Introduction

In the last two decades, rapid advances in technology have radically changed the workplace for almost all of us. Marine pilots are no exception. Two evolutionary changes have particularly affected pilots:

1. Global trade has expanded greatly, and shipping plays a major role in the transportation of goods all around the world. Vessels are built longer and wider than ever, with ever deeper drafts. For example, recently we saw the introduction of Ultra Large Container Ships (ULCS) with dimensions of close to 400 meters in length, over 60 meters in beam, and 21 m in draft.
2. Use of a global navigation satellite system (GNSS) has become commonplace. Most of us have now heard of GPS (the American Global Positioning System), Glonass (the Russian GNSS), and Galileo (the European GNSS). GNSS has simply become an everyday tool for many of us.

Photo 1 – MSC Savona

How do these two issues affect the workplace of the marine pilot?

1. While vessels continue to increase in size, port infrastructure remains almost unchanged. Safe navigation of very large vessels is becoming ever more difficult and challenging for the marine pilot.
2. GNSS hardware has miniaturized to the point that battery powered GNSS-based portable pilot units (PPUs) are small enough and light enough for pilots to carry them aboard comfortably. Many pilots value the independence from shipboard systems that PPUs afford them.

It is for these reasons that pilots are starting to make more and more use of PPUs to assist them in handling larger vessels, particularly during berthing, lock approach and navigation in confined waters. PPUs are also extending operational hours on smaller vessels, assisting the pilot in marginal weather conditions and at night.

On the surface, GNSS positioning seems fairly straight forward. You turn on the unit and you get your position shown on an electronic map, just like your smart phone. The average user probably never asks how accurate that position is. The average user probably does not know that heading can also be derived from GNSS, or that position accuracy can be improved incrementally depending on the type of satellite corrections being fed to the GNSS receiver. In reality, GNSS technology is very complex. The type and accuracy of information available from GNSS depends on its configuration.

The nature of a marine pilot's job means he or she cannot afford to be an average user of GNSS. In order to judge the observations provided by the PPU the marine pilot simply has to understand some of the complexity of GNSS as employed in their PPU. It is critical in many cases to understand how accurate are the parameters derived from their PPU, and in particular their true effect on navigation. Remembering the pilot is interested in the exact position of each part of the ship, heading and rate of turn (ROT) accuracies are of particular interest. For example, one may know the position of a PPU antenna on a stern bridge wing to within one centimeter, but the position of the bow may be tens of meters wrong if the heading is in error by a small amount. In other words positioning inaccuracies are magnified by errors in these parameters the larger the vessel being navigated.

Unfortunately for pilots, most manufacturers of PPU's claim that their PPU's can be used for almost every task, from general navigation to harbor approach, to lock approach, to docking. Can manufacturers really make that claim, and how can pilots judge if a certain PPU is fit for a particular task? For example, ask yourself what accuracies are required from a PPU on a VLCC approaching a jetty at very low speeds of say 4 cm/second, or on a large container vessel approaching a narrow lock. This article explains the principles and pitfalls of the PPU, and how a PPU should be used. Even more importantly, the article explains how to interpret the various specifications that are published by the PPU manufacturers.

Heading Accuracy

Let's start with a simple example.

Most PPU's provide a heading derived from GPS or, for some PPU's, GPS and Glonass combined - see Figure 1. PPUs that provide heading generally use two antennas. Satellite observations from each antenna are used to compute the heading between the two antennas. When the PPU manufacturer claims a heading accuracy of 0.25 degrees, it sounds pretty accurate, but what does this number really mean for a pilot navigating a 360 meter long vessel to its berth or lock.

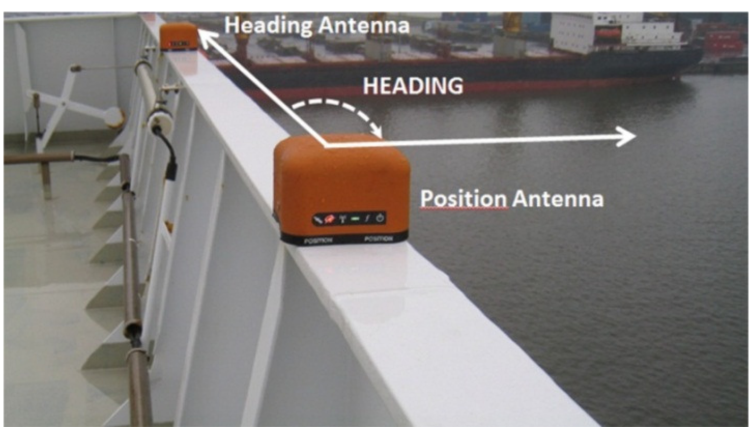

Figure 1 – Heading from GNSS

First let's have a look at the math. Assume a scenario in which we locate the PPU onshore and perform a static test of 1 hour. In other words the antennas are both fixed in location and orientation. Say we record 3600 values for heading and then calculate the mean value. The 3600 heading observations are subject to random error and will be randomly distributed around the mean value, with some values larger than the mean and some values smaller. Keep in mind that the mean value is often assumed to be the “true” value.

