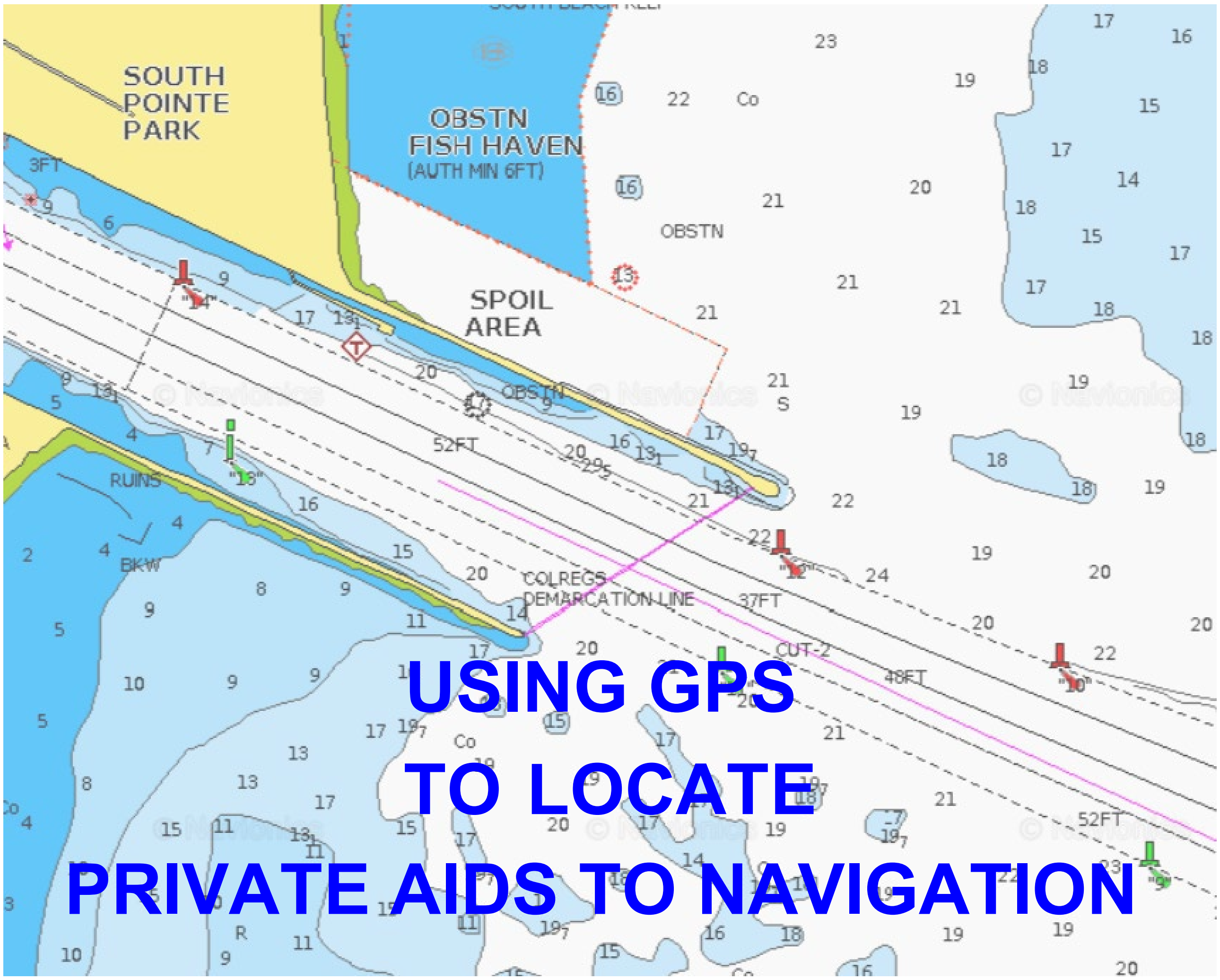
U. S. COAST GUARD AUXILIARY SEVENTH DISTRICT



USING GPS TO LOCATE PRIVATE AIDS TO NAVIGATION

This manual is not intended to, nor does it impose legally binding requirements on any party. The sole intent is to provide guidance to Auxiliarists engaged in private aid verification to achieve accuracy and precision of location measurements as close as possible to the Coast Guard standards for Federal Aids.

U.S.C.G AUXILIARY SEVENTH DISTRICT NAVIGATION SYSTEMS

D7NS 1003.C
OCTOBER 5, 2023

A. Objectives

1. The purpose of this guide is to help Auxiliarists use available GPS receivers to determine the position of Private Aids to Navigation (PATON) with an accuracy and precision as close as possible to the standards of the Coast Guard.

2. Read this document in conjunction with *U.S. Coast Guard Auxiliary Seventh District Field Guide to Locating PATON* and *Aids to Navigation – Locating Private Aids to Navigation – Determining if a PATON is in AP.* Those cover the locating standards of the Coast Guard. The CG uses an algorithm to determine if an aid is at AP or On Station. This algorithm is available to the Auxiliary via the *PATON LOCATION CALCULATOR* spreadsheet.

3. The purpose of locating aids is to verify they are as close as reasonably possible to their AP (Assigned Position in the Light List). However, being at a specific location is secondary to ensuring the actual location best marks the waterway, serves the purpose intended, and does not mislead the mariner about the navigable channel.

4. If an aid is not at AP, to be actionable, the report of that discrepancy must include:
   a. Is the aid marking good water?
   b. Is the channel marking good water?

5. When the Coast Guard locates a Federal Aid which is marking good water but not in AP, they can make the MPP (Most Probable Position) obtained from the fix become the AP in the Light List.

