Downwind Tacking

Foredeck hands are at the ready as a pair of Cal20s split tacks in downwind racing tactics.

By Arvel Gentry

SEA and Pacific Motor Boat, February, 1970

Arvel Gentry is a member of Seal Beach YC and an active racing skipper in his Cal 20 No. 1177. He started sailing in a Lido 14 and also crews on a Newport 20 and a Cal 40. If the tone of the article seems scholarly in its development, it may be because Gentry has applied his professional as well as sailing talents to the material. He is an aerodynamics engineer and works as Chief of Applied research, Aerodynamics Section, Douglas Aircraft Co. At Sea's request, Gentry listed his Cal 20 racing achievements and as a side remark noted, "In the other races...I've just tried to avoid coming in last!" Hopefully, his comments on Optimum Downwind Tacking will help other skippers in doing the same.

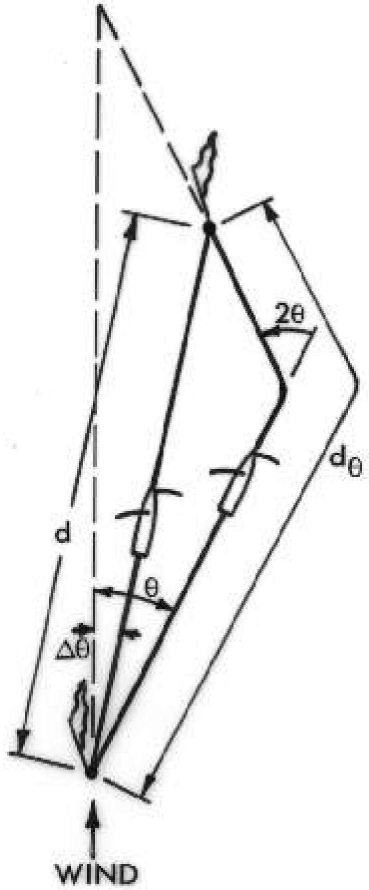
Every racing sailor has heard of downwind tacking. He may even carry in his wallet a business card from his sailboat dealer with some downwind tacking information printed on the back, such as that shown below. This information may be a tabulation of the speed increase required to break even against the increased distance traveled when deviating from the dead-downwind heading.

Degrees OFF	PER MILE Added Distance	Distance Off Course	"BREAK EVEN" SPEED INCREASE AT 2 Knots	4 Knots	6 Knots	8 Knots
5	.003 Mi.	.087 Mi.	2.01	4.01	6.02	8.02
10	.015	.177	2.03	4.06	6.09	8.12
15	.035	.268	2.07	4.14	6.21	8.28
20	.064	.364	2.13	4.26	6.38	8.51
25	.103	.466	2.21	4.41	6.72	8.82
30	.155	.577	2.31	4.62	6.93	9.24
35	.221	.700	2.44	4.88	7.33	9.77
40	.305	.839	2.61	5.22	7.83	10.44

However, this information doesn't tell the complete story since the racing skipper is not interested in just breaking even. He has to get to the finish line in the shortest time possible to win. With years of experience he might learn by trial and error what tacking angle to use for his boat in different wind and sea conditions. Most sailing literature seems to discuss only the break-even aspect of the problem. The purpose of this article is to expand this information and to show a skipper how he can easily find the best downwind tacking procedure for his own boat without suffering through years of trial and error.

In downwind sailing, the sails are primarily drag-producing devices with the drag forces giving the push that makes the boat go. Unfortunately, we usually have our sails set so that the mainsail tends to block or distort the air flow over the jib or spinnaker. As we change the relative position of the sails with respect to the wind direction by altering our course, we change the flow patterns around the sails so that the headsail gets more air and the boat speeds up. It is this increase in speed that leads to the idea of downwind tacking. We intentionally deviate from the short straight downwind course and hope that the increase in speed will more than make up for the greater distance traveled.

