Digital cameras in navigational measurement at sea. George Huxtable, 8 August 08.

It's time for the possibilities of using a digital camera to make measured celestial observations at sea to be assessed with a critical eye. I will compare it, as a tool, with the tool that's designed for the job, a sextant.

Let me start with a disclaimer. I have no special expertise in photography, digital or otherwise, as may become apparent from the words which follow, and I hope any errors will bring correction from those who know more. My only digital camera is of the cheapo mass-market variety, which attempts to take all control from the user's hands. But I have a reasonable grasp of optical principles, and even to a layman like me, proposals for using any camera seriously, for marine navigation purposes, appear overblown and implausible. Some of the difficulties I point out may perrhaps be overcome by the use of a more specialised (or expensive) camera, and it would be useful to have that pointed out by others that are familiar with such equipment..

In recent items in Navigator's Newsletter and elsewhere, I've seen digital cameras given the "gee-whiz" treatment, of "Isn't it remarkable that a simple camera can do such sophisticated work", but now Frank Reed takes that one stage further, in writing in Navlist [5989]-

"Which difficulties would you consider serious? It strikes me that a digital camera might make a much better angle-measuring instrument than a sextant (though with a very small angular range). Of course, it has to be calibrated properly, but I would say that's much easier than calibrating a sextant."

In another Navlist posting, I've described those words as "absurd", so perhaps I should do my best to back that up.

Sextant calibration.

Let's dispose of Frank's last sentence first first. Yes, a camera has to be calibrated, which is not such a simple business as has been made out, and we will deal with it later. But does a sextant? Most, I would say, buy a sextant, then use it, taking its calibration for granted according to the certificate on the box. If a minority of listmembers have done anything to check calibration, has that been more than the odd spot value, from a star-to-star distance? And if that's the case for listmembers, it must be even more true of those, outside this list, who simply take a sextant as a tool, rather than as a hobby. "Calibrating a sextant" is a non-problem, which has been invented for the occasion.

Use at sea.

We've all seen some beautiful photos of the sky, sharp-edged Moon, stars, planets (though not necessarily all at the same time) above a horizon. How many of those have been taken, handheld, at sea? And how many were taken from a tripod, on the shoreline? If they were taken at sea, was that in anything other than millpond conditions? From a small boat? In the boisterous conditions, in which a sextant remains practical? A navigational tool which is unusable in most sea-states is hardly a navigational tool at all. I am aware that image-stabilising devices, at some expense, are now doing quite a lot to minimise camera shake, but can they cope with the sort of motion that you commonly get in a small craft at sea? It would be interesting to hear from anyone who has been successful with such images in low-light conditions, and see examples.

The brilliant feature of the reflecting quadrant, and after it the sextant, is the way the two images remain locked together as they shift about together in the view, and it's that which allows its use so well under difficult sea conditions. A digital camera does its best to solve the same problem by making a very short exposure. All very well in daylight conditions (though imaging the Sun itself presents its own problems). But not so possible at twilight, when much celestial navigation gets done. Has anyone ever imaged stars over a horizon, at sea, in anything but a flat calm?

Imaging Sun, and Moon.

A sextant is fitted with different shades for different views. For the Sun, it's so black that you simply can't see anything else through it. That allows the Sun to be sharply imaged in an overlapping view with the horizon, or with the Moon.

In a camera, using a view of the Sun presents special problems, because even the shortest exposure produces a considerably over-exposed disc of a full-brightness Sun. Sometimes, a very low Sun, or one seen through hazy clouds, can show a sharp edge, and yet be comfortable to see with the naked eye, and under such conditions a camera image of the Sun, with horizon, can
be successful. But at other times, if the air is really clear, the Sun can remain blindingly bright right down to low altitudes. A highly overexposed Sun no longer shows a sharp edge to its disc. Then, a fitted circle, though still a circle and with its centre unaltered, has a diameter that depends on the chosen brightness contour, so is useless for calibrating the scale.

Same for the illuminated part of the Moon, if the exposure is set at a level which shows stars or horizon, and because of the asymmetry of the Moon's image, its centre then becomes difficult or impossible to place precisely. No such problems apply to a sextant, because shades can be chosen appropriately, and because the human eye can cope with such a wide dynamic range.

Frank has suggested, in a Navlist posting, that you could hold up a suitable filter, at arm's length, to reduce Moon overexposure, allowing stars to be seen. Not a simple operation, that, which would require the use of the observer's fourth hand, the others being fully employed in holding the camera, pressing the trigger, and hanging on to the boat. If you tried that trick using my own camera, if it could discern the filter (or hand) it would autofocus on to it, rather than at infinity as it should.

