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Race boat instruments

Part 1 – Understanding it all

Instrumentation can be as simple as a Windex and tell-tales or as in the America's cup, as sophisticated as what you'd find on a Formula 1 race car.

Let's look at what's available:
The big difference is the speed at which the raw data is collected (sampling), computed and outputted to the displays.
Before we get into the various options, let's see what actually makes up a modern instrument system:

- Wind sensor
- Boat speed sensor
- Compass
- GPS system

The information gathered by these four primary sensors is then used to compute all the major information we see on our instrument displays. Other sensors can be added for information like depth and heel.

At the lower end of the spectrum data is sampled and output at 1Hz (once per second), which sounds like plenty, but compare it to the upper end, where data can be sampled at 100Hz and output to the displays at 10Hz.
This additional sample speed can only be processed by a **central processing unit** which is considerably more powerfully than a collection of data specific displays daisy chained together. This CPU is what defines a high end system.

Each manufacturer has its target market and each is doing a good job within its respective market. The following suppliers are arguably the main players in the industry.

Tacktick, with their wireless solar powered solution, is perfect for sport boats and smaller One Design's.

Raymarine, with their "all in one" solution is perfect for 80% of the leisure market with all their products perfectly compatible, be it sailing instrument, radar, radio or autopilot.

B&G, is the only solution for superyachts and race boats, due primarily to the power of its CPU.

At a Grand Prix level, you have **Racing Bravo** and **WTP**, a B&G product, both of which are spin offs of America's Cup development. **Ockam** feature here too, but appear to be more popular in the US than elsewhere.

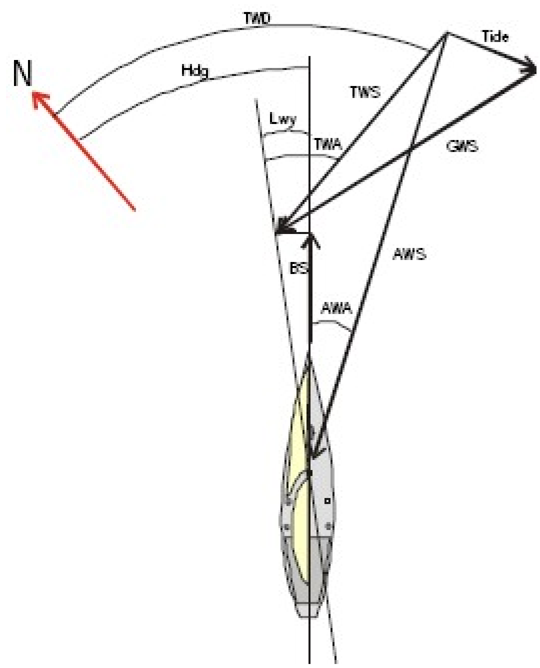
The Wind Triangle

Below you can see the primary differences between various products. (corrections *hown in italics)*

Entry level instrument system:
Mast head unit samples data at 1Hz
- *Correct for mast rotation and sensor offset*

Apparent Wind Angle / Speed
- *Factor in boat speed and heading*

True Wind Angle / Speed
True Wind Direction



Mid-range instrument system:
Mast head unit samples data at 4Hz
- *Correct for mast rotation and sensor offset*

Measured Wind Angle / Speed
- *Correct for boat speed and heading*

Calculated True Wind Angle / Speed
- *Correct for wind sheer and twist*

True Wind Angle / Speed
True Wind Direction
- *Factor in boat speed to back-calculate*

Apparent Wind Speed / Angle

Grand Prix instrument system
Mast head unit samples data at 100Hz
- *Correct for mast rotation and sensor offset*

Measured Wind Angle / Speed
- *Gyro correction for mast movement*

Corrected Measured Wind Angle / Speed
- *Correct for Heel, Leeway, Boat speed, Heading*

Ground or Original True Wind Angle/ Speed / Direction
- *Correct for Wind Sheer / Gradient and Twist*

True Wind Angle / Speed / Direction
- *Factor in boat speed to back-calculate*

Apparent Wind Speed / Angle

As you can tell, the big difference between the various options is the speed at which the data is sampled and the number of corrections (*shown in italics*) introduced into the calculation, hence the need for a powerful **central processing unit.**

Staying with the Grand Prix solution, we will now step through the process:
The reason for accurate wind data is simple.
Although we sail and trim our boat to the apparent wind speed and angle, as this is what the boat is actually seeing, the boat’s performance is measured at a given true wind speed and angle. This is because the true wind data stays constant irrespective of where the boat is pointing (Not effected by apparent wind). Effectively it’s a constant reference point.

