CHAPTER 18

SIGHT PLANNING

NEED FOR SIGHT PLANNING

1800. The Need for Sight Planning

One of the challenges of celestial navigation is sight planning. Good sight planning is essential to acquiring a good fix.

A single sight produces a **line of position (LOP)**. A fix, the determination of the observer's most likely position, requires at minimum two LOPs. The fix is the intersection of the LOPs. If the sights were perfectly accurate, then no further work would be required. However, no observation is perfectly accurate. A navigator experienced in taking sights with a sextant can, under ideal conditions, take sights accurate to a few tenths of an arc minute. Under typical shipboard conditions sights are expected to be accurate to about an arc minute. A navigator not experienced at taking sights can expect an accuracy of a few arc minutes. Sight planning is one tool for reducing errors in producing a fix. Good sight planning will reduce the effect of the errors from both taking the sights and on the derived fix.

There are several considerations that go into sight planning. Among them are:

- When should sights be taken?
- What bodies will be visible?
- What distribution of celestial bodies will produce the best fix?
- What is the best order in which to take the sights?

The process of sight planning can be broken down into three broad categories: general sight planning, daytime sight planning, and twilight sight planning.

1801. General Principles

Experienced navigators through history have come to understand that under normal conditions only about 70% of the visible sky is ideal for taking celestial observations. When it comes to sight planning it is important to appreciate that celestial body pre-selection will yield the best chance for achieving an accurate celestial fix of position when they come from bodies observed within certain altitude ranges and at certain times. For example, it is useful to understand that when selecting celestial bodies for observation. it can be difficult to accurately determine the true altitude of bodies lying low near the horizon due to refraction, while it can be equally daunting to accurately determine a celestial LOP from a body near zenith because the assumption that a straight line of position approximates the body's circle of equal attitude begins to breakdown.

Except for sights of the Sun, Moon, and sometimes Venus and Jupiter, all other bodies used in celestial navigation sights can be measured only during nautical twilight, the period during which the center of the Sun is between 6º and 12º below the horizon. During this period the sky is dark enough to make out the celestial bodies used for sights, but bright enough that the horizon is well enough defined to take an accurate sight.

The process of taking sights is weather dependent. An accurate sight requires that both the body and the horizon below it be visible at the time the sight is taken. If either the body or the horizon is obscured, but still visible, a reduced accuracy sight may still be taken. Such a sight should be taken if it is the only option. A better option is to have an extended list of possible bodies to observe. The navigator can then select those bodies that are clearly visible with a well defined horizon below them.

The process of sight planning can be broken down into three broad categories: general sight planning, daytime sight planning, and twilight sight planning.

1802. Distribution of Bodies in Azimuth

The *Nautical Almanac* contains data for reducing sights of 179 bodies: the Sun, Moon, four planets, 57 navigational stars, and 116 supplemental stars (pp. 268-273). On average, there is one body for every 230 square degrees of sky, and these bodies are unevenly distributed on the sky. An accurate fix requires the observed bodies to be well distributed in azimuth.

Figure 1802a shows two LOPs for two objects whose azimuths are separated by 15º. The LOPs also intersect with an acute angle of 15º. The result is: it is difficult to determine where the two LOPs cross along the axis bisected by the acute angle. That is, there is a large uncertainty in the fix position in that direction. The uncertainty in the fix along the axis bisected by the oblique angle is approximately the same as it would be if the LOPs met at right angles.

Figure 1802b the two LOPs are perpendicular to each other. The result is that the uncertainty in the fix is the same in all directions. The closer the separation of the azimuths of two sights comes to perpendicularity the better the chance a fix will have minimum uncertainty. Finding two

