Whither Astro?

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Mike Pepperday's original Forum article[1] provides valuable insight into how small boat navigators view the problems of position determination at sea. The ensuing contributions, tabled by expert navigators and scientists[2] are also highly relevant.

The plain man's first query can be summed up in the question 'Whither Astro?' At first sight Mr Pepperday gives mixed answers. His concluding sentence in his reply to Commander Sharpey-Schafer[2] is emphatic and is indeed cemented by his remarks in the penultimate paragraph of his original article.[1] On the other hand, however, he has taken considerable trouble to expose some of the limitations of the Nautical Almanac Office's calculator instructions – surely an unnecessary exercise if it is true that astronomical navigation has been superseded. He also quotes with approval the idea that celestial navigation classes be continued. Moreover, in this connection, well-established firms continue to advertise sextants (as well as GPS receivers). A fair summary of this state of affairs might read 'Astro is dead but won't lie down'.

The matter depends on our view of GPS, a subject on which Commander Sharpey-Schafer has something to say.[2] At first sight the statement that GPS makes astro obsolete, or at least obsolescent, is fairly obvious as far as peace-time navigation is concerned. In times of global warfare, however, it is right to examine the possible existence of a different, extremely pessimistic, scenario. GPS depends upon man-launched satellites, and an ingenious and technically expert adversary (or coalition of adversaries) could invalidate the GPS concept since the satellites are, because of their transmissions and known orbits, sitting ducks to a well-equipped enemy. Moreover, the satellites are undefended. The argument that GPS is *sacrosanct* in times of war may not stand up. What man has created, sooner or later in the heat of battle, man will destroy, examples from both ancient and recent history being easily come by. The international community, or anyone else, seems to lack the unanimity and will to prevent even localized conflicts.

While hoping and praying for the best, we must be prepared for the worst. This ghastly, pessimistic scenario is, however, grist for the mill of the rather elderly argument that, if all else fails, we still have astro, at sea anyway, though for compelling technical reasons almost certainly not in the air. So it seems right to enquire whether or not the techniques developed by small boat computer specialists[1] have a future which, in an environment, however hostile, is concerned with relatively slow-moving vessels.

The astronomical computer fraternity, well exemplified by Mr Pepperday, can be regarded as tackling the navigational problem in two stages. First is the computation of azimuth and intercept, centred, as Mike Pepperday wisely argues, on a single DR (or assumed) position for an **n**-line fix. Secondly, there is the determination of position by means of an algorithm based on the least squares principle.

Mr Pepperday's argument[1] that the electronic calculator has successfully swept away the need for routine calculation is correct in the first instance but (it is maintained) incorrect in the second. The assessment of position requires navigational judgement and common sense; it would seem unwise to leave problems to the tender mercies of an algorithm, however excellently programmed. One should examine one's data before deciding what (if anything) one should do about it.

This last, rather dogmatic, statement will command attention from the backwoodsman but perhaps not from the computer buff. Indeed, in the field of military aviation it would be *jejune* for the crew to spend time agonizing over the problem of exactly how his computer predictions (e.g. course and time to the next waypoint) are obtained. There is just no time for such a debate. At sea this argument carries less force and, fortified by a routine VDU (Visual Display Unit) facility, there is no problem in seeing the several position line data on the screen before making a positional judgement. Yallop and Hohenkirk[3] describe such an approach.

Small boat computer specialists have allowed themselves to be unduly obsessed by a diagnostic called 'Error S'[1]. The calculation of **S** is achieved *via* the summation of the squares of the distances between the 'least squares' fix and the several position lines. This diagnostic has some bearing on the quality of the fix produced by the least squares technique, but not much, certainly if **n** is small.

Thus the first thing to recognize is that **S** is not a quantity which *determines* the accuracy of an **n** line fix. This accuracy is unknown, and varies considerably from one navigator to another, and perhaps even more importantly it is dependent on the environmental conditions, such as the quality of the horizon. Such matters are discussed in the Report of the Institute's Working Party on the accuracy of astronomical observations at sea.[4] But while **S** does not determine the unknown accuracy, it at least *estimates* it, and, moreover, it is the best possible estimate, using the word 'best' in its generally accepted statistical sense (minimum variance). It is well known that, for Gaussian error distributions, estimation procedures based on maximum likelihood procedures, minimum variance concepts, and least squares all coincide. While, of course, navigation errors are certainly far from Gaussian when smeared over all possible observers and environmental conditions, as noted above, it is in general reasonable to assume that, in the absence of gross errors (for example, misreading of a sextant), a single navigator's error distribution will be roughly Gaussian.

