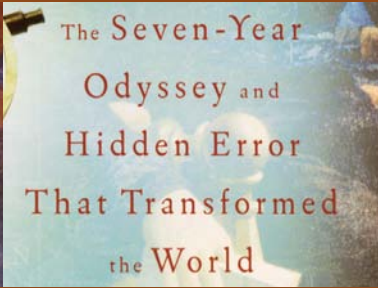


Nothing is as Practicable as a Sound Theory!



Really?

An outsider's view on Ken Alder's *The Measure of All Things*

Many drills in surveying practice are based on the common awareness that any instrument is capable of producing systematic errors in the acquired observations. Since instrument-caused errors cannot be completely prevented or excluded, a strategy is needed to detect such errors in a series of observations.

The theoretical basis for distinguishing unavoidable random errors from instrument-induced systematic errors is one of the scientific breakthroughs that resulted from a massive geodetic enterprise at the end of the 18th century in France. The goal of that enterprise was to precisely determine the shape and size of the earth. The result would support an even greater ambition, one that would produce radical consequences: such a measurement could provide a universal unit of length, the 'meter', as the basis for a unified decimal system of measures, weights and coins.

The best scientific knowledge of the time indicated that the earth's shape was ellipsoidal. Therefore, it seemed logical that the problem could be reduced to the shape and size

of any meridian. With this purpose in mind, the meridian over Paris had to be established over an arc of about 10 degrees latitude by means of a triangulation network connecting Dunkerque, France in the North and Barcelona, Spain in the South (see map). But the measurements yielded a surprise: the resulting curvature of the meridian proved to be too irregular to any longer justify an ellipsoidal shape. This outcome not only provided the inception of a gravity-based model for the shape of the earth, which we now know as the geoid, it also disqualified the planned universal unit of length, the meter, as it had lost its geometric reference. Unfortunately the French government had already established and introduced 'the meter' and the related metric system for political reasons. How could this happen, and why? Just where did the ultimately impracticable concept of an earth-referenced 'universal meter' come from? Answers to these questions, and much more, can be found in Ken Alder's compelling book *The Measure of All Things*, published in 2002.

>> By Janhein Loedeman

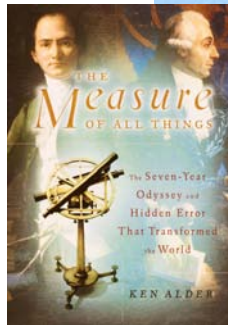


Really?

But First, Some Background

Reviews in numerous newspapers and periodicals, including surveying magazines, praise Alder's book without exception. Some months ago, I wrote my friend and *TAS* editor Marc Cheves a few lines about *The Measure of All Things*. Cheves asked me why an American surveyor should read it. I replied, "It puts measuring the world in a broader social, political and economic perspective, connecting our present with the past. Think about World Trade Organization issues, for instance..." Marc raised an eyebrow, then extended the offer for an article; I could see no valid excuse for a refusal.

The kernel of *The Measure of All Things* addresses abstract matter—the background, development and implementation of the metric system of standardized measures for length, area and volume as well as for currency and time. The story Alder tells, however, is far from abstract. His treatise forms an elucidating antidote for the tempting illusion that history is a logical sequence of events. The history he so vividly describes evolves in an utterly chaotic fashion; it is scientific historic research combined with the tale of intriguing and intricate relationships between flesh and blood characters, revealing their often-conflicting characters, notions, emotions and objectives. It reads like a psychological thriller and detective novel, complete with a surprise ending.



Theory vs. Practicality

Alder elegantly intertwines several narratives, masterfully connecting 18th century theoretical concepts about measurement errors in astronomy with 21st century political concepts about free world-markets. He also calls attention to the crucial difference between precision and accuracy.

In surveying magazines today, I have often seen instrument precision wrongly



Repetition circle built by Etienne Lenoir in Paris around 1800. This instrument is nearly identical to the ones Méchain and Delambre used during the French meridian expedition (1791-1798). It was used in the first triangulation of the Netherlands (1802-1811). The Dutch network was connected in Dunkerque with the French meridian triangulation, thereby providing a link between the French and Danish triangulation networks. *Photograph courtesy Technology Museum Delft University, The Netherlands.*

