Intro to Celestial Nav. and Sextant

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The basic principles of Celestial Navigation

Celestial navigation (aka astronavigation) is the art and science of finding one's geographic position through astronomical observations, particularly by measuring altitudes of celestial objects (bodies) like sun, moon, planet and starts.

The apparent position of a body in the sky is defined by system of coordinates. In this system, the observer is located at the center of a fictitious sphere, the so-called celestial sphere (Fig. 1). The altitude (H_o) is the vertical angle between the line of sight to the respective body and the celestial horizon, measured from 0° through 90°. The zenith distance (z) is the corresponding angular distance from 0° through 180° (the point opposite is called Nadir). True azimuth (ZN) is the horizontal direction of the body with respect to the geographic (True) north point on the horizon, measured clockwise from 0° through 360°.

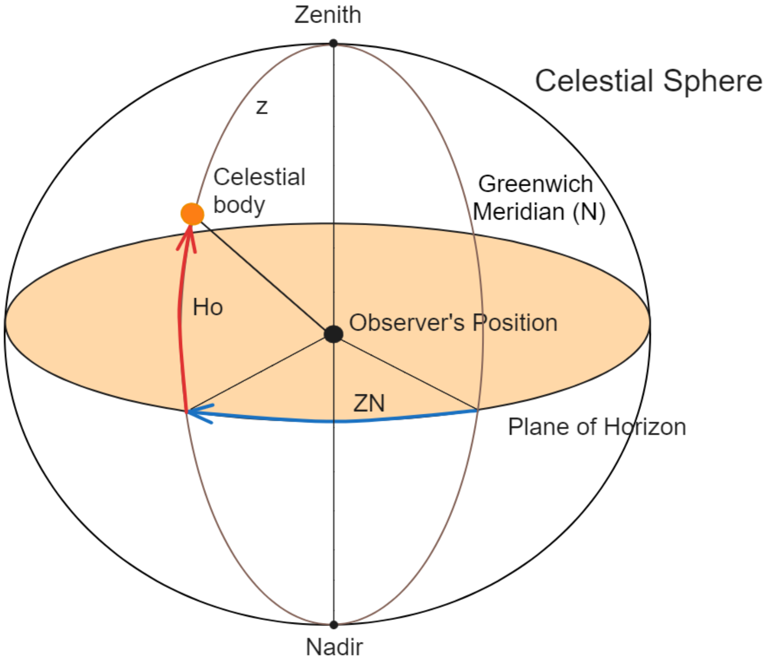


Fig. 1 – Representation of a Celestial Sphere.

A marine sextant is an instrument designed to measure the altitude of a celestial object (H_o) with reference to the visible sea horizon. By measuring object altitude (aka taking a sextant sight) we are finding the angle/altitude between the celestial object and the horizon.

Once we know the altitude, we can calculate angular distance. The distance that we are looking for in celestial navigation is the distance (r) from a Geographical Position (GP) to the observer (Fig. 2). GP is the point where a straight line from the celestial body to the center of the earth (C) intersects the earth's surface. In other words, it is a location directly overhead of the observer at altitude 90° called zenith.

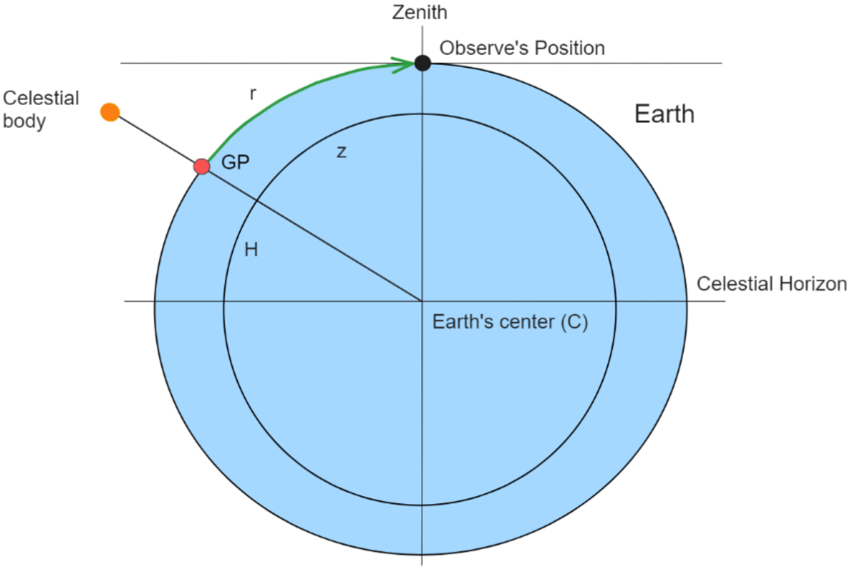


Fig. 2 – Geographical Position (GP) concept.

A celestial body appears in the zenith (z= 0°, H=90° – directly overhead) when GP is identical with the observer's position. An observer moving away from GP will observe that the altitude of the body decreases as his distance from GP increases.

The position of GP is recorded in GHA (Greenwich Hour Angle) and Declination (Dec) (Fig. 6). GHA is the angular distance of GP from Greenwich meridian (0°) measured westward from 0° through 360°. Dec is the angular distance of GP from the plane of the equator, measured northward and southward through +90°.

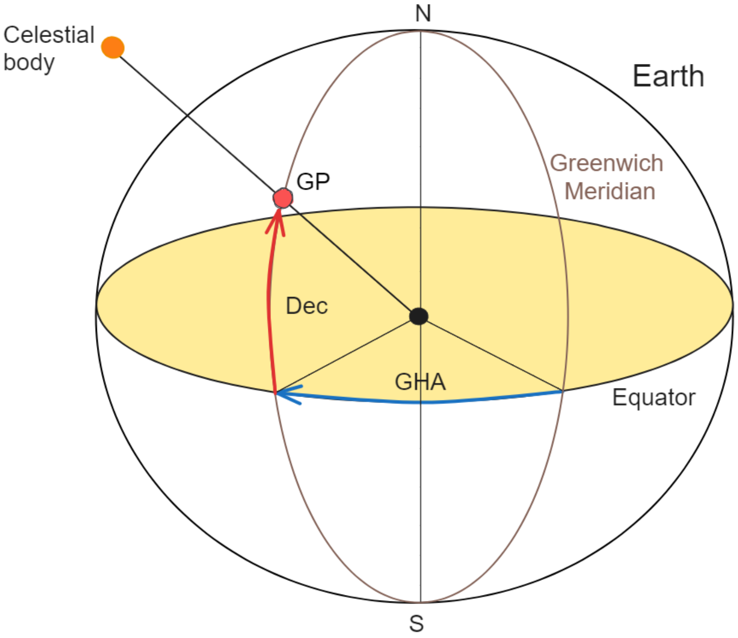


Fig. 3 – Geocentric coordinates of GP.

