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.

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HMNAO publishes five annual almanacs including *The Nautical Almanac* and *The Air Almanac*, and at five-yearly intervals it publishes *Sight Reduction Tables for Air Navigation*. It supplies astronomical data to astronomers, navigators and land surveyors, publishers of commercial almanacs, diaries and newspapers, the legal profession, religious groups, and the general public.

It is a fact that most of our income comes from the sale of *The Nautical Almanac*. Contrary to the beliefs of a number of contributors to Forum, it is a best-seller, and the main sales do not come from the Royal Navy. Moreover, the sales are not dropping off. Since it is a commercial venture I cannot reveal monetary details nor indeed too much information about the production of the book. It is unfortunate that I have to spend time trying to prevent the publication of unauthorized copies of *The Nautical Almanac*. Surely this is yet more proof of the popularity of the book and the continued use of astro, not just in the UK but throughout the world? The pirates often copy the sight reduction pages as well as the main tables, so they do not regard them as faulty. An Act of Parliament of 1828 protects the copyright of *The Nautical Almanac* within the UK. The punishments and fines that were imposed in 1828 for publishing without authority are still a sufficient deterrent.

For the 1989 volume of *The Nautical Almanac*, the opportunity arose to make the book self-contained by including short sight reduction tables produced by the Nautical Almanac Office of the US Naval Observatory. I carried out a computer simulation of these tables and found that they performed to the precision claimed by the designers (Dr P. Janiczek USNO and Rear-Admiral T. D. Davies USN, retired). At the same time formulae and methods for sight reduction and determining position at sea intended for use with programmable calculators or computers were being developed by HMNAO, for inclusion in *Compact Data for Navigation and Astronomy*. This book has recently been published together with a disk for the years 1996 to 2000. It was considered that astro-navigators would benefit from the algorithms for sight reduction that were expressed in algebra in such a way that they could be translated into the programming language of a computer. At the time calculators were in fashion and it was felt that the inclusion of the section on Sight Reduction Procedures would help to sell more copies of the book.

In his article[1] Pepperday raises so many issues that I find it difficult to see the wood for the trees. I have sought the advice of several colleagues and friends. Professor George Bennett pointed out to me that I had used the word calculator fifteen times in the sight reduction section of *The Nautical Almanac*. I have reworded the section for the 1997 edition so that the expression 'programmable calculator' occurs three times and the word 'computer' four times.

The computer method uses analogous concepts and similar terminology to that used in manual methods of astro-navigation, where position is found by plotting position lines from their intercept and azimuth on a chart. The introduction to the sight reduction procedures has been modified to explain that the method of least squares is used to calculate the fix by finding the position where the sum of the squares of the distances from the position lines is a minimum. An advantage of the method is that it is possible to improve the estimated position at the time of fix by repeating the calculation (i.e. iteration). Perhaps I should add that the solution applies to a spherical Earth, not a spheroidal one. It is possible to solve for spheroidal sailing, and if desired for the motion of the observer, but the algebra becomes much more complicated.

It is only possible to improve the solution by iteration when the problem has been properly formulated. It also provides positive proof that the method has been programmed correctly. It must be in everyone's interest to reduce the errors on the calculation side of the problem to a minimum. With a computer this is done in the twinkling of an eye. Why is Pepperday afraid of iteration?

Using motion of the observer to reduce the observed altitudes to a common location ('passage correction' is the term Pepperday uses) is not a precise technique. Dr George Kaplan of US Naval Observatory also pointed out to me that the least squares method was originally published by de Wit.[2] It is an exact mathematical translation of conventional chart-based navigation including advancing LOPS as necessary. It is the use of the motion of the observer that is non-standard, because it does not appear in Bowditch or Dutton. At this time I was independently formulating a least squares method, with the help of a colleague, Brian Emerson. The way we formulated the problem using standard techniques seemed to speak for itself, and did not require a proof. Hopefully, a proof of the method will be given in the next edition of Volume 2 of *The Admiralty Manual of Navigation*.

