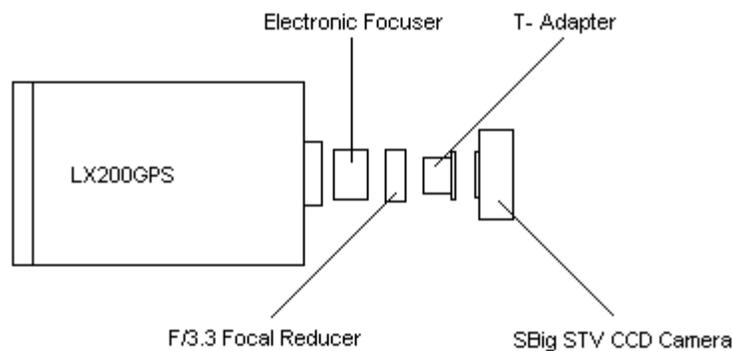
X. Imaging setup:



Figure 3

Pictured above in Figure 3 is a schematic of the imaging setup used during this experiment.  An electronic focuser is located at the rear of the optical tube assembly.  The manual focusing knob located on the back of the telescope is used to get a rough focus and then the focus is refined using the electronic focuser which has much less image shift and finer control.  After the electronic focuser is an F/3.3 focal reducer.  This lens changes the focal ratio of the telescope from F/10 and increases the field of view.  Next is a T-Adapter, which has no optical elements in it, it is simply an adapter to join the focal reducer to the CCD camera body.

The telescope can be controlled remotely via RS232 communication and a program called ScopeDriver.  The telescope can be pointed to any object in the ScopeDriver database or to any coordinates in right ascension and declination.  This is very helpful for imaging asteroids. The Lowell database of asteroid positions gives coordinates only and most of the asteroids that need more data collected on them are not listed in the ScopeDriver database.

XI. CCD:

The CCD camera that was used to take all of the images was produced by the Santa Barbara Instrument Group (SBIG). It is the STV video camera and autoguider. This camera is very versatile and is capable of taking high quality digital images, producing a video feed that can be viewed on a standard television and autoguiding a telescope for the taking of long exposure images. The CCD chip is a Texas Instruments TC237 that has a 656 x 480 pixel array that can be binned in various modes. Binning is a process where groups of pixels are added together to form one pixel in the final image. An image that has been binned 2x2 means that an array of 2x2 pixels on the CCD chip represents one pixel on the final image. Binning reduces the resolution of an image, but can dramatically increase the sensitivity of the CCD in short images. To improve imaging performance the CCD is cooled using single stage thermoelectric cooling. The STV is capable of taking images of lengths ranging from one millisecond up to ten minutes.

The equivalent of longer images can be obtained by using the STV's patented Track and Accumulate feature. In this mode, the STV takes a dark frame and then takes an image of a given length of time. The user then selects a reference star from this initial image. Once a star has been selected, the STV automatically takes a series of images, subtracts the dark frame and then co-adds each successive image with previous images, aligning them using the selected star.

The STV can be hooked up directly to the guiding port on the LX200GPS and provide automatic guiding of the telescope, however the STV cannot simultaneously guide and image. The STV is also capable of being controlled remotely. All of the functions of the camera can be controlled via RS232 communication using software provided by SBIG called STV Remote.

XII. Computers:

Mabee Observatory uses three main computers to control imaging, telescope, and live images.  The first computer is a Macintosh 6500/250 that has a video capture card in it to view the live video output of the STV.  This same image is also sent to a small TV next to the telescope control computer to allow for precise positioning and focusing.  The second computer is a Macintosh G4 that runs Virtual PC.  The STV control software, STV Remote, will only run in Windows, so that is why Virtual PC is used. The CLEA astrometry program and CCDOPS, an image processing program from SBIG also run in Virtual PC.  The third computer is also a Macintosh 6500/250 and runs the planetarium software Starry Night Pro and Voyager II.  This computer also runs ScopeDriver to control the pointing and focusing of the telescope.  This computer setup allows every aspect of observatory operation to be controlled from the work room except for dome control, which is planned for the future.  This allows one person to efficiently observe as well as be comfortable for long observing sessions.  The dome is maintained at the same temperature as the outside air, so when it is cold or hot the climate controlled work room makes observing sessions much more comfortable.

XIII. Software:

There are several software programs necessary for imaging, observing and analysis. ScopeDriver can control the position and focusing of the telescope.  It provides up to date information on where the telescope is pointing and allows specific coordinates to be entered in to go to, or the ability to search its large database of objects.

The planetarium software Starry Night Pro and Voyager II are both used as a reference to get a general idea of where objects are located in the sky as well as look up more in depth information about an object. Voyager II also has access to the Hubble Guide Star Catalogue, which is helpful in determining the field of view and orientation of images taken by the telescope.

STV Remote can control all functions of the STV CCD camera. It allows the user to change imaging modes, such as focus mode, which is a constantly updating image that allows for exact positioning and focusing. The image mode allows the user to set the parameters for an image, such as length, dark frame, binning and if the user wants just a single image or a continuous stream of images. Guiding and various equipment tests can also be controlled from the computer. This is also the interface that allows images taken by the STV to be downloaded and then saved to disk for later analysis and image manipulation.

Images taken by the STV can be opened using CCDOPS a program made by SBIG that allows for the application of flat frames, image averaging and file format conversion. It is necessary to convert all asteroid images from the native STV format to the flexible image transport system or FITS file format. This is the file format that is accepted by the CLEA astrometry program.

