Chapter Twelve

Do You Have to Be (an) Einstein to Understand Sailing?

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I. Introduction

"Prof. Albert Einstein an Bord seines Jollenkreuzers, der ihm von Freunden geschenkt wurde. (Photo: A. Harms)

Albert Einstein is widely admired as the smartest – and the "coolest" – scientist ever. After all, Time Magazine elected him the "Person of the Century" for the 1900's, and practically everyone knows his name (and associates it with "smart"). Among his many endearing traits, his love of sailing ranks right up there as a measure of his greatness (see the photo showing Einstein in his sloop "Tümmler", a gift from well-to-do friends that was custom-built for him). His groundbreaking discoveries, the Theories of Special and General Relativity, revolutionized our understanding of space and time and yielded the universally recognized equation "$E=mc^2$". But do **you** have to "be an Einstein" to get to a full and deep understanding of sailing? I mean this not in the usual sense ("being smart"), but quite literally: Do the laws of Special and General Relativity have any bearing on the ancient art (and modern practice) of sailing?

If you restrict yourself to practical matters (how to get from A to B in the fastest and safest way by use of a sailing vessel, or how to win the weeknight race around the cans), Einstein's theories of relativity have little immediate value. Ostensibly, this is so because they mostly concern themselves with extreme situations – speeds close to the speed of light (not exactly what comes to mind when describing the average cruise) and bizarre aspects of the Universe, like black holes and the big bang. A closer look, however, reveals that the philosophical underpinnings of Einstein's insights have a lot to do with the basics of sailing. Pondering these underpinnings may not necessarily make you a better sailor, but hopefully will provide something worth mulling about while ghosting along in a zephyr (or while eagerly awaiting the return of fair sailing weather in the middle of winter). You will find that, maybe without realizing it, you are making use of "Relativity" in one way or another every time you weigh anchor. Even the General Theory of Relativity, long considered the most arcane of Einstein's ideas, has a direct impact on something as mundane as navigation. In this article, I hope to provide you some guideposts along the path from everyday concepts familiar to most sailors all the way to Einstein's take on issues like time, space and motion.

II. Don't laugh at "slow" sailing - Average vs. Instantaneous Motion

A well-known jibe defines sailing as "the art of going slowly nowhere, at great expense and personal discomfort". And, sure enough, if you discount tricked-out Open 70's, America's Cup trimarans and novelties like the flying moth, most leisure sailors with limited pocketbooks rarely crack the ten knot barrier. On the other hand, our powerboating friends easily reach twenty, thirty or even forty knots on the water. No wonder they like to poke fun at the comparatively slow progress of a typical sailing cruiser. However, it all depends on your definition of velocity - if you aren't talking about instantaneous speed, but average velocity, we sailors have no reason to feel inferior.

By definition, average velocity takes the total displacement during a given time interval, and divides it by the amount of time elapsed. ("Displacement" is a physics term here, not a nautical one. It means the distance between the start and finish position.) By this reckoning, all weekend cruisers, whether laid-back sailors or high-speed motorboaters, have the same average velocity – namely zero! This is because they tend to end up right where they started – in their marina slip, or on the boat trailer from which their vessel was launched; in other words, the total distance between start and finish is zero. And zero distance divided by *any* number of elapsed hours yields zero velocity!

If we average over longer and longer time spans, sailors are doing comparatively better and better with respect to average velocity – few powerboaters venture on long blue-water cruises to distant locales, while many a sailor has traveled "over the horizon" to fulfill a life-long dream. This distinction is not just an accident – the energy source for the propulsion of a sailboat is the ubiquitous wind, which makes possible unlimited travel for years, while the fuel contained in the tank of an ordinary powerboat usually can't get it across a major ocean. (Full-displacement boats like trawlers come closest in long-distance cruising capability, albeit at the price of nearly "sailing-like" speed).