6. The purpose of accurately locating Private Aids is not to use the found location to change the Light List. The goal is to provide the Coast Guard with accurate position information so that they (or the Auxiliary when so tasked by the Coast Guard) can have the owners move their aids if not marking good water or submit the paperwork (Form 2554) for the correct location if marking good water.

B. GPS Receivers

1. Recreational-grade GPS receivers have the potential to take measurements with sufficient accuracy to locate PATON. Field testing on NGS benchmarks showed that recreational handheld receivers, in conditions free of lower atmospheric distortion, reflected signals, and without tree canopy or other obstruction, could achieve 11.0 feet 2DRMS error, with a range from 4 to 20 ft. This is well within the Coast Guard standard of 29.5 ft.

2. The key issues are:
   a. Proper technique
   b. Controlling for errors

3. Handheld GPS receivers have varying functionality Only WAAS equipped units are useable. The models listed below are examples, not a comprehensive list:
   a. Handheld receiver functioning as an external antenna for a mobile device. Connects via Bluetooth and requires a mobile app or feeds the location function of the device:

- Garmin Glo

b. Handheld receiver with built-in display and Bluetooth connection to a proprietary mobile app.

- Bad Elf Pro BE-GPS-2200

c. Handheld chartplotter:

- Garmin GPSMAP79 series

d. Handheld chartplotter with Bluetooth connection to a proprietary mobile app:

- Garmin GPSMAP 64 series

e. Handheld receiver with built-in display and Bluetooth connection to a proprietary mobile app. The receiver produces and logs the NMEA sequences required to do RTK (Real Time Kinetic) corrections in real time or through post processing:

- Bad Elf GNSS Surveyor BE-GPS-3300

f. Handheld chartplotters with Bluetooth connection to a proprietary mobile app. The receiver produces and logs the NMEA sequences required to do RTK (Real Time Kinetic) corrections in real time or through post processing:

- Garmin GPSMAP 66i/sr
- Garmin GPSMAP 86 series
- Garmin Montana 700 series

C. Proper Technique - Preparing for the Measurement

1. ***GPS Start State –*** the receiver must be in a “Hot Start” state (see Appendix A). A hot start requires that:

   a. The receiver has had time to download a valid almanac.

      i. The GPS almanac is a data set that every GPS satellite transmits. It describes the state of the entire GPS system and the coarse data (low resolution position) on every satellite. The almanac data guides the GPS receiver to locate a region of visible satellites. It also provides signals to calibrate GPS time to UTC. and to correct distortions caused by changes in the ionosphere. Transmission of an almanac requires 12.5 minutes. An almanac is valid with little dilution of precision for two weeks.

   b. The GPS has been active in the last 72 hours and knows the current time.

   c. The last fix is no more than 2 hours old.

   d. 5 or more satellites are in view with good signal strength and geometry and the receiver has valid ephemeris data from them.

      i. Each satellite transmits ephemeris data which helps GPS receivers obtain more precise fixes. It includes information about predicted and actual satellite location, time, satellite clock correction coefficients, age of data, satellite “health,” and predicted and actual satellite location valid for two hours before and after the ephemerides transmission. New messages transmit every 30 seconds.

D. Proper Technique - Taking the Measurement

1. ***Placement of the GPS receiver*** -place the receiver directly on the aid being located and hold it there until the measurement is complete.

2. ***Orientation of the GPS receiver*** – hold the receiver so that the antenna is in the correct orientation:

    a. For the Garmin Glo and the Bad Elf models, orient the device with the front facing up towards the sky (per manufacturer's recommendations).

    b. For receivers with a protruding antenna, orient the device vertically with the antenna pointing to the sky.

    c. For cell phones, the most common correct orientation is vertical with the back side away from the aid.

    d. If in doubt about the proper orientation, consult the manufacturer.

    e. Using a built-in GPS antenna in the wrong orientation can increase the position error by 50-100%.

3. ***Time to take the measurement***

    a. A GPS receiver in motion takes time to realize it has come to a stop. Field testing of the Garmin Glo and Bad Elf Pro involved walking them to a NGS benchmark while operating, then placing them on the marker. The time for the velocity to slow to 0 varied from several seconds to up to a minute.

    b. Manufacturer's recommended soak time:

        i. Garmin Support recommended a 2-minute soak (measurement time) to obtain an accurate reading.

        ii. Bad Elf conducted tests on a Bad Elf Pro and recommended a 30 second soak.