The CLEA Toolkit for CCD Astrometry is provided through Gettysburg College in Pennsylvania as a part of project CLEA, Contemporary Laboratory Experiences in Astronomy. This software gives the user everything they need to completely analyze a series of images and determine the position of the object in question. Once the positional data for an object has been calculated the software generates a report that can be sent to the Minor Planet Center so that they can include the data in their database of minor planets. Through this software, access to a

database of asteroid orbital elements is available as well as an ephemeris generator so that positional data for specific objects can be collected. The software can also search the Lowell Observatory asteroid database for asteroid data. When asteroid positions are being determined reference stars are needed. The USNO-SA2.0 supplementary catalog contains over 54.7 million star positions and is used to get reference star positions for comparison to the images taken. This catalogue is a subset of the larger USNO-A2.0 which was based off of the digitized images from the first Palomar Optical Sky Survey (http://ftp.nofs.navy.mil/projects/pmm/). This database was chosen due to its small file size, when compared to the USNO-A2.0 or USNOB -1.0 which contain half a billion and a billion star positions respectively.

XIV. Focusing:

Two methods of focusing were employed during this project. The first being the use of a Hartmann mask and then a similar method called the diffraction method. The Hartmann mask is a cheap effective focusing tool that can be made out of cardboard. The mask consists of two circular holes 80% of the diameter of the aperture apart, each 20% of the size of the aperture[17]. The drawing below (Figure 4) shows a mask and its dimensions for the 16" LX200GPS. The mask fits over the front of the optical tube assembly, much like the dust cover.
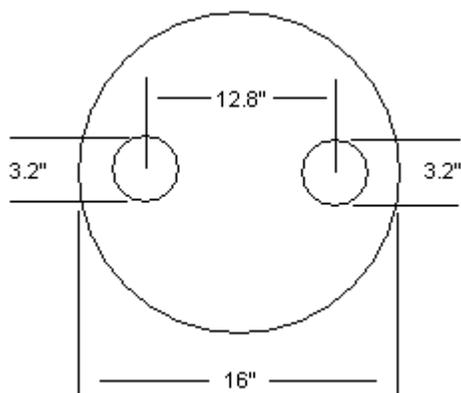


Figure 4

When the image is defocused on the CCD surface, two images of the same star will appear. As focus is reached the two images will converge and produce one image. Going past the focal plane will cause the image to split into two images again. Focus is achieved when the star that is being focused on is the smallest single point possible[18]. When choosing a star to focus on it is important to choose a star that is close to the zenith, this keeps distracting atmospheric disturbances to a minimum. It is also a good idea to choose a star of medium brightness. Too dim of a star is hard to resolve and a very bright star will have distracting diffraction artifacts that make determining when the star has converged to a point difficult.

The second type of focusing, the diffraction method, yielded better results, so once this method was tried and found to work better than the Hartmann mask it was used exclusively. Certain telescopes with secondary mirrors held up by support rods that go from the edge of the scope to the center, anywhere from one to four in number cause an optical artifact called diffraction lines. These look like the stereotypical image of a star with a bright center and rays of light projecting radially out from the center. The Meade LX200GPS employs a catadioptric design, so that while it has a secondary mirror, the support structure is the correcting lens at the front of the telescope. The diffraction method uses diffraction lines to focus. First diffraction lines must be created in the image; to do this a piece of tape is placed across the front of the telescope bisecting the aperture in half. Some people also use a cross design. Then the scope is centered on a bright star. A two second image is taken. This yields an image that has the diffraction lines projecting from the star. If the CCD is out of focus all of the diffraction lines will be in pairs. As focus is achieved the pairs of diffraction lines will merge and focusing is

complete when the pairs are merged into single rays. Below is a diagram of the aperture obstruction necessary to make the diffraction lines.
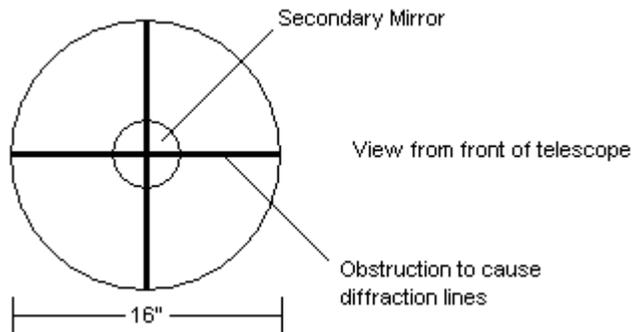


Secondary Mirror

View from front of telescope

Obstruction to cause diffraction lines

16"

Fig. 5

XV. Imaging:

The brightness of each pixel in the final image is determined by the number of photons that hit that particular pixel during the imaging process. The CCD response to light is linear, so multiple short exposure time images can be added together to gain the same image of one long exposure. This is also made possible due to the almost complete absence of a detection threshold. Traditional film requires a minimum amount of light before it will activate the film and capture an image. A CCD works by converting collected photons into electrons that are stored in individual pixels. A CCD camera may only gather a few electrons for an object, so that the number of electrons produced is less than the overall noise in the image and therefore invisible. However, multiple images can be stacked and the dim object will add up enough electrons so that its value will be larger than the background noise and will be visible. For example six ten second images added together will give the same response as a single sixty second image.

The main advantage of a CCD camera over its traditional film based camera counterpart is the level of sensitivity. The sensitivity of a camera is quantified as the camera's quantum efficiency. A CCD can be thought of as an array of light "storage" containers, or pixels. When a single photon impacts the surface of a pixel a camera with a quantum efficiency of 100% would produce one electron that is stored in the pixel. Typically the best efficiency of CCD cameras is 50%, where traditional film has a maximum quantum efficiency of 4-5%[19]. The quantum efficiency of a detector varies with wavelength. In general, CCDs show a wider response spectrum than traditional film. The pixels of a CCD can only hold a certain number of electrons, so once this number is reached electrons can spill over into adjoining pixels, an effect called blooming. This makes streaks along a column. Anti-blooming features are available, but their use should be discouraged if magnitude measurements are being made. Anti-blooming usually works by modifying the CCDs response to bright objects in a way such that it is no longer linear for the pixels illuminated by the bright object.

