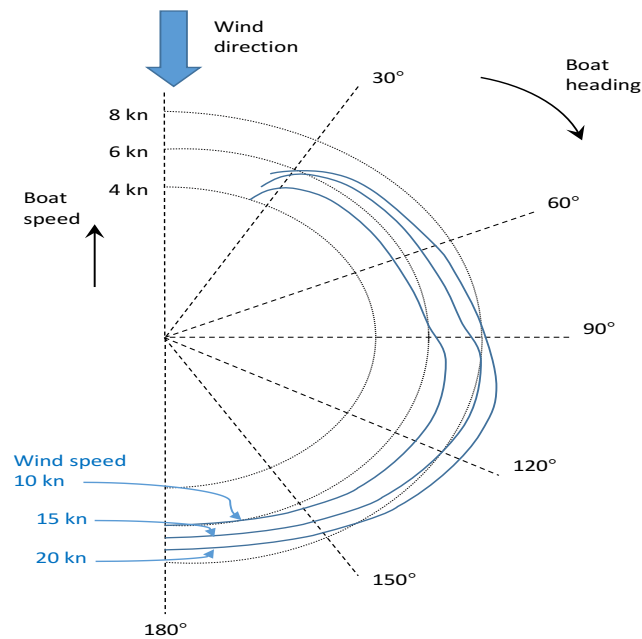


Polar plots: what are they?

By Kim Klaka PhD MRINA

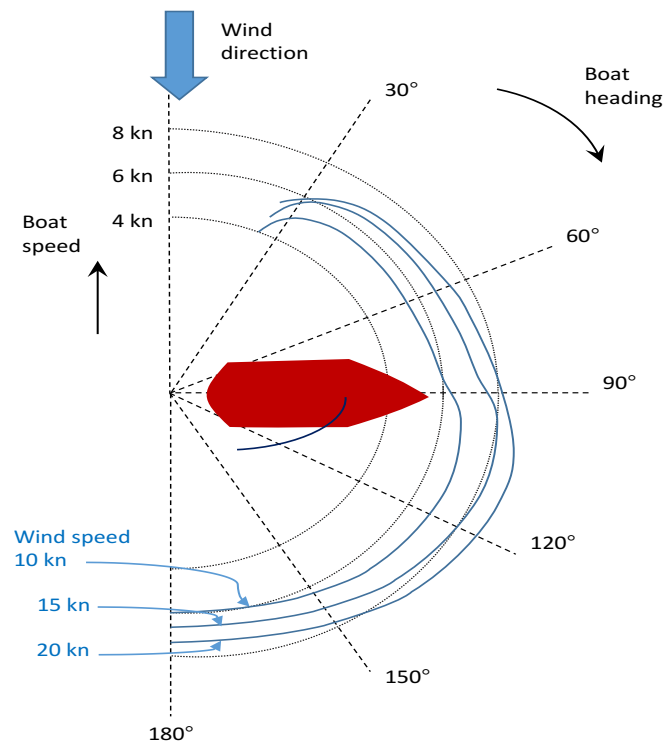
These days you will often find published in boat brochures and boat tests, a diagram showing the performance of a particular boat. The diagram is called a polar plot, and a typical one is shown in figure 1. Understanding how to use a polar plot can help make your voyages quicker and safer.

Figure 1: typical polar plot



If you already know what a polar plot is, skip to the next section. The polar plot is a very concise way of showing what your boat speed should or could be over a range of wind speeds and wind angles.

