Introduction to Celestial Navigation

Capt. Alison Osinski

Introduction to Celestial Navigation

Wow, I lost my charts, and the GPS has quit working. Even I don't know where I am.

Was is celestial navigation?

Navigation at sea based on the observation of the apparent position of celestial bodies to determine your position on earth.

What you Need to use Celestial Navigation (Altitude Intercept Method of Sight Reduction)

1. A **sextant** is used to measure the altitude of a celestial object, by taking "sights" or angular measurements between the celestial body (sun, moon, stars, planets) and the visible horizon to find your position (latitude and longitude) on earth.

Examples:

Astra IIIB $699

Tamaya SPICA $1,899

Davis Master Mark 25 $239

Price range: Under $200 - $1,900

Metal sextants are more accurate, heavier, need fewer adjustments, and are more expensive than plastic sextants, but plastic sextants are good enough if you're just going to use them occasionally, or stow them in your life raft or ditch bag. Spend the extra money on purchasing a sextant with a whole horizon rather than split image mirror.

Traditional sextants had a split image mirror which divided the image in two. One side was silvered to give a reflected view of the celestial body. The other side of the mirror was clear to give a view of the horizon. The advantage of a split image mirror is that the image may be slightly brighter because more light is reflected through the telescope. This is an advantage if you are going to take most of your shots of stars at twilight.

Today most people purchase sextants with whole horizon mirrors that have a reflective film over the whole surface of the mirror. This makes capturing sun shots easier and provides a view of the horizon without any interruption. If the preponderance of sights are to be taken during daylight, buy a sextant with a whole horizon mirror. The maker of the best-selling Astra III B sextant reports that 90% of their current sales are with whole horizon mirrors.

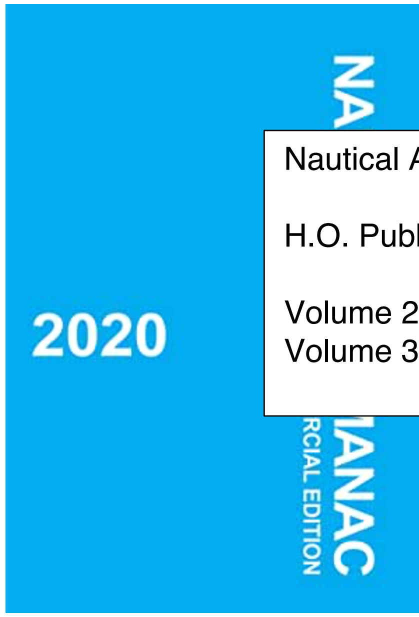
2. An Understanding of the Terminology

Celestial coordinates	Declination of a celestial object is equal to latitude and Greenwich Hour Angle is equal to longitude
Dead reckoning	Calculating position at sea by estimating direction and distance traveled from a known point or fix
Assumed Position	(AP) Point at which one is assumed to be located in order to determine a line of position
Geographic Position	(GP) Specific geographical point on earth
Declination	(DEC) Latitude. Angular distance in degrees + 0 to 90° north celestial pole or - 0 to 90° south celestial pole from the celestial equator, measured along a great circle. It is the latitude of the spot directly below any celestial object.
Greenwich Hour Angle	(GHA) Angle between the Greenwich meridian and the spot directly below the celestial body. Longitude is always measured W from Greenwich 0-360°
Local Hour Angle	(LHA) Angle between an observer's position and the geographic position of a celestial object. GHA = + E or - W longitude
GMT / UT	Greenwich Mean Time / Coordinated Universal Time
Hs	Height of the celestial body in degrees from the sextant observation

Ho	Height of the celestial body in degrees observed after correction
Hc	Height of the celestial body in degrees computed from tables
True azimuth	(Zn) Bearing of the celestial body's GP
Line of Position	(LOP) Line on which the observer is estimated to be located at the time of an observation
Azimuth	(A) Horizontal angular distance. Direction of a celestial object from the observer.
Index error	(I) Correction applied and caused by the index glass and the horizon glass of a sextant not being parallel to each other.
Dip	(D) Dip is subtracted from the observed altitude (height of eye) to give apparent altitude.
Atmospheric refraction	(R) Correction applied to the deviation of a light wave from a straight line as it passes through the atmosphere
Latitude	Angular distance of a place north or south of the equator. Measured along a meridian 0 to + 90° positive N and 0 to - 90° negative S of the equator.
Longitude	Angular distance of a place east or west of the prime meridian at Greenwich, England. Measured 0 to + 180° positive E, 0 to -180° negative W from Greenwich.
Zenith	Point on the celestial sphere directly above the observer on earth.
Zenith Distance	(ZD) The altitude difference between you and a point directly below the sun. Distance angle of the spot directly overhead (zenith) to the spot directly below any celestial object.
Intercept	(A) Difference between the observed and computed altitudes of the celestial object. Intercept distance to or away from the celestial body.