Image scale also must be taken into account, especially when the image is going to be used for astrometric measurements. Image scale is how much of the sky is imaged by a single pixel. An image scale between 2" and 3" of arc per pixel should be considered optimum. If the pixel scale is too large astrometric measurements will suffer, and if it is too small, the signal to noise ratio of the images will be too low[20]. In order to determine pixel scale it is necessary to know the physical dimensions of the CCD as well as the focal length of the telescope[21].

$$\text{Pixel Scale} = \frac{206{,}265 \text{ arcseconds } \times \text{pixel size}}{\text{Focal Length}} \qquad (13)$$

The pixel size and focal length should both be given in meters. For the STV, the pixel size is 7.4µm or 7.4 x $10^{-6}$m square and the image is binned 2x2, so the pixel size becomes 14.8 x $10^{-6}$m square. The focal length is 1.34m. This gives a pixel scale of 2.29"/pixel, well within the desired limits.

XVI. Image Processing:

In order to produce high quality, aesthetically pleasing images, an immense amount of image processing is required. This project does not require "beautiful" images. The images do not need to capture fine structure in an object. The images are of star fields and the asteroid is indistinguishable from the rest of the stars except for its motion. The goal of image processing for this project is high contrast images with a minimum of background noise and unwanted optical effects while maintaining the integrity of the originally recorded information. Care has been taken to ensure that the intrinsic characteristics of the images, needed for accurate analysis and measurement, were not altered in image processing.

There are four basic steps to begin the processing of any image. Depending on the desired use of the image all of these steps may not be needed, or may not be enough. The first of these steps is the subtraction of a dark frame. This removes any thermal or electronic noise from the image. It is a reusable image in the sense that the dark frame for all images of a certain length should be the same, but images of a longer or shorter length will require a new dark frame. The dark frame is subtracted from the original image. This is done automatically by the STV, so the image that is downloaded from the camera has already had this step done. A dark frame is simply an image the same length as the final image, only the shutter is never opened, so any response of the CCD is due to unwanted internal noise.

A flat-field frame is a way of calibrating the response of each pixel. If there is dust on the lens of the CCD, or vignetting, an optical artifact caused by parts of the instrument blocking the light path, causing uneven illumination, this can be corrected with a flat-field frame[22]. A flat field is created by taking a short image of an evenly illuminated surface. For this project the sky was used around twilight, just before it becomes dark enough to see stars. The ideal exposure length is usually less than a second, long enough to get a good signal to noise ratio without over illuminating the CCD. A new flat field must be taken each time the light path in the telescope changes, for example, each filter that is used requires a new flat field, or even if the CCD camera body is rotated in the optical tube assembly. The image being manipulated is divided by a flat field that has had a bias frame subtracted from it.

A bias frame is a measure of the precharge value of the CCD. This is the amount of residual charge that is stored by the CCD regardless of the exposure time. A bias frame is collected by taking the shortest possible exposure in complete dark.

The application of these first three procedures can be summarized by the following equation[23].

$$Final = \frac{original - dark}{flat - bias} \tag{14}$$

The final step in image processing is the adjustment of contrast, background and range. Contrast is the adjustment of the difference between darks and lights in an image. By adjusting the background level of an image, small random "snow" in the image can be eliminated. Raising the background level changes the minimum number of electrons in a pixel necessary to register. Without this minimum number the pixel is represented the same as a pixel with no charge in it,

completely black. The range parameter adjusts the number of levels of gray in an image. Increasing the range can bring out fine detail in an image, but also enhances noise in the image. In this project these three parameters were adjusted to make the stars in the image bright white with a black background so that during blinking background noise would not be distracting.

The amount of image processing for this project was minimal. A dark frame was applied to all images, a flat frame was applied only if noticeable vignetting occurred and a bias frame was never applied. Contrast, background and range were adjusted so that background noise was removed as much as possible without also removing the very dim objects in the image. In Figure 6 various stages of image calibration are shown, the bias frame and contrast/background adjustments are not shown.
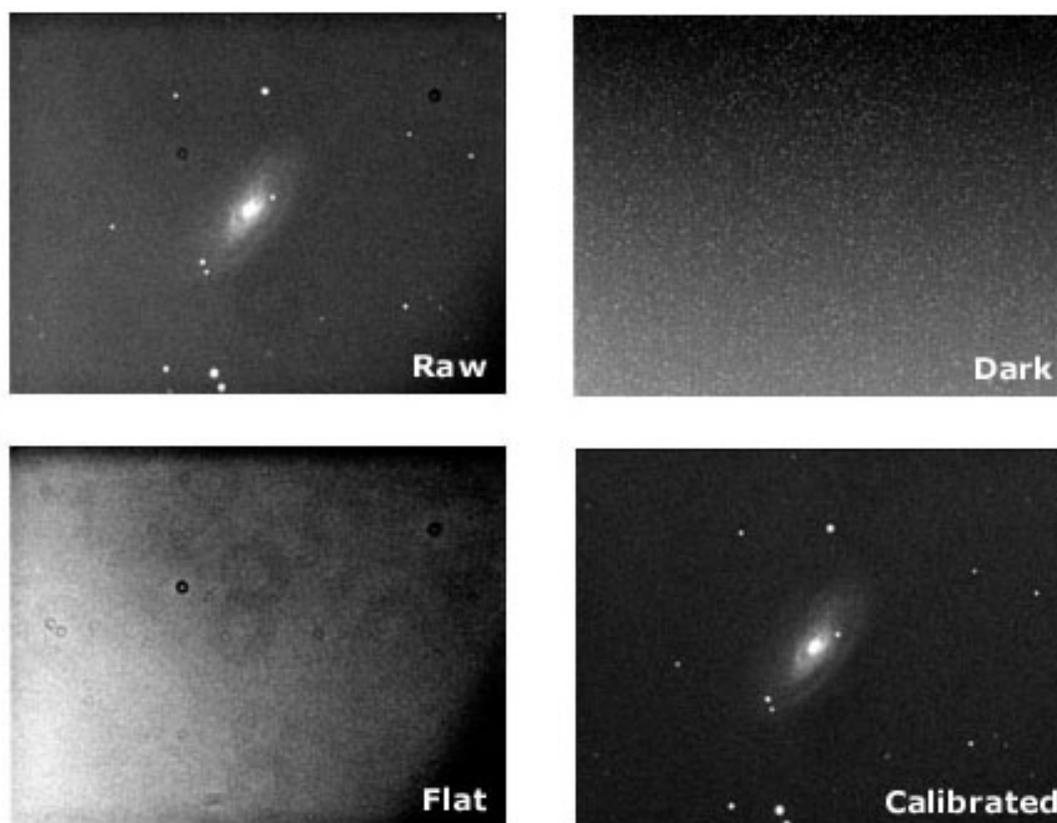