GHA and Dec are geocentric coordinates (measured at the center of the earth) and are equivalent to geocentric longitude and latitude, with the exception that longitude is measured westward and eastward through 180°.

An essential assumption of celestial navigation is that light rays originating from distant objects are virtually parallel to each other when reaching the earth (Fig. 3). That means, for a given altitude of a celestial body, there is an infinite number of positions having the same distance GP and forming a circle around the earth's surface whose center is on the line C-GP. Such a circle is called a circle of equal altitude. An observer traveling along that circle will measure a constant altitude and zenith distance of the respective body, no matter where on the circle he is. The radius of the circle (r), measured along the surface of the earth, is directly proportional to the observed zenith distance (z).

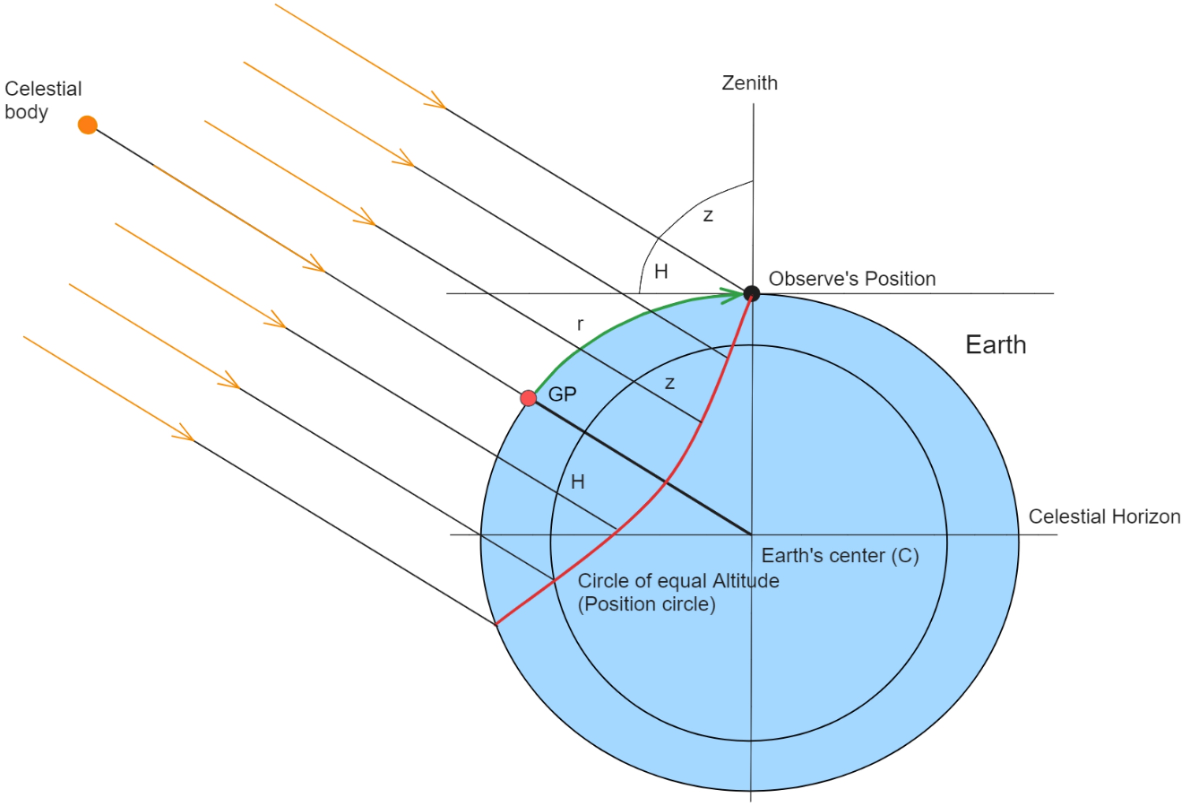


Fig. 4 – Circle of equal Altitude (aka Position circle).

Whenever we measure the altitude of a celestial body with a sextant, we have gained partial information about our own geographical position because we know we are somewhere on a circle of equal altitude with the center at GP and radius of (r). The information, is still incomplete because we can be anywhere on the circle of equal altitude which comprises of infinite number of possible positions; therefore, we call it a position circle.

We need to observe a second body in addition to the first one in order to know where we are on the position circle. Logically, we are on two circles of equal altitude now (Fig. 4). Both circles overlap, intersecting each other at two points on the earth's surface, and one of those two points of intersection is our own position.

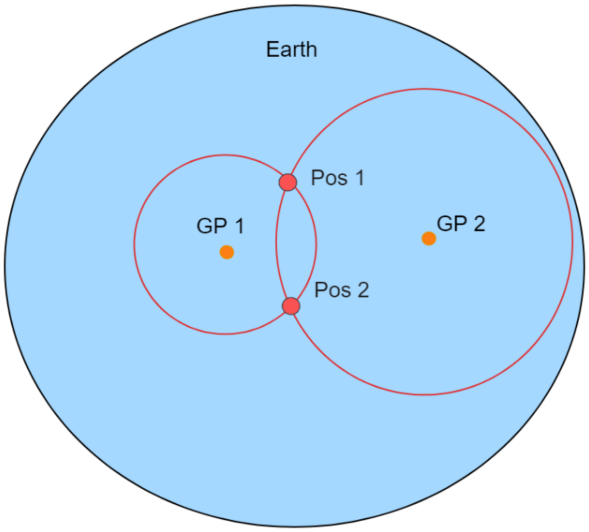


Fig. 5 – Finding observer's position by using position circles.

However, it is not possible to know which point of intersection we are in – Pos 1 or Pos 2, unless we have additional information. That could be a compass bearing of at least one of the bodies or a fair estimate of where we are (for example Dead Reckoning position). The ambiguity can also be resolved by observation of a third body because there is only one point where all three position circles intersect (Fig. 5). Similar to position lines the position circles will most likely not meet in one point but will form a triangle ("cocked hat").

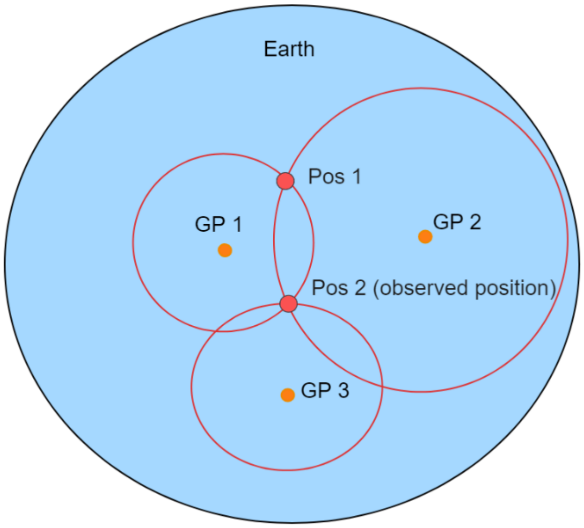


Fig. 6 – Finding observer's position by using 3 position circles.

