# PHOTOMETRY AND ORBIT DETERMINATION

Asteroid rotation provides essential information and clues that may have led to the collisional history, their dynamic evolution resulting in their current shape and size. One of the most popular and used techniques to investigate these properties is light curve photometry. The thesis shall heavily implement this method to obtain the rotational period alongside initial orbit determination for the characteristics of these NEAs. Chapter 3 focuses more on the methodology and concept that will drive the project forward. A review of the light curve is important to provide and govern concepts presented and applied in the later chapters.

## Photometry

Photometry is applied in astronomy to measure the flux and light intensity of radiated celestial objects. The measured light is done by telescopes using a photometer. The photometer is composed of electronic devices such as a charged-coupled device (CCD) photometer or a photoelectric photometer that performs light conversion into electric current by the principle of the photoelectric effect. After the conversion is done, calibration is done against known intensity’s standard stars (in the background during observation). Thus, the photometer can measure the celestial object’s brightness or apparent magnitude H [ref]. The information from the measurements yields important information such as age, distance, temperature, and rotation period.

Early observations were done by Greek astronomers who used the Hipparchus system around 130 BC. The system divided the stars into classes called magnitudes. The brightest of stars fall in the first magnitude, followed by the second magnitude of least bright stars, and the magnitude rate increased for the fainted stars having the 6th magnitude.

In the 17th century, the discovery of fainter stars led to the invention of telescopes. This enabled to further group the fainter stars, and the magnitude group was increased to the eighth magnitude. Jumping to the 19th century saw new experiments established that the apparent equal steps of magnitude were steps of a constant ratio of light energy received during observation and that the difference in the brightness of 5 magnitudes was approximate to the ratio of a hundred. In 1856, Norman Robert proposed that this ratio govern the scale of magnitude that the brightness difference would be a ratio of 2.512 in intensity, and a 5-magnitude difference would be the ratio of 2.511885. Furthermore, steps in brightness would be denoted by decimal fractions. The zero in the scale was used to cause the minimum change of the many stars in the sixth magnitude, with many stars having magnitudes less than zero.

The invention of photography paved the way for providing a means of measuring the brightness of the stars. Photographic plates are sensitive to violet and UV radiation compared to green and yellow wavelengths that are sensitive to our eyes, thus leading to the making of two separate magnitude scales, the photographic and visual scales. Their difference is that a given star led to a colour index usage that would measure the temperature of the star’s surface. Photographic photometry relied on image comparison of visuals and recorded starlight in the plates. This led to inaccuracy due to complexity from the size and density of photographic images of the stars, and the brightness of optical images was not subject to control and proper calibration.

In the early 1940s, photometry was extended to sensitivity and wavelength range due to the application of accurate photoelectric rather than photography. The magnitude was increased to twenty-four for the faintest of stars. In photoelectric photometry, the image of a lone star s passed through a small diaphragm in the telescope’s focal plane. Thereafter the image is passed through a selected filter and a field lens. Then the images go into a photomultiplier, a device that produces a strong electric current from a weaker light input. The output current can be measured in many ways. The ways are possible due to the extreme accuracy of the linear relationship between the incoming radiation and its current, making it possible to measure the current. The addition of photomultiplier tubes is sub-planted by the CCDs enabling the measurement of magnitudes in the visible, UV and infrared spectrum [ref].

Nowadays, photometry is more advanced and has a wide range of activities. The photometry of stars was further extended to other celestial objects like planets, comets, asteroids, galaxies, and nebulae. The measurements use apparent magnitude in the scale of magnitude per arcsecond^2 [ref]. Further knowledge of the area and light intensity across the objects can determine the surface brightness, while integrating the total light of the extended object can give the total magnitude or luminosity per unit surface area.