    c. Field Test Results

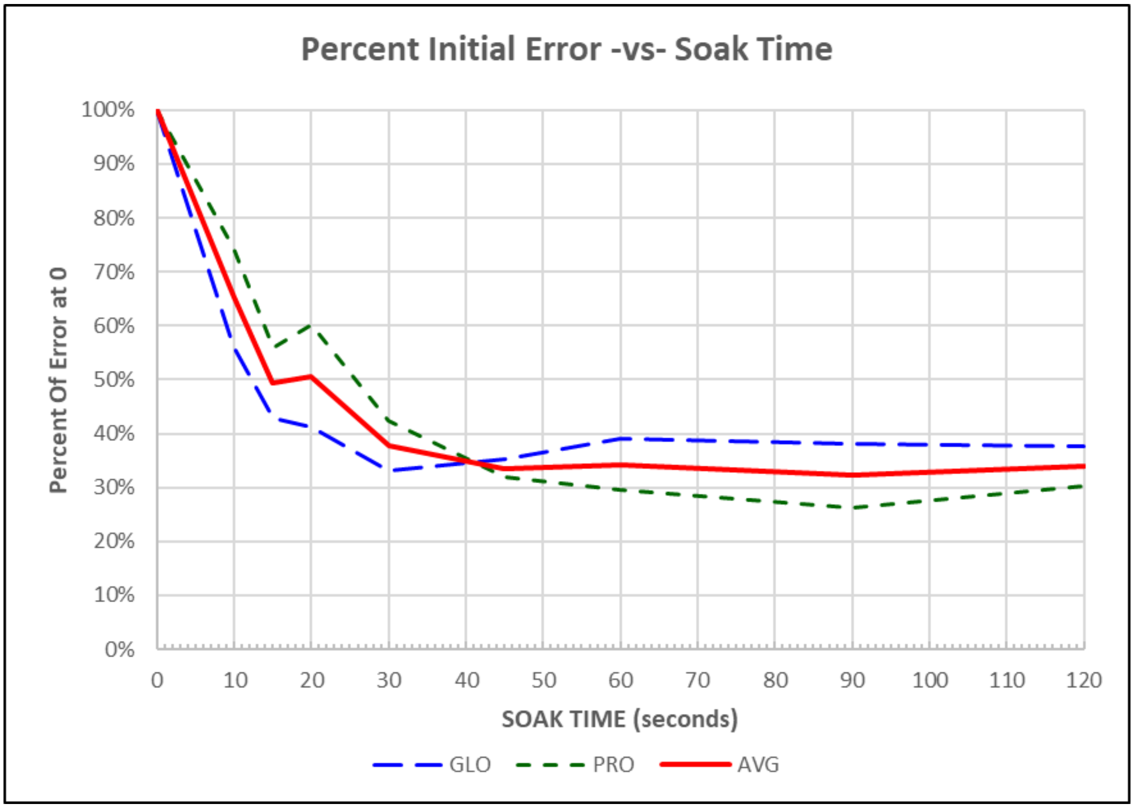
        i. Field testing used GPS receivers in a hot state placed on several NGS benchmarks (locations whose accuracy is known within a 2DRMS of 6.56 ft). Data logging used a 1 sec interval. The data in Figure 1 characterizes the Garmin Glo and the Bad Elf Pro.

        ii. The results showed the error at 30 seconds averaged 62% less that the error at 0 seconds (in other words, the 30 sec error was 38% of the T=0 error). Increasing the soak to 40 seconds reduced the error to 34%. Beyond that time, the value of additional soak was minimal up to 5-10 minutes.

        iii. A 30 -40 second soak produces optimal results. Better accuracy requires impractical times.

    a. Take a position fix at the 30 second mark or log the data (in an app or on the device) for review after the mission.

Figure 1



4. ***Safety – Boat Handling* - observe these essential safety precautions:**
    a. Maneuver the vessel into the wind and current whenever possible.
    b. Use fenders to protect the vessel.
    c. Maintain all-round watch.
    d. Do not make fast to the aid; do not grab hold onto the aid.
    e. A crewmember can use a swim safety hook to help hold the boat against the aid.
        i. Add floats to the pole so it will not sink if dropped.
        ii. Do not extend the pole more than necessary - it becomes a hazard to the crew.
        iii. Do not strain to hold the vessel in place – break off and try another approach.
        iv. Be prepared to disengage the hook immediately on command. Drop it if necessary.

5. ***Safety – Personal* - observe these essential safety precautions**:
    a. Do not reach hands outside the boat.
        i. A short board with handles for the verifier at the inboard end and a waterproof mounting for the receiver at the outboard end offers a good combination of control and safety.
        ii. Short poles, either from the GPS manufacturer or improvised also work. The disadvantage compared to a board is the difficulty of maintaining a fixed vertical orientation.

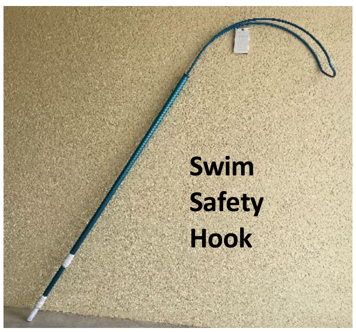
ii. Some verifiers favor long poles. All long poles challenge the verifier to maintain the receiver on the aid in the proper orientation during the measurement. District 7 does not recommend the use of long poles.

b. Personal Protective Equipment

i. Helmet - dayboards on PATON are often low enough to be in the way during a measurement. Approaching these aids requires the verifier to wear a helmet.

i. Gloves – despite the admonition to keep hands inside the boat, people tend to touch the pole to guide the vessel in, to hold it in place, or to fend off. Anyone tempted to touch a piling should wear gloves.

ii. Pads are more of a personal choice. Kneeling to hold the board/pole, bracing knees against the structure of the boat have convinced at least one verifier of the benefits of knee pads under the ODU pants. Forearm pads offer protection against hardware along the gunwale.



Board with handles – waterproof holder for GPS at outboard end. Easy to hold across the gunwale during measurements.

Short, extendable pole for Bad Elf.

Painter's pole,

Light bulb changer pole,

Swim hook pole.

Helmets

E. Controlling for Errors – Sources of Error

1. ***Sources of GPS error*** -Table 1 lists the sources of GPS error and the range of values.