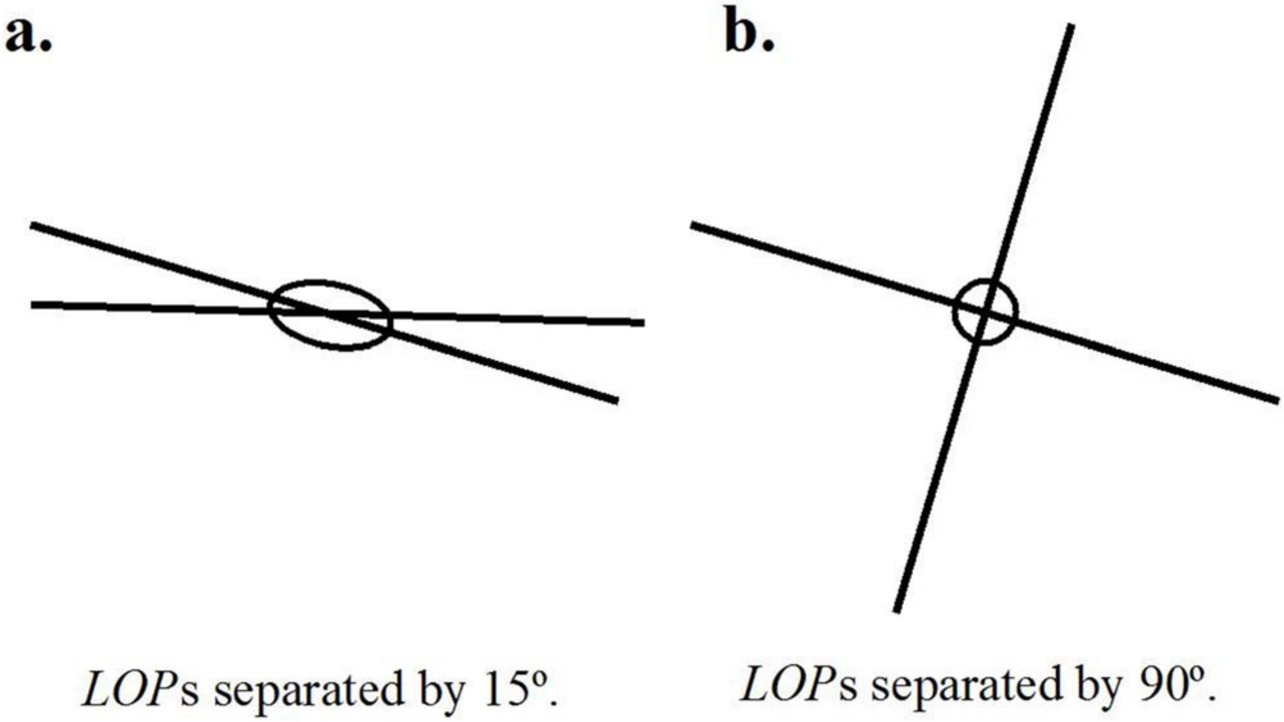

Figure 1802a. The change of error ellipse with angle of intersection.

