



Position Fixing Systems



SOME THOUGHTS

Accurately fixing your position in relation to both the nearest land and the race course was, for a long time, the essence of being a good navigator. Knowing where you were as you hurtled towards a lee-shore finish line in thirty-five knots – with the 1.5 oz up, and a night whose blackness is only relieved by the luminescence of the white horses – was no joke before the advent of electronic position fixing systems. In the days of the Global Positioning System (GPS) the problem is almost, but not quite, trivial. The skills of good position fixing now mainly consist of finding the power switch.

Once you've got the GPS installed and powered up, as a navigator, you then want latitude and longitude, and some idea of its accuracy combined with a relatively easy means of converting this into something more useful; such as cross track error or speed over the ground. The advice in this book is, of necessity, general; the detail of what you need to know can only come from the manual. Whatever they say about it being the last resort, you should read it. But what we are really interested in here is how to use this information to help you win races, and this is the topic of the final section of the chapter.



THE GLOBAL POSITIONING SYSTEM

The Global Positioning System, or GPS as it is more commonly known, has become the system of choice for all sailors, replacing the likes of Decca, Loran and Omega. It provides continuous, global, all-weather navigation in three dimensions with high accuracy and great simplicity for the end user. Its accuracy is such that it can be used for much more than just position. Starting techniques and two-boat tuning have changed because distances – to the line and between boats – can be measured more accurately than they can be assessed by eye.

So how does it work? A receiver aboard the yacht uses timed radio signals to calculate distance from several transmitting beacons. The position of the beacons is known, and the consequent lines of position are used to triangulate the yacht's position. The radio beacons are aboard (see Diagram 1.1) a constellation of 24 satellites, which orbit the

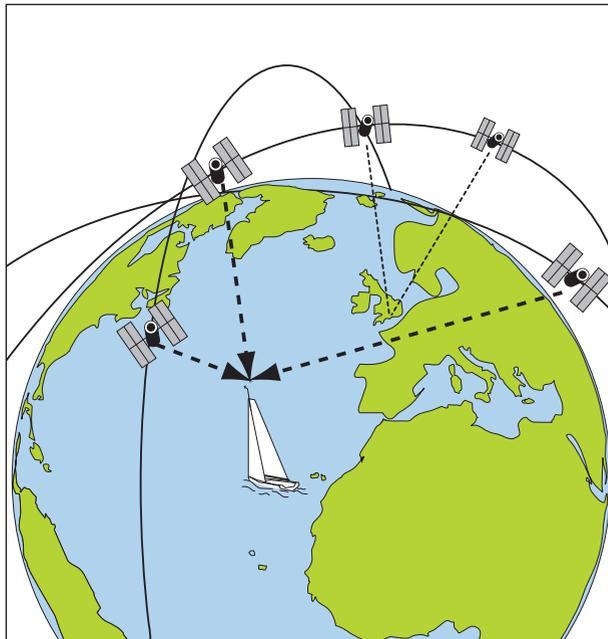


DIAGRAM 1.1 A ground control station monitors the orbit of the satellites and re-transmits corrections. Timing and orbit data is transmitted from the satellites to the yacht's receiver. Information from three satellites allows the yacht to calculate her position in two dimensions.

earth at a height of 10,900 miles. A minimum of four should be visible at any one time, which allows us to calculate position in three dimensions. Trigonometry tells us that each measurement places us on a sphere, and three of them intersecting will place us at two possible points. One of these solutions will be ridiculous, nowhere near the earth for instance, so it can be dismissed. The other point will be our position in three dimensions, latitude, longitude and altitude. To see why we need the fourth satellite we must look at how the distance measurements are made.

The distance measurement uses a concept called pseudo-random codes. A pseudo-random code is a succession of noughts and ones, apparently at random, but which actually repeats itself over a period of time. The satellite transmits these pseudo-random code messages, and the receiver listens and compares it to its own internally generated version of the code. All the satellites work on the same two frequencies and they are identified by having their own codes. The underlying assumption is that the code was issued from both sources simultaneously and so by comparing the codes, the receiver can calculate the time that the signal took to reach it.

