to find the width of each river. Page 91 shows Clark's data, all in poles and links.

For the fast-moving Corps of Discovery, none of the standard tools for measuring distance were practical. Moreover, they were using compass bearings in a vast region where the change of magnetic variation, from place to place, was unknown. Nothing other than sheer luck could have made their dead reckoning accurate.

Fortunately it didn't have to be accurate to be worth all the effort put into it. All it wanted was a little help from nautical astronomy.

Besides altitude-azimuths for magnetic variation, President Jefferson instructed Lewis to take, and carefully record, observations for both latitude and longitude at all important points, and ". . . other places and objects distinguished by such natural marks & characters of a durable kind, as that they may with certainty be recognized hereafter." Between these anchor points the expedition's dead reckoning could be adjusted to produce a geographically reliable map.

***

Rispect?

The following are some excerpts from the Moulton text regarding the unusual spellings found in the journals:

...Grammatical consistency is a vexing problem to any historical editor but particularly to an editor of Lewis and Clark materials. The men's erratic, but delightful and ingenious, manner of spelling and capitalizing creates the most perplexing difficulties of all. "This is expecially true of Clark," one investigator noted, "who was not only the master misspeller of them all, but also displayed dazzling virtuosity in his approach to punctuation, capitalization, and simple sentence structure.

...One researcher discovered that Clark spelled the word Sioux "no less than twenty-seven different ways." Little can be promised in the way of consistency, for no rule can stand against Clark's inimitable style...

...For capitalization some consistencies of the writers have been discovered; otherwise, individual letters have been judged against their rise along the line of writing and compared to the writer's normal usage. This procedure has generated a great number of capital letters. Clark again has confounded any system. One historian who struggled with his handwriting wrote: "In the matter of capitalization, one man has utterly bested me. William Clark, a creative speller, is also a versatile capilalizer—especially in handling words beginning with s. After manv attempts to work out a sane norm I have retired in confusion. Clark uses four kinds of initials and each can be interpreted as a capital."

NAVIGATION NOTES

BYGRAVE SLIDE RULE REVISITED

by Geoffrey Kolbe

Leonard Grey posed a question in the last issue, "Has anyone at the Foundation considered the Bygrave slide rule for a report in the newsletter?" A description of the "Bygrave Position Slide Rule" was given by John M. Luykx in the fall edition of the Newsletter in 1990. But as it happened, I was just in the process of making a "cardboard copy" of a Bygrave type slide rule. I offered David Burch my services to write a piece on the Bygrave slide rule for the Newsletter and he accepted. So, here it is.

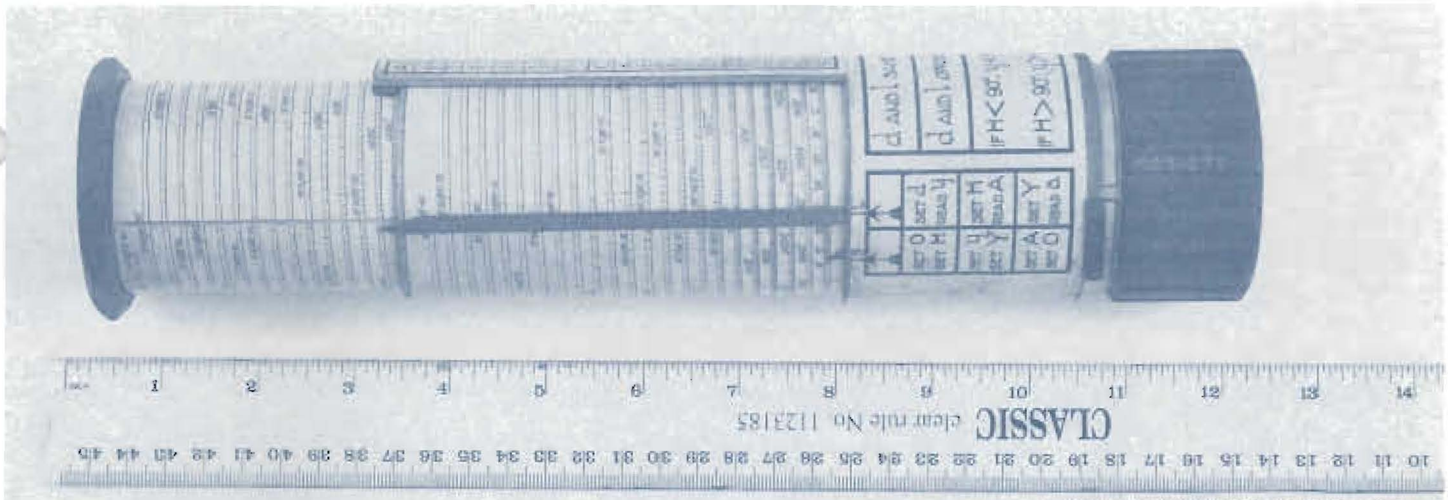
Leonard Charles Bygrave, of 4 Beaumont Avenue, Richmond, Surrey (near London in England), made an application to be granted a patent for "Improvements in Calculating Apparatus" in March 1920. The "apparatus" was a cylindrical slide rule consisting of three concentric tubes. The principal novelty appears to be that scales were wrapped helically around each of the inner two tubes. The outer tube held the cursor to relate the scales of the inner two tubes one to the other. The three tubes were free to rotate and slide within each other.