Photometry has numerous applications in the field of astronomy. The measurements can be merged with the inverse square law when the distance determines luminosity or the opposite. The inverse-square law is any scientific law stating that a specified physical quantity is inversely proportional to the square of the distance from the source of that physical quantity [ref]. Physical properties like temperature and material composition can be determined from either broad or narrow band spectrophotometry. One of the major applications that is part of the thesis study is detecting the light variations from asteroids and other minor planets. The measurements from the variations are then used to determine the rotation period of the asteroid. Different outputs from the variation measurement include the orbital period and radii of objects of an eclipsing binary star system and obtaining the total energy given out by a supernova [ref]

## CCD Photometry

CCD photometry uses a CCD camera that is made up of a grid of photometers that measure and record photons coming from all sources in the FOV. Since each CCD image records multiple objects at once, many forms of photometric extraction include relative, absolute, and differential. All three methods need the raw image magnitude extraction of the target objects and a known object for comparison. The observed signal of an object covers many pixels and follows the point spread function (PSF) of the system. PSF describes the response of an imaging system to a source point, also known as the system’s impulse response of a focused optical system. The broadening is due to the telescope’s optic and the astronomical seeing (the degradation of an image from turbulent flows from the Earth’s atmosphere).

When obtaining photometry from a point source, aperture photometry measures the flux by summating all the light recorded and subtracting the light due to the sky [ref]. The result is the output of the raw flux of the object. In the case of a crowded field like a cluster, de-blending techniques are used such as PSF fitting due to the stars overlapping each other [ref].

### Calibrations

In calibration, the object’s flux is converted into instrumental magnitude (uncalibrated apparent magnitude) from counts. The calibration method depends on the photometry type used. Most observations are done using either differential or absolute photometry. The commonly used methods are absolute, relative, differential and surface photometry. Accurate photometry is rarely used as it is more difficult when the apparent brightness is fainter for an object.

### Absolute Photometry

Absolute photometry is the measurement of the apparent brightness of an object on a standard photometric system. The measurement can then be compared with other absolute photometric measurements obtained with different telescopes or instruments. Similarly, the absolute magnitudes can be compared with magnitudes from catalogues coming from other observers. Absolute photometry has the difficulty to work with high precision, unlike differential photometry.

Absolute photometry is done by correcting the differences between the effective passband through an object and the passband that defines the standard photometric system. The effective passband is the measurement of a standard star in a varying sky location, thus requiring good and stable atmospheric conditions.

### Relative Photometry

Relative photometry is the measurement of the apparent brightness of multiple objects relative to each other. It is done by comparing the instrument’s magnitude of the object to that of a known comparison object and then correcting the measurements for spatial variations in the instrument’s sensitivity and the atmosphere extinction. It also adds temporal variations when compared objects are far apart in the sky for simultaneous observations. Performing calibration of images containing both target and comparison object on proximity will result in the measurement variations decreasing to null since the photometric filters will match that of the catalogue magnitude of the comparison object. [ref]

### Differential Photometry

Differential photometry is the measurement of the difference of two observed objects, ensuring the variations of the flux of the object that are not intrinsic to it are thereby corrected. Differential photometry can be done with the highest precision, giving it an advantage over absolute photometry. The change in magnitude in equation 3.1 is important when plotting the change of magnitude of the target object, creating a light curve. This method will be used in obtaining the rotation periods of the NEAs.

This method includes airmass variations that appear in the FOV (can include clouds as well). Therefore, the comparison star should be close to the target to bear similar airmass and atmospheric conditions. It is recommended that the comparison stars have spectral types similar to the Sun’s one for asteroids to avoid differential extinctions. However, this effect can be lowered by averaging the signal of many stars’ comparison.

The comparison of a star relies on at least two ways of checking if the signal of the other star is stable to make it sufficient. Some stars have varying brightness and should not be used with this method. An added advantage of using many comparison stars is the reduction of noise in the measurements. This also improves the accuracy of measuring small variations.

### Surface Photometry

Spatially extended objects like galaxies are measured in the spatial distribution of brightness within the galaxy rather than the total brightness of the galaxy. A givens object surface brightness is defined as the brightness per unit solid angle as seen in a projection on the sky. This method is known as surface photometry. It is best utilised when measuring a galaxy’s surface brightness, for which the surface brightness is given as a function of the distance from the galaxy’s centre. Square Arcseconds unit is used for small solid angles. The brightness is often expressed in magnitude per square arcsecond [ref].

### Aperture photometry

Aperture photometry is the measurement of an object’s flux from an image. It involves taking the total flux in a measuring aperture and normalising it to an exposure time of a second. The background flux is approximated by using the median or average of the flux in an annulus, centred like the total flux but separated by a dead zone in the measuring aperture

## Other techniques

Besides photometry, other are techniques to study asteroids that provide other useful features. These techniques are not part of the scope of the thesis but present a broader picture of other ways to learn more about asteroids.