The critical aspect of all this is the timing, due to the speed light travels the tiniest timing error will lead to quite big distance errors. So when we say the codes are issued simultaneously from the satellite and the receiver, it must be simultaneous. This requires the most accurate possible clocks on the satellite and the receiver. Putting \$100,000 atomic clocks on 24 satellites is one thing, but if every user set required one the potential market would shrink somewhat! The solution is to make an extra distance measurement. We know that the clock error will be consistent to all three measurements. If this is the case then if we introduce an extra measurement the lines of position will not meet at a point (Diagram 1.2). We tell our receiver that if this happens then it must assume it has a clock error and adjust all its measurements by the same amount until they do meet at a point.

In this way we can eliminate timing errors in the receiver. Timing errors in the atomic clocks aboard the satellites do exist, and may occasionally produce a small unknown error in our position even though they are checked and corrected by the ground control system. Of the other errors in the system the worst are probably those due to the ionosphere, which slows down the GPS radio waves by an unpredictable amount. We can take account of it using 'average' figures for the effect, but obviously this will never be absolutely right. However, it may not be such a bad solution in the marine case because we only require latitude and longitude, and ionospheric error mainly affects vertical position and time.

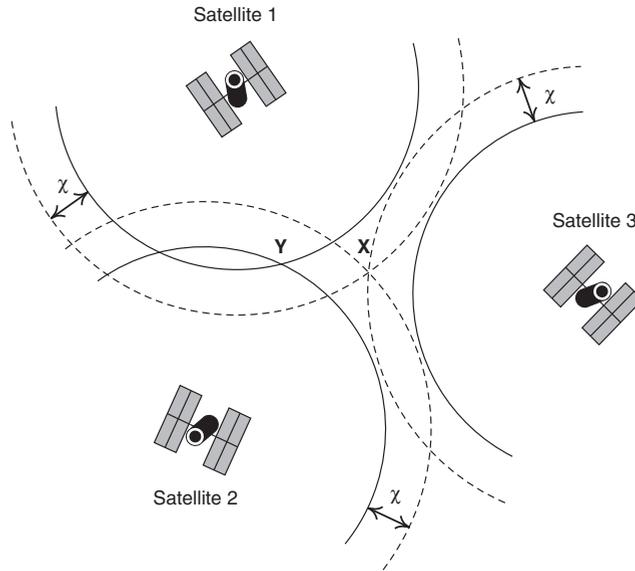


DIAGRAM 1.2 Clock Error. Given only satellites 1 and 2, the continuous lines which include the receiver's clock error meet at point Y. If we then add satellite 3 they no longer all meet. The receiver assumes that this is due to clock error and that the error (χ) is the same for all measurements. It adjusts them by the same amount until they meet at point X – the receiver's clock error corrected position.

The atmosphere does have some effect on GPS signals. Water vapour will slow and absorb them and unfortunately it is not an error that we can do much about. One that we can resolve is multi-path: the reflection of signals from other surfaces before they reach the receiver; which gives erroneous distance measurements. This can be almost eliminated by continuous tracking of the signal – but it is only something that the more expensive receivers will be likely to do.

When we look at uncertainties in the measurement we must include in our analysis Geometric Dilution of Precision, or GDOP. It effectively magnifies the other errors, depending on the angle between the satellites and the receiver; the wider the angle between the satellites that you are using, the bigger the GDOP and the bigger the overall error. The best receivers will look at all the satellites available and choose those that will reduce the GDOP as much as possible – or simply use all of them. GDOP is usually quoted as a single number; you might expect something between two at the best and ten as the outer limit of acceptability.

Initially, the highest quality GPS signal was reserved for use by the military whilst civilian GPS units could only receive a signal that was intentionally degraded, this was called Selective Availability. In 2000, Bill Clinton signed an executive order turning off Selective Availability at midnight on 1 May 2000. This resulted in the improvement of the precision of civilian GPS units from 100 metres to 20 metres.

