Lab 2

Observing the Sky

2.1 Overview

This project is focused on naked eye observations of the sky – understanding the monthly lunar orbit, visualizing the positions of the Moon, Earth, and Sun throughout this cycle, and relating the changing appearance and position of the Moon in the sky to its phase, illumination and elongation angle. Students also estimate their own latitude from the observed altitudes of the transiting first quarter Moon and Polaris. They build on general skills introduced in the first laboratory exercise by reading and interpreting figures, planning and conducting observations, recording data accurately, and analyzing the results.

This is the only project that must be scheduled in accordance with outside factors, by taking into account the phase of the Moon. It is ideally scheduled to begin a few days after the new Moon occurs, with lunar observations being completed by the full Moon. There is considerable latitude in the start date, however, because students observe the Moon for a period of only eight days, and the project contains an alternate version of the lunar activity designed to be completed during the second rather than the first half of the lunar month. (The primary difference is that certain observations then need to be conducted at dawn rather than at dusk.)

This project contains multiple activities that encourage students to develop the skill of visualization. Visualization is used in two ways throughout the exercise, in the theoretical sense to understand the observed movements of the Moon and stars relative to the Earth and Sun, and in the practical sense to construct and then properly use simple sextants to observe objects against the sky. We employ textual discussion, exposition through figures, paper lunar phase wheels, and detailed demonstrations and animations within a video tutorial to guide students who may be working through the difficult process of making observations remotely without face-to-face guidance and feedback. Not unexpectedly, different students

learn best from different subsets of these aids.

Students construct two sextant devices for this project, both built from common household materials. The first sextant (see Figure 2.1) is designed to measure the angle formed between the Moon and Sun on the sky (the lunar elongation angle). Students begin by backing a paper protractor with cardboard to form a stable plane. A sewing pin is pushed vertically through the protractor origin, with its head suspended 0.25'' above the plane. A folded paper tab at the end of the protractor marked 180° suspends a small circular target 0.25'' above the plane as well. As the student points the end of the protractor marked 0° towards the Sun, the shadow of the pinhead will fall within the circular target. The student then rotates the protractor around the 0°–180° axis until the Moon lies within the plane of the protractor, the angle between them (the lunar elongation angle) can be read off of the protractor.



Figure 2.1: The basis of the sextant used to measure the lunar elongation angle (the angle between the Sun and the Moon on the sky). The tab on the left is folded up out of the page to form a backdrop to hold the shadow of a pin stuck through the origin, thus placing the Sun along the line marked 0° .

Students measure the lunar elongation angle over eight days. They record the date and time of day of each set of observations, measuring the elongation angle three times per session and also noting the fractional illumination of the Moon and its approximate phase. They then compute the elapsed time since the new Moon for each set of observations, and combine the MES angle measurements to produce mean values and standard deviations. By observing the angle grow with time as the Moon "unwinds" its way around the Earth and away from the Sun, they strengthen their understanding of the lunar orbital path. By plotting the elongation angle over time they are able to determine the simple linear trend that it follows with time, and thus to predict the position of the Moon with each passing day. They also estimate the fractional illumination (by comparison with a table of partially illuminated images), and determine that it follows a sine wave trend over time.

Figure 2.1 shows a plot of the lunar elongation angle over time, with a weighted linear fit attached via our standard plotting tool. Error bars were estimated for each day by measuring the elongation angle three times and combining the results. Note that the small size of the error bars relative to the quality of the fit suggests that systematic errors (as opposed to randomly distributed measurement errors) play a role in the usage of the elongation angle sextant. This is usually due to minor construction flaws such as cardboard warps, and to subtle alignment biases in placing the pinhead shadow correctly.



Figure 2.2: The distribution of sample data for the lunar elongation angle, with a clear linear trend and a high correlation coefficient (R). Students make their own observations, create their own plots, and then relate the slope and y-intercept of the linear fit to physical quantities (comparing the slope to the expected number of degrees that the Moon travels around the Earth each day, for example). Note that each such plot is labeled with the time of creation (to the nearest minute) and the student name (trimmed off here to preserve privacy).

The second sextant device is also based around a protractor. In this case, the student

simply attaches a drinking straw to the $0^{\circ}-180^{\circ}$ axis and hangs a small weight from a thread looped through the origin. By finding the Moon or a star while looking through the tilted straw, its altitude can be read from the position of the thread lying along the protractor. Students use this sextant to measure the altitude of the transiting first quarter Moon (given its declination) and of the North Star, in order to estimate their own latitude. In this case the physical measurement is quite easy to make, while the larger challenge lies in connecting it conceptually to the observer's latitude. A distance education cohort of student can actually be a benefit in this instance, as students spaced out in latitude can compare their observations of the Moon's altitude made at a single time.

The GEAS website for this exercise contains a table of dates and time drawn from United States Naval Observatory data for new and first quarter Moon phases and for lunar declinations for first quarter Moon transits, as viewed from Las Cruces, New Mexico. We also provide last quarter Moon transit data for students who might need to perform their observations out of phase with their class cohorts. Data for alternate locations are added as needed, to support classes being taught in other locales.