To get the most out of your boat when sailing downwind, you must have some idea as to how its speed changes as you deviate from the dead-downwind course. An exact determination of this speed trend would require more sophisticated instrumentation than the average sailor has available. However, with the careful use of a masthead wind vane, a compass and a good knotmeter, in several afternoons of test sailing you can accomplish about the same thing. The results for the skipper will be an



Distance

$$d_\theta = d \cdot D$$

$$D = (1/\cos\theta)\cos\Delta\theta = \text{Distance Factor}$$

Speed

$$s_\theta = s \cdot S \qquad S = s_\theta / s = \text{Speed Factor}$$

Time

$$\text{Time} = \frac{\text{Distance}}{\text{Speed}} = \left(\frac{d}{s}\right)\left(\frac{D}{S}\right)$$

Where :

- θ = downwind tacking angle (theta)
- $\Delta\theta$ = angle between line to mark and dead downwind direction
- 2θ = bearing of mark at jibe point (= twice θ)
- d = distance to mark without tacking
- d_θ = distance to mark with downwind tacking
- D = distance factor
- s = speed without tacking
- s_θ = speed with downwind tacking
- S = speed factor
- D/S = downwind tacking factor
- s_0 = speed on true dead downwind course

Figure 1

increased confidence that he is sailing the best downwind course regardless of what the other boats might be doing.

Before we start out test sailing, we should first take a look at the various factors involved so we understand what we are looking for. Figure 1 contains a diagram illustrating these factors. This diagram is for the general case where the downwind mark is not dead-downwind but is at an angle, delta theta ($p\theta$), from the true dead-downwind direction. Similar diagrams shown in sailing literature are usually made only for the condition where the lee mark is dead-downwind ($p\theta=0$). In the following discussions and in the analysis of our test data, we will at first also make this simplifying assumption. However, later in this article we will look at the condition where the lee mark is not dead-downwind.

For the mathematically inclined and for convenience in the analysis of our test data, three important parameters have been defined – the distance factor, the speed factor and the downwind tacking factor. The distance factor, D, depends just upon the geometry of the path taken and is equal to one divided by the cosine of the downwind tacking angle when $p\theta=0$. The speed factor, S, is formed by dividing the speed at a given tacking angle by the speed that you would get by sailing dead-downwind. The downwind tacking factor, D/S, is formed by dividing the distance factor by the speed factor. The shortest time is obtained when the downwind tacking factor, D/S, is the smallest.

The important thing to note is that the amount of speed gained by deviating from the dead-downwind course and thus the variation of the speed factor with heading will vary a great deal between boats of different classes. Each boat will, therefore, have a different optimum downwind tacking angle. It should also be noted that on a single boat, the optimum downwind tacking angle will depend upon the wind and sea conditions involved – as if the racing skipper didn't have enough variables to contend with!

However, with a good testing procedure and a little mathematics, a skipper will be able to determine the influences of these variables.

The first step in this process is easy ... go sailing. To make the first test sailing runs easy, try to pick a day with medium winds of about 10 knots. Stay behind the breakwater, if possible, where the water is smooth and stay away from obstructions that block or deflect the wind. The more stable the wind conditions, the more consistent the test results will be. In brief, the procedure to be used involves taking a number of speed readings at different downwind headings and then returning to the club bar to complete the analysis of the data.

More likely, however, you'll do your data analysis at home in spite of the competitive skipper who is offering to pay for the drinks in exchange for a look at your results.

To gather the sailing data, first set the sails for dead-downwind sailing with the jib on a whisker pole or the spinnaker flying. It is important throughout all the measurements to do the best job that you can in setting and adjusting the sails for best speed at each heading test point. Now change the heading of the boat until the masthead wind vane indicates that the boat is headed dead-downwind. Write down this indicated dead-downwind compass reading.

The mainsail distorts the flow somewhat about the wind vane so that this reading may not represent the true dead-downwind heading. To check this, quickly jibe onto the other tack and repeat the indicated dead-downwind reading procedure. The difference between the two headings divided by two will be the correction to be applied to an indicated dead-downwind heading to obtain the true dead-downwind heading. Now you can start taking the actual speed readings.

Adjust the heading of the boat until the wind vane is pointing directly aft. Record this compass reading (the indicated dead-downwind heading) and the knotmeter reading to the nearest tenth of a knot. Since the knotmeter needle will usually be oscillating slightly because of the rocking of the boat, try to record the average reading over a period of several seconds. Now apply the indicated-to-true correction to the compass heading and adjust the boat to this new heading. Record this heading and boat speed. This will be the true dead-downwind condition and will be used in the subsequent data analysis.