3. **Nautical Almanac**

You use tables in the Nautical Almanac to find the celestial body's geographic position (GP) or when that celestial body is located directly over a point on the earth's surface. The angle between the celestial body and the visible horizon is directly related to the distance between the celestial body's GP and the observer's position.



Nautical Almanac

H.O. Publication 249

Volume 2 for latitudes 0 – 39 ° N or S
Volume 3 for the N / S latitudes > 40°

Computations, referred to as sight reductions, are used to find a measurement to plot a line of position (LOP) on a chart or plotting sheet. The observer's position is somewhere on the LOP.

The almanac also includes:

- Altitude Correction Tables for the sun, stars and planets, usually found inside the front cover to allow you to apply Hs to find Ho.
- Calendars
- Lists of moon phases, eclipses, planet visibility, times of sunrise/sunset, moon rise/moon set, standard times for countries and states, star charts, explanations on how to use the almanac, sight reduction procedures and tables
- Daily Pages for GHA and DEC (the latitude of the sun, moon, navigational stars, and planets for every hour of the year).
- Increments and Corrections found in the back of almanac, used to find longitude

You need to buy an almanac every year. The almanac will be good every 4 years again for the sun.

4. Chronometer

Use an atomic clock, or GPS. Listen to short wave radio WWV (male voice) in Fort Collins, Colorado or WWVH in Kauai, Hawaii (female voice) and tune to a frequency of 2.5, 5, 10, 15 or 20 MHz.. Both stations are operated by NIST, the U.S. National Institute of Standards and Technology a physical sciences laboratory and an agency of the Department of Commerce. Coordinated Universal Time, the time standard by which the world regulates clocks, is announced every minute, but is not adjusted for daylight savings time. You can also call the atomic clock in Fort Collins, Colorado at (303) 499-7111.

The observer using sextant observations must know the exact Greenwich Mean Time (GMT) to the second that she sights the sun. Position will be off by approximately 1 nautical mile for every 4 seconds the time is off.

5. Stop Watch

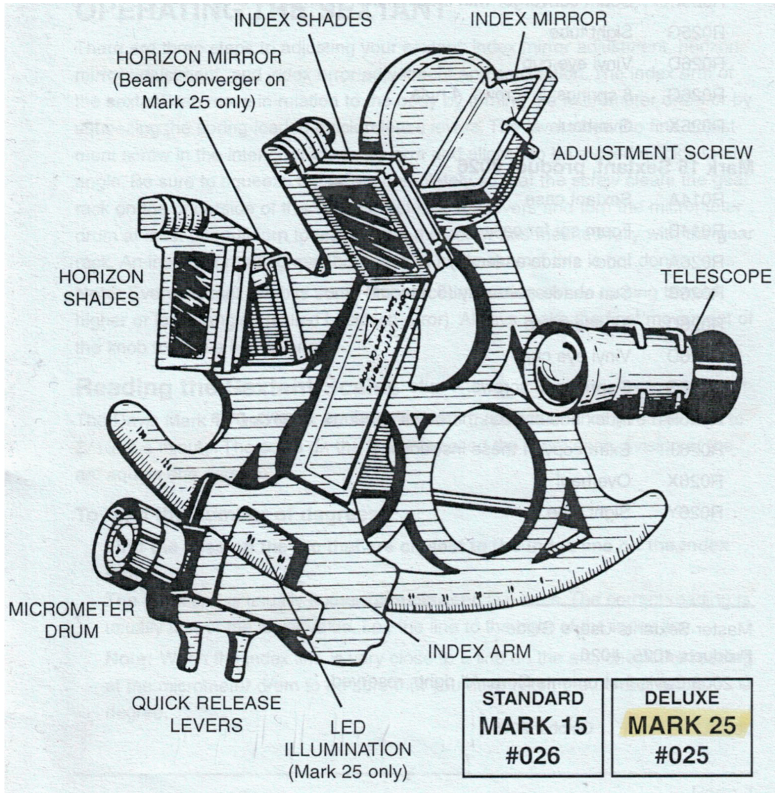
Use a stop watch and yell “Mark” when you shoot the sun with the sextant and record the exact time the sight was shot. Subtract this from the time.