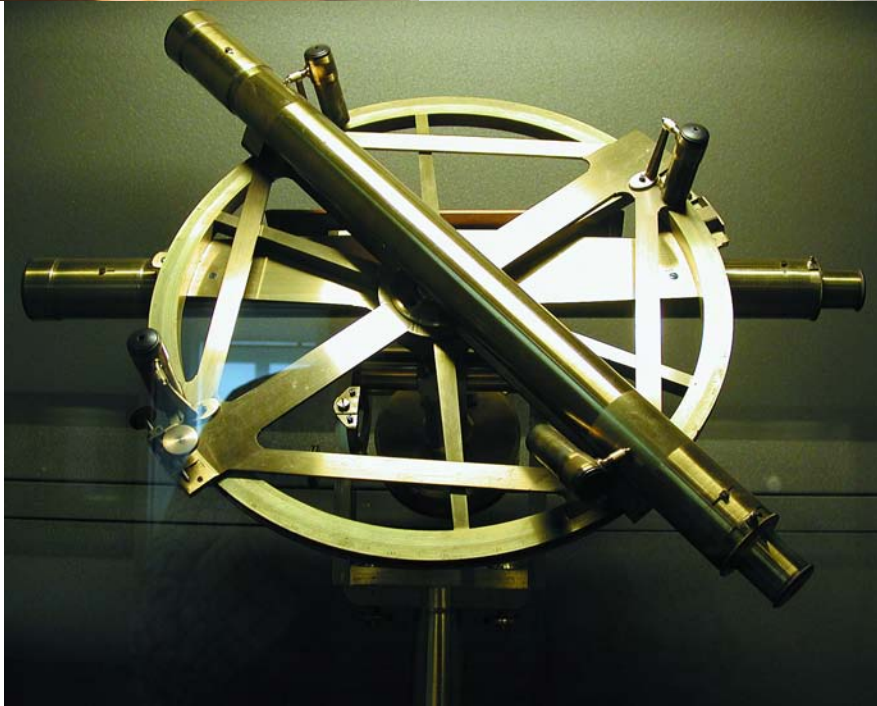


Odyssey and Hidden Error

THE SHAPE OF ALL THINGS

"The creators of the metric system believed that human beings were shaped, first and foremost, by their experience of the world. They wanted the metric system to create a new kind of citizen, much as we expect the internet to teach new political virtues to the citizens of the Information Age. Their goal was to make productivity the visible measure of economic progress and price the paramount variable in exchange. In many ways their vision has triumphed. The euro, the common currency of much of Europe in 2002, is a direct heir of the metric system. Nowadays it seems as if price has at last become the measure of all things. But even the global markets which set prices are social creations governed by human institutions and human desires. And as the labors of Delambre and Méchain amply attest, even our modern impersonal measures are the product of human ingenuity, human passion and the choices of particular people in particular times and places. So in the end there is no escaping Protagoras' 25-century-old motto: 'Man is the measure of all things.'"

—from the book's Epilogue.



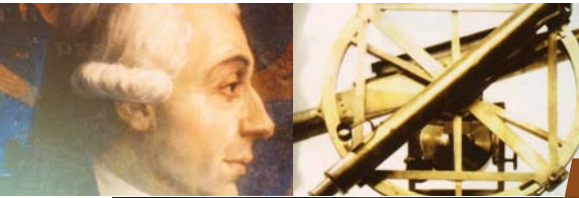
Made in 1805, this circle with telescopes is currently exhibited in the Museum of Arts and Crafts, Paris. It is similar to the instruments that Méchain and Delambre used for their 1791-1798 meridian expedition. See sidebars for an explanation of the instrument's construction and use. (Detail photos by author)

advertised as 'accuracy'. This brings to mind a statement made by Baarda, a Dutch geodesist at Delft Technical University: *"Nothing is as practical as a sound theory."* Some decades ago, Baarda laid the mathematical basis for including an *a priori* accuracy estimate in the design of control networks. The crux is to estimate beforehand the effect a Type-II error (an undetected bias in one of the observations) has on all control-point coordinates that result from a network's adjustment. The implementation of this concept is highly practical as it enables optimizing a control network according to an *a priori* accuracy criterion for the required coordinates. Starting points are the instrumental precision of the observations included and the design of the network. Despite its virtue, this design feature is not a standard part of the commercially available software for network adjustment that I am familiar with. Why not? According to a developer of network adjustment software to whom I once spoke, "Clients never asked for it."

Irrational as this may seem, the proven practicality of a scientifically derived insight does not guarantee its implementation. Alder addresses the tension between science and society, between theory and practice. Here is where politics and politicians mount the stage. The World Trade Organization (WTO) is a case in point. Initially the concept may appear artificial and far-fetched, however, Alder traces a clear, distinct, and direct development leading from the 18th century origin and conception of the abstract universal decimal metric system to the 21st century trade-skirmishes in the WTO. This development forms the 'warp' in the fabric of Alder's book. (Its 'woof' is the dramatic story of the meridian triangulation between Dunkirk and Barcelona.) The thread of a scientifically founded notion of a unified system of measures and weights runs from the Renaissance through the Enlightenment, and provides a scientific basis for the Industrial Revolution. Rationalization of production processes requires the accept-

ance of standardized measures. Alder extensively explains and illustrates the far-reaching social, economic, and political complications of the transition from varying locally accepted units to global standards. Therefore, those who control a society's standards ultimately control its economy and trade.