Now, using the compass, head up into the wind about 10 degrees above the dead-downwind heading. Adjust the sails and after the speed has stabilized, record the new heading and knotmeter reading. Repeat this heading sweep at 20, 30, and 40 degrees off of the original indicated dead-downwind heading, each time recording the heading and speed. Now return to the heading where the wind vane is again pointing directly aft. If the compass and speed readings are close to the original dead-downwind conditions, then you probably have a good set of data points with consistent wind speed and direction.

Repeat this test procedure several times to gather sufficient data to establish consistent speed-heading trends. If any repeat check point is not close to the original test point reading, then make a note on your test log sheet indicating this and then repeat the entire procedure again. If as you take a test point you sense an increase in wind speed or apparent shift in direction, then note this fact on the test log sheet, abandon the test sweep and return to the indicated dead-downwind starting condition. Continue repeating the above test procedure until you have several sets of data that seem to have been taken under consistent wind and sea conditions.

The next time out sailing, try to pick a day with more wind and repeat the data gathering procedure. As the wind and sea conditions increase, you will have more oscillations in the knotmeter needle, your measurements will be less accurate and you will have more scatter in the final plotted results. For these conditions, more data points will be required to obtain good data trends. As the wind and sea conditions continue to increase, the boatspeed will begin to fluctuate wildly as surfing conditions develop (if you have a light displacement boat). Under these conditions, downwind tacking measurements become hopeless so just hang on and enjoy the ride.

After the first day of test sailing, you will be anxious to see just how all these speed and heading measurements can improve your downwind sailing. For this we must turn from the actual sailing to the data analysis. After you get home, review your test log sheets carefully. Mark out all those test points that have notes indicating any wind speed or direction changes. Number all the remaining good test points consecutively in the order that they were taken. Calculate the indicated downwind tacking angle for each point. This is found by taking the difference between the compass heading at each data point and the indicated dead-downwind heading. Next find the true downwind tacking angle for each point by adding the correction previously determined to account for the difference between the wind vane indicated dead-downwind heading and the true dead-downwind heading.

Plot the points on graph paper and include the number for each test point so that you can see the order in which the test points were taken. Typical plots for two different wind conditions are shown in Figure 2.

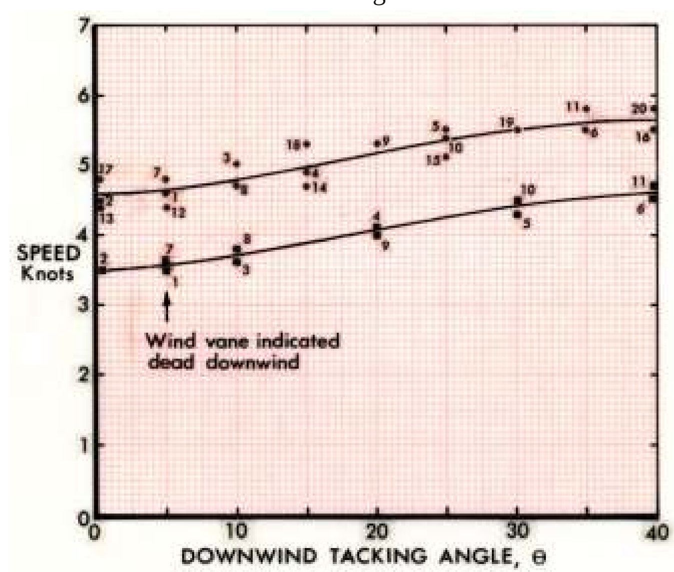


Figure 2

The lower speed set of data were taken under very smooth sea conditions and with a steady wind. The upper set of data were for a higher wind and rougher sea condition. Note the increase in data scatter and the greater number of data points used to obtain a useful data trend. The smooth lines drawn through each set of test points represents a smoothed average of the data taken and is used in subsequent calculations to find the optimum tasking angle for these wind and sea conditions.

The shortest time to the mark is obtained where the downwind tacking factor, D/S, is at a minimum. To find this condition, we use the smooth curves drawn through the test data and a few simple calculations. Sample calculations for the higher speed test data shown in Figure 2 are shown in Table I.