Figure 6

XVII. Equipment Problems:

Several problems were encountered with the equipment used and the observatory in general.  The telescope was scheduled to arrive before the summer of 2002, but due to the fact that Meade had just revamped the LX200 model line the telescope was not delivered until September of 2002.  The telescope is equipped with a global positioning system.  However, in the metal dome of the observatory the necessary satellite signals are unable to be received.  Unfortunately the engineers at Meade made the telescope so that it relies heavily on getting the necessary time, date and location information needed for precise alignment from this GPS signal.  It also became apparent as the telescope was tested and used that there were several software bugs in the controlling software and the optical encoders on the right ascension and declination axes would lose their positional information and effectively destroy the telescopes knowledge of where it was pointing in the sky.  Tracy Tuttle spent many hours on the phone with Meade trying to solve this problem and eventually all of the electronics in the telescope were replaced.  After several firmware upgrades put out by Meade, most of the software bugs were worked out and the telescope points well after it is synchronized to a star.

Perhaps the most frustrating problem was with the observatory itself.  It was noticed that the telescope was vibrating constantly.  The vibration was enough that it could be detected visually and made CCD imaging almost impossible.  The telescope is supposed to be isolated from the rest of the building structurally.  However, just down the hall from the observatory is the mechanical penthouse, full of air handling equipment that runs constantly.  Using the simple tool of a cup of water with a laser reflected off of the surface, the vibrations could be traced back to the mechanical room.  The isolation system was effective in damping out most of the vibration, a noticeable difference was seen from one side of the isolation barrier to the other, but

it was not damped completely.  Large numbers of people walking up to and in the dome also

induces vibrations.  This was solved by limiting the number of people walking in the dome and

working with Les Goerzen, head of the maintenance department, to shut down or turn off as

much of the mechanical equipment as possible during the night.  Les also helped with turning off

building lights to lessen the light pollution in the area immediately surrounding the observatory.

The vibration problem is not completely solved, but it has been fixed enough to obtain usable

results.


XVIII. Searching for Asteroids:

The two main ways of contributing to minor planet astronomy involve either the

systematic search for undiscovered minor planets, or finding more accurate positional

information of already known minor planets.  The search for new asteroids is monopolized by

the owners of large telescopes and large CCD cameras.  These large telescopes hold several

distinct advantages.  The first of which is light gathering capacity, the large apertures of these

telescopes allow for massive amounts of light to be gathered in a small amount of time for

focusing on the CCD surface.  This increases the number of images that can be taken in a given

period of time because it does not take as long to gather enough light for very dim objects to

show up on the image.  Telescopes with large CCD cameras have an advantage because they are

able to image a large part of the sky at once.  Most consumer CCD chips are several millimeters

on a side and only cover a few arc minutes of sky, while CCDs used on large telescopes can be

centimeters square and cover degrees of sky.  This is helpful because it decreases the necessary

number of pictures needed in order to ensure that a section of sky has been completely imaged.

Large telescopes are also generally located at prime observing spots, usually on mountain tops in

dry climates with limited light pollution and a maximum of clear nights, all of which are important when good CCD images are desired. There are several telescopes that have dedicated observing schedules where automated routines gather images all night long, resulting in large amounts of data for analysis.

The second way of contributing, by imaging minor planets and then using astrometry techniques to accurately determine position, is much more feasible for a smaller scope and CCD with no automated routines or complex image gathering operations. Because a general position is already known, covering large swaths of sky is not important. By gathering many accurate measurements of an asteroids position the orbital elements of the object can be determined and refined using mathematical models and statistical analysis techniques such as least squares regression analysis. These measurements are important for several reasons. One reason is the systematic cataloging of new asteroids. By accurately determining the positions of previously discovered asteroids, the likelihood that an asteroid will be "discovered twice" and two different names given to the same object is decreased. Also, in the event that an asteroid will be passing close to another astronomical body, such as a planet, most notably Earth, the likelihood of a collision can be calculated.

XIX. Procedure for gathering images:

Asteroids do not move across the sky at the sidereal rate. Sidereal time is based on the apparent motion of the stars from east to west due to the counterclockwise rotation of the Earth when viewed from above the North Pole. All stellar positions appear fixed in relation to each other due to the extreme distances involved. However, planets, asteroids and comets do not appear to be fixed. They are close enough to the earth that the motion of their orbits causes them

to "wander" across the sky. The telescope tracks across the sky at the sidereal rate. This allows

the observer to find an object such as a star, galaxy, or other deep sky object and then look at it

for long periods of time without adjusting the telescope to keep the object in the field of view.

This tracking rate allows long exposures to be taken without creating star trails or streaks across

the image. If the telescope did not track across the sky only short exposures of thirty seconds or

less would be possible. Such a short exposure time limits the number of objects that can be

observed.