6. Horizon (Unobstructed or Artificial)

An artificial horizon is a device that allows you to practice taking sun or moon shots with a sextant when an unobstructed horizon is not available. After assembling the device, you fill it with water, select the appropriate sun shades to prevent eye damage when looking at the reflection of the sun, and place it on the ground so one side faces directly into the sun, and only creates a shadow on the opposite end. You position yourself so you can see the sun’s reflection on the surface of the water, and sight through the sextant until the reflection is where the real horizon would be. For a lower limb observation, you move the index arm of the sextant until the bottom of the double reflected image of the sun is brought into alignment with the top of the image of the liquid. Apply the index correction, and take ½ the remaining angle (because the artificial horizon doubles the sextant reading), then all other corrections except dip since height of eye correction is not applicable.

Sextant

A sextant is a type of protractor that lets you measure the angle between the horizon and a celestial body (the sun, moon, planets, stars)

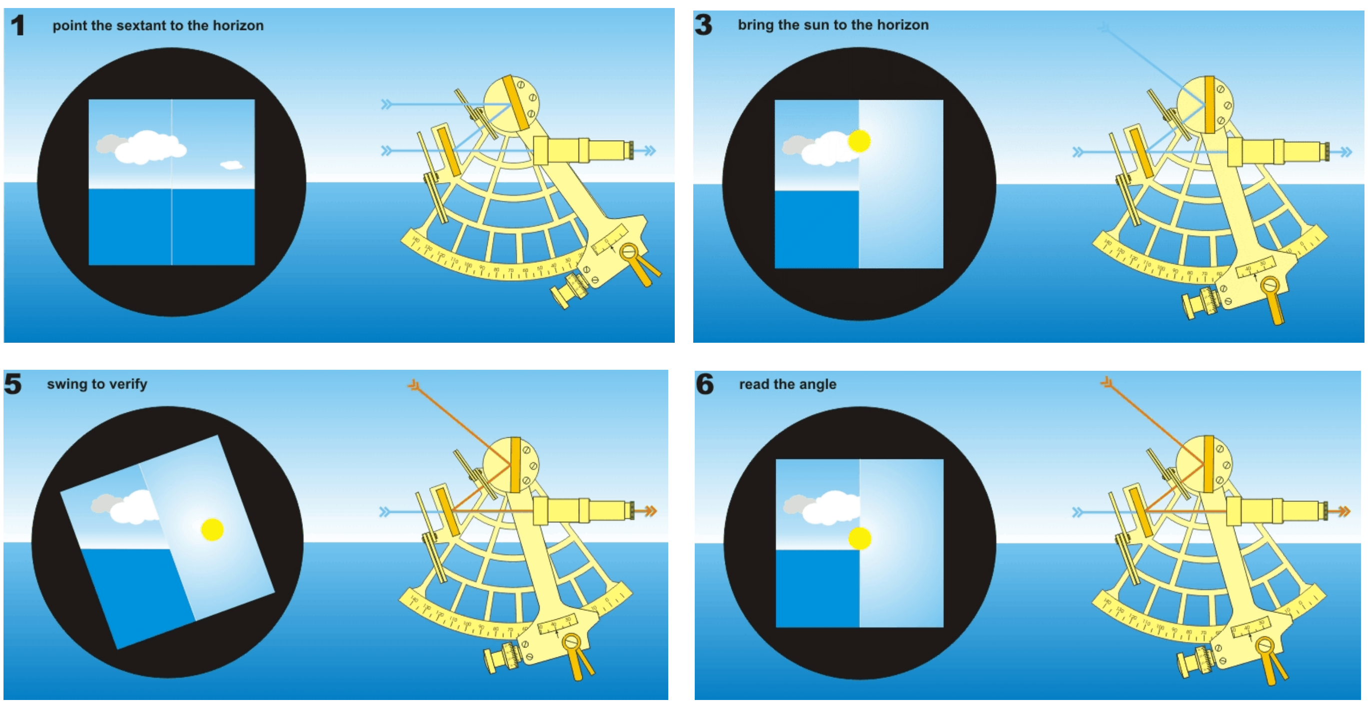


Parts of a Sextant

Frame	Supports the parts of the sextant
Handle	Used to hold the sextant with your right hand
Telescope	Used to get a better view of objects
Shades	Come in different colors and intensities and are used to dim bright objects in the sky (sun and moon). There are index shades and horizon shades.
Mirrors	A sextant works by moving 2 mirrors in relation to each other. The index mirror moves, and the horizon mirror does not.
Adjustment screws	Used for adjusting the mirrors
Index arm	You use the squeeze trigger on the index arm to move the index mirror and take gross measurements in degrees off the graduated arc
Micrometer drum	You use the micrometer drum for fine adjustments, and measurements in minutes
Vernier scale	Used for measurements in tenths of a minute