The calculations are made at 5 degree increments in the downwind tacking angle, θ. The distance factor, D, varies

Table I

θ	D $1/\cos\theta$	Speed S_θ	S S_θ/S_o	D/S
0	1.0000	4.60	1.0	1.0
5	1.0038	4.68	1.0174	0.987
10	1.0154	4.82	1.0478	0.969
15	1.0353	5.00	1.0863	0.953
20	1.0642	5.20	1.1300	0.942
25	1.1034	5.38	1.1685	0.944
30	1.1547	5.52	1.2000	0.962
35	1.2207	5.61	1.2200	1.001
40	1.3055	5.65	1.2290	1.062

with the downwind tacking angle and does not change from boat to boat. For these calculations the lee mark is assumed to be dead-downwind ($\rho\theta=0$). The speed as read from the smoothed data curve, S_θ, the speed factor, S, and the downwind tacking factor, D/S, however, are all a function of the boat and sail characteristics. As shown in Table I, the speed factor is obtained by dividing the speed at each tacking angle by the speed at zero tacking angle. The downwind tacking factor, D/S, is found by dividing the distance factor by the speed factor. The results of these calculations are shown in Figure 3 along with data for several other wind and sea conditions.

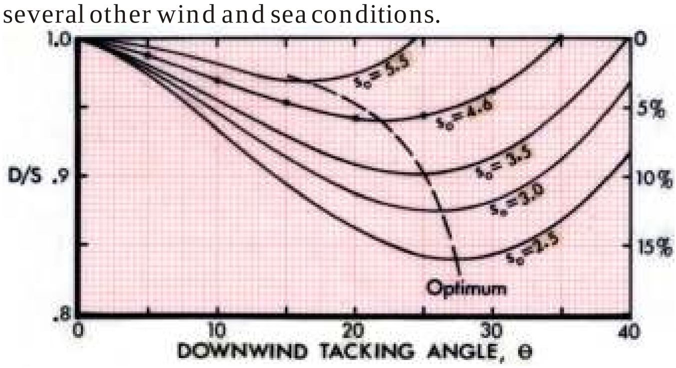


Figure 3

The numbers for S_0 on each curve give the corresponding boatspeed on a true dead-downwind heading. The lowest point on each curve gives the optimum downwind tacking angle. The percent scale on the right side of the plot gives the percent reduction in time from a dead-downwind course. For the 4.6 knot curve, the optimum tacking angle is 22 degrees and the time is 6 percent shorter than a non-tacking course. If this boat sailed at a downwind tacking angle of 15 degrees instead of the 22 degree optimum, then the time saved would be just a little less than 5 percent. Using these data for a one mile leg, the boat sailing the optimum 22 degree course will gain 3 boat lengths over a boat sailing at the 15 degree tacking angle (assuming a boat length of 20 feet). The boat sailing the dead-downwind course for these conditions will be about 18 lengths behind the optimum tacking boat.

Of course, such large differences may not be seen in an actual race because the lee mark is seldom dead-downwind. Even direct comparisons between boats of the same class is difficult because of different boat speeds due to skipper ability, different boat bottom conditions, and different sail designs.

The boat used for the measurements shown in Figure 3 had a hull speed of about 6 knots so little is gained from downwind tacking when the dead-downwind boatspeed approaches 6 knots. Of course, this chart does not apply when the wind is so high that surfing conditions exist. Note from Figure 3 that as the wind and boatspeed decreases, the amount to be gained by downwind tacking increases. For this boat, the optimum downwind tacking angle also increases as the wind speed goes down.

Before we get into the more practical aspects of using this information, we might first answer another question. How much is gained in tacking downwind when the lee mark is not dead-downwind but is at some angle off the dead-downwind? This angle is shown as $\rho\theta$ in Figure 1. The only change in the analysis procedure is that the distance factor is now given by one divided by the cosine of the tacking angle and multiplied by the cosine of $\rho\theta$. Tabulated results for a course where the lee mark is at a 10 degree angle off of the true dead-downwind are shown in Table II.