Table 1

SOURCES OF GPS ERROR	
	Error Value (ft)
Satellite geometry - satellites low on horizon or clustered	**0 - 15**
Satellite errors - small clock errors and drift from predicted orbit	**13 - 16**
Upper atmosphere (ionosphere) effects	**13 - 98**
Lower atmosphere effects	**2 - 98**
Multi-path effects - signals reflected off obstructions	**3 - 7**
Receiver errors - internal clock, software & rounding	**3 - 33**

F. Controlling for Errors – External Methods of Correcting Error – Satellite-Based Augmentation Systems

1. The WAAS (Wide-Area Augmentation System), operated by the FAA, is the US version of SBAS (Satellite-Based Augmentation System). It uses precisely surveyed ground stations for monitoring and Wide-Area Master Stations to calculate satellite position, clock errors, and estimate upper atmosphere transmission time errors. Within 6.2 seconds of the calculation, the Master Stations transmit this data to 3 active geostationary satellites which broadcast the corrections to GPS receivers on the same frequency used by GPS satellites. The specified accuracy of the WAAS system is 7 meters (23 feet). In practice, it can achieve 1.5 – 3 meters accuracy, absent lower atmospheric disturbances and reflected signals.
2. WAAS covers the continental US, most of Canada and Mexico, and Alaska. Coverage is available on the Atlantic coast and in the Gulf of Mexico.
3. Most recreational receivers have WAAS, but it may need to be manually enabled in settings to operate.
4. WAAS corrections affect *ONLY* these GPS errors:
   a. Satellite errors – satellite clock and orbit errors
   b. Wide area upper atmospheric error
5. WAAS corrections *DO NOT* affect these GPS errors:
   a. Satellite geometry (dilution of precision)

b. Localized lower atmosphere errors

c. Multi-path effects (reflected signals)

d. Receiver errors

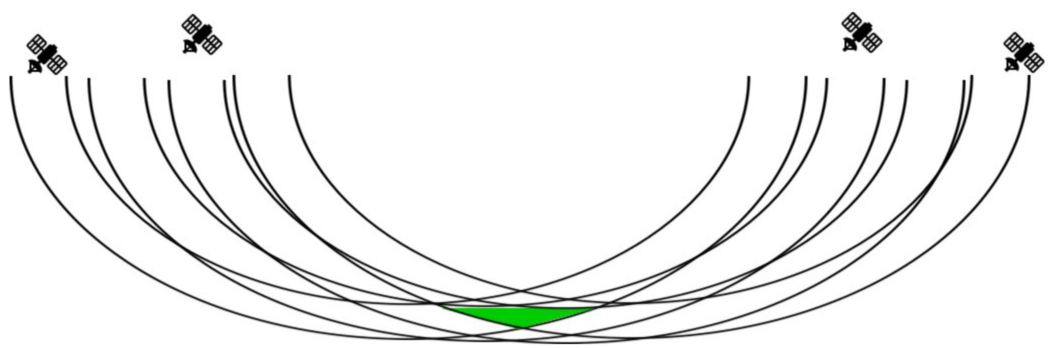
e. Effect of cover/tree canopy

G. Controlling for Errors – Detecting Errors at the Receiver - DOP

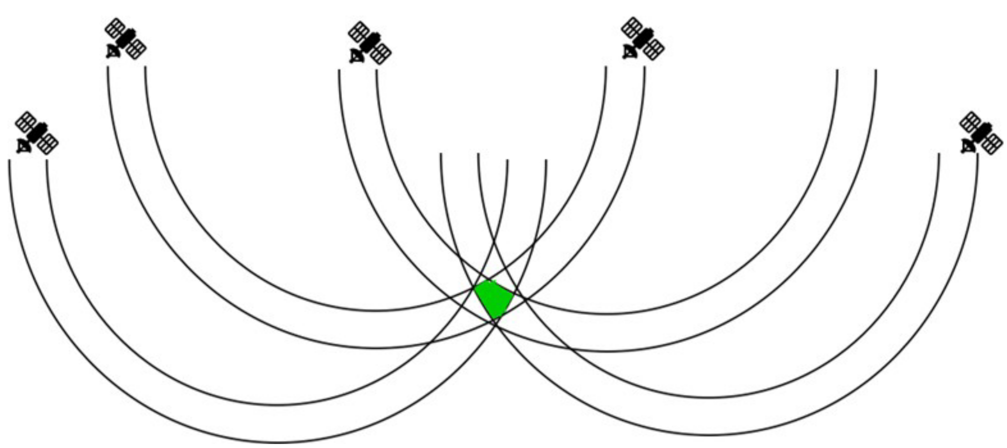
1. Recreational GPS receivers generate an error reading. Garmin does not divulge the basis or the statistical value of its reading. A variety of published sources and field testing indicate that Garmin's error values are based on DOP (Dilution of Precision). Bad Elf discloses that their error value is based on DOP.

2. In tests comparing the same NGS benchmarks on days with and without significant atmospheric errors, the 2DRMS errors of the Garmin Glo and the Bad Elf Pro increased by factors of 3 – 8 times. On a "normal" day, one benchmark averaged a 9-foot 2DRMS over multiple tests and devices. Repeating the measurements on a day with unfavorable conditions generated an average 2DRMS of 53 feet – well outside the useable range.

SATELLITES LOW ON THE HORIZON – *HIGH* HDOP >2



GOOD SATELLITE GEOMETRY – *LOW* HDOP 1 - 1.5



3. As Table 2 shows, the differences in accuracy were not due to satellite geometry, because the HDOP)Horizontal Dilution of Precision) values were all low and similar. There was nothing observable in the local weather conditions to suggest a major atmospheric disturbance.

Table 2

Benchmark	Date	2DRMS	HDOP
AG0488	07/16/21	06.4	0.9
AG0488	08/14/21	52.8	0.8
DF5817	07/19/21	19.8	1.3
DF5817	07/25/21	73.0	1.0

EXCEPT FOR ERRORS CAUSED BY DOP,

A RECREATIONAL GPS DOES NOT KNOW WHEN IT IS WRONG

H. Controlling for Errors – Correcting Errors at the Receiver - RAIM

1. The Coast Guard uses RAIM (Receiver Autonomous Integrity Monitoring) software to check for and discard errors.
   a. RAIM software requires a GPS receiver which outputs at least the NMEA (National Marine Electronics Association) GRS and GST sequences, which are not available on typical recreational receivers.
   b. RAIM requires at least 5 good satellites for horizontal measurements.
   c. The Coast Guard's RAIM uses both fault detection (FD) and fault exclusion (FDE).
   d. The GST sequence provides the noise statistics for the pseudoranges (computed distances to satellites). This allows the receiver to directly calculate the 2DRMS error for every satellite measurement, rather than infer it from DOP values.
   e. The receiver does not display a position unless it sees enough measurements within the 2DRMS upper limit of 29.5 feet. This is the horizonal integrity limit (HIL) of the RAIM.
   f. The GRS sequence provides range residual data. This allows the receiver to identify and exclude satellites with questionable measurements. (Fault Exclusion)
   g. The software calculates two solutions. If they differ by too much, that creates an error alert. (Fault Detection)

LACKING RAIM, WHAT CAN AUXILIARISTS DO TO DETECT AND CORRECT ERRORS?