How to Use a Sextant

- Point the sextant at the horizon
- Put the index arm at zero degrees, zero minutes and zero tenths of a minute (0° 0.0’)
- Set the shades
- Look directly at the sun
- Bring the sun (or any celestial body) down toward the horizon by moving the index arm forward while tilting the sextant itself down to the horizon
- Bring the sun down almost to the horizon
- Use the micrometer drum to fine tune the adjustment
- Swing the sextant in an arc to verify the lower limb of the sun is on the horizon at the bottom of the arc, and further adjust the micrometer drum if necessary
- Take the angle reading, and double check to make sure you’ve read it correctly
- Note the exact time to the second
- Do the calculations



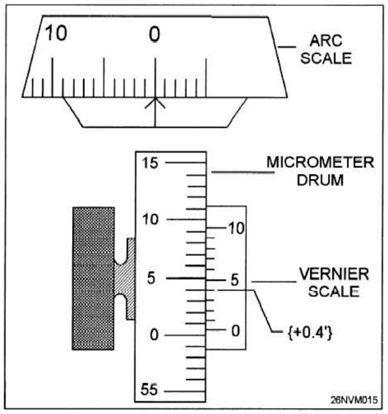
Accuracy

One minute of arc on a sextant is equal to one minute in accuracy in measurement on a chart. On a bobbing boat, accuracy will go down. The observer using sextant observations must know the exact Greenwich Mean Time (GMT) to the second that she sights the sun. Position will be off by approximately 1 nautical mile for every 4 seconds the time is off.

GPS accuracy is approximately 2 to 3 meters (< 10 feet) depending on satellite signal blockage or reflection. GPS enabled smartphones are accurate to within 4.9 meters (16 feet). Even if your sextant skills are good, your position finding using celestial navigation is likely to be 1 to 10 nm off. Celestial navigation is useful to help find your general location in the ocean and direction of travel, but will probably not help you find a 100 foot channel opening into a harbor.

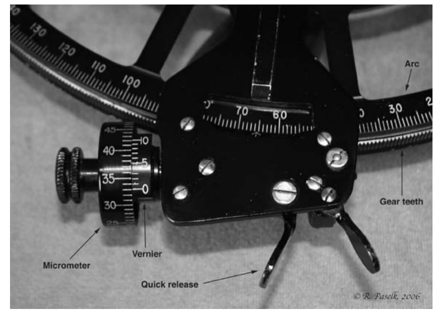
How to Read a Sextant

Read the whole degrees off the arc scale, the minutes off the micrometer drum, and the tenths of a minute off the Vernier scale.



0° 5.4’

53° 0.0’



65° 35.2’

How to take a Noon Sight

In order to find the declination of the sun at local noon you need to find the difference between local time where your boat is and Greenwich Mean Time. The sun appears to move 360° every 24 hours from east to west, so each time zone is 360° ÷ 24 = 15°. Time zones may vary because of geographic or political boundaries and daylight savings time may be applied, but typically you can find your time zone by measuring the number of 15° increments east or west of Greenwich. So Southern California is in the Pacific Time Zone which is + 8 W of Greenwich (subtract 1 hour during Daylight Savings Time = + 7).

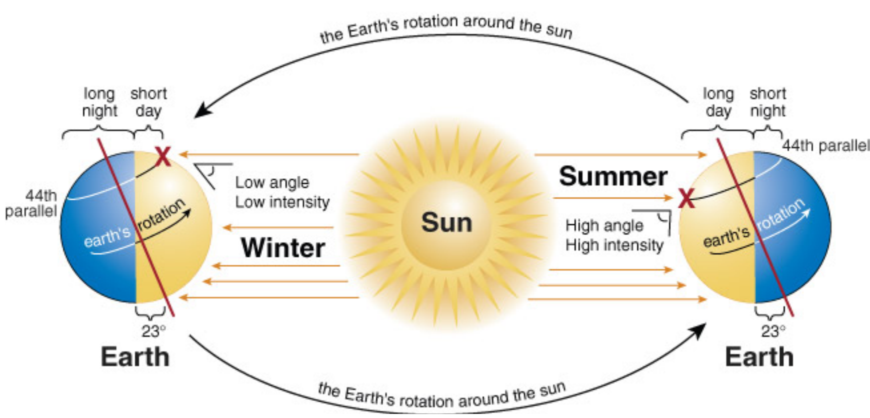
At noon, the sun is on your meridian of longitude. Sight reduction tables are not needed. You use zenith distance to find your latitude because the navigational triangle has collapsed and is now a line of longitude.