If you want better than 20 metres – and you will for start-line calculations or two-boat testing – then one way of getting it is Differential GPS. This corrects the GPS signal by having an additional ground station in a known position. It can then calculate the error in the GPS position at that point. Because the satellites are so high up this error will be the same in the area around it and the correction can be transmitted to other receivers and used to calculate their positions precisely – and precise means within two to three metres.

Another development in positioning technology that can provide greater accuracy than the standard GPS is the Wide Area Augmentation System (WAAS) in the USA, and the European Geostationary Navigation Overlay Service (EGNOS) in Europe. Both systems were developed to assist air navigation by improving accuracy, integrity and availability. The initial goal of WAAS was to enable aircraft to rely on positioning from GPS for all elements of flight, including precision approaches to landing.

Like Differential GPS, WAAS and EGNOS use a network of ground stations to measure the small variations in the GPS signals. The data from these ground stations is then collated at master stations and corrections are sent to geostationary WAAS or EGNOS satellites, where they can be beamed back down to WAAS/EGNOS enabled GPS antennas.

Typically WAAS/EGNOS enabled GPS antennas provide an accuracy of less than two metres, though the coverage is not global. It is this kind of precision that was costing America's Cup teams thousands of dollars at the start of the new millennium, but within a decade had become so affordable that it's standard in most entry level GPS receivers.

Equipping yourself with the best GPS possible will go a long way to help with any testing that you may embark on. In the 2000 America's Cup advances in Differential GPS allowed highly effective two-boat testing to take place, with two identical boats testing sails, spars and foils against each other. Instruments systems have long struggled to measure comparative performance to the kind of accuracy required to split two boats of race winning speed.

Two-boat testing in the America's Cup is no different in principle from dinghy testing – you sail the boats beside each other and see who is going faster. But this is not as simple as it sounds, if the wind heads the leeward boat will seem to get an advantage, if it lifts the windward boat will look good. Whoever is judging the test must not only assess the relative distance and angle of the boats, perhaps using a hand bearing compass or stadiometer, but they must also take account of any wind shifts. It takes practice, and even then requires a great deal of concentration not to make mistakes and come to false conclusions – conclusions that might send your whole design program up the wrong path.

It's different with a Differential or WAAS/EGNOS enabled GPS, a computer running tactical software and a couple of radios. Using this equipment it is possible for anyone to begin to make valid comparisons. It can be taken a step further by transmitting the wind data and the position of the boats via telemetry to a computer; and then it is possible to resolve the distance apart with respect to the wind. At the same time, differences in wind strength or direction between the two boats can be spotted. Given suitable hardware the computer can record the results of each test run for you.

Another consideration for any serious racing team is to get a GPS that runs at greater than the standard 1Hz update rate (one update per second) – a 5Hz update rate (5 times per second) would be a significant improvement. This becomes important in the starting sequence when a 5Hz unit is able to keep up with the rapid changes of course. When it's interfaced with tactical racing software it also helps to provide a much better picture of the start. A quick updating Differential or WAAS/EGNOS enabled GPS will call the position of the yacht relative to the start line more accurately than all but the very best bowman or woman!



USING THE GPS

The basic task of a GPS is to tell you where you are, traditionally done by displaying a latitude and longitude. This obviously has its uses, placing you on a chart or tidal atlas in relation to the shore, its effects and the tidal streams. But more often you need to know where you are in relation to the next mark. Most GPSs have ways of telling you this as well as other numbers, but exactly what data you need and how you use it depends on the type of leg you are sailing. What we will look at next is the information you can get from a GPS, and ways – and ways not – to use it.

COG and SOG; Course and Speed over the Ground

Those of us who race in tidal waters will be familiar with COG and SOG. If the water is stationary relative to the ground then your boat speed and heading tell you all you need to know about your motion relative to the mark. But if the water is moving, either through tide or current, then your course and speed across the ground will be the vector addition of your boat's motion through the water, and the motion of the water relative to the ground (Diagram 1.3). This is fine if you know the exact rate and direction of the current, but that's unlikely unless you have been able to sit by a fixed buoy and measure it, or have an extremely accurate tidal atlas.