Still, whether averaged over long time periods or measured instantaneously, sailboat velocities are hardly in the range that physicists call “relativistic”. The most counter-intuitive effects of Special Relativity (time dilation, length contraction etc., see below) only become obvious when speeds approach the universal limit of 300,000 km/s (583 million knots) – the speed of light. The speed of even the fastest powerboat pales in comparison. But read on! The connection is real, even if it is more subtle.

III. Motion relative to What? - Galilean Relativity

So far, I have been rather casual in my use of terms like “distance” and “displacement”. As a physicist, I need to define my terms more precisely. Without that, it is not even clear what we mean by our position at a given time, let alone the distance between two positions. (For now, I will pretend that the other variable entering into velocity, elapsed time, is clearly defined – after all, we have high-precision clocks and watches to measure it. But as we will see later, this is not quite unproblematic, either!)

For physicists, the fundamental concept needed here is that of a “reference frame”. We can visualize this an infinite frame, like the frame of a house, made of wooden beams, all rigidly attached at ninety degree angles to each other. A more abstract concept would simply assume a set of points in space, all with fixed and immutable distances from each other. One of these points is given a special importance – we call it the “origin” of the reference frame, and designate it with “0” distance. Any position in space can then be uniquely designated by giving both its distance from that origin, and the direction (relative to the "beams") in which you would have to move to get there.

In one dimension, the nautical equivalent would be a set of mile markers (e.g., the ones along the intracoastal waterway along the U.S. East Coast), with the origin designated by "mile marker 0" in Portsmouth, VA. Snowbirds who want to know where they are during their annual journey south on the ICW can simply look at the nearest mile marker. In three dimensions, things are a little more complicated. For sailors, two dimensions usually suffice, and the system of latitudes and longitudes serve the same purpose (with the origin on the intersection of the "Greenwich Meridian" and the equator, in the Atlantic south of Ghana). Note that this latter coordinate system is a bit tricky – for instance, you cannot easily calculate the distance between two points simply by knowing their longitudes and latitudes, because doing so has to take into account the curvature of the surface of our planet. Similarly, it is not obvious what path to follow for the shortest possible distance between two points. If you start from the East Coast of the U.S. and want to reach a point exactly due East on, say, the European continent, it turns out that following a route due East at constant latitude (the rhumb line) will **not** give you the shortest distance – that's why all transatlantic flights tend to cross over rather northerly places like Greenland. This complication of ordinary "Euclidean" geometry by Earth's curved surface has a direct analog in Einstein's General Theory of relativity, where the whole of four-dimensional space-time turns out to be curved (see below).

It is important to realize that any "fixed" reference frame is only fixed **relative to something else**, and in fact the choice of reference frame is quite arbitrary. For instance, a reference frame “fixed” to the surface of the patch of water on which you happen to sail is obviously of significant importance – after all, without any propulsion by wind or “iron genny”, you will be at rest relative to that reference frame. The faster you want to go relative to the surrounding water, the more force needs to be brought to bear on your vessel. And, as sailors know, it is the motion of the surrounding air relative to **this** reference frame that determines this force. If you want to move in the direction the wind blows you, your speed will depend directly on the wind velocity relative to the water. On any point of sail other than straight downwind, you need the balance of two forces to give you net propulsion in the forward direction (see also the essay in this volume by John D. Norton). One force is generated by the motion of air relative to your above-water foils (the sails), and the other by the motion of water relative to your underwater foils (keel or centerboard and, to a lesser extent, rudder). Successful propulsion requires that these two relative motions are not the same. If they are, all you get is drag, which will bring the boat to rest relative to both air and sea in short order.