This technical matter, the distinction between the real unknown **S** and its estimate, does not (correctly, we believe) trouble Mike Pepperday unduly, but it leads to difficulties if it is desired to erect a confidence zone (always elliptical in the case of least squares estimation, whatever the underlying error distribution) about the 'least squares fix'. It is here that the theorists[3] have come slightly adrift. After emphasizing the fact that **S** is merely an estimate (albeit the best possible one) they describe the dimensions of the ellipse as if **S** was the true unknown quantity (loc. cit., p. xxi). In fact, allowance for estimation error can be, and ought to have been, made by appealing to the well-known theory of small sample estimation, known for nigh on 100 years, which deals with the properties of the **t**, the **F**, and the **chi**-squared distributions. A typical reference is given by Kemp and Goodwin.[5] The upshot of all this is that they have underestimated the dimensions of their 95 percentage confidence ellipse (loc. cit., p. xxiv) through having failed to appreciate that sigma – the standard deviation of estimated position – is, in their example, based on a mere two degrees of freedom. Their scale factor **k** (p. xxi) applies only when the number of degrees of freedom is infinite (i.e. the estimate is exact) and a full discussion would involve tabulating **k** as a function of **n**. It is strange that neither theorists nor computer scientists have recognized the relevance of well-known small sample statistical theory.

That these matters do not trouble Mike Pepperday unduly is due to the fact that, rightly or wrongly, he does not discuss confidence zones. An orthodox statistician, living in a somewhat idealized world, might insist that no estimate of position is complete without a statement about its likely accuracy, but a realist might maintain that, in operations, there is little point in plotting an error zone until clear instructions are given to the navigator as to what to do with it once he's got it. Early enthusiasts, of whom I was an unfortunate example, took some delight in recommending procedures for combining a fix and DR position *via* the expedient of drawing an ellipse about the former and a circle about the latter. This is described on page 385 of Wing Commander Anderson's book[6] which is concerned equally with maritime and air navigation. These basic ideas might be viewed as a rather rudimentary anticipation of Kalman filter theories, produced a decade or two later. The assumption behind both approaches is that it is possible to 'model' position line and other (e.g. dynamic) errors by means of careful experimentation and operational research. This approach has some, though questionable, merit in a climate where observational errors do not exist, as in many modern air applications, or possibly also in an environment where all navigators have been trained to more or less the same standard. The matter has been discussed at length by Anderson[6] and an excellent critique of the whole idea of modelling is given by Stokes and Smith.[7] But, when all is said and done, the modelling approach is quite inapplicable in a situation where observers of widely different capabilities and in widely varying environments need a computer algorithm to automate sight reduction and position determination. So modelling, rightly, has no place in the work of small boat computer scientists.

These arguments go a long way towards validating the procedures of the small boat computer fraternity (exemplified by Pepperday) but a word of caution is now necessary. In his enthusiasm for the **S** concept, Mike Pepperday underplays the importance of actually plotting out the several lines of position on the chart before deciding what, if anything, to do with them. He does concede that the lines, suitably corrected for their different times of origin, *may* be plotted out in the usual manner[1] (p. 90). A backwoodsman would insist that the lines *must* be plotted out; a more conservative fellow might prefer the world *should*! In this connection the naïve reader with little or no experience of small boat navigation (like the author of this note) will goggle a bit, having formed the impression that a virtually unlimited number of sights can be obtained. The viewing time however, is not infinite, but in practice is restricted to a short period (about 20 minutes) during twilight.[2] How many *reliable* sextant observations can be made in such a period? Is it possible to replicate observations on some or all of each body, and is it really necessary to do this, and if so, why? How does one decide (without looking at the lines themselves) which bodies should be replicated – that is, which buttons to press and when? A brand of computer software 'limits a fix to forty sights'. Who on Earth would want to take so many sights and why? Those of us with no experience of marine, as opposed to air, astronomical navigation, would have been assisted by a (very) rough estimate of the number of sights a reasonable observer could achieve during a limited viewing period.

It is suggested that the number of sights required to determine a reliable fix (reliability should be preferred to accuracy) need not be all that many – say, half a dozen or so. Folklore rightly favours taking a third line to guard against the possibility of blunder (the extra *accuracy* achieved here is marginal), and goes on to say that if the configuration is unsatisfactory – the cocked hat 'appears to be' too large, – a fourth line will sort out the rogue. This is all very well in theory, but in one's experience (air, admittedly) the appearance of the fourth line may sometimes make matters worse!

The whole topic of **n** line determination ($\mathbf{n} \geqslant 3$) has excited considerable interest from a number of authors, and a lot of rubbish has been written upon the subject. The whole matter needs *de novo* careful consideration: in the meantime it might be best to rely on Anderson's teachings on the subject.[6] It is vital that the whole question be addressed against a backdrop of actual operational limitations.