Angular range, distortion, and scale calibration.

These topics are interlinked in a complex way, and together they become quite a big subject.

This is the one aspect of a camera for which Frank Reed acknowledges a weakness, admitting- "though with a very small angular range". A sextant, on the other hand, provides all the angular range that's required, 0 to 90º, for altitudes, and to 120º for lunar distances, maintaining full precision, and comes ready-calibrated, to a small fraction of an arc-minute, over its whole range.

What about a camera? A digital cameras comes uncalibrated, and its angular sensitivity, in pixels per subtended degree, varies with position (and direction) on the screen, on lens and zoom level, and even slightly on the focus adjustment. Somehow, it needs to be calibrated, and to a high precision, if it's to do a job of measuring angle, comparable with that of a sextant.

Calibration is sometimes attempted by comparing the image of Sun or Moon with its known semidiameter, and then extrapolating that, as a yardstick for measuring a spacing across the sky. This procedure has several drawbacks. Really, it gives little more than a rough idea of the scale, because that yardstick is such a small fraction of the quantity being measured; like using a six-inch ruler to measure a person's height. But worse than that, because the scaling-factor changes significantly across the frame. And worse still, as explained above, when the Sun or Moon is overexposed, as is often the case. A better method is called for.

Frank Reed has suggested one in his Navlist posting [5990], writing- "...You could photograph a good measuring tape for example. If it's 34.38 meters away from the camera (and arranged on an arc so that every point on the tape measure is the same distance from the camera), then every cm mark corresponds to 1 minute of arc in the image. This calibration is easy, and it's essentially permanent."

Not exactly easy, in that, even if the measured range is restricted to 10º, it calls for an immense jig to position a 6-metre tape to a surveyed arc, centred on the camera lens. If the job is to be done to a nominal 0.1 arc-minute precision over that range (as for a sextant), then it calls for that arc radius to be right, everywhere, to within about 5mm. And where, exactly, should the centre of that arc be placed, in relation to the camera lens? Not at its front surface, as it's very much a "thick lens", but at its forward "principal plane", wherever that may be. Of course, those dimensions were chosen just to make the arithmetic simple, and they could be scaled down, at the price of requiring even-greater positioning accuracy. And only as long as the scale remained in sharp focus at the nominal "infinity" setting, because refocussing affects the angular calibration, to an extent.

A better way to calibrate might be to use bright-star images in the night sky, perhaps with the camera pointing vertically up to minimise refraction, and perhaps with more than one exposure, at known intervals. There are plenty of precisely-positioned stars to choose from, but not always many bright ones, within a 10-degree circle. Then, to follow, a lot of trig (perhaps done automatically, by computer program).

But here's a difficulty. Many digital cameras, like my own, have only a zoom lens and not a fixed-focus option, and there's no scale-of-zoom (and even if there were, it wouldn't be readable to the required precision). So if an attempt is made to precalibrate that camera, then it must be at either limit of the zoom range, because those are the only settings that can be returned-to with any precision; and I don't know how exactly that return can be made anyway. A fixed lens, of suitable focal length, without zoom, would be more appropriate.

My own digital camera, an Olympus C-500 zoom, has a stated zoom range equivalent to a 35mm camera with focal length from 38mm to 114 mm, (though all those actual dimensions are much smaller). That corresponds to a subtended angle, across its full frame, which we can name W, from 49.5º to 17.5º, and somewhat more across its diagonals. We will see that the wide-angle option would present enormous and unacceptable distortion, so the only viable setting for zoom would correspond to 17.5º across the frame.

I am going to assume that everything about a camera lens is axially symmetrical, so an image of (say) a dartboard, centred at the centre of the frame (but nowhere else) will still show the exact angular spacing of its radial lines, and its circles will remain as circles, if not to their correct proportional radius. In which case, any line across the screen that passes through its centre will have the same calibration scale as any other such line, and it's along such a line that any subtended angle, and any calibration, should be measured. We need to assess the distortion of the screen in terms of angles measured across the sky, by looking at changes in the count of pixels per degree, along such a radial line through the centre.

The simplest camera lens imaginable is not a lens at all, but a pinhole. A pinhole will produce an undistorted image of a plane object, such as a flat-fronted slab office block, even if it fills the frame right to the corners, if the object is centred on, and placed square to the camera's central axis. And a simple small thin-lens, in place of that pinhole, will do exactly the same, though it won't achieve exact focus over the whole image.