The water surface is just one reference frame to keep in mind while sailing. If you plan to arrive at a certain destination (within some given time frame), you are obliged to pay close attention to the other reference frame we already encountered – the one fixed to the solid surface of Earth. Even if you really don’t care where wind and waves carry you, you still need to keep track where you are relative to this reference frame – if only to avoid shoals or other obstacles to safe navigation. And the number of possible (and relevant) reference systems doesn’t stop there – your own boat is an obvious third example, which you automatically invoke when talking about the direction of another vessel (“abeam”, “abaft” or “ahead”), or when you tell your crew to “go forward to raise the jib”. Finally, if you are a blue-water cruiser from the old school (or just like to keep your options open), you have even learned to consider the reference frame of the stars, which can help you to navigate on the open ocean. And compared to **that** frame, both the most languid sailboat and the most souped-up powerboat move with velocities that are quite impressive - and practically indistinguishable (30 km per second or 58,000 knots if you count the sun as the origin of this frame). Keep in mind that none of these various reference frames is intrinsically any more correct or fundamental than any other one; they are all equally valid, if not necessarily equally practical, for a given purpose.

Awareness of these reference frames and their relative motion helps explain many common situations encountered while sailing. Examples abound: While the wind may truly come out of the West, if you are moving due North, it will **appear** to come somewhere from a northwesterly direction relative to your boat, and this relative (apparent) wind direction determines the shape and position of your sails. Vice versa, if you and your boat are floating down a river, with a breeze of exactly the same velocity as that of the water, you will feel completely becalmed – the **relative** wind velocity is zero. So your velocity relative to the water would be zero, as well, but you would be moving at a good clip over ground. Inversely, if the wind velocity **relative to ground** were zero, you would notice a breeze blowing up the river, and if you wanted to speed up your trip, you could even use this breeze to tack back and forth, making way downstream relative to the flow of the river (and therefore be even faster than the river). On the other hand, if you have both current and wind against you, even as an excellent sailor you may not be able to make any headway above ground!

In the end, one has to keep at least three or four of these different reference frames in mind to fully understand the magic of sailing. And one should be able to easily convert positions and velocities measured in one system to any of the others. In principle, this problem has been solved a long time ago, by Galileo Galilei and other early giants of physics. Not only were they able to derive the laws describing the transformation of positions and velocities from one frame to another (e.g., velocities must be added as vectors) but they also realized an enormously important principle (nowadays called "Galilean relativity"): The laws of nature (for instance, Newton's famous three force laws) do not change no matter which (inertial[1]) reference frame one choses to describe one's observations: While the velocity measured relative to one frame may turn out to be quite different than relative to another one, its rate of change (the acceleration) is the same in all of them, and directly proportional to the net force acting. This principle has allowed us to make sense of the world around us, to send space probes to the planets and to devise many of the wonders of technology. It is perfectly adequate to understand the basic laws of sailing (even how to design a faster racing yacht). It just has a small flaw: Unbeknownst (and unknowable) to Galileo and his contemporaries, it is woefully incomplete, and the rules for transforming velocities from one system to another are simply (if subtly) wrong!

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[1] Technically, inertial reference frames are those special frames where an object at rest will remain at rest as long as no force acts on it. Most (or all) of the frames we have considered so far are not exactly inertial ones – which explains the sloshing back and forth of water in the bilge or of the tides on the ocean. However, this distinction is of minor practical importance for our purposes, and turns out to be illusory anyway in light of the General Theory of Relativity.

IV. But there are no fixed reference frames - Special Relativity

The trouble with Galilean Relativity is not that it is a wrong idea – quite the opposite: It was not encompassing enough. What Galileo couldn't know was that the laws governing electric and magnetic interactions (i.e., electromagnetism which hadn't been discovered yet) must be the same in all reference frames, as well – but they directly contradict the simple rule for the addition of velocities. Let me explain.