The patent gave an example of a particular use to which this form of slide rule could be put – namely the solution of the navigational triangle (a spherical triangle formed by a pole, the estimated or assumed position of the observer, and the geographical position of the celestial body). Luykx tells us that Henry Hughes and Son of London, famous as sextant manufacturers, started making the "Bygrave Position Calculator" in 1920. It is for this slide rule as used in navigation sight reduction that Bygrave is remembered today. It is unclear when production of this slide rule ceased, but it would seem to be sometime in the 1930's

Luykx seems to have had a Bygrave slide rule in his own collection. Alas, I am not so lucky, so I made an appointment to view an example held by the Science Museum, which is in the district of South Kensington in London.

The Bygrave slide rule was actually located at Blythe House, which is a vast late Victorian building, two hundred yards long and about eight stories high, planted in the middle of South Kensington suburbia. It has no outward indication as to its purpose and has but two relatively small entrances. Blythe House is in fact the repository for the museums in the South Kensington area where items are stored for which the museums themselves have no room. At entrance "A" I used the intercom to call security. I was expected. Having booked in, I was taken into what appeared to be the film set of the final scene in "Raiders of the Lost Ark", where the camera pans out to show the vast storage building where the Ark was locked away and effectively lost amongst innumerable other objects. I was taken to a table where, next to two life sized dolls in Victorian dress (!), the Bygrave slide rule was set out for me to examine.

In contrast to the slide rule described by Luykx, the example I saw was inscribed "Air Ministry Laboratory, South Kensington,



The original Bygrave slide rule.

August 1920". The base of the instrument bore the logo "AML". It also stated that this was a mark 2, with serial number 105, and bore the legend "Bygrave - Patent Applied For" in small letters. There was no reference to Henry Hughes & Son, which leads me to suspect that this may have been one of a pre-production run of a limited number of instruments made by the Air Ministry – perhaps for evaluation purposes.

It was about 8 inches long when closed and about 2½ inches diameter across the outer cursor tube. The tubes appeared to be made from galvanized steel about a sixteenth of an inch thick. The tubes were covered with thin, celluloid covered cardboard which had the scales and other narrative imprinted upon it – probably by some photographic process.

The spiral scale on the inner tube was graduated in log tangents, that on the middle tube in log cosines and the outer tube formed the cursor. Brief instructions on the use of he slide rule were printed on the cursor tube. The spiral scales had a pitch of three sixteenths of an inch. The log tangent scale on the inner tube ran from 0° 20' up to 89° 40' and was graduated in one minute intervals along the entire scale. Straightened out, the scale would be over 20 feet long. This compares to scales about a foot long for the linear slide rule with which those of us of a certain age will be familiar.

The log cosine scale on the middle tube had (necessarily) the same pitch and if straightened out would be a little over 14 feet long. It was graduated in one minute intervals from 60° to 89° 40', two minute intervals from 45° to 60°, five minute intervals from 20° to 45°, ten minute intervals from 10° to 20°, thirty minute intervals from 3° to 10° and one degree intervals from 0° to 3°.

Actual degrees and minutes were printed at regular intervals on both scales to the right of a graduation, and 180° minus the angle was printed to the left of the graduation.