Theoretically, we could find our position by plotting the circles of equal altitude on a globe. In fact, this method has been used in the past but turned out to be impractical because precise measurements require a very big chart. Plotting circles of equal altitude on a chart is possible if their radii are small enough (close to 90°). Assuming a degree of angular angle is equal to 60 miles (1° = 60 minutes and 1 minute = 1 mile of distance), if a celestial body appeared at 80° above the horizon, our position would be 600 miles away from the celestial body's GP. This theoretically puts us somewhere on a position circle which has a radius of 600 miles from the GP. For this reason, plotting position circles directly on a chart is rarely used.

But given the fact that a navigator should always have an estimate of his position (EP), it is not necessary to plot whole position circles but rather those parts which are near the expected position. A mathematical method using sight reduction known as "intercept" method was invented in 1875 by Commander Marcq de Saint-Hilaire of the French Navy and is in common use to this day to solve this problem.

This intercept method uses a complicated triangular mathematic (PZX triangle) to find one's position. Fortunately, a set of celestial navigation Tables were produced to make it very simple for navigators. Calculations are simple and require only basic arithmetic operations like addition and subtraction on numbers and degrees.

Besides the nautical almanac, which can be used to find the GHA and Dec of celestial bodies, we also have another set of tables known as Sight Reduction Tables. Among other things, these can be used to find pre-calculated altitudes (the height above the horizon) of celestial bodies, relative to different positions on the earth's surface. The Sight Reduction Tables are entered with information that's based on a position (rounded off), chosen by the navigator as close as possible to vessel's Dead Reckoning. By doing this, the distance between the position chosen by the navigator and the vessel is likely to be just a handful of miles, reducing the problem of distance and scale. The altitude of a celestial body found in Sight Reduction Tables is compared with the altitude of the same body measured with a sextant from the vessel.

In addition to a tabulated altitude, the Sight Reduction Tables also provide a bearing to the GP of the celestial body. This bearing also known as the azimuth is measured from the Chosen Position. By comparing the difference between the Sextant Altitude and the altitude found in the Sight Reduction tables it's possible to establish the position circle on which the vessel is located. Using the azimuth as a guide line, only a very small part of the position circle needs to be drawn. This results in a position line that's of practical use as it can be plotted on a chart at a realistic scale. Typically, a special plotting sheets are used for that purpose.

In similar way to GHA, Local Hour Angle (LHA) is a measurement of how far west the body is from a local meridian (our position) (Fig. 6). LHA is always a positive angle between 0° and 360°. The LHA needs to be calculated to be able to enter the Sight Reduction Tables.

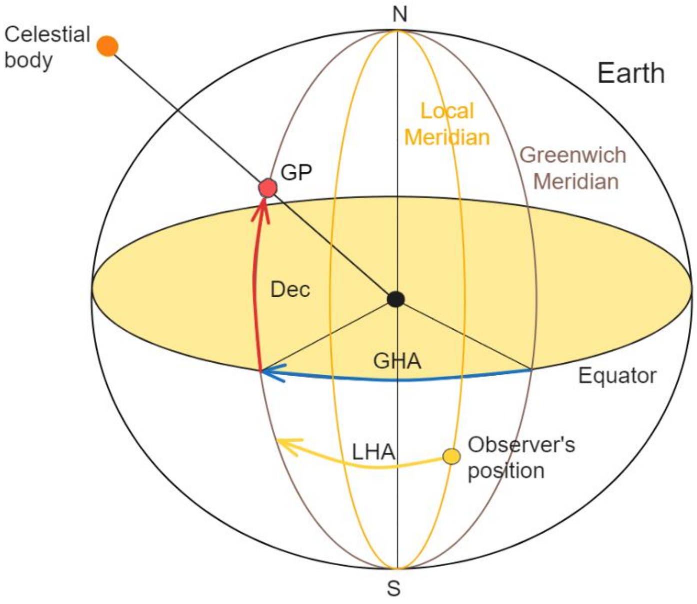


Fig. 7 – Geocentric coordinates of GP and LHA.

Although GHA and LHA are both measured towards the west, it must be remembered that longitude progresses both east and west of Greenwich. This means a navigator in the west has to subtract their local longitude from the GHA to find the LHA, while someone in the east will have to add.

It should be noted that it is very important to measure the exact time of the sights. The sun moves across the sky by:

- 360° in 24 hours
- 15° in 1 hour
- 1° in 4 minutes
- 15’ in 1 minute
- 1’ in 4 seconds

Since 1’ of angular distance is equal to 1 nautical mile, 4 seconds of time account for 1 nautical mile of distance. For example, if your watch runs slow by 4 seconds, you lose 1 miles of accuracy. So, make sure that your watch is synchronized otherwise the fixes won't be accurate. You can adjust time according to a GPS receiver (best) or the internet.

Note however, that the art of traditional navigation isn't knowing where you are, it's knowing where you could be. Our position is no longer a pin point, it's an area. This is totally fine on the open ocean where few navigational hazards exist. For example, a circle of error of radius 60Nm may sound like a lot, but over a passage of 850NM from the Canaries to Cape Verde it is only an error of around 5°.

Landfall becomes far more important. We need to establish our actual position as soon as land comes into view. You will want to identify the high land features which you might see first, and also establish how far off you will see them from.

Summary

To put all this theory into practice, finding one's position by observation of celestial objects include three basic steps:

- Taking sights: measuring the altitude of two or more chosen celestial bodies (sun, moon, starts and/or planets) using Sextant.
- Finding the GP position of each body at the time of its observation (sight) using Nautical Almanac.
- Deriving one's own position from the above data using "intercept" method and Sight Reduction Tables.

Establishing a position typically require one of the following sights to be taken:

- sun sight + noon sun sight
- sun-run-sun (two sun sights measured in an interval of a few hours)
- moon sight + sun sight
- stars and/or planets sights (morning or evening)

The most popular celestial navigation tables in use are the Sight Reduction Tables Pub. No. 249 and Almanac for Air Navigation. You can find them here.