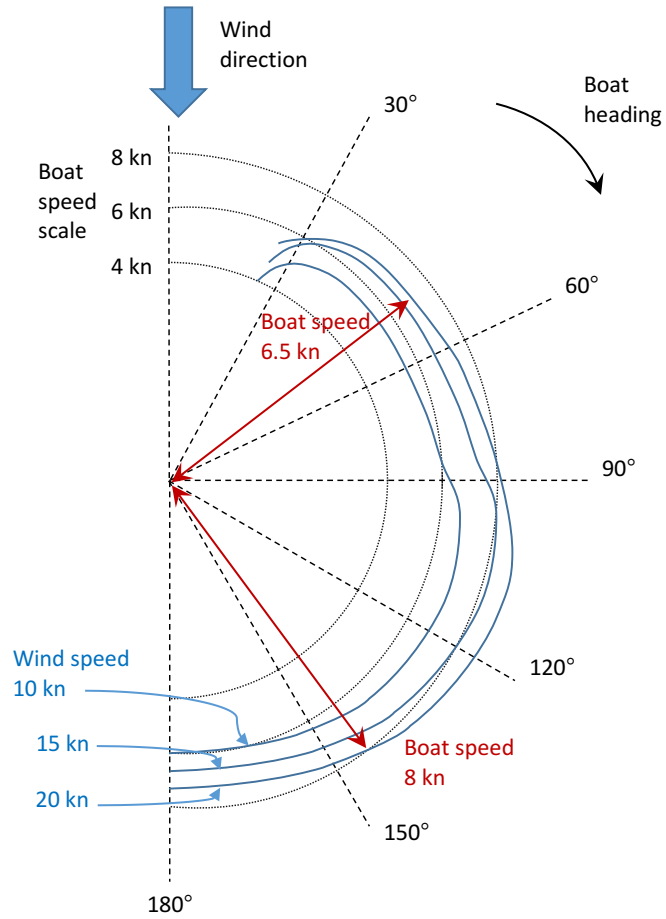
Figure 2: Port beam reach



In order to understand it, we need to get to grips with the axes used in the plot.

- a) The wind in the polar plot is blowing from the top of the page to the bottom. Using figure 2 as an example, the boat is pointing to the right of the page so the wind is coming across the boat i.e. on a port beam reach. A direction pointing to the bottom of the page represents a dead run.
- b) Next, the distance outwards (i.e. radially) from the centre of the plot represents the boat speed – see figure 3. Somewhere on the plot there will be a scale showing how many knots of boat speed is represented by how many centimetres of distance out from the centre of the plot. The further out from the centre, the higher the boat speed.
- c) Finally, there will be several curves on the plot, each one representing a different wind speed.

Figure 3: Boat speed scale



Putting this all together, if you choose a particular wind speed curve, and choose a particular wind angle, then where the curve intersects that angle, its distance from the

plot centre tells you how fast the boat will/should go at that chosen wind angle and at that chosen wind speed.

What use is a polar plot for a cruising yacht?

OK, now we know what a polar plot is; so what? It is probably obvious that it is useful for racing yachts, where knowledge of performance is everything, but how can it be useful for a cruising yacht? The answer assumes that performance is also important for a cruising yacht – shorter passage times, the ability to out-run a storm etc. If you don't consider this relevant to your way of cruising, then move on to the next article in the magazine. However, for the rest of us, the information in a polar plot can improve our chances of getting to the bar before it closes, and more.

Am I getting the most out of my boat?

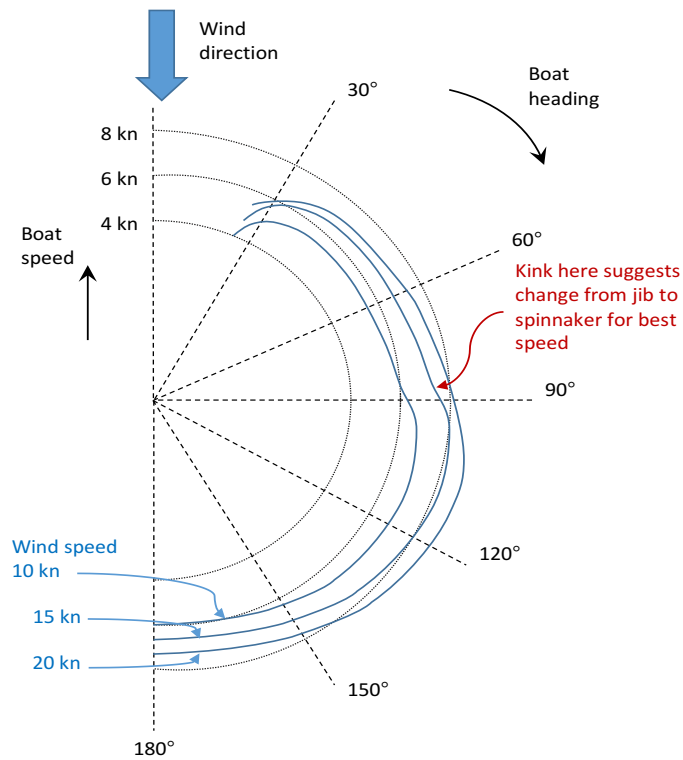
Perhaps the most obvious use of a polar plot is to answer the question "am I getting the best speed out of my boat?". Suppose you are sailing along and you note your boat speed for the wind speed and angle you are sailing at, then compare it with what the polar plot says your boat speed should be. If you are travelling slower than the polar plot indicates, you probably need to tweak the sails a bit. On the other hand, if you are travelling faster than the polar plot indicates, you are doing something magical to make the boat perform better than the designer's predictions!