Various statistics are available to express accuracy, one of which is the “1-sigma value”. The size of the 1-sigma value is computed by determining the width of the window around the mean value that contains 67% of all the observations. Let’s say that the mean of the 3600 heading values is 121.30 degrees. Let’s say that 67% of the observations distributed around the mean value fall between the values of 121.05 degrees and 121.55 degrees. In other words the window width is 0.50 degrees, centered on the mean value of 121.30 degrees. The 1-sigma value is therefore 0.25 degrees. This means that 67% of all observations will be within plus or minus 0.25 degrees of the mean value. If a manufacturer tells you that the 1-sigma heading accuracy of his PPU is 0.25 degrees, he means that you could repeat the static observations many times over, in different locations and with different orientations between the antennas, and you should find that 67% of the headings computed by the PPU will fall within a 0.50 degree window centered on the mean value every time you repeat the observations.

Be aware that the manufacturer is citing the 1-sigma value, representing 67% probability. In our static test set-up the heading may show 121.30 degrees but 5 minutes later it may have changed to 121.80 degrees, so a 0.5 degree change. Don’t complain to the PPU manufacturer, for he will tell you that his PPU is still within specification.

Since heading is so important in large vessel navigation, pilots generally prefer a more stringent PPU specification that provides them more confidence. They prefer a “2-sigma value” instead. This means that 95% of the observation values lie within a window centered on the mean (“true”) value, the width of the window being twice as wide as in the 1-sigma case above - see Figure 2.

In this case we need to redo our math by multiplying 0.25 degrees by 1.96, which means that our 2-sigma specification becomes plus or minus 0.49 degrees. In our static test set-up the heading may show 121.30 but 10 minutes later it may have changed to 122.28 degrees, so almost a 1 degree change! Again, don't complain to the PPU manufacturer, he will tell you that his PPU is still within specification.

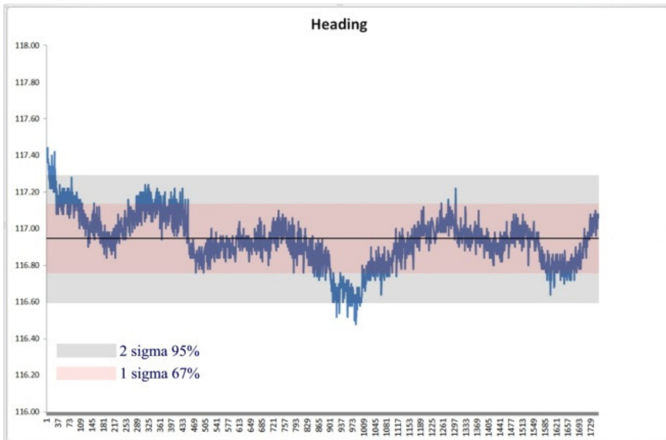

Figure 2 – Static Heading Test

So what is the practical reality of a 2-sigma = 0.49 degrees specification to a pilot? Assume the PPU is now located on our 360 m long vessel. The PPU is set up on the bridge which is located 300 meters from the bow. Since the instantaneous heading could be within a range of -0.49 degrees and +0.49 degrees of the "true" value, a variation of 0.98 degrees may lead to a 5.13 meter lateral displacement (to port or starboard) of the bow! See figure 3. This is not a problem if you are navigating in a 500 meter wide channel, but would you still use this PPU when approaching a lock with 1 meter to spare on both sides of the vessel?