But what happens if we try to image, not a plane object, but that inverted bowl we call the sky? With such a pinhole, or thin-lens, whatever the radial angular sensitivity, in pixels per degree, we get at the centre, then at the edge of the picture it will be enhanced by a factor 1 /(cos W/2) squared, caused simply by the geometry. If we chose the wide-angle zoom position on my own camera, then, with W = 49.5º, the radial sensitivity would be increased, at the edge, by a factor of 1.21, an
increase of 21% over its central value. Such an enormous degree of non-linearity would be hopelessly difficult to correct for. As a result, the only usable setting for that camera would be the telephoto setting at W = 17.5º, which enhances the scale at the edge by 2.4%; still a serious non-linearity, but one that it might be possible to live with, after careful calibration. And if you chose to restrict all measurements to radial lines through bodies that don't stray more than 5º, say, from the centre, then you could keep the local scale distortion down to 0.8%. Still needs correcting-for, though.

There's an additional type of distortion, that stems from the difficuly of mapping a spherical surface onto a flat image-plane, which is exactly the same problem as when mapping the Earth's surface, such as the polar regions, on to flat paper. If, somehow, we had managed to correct the radial distorttion described above, to make radial lines uniformly proportional to subtended angle along their length, that would end up as a "zenithal equidistant projection" of the sky, akin to the maps of Antarctica to be found in an atlas. And there, although the radius of a mapped circle, centred on the South Pole, is exaclty proportional to the angular distance from that Pole, distances measured around that Pole, along a latitude circle, at right-angles to a radius, are increasingly expanded, away from the Pole, by a factor of 1/cos of that angle from the pole, to put it on flat paper. This difference in scale, in the two directions, has the result that true circles, off-centre in the frame, are no longer truly circular, and angles are distorted.

I am aware that modern camera lenses, multi-element and particularly zoom lenses, are very different from such a thin lens, but have no information about their performance in terms of distortion. However, in all the computer optimisation that's done in the lens design, there seems little incentive to improve the "angular linearity", and my guess is that it won't be much, if any, better, in that respect, than a pinhole. It would be nice if that guess were to be shown wrong.

We may have something to learn, in this regard, from amateur astronomers, who increasingly use such light-sensitive arrays. I expect that computer software may exist, somewhere, for correcting and remapping the distortions inherent in their optical systems (and perhaps even for commercial cameras). Do any readers have a foot in that camp?

Angular range- consequences.

We've seen, above, why the angular range of a digital camera, used for sky angular measurement, has to be so severely limited, perhaps to 5º or 10º, depending on the inherent distortion and the user's ability to correct it. And that means restricting measured altitudes to objects within a few degrees of the horizon, just the sort of objects that a navigator normally tries to avoid, because refraction becomes much less predictable at low altitudes, and stars and even planets extinguish when they get low down. And if a lunar-distance is attempted (which is difficult because it requires the full accuracy of a sextant) then it has to be made of a body very close to the Moon. Normally, however, lunar distances were only ever measured (and predicted) for bodies at least 25º from the Moon, for good reasons.

Another consequence of restricting observations to only small angular differences is this; unless a high-gain telephoto lens is available, only a small fraction of the screen can be used, and all those other pixels are going to waste.

Focussing.

Not much of a problem, this, because focus at infinity is always what's wanted, and because focus always remains better at small angles, near the frame centre, to which measurements will probably be confined for other reasons.. So as long as that infinity position can be reliably set (and repeated to exactly the same setting), all's well. Care needs to be taken about that, because a change in focus can alter the scale calibration (a bit). Ideal arrangement is a manual focus adjustment with a precise click or firm end-stop at the exact infinity position. But many digital camera, mine included, have no focus control, and rely on autofocus, which examines aspects of the focussed image to achieve some sort of optimum. What does it do with a night-sky picture? Presumably, autofocus then fails, and the focus then adopts some fallback setting, which one would hope is to focus exactly at infinity. But is that always reliably the case?

Emergency Navigation?

This is a label which often gets applied, to a navigational technique that isn't really kosher, and which one would never actually use or even recommend, if it could be avoided. It applies only if it really **is** going to be available in an emergency, when all else has failed. Is that true, for a digital camera? I doubt it. Even if the camera, with its batteries, has survived the emergency, there's not much the user can do with the picture on its little screen. Some sort of computer, with image processing software, for reading out and interpreting and correcting the pixel parameters, has to remain in working order as well. Not that much of an emergency, then.

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