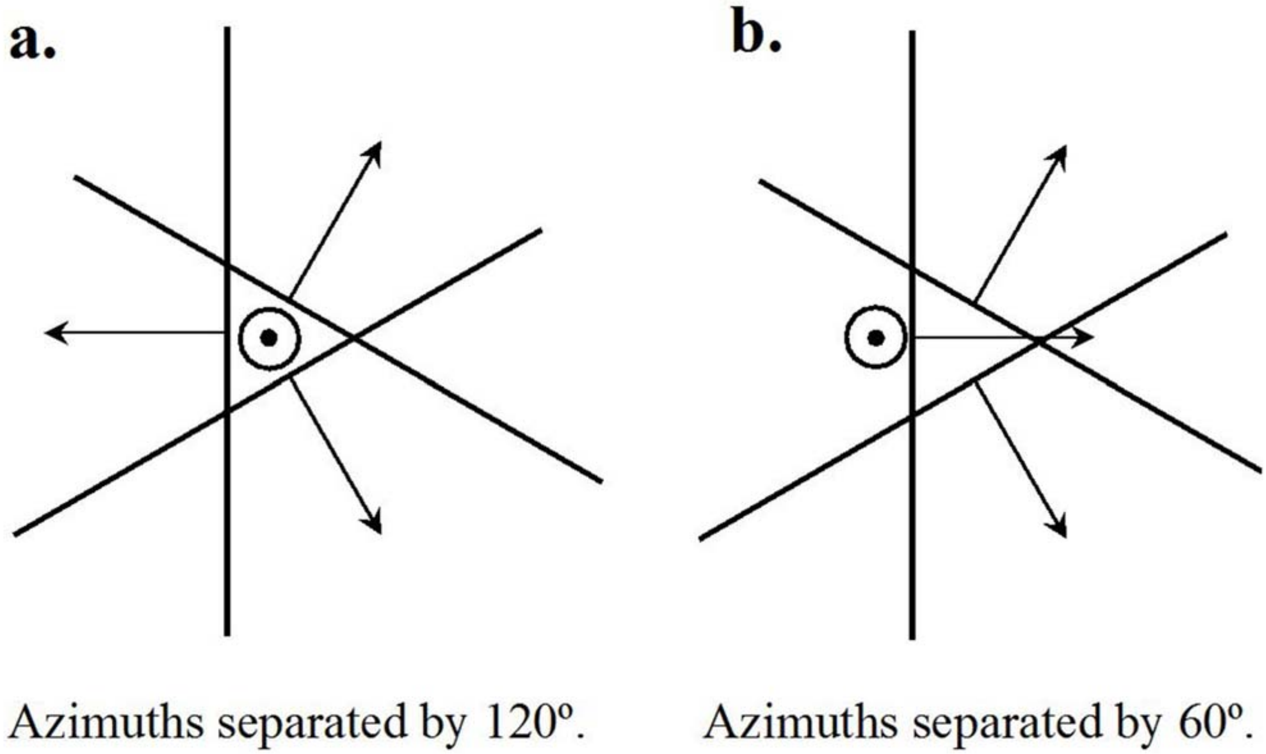

Figure 1802b. Effects of the azimuthal distribution of bodies and a systematic error on the most likely positions.

bodies with azimuths separated by exactly 90º is unlikely, so an acute angle of at least 30º is recommended to reduce the uncertainty along the axis that bisects the acute angle of two LOPs.

Sights well distributed in azimuth also act to cancel out systematic errors in determining Ho such as an incorrect index correction (IC) or error in dip. For example, Figure 1802a shows three LOPs made from bodies separated by 120º in azimuth. A systematic error in determining Ho will move the LOPs in a direction perpendicular to the LOPs themselves, indicated by the arrows. A systematic error will move all of the LOPs the same amount in directions distributed 120º in azimuth. The result is the most likely position for the fix remains at the center of the "cocked hat". In Figure 1802b, the three LOPs were plotted from bodies distributed by 60º in azimuth. The resulting "cocked hat" looks identical to the one in Figure 1802a. A systematic error, however, will move all of the LOPs the same amount in directions distributed in azimuth by 60º on either side of the center of the distribution. The result is that the most likely position for the fix is no longer at the center of the "cocked hat". The most likely position may even lie outside of the "cocked hat" altogether if the systematic error is more than a few tenths of an arc minute.

1803. Altitude of Bodies

Bodies at high altitudes are difficult to observe. They can be a challenge to acquire, to "bring to the horizon" with a sextant, and to determine their approximate azimuth to measure an accurate *Hs*. As the body gets closer to the zenith the assumption that the circle of equal distances can be approximated by an LOP breaks down. Sights of a body taken at high altitudes may also require the use of more complicated procedures, such as the use of second differences when calculating *Hc*. Taking sights of body at high altitudes, greater than 75º, should be avoided for these reasons.

Refraction affects all observations. Refraction forms part of the corrections for both dip and apparent altitude. Refraction is larger and the correction becomes more uncertain for bodies near the horizon. The correction for non-standard air temperature and pressure can be more than 1' for a sight made within 5º of the horizon and can still be several tenths of an arc minute for a sight made within 10º of the horizon.

The amount of atmosphere the light has to pass through for a body observed near the horizon is greater than for a body observed at a greater altitude. A body viewed near the horizon will appear dimmer and redder because the light is absorbed or scattered by the atmosphere. Taking sights of bodies at low altitudes, less than approximately 15º, should be avoided for these reasons.