1. *Asteroid spectroscopy* aims primarily to identify features in asteroid spectra to understand their surface composition better and link them to meteorite analogues. It works on distinct parts of the electromagnetic spectrum. Many observations lie in the visible range due to the atmosphere transparency at the visible wavelength range. The visible spectrum helps to distinguish material composition, especially carbonaceous asteroids, from the silicaceous ones. Spectroscopy in the near-infrared range is more difficult due to the strong water vapour absorption. However, current observation relies on those wavelengths because of the numerous absorption bands from different mineralogical compounds found there.
2. *Asteroid polarimetry* is the study of the effects of light polarisation after it reflects over an asteroid’s surface. The partial polarisation of the unpolarised light of the Sun depends on the texture and composition of the surface, the wavelengths, and the phase angle. The phase angle of an object is the angle between the Sun, the object, and the observer. Polarimetric observations help derive the geometric albedo, size, and taxonomic classification of an asteroid.
3. *Infrared radiometry* measures optical radiation within the IR band (from 4 μm to 30 μm) in the specific windows where the atmosphere is relatively transparent. Its applications include the determination of the size, thermal inertia, surface roughness and emissivity of asteroids. The size is derived from the measurement of the disk-integrated thermal infrared flux of the asteroid, which depends on the square of its diameter. Space-based telescopes are not limited by atmosphere transparency and thermal background. Therefore, these telescopes can observe much fainter asteroids using smaller uncertainties.
4. *Radar imaging* is the analysis of the reflection of microwaves or radio waves on the asteroid surface. The time delay gives a direct measurement of the distance. Thus, the combination of both optical and radar observations allows computing fully accurate orbits. To produce the 2-D images, one has to measure the distribution of echo power in time delay and Doppler frequency. Moreover, suppose images are obtained at enough viewing geometries. In that case, a 3-D shape can be derived as well as the rotation state (Ostro et al. (2002)). The echo power is proportional to the inverse fourth power of the distance; hence the technique is achievable for NEAs and the most prominent members of the MBA only. The most used radar astronomy facilities for such measurements are the Arecibo Planetary Radar and the Goldstone Solar System Radar (Ostro et al., 2002).
5. *A stellar occultation* is an event that occurs when the asteroid passes in front of a star and temporarily blocks its light as seen from Earth. The duration of this event, combined with the apparent velocity of the asteroid on the sky plane, allows deriving a physical length (called a chord) on the asteroid 2-D disk. When detecting several chords from various locations, the output becomes a 2-D profile. The profile is valid for the asteroid on the sky plane at the time of the event. Observation of stellar occultations ranges from small aperture to targets with small angular sizes such as the TNOs. The main difficulties with stellar occultation observations come from the uncertainties in the star and the asteroid positions. Many observers are thus needed to cover a large geographical area.

Moreover, those events are rare and thus hard to reproduce. The accuracy of a chord measurement depends on the accuracy of the timing of the star disappearance and reappearance. A big source of error comes from the absolute timing between chords from different observers when merging them. The stellar occultation technique is mainly used to determine the sizes of asteroids. Still, if one obtains enough chords, it can provide details on their shapes. In rare cases, detection of atmospheres and rings is possible. It is also helpful to set the scale to a dimensionless 3-D shape.

## Photometric measurements

The common property that is crucial to obtain from an asteroid is its rotation period. Majority of asteroids in the taxonomy appear to have their rotation periods ranging between 2 to 24 hours, while the minority have lengthy rotations that span for several days. Another factor that affects these varying rotation periods is the diameter. Asteroid with diameters less that 150m appea to have shorter periods around 2,4 hours. If the rotation period is below 2,4 hours, the centrifugal force grows much stronger for an asteroid to maintains its integrity due to the rubber pile structure. Below are discussions on the various properties of photometry.

### Rotation

Its angular moment vector , governs the fundamentals of an asteroid’s rotation, where the spin vector gives the instantaneous speed and axis rotation,also known as the angular velocity vector. The angular moment is defined in equation 3.1.

The in equation 3.1 is the f inertia tensor and is further broken down in eq. 3.2. Both the and the change over time due to collisional events and other asteroid evolution processes.