Mast Head Sensor

As stated earlier, this data is sampled at 100Hz but typically is averaged to 10Hz. To achieve good wind data, the wind sensor needs to be secure and aligned with the centreline of the boat. Vertically mounted wind sensors are used to get the wind sensor up and away from the effects of the sail plan on the wind. To get your wind sensor completely clear of these effects is not practical due to the length of the vertical wand required, however as a rule of thumb, 1 inch of wand for each foot of boat length.
So a 40' boat would have a 40" vertical wand.

- Correct for misalignment due to poor installation or mast rotation (if wind sensor is fitted to a rotating mast with the required sensor connected.)

The motion of the mast can be substantial 100' above the hull, so gyro sensors are used to compensate for this motion.

- Corrections are then made for boat speed, current, leeway and heel.

Boat speed is simple enough as is **current** thanks to GPS.

Leeway is the thorn in your side, as there is no really accurate way to measure leeway. Multiple GPS sensors have been used with varying degrees of success. The best source of expected leeway is often the boat's designer.

The accepted formula for leeway is:
*Leeway = (K * Heel) / VS²*

or

*K = (Leeway * VS²) / Heel*

So with an expected leeway angle from your designer, **K** can simply be calculated.
Typical **K** values are around 1 for an AC boat and 10-15 for a typical modern race boat.

Heel is another important part of the equation.

Measured Wind Angles can change as much as 4' when heel changes from 10' to 24'. This angle will continue to narrow as heel angle increases until the Measured Wind Angle equals 0 at 90' heel.

*Corrected MeasWA = atan (sin (MeasWA) * cos (heel)) / cos (MeasWA)*

- Now we correct for Wind Sheer and Wind Gradient. These two effects are often just called "wind sheer" although they are quiet different but generally appear together.

Wind Sheer is the change in wind direction with altitude. This is easily detected by your instruments reading different wind angles from tack to tack.

Wind Gradient is the change in wind speed with altitude, primarily due to the effect of friction between the wind and the water. The wind speed will increase with altitude and is most noticeable in lighter winds.

Finally we now have True Wind Speed / Angle and True Wind Direction. This information is what is seen on the instrument displays.

- Apparent Wind Speed / Angle are then back-calculated and available on the instrument displays.

AWS *= $\sqrt{(b^2 + c^2)}$*
AWA *=a tan (b/c)*

Where
*a = TWS * (cos TWA)*
*b = TWS * (sin TWA)*
c =ab + VS

Boat Speed Sensor: Paddle wheel or Sonic Sensor?

Sonic Sensors are very popular on superyachts due to very low maintenance.
Paddles wheels are considerably lighter and some believe more accurate and hence are normally found on race boats.
Like the wind sensor, proper installation is paramount, and boat speed sensors should be installed on the centre line of the hull, in front of the keel about 2/3 of the way back from the bow's waterline.
In this position they should not come out of the water at high speed or in big seas and will not be affected by water flow around the keel.
If your boat speed sensor can't be installed on the centre line due to hull shape, then consider 2 sensors, positioned so they are vertical when the boat is at normal heel (Which is about 15-20').
Multi-hull's often use a sensor positioned in each hull. Typically the wind angle is used to calculate which sensor's data to use.

Compass

There are a couple of options here too;
A fluxgate compass is the standard electronic compass used on most systems.
A Gyro stabilised compass is often used on systems that have an autopilot.
On race boats specialised electronic compasses are used, these often have motion sensors so they can be used for Heel and Trim outputs too. These can be as small as a domino in size.
GPS compasses are now considered top of the range and recently have become competitively priced compared with the other options. They basically use two GPS signals and a motion sensor to calculate heading. Their downside is they require specialised installation of up to three antennas.

Once again the major differences between these systems are the sample rate, with some units running at 20Hz

GPS

Global Positioning Systems is another area that has big differences between entry level and top of the range.
At entry level, units operate at 1Hz with accuracy of 15 metres and at the top end of the scale, units operate at 10Hz or faster with an accuracy of 15 cm. The price is directly related to the speed and accuracy of the system.
Any system running at 5Hz with differential beacon correction will be more than adequate for any race boat.

Calibration / Damping

Three words… calibrate, calibrate, calibrate.
The importance of calibration can't be overstated; fortunately most of the sensors only need to be calibrated occasionally while others are calibrated daily.
So why calibrate?
Now we know that the boat speed is part of the calculation for AWA so consider this:

For every 1' that the AWA is out, the TWA is 2' out. That in turn means the TWD is 4' different from tack to tack.