In addition to the general plotting tool, this project employs a specialized plotting tool that allows students to plot their measurements of lunar illumination against time with a sine wave model. Though many of our students lack familiarity with trigonometric functions, they are able to contrast the curving ascension of the sine pattern with a linear fit, and to grasp the concept of variable fitting models and lines producing better or worse fits to data.

2.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Visualize the monthly and yearly movements of the Earth and Moon around the Sun, and relate their locations in drawings to their positions in the sky.
- Understand and explain to others how the motions of the Sun, Earth, and Moon produce the monthly variations in lunar position, phase, and illumination.
- Predict the location and appearance of the Moon on a given date at a given time of the lunar month.
- Connect the latitude of an observer to the altitude of a transiting first quarter phase Moon, given its declination.
- Connect the latitude of an observer to the altitude of the North Star.
- Find the North Star and the Big Dipper in the northern sky.
- Comprehend the meaning of an angle, and relate the linear and angular sizes of an

object at a given distance to each other.

• Make appropriate predictions based on information presented in the form of figures.

2.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

For Lab #2 in particular:

This laboratory exercise contains observations to be completed during the third through eleventh days of the lunar month. Instructors should plan accordingly when scheduling it. Note that there is a poor weather back-up plan for observations to be done during the second half of the lunar month.

We *strongly* encourage instructors to perform all of the observations in this exercise for themselves, completely, before asking this of students. The difficulty of scheduling sky observations every evening for a eight-day period should not be underestimated. There also tend to be systematic biases in most of the observations that dominate the measurement er-

rors derived by repeating measurements, leading to plots where the rms deviations are larger than would be expected from plotted error bars based purely on repeated measurements.

By taking your own observational data, you will best understand the difficulties inherent in doing so. You may also discover observational challenges which are peculiar to your region (such as bright lights which dominate the sky in a particular direction, or pernicious weather patterns for wind or rain). It takes practice to become confident using the elongation angle sextant, and you will best aid your students by drawing on your own experiences.

2.4 Keywords

Altitude – The altitude of an object in the sky is the number of degrees which it lies above the horizon. At local noon the Sun could have an altitude of 90 degrees (lying directly overhead), and as it sets the altitude falls to a value of zero.

Angular size, or extent – The angular size of an object is the size of the angle that it spans on the sky, typically expressed in units of degrees.

Arcminute – An arcminute is a unit of angular size, equal to 1/60 of a degree (recall that there are 90 degrees in a right angle). There are 60 arcseconds in an arcminute (see below).

Arcsecond – An arcsecond is a unit of angular size, equal to 1/60 of an arcminute or 1/3600 of a degree (recall that there are 90 degrees in a right angle). Astronomers often measure the angular separation between neighboring objects on the sky in units of arcseconds.

Astronomical unit – The average distance between the Earth and the Sun, equal to 1.5×10^8 kilometers.

Big Dipper – The Big Dipper is made up of the seven brightest stars in the northern hemisphere constellation Ursae Majoris (the Great Bear). It is both large and bright, and so forms a useful landmark in the northern sky. The two stars which form the outer lip of the "dipper" (bowl) shape lie along a line which points toward the North Star.

Cassiopeia – Cassiopeia is a northern hemisphere constellation which looks like a letter "W", making it easy to identify. It is located opposite to the Big Dipper (on the other side of the North Star).

Celestial equator – The celestial equator is the equatorial band of the celestial sphere (see below). It lies in the same plane as the Earth's equator.

Celestial sphere – The celestial sphere is an imaginary construct designed to aid in visualizing the positions and movements of objects through the sky. It comprises a spherical surface with an arbitrarily large radius, which is centered at the center of the Earth. It has a celestial equator which lies in the same plane as the Earth's equator, and celestial north and south poles which extend along the Earth's rotational axis above and below the Earth's North and

South Poles. Objects in the sky can be projected onto the celestial sphere, and their motions understood in the context of the Earth's motions around the Sun.

Culmination – See transit.

Declination – The declination of an astronomical body is its height (in degrees) above the plane defined by the Earth's Equator. It runs from 90° (due north) to -90° (due south).

Degree – A degree is a unit for angular measurements. A right angle contains 90 degrees, and a complete circle encompasses 360 degrees.

Ecliptic plane – The plane in which the Earth orbits about the Sun (inclined by 23° to the plane containing the Earth's equator).

Elongation – The elongation of an astronomical body is the angle between the body and the Sun, when viewed from the Earth. Elongations run from 0° (object aligned with the Sun) to 180° (object on the opposite side of the Earth from the Sun).

Equator – The Equator is the area on the surface of the Earth within the plane which is perpendicular to the rotation axis (running through the North and South Poles).

Gibbous – A moon or planet in the gibbous phase appears more than half, but less than fully, illuminated.

Horizon – The horizon is the boundary observed between the Earth and the sky. It extends in all directions (north, south, east, and west) around an observer.

Latitude – The latitude of a location on Earth is the number of degrees which it lies above the plane of the Equator. It takes on values between 90° (North Pole) to -90° (South Pole).

Linear size – The linear size of an object is its length, in units of length such as centimeters (small) or miles (large).