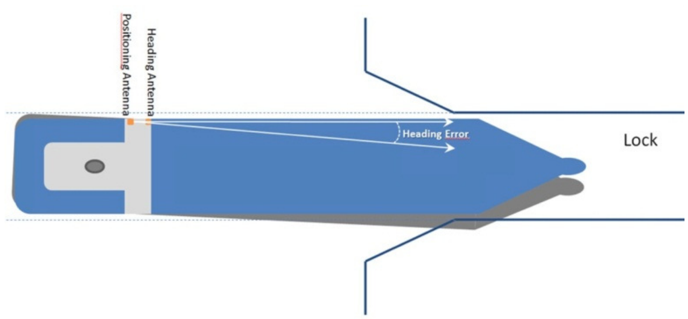

Figure 3 – Heading Error

So far we have only considered that part of the specification associated with heading. There is also absolute positioning accuracy to be considered. Some manufacturers may tell you that they can offer position accuracies of close to 1 meter, or, in the situation where GNSS differential corrections are available from a nearby differential corrections station, or from a satellite corrections system like WAAS or EGNOS, the manufacturer may claim positioning accuracy close to 0.5 m or even better. Some PPU's even use Real Time Kinematic (RTK) techniques to achieve positioning accuracies of 2 to 3 cm.

What does this mean in practice?

Essentially it only tells the pilot that the position of GNSS antenna itself, as reported to the user by the GNSS receiver, has a 95% probability of being within 1m, or 0.5m, or 2cm of its "true" position. It says absolutely nothing about the positioning of any other part of the vessel, as the heading discussion above should have already made clear. To reiterate, the positioning accuracy is almost totally irrelevant without an accurate heading. If we assume a positioning accuracy of 1 m (2-sigma) and a heading accuracy of 0.49 degrees (2 sigma), in the example above the lateral displacement uncertainty of the bow of our vessel is now 5.23 meters instead of 5.13 meters. Obviously the positioning accuracy plays a no role here.

Antenna Placement Accuracy

Now let's have a look at the placement of our PPU itself. Most PPU's are using two antennas connected by cable. This means that the separation between the antennas will usually be limited to say 2 to 4 meters. Normally the antennas are set up on the bridge wing or on the monkey island in such a way that the antennas are parallel to the vessel center axis, or perpendicular to the vessel center axis. The placement of the antennas is tricky business, especially at night or in bad weather. Placement needs to be very precise to avoid absolute heading errors. From experience we learned that 5 cm errors are easily made when trying to line up the PPU antennas with the vessel center axis. It may sound trivial, but a small error of 5 cm leads to a lateral displacement of our vessel's bow of 7.5 meter. In combination with our heading and position uncertainties, we might be already looking at a total displacement of the bow of close to 10 meters! This almost doubles the intrinsic uncertainty of the PPU and can be avoided by carefully positioning the PPU.

The foregoing makes it clear that GNSS positioning is not so simple after all. But have we now considered everything?

RoT and COG Accuracy

Unfortunately, the answer is no. In addition to knowing where the vessel is now, most pilots want to know where the bow will be in, say, 150 seconds, so they can still give the right commands to bring the vessel safely alongside the berth or jetty or in the center line of the lock. This process is called path prediction, or in other words, "show me were the vessel will be in 150 seconds if we continue with this speed, heading and Rate of Turn (RoT)"- see figure 4.

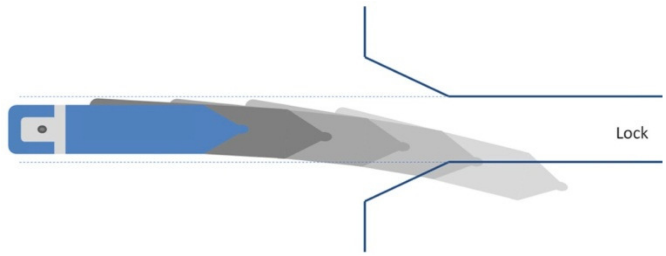

Figure 4 – Path Prediction

For path prediction we need to take account of the RoT and the Course Over Ground (COG). Most PPU's use low-cost RoT sensors based on so-called Micro Electro Mechanical Systems (MEMS) technology. Others use much more advanced RoT sensors based on high-end MEMS or even fiber optic methods. Typically specifications vary between 2 degrees/minute to 0.1 degrees/minute. Once again, ask the PPU manufacturer if this specification is based on 1 or 2 sigma.

The other observation that is used in path prediction is Course Over Ground (COG), the value of which depends on position accuracy and the roll of the vessel. Roll is a very different beast, and since there are very few PPUs available that can measure roll very accurately, we will not account for it here. Let's assume a position accuracy of 1 meter, a heading accuracy of 0.50 degrees, a RoT accuracy of 1.0 degree, and a COG/Roll accuracy of 1.0 degree. What will be the displacement uncertainty of the bow over a path prediction time of 150 seconds? You may be surprised to hear this adds up to almost 13 meters!