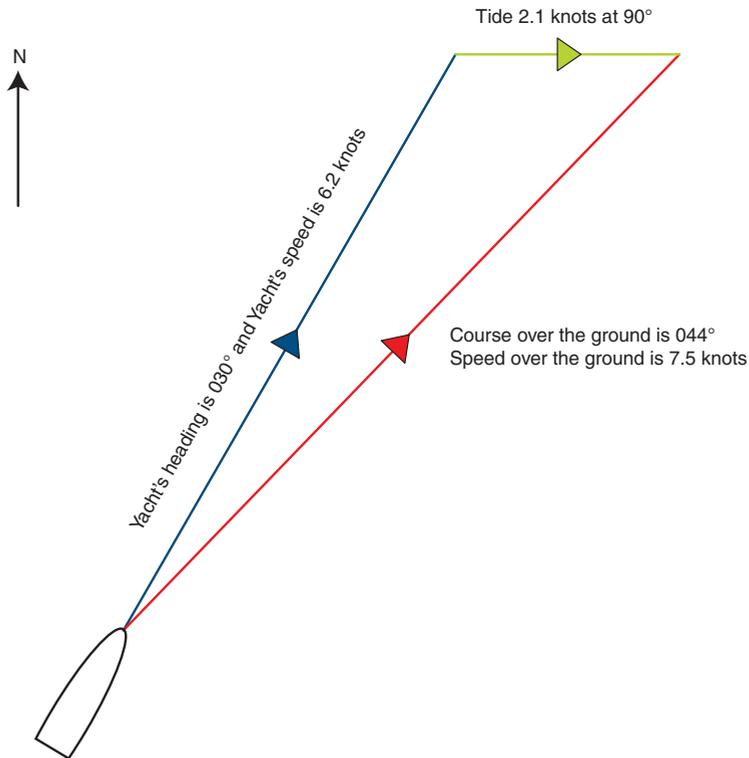


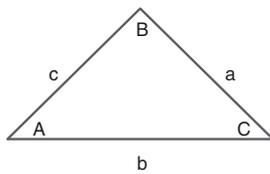
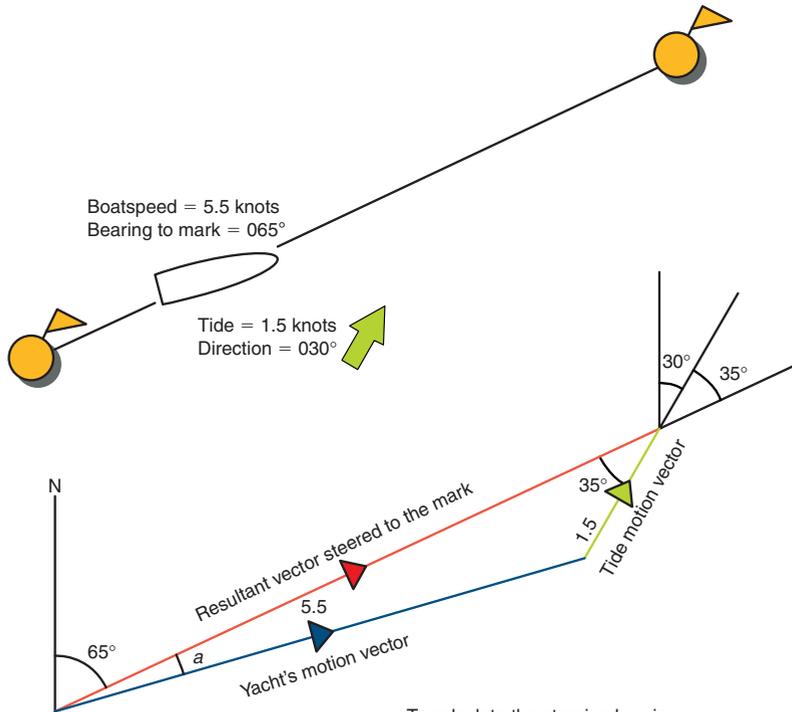
DIAGRAM 1.3 COG and SOG. The yacht's motion through the water is added to the water's motion across the ground to give the yacht's speed and course over the ground.