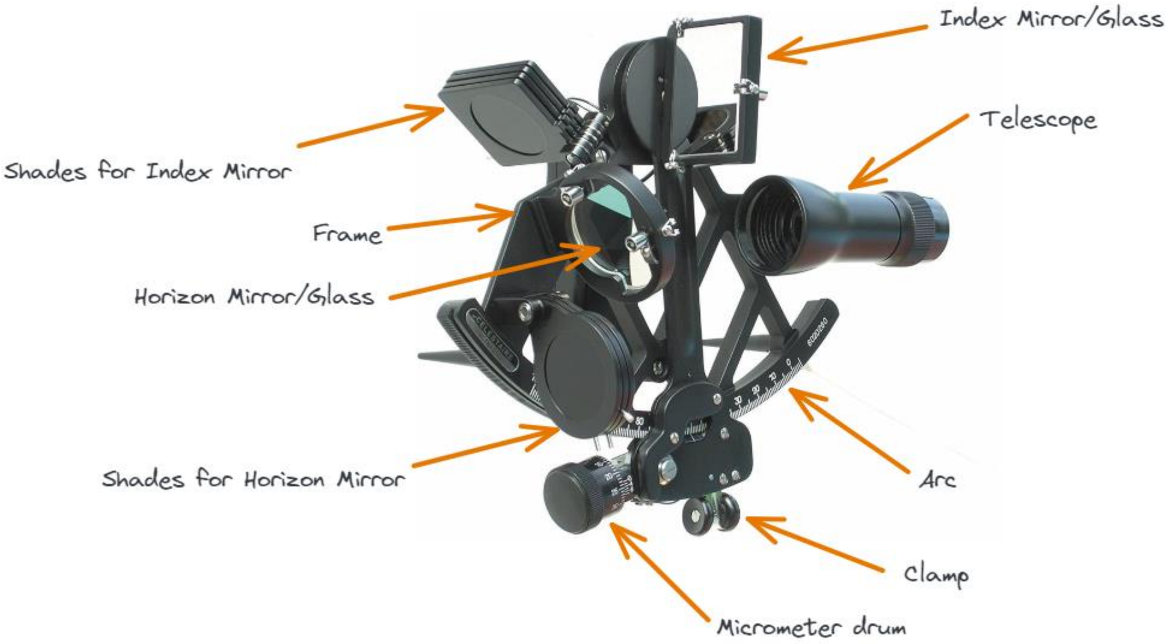
When you start with celestial navigation it is also useful to use ready proformas to aid the calculations. You can find them here.

Explaining how to use the Almanac and Sight Reduction Tables to find one's position is beyond the scope of this introduction. To learn more, read Celestial Navigation with Sight Reduction Tables from Pub. No 249 by Dominique F. Prinet and attend RYA Yachtmaster Theory Course.

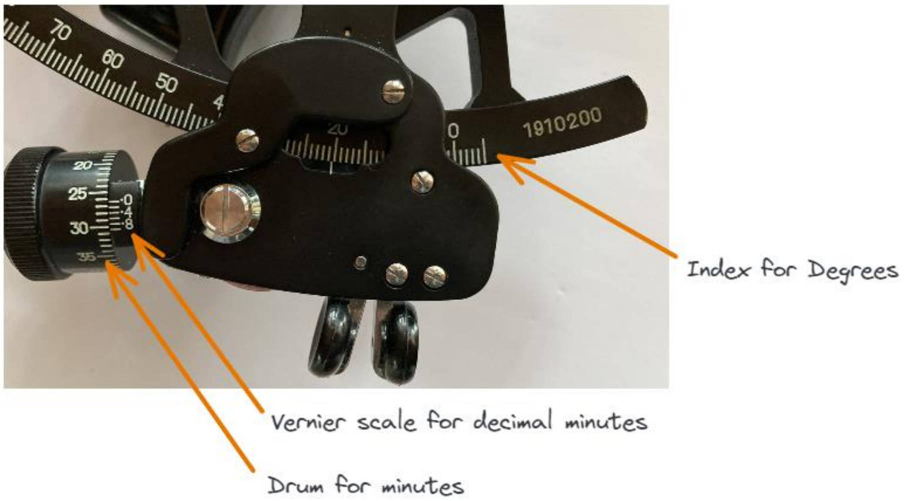
Practice is everything so join one of our trips. We use celestial navigation in all our offshore routes.

Sextant components

A sextant is an instrument for measuring angles. For example, you can measure the vertical angle between the horizon and tip of a lighthouse or an angle between the horizon and a celestial body. Sextant consists of a telescope, a horizon mirror (whole mirror or split) which the telescope "looks" through and a moving index arm on which the index mirror is fixed. By manipulating the arm with a clamp, we can bring object reflection (eg. a celestial body) to a horizon, and read the angle. Accurate adjustments are made by means of a micrometre drum.



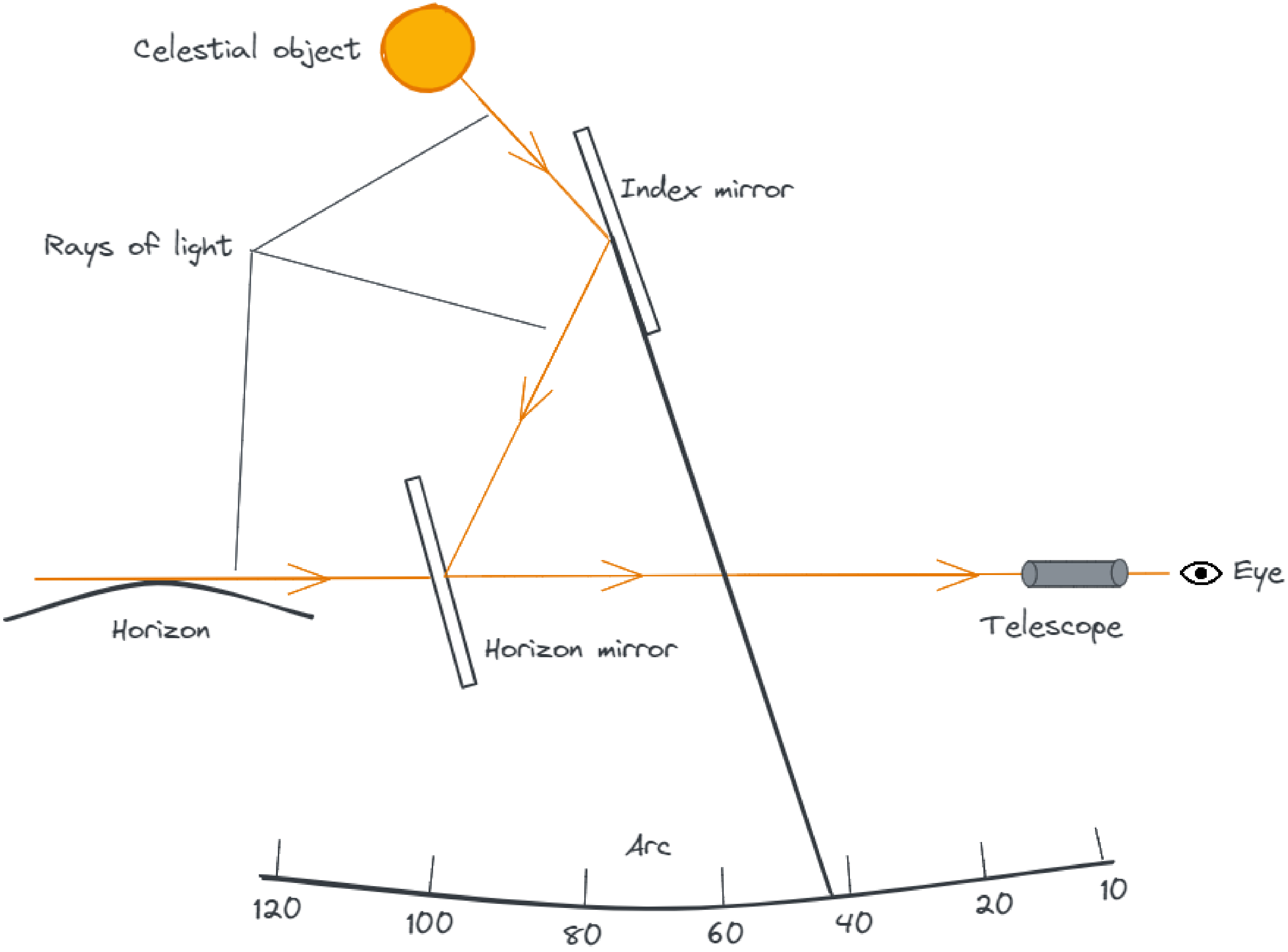
The angle can then be read off the index arm (degrees), micrometre drum (minutes) and vernier if assembled (fraction of minutes). In the example below you can read an angle of 20°26’.4