The basic ephemeris data for the navigational bodies may be taken directly from the main tabular pages of the current version of *The Nautical Almanac*. If a computer is available then *Compact Data* is the book to use because, like *The Nautical Almanac*, the time argument is UT and, in addition, it gives simple and efficient ways of calculating the positions of the navigational bodies to a consistent precision, in coordinates with which navigators are familiar. These data are intended to satisfy the needs of users like Sharpey-Schafer[3] for their ephemeris calculations. The latest edition of the book has the data on a floppy disk, together with an executable sight reduction program.

When I was developing the method I did consider solving for a systematic error in the sextant altitudes, which would introduce another degree of freedom. It complicated the algebra, and would require more observations to separate the errors. With hindsight I am glad that I decided not to do this. I have not ignored the number of degrees of freedom in the expressions for the standard deviation, however, as Parker[4] seems to think. I learnt early on in my career, when producing star places from small numbers of observations, the importance of taking into account the number of degrees of freedom when calculating errors.

Most calculators and computers work in binary arithmetic and truncate to some fixed number of binary places, so it is not possible to represent the majority of decimal or sexagesimal numbers exactly in a calculator or computer. Moreover it is not possible to represent numbers produced by trigonometric functions like sine and cosine because most of them are irrational numbers. Calculator manufacturers devise error traps to allow for errors that might occur due to this truncation. It is still a wise precaution for the programmer to include appropriate error traps, to stop the calculator or computer trying to perform a calculation that it finds it cannot do, such as trying to find the inverse cosine of a number that is slightly greater than unity, even though it could not happen if the calculation were done precisely.

This brings me to the formulae for azimuth which is used in the Sight Reduction Procedures of *The Nautical Almanac*. The 1989 edition gave the basic formula that uses the inverse tangent to determine azimuth. In the following year, it was replaced by a formula that uses the inverse cosine, because it is the one that is taught in most schools of navigation in the USA. The inverse cosine function needs more significant digits to produce the same precision as the inverse tangent for azimuth angles near 0°, 180° and 360°. To obtain azimuth I recommend the formula that was given in the 1989 edition. Basically the method of calculating altitude and azimuth is; first determine the direction cosines of the body in the equatorial system of coordinates, then rotate the coordinate system so that the direction cosines are referred to the local altitude and azimuth coordinate system. Finally convert these direction cosines into altitude and azimuth.

Using the notation and sign convention adopted in *The Nautical Almanac*, the basic equations that have to be solved are:

$$\cos Z \cos Alt = \sin Dec \cos Lat - \cos Dec \sin Lat \cos (GHA + Long)$$

$$\sin Z \cos Alt = -\cos Dec \sin (GHA + Long)$$

$$\sin Alt = \sin Dec \sin Lat + \cos Dec \cos Lat \cos (GHA + Long)$$

The third equation determines altitude uniquely. The first and second equations have to be solved simultaneously to determine azimuth.

There are many ways of ringing the changes on solving these basic equations. I recommend using only those methods that are the simplest and which avoid bad programming techniques such as inverting a cosine function to find the azimuth angle when a tangent of the variable is available. Also I recommend including an error trap to prevent the division by zero when the tangent of the azimuth is being calculated. Some computer languages, like Fortran, have a built-in function called ATAN2 which inverts a tangent and places the answer in the correct quadrant, without requiring this error trap. Likewise calculators with rectangular to polar conversion keys can be used to find the azimuth angle in its correct quadrant, without this error trap.

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KEY WORDS

1. Almanacs. 2. Astro. 3. Computers. Reduction and plotting.

*Editor's Note

As a matter of policy, papers in the main body of the *Journal* are refereed. Contributions to the Forum section are not generally refereed, and are included purely at the discretion of the editor. Forum pieces are sometimes controversial and need not always be entirely sound, but they may still be published if they could initiate, or contribute to, a useful discussion of a particular topic.