I. Controlling for Errors – Detecting Errors at the Receiver – COMPARISON METHOD

1. Limited field tests compared handheld recreational GPS receivers from different manufacturers and handhelds with fixed receivers on a facility. The results showed that:
   a. When the 2DRMS error exceeded 40 feet, the difference between simultaneous readings of two dissimilar units was ≥ 15 feet 60% of the time.
   b. When the 2DRMS exceeded 29.5 feet, the difference was ≥ 15 feet 50% of the time.
   c. This means that comparing different units does not guarantee acceptable readings, but it can potentially exclude bad readings 40-50% of the time.

J. Controlling for Errors – Detecting Errors at the Receiver – VERIFY KNOWN LOCATION

1. Although not as effective as RAIM or RTK, checking the GPS against a known point as close in time and position to the aids verified provides a check (not an assurance) against large errors.
2. Precisely known positions:
   a. The best position is an NGS (not a tidal) benchmark. These are rarely located conveniently so this option is seldom practical
   b. Verifiers can establish a convenient precisely known location. First, select and mark the exact spot in a manner that cannot be moved. Pick a location with an unobstructed or minimally obstructed view of the horizon in every direction.
      i. Using a recreational grade GPS, take and record a measurement after at least 30 minutes of soak. Repeat this to collect at least 15 daily results at the same time of day.
      i. Calculate the average latitude and the average longitude.
      ii. Calculate the standard deviation of the latitudes and longitudes.
      iii. Discard any value more than one standard deviation from the average.
      iv. Recalculate the average latitude and longitude from the remaining values.
      v. Use that as the position of your reference point.
      vi. Before a mission, ensure that your GPS reading is not more than 15 ft from the reference value,
   c. A more accurate method is to use a GPS receiver with RTK and a 60+ minute soak to determine the location of the reference point.

K. Controlling for Errors – Detecting Errors at the Receiver – USE RECEIVER WITH RTK

1. Bad Elf GNSS Surveyor BE-GPS-3300 is a handheld receiver with differential correction, having a specified 2DRMS accuracy of 2.4 meters (7.9 feet)
2. Real time RTK corrections and post processing PPK corrections came from RTK stations operated by FDOT (Florida Dept. of Transportation) using data publicly available at no cost.

3. Real time RTK requires a cellular signal. When no signal is available, the data can be logged and post processed using a historical file obtained from the RTKLIB reference station. A full description of these processes is device specific and beyond the scope of this document.
4. Testing at an NGS benchmark yielded these 2DRMS error results:

Bad Elf GNSS Surveyor	8.3 feet
Garmin Glo	28.7 feet
Bad Elf Pro	26.9 feet

5. Use of a reference station no more than 60 miles from the GPS receiver allows correction of most of the error caused by localized atmospheric disturbances.

L. Determining if a PATON is at AP

1. For a full description of the statistics of GPS and the methods used by the Coast Guard to determine if an aid is at AP or On Station, consult the *U.S.C.G. Auxiliary District 7 Field Guide to Locating PATON*. GPS error statistics are also covered in Appendix B.
   a. To determine if an aid is within positional tolerance requires a valid GPS error reading as described above:
      i. For Garmin units, assume the error reading is a CEP value and multiply by 2.4 to obtain 2DRMS
      ii. For Bad Elf units, set the device to read RMS and multiply by 2.0.
      iii. For other units, consult the manufacturer or assume the value is CEP.
2. Use AV Assistant of the *IS PATON AT AP OR ON STATION* spreadsheet to calculate the position tolerances:
   i. Enter the Light List number
   ii. Enter the date
   iii. Enter the fix latitude and longitude in the DD-MM-SS.SSS format. (A converter is available at the lower right of the sheer=t.)
   iv. Enter the AP latitude and longitude in the DD-MM-SS.SSS format.
   v. Select the error value from the choices.
   vi. Enter the error value.
   vii. Select the error units.
   viii. The spreadsheet then evaluates and reports the tolerance criteria, including a graphic display.
   ix. Use the buttons at the bottom of the sheet to PRINT or SAVE the report.

IS THIS BEACON IN ITS AP?