Now a 4' wind shift is worth 0.3 knots VMG at 6.8 knots boat speed, or 1 minute on a 2 mile beat, so you can appreciate the importance of knowing whether you have a real wind shift or just poorly calibrated instruments.

Delta VMG = Vs(cos(TWA)) - cos(TWA-shift))

Unfortunately all four of your primary sensors must be properly calibrated to get perfect wind data as they are all related to the wind triangle.

Fortunately:
The GPS does not need calibration.
The compass only needs to be calibrated on installation.
The boat speed sensor only needs periodic calibration (once or twice per season).
The wind sensor only needs calibration if it has been removed, i.e. to pull the rig.

Damping is another, often neglected, part of calibration. It allows you to slow down the data, either going into the CPU or coming out. (The values move to fast to be of use on the instrument)
Some instrument systems only allow you to dampen the data you see on the displays, while others allow you to dampen the raw data.
Most high-end systems use dynamic damping which means the damping changes based on the rate of change within that data. For example, HEADING is dampened at a certain rate, but if you suddenly tack the damping decreases until the HEADING is stable again before returning to its normal damping rate.

Some Grand Prix systems allow damping of a variable based on another variable. For example
TWD is damped at a set rate, but if the HEADING exceeds a certain threshold, the TWD damping decreases until the HEADING value returns to its threshold.
These are very powerfully tools if used properly.

Software

The good news is there is computer based software available to help with all this calibration. Most software packages had direct access to the instrument system to allow you to calibrate on the fly. Within this software is your **Wind Tables** which are used to calibrate for wind sheer and gradient. These tables will get checked daily and sometimes modified during the day.

Most instrument suppliers have there own software package, which can work on 3rd party systems if need be and there are some excellent stand alone solutions available too.

The two industry leaders are:
Expedition from Nick White – works best with Racing Bravo and Ockam, in fact almost all instrument systems.

Deckman from B&G - Works best with all B&G products

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Part 2 – What instruments tell you

Instruments don’t win races, you do.
As stated in part 1, the quality of wind data is what define a high end instrument system. Have reliable wind data is vital to winning races. Here’s why:

True Wind Speed

Knowing the TWS is vital for 2 reasons

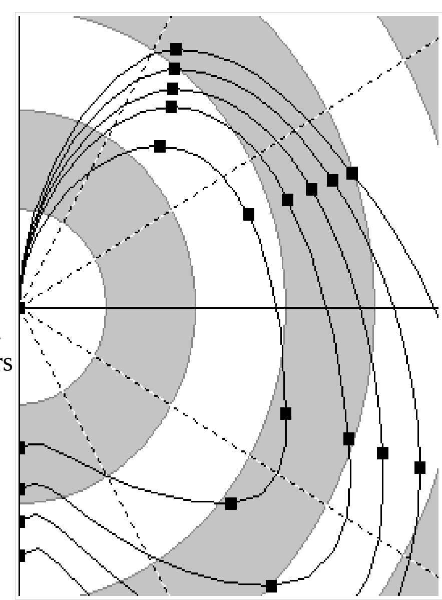
- How fast you should be going based on your polars – (available from you boat designer)
- What sail to use for the given point of sail – (available from your sail maker)

Wind Direction

Winning a race doesn't depend only on boat speed but also the ability to recognise or predict a wind shift. Wind instruments show TWD to within 1’ (Also very useful offshore when you don’t have a reference point to detect wind shifts)

Polars

Describe a boat's performance for a given TWS



In this figure, the curved lines represent the theoretical maximum boat speed for a given TWS and TWA.
The squares mark the fastest point of sail upwind and downwind. Point of maximum VMG (velocity made good) for both upwind and downwind.

VMG = cos(TWA) x VS

There is only one spot on the polar curve the get maximum VMG. If you sail higher or lower than that spot, VMG will be lost. Polars therefore give you a target wind angle (TargTWA) and a target boat speed (TargVS) to achieve the maximum VMG.

Polars can also be used to determine the best point of sail for any point between the best upwind and downwind VMG, this is called VMC (velocity made to course)

VMC = Cos(y) x VS
y = heading – heading to mark

Using polars

Once again, polars are only an aid, but a very powerfully one at that.
Polars can however challenge your conventional way of sailing especially in the lower wind range where your polars show the most change in boat speed with the increase in wind speed.