The shades are used to protect the eye when the object being looked at is bright - such as the sun or moon.

How sextant works

Sextant relies on the optical principle that if a ray of light is reflected from two mirrors in succession, then the angle between the first and last direction of the ray is twice the angle between the mirrors. And this angle can then be read off the index arc.



Source: https://www.dynagen.co.za/eugene/where/sextant.html

Taking sights of Sun or Moon

Steps:

1. Prepare shades by direct observation of the body through the shades and not using the telescope. Combine shades as required. Do that for index shades and horizon shades separately. You always need some shades for Sun sights. You may or may not need shared for moon depending on its brightness.

2. Use the selected index and horizon shades to protect your eye from the direct rays of the object. It is safest to use too many than too less filters initially and adjust later if required.

   The horizon shades are used to protect your eye from the direct sunlight coming through the clear opening in the horizon mirror. The index shades are used to protect your eye from the sun reflected in the index and horizon mirrors.

   Never directly look into the sun without applying shade glasses of necessary light reduction! Even looking for just a few seconds could seriously damage your eyesight and possibly lead to permanent blindness. The retina has no sensitivity to pain, so there is no warning that injury is occurring and the effects of retinal damage may not appear for hours.

   Sailors did not use shades in the past and eye issues were frequent which is why eye patches were so common with mariners and pirates.

3. (Optional) Check the index and side errors.

4. Set both the index arm and micrometre drum to zero.

5. Sight the object through the telescope.

   Stand facing the celestial object with the sextant in a vertical position in your right hand and look through the telescope to find the object.

6. Turn the micrometre drum a little to identify the reflected object. When you turn the drum, you should be able to observe that the actual and reflected suns split from each other.

7. Bring the reflected object to the horizon.

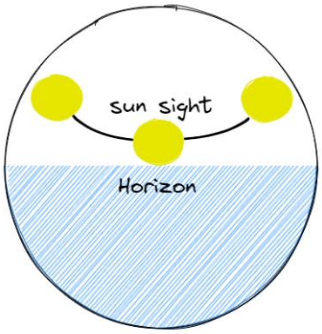
   Release the clamp levers with your left hand and slowly move the index arm forward. Follow the reflected object. You will have to bend your body rotate the sextant down synchronously towards the horizon in order to keep the reflected sun visible in the mirrors. When the horizon appears in the field of view engage the lever.

8. Adjust horizon shades if needed with your left hand so that you can clearly see the horizon.

   When you bring the reflected sun to the horizon you are no longer directly looking at the sun in the clear opening of the horizon mirror. You are looking at the reflected sun only. The horizon shades at that point are only used to reduce the brightness of the reflection of the sun on the water's surface. When the sextant is rotated to about 3/4 down towards the horizon, it is usually necessary to remove some shared from the horizon mirror. The reason is that the horizon is usually not very bright and could disappear behind the filters.

9. Carry out fine adjustments by rotating the drum until the image touches ("kisses") the horizon.

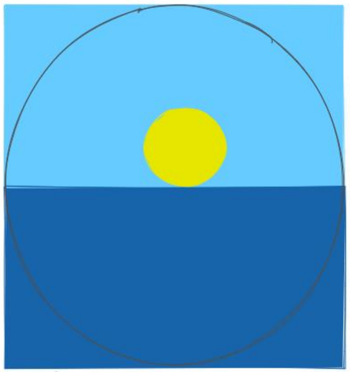
10. Gently rock (swing) the sextant from side to side to make sure the reflected image is touching ("kissing") the horizon at the bottom of the swing. While swinging make final adjustments with the micrometre drum.



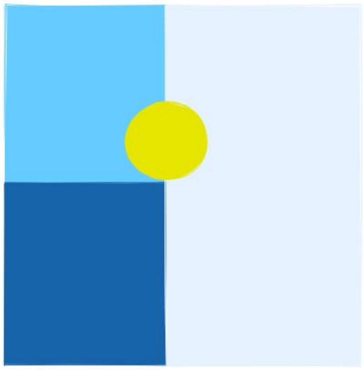
Swinging the sextant

For sun sights, the lower limb is traditionally used and is the one that is placed on the horizon. Occasionally, clouds get in the way, and the upper limb must be used. When halo is present, take the middle. In the case of the moon, the limb used depends on the phase. The stars and planets are considered punctual so we do not use that distinction.

There is a slight difference in how you would see the reflected object depending on whether you use the whole horizon or split mirror. Whole horizon mirrors are a bit more expensive but easier to use. The only disadvantage is that the reflected object is dimmer compared to traditional split mirror so taking start sights may be slightly more difficult.



Whole Horizon Mirror



Split Horizon Mirror

11. At the moment when the object perfectly touches the horizon, immediately record the time using your watch (write down the time in hours, minutes and seconds, starting with the seconds first to avoid errors), eg. 08:45:12

12. Read the angle (altitude) from the sextant, e.g. 32^{o} 4.47’
13. With your DR position and the sight (altitude and time), make necessary calculations using proformas and tables, and establish the position on a plotting sheet.