Correcting for non-standard air pressure and temperature does not guarantee that a sight will have no refraction error. The apparent position of the horizon itself is subject to phenomena such as temperature inversions. There are three things a navigator can do to reduce any systematic errors caused by uncorrected refraction:

1. Make sure the observations are well distributed in azimuth. At sea, it is usually the case that the factors that contribute to refraction are similar in all directions. Taking sights well distributed in azimuth will cause the systematic errors to cancel out.

2. Take the sights from a place close to the sea surface, if possible. Almost all of the abnormal refraction encountered is caused by that part of the atmosphere between the observer's eye and the surface of the sea. Reducing the observer's height decreases the distance to the horizon. An observer close to the sea surface will have a nearby horizon, which is more likely to have similar refraction conditions in all directions.

3. Observe celestial bodies with similar altitudes, all greater than 15°. Bodies at the same altitude have the same total values for refraction. So, the systematic effect of errors in computed refraction will tend to cancel out if the bodies are well distributed in azimuth. The change in refraction angle is small, except near the horizon, so relative altitude is a minor consideration when choosing which bodies to use.

1804. Brightness of Bodies

One source of systematic error is the **personal equation**, that is how the individual judges the position of an object that does not appear to be a perfect point. This judgment of position varies from individual to individual. One person might tend to favor an "upper edge", while another favors a "lower edge", etc.

A bright object always appears somewhat larger than a dim one with a similar apparent size, seen against the same background. This property is called *irradiation*, and is a result of the way the brain interprets what it sees. Irradiation depends more on the difference in brightness between object and background than on the apparent size of the body. So, it is particularly striking for point sources such as stars. If possible, select bodies that are approximately the same brightness, to minimize the effect of personal error arising from irradiation. This effect is usually small, so it is of less importance than other considerations in the selection of bodies for sights.

1805. Number of Sights and Number of Bodies

One method to reduce the random error in determining an LOP is to take a number of observations of the same body over a short period of time. Averaging these observations together into a single sight, taking into account the change in *Hs* with time, reduces random error with the square root of the number of observations. Averaging four observations into a sight reduces the random error to one-half that of a single observation sight and averaging nine observations into a sight reduces the random error to one-third that of a single observation. The incremental reduction in the random error quickly diminishes with the number of sights. Averaging together four or five observations into a single sight is about optimum.

The common method of averaging sights is the fit-slope method, e.g. Burch, D. 2015, *Celestial Navigation, Second Edition* (Seattle, Starpath Pub.) pp. 176-177. The fit-slope method is a graphical approximation of a linear least-squares method, e.g. Bevington, P.R. and Robinson, D.K. 1992, *Data Reduction and Error Analysis for the Physical Sciences*, (Boston, McGraw-Hill), Chapter 6. These methods assume that the rate of change of *Hs* is constant. Usually, this is a good assumption over a single sight session. But if the body is near transit, *Zn* = 0º or *Zn* = 180º, the rate of change of *Hs* may be changing quickly. In this case these linear methods will fail. But if the observed body *does* transit during the sighting session, the vessel's position can be determined using the same method to determine LAN (Sections 1910 and 1911).

Another way to perform this task is to reduce all the observations made of the same object at an observing session as individual sights, and then average together the resulting values for *a* and *Zn*. This second method consumes more time in the reduction of the individual observations, but it removes the difficulty of accounting for the change in *Hs* with time required for averaging together the observations.

It is preferable to take observations in a round-robin fashion when taking sights of more than one body at a session. Taking consecutive observations of different bodies helps assure that all the bodies are observed at least once should a sudden change in weather put an end to the observation of one or more bodies. Taking non-consecutive observations of a body helps to remove systematic errors in its observations by adding a randomizing factor to the sight taking.

Taking sights of more than two bodies can significantly reduce the random error of a fix just as taking more than a single observation can reduce the random error in an *LOP*. There are two parameters to be determined, latitude and longitude, involved in a fix. So the random error of a fix is reduced by the square root of the number of sights minus two. Determining a fix from five or six sights is about optimum to reduce the random error in a fix

By averaging a number of observations into a single sight and then combining it with other sights into a single fix, the navigator can significantly reduce the uncertainty of the vessel's position.

The difference of a course of advance and the track made good for a running fix results in a less accurate fix than one made from taking sights of two bodies at a single observing session. The best method for reducing error in a running fix is to average together multiple observations, particularly those of the latter observing session, to improve the accuracy of the *LOP*.