It is important to understand that accuracy specifications tell us something about the potential size of the errors in a particular PPU. They do not say there is definitely an error of a certain size always present in that PPU. Rather they tell you that errors could be present, and provide an indication of the potential size of those errors. It is all about statistics, so the probability of errors occurring. So today the errors of your PPU may not add up to much, but they may add up tomorrow just when approaching a narrow lock. The question then is - are we looking at real motion of the vessel or are we looking at uncertainties generated by the observations provided by our PPU?

Positioning and Speed Accuracy

As explained above, the positioning accuracy is irrelevant if the accuracy of the heading is not accurate too. For some operations, such as approaching an oil jetty with a VLCC, the speed components at stern and bow are additional parameters of utmost importance. An approach speed of more than 6 cm/second may cause serious damage to the jetty.

What are the sources of error in computing bow and stern speeds?

Because of random error, a position derived from GPS using differential, WAAS or EGNOS corrections, still shows some speed, even when the antenna is placed in a static location - see figure 5. The GPS antenna is physically static, but random error in the observations causes computed position to wander or jump around. Speed is calculated from change in computed position. In this case speed is due entirely to positioning errors and NOT to actual movement. Similarly, the accuracy of the heading and RoT will also influence the speed.

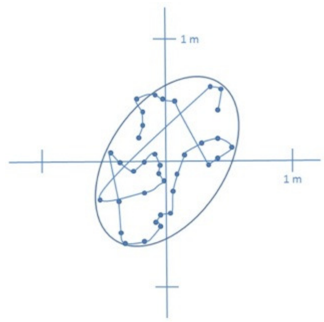

Figure 5 – Static Position

So when the speed vectors show an approach speed of 5 cm/sec, you have to ask if this is the real speed of our vessel, or is the speed simply caused by the added uncertainty of our observations, or even worse, could the real speed be 10 cm/sec. In order to obtain more accuracy in the speed vectors we can reduce the error component caused by position. To do this we might consider using an RTK solution, which is capable of positioning accuracy in the order of 2 cm. This provides an unsurpassed speed accuracy, but what is the purpose of having this kind of accuracy when the heading and RoT accuracy is not good enough. If you take the "trouble" to use RTK positioning, other parameters need to meet the highest specifications too, e.g. a heading accuracy of better than 0.02 degrees and a RoT accuracy of better than 0.1 degrees. Otherwise you are wasting your energy, time and money.

How can we increase the accuracy of heading and RoT?

GNSS Physics and Optimizing Accuracies

Irrespective of the type of PPU that is used the accuracy of a GNSS derived heading depends on two criteria, namely; the GNSS frequency band L1 and L2 and the distance between the two antennas. Most PPUs use the L1 frequency only. It is only the more precise PPUs that use both L1 and L2 frequencies. Here is a rule of thumb on how to compute the accuracy of these systems:

1. L1 PPU system: 0.50 degrees / antenna separation. So in case of an antenna separation of 2 meters, the accuracy will be in the order of 0.25 degrees (1 sigma) or 0.50 degrees (2 sigma).
2. L1/L2 PPU system: 0.25 degrees / antenna separation. So in case of an antenna separation of 2 meters, the accuracy will be in the order of 0.125 degrees (1 sigma) or 0.25 degrees (2 sigma).

Unfortunately there is nothing we can do about the physics of the GNSS signals. But we can increase the separation between the deployed antennas, although the use of cables and bars in the PPU may restrict separation distance. Recently one of the PPU manufacturers introduced a so-called "long baseline PPU". This PPU has no cables or bars and therefore the separation between the antennas can be extended up to 100 meters. Assuming a 25 meter separation between the antennas the heading accuracy can be increased to 0.01 degrees! This type of PPU also solves the antenna placement in-accuracies, since the longer the antenna baseline the lesser the effect of placement errors will be. Only this type of placement and heading accuracies, used in combination with a high-end RoT sensor and RTK positioning, will provide the accurate speed components we need for berthing and lock approach. See table 1.

Uncertainties	High-end PPU L1/L2 RTK GPS/Glonass Extended Antenna Separation	Mid-range PPU L1/L2 GPS/Glonass Fixed Antenna Separation	Low-end PPU L1 GPS Only Fixed Antenna Separation
Position Accuracy (m)	0.02	0.50	1.00
Heading Accuracy (degrees)	0.01	0.25	0.50
RoT Accuracy (deg/min)	0.10	0.50	1.00
Approach Speed Error (m/s)	0.01	0.04	0.06
Lateral Error on Bow (m)	0.05	1.20	2.40
Lateral Error on Bow (m) 150 seconds Path Prediction	1.27	6.45	12.90

Table 1 – PPU Uncertainties

The figures quoted in this table are based on a distance from the PPU to the bow of 250 m and on 2 sigma values. Placement errors of the antennas are NOT included in this table.

