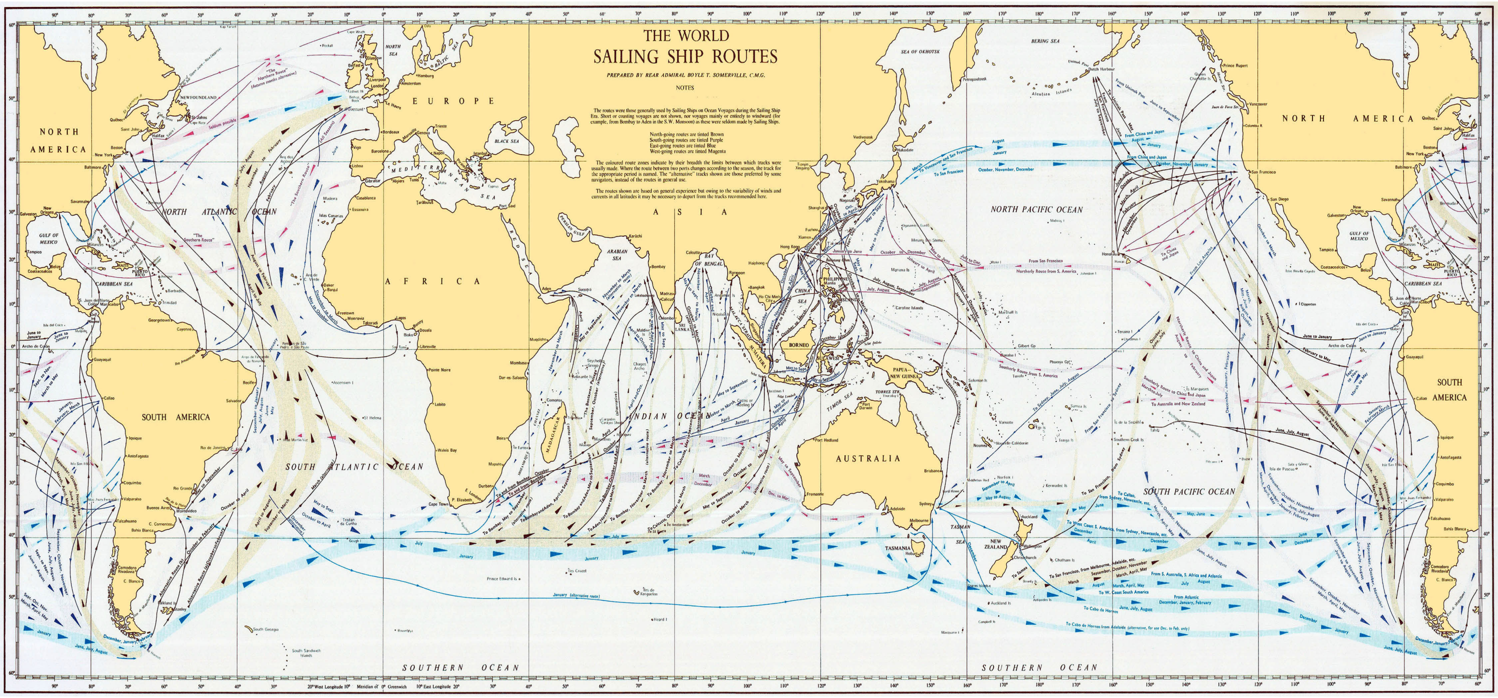
APPENDICES

APPENDIX A

THE WORLD SAILING SHIP ROUTES (2017)


THE WORLD
SAILING SHIP ROUTES
PREPARED BY REAR ADMIRAL BOYLE T. SOMERVILLE, C.M.G.
NOTES
The routes were those generally used by Sailing Ships on Ocean Voyages during the Sailing Ship Era. Short or coasting voyages are not shown, nor voyages mainly or entirely to windward (for example, from Bombay to Aden in the S.W. Monsoon) as these were seldom made by Sailing Ships.
North-going routes are tinted Brown
South-going routes are tinted Purple
East-going routes are tinted Blue
West-going routes are tinted Magenta
The coloured route zones indicate by their breadth the limits between which tracks were usually made. Where the route between two ports changes according to the season, the track for the appropriate period is named. The "alternative" tracks shown are those preferred by some navigators, instead of the routes in general use.
The routes shown are based on general experience but owing to the variability of winds and currents in all latitudes it may be necessary to depart from the tracks recommended here.
NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
ASIA
AUSTRALIA
NORTH ATLANTIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
NORTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
SOUTHERN OCEAN
ARABIAN SEA
BAY OF BENGAL
CHINA SEA
GULF OF MEXICO
CARIBBEAN SEA
BLACK SEA
SEA OF OKHOTSK
BERING SEA
TASMAN SEA
NEW ZEALAND
TASMANIA
BORNEO
PAPUA NEW GUINEA

APPENDIX B

CALCULATIONS AND CONVERSIONS

INTRODUCTION

B 1. Purpose and Scope

This chapter discusses the use of calculators and computers in navigation and summarizes the formulas the navigator depends on during voyage planning, piloting, celestial navigation, and various related tasks. To fully utilize this chapter, the navigator should be competent in basic mathematics including algebra and trigonometry (See Chapter 1 - Mathematics in Volume II) and be familiar with the use of a basic scientific calculator. The navigator should choose a calculator based on personal needs, which may vary greatly from person to person according to individual abilities and responsibilities.

B 2. Use of Calculators in Navigation

Any common calculator can be used in navigation, even one providing only the four basic arithmetic functions of addition, subtraction, multiplication, and division. Any good scientific calculator can be used for sight reduction, sailings, and other tasks. However, the use computer applications and handheld calculators specifically designed for navigation will greatly reduce the workload of the navigator, reduce the possibility of errors, and assure accuracy of the results calculated.

Calculations of position based on celestial observations have become increasingly uncommon since the advent of GPS as a dependable position reference for all modes of navigation. This is especially true since GPS units provide worldwide positioning with far greater accuracy and reliability than celestial navigation.

However, for those who use celestial techniques, a celestial navigation calculator or computer application can improve celestial position accuracy by easily solving numerous sights, and by reducing mathematical and tabular errors inherent in the manual sight reduction process. They can also provide weighted plots of the LOP's from any number of celestial bodies, based on the navigator's subjective analysis of each sight, and calculate the best fix with latitude/longitude readout.

In using a calculator for any navigational task, it is important to remember that the accuracy of the result, even if carried out many decimal places, is only as good as the least accurate entry. If a sextant observation is taken to an accuracy of only a minute, that is the best accuracy of the final solution, regardless the calculator's ability to solve to 12 decimal places. See Chapter 3 - Navigational Error in Volume II for a discussion of the sources of error in navigation.

Some basic calculators require the conversion of degrees, minutes and seconds (or tenths) to decimal degrees before solution. A good navigational calculator, however, should permit entry of degrees, minutes and tenths of minutes directly, and should do conversions automatically. Though many non-navigational computer programs have an on-screen calculator, they are generally very simple versions with only the four basic arithmetical functions. They are thus too simple for complex navigational problems. Conversely, a good navigational computer program requires no calculator per se, since the desired answer is calculated automatically from the entered data.

The following articles discuss calculations involved in various aspects of navigation.

B 3. Calculations of Piloting

- **Hull speed in knots** is found by:

  $$S = 1.34\sqrt{\text{waterline length}}\ \text{(in feet)}$$

  This is an approximate value which varies with hull shape.

- **Nautical and U.S. survey miles** can be interconverted by the relationships:
  1 nautical mile = 1.15077945 U.S. survey miles.
  1 U.S. survey mile = 0.86897624 nautical miles.

- **The speed of a vessel over a measured mile** can be calculated by the formula:

  $$S = \frac{3600}{T}$$

  where S is the speed in knots and T is the time in seconds.

- **The distance traveled at a given speed** is computed by the formula:

  $$D = \frac{ST}{60}$$

  where D is the distance in nautical miles, S is the speed in knots, and T is the time in minutes.

- **Distance to the visible horizon in nautical miles** can be calculated using the formula:

  $D = 1.17\sqrt{h_f}$, or

  $D = 2.07\sqrt{h_m}$

  depending upon whether the height of eye of the observer above sea level is in feet (h_f) or in meters (h_m).

- **Dip of the visible horizon in minutes of arc** can be calculated using the formula:

  $D = 0.97'\sqrt{h_f}$, or

  $D = 1.76'\sqrt{h_m}$

  depending upon whether the height of eye of the observer above sea level is in feet (h_f) or in meters (h_m).

- **Distance to the radar horizon** in nautical miles can be calculated using the formula:

  $D = 1.22\sqrt{h_f}$, or

  $D = 2.21\sqrt{h_m}$

  depending upon whether the height of the antenna above sea level is in feet (h_f) or in meters (h_m).

- **Dip of the sea short of the horizon** can be calculated using the formula:

$$Ds = 60 \tan^{-1}\left(\frac{h_f}{6076.1\, d_s} + \frac{d_s}{8268}\right)$$

  where Ds is the dip short of the horizon in minutes of arc; h_f is the height of eye of the observer above sea level, in feet and d_s is the distance to the waterline of the object in nautical miles.

- **Distance by vertical angle between the waterline and the top of an object** is computed by solving the right triangle formed between the observer, the top of the object, and the waterline of the object by simple trigonometry. This assumes that the observer is at sea level, the Earth is flat between observer and object, there is no refraction, and the object and its waterline form a right angle. For most cases of practical significance, these assumptions produce no large errors. A ta-

$$D = \sqrt{\frac{\tan^2 a}{0.0002419^2} + \frac{H - h}{0.7349}} - \frac{\tan a}{0.0002419}$$

  ble is computed by means of a formula:
  where D is the distance in nautical miles, a is the corrected vertical angle, H is the height of the top of the object above sea level, and h is the observer's height of eye in feet. The constants (0.0002419 and 0.7349) account for refraction.

B 4. Tide Calculations

- **The rise and fall of a diurnal tide** can be roughly calculated from the following table, which shows the fraction of the total range the tide rises or falls during flood or ebb.

Hour	Amount of flood/ebb
1	1/12
2	2/12
3	3/12
4	3/12
5	2/12
6	1/12

B 5. Calculations of Celestial Navigation

Unlike sight reduction by tables, sight reduction by calculator permits the use of nonintegral values of latitude of the observer, and LHA and declination of the celestial body. Interpolation is not needed, and the sights can be readily reduced from any assumed position. Simultaneous, or nearly simultaneous, observations can be reduced using a single assumed position. Using the observer's DR or MPP for the assumed longitude usually provides a better representation of the circle of equal altitude, particularly at high observed altitudes.

- **The dip correction** is computed in the *Nautical Almanac* using the formula:

  $D = 0.97\sqrt{h}$

  where dip is in minutes of arc and h is height of eye in feet. This correction includes a factor for refraction. The *Air Almanac* uses a different formula intended for air navigation. The differences are of no significance in practical navigation.

- **The computed altitude** (Hc) is calculated using the basic formula for solution of the undivided navigational triangle:

$$\sin h = \sin L \sin d + \cos L \cos d \cos LHA,$$

  in which h is the altitude to be computed (Hc), L is the latitude of the assumed position, d is the declination of the celestial body, and LHA is the local hour angle of the body. Meridian angle (t) can be substituted for LHA in the basic formula.
  Restated in terms of the inverse trigonometric function:
  When latitude and declination are of contrary name, declination is treated as a negative quantity. No special

$$Hc = \sin^{-1}[(\sin L \ \sin d) + (\cos L \cos d \ \cos LHA)].$$

sign convention is required for the local hour angle, as in the following azimuth angle calculations.

- **The azimuth angle** (Z) can be calculated using the altitude azimuth formula if the altitude is known. The formula stated in terms of the inverse trigonometric function is:

$$Z = \cos^{-1}\left(\frac{\sin\ d - (\sin\ L \sin Hc)}{(\cos L \cos Hc)}\right)$$

If the altitude is unknown or a solution independent of altitude is required, the azimuth angle can be calculated using the time azimuth formula:

$$Z = \tan^{-1}\left(\frac{\sin LHA}{(\cos L \tan d) - (\sin L \cos LHA)}\right)$$

The sign conventions used in the calculations of both azimuth formulas are as follows: (1) if latitude and declination are of contrary name, declination is treated as a negative quantity; (2) if the local hour angle is greater than 180°, it is treated as a negative quantity.
If the azimuth angle as calculated is negative, add 180° to obtain the desired value.

- **Amplitudes** can be computed using the formula:

$$A = \sin^{-1}(\sin d \sec L)$$

this can be stated as

$$A = \sin^{-1}\left(\frac{\sin d}{\cos L}\right)$$

where A is the arc of the horizon between the prime vertical and the body, L is the latitude at the point of observation, and d is the declination of the celestial body.

B 6. Calculations of the Sailings

- **Plane sailing** is based on the assumption that the meridian through the point of departure, the parallel through the destination, and the course line form a plane right triangle, as shown in Figure B6.

From this: $\cos C = \frac{l}{D}$, $\sin C = \frac{p}{D}$, and $\tan C = \frac{p}{l}$.

From this: $l = D \cos C$, $D = l \sec C$, and $p = D \sin C$.

From this, given course and distance (C and D), the difference of latitude (l) and departure (p) can be found, and given the latter, the former can be found, using simple trigonometry. See Chapter 12 - The Sailings, Volume I.

Traverse sailing combines plane sailings with two or more courses, computing course and distance along a series of rhumb lines. See Chapter 12 - The Sailings, Volume I.

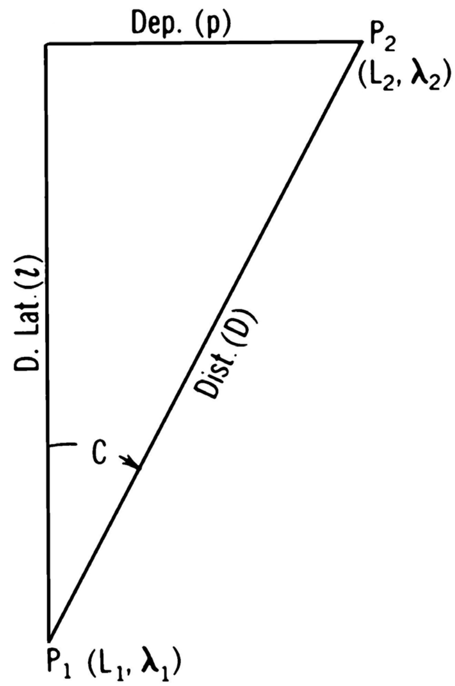


Figure B6.The plane sailing triangle.

- **Parallel sailing** consists of interconverting departure and difference of longitude. Refer to Figure B6.

$DLo = p \sec L$, and $p = DLo \cos L$

- **Mid-latitude sailing** combines plane and parallel sailing, with certain assumptions. The mean latitude (Lm) is half of the arithmetical sum of the latitudes of two places on the same side of the equator. For places on opposite sides of the equator, the N and S portions are solved separately.

In mid-latitude sailing:

$DLo = p \sec Lm$, and $p = DLo \cos Lm$

- **Mercator Sailing** problems are solved graphically on a Mercator chart. For mathematical Mercator solutions the formulas are:

$$\tan C = \frac{DLo}{m} \text{ or } DLo = m \tan C$$

where m is the meridional part from Volume II, Table 6 in the Tables Part of this volume. Following solution of the course angle by Mercator sailing, the distance is by the plane sailing formula:

$$D = l \sec C.$$

- **Great-circle solutions for distance and initial course angle** can be calculated from the formulas:

$$D = \cos^{-1}[(\sin L_1 \sin L_2 + \cos L_1 \cos L_2 \cos DLo)],$$

and

$$C = \tan^{-1}\left(\frac{\sin DLo}{(\cos L_1 \tan L_2) - (\sin L_1 \cos DLo)}\right)$$

where D is the great-circle distance, C is the initial great-circle course angle, L_1 is the latitude of the point of departure, L_2 is the latitude of the destination, and DLo is the difference of longitude of the points of departure and destination. If the name of the latitude of the destination is contrary to that of the point of departure, it is treated as a negative quantity.

- **The latitude of the vertex**, L_v, is always numerically equal to or greater than L_1 or L_2. If the initial course angle C is less than 90°, the vertex is toward L_2, but if C is greater than 90°, the nearer vertex is in the opposite direction. The vertex nearer L_1 has the same name as L_1.

The latitude of the vertex can be calculated from the formula:

$$L_v = \cos^{-1}(\cos L_1 \sin C)$$

The difference of longitude of the vertex and the point of departure (DLo_v) can be calculated from the formula:

$$DLo_v = \sin^{-1}\left(\frac{\cos C}{\sin L_v}\right).$$

The distance from the point of departure to the vertex (D_v) can be calculated from the formula:

$$D_v = \sin^{-1}(\cos L_1 \sin DLo_v).$$

- **The latitudes of points on the great-circle track** can be determined for equal DLo intervals each side of the vertex (DLo_{vx}) using the formula:

$$L_x = \tan^{-1}(\cos DLo_{vx} \tan L_v)$$

The DLo_v and D_v of the nearer vertex are never greater than 90°. However, when L_1 and L_2 are of contrary name, the other vertex, 180° away, may be the better one to use in the solution for points on the great-circle track if it is nearer the mid point of the track.

The method of selecting the longitude (or DLo_{vx}), and determining the latitude at which the great-circle crosses the selected meridian, provides shorter legs in higher latitudes and longer legs in lower latitudes. Points at desired distances or desired equal intervals of distance on the great-circle from the vertex (D_{vx}) can be calculated using the formulas:

$$L_x = \sin^{-1}[\sin L_v \cos D_{vx}],$$

and

$$DLo_{vx} = \sin^{-1}\left(\frac{\sin D_{vx}}{\cos L_x}\right).$$

A calculator which converts rectangular to polar coordinates provides easy solutions to plane sailings. However, the user must know whether the difference of latitude corresponds to the calculator's X-coordinate or to the Y-coordinate.

B 7. Calculations of Meteorology and Oceanography

- **Converting thermometer scales** between centigrade, Fahrenheit, and Kelvin scales can be done using the following formulas:

$$C° = \frac{5(F° - 32°)}{9},$$

$$F° = \frac{9}{5}C° + 32°, \text{ and}$$

$$K° = C° + 273.15°.$$

- **Maximum length of sea waves** can be found by the formula:

$$W = 1.5\sqrt{\text{fetch in nautical miles}}.$$

- **Wave height** = $0.026\ S^2$ where S is the wind speed in knots.

- **Wave speed** in knots

$$= 1.34\sqrt{\text{wavelength in feet}}, \text{ or}$$

$$= 3.03 \quad \text{wave period in seconds}.$$

UNIT CONVERSION

Use the conversion tables that appear on the following pages to convert between different systems of units. Conversions followed by an asterisk* are exact relationships.

MISCELLANEOUS DATA

Area

1 square inch	= 6.4516 square centimeters*
1 square foot	= 144 square inches*
	= 0.09290304 square meter*
	= 0.000022957 acre
1 square yard	= 9 square feet*
	= 0.83612736 square meter
1 square (statute) mile	= 27,878,400 square feet*
	= 640 acres*
	= 2.589988110336 square kilometers*
1 square centimeter	= 0.1550003 square inch
	= 0.00107639 square foot
1 square meter	= 10.76391 square feet
	= 1.19599005 square yards
1 square kilometer	= 247.1053815 acres
	= 0.38610216 square statute mile
	= 0.29155335 square nautical mile

Astronomy

1 mean solar unit	= 1.00273791 sidereal units
1 sidereal unit	= 0.99726957 mean solar units
1 microsecond	= 0.000001 second*
1 second	= 1,000,000 microseconds*
	= 0.01666667 minute
	= 0.00027778 hour
	= 0.00001157 day
1 minute	= 60 seconds*
	= 0.01666667 hour
	= 0.00069444 day
1 hour	= 3,600 seconds*
	= 60 minutes*
	= 0.04166667 day
1 mean solar day	= $24^h03^m56^s.55536$ of mean sidereal time
	= 1 rotation of Earth with respect to Sun (mean)*
	= 1.00273791 rotations of Earth with respect to vernal equinox (mean)
	= 1.0027378118868 rotations of Earth with respect to stars (mean)
1 mean sidereal day	= $23^h56^m04^s09054$ of mean solar time
1 sidereal month	= 27.321661 days
	= $27^d07^h43^m11^s.5$
1 synodical month	= 29.530588 days
	= $29^d12^h44^m02^s.8$
1 tropical (ordinary) year	= 31,556,925.975 seconds
	= 525,948.766 minutes
	= 8,765.8128 hours
	= $365^d.24219879 - 0^d.0000000614(t-1900)$, where t = the year (date)
	= $365^d05^h48^m46^s$ (–) $0^s.0053(t-1900)$
1 sidereal year	= $365^d.25636042 + 0.0000000011(t-1900)$, where t = the year (date)

	= $365^{d}06^{h}09^{m}09^{s}.5$ (+) $0^{s}.0001$(t–1900)
1 calendar year (common)	= 31,536,000 seconds*
	= 525,600 minutes*
	= 8,760 hours*
	= 365 days*
1 calendar year (leap)	= 31,622,400 seconds*
	= 527,040 minutes*
	= 8,784 hours*
	= 366 days
1 light-year	= 9,460,000,000,000 kilometers
	= 5,880,000,000,000 statute miles
	= 5,110,000,000,000 nautical miles
	= 63,240 astronomical units
	= 0.3066 parsecs
1 parsec	= 30,860,000,000,000 kilometers
	= 19,170,000,000,000 statute miles
	= 16,660,000,000,000 nautical miles
	= 206,300 astronomical units
	= 3.262 light years
1 astronomical unit	= 149,600,000 kilometers
	= 92,960,000 statute miles
	= 80,780,000 nautical miles
	= $499^{s}.012$ light-time
	= mean distance, Earth to Sun
Mean distance, Earth to Moon	= 384,400 kilometers
	= 238,855 statute miles
	= 207,559 nautical miles
Mean distance, Earth to Sun	= 149,600,000 kilometers
	= 92,957,000 statute miles
	= 80,780,000 nautical miles
	= 1 astronomical unit
Sun's diameter	= 1,392,000 kilometers
	= 865,000 statute miles
	= 752,000 nautical miles
Sun's mass	= 1,987,000,000,000,000,000,000,000,000,000,000 grams
	= 2,200,000,000,000,000,000,000,000,000 short tons
	= 2,000,000,000,000,000,000,000,000,000 long tons
Speed of Sun relative to neighboring stars	= 19.4 kilometers per second
	= 12.1 statute miles per second
	= 10.5 nautical miles per second
Orbital speed of Earth	= 29.8 kilometers per second
	= 18.5 statute miles per second
	= 16.1 nautical miles per second
Obliquity of the ecliptic	= $23°27'08''.26 - 0''.4684$ (t–1900), where t = the year (date)
General precession of the equinoxes	= $50''.2564 + 0''.000222$ (t–1900), per year, where t = the year (date)
Precession of the equinoxes in right ascension	= $46''.0850 + 0''.000279$ (t–1900), per year, where t = the year (date)
Precession of the equinoxes in declination	= $20''.0468 - 0''.000085$ (t–1900), per year, where t = the year (date)
Magnitude ratio	= 2.512
	= $\sqrt[5]{100}$*

Charts

Nautical miles per inch	= reciprocal of natural scale 72,913.39
Statute miles per inch	= reciprocal of natural scale 63,360*
Inches per nautical mile	= 72,913.39 natural scale
Inches per statute mile	= 63,360 natural scale*
Natural scale	= 1:72,913.39 nautical miles per inch

	= 1:63,360 statute miles per inch*

Earth

Acceleration due to gravity (standard)	= 980.665 centimeters per second per second
	= 32.1740 feet per second per second
Mass-ratio—Sun/Earth	= 332,958
Mass-ratio—Sun/(Earth & Moon)	= 328,912
Mass-ratio—Earth/Moon	= 81.30
Mean density	= 5.517 grams per cubic centimeter
Velocity of escape	= 6.94 statute miles per second
Curvature of surface	= 0.8 foot per nautical mile

World Geodetic System (WGS) Ellipsoid of 1984

Equatorial radius (a)	= 6,378,137 meters
	= 3,443.918 nautical miles
Polar radius (b)	= 6,356,752.314 meters
	= 3432.372 nautical miles
Mean radius (2a + b)/3	= 6,371,008.770 meters
	= 3440.069 nautical miles
Flattening or ellipticity (f = 1 – b/a)	= 1/298.257223563
	= 0.003352811
Eccentricity ($e = (2f - f^2)^{1/2}$)	= 0.081819191
Eccentricity squared (e^2)	= 0.006694380