A number of sight reduction methods divide the navigational triangle into two right-angled triangles to facilitate its solution. Probably the most famous of these is Ageton's method which drops a perpendicular from the geographical position to the observer's meridian. This enables the azimuth and altitude to be calculated using formulae containing just secants and cosecants, the logarithms of which formed a single table which was the basis of H.O. Pub No. 211. The method used by Bygrave was also to divide the navigational triangle into two right-angled triangles by dropping a perpendicular from the geographical position to the observer's meridian. But the formulae used by Bygrave were;

$$\text{Tan } y = \frac{\tan Dec}{\cos LHA}$$

Where the Latitude and Declination have opposite names, Y = co-Latitude – y

Where the Latitude and Declination have the same name, Y = co-Latitude + y

$$\text{Tan } Zn = \frac{\cos y \tan LHA}{\cos Y}$$

$$\text{Tan } Hc = \cos Zn \tan Y$$

These formulae are derived from Napier's Rules, though with some manipulation to facilitate use for a slide rule having log tangent and log cosine scales. Given that the log tangent scale can be graduated in minutes along its entire length, greater accuracy in a slide rule application will result from using formulae where the altitude and azimuth are found as the anti-log of tangents, rather than the anti-log of sines, cosines, or their reciprocal in the case of Ageton's formulae.

Additional rules for the use of the slide rule were:

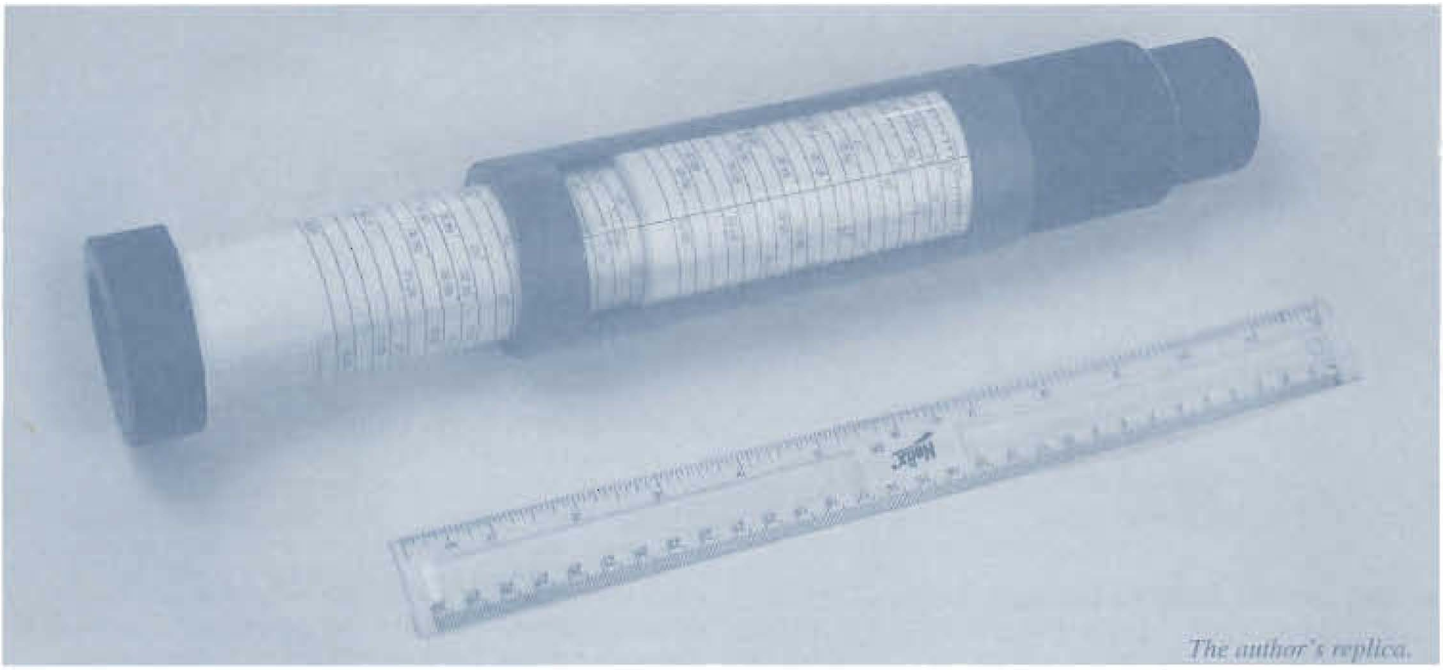
If $LHA < 90°$ then $y < 90°$, if $LHA > 90°$ then $y > 90°$

If $Y < 90°$ then $Zn < 90°$, if $Y > 90°$ then $Zn > 90°$

The Local Hour Angle was to be read from 0° to 180° either East or West. The azimuth was to be read from the pole of *opposite* name to the latitude, West if the LHA was West and East if the LHA was East.