USE THIS CALCULATOR ONLY IF YOU OBTAINED A FIX WITH THE GPS ON THE PILING

LLNR 24605 DATE 11-Nov-21

	°	'	"	
FIX				
Latitude	027	43	25.000	N
Longitude	082	28	28.507	W
AP (Assigned Position)				
Latitude	027	43	51.880	N
Longitude	082	28	28.457	W

GPS Error	Select Type	Error Value	Select Unit
	2DRMS	0.2	feet

Distance from Fix to AP 2726.97 ft = 908.99 yd

Bearing from Fix to AP 000 °T

2DRMS 0.23 ft = 0.08 yd

Distance from Fix to AP exceeds 3 yards

AP is outside the 2DRMS circle

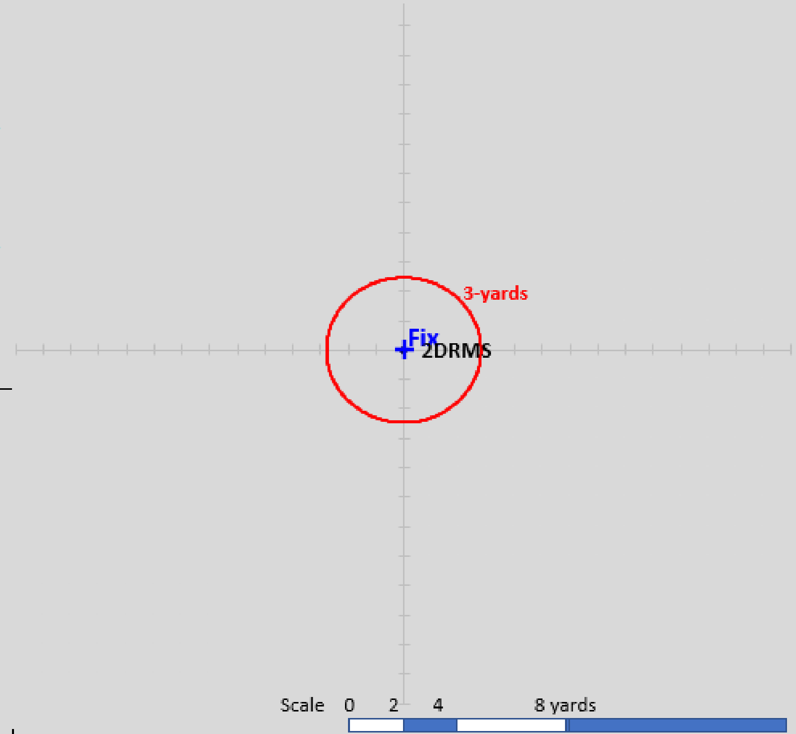
AID IS NOT IN AP

IF AP is OUTSIDE the 2DRMS CIRCLE *AND* MPP to AP > 3 yards,
Beacon is NOT IN AP

District 7 recommends that you save or print this file and include with the 7054

PRINT SAVE

Fixed Aid



Quick conversion tool:

Decimal	27.7279120	82.4781318
DM	27° 43.6747'	82° 28.6879'
DMS	27° 43' 40.483"	82° 28' 41.275"

APPENDIX A: BASICS OF SATELLITE NAVIGATION SYSTEMS

A. GNSS (GLOBAL NAVIGATION SATELLITE SYSTEMS)

GNSS stands for Global Navigation Satellite System. The term includes any satellite array that broadcasts positioning, navigation, and timing services on a global or regional basis.

There are currently 4 global satellite navigation systems:

GPS – United States – U.S. Space Force

GLONASS – Russia – Russian Space Forces

Galileo – European Union – European Union Agency for the Space Program (EUSPA)

BeiDou – China – China National Space Administration

These 4 systems offer global coverage. Many current receivers use satellites from more than one GNSS. This is advantageous in two ways. First, seeing more satellites means a faster lock on a fix. Second, when outside the coverage of any SBAS system (see below), having more satellites increases accuracy. However, no combination of GNSS systems is as accurate as GNSS with SBAS (such as GPS + WAAS).

B. GPS

The GPS (Global Positioning System) is a network of 24 satellites and related ground stations operated by the United States Space Force.

1. Frequencies
   a. GPS satellites broadcast on three frequencies.
      i. L1
         1. This is the original and universally used frequency, transmitted at 1575.42 MHz. The basic L1 signal is the C/A (Coarse/Acquisition) code and the P and P(Y) Precision codes. Recreational grade receivers use the C/A code.
         2. L1 broadcasts an M-Code used by the military (and slated to some day replace the P code in civilian receivers.)
         3. A new L1C signal, designed for interoperability with Galileo E1 is also broadcast. It is compatible with the current L1 signal but transmits at higher power and includes advanced performance features. This functionality is not yet available in recreational grade receivers.
         4. The L1 frequency has difficulty travelling through obstacles, so it is the most affected by atmospheric conditions, tree cover, and buildings.
      ii. L2
         1. L2 and the L2C frequency now being phased in (a modernized civil signal) transmit on 1227.60 MHz. This allows it to better travel through cloud cover, trees, and buildings. L2C is used in conjunction with L1 in dual-frequency military and high-end commercial receivers. The L2 signal contains CM (Civil Moderate) and CL (Civil Long) codes in addition to the P(Y) and M-Codes.

ii. The new L5 signal operates on 1176 MHz. L5 transmits I5(Nav) and Q5 (no Nav data) codes. This signal which is potentially 10x more precise than the L1 C/A signal, is available on some newer mobile phones. The L5 band is still considered pre-operational because there are fewer than 24 satellites using it.

C. SBAS – SATELLITE BASED AUGMENTATION SYSTEMS

Table A.1 lists the source and approximate magnitude of errors from the GPS system.

Table A.1 Sources and Magnitude of GPS Errors

Source of Error	Typical Error (meters)	Range of Error (meters)
Ionosphere	4.0	0 - 30
Clock	2.1	0 – 2
Ephemeris	2.1	1 - 5
Troposphere	0.7	0 -30
GPS Receiver	0.5	
Multipath signals	1.0	0 - 1
Total	10.4	

The concept of SBAS is that fixed ground stations at known locations calculate satellite position, clock errors, and estimate upper atmosphere transmission time errors. Within 6.2 seconds of the calculation (in the case of WAAS), this data is sent to SBAS satellites (currently three) which broadcast the corrections to GNSS receivers on the same L1 frequency used by GNSS satellites. The specified accuracy of the US WAAS system (operated by the FAA) is 7.6 meters (25 feet). In practice, it is achieving 1.5 – 3 meters accuracy.