That's the simple version; in practice it is rather more complicated, as you have to take account of the accuracy of the polar plot and the underlying assumptions made in deriving the plot. More of that later when we look at how the data in the plot is generated.

Should I be setting my spinnaker/asymmetric/staysail?

Some polar plots have curves which are not smooth, they have distinct lumps and bumps in places (see figure 4). This is usually because they indicate a changeover point between different sail combinations. If the curves are labelled with the sail combination assumed for each part of the curve, that will help you decide when to change from one sail combination to another, eliminating either a degree of guesswork or a very long time trialing different sail combinations and working out what is best.

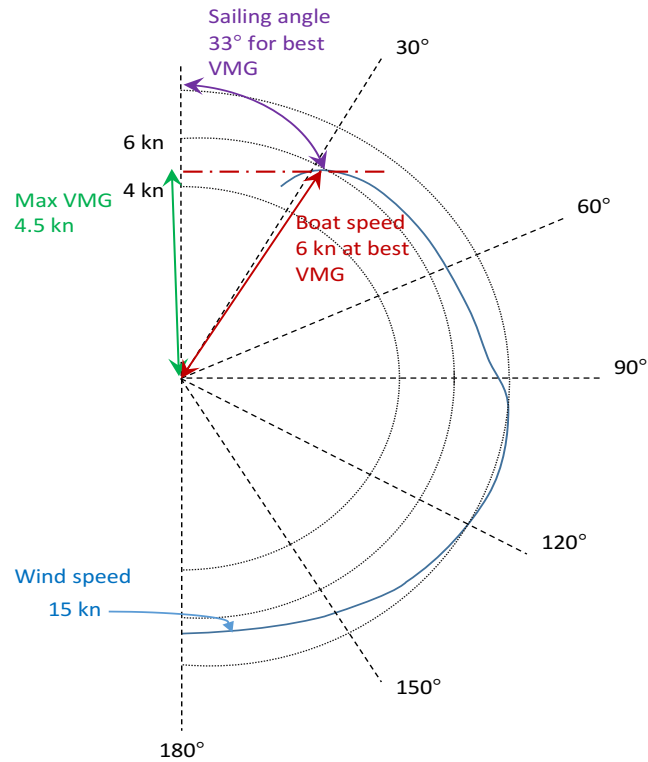
Figure 4: Sail change guide



What is the best angle to the wind when sailing to windward?

When sailing to windward, the performance objective is not to maximise the speed through the water, it is to maximize the speed to our desired destination, which is all too often directly upwind. The speed you are making directly towards the wind is called Velocity Made Good (VMG). To get the highest VMG you have to find where the best trade-off is, between pointing high but going slowly, and pointing low but going fast. In principle, the polar plot tells you exactly where this trade-off is for a particular wind speed. It lies on the part of the selected wind speed curve that is closest to the top of the page (see figure 5).