Little Dipper – The Little Dipper is made up of some of the brightest stars in the northern hemisphere constellation Ursae Minoris (the Little Bear). The North Star, Polaris, located almost due north, is the brightest star in the Little Dipper. It can be found at the end of the handle.

Mean value – The mean value μ of a set of N repeated measurements m_i is defined to be the unweighted average, or

$$\mu = \frac{1}{N} (m_1 + m_2 + m_3 + \ldots + m_N) = \frac{1}{N} \sum_{i=1}^N m_i.$$

Meridian – A meridian is an arc which projects from the North Pole to the South Pole and passes directly overhead for an observer. All observers located along a given meridian share a common longitude (the distance they lie east of the Royal Greenwich Observatory in England), but have unique longitudes corresponding to how far north or south of the Earth's equator they lie.

Mu – The Greek letter "m" (μ), often associated with the average value of a set of measurements.

North Celestial Pole – The North Celestial Pole (NCP) is the projection of the Earth's North Pole upon the celestial sphere. One can think of it as the extension of the Earth's rotational axis arbitrarily high above the North Pole. The North Star, Polaris, lies very close to the NCP on the sky.

North Star – The North Star, or Polaris (the pole star), is a star which currently happens to lie almost due north of our planet, above the North Pole and along the Earth's rotational axis. Because of its location it is always above the horizon for observers in the northern hemisphere (and never above the horizon for those in the south). The northern night sky appears to revolve around this star, moving counter-clockwise in a full circle once every 24 hours. Because the earth's rotation axis wobbles, over tens of thousands of years it points slightly away from, and then back toward, the North Star. In ten thousand years, the title of North Star will be given to another, neighboring star in the vicinity.

Parallax – A technique for estimating the distances to objects, by measuring their apparent angular shifts on the sky relative to distant objects when they are observed from two separated locations.

Perturbation – A perturbation is a disturbance (in the force, or elsewhere). When the orbit of an astronomical body varies slightly (wobbling, or shifting back and forth), we often describe the variation as a perturbation.

Phase – For a periodic function, such as sine or cosine, the word phase is often used to define the shift of the function away from the default zero point by a fraction of a full period. For the Moon, we generally describe its appearance as it shifts from shadow into full illumination and back over the course of a lunar month in terms of the new, quarter, gibbous, and full phases.

Polaris – see North Star.

Sextant – A mechanical device used to calculate the angle on the sky between two objects, or the altitude of an object (its distance above the horizon).

Sigma – The Greek letter "s" (σ), often associated with a measurement of a standard deviation.

Slope – The slope m of a line is the change in y divided by the change in x, or for two points along the line with coordinates (x_1, y_1) and (x_2, y_2) ,

$$m = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}.$$

South Celestial Pole – The South Celestial Pole (SCP) is the projection of the Earth's South Pole upon the celestial sphere. One can think of it as the extension of the Earth's rotational axis arbitrarily high above the South Pole.

Standard deviation – The standard deviation σ , also called the spread, of a set of N repeated measurements m_i with an mean (average) value μ is defined as

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (m_i - \mu)^2}.$$

Systematic error – A systematic error is one which biases all of a set of measurements in the same fashion (as opposed to making some smaller and some larger).

Transit – An astronomical object transits when it passes across the observer's meridian, an arc of constant longitude (the east/west coordinate) along the surface of the Earth connecting the North and South Poles and the observer's location. An object which is transiting lies either to the north, to the south, or or directly overhead of an observer. An object can be transiting for one observer, but appear far to the east or west in the sky for an observer at another location.

Ursae Majoris – A large, bright constellation in the northern hemisphere, named "the Great Bear." The well-known Big Dipper is a part of Ursae Majoris.

Ursae Minoris – A constellation in the northern hemisphere, named "the Little Bear." The well-known Little Dipper is a part of Ursae Minoris, as is Polaris, the North Star.

y-intercept – The y-intercept b of a line is the y coordinate of the point on the line for which x = 0, or for two points along the line with slope m and coordinates (x_1, y_1) and (x_2, y_2) ,

$$b = y_1 - mx_1 = y_1 - \left(\frac{y_2 - y_1}{x_2 - x_1}\right)x_1$$

Zenith – The zenith is the direction pointing directly overhead for an observer.

Zenith distance – The zenith distance is measured in degrees, and is equal to the angle on the sky between an observer's zenith and an object. The sum of the zenith distance and the altitude is always equal to 90° , for an object.

2.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 4: The Phases of the Moon, Chapter 5: The Seasons on Earth, Chapter 7: The Celestial Sphere, and Chapter 8: Planetary Orbits.

2.6 References and Notes

1. The observational plan (and Figure 2.4) for this exercise benefited greatly from images and information on the movements of major bodies of the solar system provided online by the United States Naval Observatory (USNO), at

http://www.usno.navy.mil/USNO/astronomical-applications/data-services

This is a great resource for planning sky observations from multiple locations or on different dates.

2. Figure 2.1 through Figure 2.3, Figure 2.5 through Figure 2.13, and the three attached sextant designs are shown courtesy of Nicole Vogt.