1806. Precomputation

Precomputation is the practice of determining the predicted values of phenomena using estimated values for the time and position and data from the almanac. Precomputed values usually include times of rise and set of the Sun and Moon, the time of local apparent noon, the times and duration of twilight, and the *Hc*'s and *Zn*'s of those bodies being considered for sight observations.

Precomputing the *Hc* and *Zn* of a body for a sight serves two purposes:

1. It determines if the selected bodies provide a good distribution in azimuths. For a running fix using a single body, it determines how much time must elapse between sights to get an acceptable minimum change in azimuth of the body.
2. It eases the process of identification. Set the sextant to the precomputed *Hc* and face the precomputed *Zn*. The chosen object will usually stand out in the reflection of the index mirror when the horizon is viewed through the horizon glass. This practice is particularly helpful in a crowded star field at twilight or when trying to pick out Venus, or occasionally Jupiter, against the bright daytime background.

DAYLIGHT SIGHT PLANNING

1807. Sun Sights

The principal activity of daylight celestial navigation is sighting the Sun to determine a vessel's position from running fixes and latitude from *Ho* at local apparent noon. Precomputing the Sun's expected *Hc* and *Zn* at various times throughout the day makes it possible to determine the optimum times to take sights for both of these activities.

For example, in the Torrid Zone (tropics) the Sun's azimuth changes slowly for most of the morning and most of the afternoon switching rapidly from east to west around local apparent noon. To achieve a good running fix, sights need to be obtained before, near-to, and after local apparent noon. Near the equator, the change in azimuth is within 30º of 180º from February through April and August through October. During these periods a sight near local apparent noon (when the Sun's azimuth is near 0º or 180º) is essential for a good running fix. At high latitudes (north or south), on the other hand, the motion of the Sun is mostly in azimuth, at approximately 15º/hr. So, a good running fix from the Sun can be made from two sights as long as at least two and fewer than ten hours have elapsed between sights and the Sun is high enough above the horizon to take an accurate sight.

Occasionally, it is necessary to take a Sun sight when it is near the horizon, to make a compass check for example. Precomputing the time and *Zn* of sunrise or sunset are useful to provide an approximate time and azimuth for making such an observation. If the Sun is more than one or two degrees above the horizon, an accurate sight for *Hs* as well as *Zn* can be determined as long as corrections are made for the change in refraction from non-standard temperature and air pressure. The upper limb of the Sun can be observed to further reduce possible complications from non-standard refraction.

1808. Moon Sights

When the Moon is more than a few days from New Moon it is bright enough to be easily visible during the daytime. It is also well separated from the Sun. It is best situated for daytime sights around the times of First Quarter (age 6 to 8 days) and Last Quarter (age 21 to 23 days). Near Full Moon the Sun and Moon are opposite each other in the sky, so the resulting *LOP*s may be nearly parallel and the resulting fix would be poor. Instead, sights of the Full Moon should be combined with sights of celestial bodies other than the Sun.

It is more difficult to observe and make accurate measurements of the dark side of the Moon than of its bright side. Select the lighted limb when taking sights, and avoid taking sights when the "horns" of either the lighted or unlighted side point parallel to the horizon as in Figure 1808.