Figure 5: best upwind sailing angle



Using the example plot of figure 5, for a wind speed of 15 kn the wind angle at which the curve is at its highest is about 33 degrees. So your best VMG of 4.5 kn in this wind speed will be achieved by sailing at wind angle of 33 degrees and you should be able to achieve a boat speed of about 6 kn. If you are unable to achieve that boat speed when sailing at that wind angle, then you need to look at how you are setting the sails (or maybe the bottom is dirty, or the keel misaligned). Regardless, the chances are that the optimum wind angle inferred from the polar plot is roughly where the “sweet-spot” is for sailing to windward.

As an informative aside, the shape of the polar plot provides a further piece of information which could be especially valuable when deciding whether to buy a particular design. If the curve is very flat (horizontal) around this best-VMG sailing angle, then it means the boat has a very wide “groove” i.e. you can deviate from the optimum wind angle quite a bit and you will still be making very close to your best VMG. This makes for a boat that will perform well even with a novice at the helm. On the other hand, if the curve is very, er, curved at the optimum wind angle, this means your performance will drop off a lot if you stray even a little bit from that optimum wind angle. This means the boat might have great performance at its optimum angle, but you must apply a lot of concentration in order to keep it at that optimum – put a novice on the helm and performance will suffer markedly.

What is my best gybing angle for sailing downwind?

The principle for determining the sailing conditions for maximum upwind VMG can be applied to obtaining the best downwind VMG. If you have a conventional heavy displacement boat and only use white sails, then max VMG downwind is more often than not achieved by sailing dead downwind. However, lighter boats with a potential for surfing, or boats which use coloured spinnakers or asymmetrics, need to examine the situation a bit more closely.

If you are travelling at a certain boat speed and a certain wind angle downwind, you are probably continually asking yourself the question “if I sailed a bit lower, would the shorter distance sailed compensate for the loss of boat speed; or if I headed up and went faster, would this overcome the increased distance I have to sail?”

You can answer this question by examining the polar plot for your boat as already described for upwind sailing. However, I have done the hard work for you and generated a table which is usable for all boats in all wind speeds - figure 6. Copy it and put it next to the chart table or helm position.

Figure 6: Downwind sailing angles

	VMG										
TWA	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5
180	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
170	4.6	5.1	5.6	6.1	6.6	7.1	7.6	8.1	8.6	9.1	9.6
160	4.8	5.3	5.9	6.4	6.9	7.4	8.0	8.5	9.0	9.6	10.1
150	5.2	5.8	6.4	6.9	7.5	8.1	8.7	9.2	9.8	10.4	11.0
140	5.9	6.5	7.2	7.8	8.5	9.1	9.8	10.4	11.1	11.7	12.4
130	7.0	7.8	8.6	9.3	10.1	10.9	11.7	12.4	13.2	14.0	14.8

Black figures are boat speed.

To use this table, identify the row corresponding to the True Wind Angle (TWA) you are sailing at. Look across that row until you find the boat speed you are sailing at (or its closest number). Now look at the boat speeds in that column; they are the speeds you have to attain if you change your wind angle, in order to make the same downwind progress. For example, if you are sailing at 160 degrees TWA with a boat speed of 8 kn, then you are in the 7.5 kn VMG column. If you point up and bring the wind direction forward to, say 150

degrees, you will have to increase your boat speed to at least 8.7 kn in order to make the same progress in a downwind direction.

Drawbacks and limitations of polar plots

If the polar plots were a perfect representation of the boat's performance, and the boat was always sailed to its maximum potential, then this section of the article wouldn't exist. The fact that polar plots are not accurate changes the way we use them to some extent. A first step in this process is to understand how polar plots are generated, and the constraints that places on their accuracy and validity. There are two ways of developing a polar plot:

From computer predictions

Most polar plots are derived from the output of a computer program called a Velocity Prediction Program (VPP). The first full VPPs were written nearly 40 years ago, and they have come a long way since those days. Nevertheless, how best to write a VPP is still the subject of much research in yacht design. For brevity I will just describe the starting point (input), the output (the polar plot) and some of the more dubious assumptions made in the formulae used.