It would be far more useful if we could do the calculation the other way around. If we knew course and speed across the ground then we could subtract our boat speed and heading through the water, and the result would be the direction and speed of the tide/current. This is one use of the COG and SOG figures produced by the GPS, they allow you to calculate the tide/current you are sailing in and then, hopefully, turn it to your advantage. Some instrument systems, if interfaced to the GPS, will calculate tide/current for you. The accuracy with which this can be done depends on the quality of the GPS. But a decent unit will allow you to take advantage of very subtle differences – dodging out of a couple of tenths more Solent tide is quite possible these days.

Using COG and SOG to dodge unfavourable tides is straightforward, but tidal strategy gets more subtle. Take as an example a reaching leg that is sufficiently long for the tide to change significantly, in rate or direction, during the leg. A situation that is different from one where the leg is so short that the tide is more or less constant. In both cases the shortest course is the one which you can sail on a steady compass bearing. Now if the tide is constant the COG will also be a steady bearing, but if the leg is long enough for the tide to change, the COG will vary whilst your steering bearing will be the same. Trying to keep the COG the same on a reaching leg with a changing tide is wrong. In a constant tide, we are trying to achieve a heading that will compensate for the effect of the tide and allow us to sail on both a steady steering bearing and a steady COG. The COG should be the direct line across the ground between the marks. The steering bearing can be calculated if you have an estimate of the tide (Diagram 1.4). But in these days of on-deck navigation, or if you do not know the exact strength and rate of the tide, then the COG can be used as a 'cheat'. You just sail the boat at whatever steering bearing gives you the necessary COG to the mark.

But this technique is disastrous if you try to employ it on a leg where the tide is changing. No sooner have you settled on a steering bearing that gives you the right COG than the tide changes and you find the COG changing with it. So you correct the steering bearing again to get the COG right and off you go. But as the tide changes the COG will alter once more, and so you will have to change your steering bearing again. This cycle continues with you steering dog-legs across the ocean – not fast at all.

What you need to calculate is the total amount of tide for the time you are on the leg. Then you can set a course that will compensate for the net effect of the tide over the whole leg. Your calculation will start with an estimate of your speed and the distance to the mark to work out how long you will be on the leg. Then, using tidal data you can work out how far you will be pushed off the rhumb line by the tide during each of those hours. Adding them all together you will be left with a net amount of tide pushing you



To calculate the steering bearing we draw a triangle for 1 hour of sailing, so that the course over the ground = bearing to the mark.

We need to find 'a' – which for the general triangle (shown left) can be done using the sine rule

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

So
$$\frac{1.5}{\sin a} = \frac{5.5}{\sin 35^\circ}$$

and $a = 9^\circ$

The steering bearing = $65 + 9 = 74^\circ$

DIAGRAM 1.4 Calculation of a steering bearing for a course affected by constant tide.

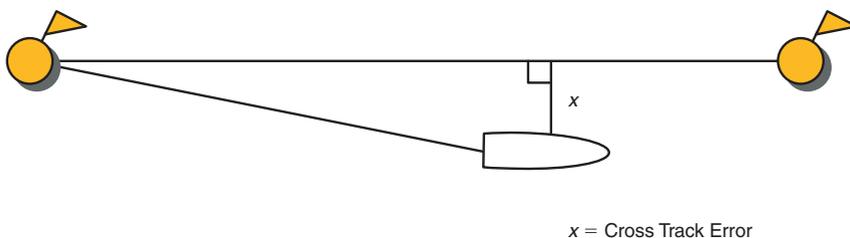


DIAGRAM 1.5 Cross Track Error is the perpendicular distance from the straight line to the mark.

one way or the other – you then calculate a tidal offset to account for just this much tide in the same way as you would for a constant tide. You should be able to sail on the resultant bearing for the whole leg and end up on the mark. Of course, it doesn't usually work like that, if the wind varies in strength or direction the time you spend on the leg will change, and the tidal estimates are rarely that accurate. So the calculation is one that you must continually repeat as you sail down the leg.