The terms and are moments of inertia along the axis x, y, and z, while the rest of the terms are the inertia products. The moment of inertia tensor explains how an asteroid’s mass is distributed around any instant spin rotation axis. Any asteroid shape has a given unique XYZ coordinate system. Every non-diagonal term from equation 3.2 becomes zero, as shown in equation 3.3. The diagonal terms now become the principal moments of inertia, and their corresponding axes are the principal axes of inertial. The principal axis governs the rotation of asteroids over a lengthy period and is further explained in section 3.1.2 [ref].

### Principal axis

The of an asteroid does vary with time because of the change in the inertia moment about the instantaneous rotation axis. It is not a constant due to changes in the inertia moment about the instantaneous spin axis. Asteroids that bear this feature are referred to as non-principal axis rotators have the and the not aligned. The unalignment leads to a complex and non-periodic rotation. The rotation state can also be referred to as an *exciting rotation*. Such a motion creates a cyclical stress/strain on the body. However, due to the nature of asteroids not truly being rigid bodies but instead composed of elastic and loosely structured materials, the interior dissipates the rotational energy. With time, the rotation attains minimal rotational energy causing the rotation to occur on the principal axis with the largest moment of inertia.

The damping timescale of a non-principal axis rotation of an asteroid is express as follows based on the contributions from Harris [Harris]. The period is the rotation period of the asteroid and is expressed in hours. At the same time, is the mean diameter of the asteroid expressed in kilometres, and is a constant, usually approximated t the value of 17.

The value of can range from thousand to billion years. Most asteroids have a smaller resulting in most of them rotating in their principal axis rotation states. Furthermore, this results in the possibility to measure the rotation period using light curve photometry. Light curve observations do not require much cost but demand more time for observation, for which most of the observation is done at night. These observations are done over several years to provide a clear solution of .

### Rotation measure

The of an asteroid is a calculation done by using the and for a given estimate of inertia that is based on the size, shape and density of the asteroid being measured. An accurate measure of the moment of inertia estimate uses in situ measurements. The reason the is crucial for obtaining the is because cannot be measured from any ground-based observation centre.

Gound based techniques alongside radar and optical measurements are used in the asteroids spin vector characterisation. Asteroids in a family and that are very reflective can be measured using radar imagery. Radar imagery helps to obtain information on the shape and rotation vector of the asteroid.

### Air Mass

Observations of asteroids are affected by air mass due to the variation of the air amount in any direction when observing an asteroid or other celestial bodies. Therefore, airmass is the light’s path length that goes through the atmosphere and reaches the observer and relates to its attenuation by air. Air mass is greater when near the horizon than in the zenith position (equal to 1), increasing the measurement flux. This is because light travels on a long path for a target observed near the zenith region, resulting in dim data. Airmass can be shown in a simple equation where is the zenith distance

The cause for this increment in airmass is due to changes in humidity, air pressure, clouds, haze, and air pollution. Therefore, if light travels inside the air before detection would result in a lower flux. Air mass also causes the scattering of blue light, making the red light prominent when viewing objects.

Airmass leads to extinction which is the sequential scatter and absorption of electromagnetic radiation by gas and dust between the emitting celestial body and the observer [ref]. Observers on earth experience extinction from the interstellar medium and the Earth’s atmosphere (dust mainly). As mentioned earlier, red light is less attenuated, leading to interstellar redding [ref]. Lower altitudes areas are usually not chosen due to differential extinction across frames, making the object smaller like a mini spectrum and the position of blue stars changes to that of red ones. This effect is also due to differential fraction and higher scintillation that makes the data noisier (further discussed in section 3.3.6).

Astronomers apply the first-order extinction when there appears to be a dimming effect of the celestial’s object light. Like airmass, extinction increases as one moves closer to the horizon due to light scattering. It is a wavelength-dependent factor. The units for the first order extinction are of the degree of magnitudes per airmass. A second-order extinction focuses on the target’s colour and the airmass present at that time. Similar to the first order, second order extinctions add a third measurement unit called the colour index. A colour index is the difference of the magnitudes from the different filters in use at the moment of observation. [ref].