A typical set of input data would be the boat's design dimensions (hull shape, sail plan, centre of gravity etc.). The more data that is input, and the more accurate that data, then the greater the chance of getting an accurate polar plot as the output. However, it can be quite difficult getting all the data (e.g. the exact section shape of the keel and rudder, or the actual weight of the boat with all its clobber). So if you have a boat whose design doesn't conform to the input data, then the output isn't going to be accurate – rubbish in, rubbish out.

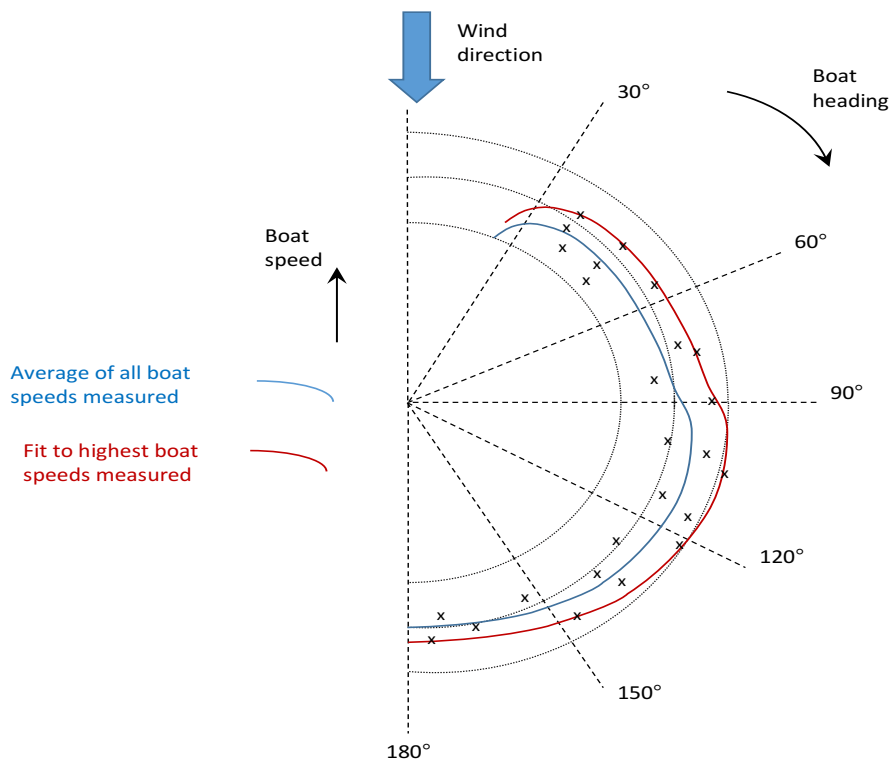
Secondly, there will be some inherent assumptions in the VPP that might be violated when you are out on the water. To give just a couple of examples: Firstly, the VPP will assume that your sails are set to their best possible, whereas you may have old baggy sails, or you cannot set the headsails as far inboard as the VPP assumes. Secondly, most VPPs assume either that you are sailing in flat water, or for the more advanced VPPs, it is assumed that the wave height and angle are determined solely by the wind speed and direction. We have all sailed in a sloppy sea from a left-over storm, where the wave height is higher than that expected for the prevailing wind. And many of us have noticed different performance on port and starboard tack which can be attributed to the waves not coming from exactly the same direction as the wind. In both of these situations the VPP output is not realistic, so the polar plot will not be right. This is nowhere more evident than for close-hauled sailing angles at high wind speeds. If your polar plot shows that your boat can sail at higher and higher boat speeds to windward as wind speed increases, you know this is wrong. It simply does not happen in real life and it is a sure sign that the VPP is not taking proper account of the waves generated by the wind.

From on-board measurements

By the 1980s polar plots generated from VPPs were becoming fairly commonplace in racing circles, and their limitations were starting to become apparent (e.g. the wave effects described above). By the late 1980s the advent of micro-processors meant that on-board instrumentation had become very much more sophisticated. And some bright spark realised that if you continually recorded the performance of the boat (boat speed, wind angle and wind speed), you could generate a polar plot from this data without having to go anywhere near a VPP. Not only that, it should also be more accurate than a VPP-generated polar plot because there was no need to make assumptions about things like the keel section shape or

how the sails are set – all those factors were implicitly allowed for in the collected data. Unfortunately those advantages are offset by a fairly big disadvantage. Because the data is for the boat as it is actually sailed, it will include the times when you are not sailing at your best, so there will be a huge amount of scatter in the data. This presents a dilemma when generating the polar plot: should you just take an average of all the scattered data, or should you use only the data where the highest boats speeds are recorded? See figure 7.