Electromagnetic phenomena are of course a constant companion of any mariner, sailing or otherwise. Magnetic compasses have been crucial navigation tools for centuries, and the power of electric currents in the form of lightning strikes have inspired awe and fear in seafarers from the ancient past to this day. Modern sailboats typically make much more comprehensive use of electromagnetic processes (depending on how much money the owner likes to spend on electronics). From the electrical system powering navigation and cabin lights (and windlasses, microwaves, air conditioners and other "necessities" of cruising life) to the multiple receivers and emitters of radio waves (VHF, radar, GPS, cell and satellite phones), electromagnetism seems indispensable for most sailors. However, only in the nineteenth century was a complete and unified understanding of all the different manifestations of electricity and magnetism accomplished, with the crowning achievement of the four differential equations now named after Maxwell. Among the astonishing consequences of these equations, scientists were able to **predict** that varying electric and magnetic fields should be able to propagate together through vast expanses of space, traveling in the form of electromagnetic waves (just like water waves travel on the open sea). Even more astonishing, the speed of propagation for these waves turned out to be a number already fairly well known – 300,000 km/s, the speed of light. This insight did not only explain light as just one more electromagnetic phenomenon – it also predicted the existence of, and subsequently allowed the generation of, a vast array of other electromagnetic waves – radio, radar, infrared, ultraviolet up to x-rays and gamma rays. All of these waves were predicted to propagate with the same speed. Subsequent experiments confirmed these ideas with increasing precision, and many ingenious devices (like the ones mentioned above) are based on them.

There is only one problem. As we've just learned, velocities must always be measured relative to a reference frame, and the result should change if we change reference frames. Surely, if light travels 300,000 km/s relative to the frame of a fixed star, an observer on Earth (using a ground-based frame) would measure either 300,030 km/s while Earth is moving towards that star (in Spring, say) or 299,970 km/s in the opposite case (in Fall). This is totally equivalent with the head wind one would experience in our earlier example of a sailboat floating on a fast river during a calm day. But the laws of electromagnetism don't allow such a change of wave velocity with the reference frame – and all experiments devised to find it have failed. No matter where the light comes from, and no matter your own motion, the velocity measured always turns out to be exactly the same 300,000 km/s. If you don't find that weird, you haven't thought this through. The radio wave carrying a "mayday" call arrives at your boat with exactly the same (relative) velocity, whether you are moving at a good clip or are at anchor. The same is true with the light from navigation aids, the radar beam that gets bounced back to you from an obstacle, or any other electromagnetic wave. Even the signal from the GPS satellites that help you determine your position arrives with that same unchanging velocity, no matter how fast those satellites are moving relative to ground (in fact, several km/s). This is the same as if a 15 knot breeze from the north would always feel exactly the same to a sailor, whether she is sailing close-hauled, at a beam reach or downwind! If the laws of physics (including electromagnetism) really are the same in all reference frames, something else has to give. That something turns out to be our very notion of time and space. To understand why, we have to go back to our definition of a reference frame.

Remember the blithe assumption that one can measure positions and distances relative to a reference frame by using “rigid wooden beams” or “fixed markers”? In fact, the first idea is utterly impractical for obvious reasons, while the second has more subtle flaws. Sailors understand more readily than landlubbers the ultimate impermanence of things that seem to be quite solid: Channel markers can be moved or succumb to waves and weather, floating markers can move, sand and clay bottoms can shift, and so on. On a long enough time scale, the inexorable drift of the continental plates means that literally nothing stays in exactly the same place (even if measured from one “fixed” point on Earth to the next). And Earth is the most permanent frame there is – how about the reference frame of the water itself? Currents change not only with time and tides, but vary also from one location to the next. What is fixed here relative to what? Does it even make sense to talk about **the** reference frame of the water surface? Ultimately, which method of measuring positions (and times!) can be considered truly reliable?

When Einstein pondered this conundrum, he realized that the apparent **problem** in the laws of electromagnetism actually yielded the (only) solution: Once we **know** that the speed of light (or other electromagnetic waves) is the same under all circumstances, we can use this fact to measure the distance between any two points simply by measuring the time light takes to travel from one to the other. To determine a three-dimensional position in space, in general one needs to measure the distance from (at least) three points with known coordinates. If each of these three points were to send out a short light pulse simultaneously, we would only have to measure the arrival times of these three pulses to fix our position. There is one remaining problem, though: How can we be sure that our own (on-board) clock is exactly synchronized with the clocks that determine the start time of the three light pulses? Otherwise, we couldn't reliably measure the travel time. Well, it turns out you **can't** be sure unless you include a **fourth** sender at yet another position. Admittedly, this is getting a bit complicated, but I hope it makes sense: To determine the four coordinates of position in space and point in time simultaneously, you need four pieces of independent information – which the arrival time of the four light pulses can provide.