Taking sights of Stars and Planets

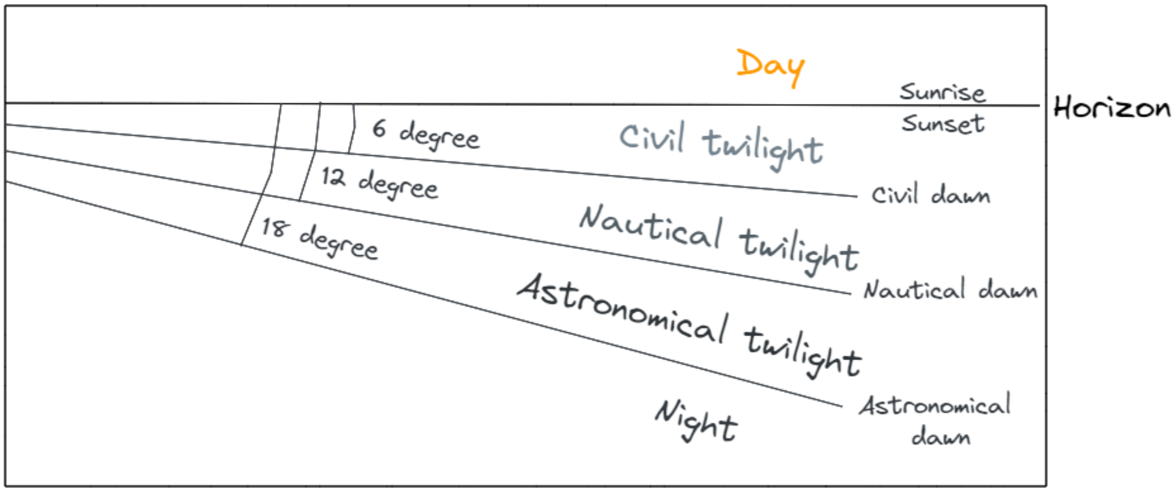
Taking sight of stars and planets is more difficult because the objects are much smaller and harder to find than the sun or moon. The good news is that you do not need to use any shades as starts and planets can be directly looked at safely. A total of 57 stars and 4 planets (Venus, Mars, Jupiter, Saturn) can be used for celestial navigation using sight reduction tables.

Steps:

1. Pre-calculate the expected altitude (angle) and azimuth (bearing) of the objects (stars and/or planets). There is a simple method for doing that using Tables.

2. Calculate the time of the twilight observation period to know when to appear on deck.

   Note that you cannot do sights during the night because you will not be able to see the horizon. Instead, the sights are done from the middle of civil twilight to the middle of nautical twilight. During that time both the horizon and the celestial objects can be observed.



3. Appear on deck before the twilight observation period.

4. (Optional) Check the index and side errors.

5. Locate the objects that you pre-planned to shoot one by one. You may have to wait a little until they become bright enough to be visible through the telescope.

6. With hand bearing compass and pre-calculated azimuth (bearing) establish the approximate direction at which you should be looking at the object.

7. Preset the sextant according to the pre-calculated altitude of the object.

8. Look through the telescope at the given azimuth (bearing) near the horizon and the reflected image of the object should appear somewhere above or below the horizon.

   Note that stars twinkle while planets don't because stars are so much further away from Earth. This makes them appear as concentrated points of light, and that light is more easily disturbed by the effects of Earth's atmosphere).

9. Carry out fine adjustments by rotating the drum until the reflected object touches ("kisses") the horizon.

10. Gently rock (swing) the sextant from side to side to make sure the reflected object is touching the horizon at the bottom of the swing. While swinging make final adjustments with the micrometre drum.

11. At the moment when the object perfectly touches the horizon, immediately record the time using your watch (write down the time in hours, minutes and seconds, starting with the seconds first to avoid errors), e.g. 08:45:12

12. Read the angle (altitude), e.g. 32° 4.47’

13. Take sight of another object by repeating the process from step 6. You need at least two sights to get a position fix. The more sights you are able to take the better.

14. With your DR position and the sight (altitude and time), make necessary calculations using proformas and tables, and establish the position on a plotting sheet.

Sextant Errors and Corrections

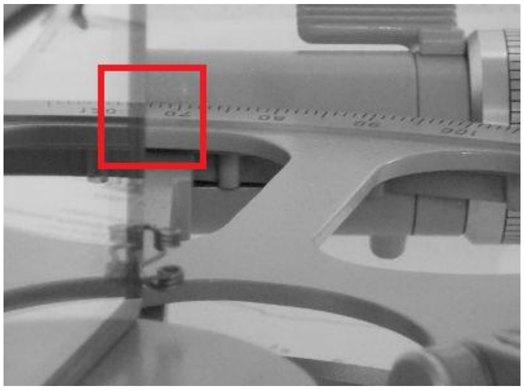
The sextant is subject to a number of errors and adjustments.

Perpendicularity error

Perpendicularity error is caused by the index mirror not being perpendicular to the plane of the instrument.

Correcting Perpendicularity Error (Checking for Perpendicularity)

1. Hold the sextant horizontally, with the index arm set around the middle of the scale so that the scale of the arc can be seen in the index mirror.
2. Look at the sextant arc reflected in the index mirror. Adjust the index mirror screws until the real and reflected arc is continuous and flat.



Side Error

Side error is caused when the horizon mirror is not perpendicular to the plane of the instrument. Correcting side error is an iterative process. When you correct for side error, you may introduce a bit of index error. Similarly, when you continue adjusting screws to correct the index error you may reintroduce a bit of side error.

Correcting side error by horizon observation

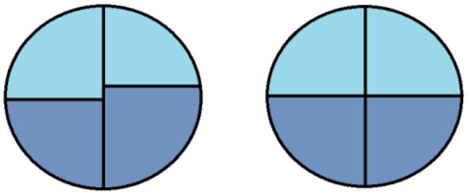
1. Clamp the index bar to zero.
2. Hold the sextant vertically and view the horizon through the telescope.
3. When looking at the horizon, tilt the sextant 45 degrees to the right.
4. If the side error is present, there will be a step on the horizon.
5. To eliminate the side error, adjust the screw on the side of the horizon mirror (the one furthest away from the sextant frame). Keep looking through the telescope until you bring the horizon back into line. Turn the screw rightwards (clockwise) to move the reflected image to the right and leftwards (anticlockwise) to move it to the left of the true object.
6. Hold the sextant vertically again and view the horizon through the telescope, and check that the horizon is still in line. If not, you have to correct for index error.