SBAS systems function only with the specific GNSS system with which they are paired. That means that WAAS adds accuracy to GPS signals but has no impact on GLONASS or Galileo.

SBAS systems are regional – not global. GPS with WAAS is more accurate in the United States than any combination of GPS and other GNSS systems.

The two main SBAS systems currently in operation are:

WAAS – Wide Area Augmentation System – United States – Federal Aviation Administration (FAA)

EGNOS – European Geostationary Navigation Overlay Service – European Union – EUSPA

There are other systems under development in Russia (SDCM) and China (SNAS).

Current SBAS systems operate on the L1 frequency only. Future development will include a second frequency for additional accuracy.

WAAS covers the continental US, most of Canada and Mexico, and Alaska. Coverage is available on the Atlantic coast and in the Gulf of Mexico. Enabling EGNOS on a GPS receiver in North America has no effect because it is outside the EGNOS coverage area.

Most recreational receivers have WAAS, but it may need to be manually enabled in settings to operate.

D. KEY GPS RECEIVER SPECIFICATIONS

1. GPS Receiver Accuracy: ***The manufacturer's specifications for GPS receiver accuracy are for a stationary receiver under an unobstructed sky, generally after 2 minutes in that position.*** Moving the receiver even at walking speed degrades the accuracy. The manufacturer's specifications for the latest recreational GPS receivers with WAAS typically are 2.5 – 3 meters accuracy, with 95% probability.

2. GPS Receiver Update Rate: Recreational GSP receivers have an update rate between 1 and 10 Hz. That means they report a position between 1 and 10 times per second. However, this does not mean that the receiver can accurately measure changing positions at that rate.

3. GPS Receiver Channels: Each satellite requires a dedicated channel in the receiver. Therefore, multi-channel receivers are standard. At some point, however, the number of channels exceeds the entire constellation of visible satellites and ceases to add performance.

4. Time To First Fix (TTTF): Although a GPS receiver in a warm or hot state (see below) provides a continuous position display, that does not mean it is providing a current or accurate fix. To understand this, we first need to examine the two key data streams a GPS receiver needs to take a fix.

   a) GPS Almanac Data: The GPS almanac is a data set that every GPS satellite transmits. It describes the state of the entire GPS system and the coarse data (low resolution position) on every satellite. The almanac data guides the GPS receiver to locate a region of visible satellites. It also provides signals to calibrate GPS time to UTC. and to correct distortions caused by changes in the ionosphere. Transmission of an almanac requires 12.5 minutes. An almanac is valid with little dilution of precision for two weeks.

   b) GPS Ephemeris Data: This data is transmitted by each satellite and helps GPS receivers obtain more precise fixes. It includes information about predicted and actual satellite location, time, satellite clock correction coefficients, age of data, satellite "health," and predicted and actual satellite location valid for two hours before and after the ephemerides transmission. New messages are output every 30 seconds.

1. GPS Start Types: The next factor to consider in Time To First Fix is the state of the GPS, referred to as the start type.

   a) GPS Start Types: There are three types of start for a GPS. The TTFF depends on the type of start and the design of the receiver.

      i. Cold Start – any of the following applies:

      - The GPS has been manually reset.
      - The receiver has moved more than 60 miles from the location of the previous fix.
      - Current time in the receiver is unknown or inaccurate.
      - Incoming signal levels are marginal, usually because of obstructions between the receiver and the satellites.

In this situation, the receiver cannot predict or verify which satellites are in view. The receiver will work through an internal list of satellites, trying to acquire each one in turn. If the GPS does not have a current almanac, at least 15 minutes is required for a cold start.

ii. Warm Start:

- The receiver has a valid almanac.
- The current location is within 60 miles of the last fix location.
- The current time is known (the GPS has been active in the past 72 hours).
- No ephemeris data has been stored or it has become stale.
- 4 or more satellites are in view with good signal strength and geometry,

The receiver can predict which satellites are overhead but need to download current Ephemeris data.

Hot Start:

- All Warm Start conditions are met.
- A fix has been established in the last 2 hours.
- The receiver has valid ephemeris data for at least 5 satellites.

The receiver can rapidly track the overhead satellites and needs to download a minimum of data to establish a position.

More satellites in good positions reduces TTFF and improves accuracy.

Table A.2	**GPS RECEIVER START TIMES (seconds) Stationary under unobstructed sky**		
	Typical	Garmin Glo 2	Bad Elf Pro
Cold Start(1)	120 – 240	60	30 -35
Warm Start	45	35	15 – 34
Hot Start	22	3 - 5	1 - 5

Garmin and Bad Elf data from manufacturer's specifications and inquiries to customer service.

(1) Following a manual cold start, or if the GPS does not have a current almanac, the receiver must have a continuous fix for a least 15 minutes to enter warm or hot start states.

.

APPENDIX B: STATISTICS OF GNSS PRECISION

A. SCATTER OF GPS DATA

The data collected by a stationary GPS receiver will show scatter as the signal drifts due to constantly changing measurement errors. Note that this phenomenon is not seen in a moving receiver because of smoothing software.

This data is from a Garmin Glo (tested by GPS Tracklog in 2013) and a Bad Elf GPS Pro tested by the author in 2021. These are not side-by-side tests, so direct comparisons cannot be made.