Table II

$\Delta\theta$	θ	D $\frac{\cos\Delta\theta}{\cos\theta}$	Speed S_θ	S S_θ/S	D/S
10	10	1.0000	4.82	1.0000	1.000
	15	1.0196	5.00	1.0373	0.983
	20	1.0479	5.20	1.0788	0.972
	25	1.0867	5.38	1.1162	0.974
	30	1.1372	5.52	1.1452	0.993

The downwind tacking factor results of these calculations are presented in Figure 4 together with the previously determined line where the lee mark was dead-downwind. Note that the curve for the $\rho\theta=10$ has exactly the same shape as the $\rho\theta=0$ curve except that it is shifted up so that it passes through the D/S=1.0 point at a downwind tacking angle of 10 degrees. The optimum downwind tacking angle will, therefore, remain the same at 22 degrees. However, the reduction in time from a no-downwind tacking course is only about 3 percent.

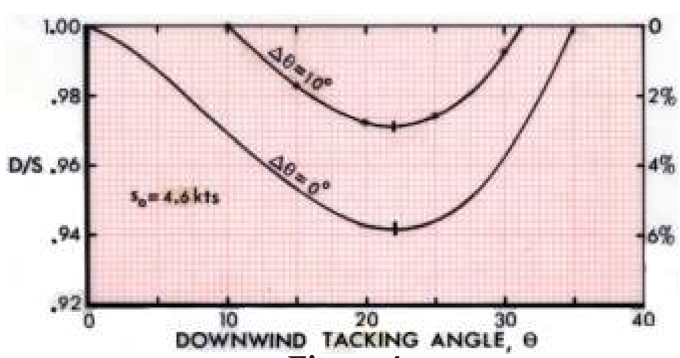
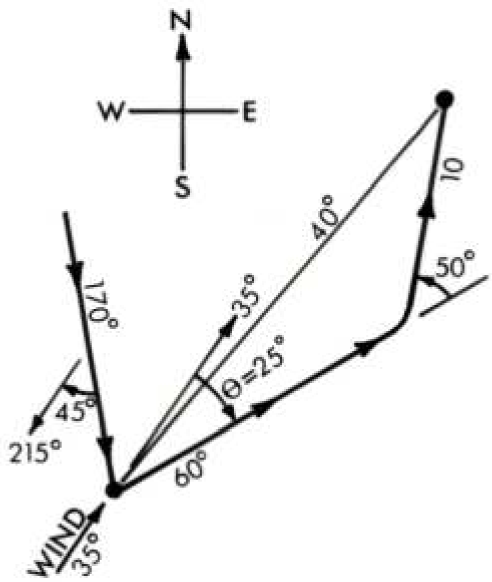


Figure 4

We will now turn to the practical considerations of actually applying this knowledge on downwind tacking in actual racing conditions. First, let's take the armchair-mathematical approach and after that we'll see what happens out on the race course.



Close hauled course = 170° (starboard)
+ 45°
True wind from = 215°
-180°
Dead downwind heading = 35°
Close hauled speed = 3.3 kts
Estimated speed for
dead downwind = 3.5 kts
Heading to lee mark = 40° (starboard tack)
Optimum tacking angle = 25°
Estimated course heading = 35° + 25° = 60°
Jibe when bearing of mark is 50° off of port bow

Figure 5

Let's assume that we are approaching a windward mark to be followed by a run downhill and we are trying to decide on the best downwind tacking procedure. First, we must determine the direction of the wind (true dead-downwind heading). Note the compass heading as you sail close hauled toward the weather mark. From this heading and knowing how close your boat sails to the true wind (usually about 45 degrees), you will be able to find the true wind direction. Having previously measured all course headings on the night before the race, you can quickly calculate the difference between the straight line course to the lee mark and the dead-downwind direction. You now consult your chart of downwind tacking factor (D/S) versus tacking angle (θ) and select the curve that best matches the wind and sea conditions. Knowledge of how the dead-downwind speed of the boat varies with close hauled boatspeed will help in selecting the D/S vs. θ curve to use in these preliminary calculations. An example of these calculations is given in Figure 5.

So much for the armchair sailing. Few racing skippers will be willing to follow this detailed mathematical procedure in actual racing conditions. Then what do we do? One answer which follows the above procedure in principal is to use one of the small plastic circular sailing computers now available. I have found the *Command Computer* excellent for this purpose. A quick setting and reading of this device by the skipper or crew gives a very rapid solution and allows the skipper to anticipate the conditions that he should expect even before he starts on the downwind leg.