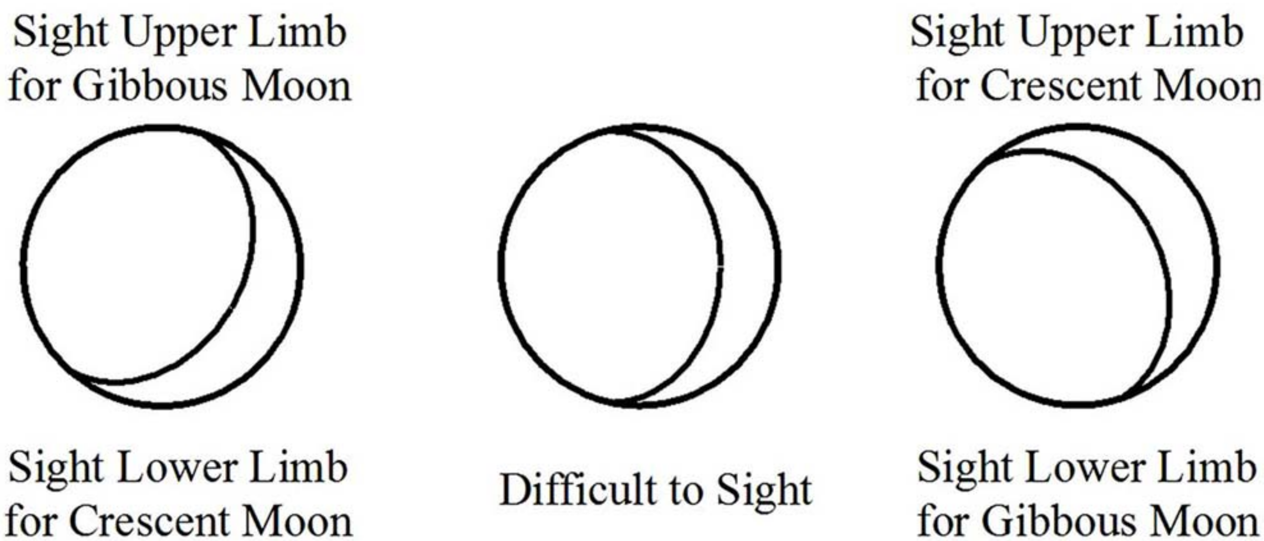

Figure 1808. Where to sight Moon with phase.

The local times of moonrise and moonset at 0º longitude are tabulated as a function of latitude for each day in the daily pages of the *Nautical Almanac*. The tabulation interval is 10º from the equator to latitude 30º, 5º from latitude 30º to latitude 50º, and 2º from latitude 50º to the limit for each hemisphere. Times of moonrise and moonset at high northern latitudes, 65º N to the North Pole, can be estimated using the semiduration of moonlight graph on pages 323 through 325 of the *Nautical Almanac*. Interpolation in both latitude and change in time of the phenomenon with longitude need to be performed to determine the LMT of moonrise or moonset. The Moon's phase and age at 12^h UT for each day are also tabulated on the daily pages.

1809. Planet Sights

Venus can be observed during the daytime when it is well separated from the Sun, particularly when its altitude is greater than the Sun's. Jupiter can also occasionally be observed during the daytime. Both planets can be observed immediately after sunset or before sunrise rather than waiting for nautical twilight. The best way to find Venus against the bright daytime sky is to precompute its *Hc* and *Zn*, set the sextant for the expected altitude, and then use a compass to view along the expected azimuth.

The navigational planets move against the backdrop of the "fixed" stars from night to night, but their motions are small enough that they can be found in the same general area of the sky for several weeks. Also, they are bright enough to be easily identifiable. One way to take advantage of these properties when using an aid such as a star finder is to mark the planets positions at the expected middle of a voyage.

TWILIGHT SIGHT PLANNING

1810. Determining the Period of Twilight

Good sight planning is essential to make good use of the short period of nautical twilight for taking sights and minimize errors. Sight planning for twilight observations consists of three tasks:

1. Determine the period of nautical twilight.
2. Select the celestial bodies to be observed.
3. Determine the order in which to observe the bodies.

The length of the period of nautical twilight is a function of latitude and time of year. For most practical celestial navigation work, it lasts between 24 minutes in the tropics to an hour or more at high latitudes (near the poles, twilight can last days or weeks). Local weather conditions such as clouds and fog may significantly modify the period during which sights may be taken. During the period of nautical twilight only the brightest celestial bodies are visible.

The daily pages of the *Nautical Almanac* tabulate the LMT of beginning of morning nautical and civil twilight and the ending of evening civil and nautical twilights, to the nearest minute, for the middle of each three-day period from N 72º to S 60º. The tabulation interval is 10º from the equator to latitude 30º, 5º from latitude 30º to latitude 50º, and 2º from latitude 50º to the limit for each hemisphere. Times of twilight at high northern latitudes, 65º N to the North Pole, can be estimated using the semiduration of sunlight graph on page 322 of the *Nautical Almanac*. These intervals are adequate to interpolate the LMT twilight times to the DR latitude. It is advisable to also interpolate the times of twilight between the values on the current page and either the preceding or subsequent page if:

1. the latitude is greater than 20º,
2. the time of the phenomenon is more than 18 hours from the UT of the middle of the three-day interval, and
3. the date is within two months of either the vernal equinox (March 21) or the autumnal equinox (September 23).