Upwind:

Upwind is easier as the TWA changes less to maintain maximum VMG, consider this:

TWS increases in a gust = Velocity lift
Gust comes, if using just telltales your natural reaction is to head up to chase the telltales, but if using instruments, as TWS goes up so does TargVS (you now going to slow), so it's actually better to trim the sails for speed and as you approach the new TargVS come up to TargTWA – This requires finesse and good communication between the helmsman and trimmers.

And if the TWS decreases in a lull = Velocity header
Lull comes, if using telltales your natural reaction is to bear way to chase the tell tales, but once again if using instruments you will see your new TargVS is actually lower so you are going to fast. The best way to burn this speed would be to continue sailing straight until you close to the new TargVS then come down to the new TargTWA

The best VMG with be achieved this way and is sometimes called "wallying"

Downwind:

Downwind is considerably harder, especially in lighter winds where the change in TargTWA is greatest to maximise VMG.

TWS increases in a gust:
Gust comes, your natural reaction is to would head down in puffs, however your TargVS would be to slow for this new TWS, so rather keep your course until you approach your new TargVS and then come down to course.

And if the TWS decreases in a lull:
In a lull your TargVS with now be to fast, so you should rather keep your course until the trimmer loses "feel" of the spinnaker or you reach your new TargVS and the return to TargTWA.

This will maximise your VMG but requires a lot of finesse between helmsman and trimmer.
(This technique is more effective of heavy boats)

Generally you want to sail to your TargTWA downwind, but paying attention to the TargVS in the gusts and lulls.

In medium breeze and surfing conditions the changes in TargTWA are smaller so the more traditional "down in puffs and up in lulls" is closer to the truth.

Reaching:

Sailing to target boat speeds is a short course technique and usually for upwind and downwind courses to maximise VMG.
If on reaching leg it will be fastest to sail straight for the mark if you not expecting the wind to change and you must concentrate on maximizing boat speed as per your polar curve.

However if you are expecting a wind shift, like on a offshore race, then you need to use VMC (Velocity made to course)

When sailing VMC remember these two rules:

- Select the quickest course to the next mark (when in doubt reach)
- Consolidate with the fleet if an opportunity presents itself (don't go off blindly hoping for a shift)

Effects on polars:

Polars, like instrument are just tools, knowing when you trust them and when not to is the key to winning races. It is therefore equally important to tweak them as you learn to maximise the performance from your boat.

What affects them and how to identify the errors?

Grand Prix system, like the WTP with Decman can easily detect and correct these effects, the biggest being:

- **Wind gradient** - Change in wind speed with attitude, take a look at the difference 2 knots TWS does to the target boat speed – especially at the lower wind speeds.

- **Wind sheer** - Change in direction with altitude, instruments read differently tack to tack **–** If starboard tack bigger, the wind is more to the right aloft.

How to spot it?

If wind looks less on water or has no "power" there's a good chance of wind gradient. Wind sheer and wind gradient often occur together and are generally called "wind shear"

Wind sheer is easily detected by different wind angles tack to tack or the tell tales break at top on one tack and not the other. (Assuming the leads are in the same place on both tacks) This can sometimes even be seen on a dinghy. On a bigger boat the AWA will be different tack to tack.

Why must we detect it?

- If the wind is stronger high up, put another way, less lower down, the sail selection could be different and the target boat speed and angle might be incorrect. Both **Deckman** and **Expedition** have options to correct for this.
- The wind will probably shift in the direction of the wind shear.

What causes it?

Most common reason for shear and gradient is a developing sea breeze, so never calibrate instruments in a developing sea breeze!

Warm air above cold water below creates a large thermal gradient.
At the start of this gradient you can expect up to 20' sheer and 30 to 40% gradient on a mid sized keelboat.
As the sea breeze develops the wind will become more mixed and once properly mixed sheers becomes 0 and gradient is around 10 – 15%.

Another reason to identify sheer early is a good indication of what to expect the wind to do.
If sheer is present the wind will in general shift in the direction of the sheer.
If there is no sheer present the wind should oscillate through out the day.

Other factors to consider when sailing in wind shear:

- Polars are generally calculated for a wind speed at 10m above the water.
- You might struggle to reach your target speed on one or both tacks due to wind gradient.
- On one tack you will be sailing in a "lift" so your boat speed will be higher or feel easier to reach. The other tack which will "feel" terrible as you will be sailing in a "header" and probably under target boat speed.
- Set up different tack to tack but don't go chasing target boat speed, rather use it as a guide.
- If there is sheer present, you might want to protect that side of the course as the wind should shift that way through out the day.

As stated earlier, provided they are properly installed and calibrated a good instrument system is the best investment you can make on a race boat...