Because asteroids do not move at the sidereal rate, images of the asteroid spaced apart by

a time interval will show the asteroid moving across the stationary background of stars. The

easiest method to determine whether or not an asteroid has been imaged with the CCD camera is

to blink a series of images. A series of images are spaced apart by a time interval, and then

aligned so that when one image is placed on top of the next, the stationary stars line up and the

asteroid moves across the image. It is important to make the images as similar as possible so that

large changes in brightness, contrast and size do not make the identification of the asteroid
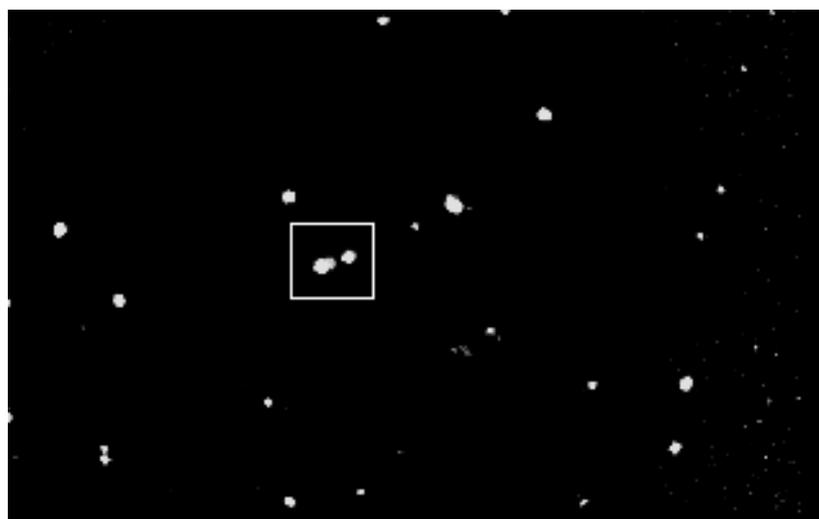
impossible.



Figure 7

In figure 7, a series of images have been overlaid and the stars aligned.  The asteroid can be seen moving across the image inside of the white box.  Taken with a Meade LX200 GPS and STV CCD camera at prime focus F/3.3.

The following procedure was used to gather images for comparison.  The telescope must first be aligned so that the position in the sky that the telescope is pointing is accurately known.  This is important for determining the exact position of the asteroid in later image analysis.  The procedure for alignment is described in section VIII.  After the telescope has been aligned, the target asteroid must be determined.  This is done using software provided by project CLEA called "Toolkit for CCD Astrometry".  Through this software, a database of all currently known asteroids is accessible.  This database is provided by Lowell Observatory and is available through ftp at ftp.lowell.edu/pub/elgb; the data file is called "astorb.dat.gz" and must be uncompressed and placed in the same directory as the toolkit software.   The first time a new database file is accessed by the CLEA software it is automatically converted into an internal format and called "astorb.cmo".  It is important to update this database file frequently in order to make sure that the newest data is being used.

Most asteroids lie near the ecliptic, which is the path of the sun across the sky.  This is also the plane of the Earth's orbit.  Aside from a minority of asteroids that have highly inclined orbits that take them out of the plane of the solar system this is where the majority of the asteroids are located in the sky.  A general area near the ecliptic is chosen in the eastern part of the sky for several reasons.  1) Because a time series is needed over a period of at least an hour to ensure enough asteroid motion to be visible, a position in the west is undesirable because as the night progresses the asteroid will move towards the horizon where light pollution and increased atmospheric disturbances make images more washed out and maximum sharpness and

magnitude are lost.  2) By choosing an asteroid in the east, as the night progresses it will move higher and higher in the sky, and be closer to the ideal location for imaging, which is directly overhead, or zenith.  This is generally the darkest, clearest part of the sky with a minimum layer of atmosphere between the telescope and the object.  At the location of the observatory on the Bethel College campus, there is much less light pollution in the eastern sky than in the west.

Once a general location is determined it can be entered into the search parameters of the Lowell database.  The search results are dependent on the time, field center, field size, magnitude range and distance range.  Without these limitations, the database would be very cumbersome to work with.  There are over two hundred thousand known asteroids currently catalogued.  A field size of ten degrees usually guarantees at least fifty asteroids to choose from.  The results of the search can then be sorted according to magnitude.  This is useful for choosing an asteroid that is within the magnitude limits of the telescope.

Imaging extremely dim objects require long exposures and guiding is necessary to avoid streaking on the image.  The observatory does not currently have adequate equipment to guide for long periods of time.  This allows for images of a minute long before errors start to become noticeable in the images.  The dimmest object detected with a one minute exposure was a magnitude 16.4 asteroid.  To image dimmer objects a function of the CCD camera called Track and Accumulate was employed.

The database search results give right ascension and declination coordinates for the asteroid, apparent magnitude, distance in astronomical units, as well as several columns of observing notes.  The fourth column is designated for importance of additional observations. This column holds a scale from one to ten with ten meaning the greatest need for additional observations.  This is also helpful in choosing an asteroid to image.  Double clicking on the

asteroid entry in the database will display the orbital elements of that object. Once an asteroid has been chosen for observation based on magnitude, importance of additional observations and location in the sky the actual imaging process can begin.

To increase the pointing accuracy of the telescope a bright star relatively close to the listed coordinates of the asteroid is chosen and then the telescope is synchronized to that star. This is done by setting the CCD camera up to take a continuous series of short exposures that have a cross hair superimposed over the image and precisely center the star. After the known star is centered the telescope computer is synchronized to that star. This tells the controlling computer that it is pointed exactly at the star. This procedure has been shown to dramatically increase the pointing accuracy of the telescope. Once the telescope is synchronized to the star the database coordinates of the asteroid in question can be entered in using ScopeDriver.