Length

1 inch	= 25.4 millimeters*
	= 2.54 centimeters*
1 foot (U.S.)	= 12 inches*
	= 1 British foot
	= $^1/_3$ yard*
	= 0.3048 meter*
	= $^1/_6$ fathom*
1 foot (U.S. Survey)	= 0.30480061 meter
1 yard	= 36 inches*
	= 3 feet*
	= 0.9144 meter*
1 fathom	= 6 feet*
	= 2 yards*
	= 1.8288 meters*
1 cable	= 720 feet*
	= 240 yards*
	= 219.4560 meters*
1 cable (British)	= 0.1 nautical mile
1 statute mile	= 5,280 feet*
	= 1,760 yards*
	= 1,609.344 meters*
	= 1.609344 kilometers*
	= 0.86897624 nautical mile
1 nautical mile	= 6,076.11548556 feet
	= 2,025.37182852 yards
	= 1,852 meters*
	= 1.852 kilometers*
	= 1.150779448 statute miles
1 meter	= 100 centimeters*
	= 39.370079 inches
	= 3.28083990 feet
	= 1.09361330 yards
	= 0.54680665 fathom

	= 0.00062137 statute mile
	= 0.00053996 nautical mile
1 kilometer	= 3,280.83990 feet
	= 1,093.61330 yards
	= 1,000 meters*
	= 0.62137119 statute mile
	= 0.53995680 nautical mile

Mass

1 ounce	= 437.5 grains*
	= 28.349523125 grams*
	= 0.0625 pound*
	= 0.028349523125 kilogram*
1 pound	= 7,000 grains*
	= 16 ounces*
	= 0.45359237 kilogram*
1 short ton	= 2,000 pounds*
	= 907.18474 kilograms*
	= 0.90718474 metric ton*
	= 0.8928571 long ton
1 long ton	= 2,240 pounds*
	= 1,016.0469088 kilograms*
	= 1.12 short tons*
	= 1.0160469088 metric tons*
1 kilogram	= 2.204623 pounds
	= 0.00110231 short ton
	= 0.0009842065 long ton
1 metric ton	= 2,204.623 pounds
	= 1,000 kilograms*
	= 1.102311 short tons
	= 0.9842065 long ton

Mathematics

π	= 3.1415926535897932384626433832795028841971
π^2	= 9.8696044011
$\sqrt{\pi}$	= 1.7724538509
Base of Naperian logarithms (e)	= 2.718281828459
Modulus of common logarithms ($\log_{10}e$)	= 0.4342944819032518
1 radian	= 206,264.″80625
	= 3,437′.7467707849
	= 57°.2957795131
	= 57°17′44″.80625
1 circle	= 1,296,000″*
	= 21,600′*
	= 360°*
	= 2π radians*
180°	= π radians*
1°	= 3600″*
	= 60′*
	= 0.0174532925199432957666 radian
1′	= 60″*
	= 0.000290888208665721596 radian
1″	= 0.0000048481368110953599 33 radian
Sine of 1′	= 0.000290888204563424 60
Sine of 1″	= 0.0000048481368110763 7

Meteorology

Atmosphere (dry air)

Nitrogen	= 78.08%	99.99%
Oxygen	= 20.95%	
Argon	= 0.93%	
Carbon dioxide	= 0.03%	

Neon	= 0.0018%
Helium	= 0.000524%
Krypton	= 0.0001%
Hydrogen	= 0.00005%
Xenon	= 0.0000087%
Ozone	= 0 to 0.000007% (increasing with altitude)
Radon	= 0.000000000000000006% (decreasing with altitude)
Standard atmospheric pressure at sea level	= 1,013.250 dynes per square centimeter
	= 1,033.227 grams per square centimeter
	= 1,033.227 centimeters of water
	= 1,013.250 hectopascals (millibars)*
	= 760 millimeters of mercury
	= 76 centimeters of mercury
	= 33.8985 feet of water
	= 29.92126 inches of mercury
	= 14.6960 pounds per square inch
	= 1.033227 kilograms per square centimeter
	= 1.013250 bars*
Absolute zero	= (–)273.16°C
	= (–)459.69°F

Pressure

1 dyne per square centimeter	= 0.001 hectopascal (millibar)*
	= 0.000001 bar*
1 gram per square centimeter	= 1 centimeter of water
	= 0.980665 hectopascal (millibar)*
	= 0.07355592 centimeter of mercury
	= 0.0289590 inch of mercury
	= 0.0142233 pound per square inch
	= 0.001 kilogram per square centimeter*
	= 0.000967841 atmosphere
1 hectopascal (millibar)	= 1,000 dynes per square centimeter*
	= 1.01971621 grams per square centimeter
	= 0.7500617 millimeter of mercury
	= 0.03345526 foot of water
	= 0.02952998 inch of mercury
	= 0.01450377 pound per square inch
	= 0.001 bar*
	= 0.00098692 atmosphere
1 millimeter of mercury	= 1.35951 grams per square centimeter
	= 1.3332237 hectopascals (millibars)
	= 0.1 centimeter of mercury*
	= 0.04460334 foot of water
	= 0.039370079 inch of mercury
	= 0.01933677 pound per square inch
	= 0.001315790 atmosphere
1 centimeter of mercury	= 10 millimeters of mercury*
1 inch of mercury	= 34.53155 grams per square centimeter
	= 33.86389 hectopascals (millibars)
	= 25.4 millimeters of mercury*
	= 1.132925 feet of water
	= 0.4911541 pound per square inch
	= 0.03342106 atmosphere
1 centimeter of water	= 1 gram per square centimeter
	= 0.001 kilogram per square centimeter
1 foot of water	= 30.48000 grams per square centimeter
	= 29.89067 hectopascals (millibars)
	= 2.241985 centimeters of mercury
	= 0.882671 inch of mercury
	= 0.4335275 pound per square inch
	= 0.02949980 atmosphere
1 pound per square inch	= 68,947.57 dynes per square centimeter
	= 70.30696 grams per square centimeter
	= 70.30696 centimeters of water
	= 68.94757 hectopascals (millibars)
	= 51.71493 millimeters of mercury
	= 5.171493 centimeters of mercury

= 2.306659 feet of water
= 2.036021 inches of mercury
= 0.07030696 kilogram per square centimeter
= 0.06894757 bar
= 0.06804596 atmosphere

1 kilogram per square centimeter _ _ _ _ _ _ = 1,000 grams per square centimeter*
= 1,000 centimeters of water

1 bar _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ = 1,000,000 dynes per square centimeter*
= 1,000 hectopascals (millibars)*

Speed

1 foot per minute _ _ _ _ _ _ _ _ _ _ _ _ = 0.01666667 foot per second
= 0.00508 meter per second*

1 yard per minute _ _ _ _ _ _ _ _ _ _ _ _ = 3 feet per minute*
= 0.05 foot per second*
= 0.03409091 statute mile per hour
= 0.02962419 knot
= 0.01524 meter per second*

1 foot per second _ _ _ _ _ _ _ _ _ _ _ _ = 60 feet per minute*
= 20 yards per minute*
= 1.09728 kilometers per hour*
= 0.68181818 statute mile per hour
= 0.59248380 knot
= 0.3048 meter per second*

1 statute mile per hour _ _ _ _ _ _ _ _ _ _ = 88 feet per minute*
= 29.33333333 yards per minute
= 1.609344 kilometers per hour*
= 1.46666667 feet per second
= 0.86897624 knot
= 0.44704 meter per second*

1 knot_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ = 101.26859143 feet per minute
= 33.75619714 yards per minute
= 1.852 kilometers per hour*
= 1.68780986 feet per second
= 1.15077945 statute miles per hour
= 0.51444444 meter per second

1 kilometer per hour _ _ _ _ _ _ _ _ _ _ _ = 0.62137119 statute mile per hour
= 0.53995680 knot

1 meter per second_ _ _ _ _ _ _ _ _ _ _ _ = 196.85039340 feet per minute
= 65.6167978 yards per minute
= 3.6 kilometers per hour*
= 3.28083990 feet per second
= 2.23693632 statute miles per hour
= 1.94384449 knots

Light in vacuum_ _ _ _ _ _ _ _ _ _ _ _ _ = 299,792.5 kilometers per second
= 186,282 statute miles per second
= 161,875 nautical miles per second
= 983.570 feet per microsecond

Light in air_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ = 299,708 kilometers per second
= 186,230 statute miles per second
= 161,829 nautical miles per second
= 983.294 feet per microsecond

Sound in dry air at 59°F or 15°C
and standard sea level pressure _ _ _ _ _ = 1,116.45 feet per second
= 761.22 statute miles per hour
= 661.48 knots
= 340.29 meters per second

Sound in 3.485 percent saltwater at 60°F _ _ _ = 4,945.37 feet per second
= 3,371.85 statute miles per hour
= 2,930.05 knots
= 1,507.35 meters per second

Volume

1 cubic inch	= 16.387064 cubic centimeters*
	= 0.016387064 liter*
	= 0.004329004 gallon
1 cubic foot	= 1,728 cubic inches*
	= 28.316846592 liters*
	= 7.480519 U.S. gallons
	= 6.228822 imperial (British) gallons
	= 0.028316846592 cubic meter*
1 cubic yard	= 46,656 cubic inches*
	= 764.554857984 liters*
	= 201.974026 U.S. gallons
	= 168.1782 imperial (British) gallons
	= 27 cubic feet*
	= 0.764554857984 cubic meter*
1 milliliter	= 0.06102374 cubic inch
	= 0.0002641721 U.S. gallon
	= 0.00021997 imperial (British) gallon
1 cubic meter	= 264.172035 U.S. gallons
	= 219.96878 imperial (British) gallons
	= 35.31467 cubic feet
	= 1.307951 cubic yards
1 quart (U.S.)	= 57.75 cubic inches*
	= 32 fluid ounces*
	= 2 pints*
	= 0.9463529 liter
	= 0.25 gallon*
1 gallon (U.S.)	= 3,785.412 milliliters
	= 231 cubic inches*
	= 0.1336806 cubic foot
	= 4 quarts*
	= 3.785412 liters
	= 0.8326725 imperial (British) gallon
1 liter	= 1,000 milliliters
	= 61.02374 cubic inches
	= 1.056688 quarts
	= 0.2641721 gallon
1 register ton	= 100 cubic feet*
	= 2.8316846592 cubic meters*
1 measurement ton	= 40 cubic feet*
	= 1 freight ton*
1 freight ton	= 40 cubic feet*
	= 1 measurement ton*

Volume-Mass

1 cubic foot of seawater	= 64 pounds
1 cubic foot of freshwater	= 62.428 pounds at temperature of maximum density (4°C = 39.2°F)
1 cubic foot of ice	= 56 pounds
1 displacement ton	= 35 cubic feet of seawater*
	= 1 long ton

Prefixes to Form Decimal Multiples and Sub-Multiples of International System of Units (SI)

Multiplying factor		Prefix	Symbol
1 000 000 000 000	$= 10^{12}$	tera	T
1 000 000 000	$= 10^{9}$	giga	G
1 000 000	$= 10^{6}$	mega	M
1 000	$= 10^{3}$	kilo	k
100	$= 10^{2}$	hecto	h
10	$= 10^{1}$	deka	da
0. 1	$= 10^{-1}$	deci	d
0. 01	$= 10^{-2}$	centi	c
0. 001	$= 10^{-3}$	milli	m
0. 000 001	$= 10^{-6}$	micro	μ
0. 000 000 001	$= 10^{-9}$	nano	n
0. 000 000 000 001	$= 10^{-12}$	pico	p
0. 000 000 000 000 001	$= 10^{-15}$	femto	f
0. 000 000 000 000 000 001	$= 10^{-18}$	atto	a

NGA MARITIME SAFETY INFORMATION NAUTICAL CALCULATORS

NGA's Maritime Safety Office website offers a variety of online Nautical Calculators for public use. These calculators solve many of the equations and conversions typically associated with marine navigation. See the link provided below.

Link to NGA Nautical Calculators. https://msi.nga.mil/Calc

List of NGA Maritime Safety information Nautical Calculators https://msi.nga.mil

Celestial Navigation Calculators
Compass Error from Amplitudes Observed on the Visible Horizon
Altitude Correction for Air Temperature
Table of Offsets
Latitude and Longitude Factors
Altitude Corrections for Atmospheric Pressure
Altitude Factors & Change of Altitude
Pub 229

List of NGA Maritime Safety information Nautical Calculators https://msi.nga.mil

Compass Error from Amplitudes observed on the Celestial Horizon
Conversion Calculators
Chart Scales and Conversions for Nautical and Statute Miles
Conversions for Meters, Feet and Fathoms
Distance Calculators
Length of a Degree of Latitude and Longitude
Speed for Measured Mile and Speed, Time and Distance
Distance of an Object by Two Bearings
Distance of the Horizon
Distance by Vertical Angle Measured Between Sea Horizon and Top of Object Beyond Sea Horizon
Traverse Table
Geographic Range
Distance by Vertical Angle Measured Between Waterline at Object and Top of Object
Dip of Sea Short of the Horizon
Distance by Vertical Angle Measured Between Waterline at Object and Sea Horizon Beyond Object
Meridional Parts
Log and Trig Calculators
Logarithmic and Trigonometric Functions
Sailings Calculators
Great Circle Sailing
Mercator NGA Sailing
Time Zones Calculators
Time Zones, Zone Descriptions and Suffixes
Weather Data Calculators
Direction and Speed of True Wind
Correction of Barometer Reading for Height Above Sea Level
Correction of Barometer Reading for Gravity
Temperature Conversions
Relative Humidity and Dew Point
Corrections of Barometer Reading for Temperature
Barometer Measurement Conversions

APPENDIX C

SATELLITE NAVIGATION SIGNAL CODING

GPS SIGNAL CODING

C 1. The GPS L1 Band

The GPS L1 band (1575.42 MHz) has turned out to be the most important band for navigation purposes. Indeed most of the applications in the world nowadays are based on the signals transmitted at this frequency. Three signals are transmitted at the moment by GPS in L1: C/A Code, P(Y) Code and M-Code. In the future, an additional new civil signal, known as L1C, will also be transmitted. We describe all of them in the next lines:

- The Coarse/Acquisition (C/A) code signal was primarily thought of for acquisition of the P (or Y) code and has become nowadays the most important signal for mass market applications.
- The P Code is the precision signal and is coded by the precision code. Moreover the Y-Code is used in place of the P-code whenever the Anti-Spoofing (A/S) mode of operation is activated as described in the GPS ICDs 203, 224 and 225.
- The modernized military signal (M-Code) is designed exclusively for military use and is intended to eventually replace the P(Y) code [E. D. Kaplan and C. Hegarty, 2006]. The M-Code provides better jamming resistance than the P(Y) signal, primarily through enabling transmission at much higher power without interference with C/A code or P(Y) code receivers [B.C. Barker et al., 2000]. Moreover, the M-Code provides more robust signal acquisition than is achieved today, while offering better security in terms of exclusivity, authentication, and confidentiality, along with streamlined key distribution. In other aspects, the M-Code signal provides much better performance than the P(Y) Code and more flexibility.
- The L1 Civil signal (L1C), defined in the [GPS ICD-800], consists of two main components; one denoted $L1C_P$ to represent the pilot signal, consisting of a time-multiplexing of Binary Offset Carrier BOC(1,1) and BOC(6,1), thus without any data message, and $L1C_D$ with a pure BOC(1,1), for the data channel. This is spread by a ranging code and modulated by a data message. The pilot channel $L1C_P$ is also modulated by an SV unique overlay secondary code, $L1C_O$.

GNSS System	GPS	GPS		GPS	GPS
Service Name	C/A	L1C		P(Y) Code	M-Code
Center Frequency	1575.42 MHz	1575.42 MHz		1575.42 MHz	1575.42 MHz
Frequency Band	L1	L1		L1	L1
Access Technique	CDMA	CDMA		CDMA	CDMA
Signal Component	Data	Data	Pilot	Data	N/A
Modulation	BPSK(1)	TMBOC(6,1,1/11)		BPSK(10)	$BOC_{sin}(10,5)$
Sub-carrier Frequency [MHz]	-	1.023	1.023 & 6.138	-	10.23
Code Frequency	1.023 MHz	1.023 MHz		10.23 MHz	5.115 MHz
Primary PRN Code Length	1023	10230		6.19×10^{12}	N/A
Code Family	Gold Codes	Weil Codes		Combo and short cycling of M-sequences	N/A
Secondary PRN Code Length	-	-	1800	-	N/A
Data Rate	50 bps/ 50 sps	50 bps/ 100 sps	-	50 bps/ 50 sps	N/A
Minimum Received Power [dBW]	-158.5	-157		-161.5	N/A
Elevation	5°	5°		5°	5°

Table 1. GPS L1 signal technical characteristics.

For more details on the code generation refer to the [GPS ICD 200] and [GPS ICD-800]. Finally, the technical characteristics of the existing and planned GPS signals in the L1 band are summarized in the following Table 1.

Of all the signals shown in Table 1, the C/A Code is the best known as most of the receivers that have been built until today are based on it. The C/A Code was open from the very beginning to all users, although until May 1, 2000, an artificial degradation was introduced by means of the **Select Availability** (**SA**) mechanism which added an intentional distortion to degrade the positioning quality of the signal to non-desired users. As we have already mentioned, the C/A Code was thought to be an aid for the P(Y) Code (to realize a Coarse Acquisition). The M-Code is the last military signal that has been introduced in GPS.

For a long time different signal structures for the M-Code were under consideration [J.W. Betz, 2001] being the Manchester code signals - **Binary Phase Shift Keying** (**BPSK**) and the **binary offset carrier** (**BOC**) signals the two favored candidates. Both solutions result from the modulation of a non-return to zero (NRZ) pseudo random noise spreading code by a square-wave sub-carrier. While the Manchester code has a spreading code of rate equal to that of the square-wave, the BOC signal does not necessarily have to be so, being the only constraint that the rate of the spreading code must be less than the sub-carrier frequency.

The interesting aspect about these signals is that, like the conventional sub-carrier modulation, the waveform presents a zero at the carrier frequency due to the square-wave sub-carrier. In fact, their split-power spectra clearly facilitate the compatibility of the GPS military M-Code signal with the existing C/A Code and P(Y) Code. See Figure 1 - *Spectra of GPS signals in L1*.

We can clearly recognize that GPS L1C concentrates more power at higher frequencies - due to BOC(6,1) - in the pilot channel than in the data channel.

Finally, it is important to note that for all the figures next the commonly used expressions for bandwidths in MHz must be understood as multiplied by the factor 1.023. Thus BPSK(10) refers in reality to a BPSK signal with a chip rate of 10.23 MHz. This remains valid for all the bandwidths in this thesis, unless different stated otherwise

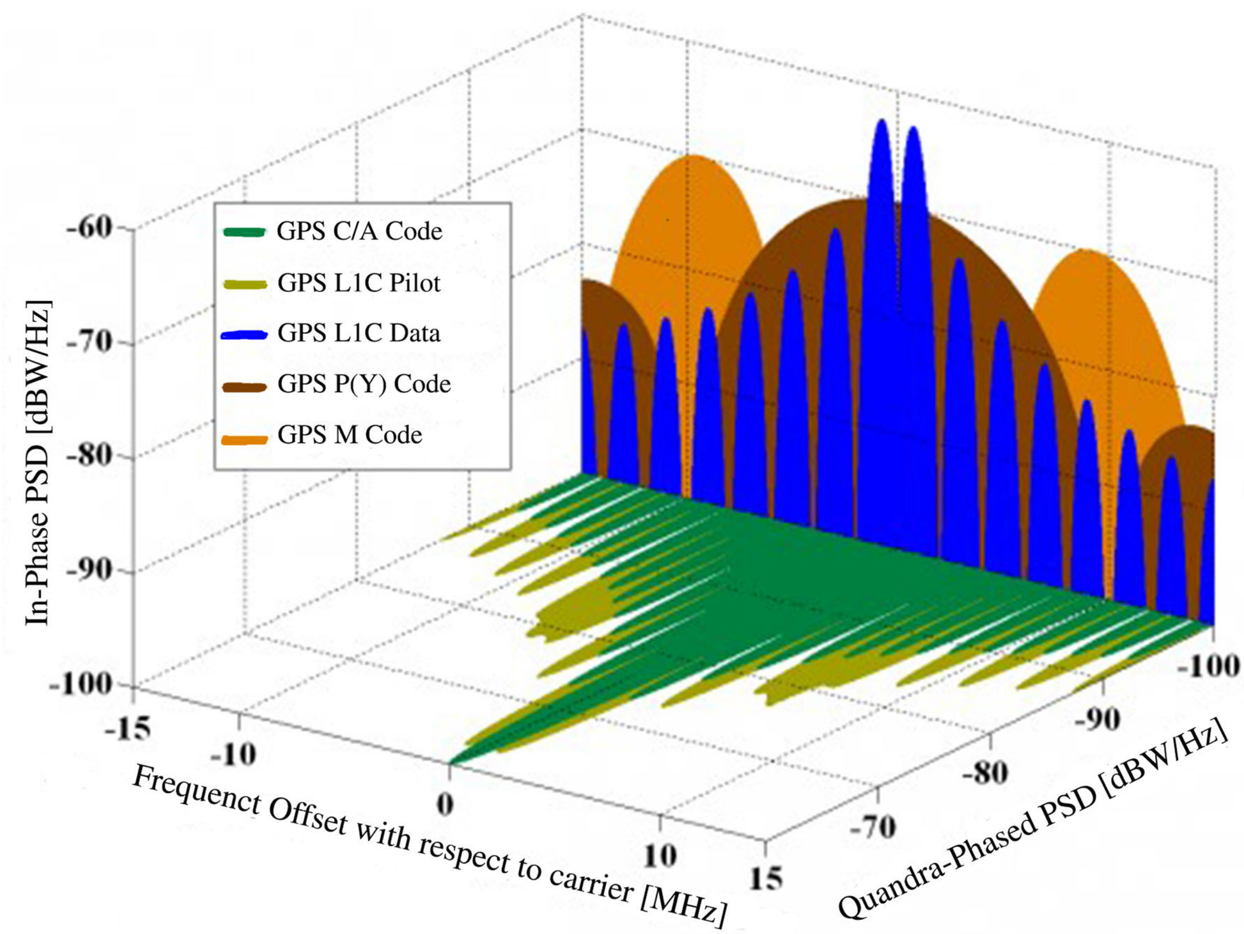


Figure 1. Spectra of GPS signals in L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

C 2. The GPS L2 Band

GPS is transmitting in the L2 band (1227.60 MHz) a modernized civil signal known as L2C together with the P(Y) Code and the M-Code. The P(Y) Code and M-Code were already described shortly in the previous chapter and the properties and parameters are thus similar to those in the L1 band. In addition, for Block IIR-M, IIF, and subsequent blocks of SVs, two additional PRN ranging codes will be transmitted. They are the L2 Civil Moderate (L2 CM) code and the L2 Civil Long (L2 CL) code. These two signals are time multiplexed so that the resulting chipping rate is double as high as that of each individual signal. We further describe them in the next lines more in detail:

- L2 CM Code is transmitted in the IIR-M, IIF, and subsequent blocks. The PRN L2 CM Code for SV number i is a ranging code, $CM_i(t)$, which is 20 milliseconds in length at a chipping rate of 511.5 Kbps. The epochs of the L2 CM Code are synchronized with the X1 epochs of the P-code. The $CM_i(t)$ sequence is a linear pattern which is short cycled every count period of 10,230 chips by resetting with a particular initial state. Furthermore, for Block IIR-M, the navigation data is also Modulo-2 added to the L2 CM Code. It is interesting to note that the navigation data can be used in one of two different data rates selectable by ground command: 1) D(t) with a data rate of 50 bps, or 2) D(t) with a symbol rate of 50 symbols per second (sps) which is obtained by encoding D(t) with a data rate of 25 bps coded in a rate 1/2 convolutional code. Finally, the resultant bit-train is combined with the L2 CL Code using time-division multiplexing.
- L2 CL Code is transmitted in the IIR-M, IIF, and subsequent blocks. The PRN L2 CL Code for SV number i is a ranging code, $CL_i(t)$, which is 1.5 seconds in length at a chipping rate of 511.5 Kbps. The epochs of the L2 CL Code are synchronized with the X1 epochs of the P Code. The $CL_i(t)$ sequence is a linear pattern which is generated using the same code generator polynomial as of $CM_i(t)$. However, the $CM_i(t)$ sequence is short cycled by resetting with an initial state every count period of 767,250 chips.

Finally, it is important to note that the GPS L2 band will have a transition period from the C/A Code to L2C and mixed configurations could occur. Figure 2a shows the baseband L2 signal generation scheme. As we can recognize, although the chipping rate of the L2 CM and L2 CL signals is of 511.5 Kbps individually, after the time multiplexing the composite signal results in a stream of 1.023 MHz.

The technical characteristics of the GPS L2 signals are summarized in Table 2 and the spectra of the different signals (L2C, P(Y) Code, and M-Code) are given in Figure 2b.