Satellite Availability

There is yet another consideration for positioning accuracy. Most PPU systems are based on GPS only. Some others combine GPS with the Russian satellite system Glonass. Although it seems that the GPS constellation alone has plenty of satellites available, there are still periods when only 5 or 6 GPS satellites can be used even when perhaps 6 or 7 satellites are theoretically available. Often one or two "lower" satellites are not used in the position computation because they are temporarily blocked by the vessel's wheelhouse, or some other obstruction on the vessel. This may lead to short periods when positioning accuracy is so heavily degraded that it is not good enough for critical operations like berthing, or lock approach.

For many years the Russians struggled to keep up a minimum number of operational satellites in their Glonass GNSS. The situation has improved and, for the last few years, we have seen a gradual increase in the number of Glonass satellites to 23 fully operational satellites in early July 2011 - see table 2.

GLONASS constellation status, 07.07.2011г.

Total satellites in constellation	27 SC
Operational	23 SC
In commissioning phase	1 SC
In maintenance	3 SC
Spares	-
In decommissioning phase	-

Table 2 – Glonass Satellites

A combined GPS/Glonass PPU tracks an average of 15 to 20 satellites, so even an uncorrected position solution often provides accuracies of 1 meter or better. What is even more important to the pilot than absolute accuracy is the reliability of the available position. Since we may lose a couple of satellites as a result of blocking, combining GPS and Glonass means the pilot can always count on the availability of enough satellites for critical operations.

Photo 2 – Lock Approach Panama

Scalable Pilotage and Value for Money

At home and in our place of work, we are nearly all faced with adapting to, and learning about, new technology that impacts our lives, whether we like it or not. Surrounded by new gadgets and technological breakthroughs, we all face the challenge of sifting through product specifications so we can make an informed decision about that tools are useful, and how appropriate they are in dealing with the various tasks with which we are faced, some more complex and challenging than others. We all want a tool with functionality sufficient to the task, without it being overkill. Usually the decision requires a balance between functionality and price. Invariably the bottom line is summed up in the universal phrase "Value for Money".

Much as they would like to think differently, pilots are no different than the rest of us. The scope of their work varies from port to port, and sometimes even within a port. Some of the tasks are simple and straightforward, and others require more knowledge, more information and more tools. For example, the sheer size of today's VLCC's and ULCS's, and the huge volume of vessel traffic now makes at least part of the modern pilot's job more and more challenging, even when navigating smaller vessels through confined waters. To meet these challenges, the responsible pilot looks for additional information that can clarify and even enhance his situational awareness in order that he can navigate safely. With better technology various types of useful information are now available, some of it in real time. For example, the real-time display of own ship position and positions of AIS target ships within VHF range, all on electronic navigation charts is taken for granted these days, although the technology has not been in place that long.

Just as computers have helped millions to make their work easier, faster, and more efficient, the use of PPUs as an aid to navigation has grown, and will continue to grow in the world of marine pilots. These units have evolved from simple GPS units providing position independent of the shipboard GNSS, to sophisticated units that provide their own very accurate position, speed, RoT and heading. Some even communicate with data servers to provide real-time tide, the VTS traffic image, currents and other meteorological information pertinent to safe ship navigation.

As more and more PPUs reach the marketplace, and as their technology evolves, it becomes more crucial for pilots to understand what these systems are actually providing in terms of accuracy and reliability. In order to match the tool to the task, and to ensure "value for money", the pilot must be able to decipher PPU specifications, which, like many other products, are not always consumer friendly and in some cases even misleading.

Hopefully the foregoing discussion has served to provide enough knowledge for a pilot to ask intelligent questions of the PPU manufacturer and to decide for himself whether he is obtaining "value for money". Is the PPU suitable to the task? A low-end PPU may do a perfect job when navigating in wide and open waters, but the same unit should not be used for critical operations. It can even lead to serious accidents when the observations from the PPU do not reflect the actual movement of our vessel.

All this is called "scalable pilotage", so from situational awareness, to navigating in confined waters to the most complex berthing and lock approach operations, just make sure you select a PPU based on specifications before making decisions based on price.

Uncertainty Propagation Explained

The total uncertainty of the bow position consists of both the uncertainty in the heading and the uncertainty in the antenna position. However the factors can either add up or even each other out. The rules of uncertainty propagation state that for unrelated uncertainties, the total uncertainty is the root of the sum of the squares:

$$U_{total} = \sqrt{U_a^2 + U_b^2 + U_c^2 + \cdots}$$

The result of this is that there is usually one uncertainty that obscures all other uncertainties.