1811. Twilight Moon Sights

When the Moon is between about 5 and 24 days old it is bright enough that it visibly lights the sea surface near the Moon's azimuth. Confusion between the horizon and the glint of moonlight off of the sea surface closer to the observer may occur at these times. A sight taken where the lighted sea is mistaken for the horizon will result in a value of *Hs* that is too high. To reduce this problem, twilight sights of the Moon or other bodies with a similar azimuth should be taken, if possible, shortly after sunset or before sunrise when the horizon is easily distinguishable and the glare of moonlight is minimal. If a sight must be taken when there is significant glare:

- Observe from a position near the sea surface. A sight taken near the sea surface has a closer horizon, so the effect of the glare off the sea surface is minimized.
- Check the horizon under the Moon with a powerful pair of binoculars to determine if the glare extends to the apparent horizon.

1812. Selection of the Celestial Bodies for Sights

The most important consideration in selecting bodies for a fix is to ensure that the bodies are well distributed in azimuth. A fix from twilight observations alone requires sights of a minimum of two celestial bodies. Separating the bodies by at least 30º degrees in azimuth is desired to improve the acute angle of the intersection between *LOP*s. A fix made from at least three bodies that are well distributed in azimuth minimizes systematic errors in determining *Ho*. Observing four to six bodies significantly reduces the uncertainty of a fix. Precomputing the approximate altitudes and azimuths for eight to ten bodies will provide a sufficient buffer for weather and other obstructions to observing.

Another important factor to consider is that bright bodies are much easier to identify during early twilight when the horizon is still sharp. Venus and Jupiter, when available, are among the brightest objects in the sky, so they should be among the first bodies chosen. The Moon is also easy to identify, but is not always a good target. It should be used when either the upper or lower limb is well defined (the Moon's "horns" are not parallel to the horizon) and the glint of moonlight on the sea surface is not bright enough to cause a problem in determining the location of the horizon.

A third consideration is to select bodies with an altitude greater than 15º to minimize systematic errors in refraction, and with an altitude less than 75º to prevent errors arising from the break down in the approximation that an *LOP* is equivalent to a circle of equal altitude. Select bodies that are at a similar altitude and of a similar brightness to further minimize systematic errors in taking sights

1813. Order of Observation

Take sights in a round-robin fashion, when possible. A number of individual observations of each body is desirable, but taking consecutive observations of different bodies helps assure that at least one observation is made of each body in case there is a sudden change in the weather or the horizon becomes obscured. Taking non-consecutive sights of a body adds an element of randomness preventing systematic errors from creeping into the observations.

Brighter bodies are visible earlier during evening twilight and later during morning twilight. The Moon, Venus, and Jupiter can be observed before sunset or after sunrise, and the brightest stars can be observed during civil twilight. Sights of these objects made during these periods are more likely to have a well defined horizon, and allows more time for taking sights of dimmer stars and navigational planets during nautical twilight. Making observations of the brighter bodies during civil twilight can be particularly helpful in the Torrid Zone (tropics) where the length of nautical twilight is less than half an hour.

During twilight, the horizon remains well defined near the azimuth of sunset or sunrise for a longer period of time than it does 180º away from that azimuth. Plan to take sights closer to that azimuth later during evening twilight and earlier during morning twilight. Precomputing the approximate azimuth of sunrise or sunset from the data in daily pages of the *Nautical Almanac* can aid in planning.

AIDS TO SIGHT PLANNING

1814. Aids to Sight Planning

There are a number of aids to help the navigator in sight planning:

The ***Nautical Almanac*** contains a planet location diagram on pp. 8 and 9, and star charts on pp. 266 and 267.