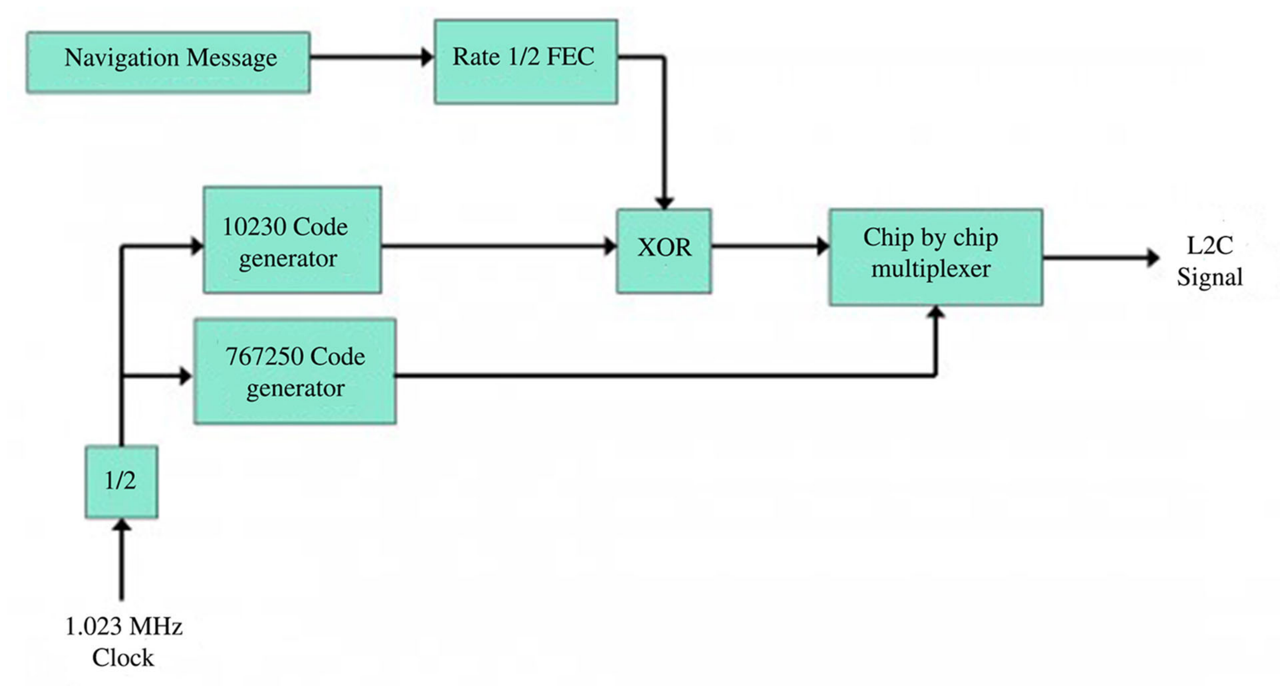


Figure 2a. Modulation scheme for the GPS L2 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	GPS	GPS	GPS	GPS
Service Name	L2 CM	L2 CL	P(Y) Code	M-Code
Center Frequency	1227.60 MHz	1227.60 MHz	1227.60 MHz	1227.60 MHz
Frequency Band	L2	L2	L2	L2
Access Technique	CDMA	CDMA	CDMA	CDMA
Spreading Modulation	BPSK(1) result of multiplexing 2 streams at 511.5 kHz		BPSK (10)	$BOC_{sin}(10,5)$
Sub-carrier Frequency [MHz]	-	-	-	10.23
Code Frequency	511.5 kHz	511.5 kHz	10.23 MHz	5.115 MHz
Signal Component	Data	Pilot	Data	N/A
Primary PRN Code Length	10,230 (20 ms)	767,250 (1.5 seconds)	6.19×10^{12}	N/A
Code Family	M-sequence from a maximal polynomial of degree 27		Combo and short cycling of M-sequences	N/A
Secondary PRN Code Length	-	-	-	N/A
Data Rate	IIF 50 bps / 50 sps IIR-M Also 25 bps 50 sps with FEC	-	50 bps/ 50 sps	N/A
Minimum Received Power [dBW]	II/IIA/IIR -164.5 dBW IIR-M -161.5 dBW IIF -161.5 dBW		II/IIA/IIR -164.5 dBW IIR-M -161.4 dBW IIF -160.0 dBW	N/A
Elevation	5°		5°	5°

Table 2. GPS L2 signal technical characteristics.

C 3. The GPS L5 Band

The GPS L5 (1176.45 MHz) signal will be transmitted for the first time on board IIF satellites. The GPS carriers of the L5 band are modulated by two bit trains in phase quadrature: the L5 data channel and the L5 pilot channel. Moreover, two PRN ranging codes are transmitted on L5: the in-phase code (denoted as the I5-code) and the quadra-phase code (denoted as the Q5-code). The PRN L5-codes for SV number i are independent, but time synchronized ranging codes, $X_I^i(t)$ and $X_Q^i(t)$, of 1 millisecond in length at a chipping rate of 10.23 Mbps [GPS ICD-705]. For each code, the 1-millisecond sequences are the modulo-2 sum of two sub-sequences referred to as XA and XBi with lengths of 8,190 chips and 8,191 chips respectively, which restart to generate the 10,230 chip code. The XBi sequence is selectively delayed, thereby allowing the basic code generation technique to produce the different satellite codes.

See Figure 3a for the modulation scheme for the GPS L5 signals. See Figure 3b for the spectra of the GPS signals in L5. For more detail on L5, refer to (E.D. Kaplan and C. Hegarty, 2006). See Figure 3c for the technical characteristics of the GPS signal in L5.

THE GALILEO SIGNAL PLAN

C 4. Galileo E1 Open Service Band

The E1 Open Service (OS) modulation receives the name of CBOC (Composite Binary Offset Carrier) and is a

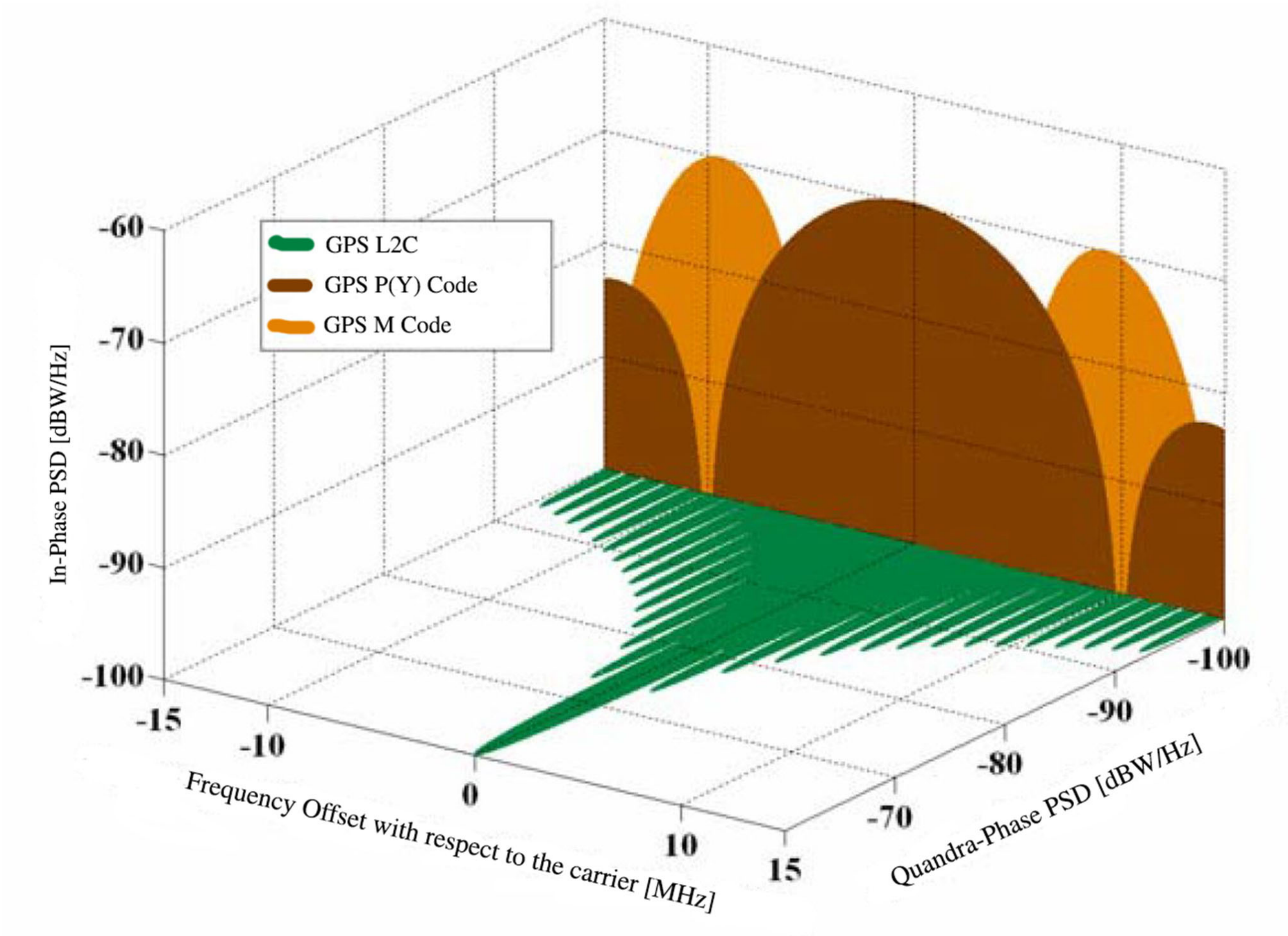


Figure 2b. Spectra of the GPS signals in L2. Image courtesy of Dr. Jose Angel Avila Rodriguez.

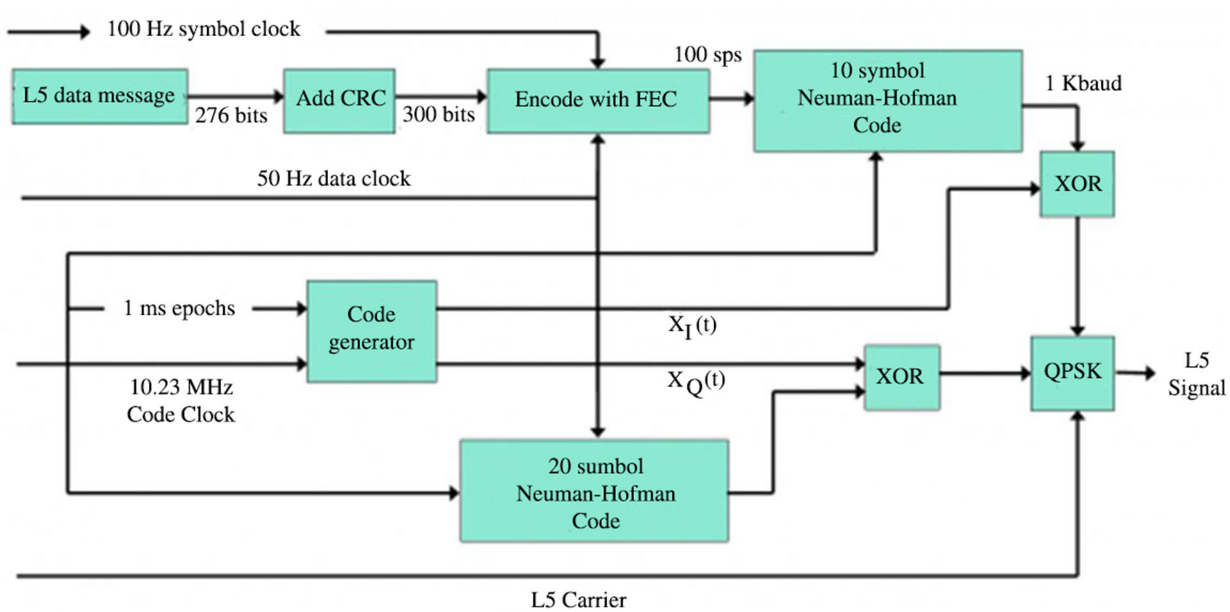


Figure 3a. Modulation scheme for the GPS L5 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

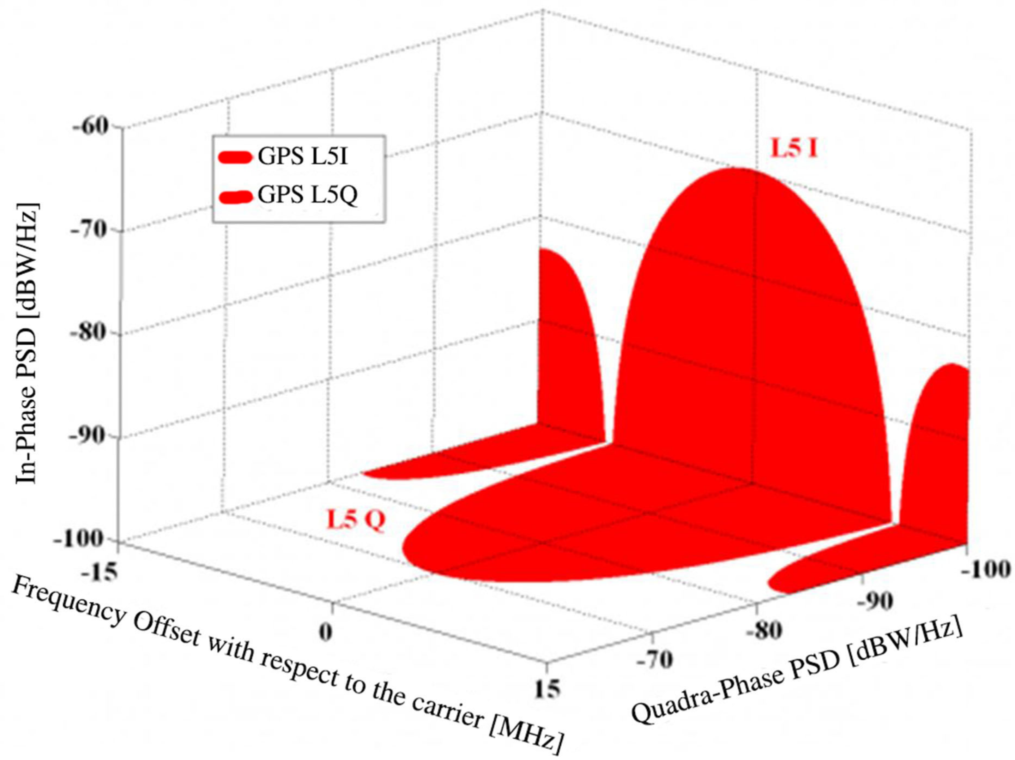


Figure 3b. Spectra of the GPS signals in L5.Image courtesy of Dr. Jose Angel Avila Rodriguez.

particular implementation of MBOC (Multiplexed BOC) [J.-A. Avila-Rodriguez et al., 2007]. MBOC(6,1,1/11) is the result of multiplexing a wide band signal - BOC(6,1) - with a narrow band signal - BOC(1,1) - in such a way that 1/11 of the power is allocated, in average, to the high frequency component. This signal was the last one to be defined.

The normalized (unit power) power spectral density, specified without the effect of band-limiting filters and payload imperfections, is given by $G_{MBOC(6,1,1/11)}(f) = \frac{10}{11}G_{BOC(1,1)}(f) + \frac{1}{11}G_{BOC(6,1)}(f)$.

As in [Galileo SIS ICD, 2010], the generic view of the E1 Open Service signal generation can be depicted as follows [J.-A. Avila-Rodriguez et al., 2007] in Figure 4a - *Modulation Scheme for Galileo E1 OS Signals.*

The whole transmitted Galileo E1 signal consists of the multiplexing of the three following components:

- The E1 Open Service Data channel $e_{E1-B}(t)$ is generated from the I/NAV navigation data stream $D_{E1-B}(t)$ and the ranging code $C_{E1-B}(t)$, which are then modulated with the sub-carriers $SC_{E1-BOC(1,1)}(t)$ and $SC_{E1-BOC(6,1)}(t)$ of BOC(1,1) and BOC(6,1) respectively.
- The E1 Open Service Pilot channel $e_{E1-C}(t)$ is generated from the ranging code $C_{E1-C}(t)$, including its secondary code, which is then modulated with the sub-carriers $SC_{E1-BOC(1,1)}(t)$ and $SC_{E1-BOC(6,1)}(t)$ in anti-phase.
- The E1 PRS channel, also denoted as E1-A, which results from the modulo-two addition (respectively product if we consider the physical bipolar representation of the signal) of the PRS data stream $D_{PRS}(t)$, the PRS sequence $C_{PRS}(t)$ and the sub-carriers $SC_{PRS}(t)$. This sub-carrier consists of a BOC(15,2.5) in cosine phasing.

See Figure 4b for the *Spectra of Galileo Signals in E1* and Figure 4c for the *Spectra of both GPS and Galileo Signals in L1*.

It is important to recall that for a long time the actual E1 band received the name of L1 band in analogy with GPS and it was not until the publication of the [Galileo SIS ICD, 2008] that L1 changed to the current E1.

The E1 Open Service (OS) codes are, as well as the E6 CS codes that we will see later, also random memory codes. The plain number of choices to set the 0's and 1's for the whole code family is enormous and thus special algorithms have to be applied to generate random codes efficiently [J.-A. Avila-Rodriguez et al., 2007].

Finally, the technical characteristics of all the Galileo signals in E1 are summarized in Table 4.

GNSS System	GPS	GPS
Service Name	L5I	L5Q
Center Frequency	1176.45 MHz	1176.45 MHz
Frequency Band	L5	L5
Access Technique	CDMA	CDMA
Spreading Modulation	BPSK(10)	BPSK(10)
Sub-carrier Frequency [MHz]	-	-
Code Frequency	10.23 MHz	10.23 MHz
Signal Component	Data	Pilot
Primary PRN Code Length	10,230	10230
Code Family	Combination and short-cycling of M sequences	
Secondary PRN Code Length	10	20
Data Rate	50 bps / 100 sps	-
Minimum Received Power [dBW]	-157.9 dBW	-157.9 dBW
Elevation	5°	5°

Figure 3c. GPS L5 signal technical characteristics.

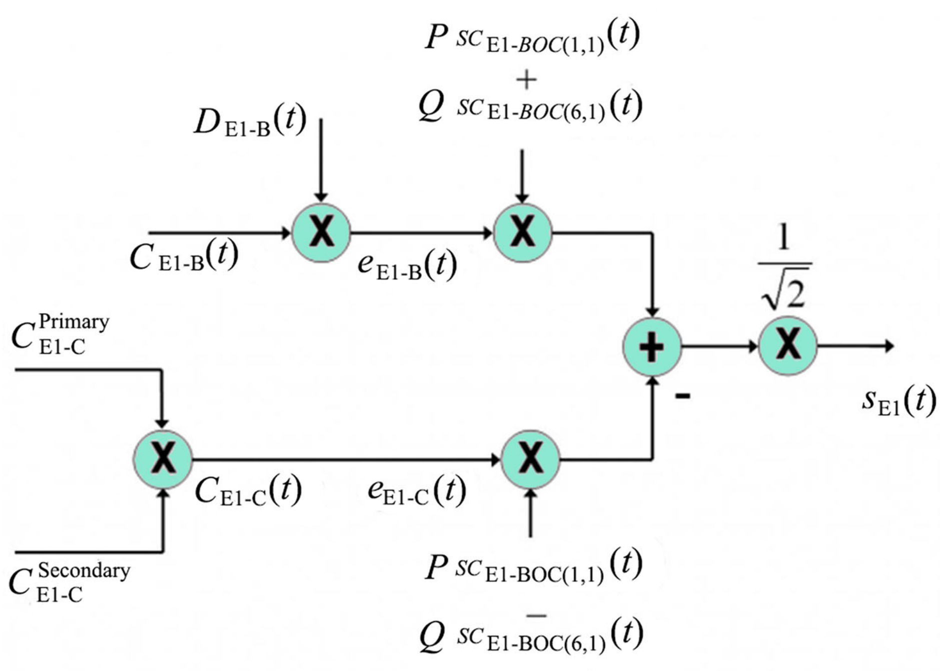


Figure 4a. Modulation scheme for Galileo E1 OS signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	Galileo	Galileo	Galileo
Service Name	E1 OS		PRS
Center Frequency	1575.42 MHz		
Frequency Band	E1		
Access Technique	CDMA		
Spreading modulation	CBOC(6.1.1/11)		BOC_{cos}(15,2.5)
Sub-carrier Frequency	1.023 MHz and 6.138 MHz (two-sub-carriers)		15.345 MHz
Code Frequency	1.023 MHz		2.5575 MHz
Signal Component	Data	Pilot	Data
Primary PRN Code Length	4092		N/A
Code Family	Random codes		N/A
Secondary PRN Code Length	-	25	N/A
Data Rate	250 sps	-	N/A
Minimum Received Power [dBW]	-157 dBW		N/A
Elevation	10°		N/A

Table 4. Galileo E1 signal technical characteristics.

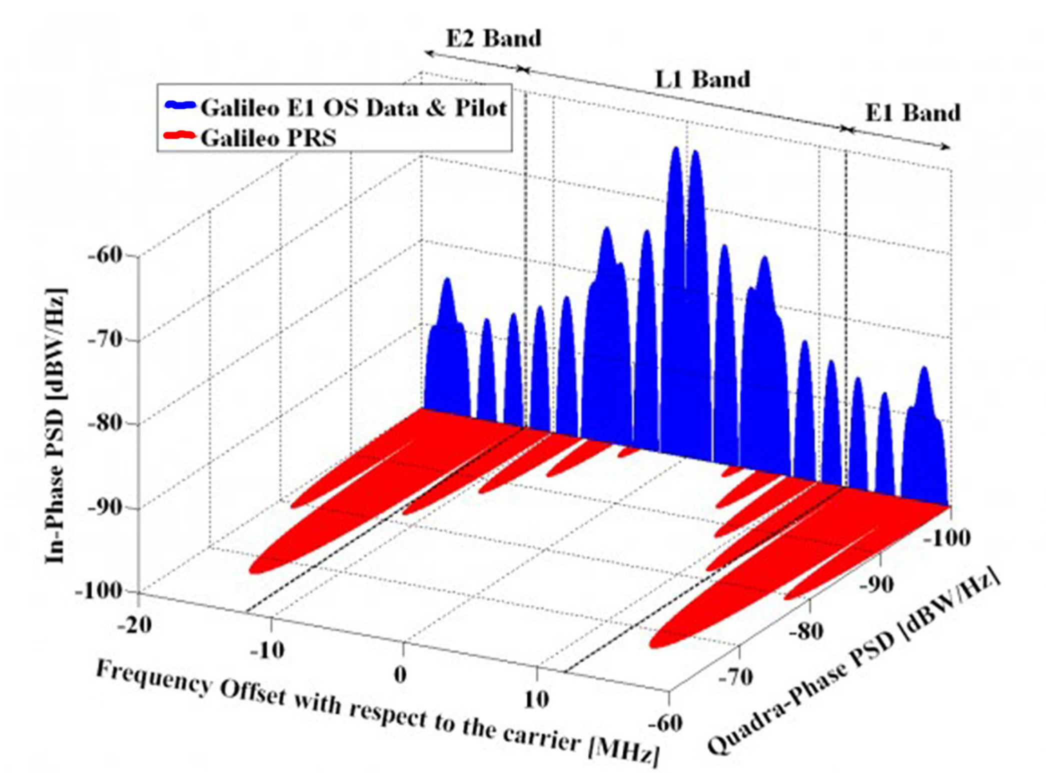


Figure 4b. Spectra of Galileo signals in E1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

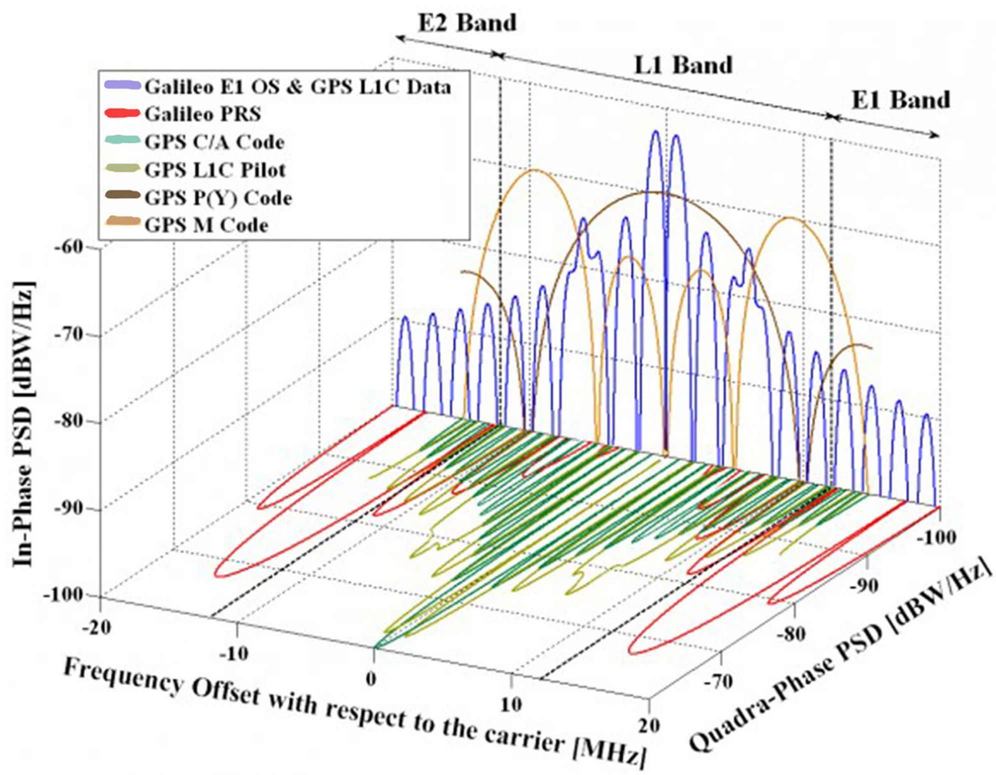


Figure 4c. Spectra of GPS and Galileo signals in L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

C 5. Galileo E6 Band

As shown in [Galileo SIS ICD, 2010], the transmitted Galileo E6 signal consists of the following three components:

- The E6 Commercial Service (CS) data channel: this modulating signal is the modulo-two addition of the E6 CS navigation data stream $D_{CS}(t)$ with the CS data channel code sequence $D_{CS}^{D}(t)$. This last one is already modulated by a BPSK(5) at 5.115 MHz.
- The E6 Commercial Service (CS) pilot channel: this modulating signal is the modulo-two addition of the E6 CS pilot channel code $C_{CS}^{P}(t)$ with a BPSK(5) at 5.115 MHz.
- Finally, the E6 PRS channel is the modulo-two addition of the E6 PRS navigation data stream $D_{PRS}(t)$ with the PRS channel code sequence $C_{PRS}(t)$ at 5.115 MHz. This signal is further modulated by a sub-carrier of 10.23 MHz in cosine phasing.