About 15 minutes before noon, start shooting the sun with your sextant every few minutes. The sun will be very high in the sky and approaching a bearing of true south. Keep eliminating the gap by turning the micrometer drum and swinging the arc to keep the sun on the horizon. Write down the readings. This is the Hs, the uncorrected sextant reading, and height of the sun in degrees from the sextant observation. The numbers (minutes) will keep going up.

The sun will continue climbing, then you will get the same Hs several times in a row and the sun will seem to hang in the sky right on the horizon for about 5 minutes. This is local noon.

Following local noon, the sun will start falling. The lower edge of the sun will start dipping in to the horizon, and numbers (minutes) will start decreasing because the sun is on it's way back down to the horizon. Don't use the micrometer to put the sun back on the horizon – it is after noon.

Round off GMT to the nearest hour so you can find the declination either north (sun is north of the equator, northern hemisphere summer) or south (sun is south of the equator, northern hemisphere winter). Because the earth is tilted 23.5 degrees always in the same direction regardless of time of year, the tilt is either toward or away from the sun. In the summer, the sun arcs higher and the days are longer than the nights. Sun declination is much higher and the sun appears to move much faster in the summer. The sun's path is lower in the winter, and nights are longer than days. The arc is flat and the sun appears to move more slowly across the sky in winter. The pole tips toward the sun, the sun is over the Tropic of Cancer, 23.4 degrees north of the Equator and the June solstice is the longest day of the year for the northern hemisphere, and longest night for the southern hemisphere. The December solstice is the opposite. In December, the pole tips away from the sun, the sun is over the Tropic of Capricorn south of the Equator, giving the southern hemisphere its longest day, and northern hemisphere its longest night.



With the exception of the equinox (March 20) when the sun's GP is directly above the equator and latitude is equal to ZD you need to find certain pieces of information or make corrections to improve accuracy in order to find latitude.

Geographic Position

For every celestial body there is one spot on earth directly below it. If you were standing on that spot, it would be at your zenith and 90° directly above you. We use the horizon as the zero point and measure up to the object. What we really want to find though is the distance of the spot directly overhead (zenith) and to the object called zenith distance.

Using the sextant, measure the angle from the spot directly above your head (Z) to the spot directly below the celestial object (ZD). The angular distance between the two points is distance in nautical miles. We calculate ZD by measuring the distance from the horizon of the object and subtracting that from 90°.

Measure the distance from the sun to the horizon with the sextant. The sextant reading is Hs.

To find latitude, use the Nautical Almanac and a worksheet

Make corrections for index error (IC) by adjusting the sextant so the horizon is level, if broken or unaligned when set at 0° 0.0'. If the reading is above 0, Ex. 2.0' then it is On the arc and you subtract 2.0' from the Hs. If the reading is below 0, then the reading is OFF the arc and the value needs to be added to the Hs.

You need to correct for the height of eye above the horizon from which the sextant reading was taken. Use the table located in the front of the Nautical Almanac labeled DIP. Dip adds to the angle so always subtract the value from Hs.

After adding or subtracting the IC and DIP corrections you have found the apparent altitude Ha.

Make the main correction for refraction (the atmospheric bending of images) and semidiameter (to compensate for using the limbs rather than the geographic center of an object). Use the Nautical Almanac from block 1, the Altitudes & Corrections tables near the front of the book. Find the month and whether you shot the lower or upper limb. You've found the Observed Altitude and corrected sextant, Ho.
Subtract he Ho from 90° (89° 60') to obtain the ZD, the distance between you and the sun's GP in degrees, minutes and tenths of a minute of arc.

Look in the Nautical Almanac DEC tables for the day of the year and time to the nearest hour and apply the declination to ZD. Interpolate if necessary.

Draw the relationship between the equator your ship and the GP of the sun so you use the correct formula.