Once the telescope has slewed to the coordinates and the observatory dome has been moved into position the imaging can begin. Generally several images of varying length are taken to determine the best exposure length, with longer exposures used for dim objects. Once an exposure length is decided on the image series can begin. A standard length is used so that the images will be as close to each other in brightness and contrast so as not to be distracting during the blinking of the images. Each image is preceded by a dark frame image of the same length of the actual exposure. This dark frame is automatically subtracted out and the final image only needs contrast adjusted and a flat frame applied.

After the image is taken and downloaded to the CCD control computer it is saved in a standard file format with the filename consisting of the name of the asteroid and then a three digit number designating the order of the image. For example the first image of the asteroid Vesta would be called vesta001.stv. Generally only about five images are taken throughout the

course of the night. Sometimes it is necessary to take several images back to back to ensure a good image has been captured for the given time interval. The time between images in the series should be at least fifteen minutes to a half an hour apart. If the time interval is much smaller the asteroid does not move a sufficient amount through the field in order for motion to be detected during the image blinking.

Once an image in the series has been taken the CCD camera is then used to guide. Guiding is a process in which very small adjustments in the telescopes right ascension and declination are made to keep the field of view in exactly the same position. This is important so that when the images are stacked to blink, they all show the same field of view and contain the same stars for use when the asteroid position is determined. The STV CCD camera has an automatic guiding routine programmed into it so that once guiding is started no intervention is necessary.

While the telescope is guiding between images initial image processing can be done. Using CCDOPS the image contrast can be corrected and a flat field applied. Once the image is adjusted so that the stars are white on a black background with a minimum of noise the image is converted from the STV format into the FITS format so that it can be analyzed using the CLEA software. Once a series of at least five images have been collected, usually over a period of several hours, they can be processed with the CLEA software to determine if the asteroid has been imaged successfully.

The CLEA astrometry software can only handle four images at a time for blinking, so generally it is a good idea to use the first and last images of the series and an image a third of the way through the series and the final image two thirds of the way through the series. If one of these images turns out to be bad, then one of the other "backup" images can be used. The

images are loaded into the software one image at a time and then adjusted for contrast and range. Next, *blink* is selected from the *images* menu. This starts the alignment process. The software prompts for the user to select the first reference star. The star is selected by clicking on it with the mouse and a colored box appears around the star, after clicking OK a second reference star is selected in the same way. Then the user selects these same two stars on each subsequent image. The software then stacks the images on top of each other so that the stars are aligned with each other. Once this is complete the images can be blinked and the asteroid identified by its motion across the field. After the asteroid has been identified in the images, astrometric measurements can be made to determine the asteroids position in right ascension and declination.

XX. Determination of Asteroid Position:

Once it has been determined that an asteroid has been imaged, the next step is to determine its position in space as well as its motion through space. This is accomplished using the CLEA software and several other simple formulas. Only basic knowledge of math is necessary to perform these calculations. This procedure is taken from the Student Manual for Astrometry of Asteroids[24].

After starting the CLEA software, the image that is going to be measured is loaded and *measure image 1* is selected from the images menu. This will bring up a dialogue box where the following information needs to be entered, the field center in right ascension and declination, the field size, and magnitude limit. The field center is the same coordinates as were found from the Lowell observatory asteroid search for the asteroid in question. The field size should be a little bit larger than the field of the image in case the field center is a little bit off and the limiting magnitude is defaulted to 20 unless it is changed, this should provide sufficient reference stars.

The software will then search the USNO-SA2.0 catalogue and display a window on the left with the reference star field from the catalogue and the image being measured on the right. The image being measured should be rotated so that north is pointing to the top of the screen. The next step is to tell the computer which stars you want to use for comparison. This is done by choosing the stars in the left image with the mouse, after selection the reference stars will be outlined with a box and numbered. The minimum number of stars needed to calculate a position is three stars, however, choosing more stars will increase the accuracy of the results and errors will be easier to detect. The software will then prompt the user to select the reference stars in the image being measured on the right. After selecting all of the reference stars the computer will ask for the selection of the object being measured, in this case the asteroid. The computer will then generate a solution and display the results. These results are recorded into a report file that is the correct format for submission to the Minor Planet Center. After measuring the first image the other images of the asteroid in question should be measured and added to the report. The Minor Planet Center prefers to get results of three different images per night observed and two nights of observation separated by several days. This allows greater accuracy in the calculation of the asteroids orbital elements and generation of ephemerides. The results should be reported via email to mpc@cfa.harvard.edu. The report should include accurate time of the exposures. This should be the midpoint time, so if the exposure is a five minute exposure, the reported time of observation is the UTC (Coordinated Universal Time) time at 2.5 minutes into the exposure. The Minor Planet Center will make the adjustment to TT (Terrestrial Time). Each measured frame should have its own magnitude calculated and all magnitude measurements should be submitted with position measurements. All position data for any moving object in the image should be reported, if there are two asteroids in the frame, both should be measured and reported.

Once the results have been received a confirmation email is sent. If no results have been received from that particular observing location and the results are of sufficient quality, the Minor Planet Center will issue a permanent observatory code. This is a unique identifier that is linked to an observatory's location and elevation for translating observations from topocentric[25] positions to geocentric positions. After all positional measurements have been made the results should be checked to see if they make sense. Over the short time period of the series of images the asteroid should appear to move in a straight line, so a change in the right ascension and declination should be noticed. The right ascension should increase for eastward moving objects and decrease for westward moving objects. Asteroids moving north should show an increase in declination and a southward moving asteroid should show a decrease in declination.

XXI. Angular Velocity:

Once the position of the asteroid has been measured in all of the images, the next step is to determine the angular velocity of the asteroid. This is done by subtracting the starting coordinates in the first image, from the final coordinates in the last image, this will give us the angle that the asteroid has traveled through, and then, by determining the time between the midpoints of the exposures we have a time. The angular velocity can then be expressed as follows:

$$\mu = \frac{\Delta\theta}{\Delta t} \qquad (15)$$

Where $\mu$ is the angular velocity, delta theta is the change in the angle and delta t is the change in time. The elapsed time is found by subtracting the midpoint times of the first and last exposures.