This is graphically shown in Figure 5a - *Modulation Scheme for the Galileo E6 Signals* and Figure 5b - *Spectra of Galileo signals in E6*. Table 5 provides the technical characteristics of the Galileo E6 signal.

The E6 Commercial Service (CS) codes are random codes [J. Winkel, 2006]. The main idea behind is to generate a family of codes that fulfills the properties of randomness as well as possible [J.-A. Avila-Rodriguez et al., 2007]. The codes can be driven to fulfill special properties such as balance and weakened balance, where the probability of 0's and 1's must not be identical but within a well-defined range, or to realize the autocorrelation side-lobe zero (ASZ) property. This latter property guarantees that the autocorrelation values of every code correlate to zero with a delayed version of itself, shifted by one chip.

C 6. Galileo E5 Band

The different Galileo E5 signal components are generated according to the following [Galileo SIS ICD, 2010]:

- The **E5a data channel**: This channel is the modulo-two addition of the E5a navigation data stream $D_{E5a}(t)$ with the E5a data channel PRN code sequence $C_{E5a}^{D}(t)$ of chipping rate 10.23 MHz.
- The **E5a pilot channel**: This channel is the E5a pilot channel PRN code sequence $C_{E5a}^{P}(t)$ of chipping

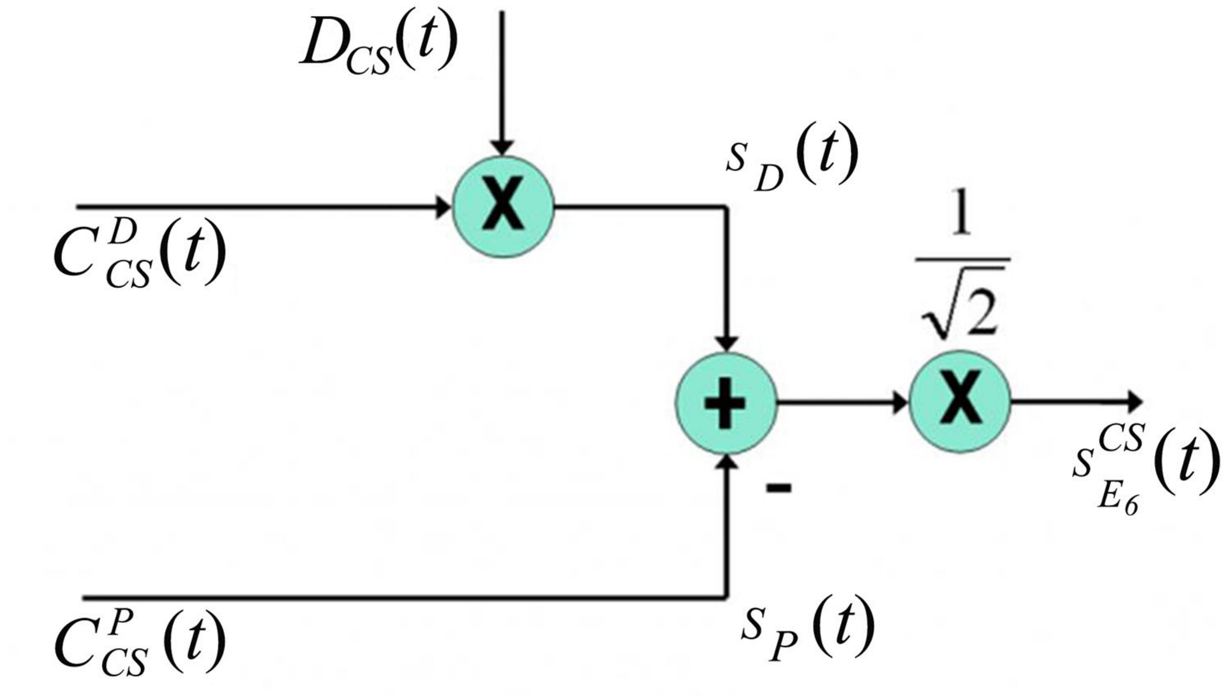


Figure 5a. Modulation scheme for Galileo E6 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

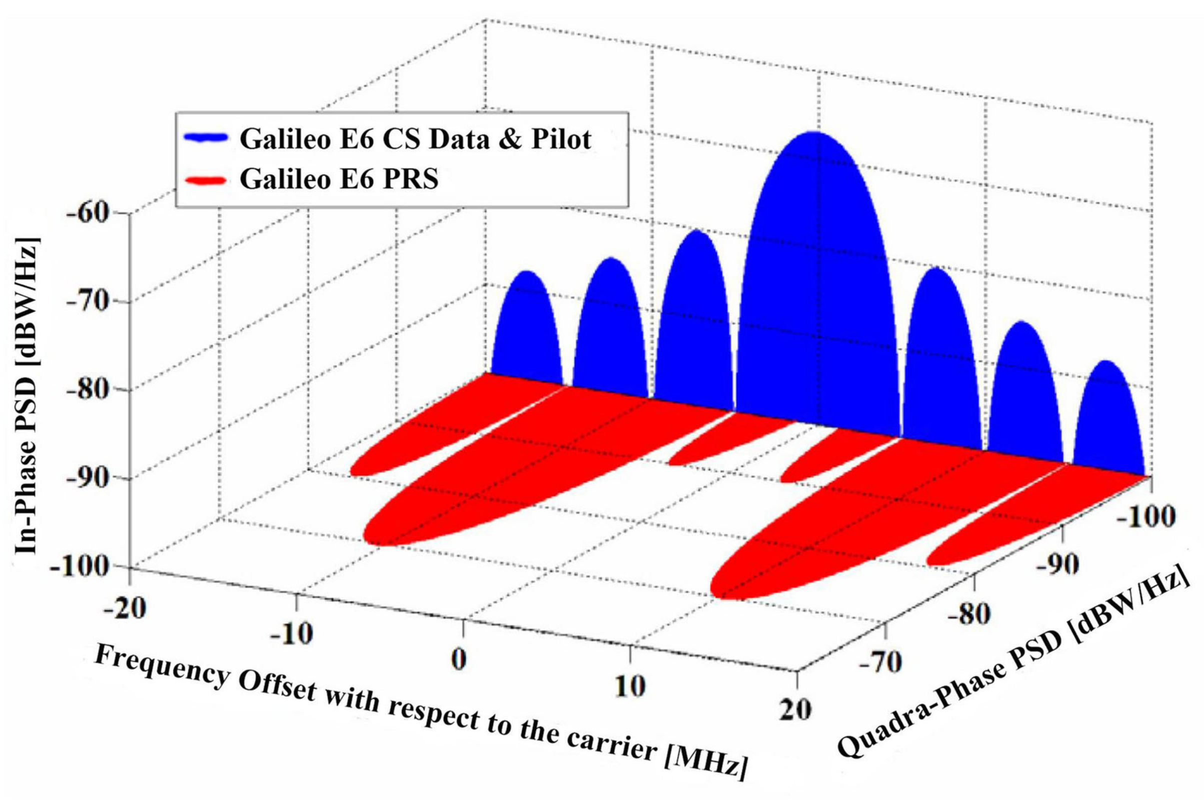


Figure 5b. Spectra of Galileo E6 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	Galileo	Galileo	Galileo
Service Name	E6 CS data	E6 CS pilot	E6 PRS
Center Frequency	1278.75 MHz		
Frequency Band	E6		
Access Technique	CDMA		
Spreading modulation	BPSK(5)	BPSK(5)	$BOC_{cos}(10.5)$
Sub-carrier Frequency	-	-	10.23 MHz
Code Frequency	5.115 MHz		
Signal Component	Data	Pilot	Data
Primary PRN Code Length	5115	5115	N/A
Code Family	Memory codes		N/A
Secondary PRN Code Length	-	100	N/A
Data Rate	1000 sps	-	N/A
Minimum Received Power [dBW]	-155 dBW		N/A
Elevation	10°		N/A

Table 5. Galileo E6 signal technical characteristics.

rate 10.23 MHz.

- The **E5b data channel**: This channel is the modulo-two addition of the E5b navigation data stream $D_{E5b}(t)$ with the PRS channel code sequence $C_{PRS}(t)$ with the E5b data channel PRN code sequence $C^{D}_{E5b}(t)$ of chipping rate 10.23 MHz.
- The **E5b pilot channel**: This channel is the E5b pilot channel PRN code sequence $C^{P}_{E5b}(t)$ of chipping rate 10.23 MHz.

The E5 modulation receives the name of AltBOC and is a modified version of a Binary Offset Carrier (BOC) with code rate of 10.23 MHz and a sub-carrier frequency of 15.345 MHz. AltBOC(15,10) is a wideband signal that is transmitted at 1191.795 MHz. Figure 6b shows the Galileo E5 signal modulation diagram.

The power spectral density for the modified AltBOC(15,10) modulation with constant envelope is shown to adopt the form in Figure 6a.

The spectrum of the E5 signal modulation is shown in Figure 6c.

As we can recognize from both figures, the AltBOC(15,10) modulation is very similar to two BPSK(10) signals shifted by 15 MHz to the left and right of the carrier frequency. Indeed, since to acquire all the main lobes of the modulation a very wide bandwidth is necessary, many receivers will operate correlating the AltBOC signal with a BPSK(10) replica.

To have a better feeling about the overlapping between GPS and Galileo in E5, Figure 6d shows all the signals described so far for this band.

The E5 primary codes can be generated with shift registers. Indeed, the outputs of two parallel registers are modulo-two added to generate the primary codes. For more details on the start values of the primary codes and the corresponding secondary codes of each satellite, refer to [Galileo SIS ICD, 2010]. Finally, some details on the technical characteristics of the E5 signal are presented in Table 6.

THE GLONASS SIGNAL PLAN

C 7. GLONASS Signal Coding

GLONASS, unlike the other GNSS systems, makes use of a different DSSS technique [G.W. Hein et al., 2006c] based on Frequency Division Multiple Access (FDMA) to transmit its ranging signals.

$$G_{\mathrm{AltBOC}}(f) = \frac{4f_c}{\pi^2 f^2}\frac{\cos^2\left(\frac{\pi f}{f_c}\right)}{\cos^2\left(\frac{\pi f}{2f_z}\right)}\left[\cos^2\left(\frac{\pi f}{2f_z}\right) - \cos\left(\frac{\pi f}{2f_z}\right) - 2\cos\left(\frac{\pi f}{2f_z}\right)\cos\left(\frac{\pi f}{4f_z}\right) + 2\right]$$

Figure 6a. Equation for the power spectral density of the modified AltBOC (15,10).

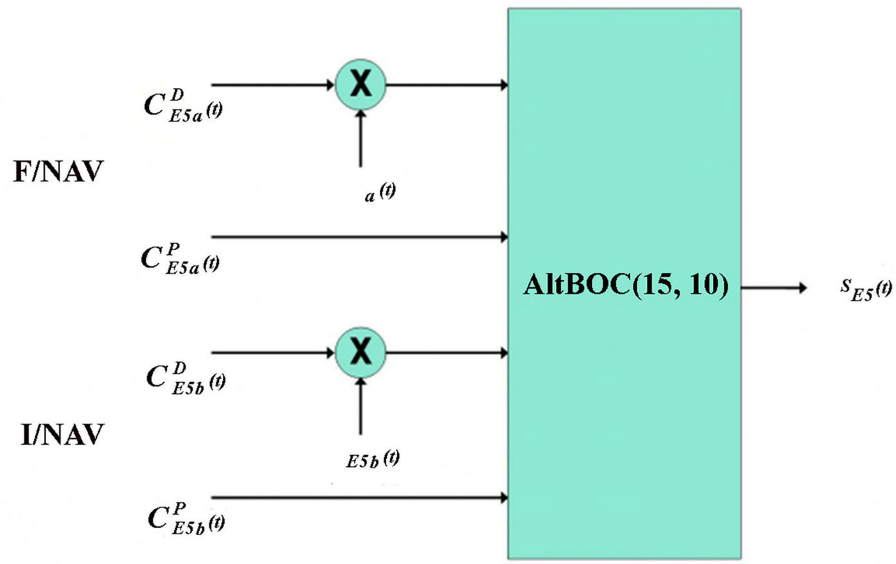


Figure 6b. Modulation scheme for Galileo E5 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GLONASS uses FDMA in both the L1 and L2 sub-bands. According to this scheme, each satellite transmits navigation signals on its own carrier frequency, so that two GLONASS satellites may transmit navigation signals on the same carrier frequency if they are located in antipodal slots of a single orbital plane [GLONASS ICD, 2002]. Indeed the actual constellation is taking advantage of this property since 2005 when the higher frequency channels had to be turned off to fulfill the CCIR Recommendation 769. We can clearly see this if we have a look at the satellites assigned to each of the GLONASS planes as shown in the following figure with status as of May 2008. As is clear to see, antipodal satellites are transmitting at the same frequency.

See Figure 7 for a depiction of the three GLONASS orbital planes.The red slots indicate that the satellite is in maintenance. Blue means correct operation. Moreover, two different types of signals [GLONASS ICD, 2002] are transmitted by GLONASS satellites: Standard Precision (SP) and High Precision (HP) in both the L1 and L2 bands. The GLONASS standard accuracy signal, also known as C/A Code, has a clock rate of 0.511 MHz and is designed for use by civil users worldwide while the high accuracy signal (P Code) has a clock rate of 5.11 MHz and is modulated by a special code which is only available to users authorized by the Ministry of Defense. Since GLONASS-M, both L1 and L2 provide users with the standard accuracy code C/A. Moreover, the modernized GLONASS will also transmit FDMA signals on the L3 band and CDMA signals in L1 and L5.

The nominal values of the FDMA L1, L2 and L3 carrier frequencies are defined as:

$$\begin{aligned} f_{kL1} &= f_{0L1} + k\Delta f_{L1} \\ f_{kL2} &= f_{0L2} + k\Delta f_{L2} \qquad (1) \\ f_{kL3} &= f_{0L3} + k\Delta f_{L3} \end{aligned}$$

where:

k represents the frequency channel,

f_{0L1} = 1602 MHz for the GLONASS L1 band,

Δf_{L1} = 562.5 kHz frequency separation between GLONASS carriers in the L1 band,

f_{0L2} = 1246 MHz for the GLONASS L2 band,

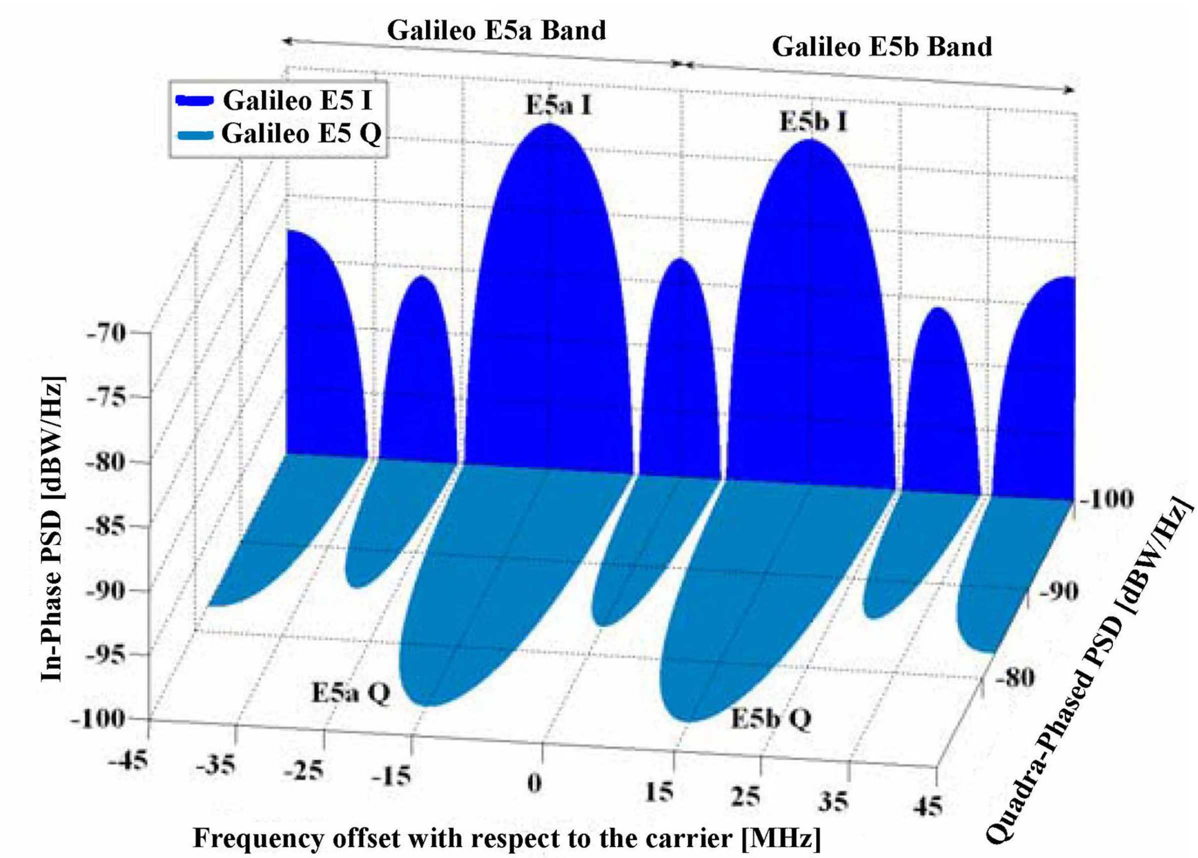


Figure 6c. Spectra of Galileo signals in E5. Image courtesy of Dr. Jose Angel Avila Rodriguez.

Δf_{L2} = 437.5 kHz frequency separation between GLONASS carriers in the L2 band,

f_{0L3} = 1201 MHz for the GLONASS L3 band, and

Δf_{L3} = 437.5 kHz frequency separation between GLONASS carriers in the L3 band.

As we can see, the GLONASS L2 carrier reference signal is $^7/_9$ of the L1 carrier reference and the GLONASS L3 carrier reference is $^3/_4$ of the L1 carrier reference. Moreover, it must be noted that until 2005 the GLONASS satellites used the frequency channels k = 0,...,12 without any restrictions and the channel numbers k = 0 and 13 for technical purposes.

Since then GLONASS is only using the frequency channels k = -7,...,+6 and all the satellites launched beyond that year will use filters, limiting out-of-band emissions to the harmful interference limit contained in CCIR-ITU Recommendation 769 for the 1610.6 - 1613.8 MHz and 1660 - 1670 MHz Radio-Astronomy bands. It is interesting to note that although the limitation to use the higher frequency channels does only affect the L1 band, since the parameter k determines the channel in both the L1 and L2 bands, the upper frequencies of L2 corresponding to channels +7 to +13 were automatically sacrificed.

To have a clearer insight into how the spectra of the GLONASS signals look like, we study next all the bands in detail.

C 8. GLONASS L1 Band and Signal Structure

The transmitted navigation signal is in both services of L1 a bipolar phase-shift key (BPSK) waveform with clock rates of 0.511 and 5.11 MHz for the standard and accuracy signals respectively. The L1 signal is modulated by the Modulo-2 addition of the pseudo random (PR) ranging code, the digital data of the navigation message and an auxiliary meander sequence. All above-mentioned frequencies are generated coherently using a single onboard time/frequency oscillator standard [GLONASS ICD, 2002]. For the case of the standard accuracy signals (C/A), the PR ranging code is a sequence with length the maximum of a shift register (m-sequence) and a period of 1 millisecond with bit rate of 511 kbps. The navigation message is sent at 50 bps and the auxiliary meander sequence at 100 Hz.

Moreover, it is important to note that the GLONASS FDMA L1 band does not exactly coincide with the GPS and Galileo L1 band. In fact, the GLONASS L1 band ranges

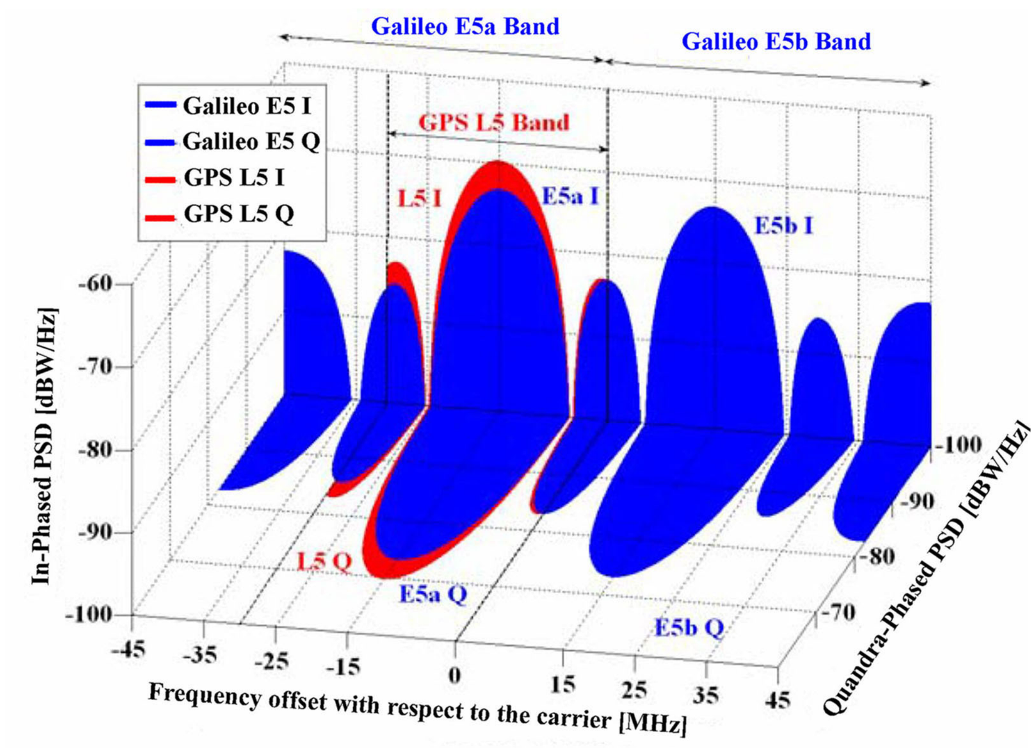


Figure 6d. Spectra of GPS and Galileo Signals in E5.Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	**Galileo**	**Galileo**	**Galileo**	**Galileo**
Service Name	E5a data	E5a pilot	E5a data	E5b pilot
Center Frequency	1191.795 MHz			
Frequency Band	E5			
Access Technique	CDMA			
Spreading modulation	AltBOC(15, 10)			
Sub-carrier Frequency	15.345 MHz			
Code Frequency	10.23MHz			
Signal Component	Data	Pilot	Data	Pilot
Primary PRN Code Length	10230			
Code Family	Combination and short-cycling of M-sequences			
Secondary PRN Code Length	20	100	4	100
Data Rate	50 sps	-	250 sps	-
Minimum Received Power [dBW]	-155 dBW		-155 dBW	
Elevation	10°		10°	

Table 6. Galileo E5 signal technical characteristics.