- Sun is in the opposite hemisphere as your boat:
  Latitude = ZD - Dec
- Boat and sun are in the same hemisphere but the sun is closer to the equator:
  Latitude = ZD + Dec
- Boat and sun are in the same hemisphere but the sun is further away from the equator than the boat:
  Latitude = Declination - ZD

LATITUDE BY NOON SIGHT

SAT. NEWPORT HARBOR

Date: FEB. 2, 2019 Lat: 33° 35' N Lon: 117° 52' W Height of Eye 9'

Index Correction: 0 On Arc 0 Off Arc

Watch Time: 1205 (When sun dips into horizon)

Watch Error: - fast; + slow 0

Universal Time Difference: +8 PST (+7 hrs till 11-2. Then +8)

UT (Aka GMT): 2005

Sextant Reading (Hs) 39° 30.3'

Index Correction (IC) - 0 (On -; Off +)

Height of Eye Corr (Dip) - 3.1 (NA page 2, Block 3)

39° 27.2'

Apparent Altitude (Ha) ====================

Refraction & Semi Diam + 15.2' (NA (Page 2, Block 1)

39° 42.4'

Observed Altitude (Ho) =====================

89° **60'** (90° 00' written to facilitate subtraction of Ho)

\- Ho 39° 42.4

50° 15.6

z ================ (Distance between you and sun's GP in degrees and minutes of arc (').

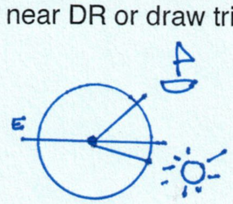
Declination - S 16.43.0 (From Nautical Almanac page for date and nearest hour. Combine with **z** to come out near DR or draw triangle diagram.)

49° 75.6'

\- 16° 43.0'

33° 32.6'

LATITUDE ================



SUN GP IS IN OPPOSITE HEMISPHERE AS SHIP ∴ LAT = ZD - DEC

Find LOP (Line of Position)

A line of position (LOP) is a navigational line drawn on a chart to a known object. A single line of position lets you know your position is located somewhere along this line. The line of position at noon is a line of latitude perpendicular to the local meridian. At times of day other than noon, the direction of the sun will be some other compass bearing, or the azimuth, perpendicular to the meridian.

- Write down the date
- Find exact GMT of the sight in hours, minutes and seconds
- Write down the Hs
- Write down the IC
- Estimate your position and write it down
- From the Sun column in the Daily Pages write down the DEC at your GMT
- Write down the d figure from the bottom left corner of the page in the Sun column to get the exact DEC at the time of the sight
  + d if the declination column is getting larger by the hour
  - d if the declination column is getting smaller by the hour
- From the daily pages, write down GHA for the hour the sight was taken
- Use Increments & Correlations to minutes to add to the GHA hours to get the exact GHA of the sight time
- Find GHA
- Total the DEC and GHA, round off to the nearest minute
- Find Local Hour Angle
  To GHA, add assumed longitude and write assumed degrees and same minutes as in GHA
  Write down the assumed position and round off latitude to the nearest degree because this will be your starting point to plot your LOP
  If the assumed longitude is greater than GHA add 360° to GHA then subtract the assumed longitude from GHA to get the LHA
- Find HC using the Sight Reduction Tables
  There are two sets of tables for each degree of latitude: same and contrary
  Use same if your latitude and sun's declination are on opposite sides of the equator
  Look up your height + d or – d, corr, Z and Zn if LHA is greater than 180°
  If LHA is less than 180° ZN = 360° - Z
- Enter Hc
- Subtract Ho
  If Ho is greater than Hc, circle T for toward the sun
  If Ho is less than Hc, circle A for away from the sun
- From the assumed position, chart the answer

You're located *somewhere* along the LOP that was just drawn. To obtain a position fix you must wait about 1 hour and take another observation of the sun and perform another sun sight reduction and plot the resulting LOP. If you're at sea, the first LOP would have to be advanced in the true direction (not magnetic) you have been traveling and the DR distance. Where the two LOPs intersect is the position fix or where you were at the time of the second sun sight.

Celestial Navigation Historical Instruments

Mariner's **astrolabe** is a device used originally by Portuguese navigators since the 13^{th}/15^{th} centuries to measure angles of slope and elevation, and altitude of a celestial body above the horizon during the day or night. It would have replaced the quadrant and cross staff. It was used to identify planets and stars and determine latitude if you knew the time, or time if you knew the latitude.

Marine **sandglass** were used on ships to measure 30 minute watch times starting when the sun was at its zenith at celestial noon. The ship's bell was rung 8 times. After the glass emptied for the first time 30 minutes later, the bell was rung once. The glass was turned and after another 30 minutes it was rung twice. This continued for 4 hours until the bell was again rung 8 times and the watch ended.