Checking side error by star or planet observation

1. Clamp the index bar to zero.
2. Hold the sextant vertically, and observe a star through the telescope.
3. If the side error is present, the reflected object will not be aligned sideways (shifted left or right).
4. To eliminate the side error, adjust the screw on the side of the horizon mirror (the one furthest away from the sextant frame). Keep looking through the sextant until the true object and the reflected object are aligned.
5. Hold the sextant vertically again and view the horizon through the telescope, and check that the horizon is still in line. If not, you have to correct for index error. Turn the screw rightwards (clockwise) to move the reflected image to the right and leftwards (anticlockwise) to move it to the left of the true object.

Index Error

The index error is caused when the index mirror and horizon mirror are not parallel to each other when the index bar is set to zero. A small amount of index error is acceptable as this can be corrected during calculations.


Sextant set at 0 - horizon split due to index error

Index error corrected for horizon level

Checking index error by horizon observation

1. Clamp the index bar to zero.
2. Hold the sextant vertically and view the horizon through the telescope.
3. If the true horizon and its reflected object appear in one line, the index error is not present.
4. If they appear vertically displaced that means index error is present.
5. To eliminate the index error, clamp the index bar at zero. Look through the telescope, and turn the upper screw on the horizon glass (the one nearest to the sextant's frame) till the true horizon and its reflection appears in alignment. When looking through the telescope, turn the screw rightwards (clockwise) to reduce the reading "On the Arc" and increase "Off the Arc". Turn the screw leftward (anticlockwise) to reduce the reading "Off the Arc" and increase "On the Arc".

You can also use this procedure on any horizontal line which is at a distance of at least 3 NM.

Checking index error by sun observation

1. Clamp the index bar to zero.
2. Hold the sextant vertically.
3. Using the necessary shades, view the sun through the telescope.
4. Turn the micrometre "On the Arc" (micrometre reading is positive) until the upper limb of the reflected sun touches the lower limb of the True Sun.
5. Note down the reading "On the Arc".
6. Turn the micrometre "Off the Arc" (micrometre reading is negative) until the lower limb of the reflected

sun touches the upper limb of the true sun.

7. Note down the reading "Off the Arc".
8. If the two readings are the same, it indicates no index error is present.
9. If there is a difference between the two readings, it means the index error is present.
10. To find the value of the index error, take the difference of the two values obtained by the above method and divide it by 2.
11. "On the Arc" or "Off the Arc" should be given according to whether the "On the Arc" or "Off the Arc" reading was larger.

12. To eliminate the index error, clamp the index bar at zero. Look through the telescope, turn the upper screw on horizon glass (the one nearest to the sextant's frame) till the true horizon and its reflection appears in alignment. When looking through the telescope, turn the screw rightwards (clockwise) to reduce the reading "On the Arc" and increase "Off the Arc". Turn the screw leftward (anticlockwise) to reduce the reading "Off the Arc" and increase "On the Arc".

Example:
Reading on the arc= 31.5
Reading off the arc= 31.1

Index Error = (31.5 - 31.1) / 2 = 0.20 On the Arc (because On the Arc reading is greater than Off the Arc reading)

Verify the accuracy of the index error based on sun observation

1. Obtain the semi-diameter of the sun = sum of two readings / 4

   (31.5 + 31.1) / 4 = 15.7'.

2. Get the true semi-diameter (SD) of the sun from the almanac for that date.
3. If the value of obtained semi-diameter and true semi-diameter of the sun are equal, it means the value of the index error obtained is correct.

Checking index error by a star or planet observation

1. Clamp the index bar to zero.
2. Hold the sextant vertically, and observe a star through the telescope.
3. If the star and its reflection are not displaced vertically, it indicates index error is not present.
4. If they appear vertically displaced that means index error is present.
5. To eliminate the index error, clamp the index bar at zero. Look through the telescope, turn the upper screw on horizon glass (the one nearest to the sextant's frame) till the true horizon and its reflection appears in alignment. When looking through the telescope, turn the screw rightwards (clockwise) to reduce the reading "On the Arc" and increase "Off the Arc". Turn the screw leftward (anticlockwise) to reduce the reading "Off the Arc" and increase "On the Arc".

Other errors

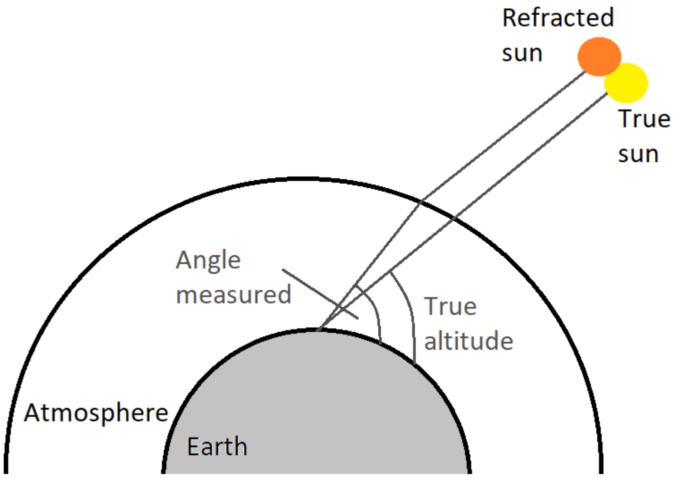
Altitudes measured by sextant have to be converted to true altitudes by applying corrections to other errors. In practice, the corrections are read from Altitude Correction Tables in Nautical Almanac.

Dip is an adjustment made for the height of the eye above sea level.

Parallax corrections are needed if the observed body is relatively close: a planet, the sun or the moon. In theory, sextant readings are taken from the centre of the terrestrial sphere. In practice, of course, the sextant is used on the earth's surface. This means that an altitude measured at the surface will almost always be different from the theoretical one unless the body is directly overhead.

Semi-diameter correction is needed if the observed body is the sun or the moon since they are relatively big when sighting. The true altitude reading of the sun or moon is computed from the centre of the body. When taking a sight, an observer will bring either the upper or lower edge (limb) to the horizon, because it's practically impossible to judge accurately where the centre of the sun is when taking a sight.

Refraction allows for the "bending" of light rays as they travel through successive layers of varying density air.



Non-Correctable errors

Consult the sextant's calibration card to account for non-correctable errors, e.g.

- Centering error: Index arm does not pivot at the centre of the sextant arc.
- Prismatic error: Faces of the mirrors are not parallel to each other.
- Shade error: Shades are not parallel to each other.
- Graduation error: Graduations along the sextant arc or micrometre are not precise.
- Worm & Rack error: Gearing of the arm and micrometre are not precise.
- Collimation error: Telescope is not parallel to the plane of the sextant.

A new sextant should normally be free of these errors.