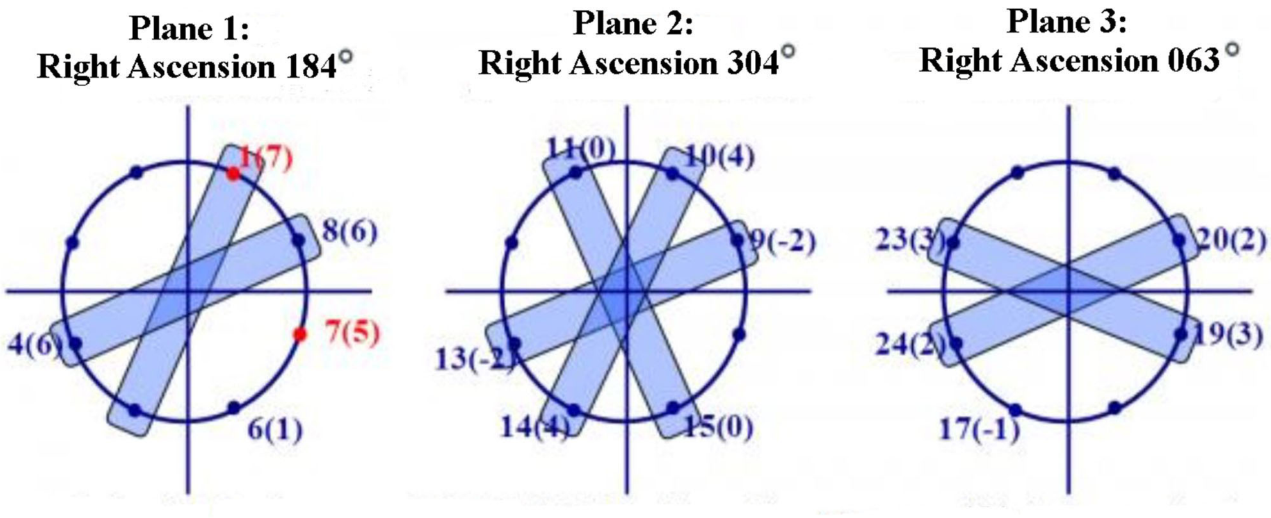


Figure 7. Antipodal assignment of GLONASS satellites. The parameter i(k) indicates that the satellite in almanac slot i transmits on frequency number k. Image courtesy of Dr. Jose Angel Avila Rodriguez.

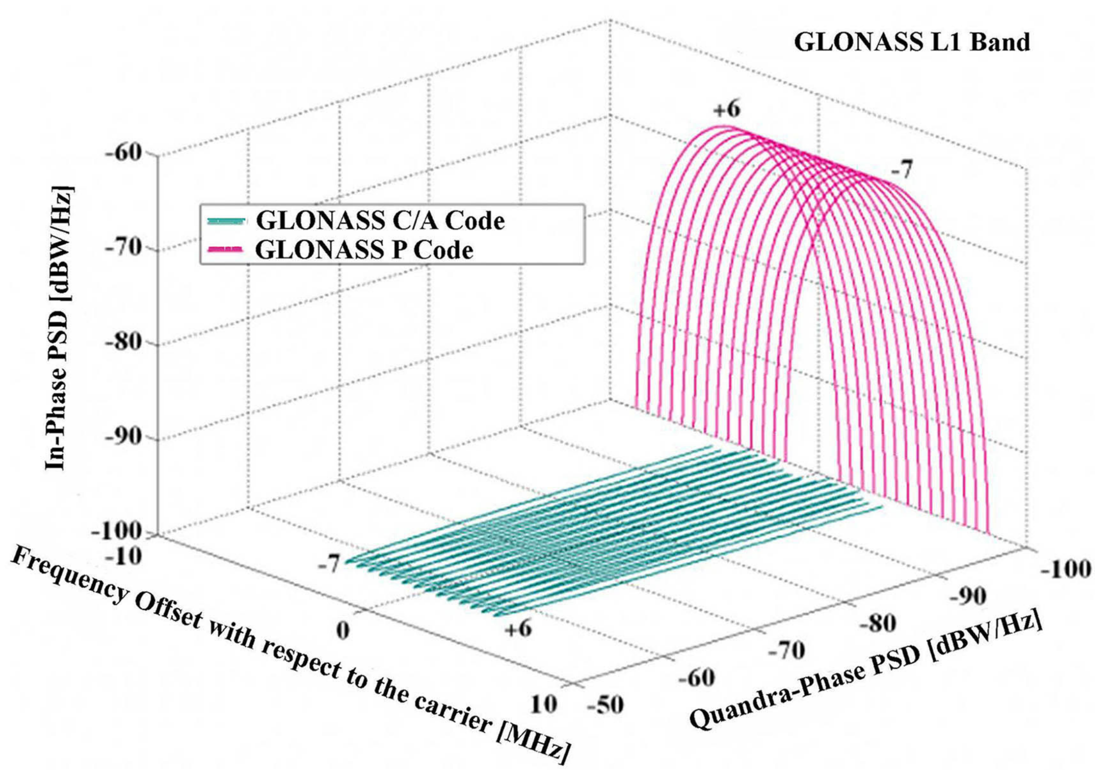


Figure 8a. Spectra of GLONASS signals in L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

from 1592.9525 MHz to 1610.485 MHz when only the 14 channels k = -7...+6 are employed. In the next figures, each of the channels was filtered to only transmit the main lobe of the BPSK signal and the PSD was normalized to have unit power within the corresponding transmission bandwidth.

The PSDs of the GLONASS signals are shown in Figure 8a.

Once again, in order to have a clearer picture of how overcrowded the RNSS bands are becoming as more and more countries claim their rights to have their own GNSS, Figure 8b hows GPS, Galileo and GLONASS signals in the E1/L1 band.

It is important to note that the GPS L1C pilot and data

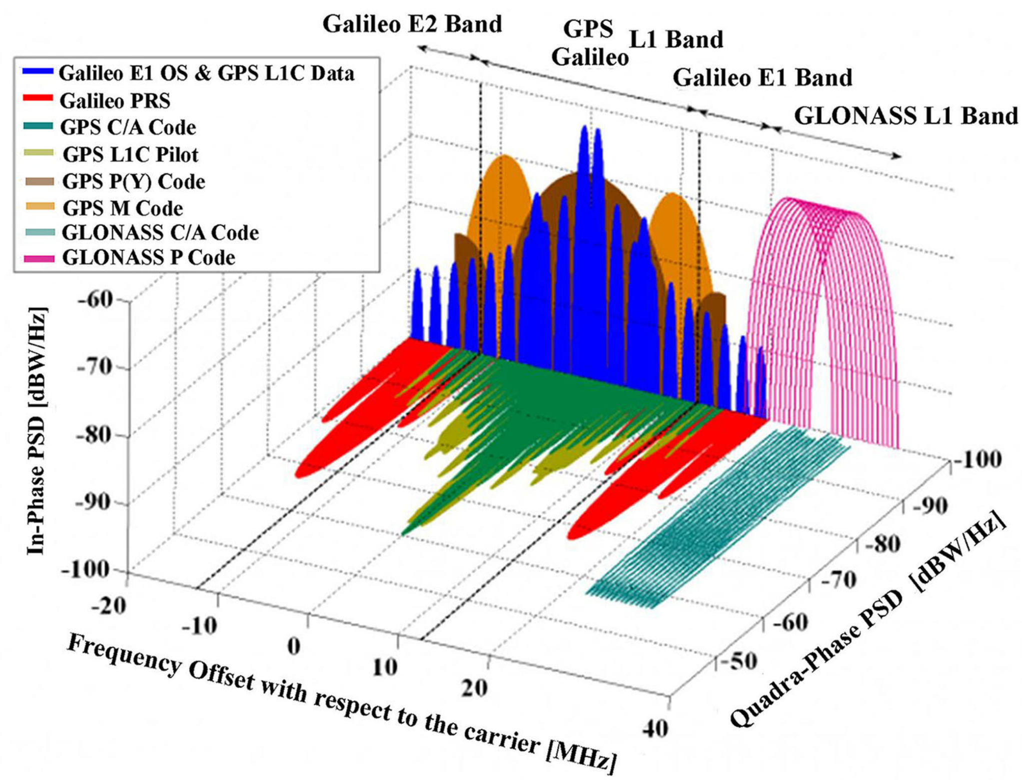


Figure 8b. Spectra of GPS, Galileo and GLONASS signals in E1/L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

signals are shown in quadrature in Figure 8b although according to [GPS ICD-800, 2006] the final phasing is still open. To finalize some details on the technical characteristics of the GLONASS L1 signals are presented Table 8.

It is important to note that unlike for the case of GPS and Galileo, the frequencies do not have to be multiplied by the factor 1.023.

GNSS System	**GLONASS**	**GLONASS**
Service Name	C/A Code	P Code
Center Frequency	(1598.0625-1605.375) MHz [+ or -] 0.511 MHz	
Frequency Band	L1	L1
Access Technique	FDMA	FDMA
Spreading modulation	BPSK(0.511)	BPSK(5.11)
Sub-carrier Frequency	-	-
Code Frequency	0.511 MHz	5.11 MHz
Signal Component	Data	Pilot
Primary PRN Code Length	511	N/A
Code Family	M-sequences	N/A
Meander sequence	100 Hz	N/A
Data Rate	50 bps	N/A
Minimum Received Power [dBW]	-161 dBW	N/A
Elevation	5°	N/A

Table 8. GLONASS L1 signal technical characteristics.

C 9. GLONASS L2 Band and Signal Structure

The transmitted navigation signal is, as also in L1, a bipolar phase-shift key (BPSK) waveform with similar clock rates as in the L1 band. The L2 signal is modulated by the Modulo-2 addition of the PR ranging code and the auxiliary meander sequence. For the case of the standard accuracy signals (C/A), the PR ranging code is a sequence of the maximum length of a shift register (M-sequence) with a period of 1 millisecond and a bit rate of 511 kbps. The navigation message is sent at 50 bps and the auxiliary meander at 100 Hz.

Figure 9a shows the spectra of the GLONASS signals in L2 and Figure 9b shows spectra of both the GLONASS and GPS signals in L2.

Details on the technical characteristics of the GLONASS L2 signals are presented in Table 9.

It is important to note again that unlike for the case of GPS and Galileo in the previous chapters, the frequencies do not have to be multiplied by the factor 1.023.

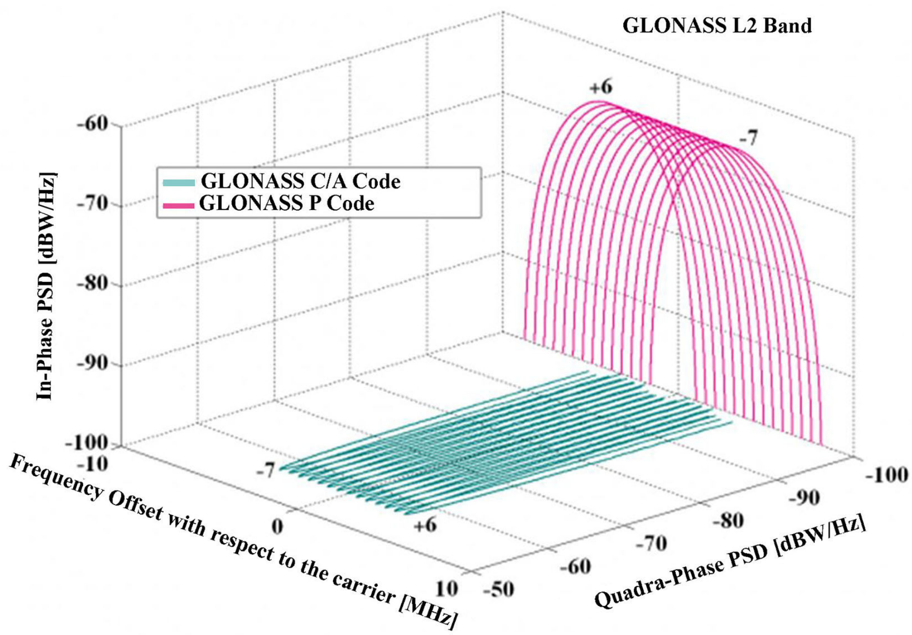


Figure 9a. Spectra of GLONASS signals in L2. Image courtesy of Dr. Jose Angel Avila Rodriguez.

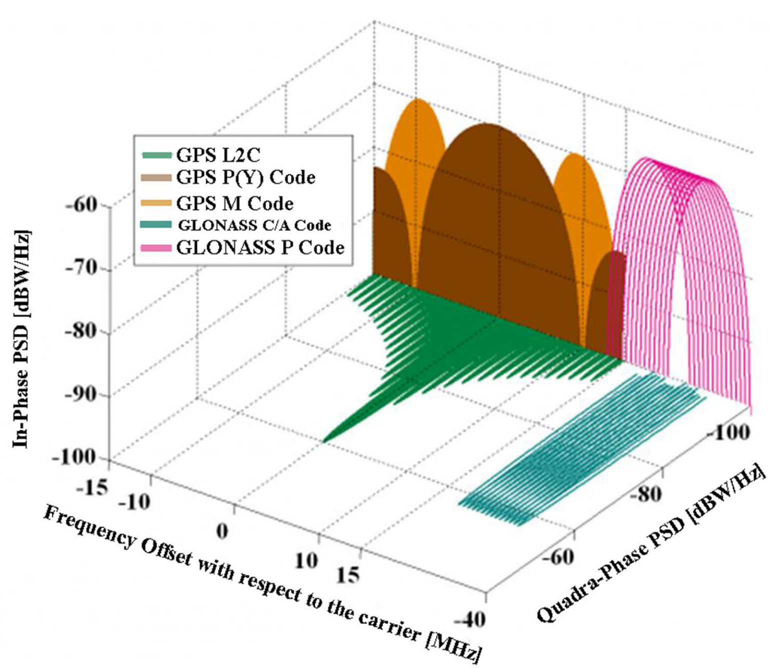


Figure 9b. Spectra of GPS and GLONASS signals in L2. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	GLONASS	GLONASS
Service Name	C/A Code	P Code
Center Frequency	(1242.9375-1248.625) MHz [+ or -] 0.511 MHz	
Frequency Band	L2	L2
Access Technique	FDMA	FDMA
Spreading modulation	BPSK(0.511)	BPSK(5.11)
Sub-carrier Frequency	-	-
Code Frequency	0.511 MHz	5.11 MHz
Signal Component	Data	Pilot
Primary PRN Code Length	511	N/A
Code Family	M-sequences	N/A
Meander sequence	100 Hz	N/A
Data Rate	50 bps	N/A
Minimum Received Power [dBW]	-167 dBW	N/A
Elevation	5°	N/A

Table 9. GLONASS L2 signal technical characteristics.

Figure 9c. Image of the next generation GPS III satellite built by Lockheed Martin

C 10. References

Ávila Rodríguez, José Ángel. (2008). *On Generalized Signal Waveforms for Satellite Navigation*. University FAF, Munich. **Sections reproduced with permission**.

APPENDIX D

US GOVERNMENT AND PUBLIC VESSELS

TERRESTRIAL NAVIGATION

D 1. Introduction

This Appendix is meant to supplement the existing information in the various chapters of both Volumes of the 2024 edition of *The American Practical Navigator*. U.S. Government and public vessels, including U.S. Navy (USN), U.S. Coast Guard (USCG), and Military Sealift Command (MSC) ships, have access to software and forms that are not available to the typical civilian mariner. These services still adhere to *The American Practical Navigator* as their primary source for navigation knowledge, but are provided software and methods to standardize navigation across the hundreds of ships that they maintain. They also impose further requirements through other publications and instructions.

D 2. U.S. Government Navigation Requirements

Along with maintaining *The American Practical Navigator* as the "Bible" of navigation, the U.S. Navy also utilizes the Navigation Department Organization and Regulations Manual **(NAVDORM)** to establish consistency and standards for all Naval Surface Ships to follow. The manual is broken down into chapters and appendices. The NAVDORM chapters consist of, but are not limited to, the duties and responsibilities of the navigation watchteam members, general policies, requirements and procedures while underway, and requirements for all navigational records, logs and forms.

The appendices include amplifying information and enclosures such as inspection forms, sample evolution checklists, navigational term definitions, and applicable contact information. The NAVDORM is updated as required and may have changes released as Advance Change Notices (**ACN**s) between versions for temporary corrections. It is vital for all navigation team members on a naval surface ship to be familiar with this document and have the most up-to-date information from it.

D 3. U.S. Government Backup Navigation

A prudent government navigator will be intimately familiar with Chapter 29, Sections 2900 - 2902. They should be able to navigate their vessel in any emergency and be unduly familiar with available backup methods. While ECDIS will remain the primary navigation suite, ships must be prepared for these systems' potential failure and destruction in case of a casualty or attack. This is especially true for government ships, which will be on the front lines of any major conflict. A minimal set of paper charts and position plotting sheets for the area where a ship intends to operate should be kept onboard for such an event. Paper charts provide valuable information for voyage planning, situational awareness, training, and for use in an emergency. Electronic systems are vulnerable to degradation by carelessness or enemy action. No Navigator should ever become completely dependent on electronic methods.

In an emergency or loss of electronic systems, the ability to switch effortlessly to all backup navigation sources is essential. A Navigator who is able to use backup GPS receivers, STELLA (see Section D 16), analog celestial navigation techniques, paper charts, position plotting sheets, and dead reckoning will be able to navigate their ship to safety under any condition. Using STELLA and celestial navigation concepts can provide accurate positioning and dead reckoning. These positions can then be plotted on paper charts or position plotting sheets (see Chapter 5 and Section 522). Dead reckoning out from these positions will give the Navigator a **most probable position** (MPP, see Section 2902) on the ship's track between fixes. These methods are reliable and effective for safe navigation when used in conjunction. For a more expansive list of best practices dealing with emergency navigation, refer to Chapter 29.

D 4. U.S. Navy Restricted Waters Plotting Standards

Chapter 10, Section 1002 outlines procedures for plotting LOPs, fixes, and dead reckoned positions while clearly labeling the plot. Navy units, for consistency and clarity, should codify plotting procedures in their **Navigation Bill** in accordance with the NAVDORM. Suggestions and examples are provided here.

The NAVDORM categorizes phases of navigation more specifically than Chapter 1, Section 102, with precise distance thresholds based on the ship's safety depth. The most hazardous of these phases, referred to as "Restricted Waters" in the NAVDORM, is comparable to the Inland Waterway Phase and places the strictest requirements on the crew to fix the ship's position and assess navigational hazards. Given the scale of charts so close to shore and the required frequency of fixes, it is likely that many labels will be near each other or even overlapping. Plotters should follow precise conventions to prevent confusion of one label for another.

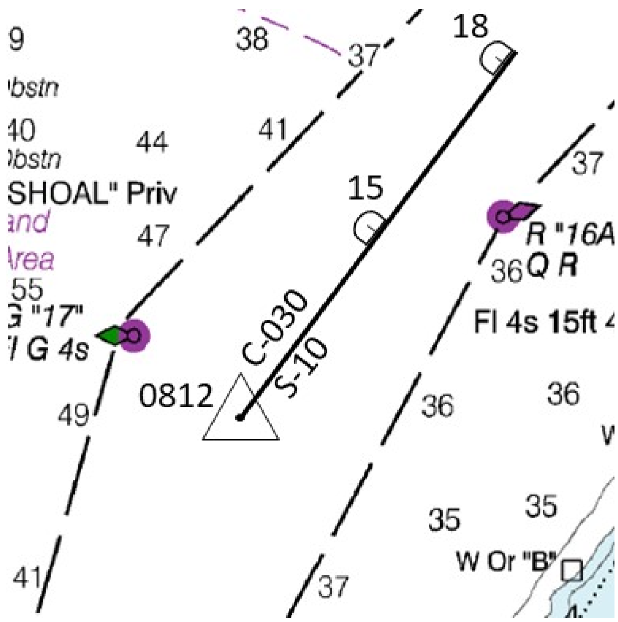


Figure 4a. A radar fix with DRs clearly labeled.

Two examples of such conventions are shown in Figure 4a and Figure 4b. Figure 4a differentiates fix labels from DR labels by always keeping the fix time in four digits and the DR time in two digits, specifically those denoting minutes. Course and speed are written above and below the line representing the ordered course and speed at the time of the fix and are written as close to the fix as can be managed.

Figure 4b differentiates fix labels from DR labels with fix time written in four digits horizontally, on a rough 270/090ºT axis. DR labels are also written in four digits at a 45-degree angle relative to the fix time. The plotter should judge whether that 45-degree angle is ascending (on a 225 - 045ºT axis) or descending (on a 315 - 135ºT axis). They should also consider the importance of quick, clear legibility when placing the labels for course and speed. Figure 4b shows that when a course is a near-vertical line, course and speed may be more clearly read when written horizontally near the fix than when written on the line of the ordered course.

While compiling and delivering a report on the ship's position and proximity to navigational hazards, the **quality of the fix** should be assessed and included in the report: excellent, good, or poor. This concept applies to both electronic charting and analog paper plotting.

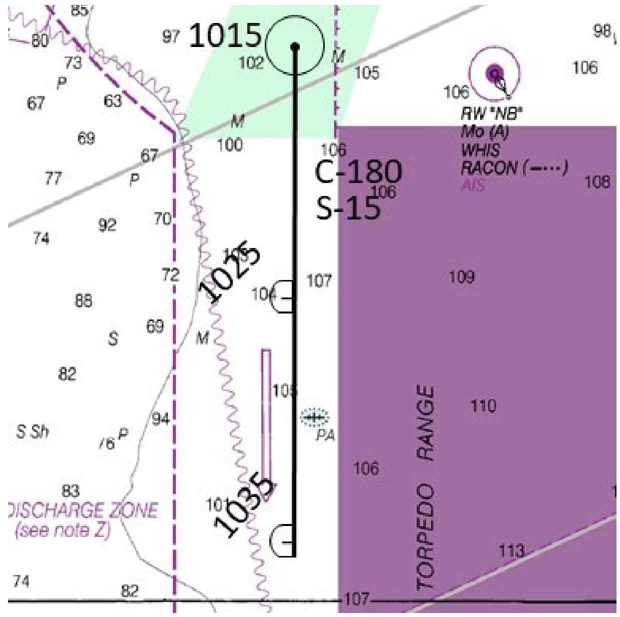


Figure 4b. A visual fix with DRs clearly labeled.

There are no quantifiable distinctions between these ratings, only the judgment of a competent mariner. Among the factors to be considered in such an assessment are the size of the area enclosed by three or more LOPs and how well the area aligns with the corresponding DR, expected environmental forces, and navigational aids like buoys and visual ranges. Figure 4c, Figure 4d, and Figure 4e show fixes of varying quality.

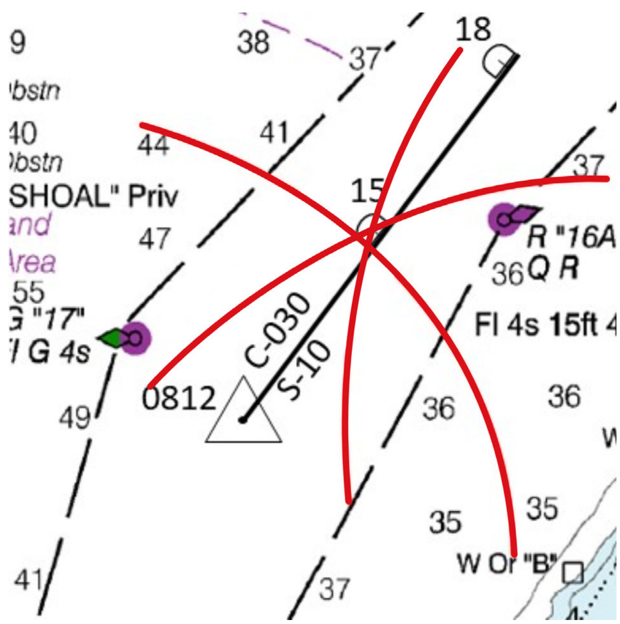


Figure 4c. An "excellent" radar fix, with the LOPs aligned nearly perfectly.

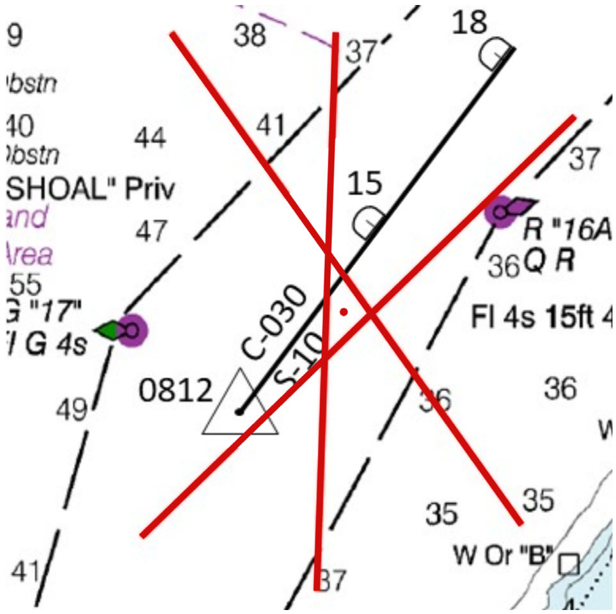


Figure 4d. A "good" visual fix. The LOPs strongly suggest that the ship is right of the track. Thus, is on the Eastern side of the channel, which can be supported by looking for a red buoy labeled "16A" to the Northeast.