Figure 7: Scatter in measured data



There is no right or wrong answer, but it is very important to know what method has been used i.e. are you looking at the best possible achieved boat speeds, or the average speeds including the times when your concentration at the helm lapsed.

If that was the only problem with polar plots generated from on-board measurements, we could probably have dealt with it years ago. However, there are at least two more matters to be aware of. The first is that hoary old chestnut, the waves being experienced. Their effect is embedded in the collected data, and without some kind of on-board wave measuring device you just end up with even more scatter in the data, making it extremely difficult to interpret. The other factor is the inaccuracies and assumptions made in recording and processing the on-board performance data. This is a very technical subject in its own right. If you want to dip your toe into it, read the manual for your fully-linked onboard instrumentation system.

The end result of this is not that one source of polar plot data is any better or worse than the other; rather you have to be aware of the limitations of each method in order to get the best out of interpreting the polar plot data.

Conclusion

The polar plot for your boat can help make your voyages quicker by:

- Acting as a yardstick for how well you are sailing the boat
- Helping you decide what sail combinations to use
- Determining your best pointing angle for sailing to windward
- Guiding you to the best gybing angles when sailing downwind

But to get the best out of a polar plot you need to know its limitations.

Terminology

Acronyms abound in this technical maze, here a few of the main ones are explained. They are not listed alphabetically; they are listed in a sequence that makes each successive term easier to understand.

TWS

TWS stands for True Wind Speed. It is the speed of the wind measured by weather stations etc.

AWS

Apparent wind Speed (AWS) is the speed of the wind that you feel on your face on board the boat, and it is also the speed of the wind measured by your anemometer at the top of the mast. So if you feel the wind blowing at 20 kn, that is the AWS. Easy! Why isn't this the same as True Wind Speed TWS? One way of explaining this is to go back on land, and imagine driving a car down the freeway at 80 kph into a head wind of, say, 10 kph. So the TWS is by definition 10 kph but if you (foolishly) stick your head out of the window of the moving car, you will feel a wind speed of 90 kph (80 due to the speed of the car plus 10 due to the true wind speed). So your Apparent Wind Speed AWS is 90 kph. Now get back on the boat, the same principle applies – the wind speed you feel on your face is a combination of the true wind speed and the speed of the boat.

TWA

TWA stands for True Wind Angle. It is the angle of the wind as measured by weather stations etc. (subtle difference: for a weather station TWA will be measured as a compass bearing relative to north e.g. 225 degrees, whereas on a boat it will be measured as a compass bearing relative to where the boat is pointing e.g. 60 degrees to port)

AWA

This is the angle from the bow that you feel the wind on your face, which is also the angle the windex arrow (if you have one) at the top of the mast points to. So, for example, if you feel the wind coming from 60 degrees on your port side, the AWA is 60 degrees port. Easy again! But why isn't this the same as True Wind Angle TWA? Let's revisit the car-on-freeway-explanation, modifying it slightly. Let's keep the True Wind Speed at 10 kph, but instead of being a head wind let us imagine it now blowing from the side of the car i.e. trying to blow it into the next lane. So the True Wind Angle is 90 degrees, but because the car is doing 80 kph, when you stick your head out of the window, you will feel the wind coming from almost dead ahead. I say almost, because the wind angle you feel on your face is pulled round a bit by the true wind coming from the side of the car. Take this to its extreme and imagine the car doing only 1 kph with the same true wind of 10 kph from the side, and the wind you would feel on your face would be coming more or less from the side, not from ahead. So the Apparent Wind Angle AWA is determined from the combined effects of the TWA and the boat speed. The way it is calculated is by use of vector triangles, which we won't go into here (but note it is the same principle used in working out course to steer in a cross-current).