At long last it is now opportune to enquire whether or not the techniques developed by small boat computer specialists have any long-term future. Judging by Mike Pepperday's three-word sentence at the end of his Forum reply to Commander Sharpey-

Schafer,[2] the answer is a definite negative. But all this assumes a peace-time scenario. It is impossible to predict the future and it would be idle to speculate upon the probability of a third global catastrophe, for we cannot know how, who, and when a potential coalition of aggressive states could decide to initiate a third World War. It would be realistic to assume that the potential aggressor(s) have fully up-to-date technology, and would be able to indulge, if he or they wish, to squiff GPS satellites – clay pigeon shooting. A compendium of navigational systems in order of immunity to enemy interference would certainly include astro (probably at the top of the list) and it could reasonably be assumed that systems associated with the Earth's magnetic properties, self-contained systems based on inertial concepts (INS) and, in the field of air navigation, Doppler, will also appear, together with some types of radar. So, assuming the unavailability of GPS, astro is distinctly in the field and the sight reduction techniques pioneered by the small boat computer specialists are indispensable. As for sight taking, a round half dozen on different bodies seems a good par for the course. Enough is as good as a feast.

How to determine position from this clutch of lines presents a problem to computer designers. Some of the lines may in fact be non-astro, so a computer based aid to solving the problem (the word 'aid' is vital) will include already available VDU facilities (essential) plus techniques for evaluating azimuths and intercepts, using the same DR position as those chosen for all the astro sights. The fact that it is no longer true that all lines have the same intrinsic accuracy, disturbing to the theorist who insists that it is weighted, not unweighted, least squares that should be used here, need not trouble us unduly, not only because in operations nobody has a precise idea of what the weights should be, but also because techniques based on the assumption that all lines carry the same weight (when in fact they almost certainly do not) will seldom lead one seriously astray. The end product of all this may well be a VDU picture of all lines, converted by the computer to a time origin that is the time of the last line or possibly greater. The next stage is to try and make sense of this modest melange of lines, bearing in mind that there is a small probability of blunder (hopefully very small in the case of astro, thanks to the automation of sight reduction which effectively discharges mistakes made in using almanacs and reduction tables). If there are several sights taken on each body (time may well not permit this) observation blunders could be sorted out, as Mr Pepperday describes[2] but an examination of the consistency of the half dozen or so single shots will do equally well. An experienced navigator could now do worse than put a pin in the middle of his soup, having optically eliminated any gross outlier. Those who feel uneasy about such a subjective assessment might prefer an (unweighted) least squares approach as follows:

(a) All lines look consistent, in which case use the available least squares program.

(b) One line looks wrong; (the risk that two or more lines are also blunders is so small that it can be accepted). Here one expunges the bad line using the facility described by Mike Pepperday, using least squares on the remaining (**n**-1).

(c) The navigator looks at his lines and is a bit unhappy. There is no obvious outlier but the configuration looks a bit too diffuse. In such a case, it is reasonable to proceed *as if* all lines were reliable, using least squares in the usual manner.

No solution is fool-proof. The above suggestions are tentative only and require screening first by marine navigators and then by theoreticians, statisticians and computer experts. Other factors, difficult if not impossible to computerize, such as proximity to danger, have also to be considered. Whether a probability zone surrounding the fix should be provided, possibly just as an option, remains a matter for debate but here an understanding of the theory of small sample statistics is a prerequisite.

In the last resort it is navigational know-how, rather than unaided computer technology, that is required.

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KEY WORDS

1. Astro. 2. Errors and accuracy. 3. Computers.

The Nautical Almanac and the changing role of HM Nautical Almanac Office

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This is an attempt to correct some of the misguided (and unrefereed)* comments that have been published in the Forum section regarding *The Nautical Almanac*, which have appeared over the last year or so.

First I have to give some background information.

The Nautical Almanac is produced jointly by HM Nautical Almanac Office (HMNAO), Royal Greenwich Observatory and by the Nautical Almanac Office, United States Naval Observatory. Suggestions for modifications and improvements to the book are always welcome and should be sent to one of these two institutions. It is now easy to contact HMNAO on Internet, our e-mail address is nao@ast.cam.ac.uk. We are also on the World Wide Web; our home page is http://www.ast.cam.ac.uk//~nao. Browse around and you will find information on our other services and publications.

In 1965 the Hydrographer of the Navy relinquished responsibility for HMNAO to the Science Research Council (SRC). The SRC policy of HMNAO was that it should become self-financing by selling its books and charging for its services. SRC changed its name to SERC in 1980, and in 1994 SERC was replaced by the Particle Physics and Astronomy Research Council (PPARC). HMNAO continues as a department of the Royal Greenwich Observatory, under the control of PPARC. Its future is safe, provided that the income HMNAO receives from the sale of its books and services is sufficient to pay for the salaries and overheads of its staff. It is not funded by the tax-payer.