I would have liked to try reducing a sight on the Bygrave, but the inner log tangent scale tube was very stiff and I did not want to force things.

A very similar device called the "Besteck-Höhenrechenschieber MHR1" (which literally translates as "Height Calculator Slide



The author's replica.

Set MHR1") was produced by Dennert & Pape in Germany in the 1930s and during WWII. It seems to have been used by the German airforce and navy—possibly the submarine service. On the same day that I viewed the Bygrave slide rule, I took a trip across London to Greenwich and the repository where the National Maritime Museum store all the items for which *they* do not have room.

The National Maritime Museum has a number of examples of the MHR1. On inspecting one, it was quite obvious that this was a direct copy of the earlier Bygrave slide rule as the scales and dimensions of the instrument are almost identical. However, the MHR1 is much the superior instrument in construction and layout. For example, the cursors on the Bygrave consist of two steel pointers, one short one for the log cosine scale and one thin long one for the log tangent scale, which is rather exposed and delicate. The MHR1 has two clear plastic screens—one for each scale—with thin red cursor lines. This makes for greater accuracy in reading the scale and greater robustness in the instrument itself. The MHR1 also has a knob on the top which, when rotated, locks the two scale tubes together. This ensures the scale tubes do not move relative to each other when the cursor tube is being moved. The MHR1 seems to be made from a bakelite plastic and was somewhat heavier than the Bygrave—I would judge about a pound weight, twice that of the Bygrave. The scales appeared to be imprinted photographically on paper sheet, which was then stuck to the tubes.

There is one essential difference between the two instruments, which is that co-tangents were used on the MHR1 place of tangents on the Bygrave. The formulae then became:

$$\text{Cot}\ y = \cos LHA \cot Dec$$

$$\text{Cot}\ Zn = \frac{\cos \text{Y} \cot LHA}{\cos y}$$

$$\text{Cot}\ Hc = \frac{\cot \text{Y}}{\cos Zn}$$

The restrictions on the log tangent or co-tangent scales on either instrument means that it is not possible to enter declinations or LHA's, or read off azimuths and altitudes, within 20 minutes of 0°, 90° or 180. Sight reductions for Polaris or the sun near local noon for example, or bodies near the prime vertical, would not be possible using either of these slide rules. In its description of the Bygrave slide rule, Bowditch (1984) tells us that "altered procedures are required if the azimuth angle is near 90°, or the meridian angle or declination is very small". What these "altered procedures" may conceivably be, I have no idea.

I have to confess too that a good reason why Dennert & Pape should have decided to use co-tangents for the MHR1 rather than tangents eludes me. It crossed my mind that most of the myriad sight reduction formulae created down the years falter somewhere at angles of either 0° or 90° and it may be that the co-tangent formulae are preferable in some way in this respect. But since the scales on either the Bygrave or the MHR1 do not allow angles of 0° or 90° to be entered or read, such considerations are purely academic.

Both the Bygrave and the MHR1 are now very rare and hard to find, which is a pity for anyone wanting to gain experience using one. However, all is not lost in that a cardboard copy is fairly easy to make using cardboard tubes – which is what I did. The attached photo shows the results of a weekend's effort. It is actually more a copy of the MHR1 in that it uses a log co-tangent scale and the cursor tube has a clear plastic window with a cursor line inscribed on it.

Cardboard tubes come in such a variety of different sizes that it is not hard to find at least two tubes around two inches diameter that are a relatively close coaxial fit. A third tube that slides neatly inside or outside the other two can be more difficult to find however. I made the cursor tube for my cardboard copy by cutting a near size thin tube up the spiral wrap on the outside. It was then opened out slightly and fixed by gluing it onto a piece of paper wrapped around the tube over which it was to fit. Another piece of paper wrapped and glued to the outside made a nice strong, stiff tube.

To form the cursor, I cut a window in the cursor tube and fitted in a piece of clear overhead-projector sheet onto which had been printed the cursor line. The cursor line sits directly on top of the log cosine scale, so reading log cosines to good accuracy was not a problem. But there is a gap between the cursor window and the log co-tangent scale on the inner tube, which was of smaller diameter. A thin piece of shim was inserted into the cursor tube at the top of the window so effectively carrying the cursor down to the log co-tangent scale. This was essential to achieve good accuracy for the instrument.

The only real problem is the construction of the scales, which can take many hours of work at the drawing board, depending on how much detail is required.