A **chip log** was also used to measure boat speed. The navigator multiplied the time from the sandglass and speed from the chip log, and plotted his position on a chart using dead reckoning.

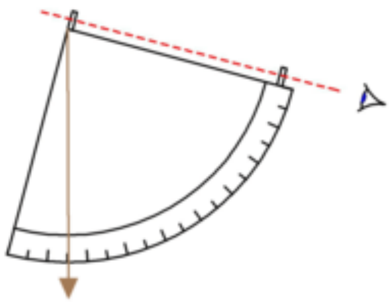
A **traverse board**, a type of wooden peg board overlaid on a 32 point compass rose with 8 rows of holes extending out each point, was used to track the direction a ship was sailing over the same 4 hour period. Every half hour, direction the ship was sailing was measured using a compass. After the first half hour, a peg was inserted into the first hole from the center of the rose corresponding with the direction of travel. Each hole represented 30 minutes of travel. Beneath the compass rose on the traverse board there were 4 rows and 18 columns of holes, divided in to right and left sides, and used to represent speed rather than direction of travel. After the first half hour of the watch, a peg was placed in the top row on the left. Each column represented speed in knots (1, 2, 3… from left to right). At the end of each half hour a peg was placed first using the rows on the left, then rows on the right, until the watch ended after 4 hours. At the change in watch, the board would be cleared.

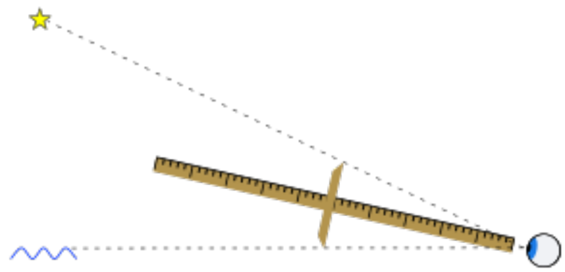


Early explorers relied on the noon sight. For example, if they departed from the Canary Islands and wanted to sail to the Caribbean, they would sail to the latitude of their destination and turn west. They stayed on that latitude until they got to their destination. They would take noon sights every day, make adjustments as needed and continue until they got close enough to see land.

They didn't have almanacs until the 1700s.

English clockmaker John Harrison built the first precision chronometer that solved the problem of finding longitude in 1735, but had trouble collecting the prize from Parliament because astronomers didn't want to believe that longitude could be solved by a mechanical device, a timepiece that kept reliable time on a moving ship.





Liferaft Navigation

Estimating Time 'til Sunset

You can estimate time until the sun sets by holding your arm out away from your body and placing your stacked fingers between the horizon and the lower limb of the sun. The width of each finger covers about 15 minutes of time.

Visibility

Distance to the horizon in nautical miles = 1.17 x (square root of your eye height)

Distance at which an object becomes visible
1.17 x (square root of your eye height) + 1.17 x (square root of the height of the object)

Measuring Boat Speed in Knots

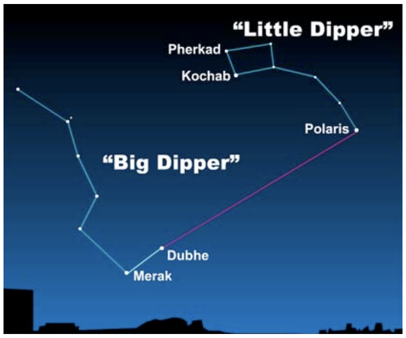
Needed:
- A 15 second timer. Traditionally, a 15-second hourglass (1/240th of an hour) was used
- A reel of line with knots tied in the line every 25' 4" (1/240th of a nautical mile)

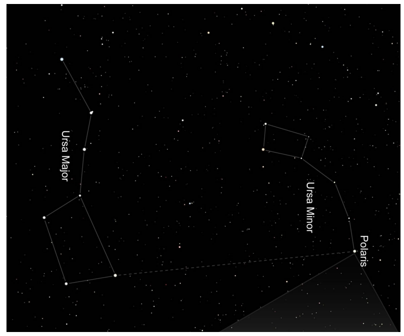
Standing at the stern of the boat, let the line feed off the reel. Count the number of knots that passed through your hands in 15 seconds. The number of knots will be your boat speed in nautical miles per hour (AKA: knots)

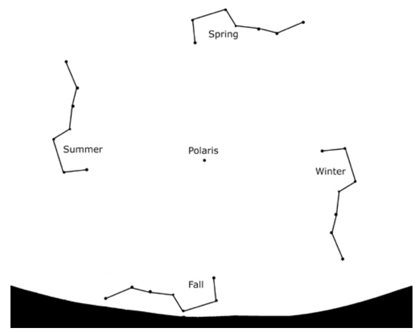
Use Polaris to Find Latitude

The angle between the horizon and Polaris, AKA the North Star located at the tip of the handle in the constellation of Ursa Minor is latitude. The pointer stars in the Big Dipper point at Polaris.