### Seeing

Seeing is the phenomenon that measures turbulences from the atmosphere due to the temperature differences in the layers of the atmosphere. Seeing is a factor that affects the accuracy of the observation. Ideally, the target object should observe it using a light source, though this is not possible for ground observation. When the layers of the atmosphere have varying temperatures, the light path would not appear parallel. The final light reaches the observer at a non-zero angle due to the difference in the refraction indexes from the layers of the atmosphere. The layers also cause the object to appear large in the image and occupy most image pixels. The SI unit for seeing is arc seconds and presents the object’s size at a Full Width at Half Maximum (FWHM) of the object’s profile, and ranges from 0.5~3.0 arc seconds [ref].

### Scintillation

Scintillation, also known as twinkling, is a phenomenon that arises when small air cells in the atmosphere cause the light of an object to arrive in several packets. It is causing the sparkling of light observed in the night sky. It is because the light is reaching the observer not in a simple packet but in several. Small apertures cause an object to twinkle, resulting in fast variations of brightness. Stars do twinkle because they are far away from the Earth, having their light sources disturbed by the atmosphere causing light diversion. Therefore, using a large aperture and longer exposure times would lower the scintillation effects [ref].

### Opposition effect

The “opposition effect” can help to determine the asteroid’s surface composition. As the asteroid approaches’ opposition, that means low phase angles (the angle Sun-asteroid-Earth), a non-linear rise of about 0.3 to 0.5 magnitudes occurs [ref]. This happens because the particles in the asteroid’s surface scatter the sunlight, and it is independent of rotational variations. [ref] Important factors are the roughness of the surface, the size, the shape, and the porosity of the particles. Thus, low albedo results in little “opposition effect.” However, the brightness of an asteroid can be different from opposition to opposition due to different obliquity. This means that the angle between the asteroid’s spin axis and the ecliptic plane is not always the same from one opposition to another. The larger the angle means more area of the asteroid’s surface is lighted, and the asteroid is brighter at that time.

## Light curves

A light curve is a light-intensity graph of a celestial object as a function of time. Whereas light curve photometry is an asteroid’s optical observation, done over time, to be able to find its rotational properties. Since asteroid spin around their axes, they appear to have variations of light bouncing of their surfaces during observations. These variations in light are what builds on the foundation of the measurement to generate the light curve. The light curve plot comprises of a vertical axis that shows the magnitude, and in some cases the use of flux. In the vertical, phase angle is used, or time to show one complete rotation of the asteroid. From the plot, an observer can therefore, determine the rotation period of the asteroid because of its spinning and the amplitudes present in the plot. Fig. 3-1 shows a plot of the asteroid 201 Penelppe that was created from the observation obtained from the Mount John university observatory. Its rotation period was found to be 3.7474 hours.

## Chart, line chart, histogram Description automatically generated

Figure ‑: The Light curve of the asteroid 201 Penelope. [ref]

The period for an asteroid is equal to the light curve period. The amplitude from a light curve can generate general shapes of an asteroid using the equation where and are the minimum and maximum cross-sectional area of an asteroid, respectively.

Howwever a researcher can keep on with further analysis. By gathering data for a relatively short period of time and plotting them, unexpected “dips” (usually a dimming of 0.01-0.03 magnitudes) in the general light-curve [11] may appear, supporting the claim that the asteroid is a binary system. Also gathering data for a longer time (several months or years) may lead to the deriving of the shape [11] taking also into account the variations of its light-curve‟s amplitude. Furthermore scientists can determine the direction of its spin axis. [11] This can lead to the determination if the asteroid has a prograde or retrograde spin and belongs or not to an asteroid family of interest setting the limits in the V-shape of the family.

It is essential though that the observations include several different apparitions of the asteroid-target. This is because with every apparition the asteroid‟s spin axis has a different angle from the line of sight to the observer [11]. As a result the amplitude of the curve is different for each apparition. The researcher can measure these changes over time and result in the determination of the pole orientation (spin axis) with only five to seven light-curves. [11]

Radar observations can be used to measure the frequency shift of the signal sent to the asteroid and its distance from the researcher. A further step to the analysis is the deriving of the shape of the asteroid and whether if it has a companion body. Light-curve photometry can be used to pinpoint if a radar observation of an asteroid-target will be valuable. If the optical and radar observations are taking place at the same time then the light-curve photometry can put constraints to the results of the radar observations. [11]

## Observations

## Preliminary orbit determination