The ***Air Almanac*** contains a set of sky diagrams on pp. A26-A121. These diagrams show the altitudes and bearings of the Sun, Moon, navigational planets and stars at selected hours of the day, throughout the year, and for various latitudes. Each set includes diagrams for the North Pole and latitudes from 75º N to 50º S at an interval of 25º. A complete explanation of the sky diagrams is found on pages A24 and A25. The *Air Almanac* also includes a moonlight interference diagram on page A125 and star recognition diagrams for 40 (22 in the northern hemisphere and 18 in the southern hemisphere) of the 57 navigational stars on pp. A126-A129. Both sets of diagrams include instructions for their use.

STELLA (System To Estimate Latitude and Longitude Astronomically) is a software application for Windows computers that automates the sight reduction process. It includes a sight planning utility. STELLA also automatically logs all data entered for future reference. It is an allowance list requirement for U.S. Navy ships, and is also utilized by the U.S. Coast Guard. It is available for Navy or DoD components from the U.S. Naval Observatory.

MICA (Multiyear Interactive Computer Almanac) can, for a given location and time, compute the apparent altitude and azimuth of celestial bodies. It can compute the times and azimuths of rise and set and time and altitude of transit for a given location and date. For circumpolar bodies it computes the times and altitudes of both upper and lower transit. It can also compute the times of civil and nautical twilight. A catalog of the 57 navigational stars is included with MICA, and other catalogs can be added. MICA is produced by the Astronomical Applications Department of the U.S. Naval Observatory. It is available from Willmann-Bell, http://www.willbell.com, for the general public, and from the U.S. Naval Observatory for Department of Defense Components.

The **Data Services** section of the USNO - Astronomical Applications Department **website** includes several calculators for use in sight planning (see Figure 1814a for the link):

Figure 1814a. USNO Data Services
http://aa.usno.navy.mil/data/index.php

1. The ***Complete Sun and Moon Data for One Day*** page computes the times and azimuths of rise, set for the Sun and Moon, and the times and altitudes of the transits and times of civil twilight.
2. The ***Rise/Set/Transit Times for Major Solar System Bodies and Bright Stars*** page computes the times and azimuths of rise, set and the times and altitudes of the transits for the Sun, Moon, planets and 22 of the navigational stars. .
3. The ***Celestial Navigation Data for Assumed Position and Time*** page computes the *Hc*, *Zn*, *GHA*, and *Dec* of the Sun, Moon, planets and navigational

stars. It also calculates the standard correction for refraction for all bodies and the corrections for the semi-diameter and parallax for the Sun, Moon, and planets. This service determines which bodies are available at a given time and place and color-codes the results for ease of use. See the Notes on the Data Services web page for details.

UK Rapid Sight Reduction Tables for Navigation NP 303 / AP/3270 (formerly Pub. 249 Vol. 1, Sight Reduction Tables for Air Navigation Vol I (Selected Stars)) provides a list of the seven navigational stars by LAT (latitude) and LHA. It also marks the three stars most appropriate for making a fix from stars well distributed on the sky. This publication has the advantage that it can be used in situations where electric power is not available and values of *Hc* and *Zn* can be determined swiftly near the epoch of the edition. Its main disadvantage is that values of *Hc* and *Zn* are sensitive to precession and can change by up to 0.'8 per year. So, *Hc* and *Zn* must be interpolated for precession for dates more than one or two years from the epoch of the edition used. (See the Correction for Precession and Nutation table in *Pub. NP 303/AP3270* for instructions on its use.) The correction table is designed only for observations made within an eight-year span (four years of the epoch of a particular edition), so a new edition of this volume is published every five years.

The ***RUDE 2102-D*** star finder is device designed to estimate the approximate *Hc* and *Zn* of the 57 navigational stars given the observer's Lat and LHA of Aries. It can be used to find the positions of the planets and Moon as well with some additional effort. See Cutler, T.J. 2004, *Dutton's Nautical Navigation, Fifteenth Edition* (Annapolis, MD: Naval Institute Press) articles 2101-2105 for details of its description and use. The advantage of the star finder is that it can be used in situations where electric power is not available. Its principle disadvantage is it can take a while to use and interpret its data for a navigator not practiced in its use.