Polaris lies in an almost direct line with the earth's rotational axis above the north pole and because it seems motionless, the stars in the northern sky, including the Big Dipper seem to rotate around it.







Finding Longitude from Local Noon: Calculate Longitude using Sun Shadows

Use a blank sheet of paper or cardboard. Pound a nail point up in the board. The nail will create a shadow. In winter, start at about 1130 and in summer around 1230 (to account for daylight savings time). Observe the shadow every 5 minutes and put a dot on the paper right at the end of the shadow and mark the time. The shadow will continue to decrease in height. Continue to mark the shadows until the shadows begin to increase in size. The shortest shadow will be at solar noon because the sun sits highest in the sky and casts the shortest shadow. Use a ruler to measure the shortest shadow and note the time.

For example, if the shortest shadow was at 1155 PST, GMT would be 1955. The sun would have moved 7 hours and 55 minutes since solar transit at noon GMT – 7.916 hours @15° of longitude per hour or 118.74° Compare to actual longitude. If the numbers are not the same, the source of error might be due to the Equation of Time. Solar time varies from clock time. The combination of the earth's elliptical orbit and the fact that earth actually rotates every 3 hours and 56 minutes (not exactly 24 hours) and this 4-minute difference is not the same every day accounts for the variance. The earth moves fastest when it is closest to the sun so the sun's apparent rate of motion along the ecliptic is fastest in January and slowest in July.

Here are 2 good videos demonstrating this method of finding latitude:

https://video.search.yahoo.com/yhs/search?fr=yhs-Lkry-SF01&hsimp=yhs-SF01&hspart=Lkry&p=You+Tube+calculating+noon+using+sun+shadows#id=2&vid=d3b9ff9f050ca11bf221e808133baffe&action=view

https://www.youtube.com/watch?v=b7yoXhbOQ3Y

Determine Longitude by Bracketing Noon

You can determine longitude by using the times of sunrise and sunset without the use of a sextant. At sunrise and sunset, altitude is 0°. Look up the GHA for that time in hours, minutes and seconds and that's the longitude where you were at noon.

For example: Sunrise 0650
Sunset 1737
2387 = 2427 ÷ 2 = 1213 + 8 = 2013
In the Nautical Almanac look for the for date in GHA column = 116° 34.4' west of Greenwich longitude

Recommendations:

Bishop Museum, 1525 Bernice St, Honolulu, Hawaii 96817, (808) 843-7654, J. Watumul Planetarium (808) 848-4168, www.bishopmuseum.org
Wayfinders planetarium show: This fulldome program puts you on the deck of the voyaging canoe *Hōkūle'a* as you explore traditional Polynesian navigation and find your own way to Tahiti from Hawaii. Produced by Bishop Museum in collaboration with Polynesian Voyaging Society.

Ranger talks on navigational instruments used by the early California explorers
Cabrillo National Monument, 1800 Cabrillo Memorial Dr., San Diego, CA 92106, (619) 557-5450, (619) 222-4747, www.sandiego.org/.../cabrillo-national-monument.aspx

Celestial navigation workshops taught by Hewitt Schlereth, author and one of the last of the ancient mariners, (858) 249-8591, hhew36@gmail.com

Lewis, David. (1994). We, the navigators: The ancient art of landfinding in the Pacific, 2nd ed. Honolulu: University of Hawaii Press.

Sobel, Dava. (2011). Longitude: The true story of a lone genius who solved the greatest scientific problem of his time. New York: Walker and Company.

You Tube videos by Chris Nolan aboard S/V Navigator on "Getting Started in Celestial Navigation"

1 Marine Sextant
https://www.youtube.com/watch?v=DrAkrgZRb9Y

2 Noon Sight
https://www.youtube.com/watch?v=BWGOlpj4YwE

3 Precision (Index error, Dip and height of eye)
https://www.youtube.com/watch?v=uNWTN2LQ-TU