Figure A.1

Garmin Glo

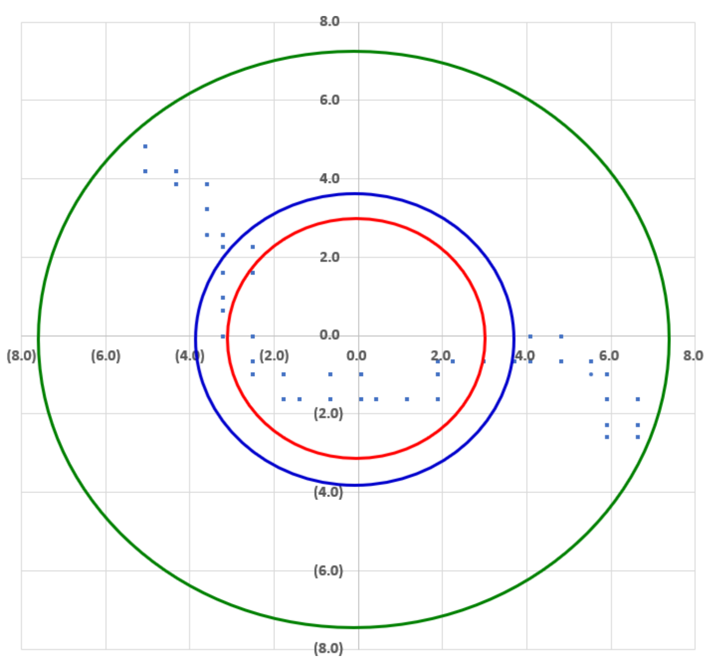


Figure A.2

Bad Elf GPS Pro

100% of the measurements by the GLO fell within a 4-meter circle. The Bad Elf Pro, in this separate test, had 100% of the readings inside a 2.9-meter circle.

B. STATISTICS OF GNSS DATA SCATTER

Using some simplifications, because the actual distribution of GPS scatter is not entirely Gaussian, the following terms are used to describe the precision of GPS data. Precision, in this context, means the amount by which individual measurements vary from the mean (average).

Table B.1	GPS PRECISION MEASUREMENTS		
Measure	Abbreviation	Percent of Values inside Circle	Conversion Factor
Circular Error Probable	CEP	50%	1.0000
Distance root mean square	DRMS	63-68%	1.2011
95% Radius	R95	95%	2.0789
Twice distance root mean square	2DRMS	95-98%	2.4022
99.7% Radius	R99.7	99.7%	2.8950

More detail on the math behind these measurements can be found at the end of this appendix.

The Coast Guard uses the 2DRMS value as the criteria for accepting GPS position fixes. The maximum allowable 2DRMS is 9 meters (9.8 yards, 29.5 feet.)

C. USDA HANDHELD GPS TEST RESULTS

In 2019, the Forest Service of the USDA (Department of Agriculture) field tested several handheld GPS models under unobstructed, clear skies and with medium forest cover.

Table B.2	**USDA TESTING OF HANDHELD GPS MODELS**				
Model	**2DRMS Value**		**Model**	**2DRMS Value**	
	Open Sky	**Light-Medium Canopy**		**Open Sky**	**Light-Medium Canopy**
Garmin GPSMAP 66st	5.83	25.63	Apple iPad Pro 9.7	11.41	21.75
Garmin GPSMAP 76CSx	11.51	13.90	Samsung Galaxy S9	7.45	12.42
Garmin GLO	9.15	16.85	Samsung Galaxy S10e	7.58	21.77
Garmin Montana 650	10.58	16.78	Samsung Galaxy Tab S7	4.92	12.57
Bad Elf GPS Pro	6.69	23.86	Magellan Explorist 710 WAAS	10.97	16.63
Bad Elf GNSS Surveyor	5.09	17.86	Panasonic Toughbook CF-20	5.90	19.51
Apple iPhone 11	10.60	44.30	Delorme Earthmate	7.18	7.58
Apple iPad 9.7 6th Gen	17.91	20.10	Trimble Geo 7X	0.69	6.03

D. CALCULATING GNSS PRECISION VALUES

1. Measurements in 3-Dimensional Space.
   When we speak of either the accuracy or precision of GPS measurements, they exist in 3 dimensions. For each position there is a horizontal, vertical, and spatial (combined) error. It is not always clear which value a GPS receiver or app is reporting. It is important to understand which value it is because the only error of concern in locating aids to navigation is the horizontal error. The vertical error will always be greater than the horizontal because of geometry – relatively speaking, all satellites are above the receiver's position. The spatial (3-dimensional) error will also be larger than the horizontal.

2. CEP – Circle of Equal Probability.

   CEP is the radius of a circle in the horizontal plane within which 50% of measurements at a location will fall.

   CEP = 0.59 x $(\sigma_x + \sigma_y)$ where σ is the standard error from the true position in the N/S and E/W axes.

   Some GPS manufacturers use CEP as the basis for their accuracy/precision specification.

3. DRMS – Distance Root Mean Square

   DRMS is the radius of a circle in the horizontal plane calculated as follows:

   DRMS = $(\sigma_x^2 + \sigma^2)^{1/2}$ where σ is the standard error from the true position in the N/S and E/W axes.

   63 – 68% of measurements at a location will fall within this circle.

   Caution – some publications cite RMS values which sometimes, but not always, stand for DRMS values. Some but not all publications use DRMS as the value of HDOP (Horizontal Dilution of Position). In other publications HDOP is defined as a ratio of the actual accuracy of a set of GPS measurements relative to the maximum (specified) accuracy. In that case, for a GPS with a specified accuracy of 2.5m CEP, and HDOP of 1.5 would mean that the accuracy achieved during that set of measurements was 1.5 * 2.5 = 3.75.

4. 2DRMS – Twice Distance Root Mean Square

   2DRMS is the radius of a circle in the horizontal plane calculated as follows:

   2DRMS = 2 x $(\sigma_x^2 + \sigma^2)^{1/2}$ where σ is the standard error from the true position in the N/S and E/W axes.

   94.5 – 98% of measurements at a location will fall within this circle.