Our main interest here is how the instruments can help us to sail a leg like this, and this is a good time to introduce Cross Track Error, a GPS function that can be particularly useful on this type of leg. Cross Track Error is your perpendicular distance from the straight line course between the last waypoint and the one you are sailing to (Diagram 1.5). For the GPS to be able to calculate this you will need to have programmed in the relevant waypoints. Its use in this instance is that it enables you to keep a track of exactly how much you are getting swept off the rhumb line as you sail down the leg. If after two hours you reckoned you would be half a mile south of the rhumb line, and the Cross Track Error only puts you a quarter mile south, then it gives you plenty of time to try and work out what is happening and how to correct it – before you end up a quarter mile south of the buoy and beating back up to it in a foul tide. A move that is unlikely to endear you to any but the most relaxed of skippers.

So much for reaching, the next two GPS functions we will look at are often of more use on a beat or run. On these legs the navigator abdicates much of the responsibility, particularly on short courses, to the tactician. The COG, SOG and Cross Track Error are not directly relevant to the boats heading, though they still need to be considered. Positional information that the tactician needs to know is the range and bearing of the next mark, and hence your proximity to the two laylines (Diagram 1.6). Whatever

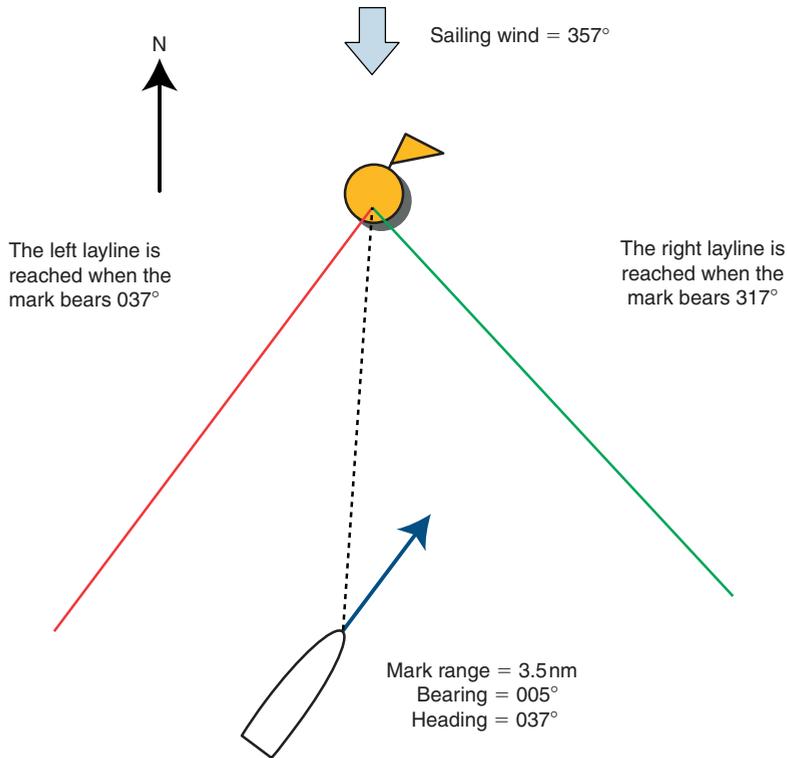


DIAGRAM 1.6 If you check your heading on each tack you can work out your tacking angle – in this case 80°. Then even if the wind shifts you will know what the mark must bear in order to lay it. If the mark is in your GPS, checking its bearing will tell you when to tack. When there is tide you can either work out how much to compensate in the normal way, or watch your COG to see how it is affecting you. Your COG on each tack will be the layline bearing – but check the wind, if it alters so will your COG.

tactical considerations he may have up the beat; wind, tide, shore effects or other boats, he will want to place the boat carefully on the course. Not getting too much to either side too early, and certainly not overstanding. You can use the range and bearing to the mark, together with a knowledge of your COG and SOG to give him this information.