The log co-tangent scale on this copy is only 12 feet long, a little over half the length of that on the Bygrave, due to the use of a smaller diameter cardboard tube. Graduations are every ten minutes on the co-tangent scale, so some care is needed in interpolating the resulting azimuth and altitude.

Luykx tells us that "nine steps (settings) are required to complete the sight reduction process from given values of LHA, Lat and Dec." A setting was defined as a rotation of one or other of the scale tubes and its alignment with the cursor. Using this definition, I actually count twelve settings are required, the azimuth (Zn) being achieved at the ninth setting and the altitude (Hc) at the twelfth. Pencil and paper are required to calculate Y, (from the co-latitude and y). The azimuth equation requires a two stage calculation with the slide rule and it helps to write down the intermediate result for the multiplication needed in the numerator. The MHR1 actually had a small piece of matt white plastic attached to the cursor tube on which the intermediate and final results could be conveniently written down. With a little practice, one becomes quite facile in the manipulation of the slide rule. Luykx tells us and it is possible to reduce a sight in around two minutes and my experience confirms this.

Despite the coarseness of the graduations on the scales, results using my cardboard copy are actually surprisingly accurate. Azimuths and altitudes as generated on the slide rule are generally within one or two minutes of the result as computed on a calculator – pretty much in line with what Luykx found with his real Bygrave. I tested the slide rule for tendency to be less accurate for altitudes and azimuths near 0°, 45° or 90°. But results seem to be uniformly good regardless of which part of the scales I explored.

Given the evident popularity of the Bygrave and the MHR1 for aircraft navigation in the inter-war years, it is interesting to ask why they lost popularity, and why navigational calculators of this sort were not really made at all after WWII. I think part of the answer was that with the increasing speed of aircraft, the nature of navigation in aircraft changed during WWII. In the early years of aircraft navigation, it was usual to compute position lines during the flight, as one would on a ship. For this, the compactness of a slide rule like the Bygrave - compared to the volumes of look-up tables routinely used on ships - was a great asset given the very restricted space of the aircraft of those days. But with increased aircraft speed, the time it took to do sight reductions became impractical and the use of pre-computed altitudes became the norm. The process of sight reduction was done back at base, where the bulk of a shelf full of look-up tables was not a problem. During WWII, electronic means of navigation, such as LORAN, were introduced which further eroded the need for compact on-board sight reduction equipment.

Then there was the expense. I don't know what a Bygrave or MHR1 would have cost, but considering the time that would have been required to produce the masters for the scales, I don't think they would have been cheap. They would have been more expensive than the volumes of sight reduction tables they were to replace. So was there any advantage in speed? Given that it takes about two minutes to reduce a sight on a Bygrave type slide rule and (for example) it also takes about two minutes to reduce a sight using the NAO sight reduction tables that now come "free" with every Nautical Almanac, it is easy to see why the practical advantage of a Bygrave like slide rule has to be questioned.

But then, truth be told, there is no practical advantage to the use of celestial navigation these days. A GPS receiver is a thousand times more accurate, a hundred times easier to use and a tenth the price of a good sextant. By and large, practitioners of celestial navigation these days do it because – for a variety of reasons – they enjoy doing it. And that, in the end, is the justification for the construction of my cardboard copy of a Bygrave/MHR1 slide rule. It was good fun.

I would like to acknowledge Zvi Doron, who has a passion for slide rules as well as for celestial navigation, for his inspiration to make this cardboard copy of the Bygrave/ MHR1. In particular, I would like to thank Zvi for his help in making the scales which saved me many hours of laborious effort.

Geoffrey Kolbe runs a precision engineering business located in the outbuildings of an old farm in the Borders of Scotland. He lives in the farm house with two neurotic cats! In a previous incarnation, Geoffrey Kolbe did research on the physics of hot plasmas, such as found in the surface of the sun - or an atomic bomb. In this connection, he spent two years in the mid 1980's working at Lawrence Livermore Laboratory in California. It was here that he grew interested in celestial navigation and bought his first Link A-12 bubble sextant. (Livermore is 50 miles from the coast.) Being irked by the necessity of buying a new Nautical Almanac each year, his attention was drawn to the Long Term Almanac in Bowditch (1981 edition) but found it to be inaccurate - so, he wrote his own! The Long Term Almanac 2000 - 2050, for the Sun and Selected Stars *is published by Pisces Press. A revised edition is currently being worked on.*

***