The time is converted to decimal for ease of subtraction.  This is done by dividing minutes by 60 and seconds by 3600, the decimal fractions are then added to get decimal time.  The time should be calculated to at least five decimal places.  The final angular velocity will be expressed in minutes of arc per second, so convert the decimal time in hours to seconds by multiplying by 3600.

The only other thing left is to determine the angular distance traveled.  Over the short time period of the images the asteroid appears to move in a straight line, so the Pythagorean theorem can be used:

$$c = \sqrt{a^2 + b^2} \qquad (16)$$

Where c is the angular distance, and a and b are the changes in right ascension and declination. This is illustrated below.
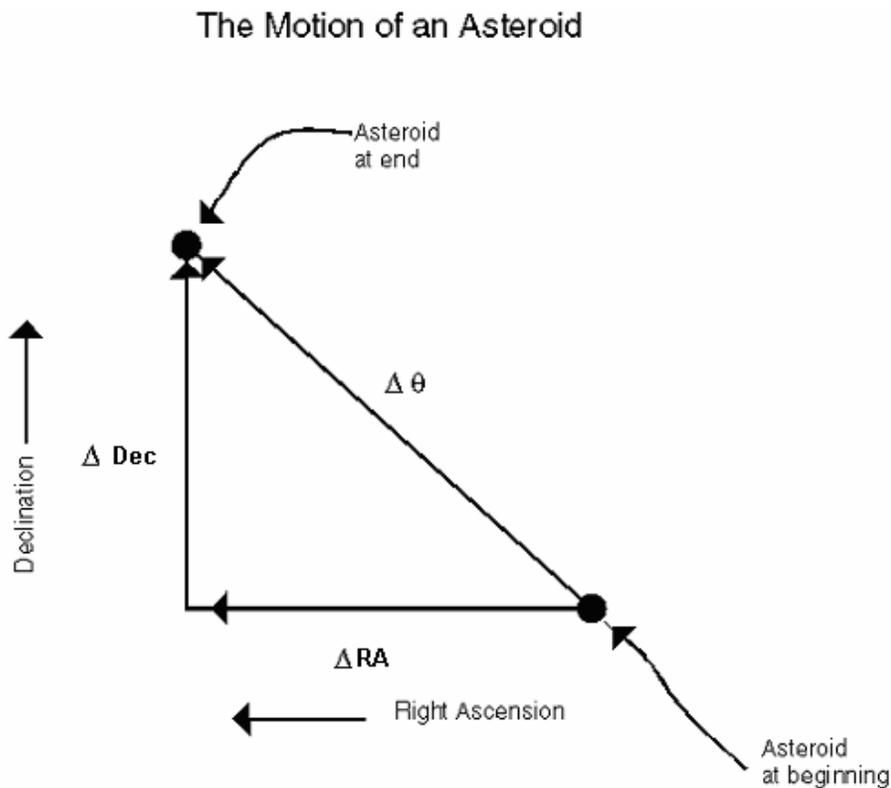


Fig. 8 taken from reference #4

The declination of the first and last images should be converted to decimal in the same way as the time, dividing the minutes by 60 and the seconds by 3600. These are subtracted to find the difference to five decimal places. This difference is converted to arc seconds by multiplying by 3600. The same procedure is followed for converting the right ascension to decimal and then converting to seconds of right ascension by multiplying by 3600. However one further correction needs to be made to the right ascension. On the celestial sphere, the lines of right ascension come together at the poles, so there are smaller angles between them at higher declinations. This can be corrected for with:

$$\Delta RA_f = \Delta RA \times 15 \times \cos(Dec) \tag{17}$$

Where $\Delta RA_f$ is the corrected right ascension and *Dec* is the decimal declination of the asteroid in either image. Then plugging change in right ascension and declination into the Pythagorean theorem gives.

$$\Delta\theta = \sqrt{(\Delta RA)^2 + (\Delta Dec)^2} \tag{18}$$

We now have an angle, $\Delta\theta$ and a time in seconds, inserting these values into equation (15) gives the angular velocity of the asteroid in seconds of arc per second. In order to finds its velocity in km/s we must know its distance.

XXII. Distance:

Asteroids are located in the solar system; this means that they are close enough to the earth that their positions can be determined using parallax. Parallax is the angular difference in position relative to very distant background stars on images from observing sites separated by a baseline. All that is needed for parallax measurements is two images of the object taken at the same time and a measure of the distance between the two observing sites.

First the asteroid positions are measured in each of the two images and converted to decimal degrees for subtraction to find the difference and then converted back to arcseconds. This is done for right ascension as well, remembering to correct for declination using equation (17) and then using equation (18) again to find the parallax angle. Once this is determined the distance to the asteroid is:

$$\text{Distance} = 206{,}265 \left( \frac{\text{Baseline}}{\text{Parallax}} \right) \tag{19}$$

Where baseline is the distance between the observing sites in kilometers and parallax is in arcseconds. The number 206,265 is the number of arcseconds in one radian. This can then be further converted into astronomical units or AU, the traditional unit of distance for solar system objects.

XXIII. Tangential Velocity:

Knowing the angular velocity and the distance, the tangential velocity can easily be found.

$$V_t = \frac{(\text{angular velocity} \times \text{distance})}{206,265} \qquad (20)$$

This gives the tangential velocity of the asteroid in km/second.