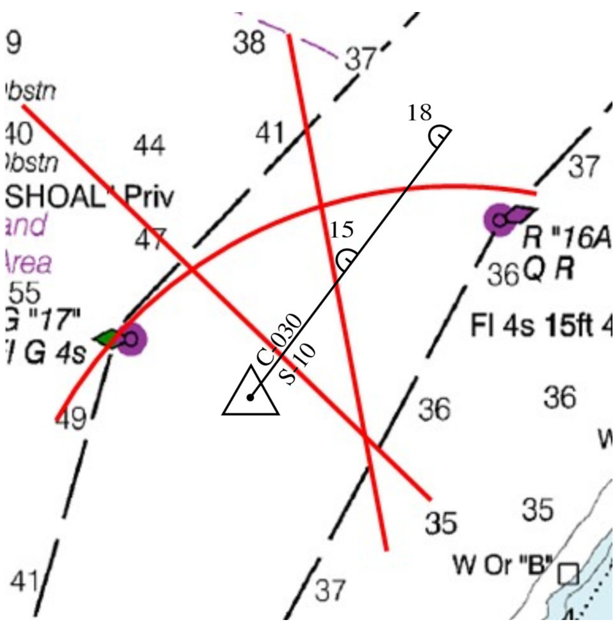


Figure 4e. A "poor" composite fix. The LOPs are spread out enough to suggest the ship could be anywhere between the Eastern or Western extremities of the channel.

D 5. ECDIS-N

In 1998, the U.S. Navy issued a policy letter for a naval version of ECDIS, called ECDIS-N. It included a performance standard that not only conforms to IMO Performance Standards but extends them to meet the unique requirements of the U.S. Department of Defense (US DoD). A major difference from an IMO-compliant ECDIS is the requirement that the ECDIS-N system electronic nautical chart (SENC) may be either the Digital Nautical Chart (DNC) issued by the National Geospatial-Intelligence Agency (NGA) or an S-57 standard ENC verified by NGA to meet adjusted requirements to satisfy DoD needs. The DNC conforms to the U.S. DoD standard Vector Product Format (VPF), implementing the NATO DIGEST C Vector Relational Format.

The U.S. Navy uses the Voyage Management System (VMS) software as the ECDIS-N-compliant system. VMS was selected for use by the Navy in 2002, based on the large presence of VMS in the surface fleet Integrated Bridge Systems and in the submarine fleet AN/BPS radar system. The current series of VMS software, the 9.X series, began fielding in 2017. This replaces the 6.X, 7.X, and 8.X versions in the Fleet and reduces the number of fielded variants of VMS. As of 2024, all surface combatant vessels are certified to operate solely on VMS.

A new program of record called **Navy ECDIS (NECDIS**) began fielding in 2023, which is expected to replace VMS as the fleet's standard navigation software system. NECDIS is based on the NATO Warship ECDIS (WECDIS, see Section D 7) standard and also on a U.S. Navy-specific Software Requirements Document (SRD). NECDIS will use S-57 ENCs as the primary chart display format, using the legacy DNC-format chart only to cover gap areas in the ENC database until worldwide coverage is achieved.

D 6. Digital Nautical Chart

NGA produces DNC, a vector-based digital product housed in a global database designed to support marine navigation and Geographic Information Systems (GIS) applications. This product contains vector data and feature content thematically layered and relationally structured to support ECDIS. DNC is produced in the standard VPF, a non S-57 data format, and conforms to DNC (MIL-PRF-80923) specifications, which allows for modeling real world features in digital geographic databases. The database underlying the DNC portfolio uses a table-based geo-relational data model containing significant maritime features considered essential for safe marine navigation. It is designed to conform to the IMO Performance Standard and IHO specifications for ECDIS.

The DNC database is based on and developed with feature content from traditional paper charts produced by NGA and NOS. This content is updated regularly with both foreign partner charts and NOS charts to reflect the latest information from the various charting authorities. Although the majority of the DNC portfolio is unclassified, a significant portion is labeled Limited Distribution (LIMDIS) to protect the copyrights and sensitive feature data provided by NGA's foreign partners, therefore, DNC is primarily

DNC Library Categories		
Library Category	Scale	Purpose
General	> 1:500K	The smallest scale charts used for planning, fixing position at sea, and for plotting while proceeding on an ocean voyage. The shoreline and topography are generalized and only offshore soundings, the principal navigational lights, outer buoys, and land-marks visible at considerable distances are shown.
Coastal	1:75K - 1:500K	Intended for inshore coastwise navigation where the course may lie inside outlying reefs and shoals, for entering or leaving bays and harbors of considerable width, and for navigating large inland waterways.
Approach	1:25K - 1:75K	Intended for approaching more confined waters such as bays or harbors.
Harbor	1 < 1:50K	Intended for navigation and anchorage in harbors and small waterways
Browse Index	1:3,1000,000	Provides a global overview of the DNC coverage displaying geographical boundaries.

Table 6. DNC library categories according to scale.

developed and maintained for use by DoD agencies and departments including, the U.S. Navy, U.S. Coast Guard, government agencies, and government/US military sponsored contractors. DNC data for U.S. waters is generally available for public use and is available for download from NGA's website.

The DNC database consists of 29 DNC geographic regions that provide a worldwide footprint containing over 5,000 charts of varying scales resulting in global coverage between 84 degrees N and 81 degrees S. The 29 regions are further broken down by libraries. The DNC portfolio comprises some 3,800 or more DNC libraries created from over 8,600 Standard Nautical Charts (SNC). Each DNC library represents a different geographic area of interest and level of detail (i.e. scale). The libraries are organized as tiles according to the World Geodetic Reference System (GEOREF) tiling scheme. The libraries have been designed to support various navigation and piloting maneuvers as well as GIS applications.

The Horizontal datum in DNC is WGS 84 (considered equivalent to NAD 83 in the U.S.). There are three vertical datums within the DNC database; two vertical datums related are topographic and the third is hydrographic. Topographic features are referenced to Mean Sea Level, and the shoreline is referenced to Mean High Water. Hydrography is referenced to a low water level most suitable for the region being charted. All measurements are metric.

The DNC data is stored in libraries; each library represents a different geographic area of interest and level of detail (i.e. scale). The libraries are as tiles according to the GEOREF tiling scheme. The DNC contains four library categories: Harbor, Approach, Coastal, and General, based on scale (from largest to smallest scale, respectively) and purpose. A Browse Index provides library names and footprints.

The DNC data is grouped and stored in the following five library scales in Table 6. For voyage planning NGA provides a DNC Regions graphic, which is available on the DNC website (see Figure 6).

The naming convention used for Harbor and Approach libraries are the same (e.g., H0145820 or A1708470). The first character signifies the category type (Harbor or Approach). The next two characters are the DNC geographic region number (e.g., 17 is the East Coast of the United States). The last five characters are the five-digit World Port Index (WPI) number.

The naming convention used for Coastal and General libraries start with a three letter code (COA or GEN) followed by the two-digit disc/geographic region number and a letter if the disc includes more than one library of that type (e.g., GEN1720a and GEN20b). The World Port Index reference is not included in the Coastal and General library naming convention.

DNC data is classified into and layered in 12 related feature class thematic layers:

- Cultural Landmarks (CUL)
- Data Quality (DQY)
- Earth Cover (ECR)
- Environment (ENV)
- Hydrography (HYD)
- Inland Waterways (IWY)
- Landcover (LCR)
- Limits (LIM)
- Aids to Navigation (NAV)
- Obstructions (OBS)
- Port Facilities (POR)
- Relief (REL)

Also, there are two additional layers found within the DNC data structure called Library Reference (LIBREF)

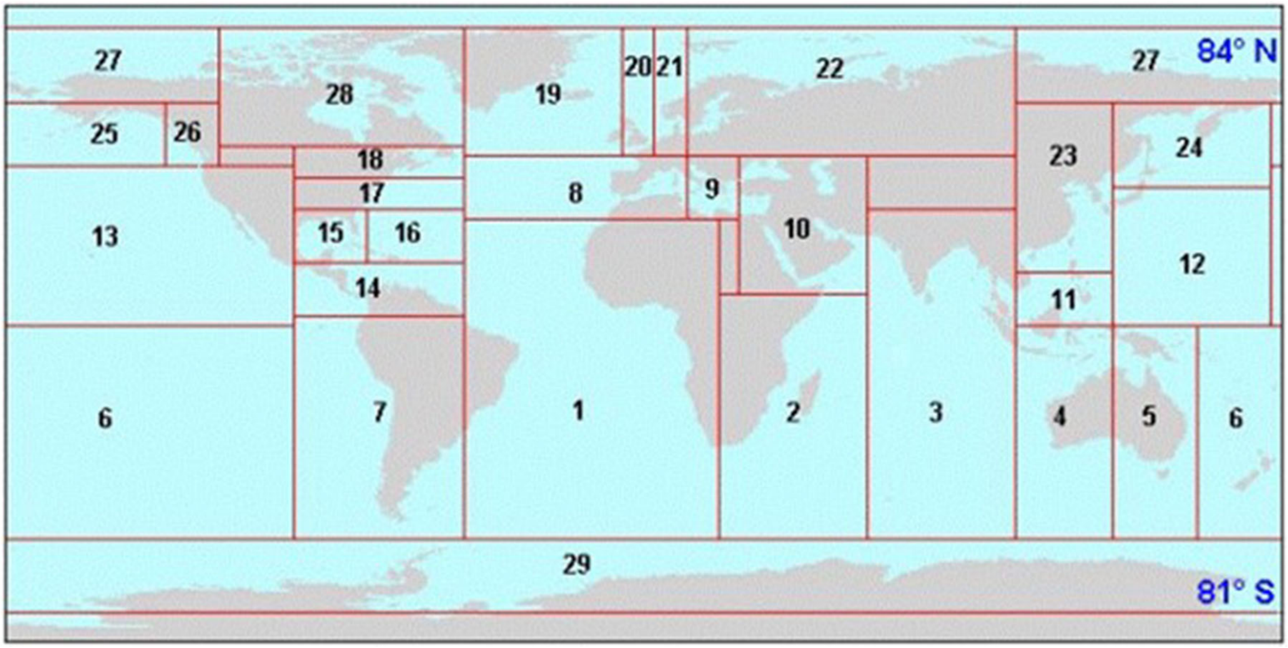


Figure 6. DNC Regions graphic.

and Tile Reference (TILEREF). These layers are used within the ECDIS-N to find the stored DNC data. DNC content is generally aligned to mirror what is found on a SNC printed on paper. However, one of the advantages of a digital product is the ability to provide the mariner with additional information when necessary to help them augment their understanding of the navigation space.

The publicly releasable DNC data is available for download at the following web location:

WWW: https://dnc.nga.mil

The full set of DNC data, to include the Limited Distribution information, is available via the following web locations:

NIPRNET: https://dnc.geo.nga.mil

SIPRNET: http://dnc.nga.smil.mil

JWICS: https://dnc.nga.ic.gov

Tactical Ocean Data (TOD) is an overlay to DNC. TOD data is bathymetric in nature and intended to support naval operations. Original TOD specifications provide for a total of six levels as outlined below:

Level 0 - Naval Opeating Area (OPAREA), Range, and Naval Exercise Areas (NAVEX) charts

Level 1 - Bottom Contour Charts (BC)

Level 2 - Bathymetric Navigation Planning Charts (BNPC)

Level 3 - Shallow Water Charts

Level 4 - Hull Integrity Test Charts

Level 5 - Strategic Straits Charts

In recent years, changes in policy resulted in the combination of TOD levels 1, 3 and 5 into TOD Level 2. The current TOD Levels are referenced below:

Level 0 - OPAREA, Range, and NAVEX charts

- TOD0 provides worldwide databases of nautical information in Vector Product Format (VPF). The data content and coverage is intended to closely replicate NGA's Naval Operating Area (OPAREA) Chart, Range Chart, and NAVEX Chart series.

Level 2 - Bathymetric Navigation Planning Charts (BNPC)

- TOD2 provides worldwide databases of nautical information in VPF. The data content and coverage is intended to closely replicate NGA's BNPC series. includes data from:

  — Bottom Contour Charts (BC)
  — Shallow Water Charts
  — Strategic Straights Charts

Level 4 - Hull Integrity Test Charts (HITS)

- TOD4 is a vector-based digital product that portrays detailed bathymetric data for submarine Hull Integrity Test Sites (HITS) in a format suitable for computerized subsurface navigation. TOD4 data is designed for use during submarine hull integrity tests conducted as a part of builder's trials and after submarine hull maintenance. TOD4 data is provided primarily to support deep submergence rescue vessel operations and to enhance coordination between units during escorted test dives.

D 7. Warship ECDIS (WECDIS)

NATO Standard ANP-4564 defines WECDIS. WECDIS is a system that takes inputs from and provides information to disparate tactical sources (including the Command System), providing the user with a controllable set of information additions to overlay onto electronic charting and position displays for the safety of navigation and enhanced tactical awareness.

WECDIS is delivered via a dedicated user interface and chart display. When required by the user (for example, in a benign tactical environment), WECDIS shall be capable of operation as an IMO-compliant ECDIS. The primary function of WECDIS is to enhance military mission effectiveness by supporting safe and efficient navigation. The IMO Performance Standards for ECDIS define the minimum requirements for functionality concerning route planning, monitoring, alarms, and voyage recording.

However, warships can operate under circumstances not anticipated by IMO, including the core WECDIS capabilities of dived navigation, high-speed navigation, waterspace management, the integration of Additional Military Layers (AML), and the transfer of NATO User Defined Layers (NUDL) between NATO units. These circumstances impose additional requirements on WECDIS beyond those mandated by IMO.

WECDIS based solely on IMO specifications will not achieve the functionality required in a wartime scenario. Therefore, NATO adds its own requirements to this WECDIS standard; these can be further expanded based on national requirements.

Although warships, naval auxiliaries (such as MSC ships), and other vessels owned or operated by a contracting government and used only on governmental non-commercial service are exempt from the provisions of SOLAS Chapter V Regulations 18 and 19 (Ref A), WECDIS shall have the capability to be functionally compliant with the requirements of the latest IMO ECDIS performance and IHO chart presentation standards when selected by the user. Nations shall ensure that appropriate verification is completed to ensure functional compliance with IMO performance standards when operating in this mode.

Two operational modes, WECDIS mode and IMO compliant mode, categorize the requirements listed in this standard.

WECDIS mode: the system operates in this mode when any currently activated system functionalities render it non-ECDIS IMO compliant.

IMO compliant mode: the system operates in this mode when no currently activated system functionalities compromise compliance with ECDIS IMO regulations.

D 8. ECDIS-N Chart Updates

Charts loaded into an ECDIS-N system are provided by NGA at the PKI-protected ESYNC portal or by direct delivery of discs from the Defense Logistics Authority (DLA) distribution. The ESYNC portal can be found at https://esync.gs.mil/navwebsite; current DoD PKI certificates are required for access.

D 9. Predicting Tides and Currents

As discussed in Chapter 11 and Chapter 36 of this publication, understanding and anticipating a port's predicted tides and tidal currents is critical to safe navigation into any harbor. A graph of these predictions spanning at least 24 hours surrounding arrival to or departure from the port of call is prudent. These graphs should be posted on the bridge and in any other controlling watch stations throughout the vessel for ready reference. Refer to the NAVDORM for specific guidance on these graphs' time intervals and placement.

Data published by NOAA is the preferred source of information for tide and tidal current predictions. NOAA tide and tidal current predictions can be accessed via https://tidesandcurrents.noaa.gov/tide_predictions.html and https://tidesandcurrents.noaa.gov/noaacurrents/Regions, respectively. These NOAA predictions are also published in the annual Tide and Tidal Current Tables, as shown in Figure 9a and Figure 9b, distributed in the NGA quarterly disc for government vessels; these can also be downloaded via the NOAA website listed above. It is recommended that each ship develop a ready list of likely ports in order to download and make available for use these Tide and Tidal Current Tables in case of future poor or absent internet connectivity.

D 10. Quarter-Tenth Method (Tides)

If graphs from neither the NOAA website nor Admiralty Total Tide (ATT, see Section D 12) are available for use, a graphic representation of the data from the NGA Tide and Tidal Current Tables should be created using the Quarter-Tenth Method for tides.

Quarter-Tenth Method (Tides):

1. Obtain high and low water times and heights from Tide Tables or ATT.
2. Plot coordinates as (times, height) with heights above Mean Lower Low Water (MLLW) or applicable datum shown as positive y-values and heights below MLLW as negative y-values.
3. Find the difference between sequential times and divide this into four ("quarter") equal intervals.
   i. Add these to the first of the given high/low water times to find the times of the three quarter points (1/4, 2/4 or mid, 3/4) between given high and low water times.
4. Find the difference between sequential heights (range of tide) and divide by four.

StationId: 8443970
Source: NOAA/NOS/CO-OPS
Station Type: Primary
Time Zone: LST
Datum: MLLW

NOAA Tide Predictions

Boston, MA,2023
(42 21.2N / 71 03.0W)
Times and Heights of High and Low Waters

January							
Day	Time (h m)	Height (ft)	Height (cm)	Day	Time (h m)	Height (ft)	Height (cm)
1 Su	00:17	0.7	21	16 M	05:32	9.3	283
	06:42	9.7	296		11:58	1.0	30
	13:02	0.6	18		18:05	8.2	250
	19:17	8.7	265				
2 M	01:14	1.0	30	17 Tu	00:12	1.2	37
	07:38	9.8	299		06:26	9.6	293
	14:03	0.5	15		12:57	0.6	18
	20:17	8.5	259		19:05	8.3	253
3 Tu	02:08	1.2	37	18 W	01:08	1.1	34
	08:30	9.8	299		07:23	10.0	305
	14:58	0.3	9		13:57	0.1	3
	21:11	8.5	259		20:06	8.5	259
4 W	02:59	1.3	40	19 Th	02:07	0.8	24
	09:18	9.9	302		08:20	10.5	320
	15:46	0.2	6		14:55	-0.4	-12
	21:58	8.5	259		21:05	8.8	268
5 Th	03:44	1.3	40	20 F	03:04	0.4	12
	10:01	9.9	302		09:17	11.0	335
	16:29	0.1	3		15:51	-1.0	-30
	22:41	8.5	259		22:01	9.3	283

February							
Day	Time (h m)	Height (ft)	Height (cm)	Day	Time (h m)	Height (ft)	Height (cm)
1 W	01:39	1.7	52	16 Th	00:41	1.2	37
	08:03	9.2	280		06:56	9.9	302
	14:35	0.8	24		13:33	0.2	6
	20:49	8.0	244		19:45	8.3	253
2 Th	02:34	1.6	49	17 F	01:45	0.9	27
	08:56	9.3	283		08:01	10.3	314
	15:26	0.6	18		14:36	-0.3	-9
	21:38	8.1	247		20:48	8.8	268
3 F	03:23	1.5	46	18 Sa	02:47	0.4	12
	09:42	9.5	290		09:02	10.8	329
	16:09	0.4	12		15:33	-0.9	-27
	22:20	8.3	253		21:45	9.4	287
4 Sa	04:06	1.3	40	19 Su	03:45	-0.2	-6
	10:23	9.7	296		09:59	11.3	344
	16:47	0.3	9		16:26	-1.3	-40
	22:59	8.5	259		22:39	10.0	305
5 Su ○	04:47	1.1	34	20 M ●	04:40	-0.8	-24
	11:02	9.8	299		10:54	11.5	351
	17:23	0.2	6		17:17	-1.6	-49
	23:36	8.7	265		23:30	10.4	317

March							
Day	Time (h m)	Height (ft)	Height (cm)	Day	Time (h m)	Height (ft)	Height (cm)
1 W	00:06	2.0	61	16 Th	05:31	9.7	296
	06:29	8.8	268		12:08	0.5	15
	13:02	1.3	40		18:21	8.2	250
	19:19	7.7	235				
2 Th	01:07	2.1	64	17 F	00:23	1.3	40
	07:31	8.8	268		06:38	9.9	302
	14:04	1.2	37		13:14	0.3	9
	20:19	7.8	238		19:29	8.6	262
3 F	02:05	1.9	58	18 Sa	01:30	0.9	27
	08:28	9.0	274		07:46	10.2	311
	14:57	1.0	30		14:17	-0.1	-3
	21:09	8.1	247		20:32	9.1	277
4 Sa	02:57	1.6	49	19 Su	02:33	0.4	12
	09:17	9.3	283		08:50	10.6	323
	15:40	0.8	24		15:14	-0.6	-18
	21:51	8.4	256		21:29	9.8	299
5 Su	03:42	1.3	40	20 M	03:31	-0.3	-9
	09:59	9.5	290		09:47	11.0	335
	16:17	0.5	15		16:06	-1.0	-30
	22:29	8.8	268		22:20	10.4	317

Figure 9a. Annual NOAA Tide Table predictions for January/February/March 2023 for Boston, MA. Data is organized by port and chronologically.

Station ID: COI0418 Depth: 21 feet
Source: NOAA/NOS/CO-OPS
Station Type: Harmonic
Time Zone: LST

NOAA Tidal Current Predictions

Kennedy Entrance, 2023
Latitude: 59.0658° N Longitude: 151.9823° W
Mean Flood Dir. 308° (T) Mean Ebb Dir. 110° (T)
Times and speeds of maximum and minimum current, in knots

July							
Day	Slack (h m)	Maximum (h m)	knots	Day	Slack (h m)	Maximum (h m)	knots
1 Sa	01:18	04:36	-2.1E	16 Su	02:12	05:30	-2.0E
	08:00	11:30	2.4F		09:06	12:12	2.3F
	14:48	17:24	-1.4E		15:42	18:24	-1.3E
	20:24	23:36	1.6F		21:30		
2 Su	02:00	05:24	-2.3E	17 M ●		00:18	1.6F
	08:48	12:18	2.7F		02:54	06:18	-2.0E
	15:30	18:12	-1.5E		09:42	12:48	2.4F
	21:12				16:18	19:06	-1.3E
					22:06		
3 M ○		00:24	1.8F	18 Tu		00:54	1.6F
	02:48	06:12	-2.4E		03:24	06:54	-2.0E
	09:30	13:00	2.9F		10:12	13:24	2.4F
	16:18	19:06	-1.7E		16:48	19:36	-1.4E
	22:00				22:36		
4 Tu		01:06	1.9F	19 W		01:30	1.6F
	03:30	07:00	-2.6E		04:00	07:30	-2.0E
	10:18	13:42	3.0F		10:42	14:00	2.3F
	17:06	19:54	-1.8E		17:24	20:06	-1.4E
	22:48				23:06		
5 W		01:54	2.0F	20 Th		02:06	1.6F
	04:24	07:48	-2.6E		04:36	08:00	-1.9E
	11:06	14:30	2.9F		11:12	14:36	2.2F
	17:48	20:36	-1.8E		17:54	20:42	-1.4E
	23:36				23:36		

August							
Day	Slack (h m)	Maximum (h m)	knots	Day	Slack (h m)	Maximum (h m)	knots
1 Tu ○		00:06	2.0F	16 W ●		00:36	1.8F
	02:36	06:00	-2.5E		03:18	06:36	-2.0E
	09:24	12:42	3.0F		09:54	13:06	2.4F
	16:00	18:48	-1.9E		16:18	19:12	-1.6E
	21:48				22:12		
2 W		00:54	2.2F	17 Th		01:12	1.9F
	03:30	06:54	-2.7E		03:48	07:12	-2.0E
	10:06	13:24	3.1F		10:18	13:36	2.4F
	16:42	19:36	-2.1E		16:42	19:42	-1.7E
	22:36				22:42		
3 Th		01:36	2.4F	18 F		01:48	1.9F
	04:18	07:42	-2.7E		04:24	07:42	-2.0E
	10:48	14:06	3.1F		10:48	14:06	2.3F
	17:24	20:18	-2.2E		17:12	20:06	-1.7E
	23:18				23:06		
4 F		02:24	2.4F	19 Sa		02:18	1.8F
	05:12	08:24	-2.6E		05:00	08:12	-1.9E
	11:36	14:54	2.9F		11:12	14:42	2.1F
	18:06	21:00	-2.2E		17:36	20:36	-1.7E
					23:36		
5 Sa	00:06	03:12	2.3F	20 Su		02:54	1.7F
	06:06	09:12	-2.3E		05:36	08:42	-1.7E
	12:18	15:42	2.5F		11:36	15:12	1.8F
	18:42	21:42	-2.1E		18:06	21:00	-1.7E

September							
Day	Slack (h m)	Maximum (h m)	knots	Day	Slack (h m)	Maximum (h m)	knots
1 F		01:18	2.8F	16 Sa		01:24	2.2F
	04:06	07:24	-2.8E		04:06	07:12	-2.0E
	10:30	13:42	3.1F		10:18	13:36	2.3F
	16:48	19:48	-2.5E		16:24	19:30	-2.0E
	22:54				22:30		
2 Sa		02:00	2.8F	17 Su		01:54	2.2F
	05:00	08:06	-2.6E		04:42	07:48	-1.9E
	11:12	14:24	2.8F		10:42	14:06	2.1F
	17:24	20:30	-2.5E		16:48	19:54	-2.0E
	23:36				23:00		
3 Su		02:48	2.6F	18 M		02:24	2.0F
	05:48	08:48	-2.3E		05:18	08:12	-1.7E
	11:48	15:06	2.4F		11:12	14:30	1.8F
	18:00	21:06	-2.3E		17:18	20:24	-1.9E
					23:30		
4 M	00:18	03:36	2.3F	19 Tu		03:00	1.8F
	06:42	09:30	-1.8E		06:00	08:48	-1.5E
	12:30	15:54	1.9F		11:42	14:54	1.5F
	18:42	21:48	-2.0E		17:54	20:54	-1.8E
5 Tu	01:06	04:36	2.0F	20 W	00:06	03:42	1.6F
	07:36	10:24	-1.3E		06:48	09:24	-1.2E
	13:12	16:54	1.5F		12:12	15:12	1.1F
	19:24	22:36	-1.7E		18:30	21:36	-1.6E

Figure 9b. Annual NOAA Tidal Current predictions for July/August/September 2023 for Kennedy Entrance, AK. Data is organized by port and chronologically.

i. Add this difference to the given low water height and subtract this from the high water height to find the quarter points. Add this difference again to the lower of the two quarter points to find the midpoint. Plot these as the y-value for the corresponding x-value times found in step 3.i.