The other possible solution is to develop the experienced skipper's “feel” for the optimum downwind course. But how do we do this without the years of experience under our hat? Again, a few practice sailing sessions may do the trick. Take the time to use the detailed hand calculation procedure shown in Figure 5 when you are not under the pressure of racing conditions. Repeat the exercise several times in a single practice session. These exercises will begin to give the skipper a better understanding of how his sails should look and in what direction the masthead wind vane should point for the optimum downwind conditions.

You may find it helpful to fix a reference pointer at the masthead to help judge when the wind vane is pointing in the right direction for optimum downwind performance. This ability to look up at the wind vane and know that you are on the optimum course is the most important single piece of knowledge to be gained from all these speed measurements and calculations, and represents the final approach attained by the expert skipper with his years of experience.

There is yet another way of handling the downwind tacking procedure and that is to make your measurements and analysis during actual race conditions. Most of the proceeding discussions have dealt with round the buoy racing. However, for the long distance racer the speed-versus-heading measurements and optimum course calculations may be best made under the actual race itself. In a long race, the time required to make the speed-heading measurements and calculations shown in Table I will be well worthwhile.

The previous discussions have neglected all considerations of what the rest of the fleet is doing. The first problem of this type occurs as you approach the mark with a number of other boats before starting the run. Having decided upon your downwind tactics in advance, round the mark, set the spinnaker or put the jib on the whisker pole, and above all, search for clear air in the direction that you have established. Once you have clear air away from the boats behind, you may want to take a few seconds to verify your original estimates as to the optimum tacking procedure.

Using your masthead wind vane, bear away to the indicated dead-downwind direction. If the wind direction checks with your original estimate, then pull back up to your optimum downwind tacking course. If your original estimate was wrong or the wind has shifted, use the new wind direction and recalculate your optimum downwind tacking procedure. The primary purpose of this is to ensure that you are starting off on the right tack.

Throughout the rest of the downwind leg, sail by watching the masthead wind vane to keep the boat at the optimum angle relative to the wind at all times. Boats with relative wind direction gauges will find them particularly useful in maintaining the optimum angle relative to the wind. Without such electronic gadgetry, you may find it helpful to fix a reference pointer at the masthead under the wind vane to help judge when the wind vane is pointing in the right direction for optimum downwind performance.

If you have a good lead with clear air, or in varying wind conditions, you may want to jibe several times to stay in the general path being taken by the other boats since you at least want to get all the strong puffs of air that they get. While ahead, you wouldn't want to tack away from the fleet and then get caught in a spot with no wind. However, if you are in the lead, they may just follow you, regardless of what course you are sailing.

There is one remaining question. When do you jibe on to the other tack to lay the lee mark? You may have noticed in Figures 1 and 5 that the relative bearing from the boat of the lee mark at the moment of the jibe is twice the optimum downwind tacking angle. The proper jibe point is difficult to judge so it may be wise to resort to the use of angular marks on the cabin top or a pelorus in deciding when you have reached the jibe point. With the relative bearing of the mark for the jibe known, you can make frequent sightings over the cabin top marks or the pelorus to determine when the jibe should be made.

One last point to remember. Different boats have different optimum downwind tacking angles. Different sail combinations on a given boat will also give different optimum tacking angles. And, of course, the wind and sea conditions always have their effect.

Don't try to rely on the numbers given in the samples in this article. Go out and determine the optimum tacking angles for your boat and stay ahead of the pack. If, however, they have read this article and are using optimum downwind tacking procedures they will be right behind you. In that case, keep your air clear, and good luck!

From Robert Altounian:

I too own a Cal 20 and have just started racing, and have found the downwind run quite perplexing when racing with experienced sailors. I also had some difficulty understanding your reference to a means of estimating the masthead wind indicator's position relative to some fixed reference. Do you mean you have some fixed indicating device attached to the mast head beneath the plane of rotation of the wind indicator?

Gentry's Response:

Yes, I do have a reference indicating device fixed to the masthead just below the wind vane. A small block of wood is attached to the masthead fitting with epoxy and the reference card is held on with a screw into the wood block. The indicator card itself is a 90 degree plastic pie-shaped section that I cut out of the bottom of a child's sand pail. The indicator card has saw-toothed notches cut into it at appropriate angles from the boat centerline. The installation is simple, light, and cheap.