XXIV. Magnitude:

Magnitude is a measure of brightness of an astronomical object with higher magnitudes representing dimmer objects. It can be expressed in either apparent or absolute magnitude. Apparent magnitude was used for this study. Apparent magnitude is how bright an object appears to an observer, so an extremely bright object that is located very far away can have a high magnitude. Absolute magnitude is the magnitude of an object if it were observed from a standard distance of 10 parsecs[26]. The magnitude of the asteroids can be determined with software. In this case CCDOPS from SBIG was used. Because CCDs have a linear response, the relative number of electrons collected by the CCD relates directly to its apparent magnitude. By telling the software the magnitude of a known object in the image, such as one of the reference stars, the software can determine the magnitude of an unknown object.

XXV. Refinement of procedure and submission of results:

Once the process of minor planet imaging and position calculation has been practiced it needs to be refined and modified to produce useful results worthy of submission to the Minor Planet Center. The Minor Planet Center operates at the Smithsonian Astrophysical Observatory and is a non-profit part of the International Astronomical Union. (http://cfa-www.harvard.edu/cfa/ps/mpc.html). The refinements necessary include more practice using the Track & Accumulate function on the STV so that dimmer objects can be detected. It is

necessary to set up observing routines so that observations can be made on subsequent nights. The next step is to get repeatable results, to be able to find asteroids multiple times, determine their positions and magnitudes and report these results regularly.

XXVI. Summary and conclusions:

Over the course of the investigation seven different asteroids were searched for. Three of these asteroids were imaged successfully. None of these asteroids positions were submitted to the minor planet center. The minor planet center recommends that asteroid positions for successive nights or two nights close together be submitted. This makes determining the orbits so that ephemerides can be generated much easier. This was tried for two of the asteroids, but the successive nights were either cloudy or the asteroid could not be found again. This project will be continued in the hopes of producing results worthy of submission.

A great deal was learned about the field of astrometry. I now feel comfortable with the necessary corrections for the determination of accurate and precise object positions. Mabee Observatory is most certainly capable of producing usable results. The dimmest asteroid found was magnitude 16.4. This is not the limit of the observatory. Refinement of the Track & Accumulate procedure should produce increased sensitivity. This problem could be eliminated if a large format CCD camera were purchased to be used alongside the STV. The STV was designed mainly as a guiding CCD. The CCD chip is also relatively small. A larger CCD would enable larger fields to be imaged without the need for focal reduction. The STV could then be used as an electronic finder scope as well as an auto guider for long exposures. This would produce better results than the Track & Accumulate. Overall this project could be used as an

example for future projects or a continuation of this project.  The procedures are simple enough that any undergraduate physics student could perform the basic steps and calculations.

[1]Binzel, Richard P. "Asteroids Come of Age". Science 22 Sept. 2000, Vol. 289 Issue 5487, p2065.

[2]The Titius-Bode law of planetary distances is a numerical relationship found by Johann Titius and Johann Bode that approximates distances to planets as measured in astronomical units.

[3]An ephemerides is a list of object positions at increments of time, for example it might contain the right ascension and declination coordinates of a comet for each evening of the month.

[4]Project CLEA. Astrometry of Asteroids Student Manual. Gettysburg:  Gettysburg College. ftp://io.cc.gettysburg.edu/pub/clea_products/manuals/Ast_sm.pdf (April 16, 2003).

[5]Tatum, Jeremy B. "The Measurement of Comet Positions." Journal of the Royal Astronomical Society of Canada (1982). http://adsabs.harvard.edu/journals_service.html (April 16, 2003).

[6]Tatum, Jeremy B. "Celestial Mechanics." http://astrowww.phys.uvic.ca/~tatum/ (April 16, 2003).

[7]Project CLEA. Astrometry of Asteroids Software User's Guide. Gettysburg:  Gettysburg College. ftp://io.cc.gettysburg.edu/pub/clea_products/manuals/Ast_ug.pdf (April 16, 2003).

[8]Chauvenet, William. A Manual of Spherical and Practical Astronomy. Vol. II. New York: Dover Publications, Inc. 1960. 2 vols. Pp. 469.

[9]Hosmer, George L. Geodesy. New York: John Wiley & Sons, Inc. 1930. Pp. 402.

[10]Reference #8 Pp. 472.

[11]Kreyszig, Erwin. Advanced Engineering Mathematics. 8th Ed. John Wiley & Sons, Inc. 1999. Pp. 914-915.

[12]Reference #6 Ch. 11. Pp. 9.

[13]Reference #6 Ch. 11. Pp. 12.

[14]Reference #7 Pp. 15.

[15] "Meade Optical Coatings" http://www.meade.com/catalog/uhtc/index.html (April 16, 2003).

[16]Meade LX200GPS Product Manual.  Meade Corporation. 2002.

[17]Santa Barbara Instrument Group. Operating Manual STV Video camera and Autoguider. 2002. Pp. 51.

[18]Lee, Steven. "The Art of CCD Imaging." http://www.aao.gov.au/local/www/sl/sl-iproc.html#tti. (April 16, 2003).

[19]Martinez, Patrick, Klotz, Alain. A Practical Guide to CCD Astronomy. United Kingdom: Cambridge University Press, 1998.

[20]"Guide to Minor Body Astrometry." http://cfa-www.harvard.edu/iau/info/Astrometry.html. (April 16, 2003).

[21]"Will It Fit on the Chip?." http://hou.lbl.gov/~vhoette/Explorations/OpticalPowers/9b-fieldofview-s.html. (April 16, 2003).

[22]Reference #17 Pp. 58.

[23]Reference #19 Pp. 111. Figure 3.18.

[24]Reference #4 Pp. 14-27.

[25]Topocentric coordinates for an object are those of the object as viewed from a specific location on the surface of the earth. Geocentric coordinates are coordinates of the object if it were viewed from the center of the earth. The conversion is necessary for accurate orbit determination.

[26]Arny, Thomas T. Explorations an Introduction to Astronomy. 2ed. 2000 Update. McGraw Hill. 2000. Pp. 362.