5. Find the difference between high and low water heights and divide by ten ("tenth").
   i. Add this to the height of the quarter point closest to high water. Subtract this from the height of the quarter point closest to low water. These will be your updated quarter points. Your midpoint will

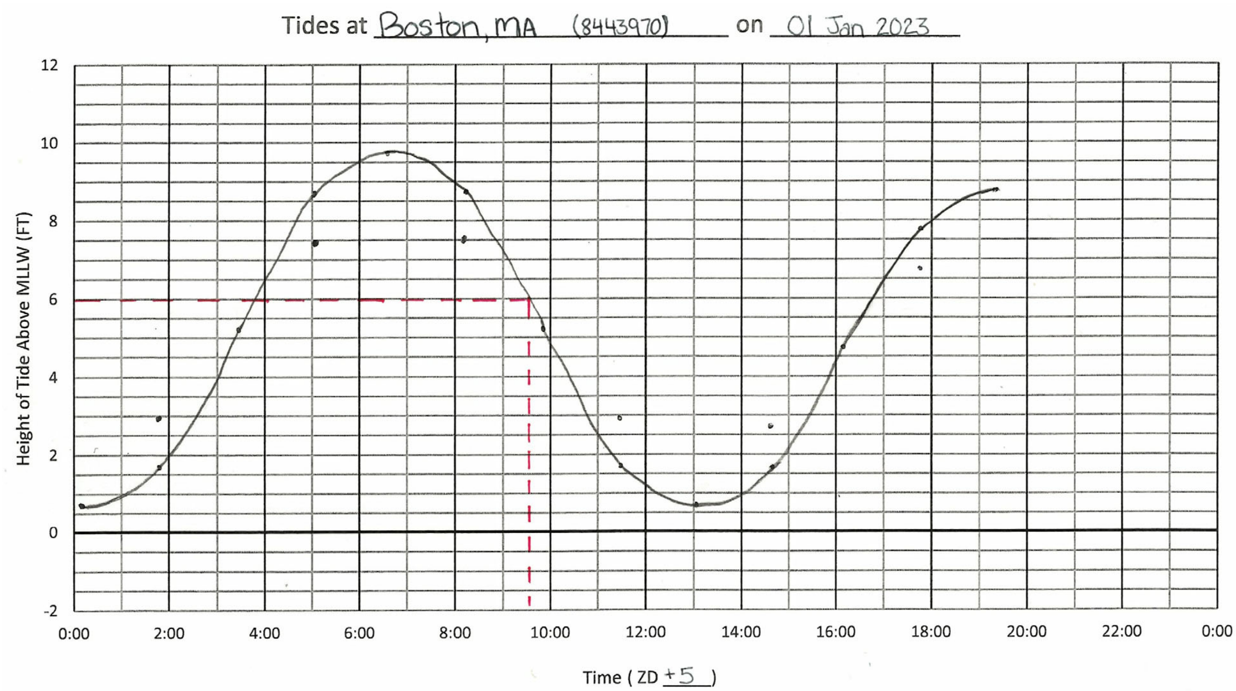


Figure 10. Completed Quarter-Tenth Method Graph for January 1, 2023, at Boston Harbor, MA

not change.

6. Plot updated quarter points and erase previous ones, if plotted.
7. Connect all plotted points sequentially with a smooth sine curve.
8. Repeat steps 1-7 between each high and low water to create a full tidal day prediction graph.

Example: *Plot a Quarter-Tenth Method graph for January 1, 2023, for Boston, MA. Determine the height of the tide at 0930 ZT. Use Figure 9a for tidal data.*

Solution:

1. *0642 ZT; +9.7 ft. (High Tide)*
   0017 ZT; +0.7 ft. (Low Tide)
2. *See Figure 10*
3. *0642 - 0017 ZT =* $\boldsymbol{6^h25^m}$
   $6^h25^m = 6.42^h$
   $6.42^h / 4 = 1.60^h = \boldsymbol{1^h36^m}$

   Low Tide: ***0017 ZT***
   0017 ZT + 1^h36^m *=* ***0153 ZT***
   0153 ZT + 1^h36^m *=* ***0329 ZT***
   0329 ZT + 1^h36^m *=* ***0505 ZT***
   High Tide: ***0642 ZT***
4. *High Tide: +9.7 ft*
   Low Tide: +0.7 ft
   Range: ***9.0 ft***
   9.0 ft / 4 = ***2.25 ft***

   Low Tide (0017 ZT): ***+0.7 ft***
   0153 ZT: +0.7 ft + 2.25 ft = ***+2.95 ft***
   0329 ZT: +2.95 ft + 2.25 ft = ***+5.2 ft***
   0505 ZT: +9.7 ft - 2.25 ft = ***+7.45 ft***
   High Tide (0642 ZT): ***+9.7 ft***
5. *High Tide: +9.7 ft*
   Low Tide: +0.7 ft
   Difference: ***9.0 ft***
   9.0 ft / 10 = ***0.9 ft***
6. *See* Figure 10
7. *See* Figure 10
8. *Repeat steps 1-7 for the rest of the day.*

Follow the x-axis of the graph to the desired time, then follow that time up until it intersects with the tidal curve. Follow that point of intersection to the y-axis to find the height of the tide.

Answer: *At 0930 ZT, the height of the tide will be +6.0 ft above the charted depth.*

D 11. Straight Line Method (Tidal Currents)

1. Obtain maximum current strengths and times, as well as slack water times from annual Tidal Current Tables or ATT.
2. Plot coordinates (times, strength) with flood currents shown as positive y-values and ebb currents shown as negative y-values. Plot slacks with a y-value of zero.
3. Connect coordinates sequentially with straight

lines.

4. Repeat steps 1-3 between each maximum current and slack waters to create a full current day prediction graph.

Example: *Plot a Straight Line Method graph for July 5, 2023, for Kennedy Entrance, AK. Determine the strength and direction of the current at 0630 ZT. Use Figure 9b for current data.*

Solution:

1. Max: ***0154 ZT**, **2.0 kts (flood)***
Slack (high water): ***0424 ZT***
Max: ***0748 ZT**, **2.6 kts (ebb)***
Slack (low water): ***1106 ZT***

2. *See Figure 11 for steps 2-4*

Follow the x-axis of the graph to the desired time, then follow that time up until it intersects with the current line. Follow that point of intersection to the y-axis to find the speed of the current.

Answer: *At 0630 ZT, 1.7 kts of current will flow toward 110°T (ebb).*

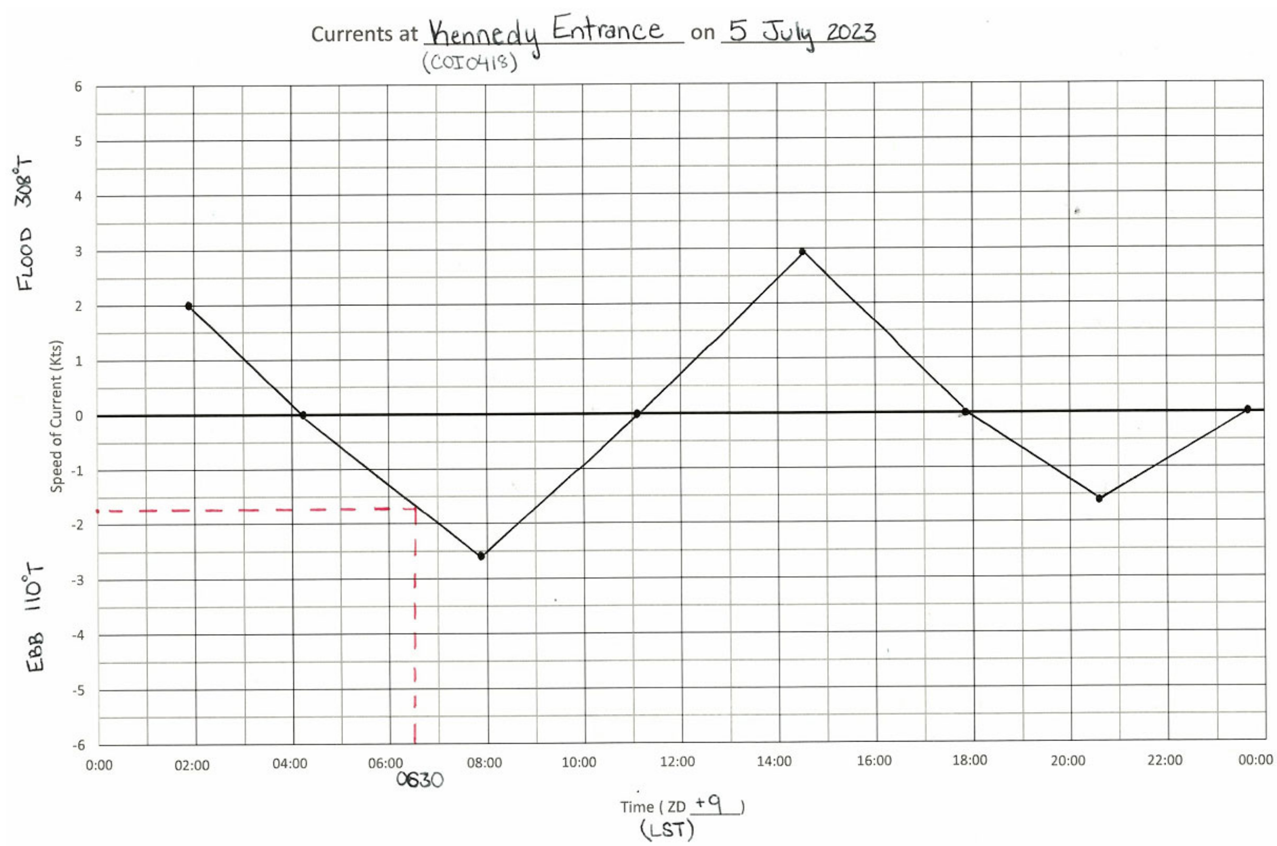


Figure 11. Completed Straight Line Method Graph for currents on Jul 5, 2023, at Kennedy Entrance, AK.

D 12. Admiralty Total Tide

When NOAA tide and tidal current prediction data is unavailable, specifically when operating outside the United States and its territories, the computer program Admiralty Total Tide (ATT) will be utilized. This non-web-based program has data for over 7,000 tidal ports and over 3,000 tidal streams, allowing for accurate predictions without internet connectivity.

Updates are applied regularly and must be installed when a new version is received onboard to ensure the most accurate tide and tidal current information is used. ATT installation discs can be ordered via the government supply system for U.S. Government vessels, and products can also be purchased through an authorized Admiralty distributor.

Tidal information is contained in either standard ports (indicated by red squares) or secondary ports (indicated by blue or yellow squares). Tidal current information is contained in tidal streams (indicated by purple arrows). The homepage is centered on a scrollable world map with a geographical index on the left side of the screen and a numerical port index below. Tide and tidal current stations can be selected by map, geographical area, port name, or index number. Tidal stations and tidal current streams can provide maximum high water, minimum low water, and maximum ebb and flood current times predicted down to the minute.

D 13. Celestial Navigation

Government Navigators have fewer options but more requirements than merchant mariners in celestial navigation. The U.S. Navy still trains its navigation experts, both enlisted Quartermasters and officer Navigators, to complete a Celestial Day's Work in Navigation (DWIN) in a very similar manner to Chapter 20, Section 2021. The U.S. Navy has chosen to teach analog computations techniques for the practice of celestial navigation, rather than relying solely on electronic systems, because these longhand processes lay the foundation for subsequent mastery of celestial navigation, rather than just typing numbers into a computer program.

All U.S. Government ships must be able to accomplish their missions and transit back to the closest U.S. Navy base, with or without all of their electronic systems. For this reason, the U.S. Navy will for the forseeable future continue to teach both the analog completion of Celestial DWIN using strip forms and hardcopy publications, as well as the digital computation using its only authorized celestial navigation software, **STELLA (System To Estimate Latitude and Longitude Astronomically).**

D 14. Sight Reduction Procedures

Developing a practical procedure to reduce celestial sights consistently and accurately is essential. Sight reduction involves several steps. An accurate sight reduction requires that each step be concisely and accurately performed. Sight reduction tables reduce the mathematics involved as much as possible to addition and subtraction. Careless errors, however, can render the LOP inaccurate, even if deduced from the most skillfully measured sights. The Navigator must work methodically to avoid errors.

Naval Navigators will most likely use OPNAV 3530/1, *U.S. Navy Navigation Workbook*, which contains "strip forms" to aid in the reduction of sights using either NGA *Pub. 229* or *Pub. 249* with either the *Nautical Almanac* or the *Air Almanac*. OPNAV 3530/1 also contains strip forms to aid in determining the ship's latitude by Polaris and the local times of Sunrise, Sunset, Moonrise, and Moonset using data from either the *Nautical Almanac* or the *Air Almanac*. The *Nautical Almanac* includes a strip form designed specifically for use with its concise sight reduction tables. Use of other strip forms is authorized with the proviso that they become an official part of the record for the workbook being used.

Figure 14 reproduces the OPNAV 3530/1 strip form for sight reduction using the *Nautical Almanac* and *Pub. 229*. Working from top to bottom, the entries are as follows:

Date: The UT date of the sight.

Body: The name of the body whose altitude was measured. Indicate whether the upper or lower limb was measured if the body was the Sun or the Moon.

GMT: (Greenwich Mean Time) The UT (GMT is an outdated name for UT) of the observation. The UT is the *Watch Time* of the observations adjusted for the *Watch Correction* and *Zone Description* (see Chapter 17).

IC: (Index Correction) The instrumental correction for the sextant used. Chapter 15 discusses sextant instrument errors and adjustments.

D: (Dip) Dip correction is a function of the observer's height of eye and atmospheric refraction. Its magnitude is determined from the Dip Table on the inside front cover of the *Nautical Almanac*.

Sum: The sum of *IC* and *D*.

hs: (Sextant Altitude) The altitude of the body measured by the sextant.

ha: (Apparent Altitude) The sum of *Hs* and the *IC* and *D* corrections.

Alt Corr: (Altitude Correction) Every observation requires an altitude correction. This correction is a function of the apparent altitude of the body. The *Nautical Almanac* contains tables for determining these corrections. The tables for the Sun, planets, and stars are located on the inside front cover and facing page, pages A2 and A3. The tables for the Moon are located on the back inside cover and preceding page, pages xxxiv and xxxv.

These tables are based on observations taken under "standard" weather conditions: temperatures near 50º F and air pressures near 1010mb. If observations are taken in conditions that deviate much from this, an additional altitude correction is needed; see the *Nautical Almanac* table on page A4.

Note that the correction found on A4 is to be applied in addition to those found on pages A2, A3, xxxiv, or xxxv.

Add'l Corr/Moon HP Corr: (Additional Correction/Moon Horizontal Parallax Correction) An additional correction is required for sights of Mars, Venus, and the Moon. It adjusts for the phase and parallax of these bodies. The correction is a function of the body observed, the epoch of observation, and *Ha*. The corrections for Venus and Mars are listed inside the front cover of the *Nautical Almanac*. These corrections change from year to year. The correction for the Moon is a function of the Moon's *Ha*, its *HP*, and whether the upper, *U*, or lower, *L*, limb was observed. The tables for this correction are located inside the back cover of the *Nautical Almanac* and on the preceding page. Enter the table using the appropriate values for *Ha* and *HP*, and then choose the value associated with the *L* or *U* column as appropriate. If the upper limb was observed, subtract 30' as well.

Ho: (Observed Altitude) Add *Ha*, the Altitude Correction, and the Additional Correction or Moon *HP* Correction, as appropriate. The result is the observed altitude, *Ho*.

GHA (h): (Tabulated Greenwich Hour Angle, hours) The tabulated value for the whole hour immediately preceding the time of the sight observation. For the Sun, the Moon, or a planet, extract the tabulated value for that body's Greenwich Hour Angle, GHA, from the daily pages of the *Nautical Almanac*. For example, if the sight was obtained at

OPNAV 3530/40 (4-73) H.O. 229 NAUT ALM	NAVIGATION WORKBOOK OPNAV 3530/1 (Rev. 8-01)
Date	DATE/DR POSIT
Body	
GMT	
IC	
D	
Sum	
hs	
ha	
Alt Corr	
Add'l Corr Moon HP/Corr	
Ho	
GHA (h)	
Incre (m/s)	
v/v Corr SHA	
Total GHA	
± 360°	
aλ (+E, –W)	
LHA	
Tab Dec	
d# / d cor	
True Dec	
a LAT Same Contrary	
Dec Inc / d	
Tens / DSD	
Units / DSD Corr	
Total Corr	
Hc (Tab)	
Hc (Comp)	
Ho	
a	
Z	
Zn	
Fix Lat	
Long	M
Fix Time	
Sounding	
Signature	

Figure 14. Sight reduction strip form for use with the Nautical Almanac and Pub 229.

$13^h50^m45^s$ UT, extract the GHA value for 13^h. For a star sight reduction, extract the tabulated value of the GHA of Aries ♈.

Incre (m/s): (Increments, minutes/seconds) The GHA increment is an interpolation factor, correcting for the time that the sight differed from the whole hour. For example, if the sight was obtained at $13^h50^m45^s$ UT, this increment correction accounts for the 50 minutes and 45 seconds after 13^h. The increment value is tabulated in the Increments and Corrections tables on pages ii through xxxi in the *Nautical Almanac*. The entering arguments are the minutes and seconds after the hour. Select the correction from the appropriate column. Use the column labeled Aries for sights of stars.

v/v Corr/SHA: (v/v Correction/Sidereal Hour Angle) The true rate of motion in hour angle for the Moon and planets usually varies from the mean motion used to determine the increments. The parameter *v* is the difference between the mean and true motion in arc minutes per hour. The change in hour angle arising from *v* of the body at the time of the sight observation is accounted for with the v correction. The value of *v* for a planet sight is found at the bottom of the planet's column in the daily pages of the Nautical Almanac. The value of *v* for the Moon is located directly beside the tabulated hourly GHA values on the daily pages of the *Nautical Almanac*. A body's *v* is positive unless listed with a negative sign. Enter the value for *v* on the left-hand side of the strip form. The *v* correction is found using the Increments and Correction tables on pages ii through xxxi in the back of the *Nautical Almanac*. Enter the table using the observation time minutes. Find the value in the "*v* or *d*" columns corresponding to the value of *v* for the observation time. Enter the corresponding correction on the right-hand side of the strip form with the same sign as *v*.

The Sidereal Hour Angle (SHA) is the difference between the GHA of a star and the GHA of Aries. The SHA of a star changes very slowly. The SHA's of the 57 navigational stars are listed, in alphabetical order of the stars' names, in the star column of the daily pages of the Nautical Almanac. The mean monthly SHA's of 173 stars, including the 57 navigational stars, are listed in order of SHA on pages 268 through 273 of the Nautical Almanac. Enter the SHA in place of the v correction in the strip form if reducing a star sight.

Total GHA: The total GHA is the sum of the tabulated GHA, the GHA increment, and either the *v* correction or the star's SHA.

±360°: Since the LHA will be determined by subtracting or adding the assumed longitude to the GHA, adjust the GHA by 360º if needed to facilitate the addition or subtraction.

Rule of Thumb:

In East Longitudes, LHA = GHA + Longitude (-360º as necessary)

In West Longitudes, LHA = GHA - Longitude (+360º as necessary)

Example: For a longitude of 090º East and GHA of 300º LHA = GHA + Longitude - 360º (300º + 090º = 390º - 360º = 030º).

aλ (+E, -W): (Assumed Longitude) Choose an assumed longitude, aλ. If the vessel is West of the prime meridian, LHA = GHA - aλ, where LHA is the Local Hour Angle. If the vessel is East of the prime meridian, LHA = GHA + aλ. The aλ is chosen so that it is the longitude closest to that DR longitude where the LHA is a whole degree.

LHA: (Local Hour Angle) The LHA is the hour angle of the observed body at aλ. The LHA is GHA - aλ, for West longitudes and GHA + aλ for East longitudes. Note that this should be a whole degree, else you have chosen the aλ incorrectly.

Tab Dec: (Tabulated Declination) Obtain the tabulated declination for the Sun, Moon, stars, or planets from the daily pages of the Nautical Almanac. The declination values for the Sun, Moon, and planets are listed in hourly increments. Enter the declination value for the whole hour immediately preceding the sight for these bodies. For example, if the sight is at $12^h58^m40^s$, enter the tabulated declination for 12^h. The declinations of the 57 navigational stars are listed, in alphabetical order of the stars' names, in the star column of the daily pages of the Nautical Almanac. The mean monthly declinations of 173 stars, including the 57 navigational stars, are listed in order of SHA on pages 268 through 273 of the Nautical Almanac.

d#/d cor: (Declination Change/Declination Correction) The Sun's, Moon's, and planets' declinations change with time. The parameter *d* is the change in declination in arc minutes per hour. The change in declination of the body at the time of the sight observation is accounted for with the *d* correction. The value of *d* for a planet sight is found at the bottom of the planet's column in the daily pages of the *Nautical Almanac*. The value of *d* for the Moon is located directly beside the tabulated hourly declination values in the daily pages of the *Nautical Almanac*. Enter the value for *d* on the left-hand side of the strip form. The sign of the d correction is determined by observing the trend of declination value. For example, for a sight taken at $12^h30^m00^s$, compare the declination values for 12^h and 13^h and determine if the declination value has increased or decreased. If it has increased, the *d* correction is positive; if it has decreased, the *d* correction is negative. The magnitude of the *d* correction is found using the Increments and Correction tables on pages ii through xxxi in the *Nautical Almanac*. Enter the table using the observation time minutes. Find the value in the "*v* or *d*" columns corresponding to the value of *d* for the observation time. Enter the corresponding correction on the right-hand side of the strip form. The rate of change in the declination of the stars is so small that their sights do not require a *d* correction.

True Dec: (True Declination) The sum of the tabulated declination and the d correction is the true declination.

aLAT Same Contrary: (Assumed Latitude) Choose the whole degree of latitude closest to the vessel's DR latitude as the assumed latitude, *aLAT*. If the assumed latitude and declination are both North or both South, label the assumed latitude *Same*. If one is North and the other is South, label the assumed latitude *Contrary*.

Dec Inc / d: (Declination Increments) Two of the three arguments used to enter the main table of *Pub. 229*, LHA and *aLAT*, are whole degree values. The third argument, declination, is interpolated in *Pub. 229*. The method for interpolating declination is described on pages X-XIV of each volume of *Pub. 229*. The interpolation tables are located on the inside of the front cover and following page and inside of the back cover and preceding page of each volume of *Pub. 229*.

Interpolation is done using the declination increment, *d*. (This *d* differs from the *d* factor in the *Nautical Almanac*.) From the main table of *Pub. 229*, extract the value of *d* for the tabular declination value preceding the body's declination. For example, if the body's declination is 30º 35.1', then record the tabular values in the row for Dec. = 30º. If the value for *d* is printed in italics and followed by a dot, then second-difference interpolation is required to maintain precision. In this case record the preceding and following entries for the value of *d* as well. For example, for LHA = 28º, *aLat* = 15° Same, Dec. = 16º, the entry for *d* is +0.8'. The preceding entry is +2.8'˙, and the following entry is -1.3'˙. Record all three entries in order.