During Einstein's time at a Swiss patent office, this whole arrangement of light senders and receivers would have appeared extremely contrived and utterly impractical – for one, to get good accuracy in position, you would have to measure the elapsed times to a precision of the order one billionth of a second (= 1 nanosecond)! This is because light travels so insanely fast – by a whole foot in that 1 nanosecond. Such precision was completely out of reach at the beginning of the twentieth century. Einstein therefore considered this method of measuring position and time as a purely mental exercise – a “Gedankenexperiment”. Amazingly, a hundred years later his method is exactly how most of us measure where we are during our sailing trips (and even on the car ride to the marina)! And all of the complicated calculations necessary can be done by a little electronic box no larger than a transistor radio – the GPS receiver, requiring only a modicum of operator training (as compared to celestial navigation). Of course, the details are quite a bit more complicated than I could possibly explain here, but the basic idea is sound: By measuring the time it takes for electromagnetic waves (radio, in this case) to reach the GPS receiver from any of a number of satellites that are constantly sending them out, we can not only calculate our position (and plot it on an electronic chart), but also the actual time of the day (your GPS knows it a lot better than your beautiful brass clock down below)!

But Einstein’s idea goes way beyond a convenient new navigation method – he realized that this method (and assuming a fixed velocity of light) are the **only** reliable way to synchronize clocks and measure distances. This has profound consequences that lead to all the confusing paradoxes that come with his Special Theory of Relativity: First, the length of an object contracts if measured from a reference frame in which it moves. For example, your boat, as measured from shore, is shorter than the nominal LOA, if only by one trillionth of 1/32 of an inch, (assuming a 27-foot yacht moving at eight knots). Secondly, time appears to pass more slowly for a clock that is moving relative to the observer (time dilation). After a 24-hour day of sailing with those same eight knots, even the most perfect onboard clock will show eight trillionths of a second less elapsed time than an on-shore one. Thirdly, the notion of two things happening simultaneously no longer can be assumed to be universal. Ultimately, this is the biggest jolt to our understanding. It is also the reason why these things only appear to be paradoxical.

To understand this, imagine yourself exactly in the middle between two GPS satellites (let's pretend for now they are at rest relative to Earth, which is of course far from true). Both of them send out a radio pulse at exactly the same time. If you are at anchor, you will receive those two waves exactly at the same (later time), and since you (or, rather, your GPS receiver) know about the relative position of your boat and those satellites and the constant speed of radio waves, you can indeed conclude that they must have been emitted simultaneously. However, what happens if you are making eight knots towards one and away from the other satellite? Since it takes a little while (a fraction of a second) for the radio waves to reach your position, you will have moved away from the point exactly in the middle between the two satellites and you will have moved closer to one than the other by the time you receive them. However, since you must assume that the speed of radio waves is still 300,000 km/s in either direction, you will have to conclude that the satellite ahead of you emitted its signal a smidgen earlier than the one behind you. And you are not wrong with that conclusion! The whole notion of simultaneity depends on your reference frame, and a moving boat has a different one than a boat at anchor.

Of course, I hasten to add that all of these seemingly paradoxical consequences are miniscule in magnitude unless your boat is going close to the speed of light, so you can safely ignore them while cruising. However, without careful consideration of Special Relativity, the GPS system wouldn't work. And there are other consequences of Einstein's discovery: The mass (*m*) of an object is not a constant, but depends on its state of motion and, more generally, its energy (*E*): $m = E/c^2$. (If you remember a little algebra, you will quickly realize that this equation has the exact same meaning as the famous one quoted in the introduction.) Again, the increase in the mass of a five-ton yacht underway due to this relationship is so miniscule to be entirely negligible. However, only recently a group of physicists made the stunning discovery that, quite apart from nuclear power and other more well-known applications of this famous equation, even such mundane devices as lead batteries (ubiquitous in today's yachts) would not work, or at least not as well[2].