There is one important use of COG or Cross Track Error on a windward leg. This example is when you are beating for several hours towards a mark whose bearing lies approximately perpendicular to the tidal stream. In that time you may have several

hours of tide running left to right, then several hours of tide running right to left. It is a basic strategy of this type of leg that you set off on the tack which puts the tide under your lee bow. I do not want to get into the lee bow effect here, mainly because it would pre-empt what I want to say in the next section, but there is no question that if you have a tide running across a beat, the tack that puts the tide under your lee bow will take you a lot closer to the mark than the one which puts it on the weather bow (Diagram 1.7). The

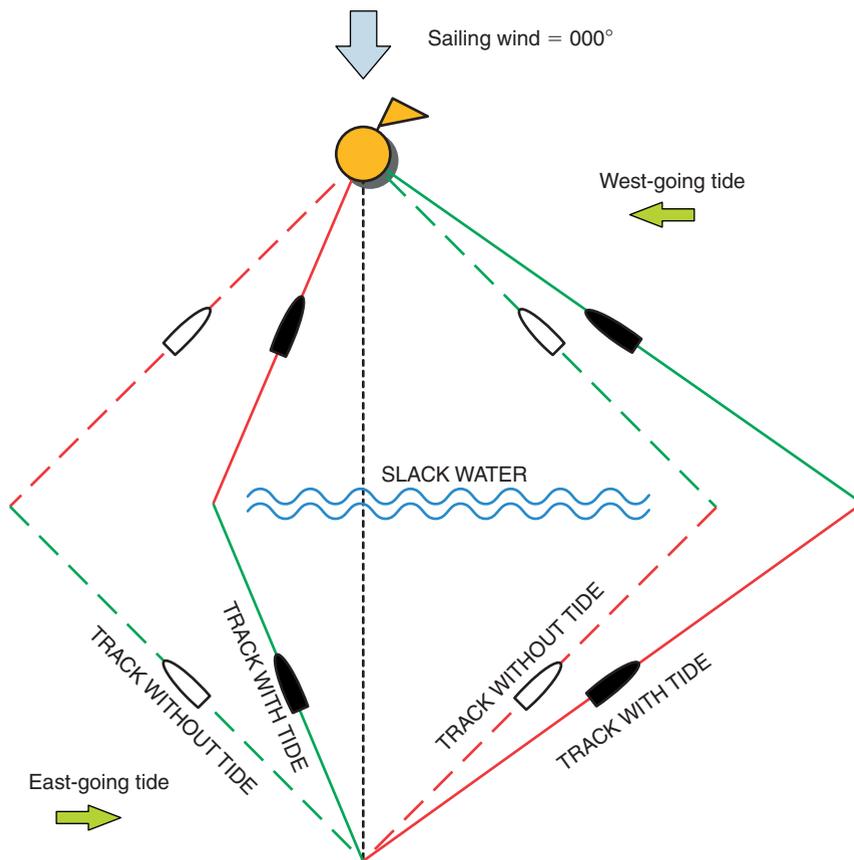


DIAGRAM 1.7 Sailing with the tide under the lee bow keeps the boat closer to the rhumb line (and optimises VMC). COG and Cross Track Error can be used to work out when the tide is changing, which is also the time to tack. Other advantages of this technique follow in the next section.

beauty of a long beat where the tide changes half way up is that you can then flop over onto the other tack and so spend the entire time with the tide under your leebow. The advantage of doing this is so great that you would have to have some extraordinarily good reason for not doing it – such as a big, and guaranteed, wind shift!

So where does COG and Cross Track Error come into this? Well, the key to it is spotting when the tide has changed and the other tack now has the leebow. Cross Track error will tell you this quickly. When the tide is on the leebow it will be pushing you up onto the rhumb line, and so the Cross Track Error is a lot smaller than it would be without the tide. As soon as the tide changes the Cross Track Error starts to shoot up as the tide is then taking you away from the rhumb line. The speed with which it increases is your indicator on when to tack. Similarly, with COG it will be steady until the tide goes round, when you see it start to alter then it is time to go.

Unfortunately we rarely get a windward leg with steady wind and a tidal change exactly half way along it, and even if we did there may well be some other complicating factors at the next mark, such as a shoreline effect. But what this technique of leebowing does do is maximise your speed towards the mark – in the jargon: it optimises your VMC. Whether or not this is a good general strategy is something we are going to discuss in the final chapter on instrument techniques using the polar table.