Tens/DSD: (Tens/Double Second Difference) If *d* is greater than 10', then extract the interpolated value for the tens of *d* from the interpolation tables in *Pub. 229*. Refer to the description for use of the interpolation tables on pages XI-XII of any volume of *Pub. 229* for details.

Units/DSD Corr: (Units/Double Second Difference Correction) Extract the interpolated value for the units of *d* from the interpolation tables in *Pub. 229*. Refer to the description for use of the interpolation tables on pages XI-XII of any volume of P*ub. 229* for details. If a second difference correction is required, subtract the value of the following entry for *d* from the preceding value. For example, if the preceding entry is +2.8', and the following entry is -1.3', then the result is 2.8' - (-1.3') = 4.1'. Use this value to enter the appropriate part of the second difference portion of the interpolation table in *Pub. 229*. Refer to the description for the use of the second difference interpolation on page XIV of any volume of *Pub. 229* for details. Add the second difference correction to the units correction before entering it in the strip form. Failure to include the second difference correction may result in an error of as much as 2.1' in the final value of *Hc*.

Total Corr: (Total Correction) The sum of the tens and units corrections is the total correction.

Hc (Tab): (Computed Height, Tabulated) The tabulated value of *Hc* from the same entry in *Pub. 229* from which *d* was extracted.

Hc (Comp): (Computed Height) The sum of *Hc*

(Tab.) and the total corrections is *Hc* (Comp.).

Ho: (Observed Altitude) The observed altitude calculated above.

a: (Altitude Intercept) The absolute value of the difference between *Hc* and *Ho* is the altitude intercept, *a*. If *Ho* is greater than *Hc*, then label *a* as Toward. If *Hc* is greater than *Ho*, then label *a* as Away. Remember, "*computed greater away*".

Z: (Azimuth Angle) The tabulated value of the azimuth angle, *Z*, is extracted from the same entry in *Pub. 229* from which *Hc* and *d* were extracted. Interpolation is not required.

Zn: (True Azimuth) The azimuth, *Z*, is the angular distance between the direction towards the observed body and the direction towards the elevated pole. The true azimuth, *Zn*, is the angular distance measured Eastward from the direction towards the North Pole to the direction towards the observed body. The value of *Zn* is a function of *Z*, LHA, and whether the observer is located North or South of the equator.

N. Lat. { L.H.A. greater than 180° .....Zn=Z
L.H.A. less than 180°............Zn=360°–Z

S. Lat. { L.H.A. greater than 180° ....Zn=180°–Z
L.H.A. less than 180°...........Zn=180°+Z

Fix, Lat, Long, Fix Time: Enter the point of intersection and time when two or more LOPs are plotted to determine a fix. The time of the fix is not necessarily the time of the sight because LOPs may be advanced or retired based on the ship's ordered course and speed. The diagram may be used to sketch the *Zn*'s and *a*'s used to determine the fix, a process outlined in Section 2003.

Sounding: If a sounding is available, its value may be entered here.

Signature: The sight reduction is a part of the ship's official record and must be signed by the Navigator.

D 15. Computer Sight Reduction

The purely mathematical process of sight reduction is an ideal candidate for computerization, and several different hand-held calculators, apps, and computer programs have been developed to relieve the tedium of working out sights by tabular or mathematical methods. The civilian Navigator can choose from a wide variety of hand-held calculators and computer programs that require only the entry of the DR position, measured altitude of the body, and the time of observation. Even knowing the name of the body is unnecessary because the computer can identify it based on the entered data. The government Navigator only has one option for computer sight reduction: STELLA.

D 16. STELLA

The information in this section is meant to give a broad overview of the U.S. Government program celestial navigation software known as **STELLA (System To Estimate Latitude and Longitude Astronomically)**, which U.S. Navy and Coast Guard Navigators can access. The Astronomical Applications Department of the U.S. Naval Observatory developed STELLA in response to a Navy requirement.

When perfect sights are inputted, STELLA algorithms provide a fix accuracy of one arc-second on the Earth's surface, a distance of about 30 meters. These algorithms consider the Earth's oblateness, vessel movement during sight-taking, and other factors not fully addressed by traditional methods. While this accuracy is far better than can be obtained using a sextant, it does support possible naval needs for automated navigation systems based on celestial objects. With a few months of daily practice, a competent mariner can consistently attain fixes within a mile or two of their actual position.

STELLA can perform almanac functions, position updating/DR estimations, celestial body rise/set/transit calculations, compass error calculations, sight planning, and sight reduction; online help and a user's guide are included (most of the information about STELLA in these sections comes from the user's guide). Sunrise/Sunset times are accurate to a minute or two in the latitude range 70ºN to 70ºS. Moonrise/Moonset times are accurate to a minute or two in the latitude range 60ºN to 60ºS. Their accuracy degrades gradually at higher latitudes. A maximum of 25 sextant sights can be recorded in the log after the last fix. STELLA is now automatically distributed to each naval ship; other Navy users may obtain a copy by contacting the below address:

Superintendent
U.S. Naval Observatory
Code: AA/STELLA
3450 Massachusetts Ave. NW
Washington, DC, 20392-5420

D 17. Celestial Fixes in STELLA

The **STELLA LOP (Line of Position) Plot** is used to record sextant altitude observations and then to use these observations to compute a celestial fix. The observations can be spread across as many as three course or speed changes. If enough observations (with a suitable spread) are available, corrections to course and speed will be computed along with the fix. A latitude-longitude plot is generated showing all the LOP's) contributing to the fix (advanced or retired to the time of the fix), along with the fix location and its error ellipse. The observation reduction of each LOP can be displayed in a 'strip form' format (see Figure 18). The plot can be used to edit the observation set interactively,

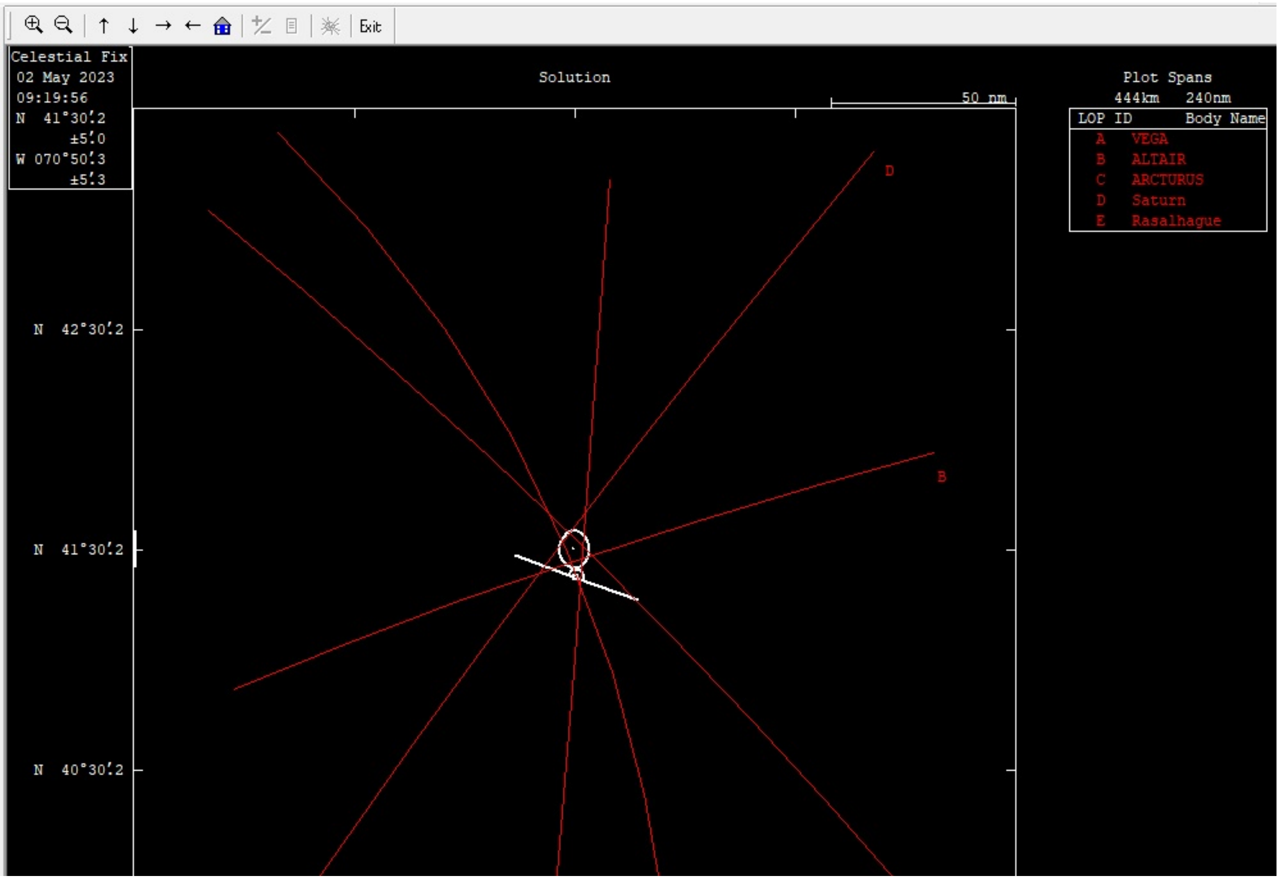
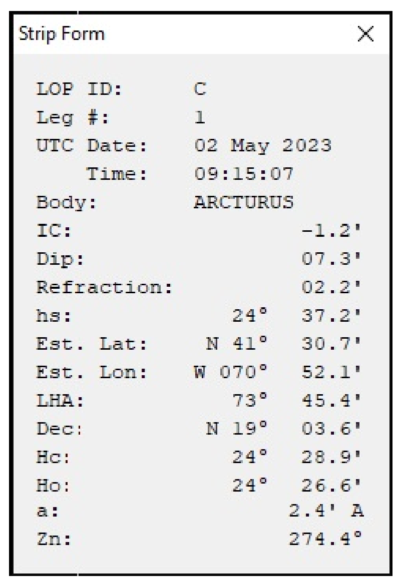


Figure 17. STELLA LOP Plot.

and the fix can be recomputed until the results are satisfactory.

The DR position of the ship is in the center of the plot. The vessel course line is also shown on the plot (in white) for the time selected for the fix. The course line indicates constant vessel motion along the DR track from one hour before until one hour after the time of the DR positions. The linear scale of the plot is indicated above the top right corner of the plot. Every LOP in the plot is assigned a letter ID. The table at the right of the plot identifies LOP labels with observed bodies.

After a solution for the celestial fix has been calculated, the STELLA solution plot shows all of the previous information but now also includes the fix position (see Figure 17). If more than two observations were included, the error ellipse is also shown. The fix solution (date, time, fix latitude, fix longitude, and errors of the fix) is displayed in the upper left corner of the LOP plot.



Strip Form

LOP ID:	C
Leg #:	1
UTC Date:	02 May 2023
Time:	09:15:07
Body:	ARCTURUS
IC:	-1.2'
Dip:	07.3'
Refraction:	02.2'
hs:	24° 37.2'
Est. Lat:	N 41° 30.7'
Est. Lon:	W 070° 52.1'
LHA:	73° 45.4'
Dec:	N 19° 03.6'
Hc:	24° 28.9'
Ho:	24° 26.6'
a:	2.4' A
Zn:	274.4°

Figure 18. STELLA Strip Form.

D 18. STELLA Strip Form

A strip form for a reduced sight is the STELLA counterpart of the form used with the U. S. Navy Navigation Workbook. There are certain differences, but many entries are the same for essential data. This STELLA strip form (see Figure 18) contains much of the same information as the strip form. STELLA lists the date and time of the sight, the estimated position of your vessel at the time of the sight, the LHA, Dec, *Ho*, *Hc*, *a*, and *Zn* of the body, and the *IC*, dip, and refraction corrections.

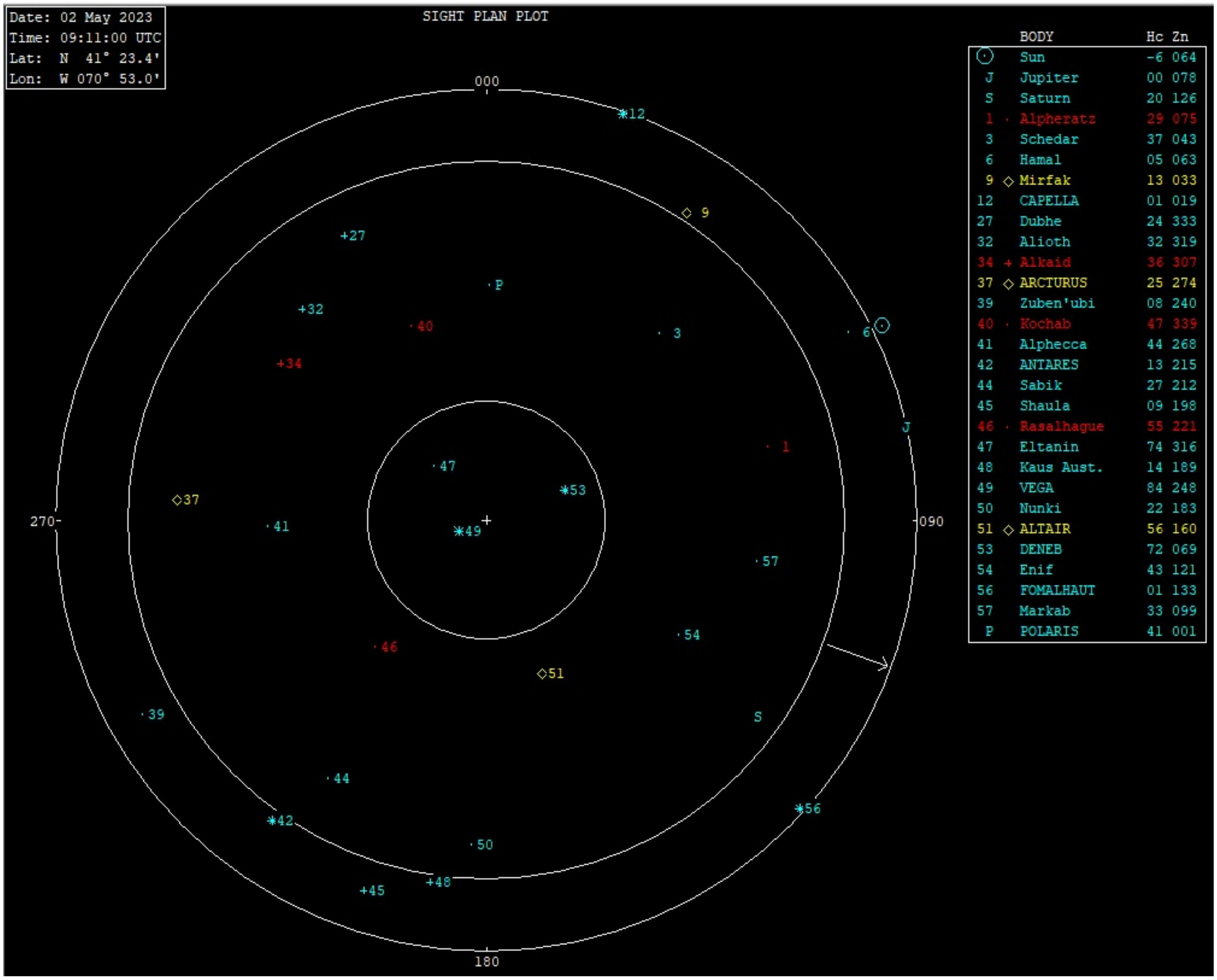


Figure 19a. STELLA Sky Chart for morning civil twilight on May 2, 2023, in Newport, RI.

D 19. Aids to Sight Planning

STELLA also includes a sight planning utility and automatically logs all data entered for future reference. Given an external initial fix, it can provide a “Sky Chart” or “Selected Stars.” A **Sky Chart** (see Figure 19a) is a picture of the sky at an instant in time and contains many stars, planets, the Sun, and the Moon, including full degrees of computed altitude (*Hc*) and true bearing (*Zn*). The Sky Chart has two major parts. The Sky Chart plot is displayed on the left side of the window, and a list of the bodies shown is displayed on the right side of the screen. The Sky Chart is a polar diagram centered on the vessel's zenith at the date and time chosen for planning data. Outward from the zenith, concentric circles are displayed at 65, 15, and 0 degrees altitude (the horizon). An arrow indicating the course is displayed between the circle at 15 degrees altitude and the horizon.

The diagram shows relative positions for any of the 57 navigational stars, Polaris, Sun, Moon, and four navigational planets above the horizon at the specified date and time. If the Sun is below the horizon (altitude between 0 and -6 degrees), its symbol appears tangent to the horizon at the proper azimuth. Each star is identified by the *Nautical Almanac* star number (except for Polaris, which is denoted by its initial letter). The symbol size is correlated with the brightness of a given star: a large asterisk (*) for stars brighter than 0.5 magnitude (49 VEGA in Figure 19a); a small asterisk (*) for stars between 0.5 and 1.0 magnitude (42 ANTARES); a plus sign (+) for stars between 2.0 and 1.5 magnitude (27 Dubhe); and a dot (·) for stars fainter than 2.0 magnitudes (41 Alphecca). Yellow open diamonds ◇ identify stars recommended for the 3-star fix (9 Mirfak, 37 ARCTURUS, and 51 ALTAIR in Figure 19a). The other four *Pub. 249* selected stars are displayed in red (1 Alpheratz, 34 Alkaid, 40 Kochab, and 46 Rasalhague in Figure 19a). Planets are designated by initial letters: V = Venus, M = Mars, J = Jupiter, S = Saturn. A circle with a dot at the center ⊙ indicates the Sun's position. The symbol for the Moon ☾ is an approximate representation of its phase. The illuminated portion of the Moon's disk is in proper orienta-

```
                         SIGHT PLANNING - STARS

                                 o   ,
                           Lat:   N 41 23.4
                           Long:  W070 53.0
                           Ht:       56 ft.
 02 May 2023
    |    <>    |          |    <>    |          |    <>    |          |          |
    | Mirfak   |Alpheratz| ALTAIR   |Rasalhag.|ARCTURUS | Alkaid   | Kochab   |
 UTC|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|
 h m| o  ,    o| o  ,    o| o  ,    o| o  ,    o| o  ,    o| o  ,    o| o  ,    o|
0911|13 25 033|29 07 075|56 05 160|54 54 221|25 15 274|35 59 307|46 30 339|CTw
0915|13 50 034|29 51 076|56 20 162|54 24 223|24 30 274|35 23 308|46 14 339|CTw
0919|14 15 034|30 35 076|56 34 164|53 53 224|23 45 275|34 47 308|45 58 339|CTw
0923|14 40 035|31 19 077|56 46 165|53 21 226|23 00 276|34 12 308|45 41 339|CTw
0927|15 06 035|32 03 078|56 56 167|52 49 227|22 16 276|33 37 309|45 25 339|CTw
0931|15 32 036|32 47 078|57 06 169|52 15 228|21 31 277|33 02 309|45 09 339|CTw
0935|15 58 036|33 31 079|57 14 171|51 41 230|20 46 278|32 27 309|44 52 339|CTw
0939|16 25 036|34 16 079|57 20 173|51 07 231|20 01 278|31 52 310|44 36 339|Day
0943|16 52 037|35 00 080|57 25 174|50 31 232|19 17 279|31 17 310|44 19 339|Day
0947|17 19 037|35 44 080|57 29 176|49 55 233|18 32 279|30 43 311|44 03 339|Day
0951|17 47 038|36 29 081|57 31 178|49 19 234|17 47 280|30 09 311|43 46 339|Day
0955|18 15 038|37 14 082|57 32 180|48 42 236|17 03 281|29 35 311|43 30 339|Day
0959|18 43 039|37 58 082|57 32 182|48 04 237|16 19 281|29 01 312|43 13 339|Day
    |          |    <>    |          |    <>    |          |          |    <>    |
    | Mirfak   |Alpheratz|   Enif   | ALTAIR   |Rasalhag.|Alphecca | Kochab   |
 UTC|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|
 h m| o  ,    o| o  ,    o| o  ,    o| o  ,    o| o  ,    o| o  ,    o| o  ,    o|
1003|19 11 039|38 43 083|50 56 136|57 29 184|47 26 238|34 41 277|42 57 339|Day
1007|19 40 040|39 28 083|51 27 137|57 26 185|46 48 239|33 56 277|42 40 339|Day
1011|20 09 040|40 13 084|51 57 139|57 21 187|46 09 240|33 12 278|42 24 339|Day

                         SUN, MOON, PLANETS

 02 May 2023
    |Aries|   Sun    |   Moon    |   Venus    |    Mars    |  Jupiter  |  Saturn   |
    |     |          | 88% ill.| -4.2 mag.| +1.3 mag.| -2.0 mag.| +1.0 mag.|
 UTC| LHA |   Hc   Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|  Hc    Zn|
 h m|   o |  o  ,   o| o  ,    o| o  ,    o| o  ,    o| o  ,    o| o  ,    o|
0911| 287 |-05 46 064|          |          |          | 00 03 078| 19 54 126|
0915| 288 |-05 06 064|          |          |          | 00 47 078| 20 30 127|
0919| 289 |-04 25 065|          |          |          | 01 31 079| 21 06 127|
0923| 290 |-03 44 066|          |          |          | 02 15 080| 21 42 128|
0927| 291 |-03 03 066|          |          |          | 03 00 080| 22 17 129|
0931| 292 |-02 22 067|          |          |          | 03 44 081| 22 52 130|
0935| 293 |-01 40 068|          |          |          | 04 29 082| 23 26 131|
0939| 294 |-00 58 068|          |          |          | 05 14 082| 24 00 132|
0943| 295 |-00 16 069|          |          |          | 05 58 083| 24 33 133|
0947| 296 | 00 26 070|          |          |          | 06 43 084| 25 06 134|
0951| 297 | 01 08 070|          |          |          | 07 28 084| 25 39 134|
0955| 298 | 01 51 071|          |          |          | 08 13 085| 26 11 135|
0959| 299 | 02 33 072|          |          |          | 08 58 085| 26 42 136|
1003| 300 | 03 16 072|          |          |          | 09 43 086| 27 13 137|
1007| 301 | 03 59 073|          |          |          | 10 28 087| 27 43 138|
1011| 302 | 04 42 074|          |          |          | 11 13 087| 28 13 139|
```

Figure 19b. STELLA Selected Stars for morning civil twilight on May 2, 2023, in Newport, RI.

tion with respect to the Sun.

A table to the right of the polar diagram provides the correspondence of star numbers and common star names. The table also correlates the names of solar system objects with the symbols used in the diagram. As in the Sky Chart, the *Pub. 249* selected stars are displayed in red and yellow. Stars recommended for use in a three-star fix are displayed in yellow, preceded by an open diamond symbol.

The UTC date, time latitude, and longitude are displayed in the upper left corner of the sky chart.

Selected Stars provides fewer celestial bodies but more details about each body. *Hc* is given in degrees and minutes, while Zn is still given in whole degrees. The **Sight Planning** table (see Figure 19b) has two parts. Star data are given in the upper half, while data for the Sun, Moon, and planets are found in the lower half. Star data cover one hour and are listed in four-minute intervals. This interval almost equals a one-degree increase in the Local Hour Angle of Aries. The time (UTC) for tabulated data is shown in the first column. The following seven columns give the altitude and azimuth for seven stars, with those recommended for a three-star fix having a diamond above the star name at the top of the column. Stars for this table are selected according to the criteria used in the *Pub. 249*. In the far right column is an indicator of available natural light available at each time. The word Day indicates daylight, CTw indicates civil twilight, and NTw indicates nautical twilight. A blank space signifies night.

The lower half of the table resembles the upper half but gives altitude and azimuth for the Sun, Moon, and navigational planets. Again, the UTC appears in the first column; the second column has the Local Hour Angle of Aries. Because these two quantities increase at slightly different rates, two consecutive values of the (rounded) LHA Aries may be the same or may differ by up to two degrees. Names of the navigational objects are at the top of each of the following six columns. The illumination of the Moon is found directly under its name. The percentage of the Moon's disk that sunlight illuminates is calculated for the first time and is listed in the time column. Any change in illumination through one hour would be imperceptible, except during an eclipse. The magnitudes of the planets are found directly under their names.

If numerical data for the Sun, a planet, or the Moon is missing from a column in the body of the table, the object or its upper limb is below the horizon, making it unavailable for use. However, coordinates of the Sun are given through civil twilight. If Venus or Jupiter is within 10 degrees of the Sun, or Mars or Saturn is within 15 degrees of the Sun, the words “near Sun” appear in place of *Hc* and *Zn*.

The table is generated for the vessel's position at the same time as shown on the first line of the table. No account is taken of vessel motion during the period covered by the table.