V. General Relativity – can it really matter?

It took Einstein only a few years to develop his Special Theory of Relativity. However, his greatest achievement (and arguably the greatest achievement of any single scientist, ever), the General Theory, occupied him for a decade. To this day, many people (though fewer and fewer physicists) consider this ultimate theory of gravity as beautiful, but thoroughly mysterious and utterly irrelevant for daily life (including sailing). But once again, it turns out that while its consequences are miniscule, they are not exactly null, and becoming more and more

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[2] If you want to know the details: The increase in mass of the electrons in lead atoms due to their very high motional energy as they swirl around the nucleus leads to stronger binding, which in turn increases significantly the energy released by moving these electrons from cathode to anode – in other words, the battery voltage.

measurable. As philosopher-sailors, we shouldn't be content ignoring something just because it is incredibly small – maybe we should be more like obsessive racers who will fret over the tiniest barnacle adhering to the otherwise slick underbody of their sailing machines. The plain truth is that even the Special Theory of Relativity has shortcomings.

I have alluded to one problem already earlier: The ambiguous nature of notions like distance and direction if your reference frame is not strictly rectilinear and orthogonal ("flat" in geometry parlance). As sailors, we are familiar with one such coordinate system, that of longitudes and latitudes on the surface of the (emphatically not flat) Earth. We already discussed some of the non-intuitive consequences of measuring positions and directions using these coordinates. We could of course avoid these problems by using an ordinary, three-dimensional (rectilinear or Cartesian) coordinate system instead – breaking down any position into distances and directions measured relative to the center of Earth. Such a system would regain the ordinary definitions of direction and distance for the price of awkwardness – you could not even tell immediately whether any position given within this system is on the surface of planet Earth, or maybe hundreds of meters in the air (or below water).

What the General Theory of Relativity tells us, though, is that the very space itself that we take for granted (and time with it) cannot be described in terms of a purely flat geometry, even if we try. Space-time is intrinsically warped or curved by the presence of mass and energy. It is this warping that leads to all the well-known effects of gravity (e.g., falling and buoyancy) as well as the more exotic consequences of Einstein's theory – black holes and Big Bang cosmology.

And it has consequences for our very notion of distance and direction that cannot be cured by changing to a different coordinate system.

As an example, consider two ships starting out simultaneously (with the same speed) from the equator, separated by 60 nautical miles and moving exactly parallel towards the North (along fixed lines of longitude – say 0 and 1 degrees). Our everyday notion of parallel lines would imply that these two vessels will never be in danger of collision – but unfortunately on a curved space (Earth's surface) this isn't true: both will eventually reach the North Pole (ignoring intervening land masses) and therefore arrive at the same point at the same time – the definition of a collision. Similarly, light rays from one and the same distant stars can bend left and right around a massive object (say, a galaxy cluster) that they have to pass on their way to an observer on Earth. This can lead to that same star appearing at two different points in the sky at once, an effect called "gravitational lensing". (For illustration, think of two ships starting in different directions from the South Pole and reuniting at the North Pole). Yet both light rays (and both ships) simply follow the shortest possible path in a curved geometry – what we would normally call a straight line.

And it is not only space that gets affected by this "irreducible" curvature; time also becomes warped in a sense. For instance, it turns out that time elapses (slightly) more slowly close to a massive object than further away from it. Again, the effect is small – but with an ultraprecise pair of clocks, it was recently demonstrated for a change of only one foot in height above Earth (the massive object in this case). As a consequence, I can rightfully claim that you will age ever so slightly more quickly while aloft on your mast than down in the cockpit –

although only by one trillionth of a second for each quarter hour. And once again, it turns out that the effect is big enough to be corrected for when using the GPS satellites – thousands of miles above our heads – to fix our position on Earth, where time is elapsing just a tad more slowly. So, in the end, it turns out Einstein does have to tell us something about our favorite pastime – maybe one of the reasons he enjoyed sailing.