What if Sextant is broken or lost

In the very unlikely scenario that you end up without GPS and Sextant in the middle of the Ocean you can use approximate methods to establish your position. They require experienced helm steering a constant course and accurate chart-keeping.

Get approximate latitude

The simplest way is to find the right latitude to find you land, then sail across that line of latitude. In other words, keep latitude constant. To do that, all that is needed is a stick. Hold it vertically in front of an eye with a straight arm and line the top of the stick up with Polaris's star in the Northern Hemisphere. Then, carefully "nick" the stick at the point where the horizon intersects it. Every evening, check the stick against Polaris. If the "nick" is still on the horizon, you are at the same latitude. For this to be effective, you would have to mark the stick as soon as possible after the last reliable fix, use the same stick every time and the same person should do it.

Get approximate longitude

You can establish approximate longitude from local noon (sun at its highest point) by taking the time when it happens and taking the difference to noon at Greenwich using a conversion of Time to Arc (1 hour = 15°, 1 min = 15', 4 sek = 1').

When checking the sun's height against the horizon, it is not possible to look directly at the Sun. Instead, you can use a stick and a bit of paper and mark the end of the shadow every 20 seconds or so as local noon approaches. Alternatively, make a sun shadow board. This method will not be terribly accurate because it is very hard to find the exact point in time when the sun is at its highest but it will give you some approximation.

Landfall

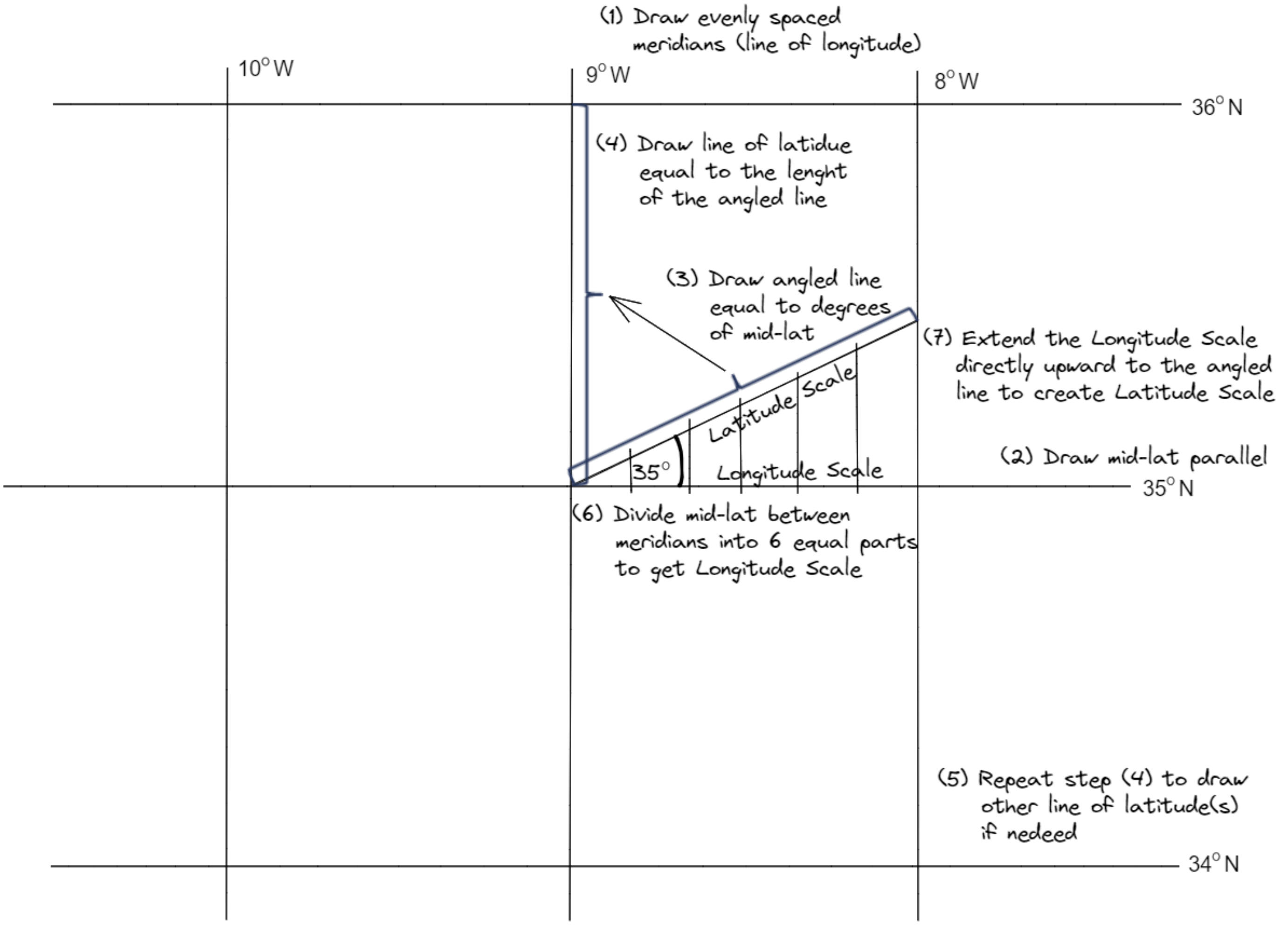
If landfall is estimated to be near, looking for birds and cumulus cloud formations on the horizon can be very useful. The smaller the bird, the closer land is likely to be, perhaps 30 - 50 miles distant. Larger birds might venture further and, of course, a single bird could always be lost. Clouds gather over land as the land heats up and convection occurs, causing sea breezes. A good sign! Finally, you should listen to VHF radio traffic and watch for other vessels. You can always ask for directions for the last miles.

What if you run out of plotting sheets

You can download and print as many plotting sheets as you want. But if you do run out of them you can easily create your own. All you need is a blank sheet of paper, a triangle or plotter with a scale and a pencil.

Steps:

1. Draw meridians (lines of longitude) on a blank sheet, evenly spaced across the page (3 or so should be enough).
2. Draw mid-lat (chosen latitude) parallel (line of latitude) across the middle of the sheet.
3. Draw a line angled upward from mid-lat. The angle it makes with the mid-lat should be equal to the 1 degree of latitude.
4. Using the length of the angled line, draw a parallel (line of latitude).
5. Draw other parallels if needed similar to step 4.
6. Divide mid-lat between two meridians into 6 equal parts to get Longitude Scale.
7. Extend the Longitude Scale directly upwards (parallel to meridians) to cross the angled line from point 3. This will form the Latitude Scale.



If you find that you can't fit as many parallels of latitude as you need using this method, or you knew that ahead of time, use the same process as above, but draw your parallels first, evenly spaced, then draw your mid-long, then draw the angled line as before to find the spacing for the rest of the meridians.