Alder brings to the stage colorful events to clarify the role standards play in the functioning of a society. True diplomats will never push through legislation that carries a demonstrable counter-productive effect to the ruling of a state, irrespective of that state's political system.



Really?

CONSTRUCTION OF

The repetition circle is an invention of Etienne Lenoir (1744-1822), who was France's premier instrument-maker. The circle carries two telescopes that serve as simultaneous sights to two points between which one takes the angular distance. The instrument is known however as 'Borda's repetition circle', because the instrument allows to apply a repetition of measurements for obtaining a specified degree of precision according to the method developed by Jean-Charles Borda (1733-1799), veteran naval commander and France's leading experimental physicist. The origin of Borda's repetition method originates from an idea in 1752 of the German surveyor and astronomer Tobie Mayer. The repetition method is explained in another side bar.

Lenoir constructed the first specimen of his repetition circle in 1784 under supervision of Jean-Charles Borda (1733-1799), veteran naval commander and leading experimental physicist. He realised the instrument in view of triangulations across the Dover Channel in 1788 for connecting the astronomical observatories in Greenwich in England and Paris in France. In its usage, Lenoir's circle proved to be an instrument comparable, if not superior, to the English theodolite of Ramsden. Based on this success, the French government ordered Lenoir to build the instruments for the French meridian expedition executed by Méchain and Delambre.

Lenoir's instrument consists of a vertical column (17) supported by a tribrach, a ground plate with three levelling screws (1). The column can rotate with the entire



Part of the circle between 140 and 160 grads (gon) showing the subdivision of one-tenth. The vernier, which is fixed to the square alidade holding the upper telescope, allows reading the circle with a precision of one-hundredth of a grad (gon).

Thomas Jefferson understood this principle just as much as did his contemporary at the other side of the Atlantic, the French emperor and conqueror Napoleon Bonaparte. The latter saved the French meridian enterprise from a premature and inglorious ruin. This legacy of the late royal *Ancien Regime* had fallen out of favor during the Reign of Terror, a regrettable episode in the French Revolution. However, despite this initial support to the scientific foundation of the universal metric system, Napoleon cancelled the introduction of the meter as its unforeseen side-effects appeared to be a menace to the operation of the local markets within his empire. Jefferson, a surveyor by profession, initially supported the French meridian enterprise. Further American-French cooperation stranded due to a wrong-headed act of the French ambassador in America.

With regard to the present hybrid system of measures and weights in the U.S., Alder states "Sooner or later it will seem time for Americans to give up their old units, not because the rest of the world

uses the metric system, but because America does." It is the very last sentence of the last chapter. Elsewhere in his text, Alder refers explicitly to advice that John Quincy Adams received two centuries ago when consulting his predecessor Thomas Jefferson about the introduction of metric measures and weights in the United States. In his reply, Jefferson referred to an ancient and unsolvable dilemma that crops up with all legislation by asking Adams "Should we mold our citizens to the law, or the law to our citizens?"

Alder thoroughly and lucidly exposes why the introduction of the metric system took so long. The design of the metric system came in response to a widely and deeply felt problem at all levels of society, locally as well as internationally. In France the introduction lasted about a century. Governments in the U.S., the U.K., and other states were faced with the same problem. While a local system protects the trade and business within the area where it is established and used, aban-

THE REPETITION CIRCLE

instrument around its vertical axis (A) and fixed by a cramp supplied with a setting screw (19). At its base, it has a toothed azimuth circle. The drive occurs by means of a pinion (2) placed at the end of an alidade (3) that has a vernier at its other end to read the azimuth angle (18).

The column can rotate around its axis (A). On top of the column is a bracket (16) attached by means of two screws. The bracket carries a horizontal cylindrical axis. This axis (B) crosses at a right angle another axis (C), likewise cylindrical, and with the same diameter. A graduated circle (8) is attached and centred to the end of this axis C. At the other end of axis C, the circle and its fittings are balanced by a counter weight (11) that is made of a brass drum filled with lead. With the circle in a horizontal position, the drum is between the two branches of the bracket. The circle's axis (C) can rotate around the horizontal axis B. This way, the circle (8) can take any inclination. The inclination of the circle's rotation plane is controlled by a small vertical quarter circle (14), which can be arrested with a cramp (15).

The two telescopes are placed at both sides of the graduated circle. They can rotate independently of each other with respect to the circle around the axis of the circle (C). The one telescope (6) is placed on the outer side and intersects the circle's axis (C), the other one (10) is at the inner side of the circle and therefore eccentric to the axis (C). The exterior telescope (11) is mounted on a square brass frame (7) of which the diagonals provide two mutually fixed alidades carrying four verniers. Each vernier is supplied with a small microscope for reading the circle. The alidade (7) can be hold

fixed to the circle (8) by means of a cramp (5) supplied with a setting screw (4). The interior telescope (10) is supported by an ordinary alidade that can be fixed to the circle by means of a cramp with a setting screw (9) to level the telescope by means of the bulb level for zenith observations (not shown in the graph). This alidade does not have a vernier. The level of the telescope carries a graduated strip that the observer can easily see during his observations making the aid of a second operator superfluous. Above the level, a strip is placed that shelters it from direct sunlight.

Lenoir has ensured in a very elegant way the slow and swift movements of the circle around the axis perpendicular to its plane. The mechanism of the slow movement is a flat drum (13), which has on its rim a helicoil

cogwheel gearing into one another with a tangent screw (12). This drum has the same diameter as the counter-weight (11), and is placed against it, supported by an axis that freely passes through it; this way it forms part of the counter-weight and does not make the instrument's shape hulking. The tangent screw is pressed on the cog-rim by a flat spring. A key allows to lift the spring and the screw and to shift to swift movement. Lenoir's attention also regarded the bulb levels necessary for assuring the perfect horizontal positioning of the instrument's axes.

The instrument measures 76 cm (30") in height, 40 cm (16") in width and 56 cm (22") in length. It weighs 20 kg (44 pounds). Materials used for the construction are wood, iron, ivory, brass and glass.

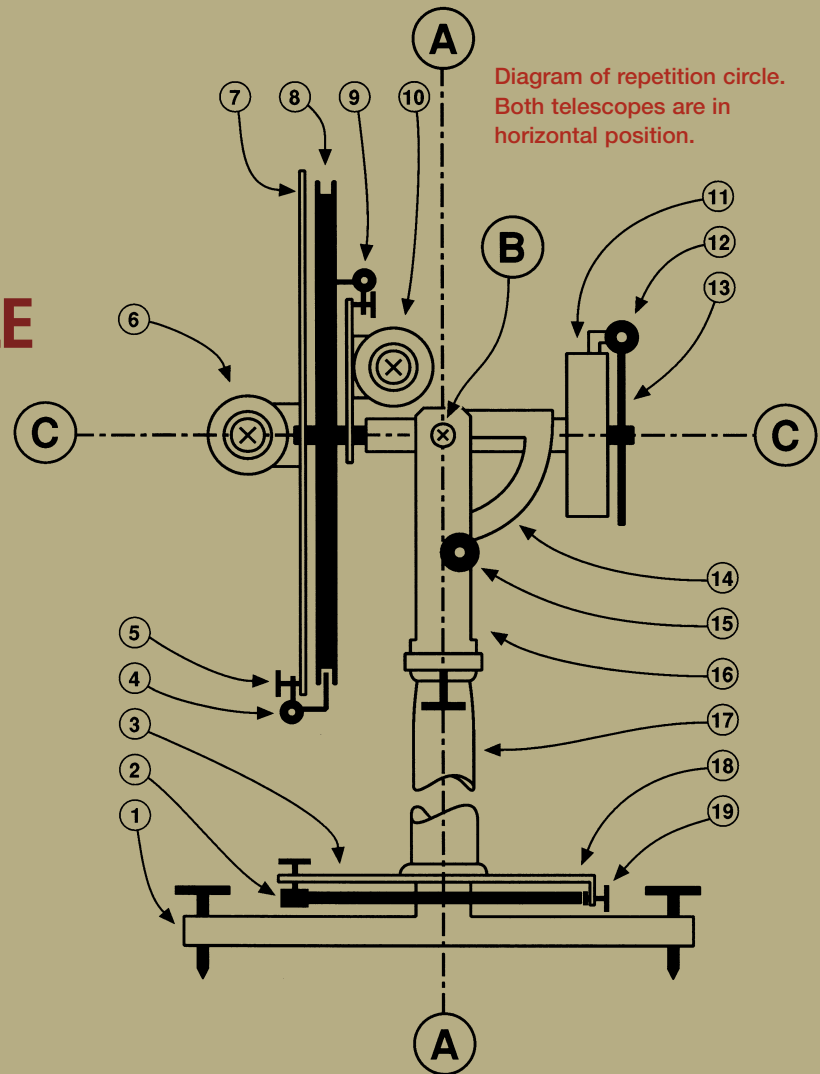


Diagram of repetition circle. Both telescopes are in horizontal position.



Really?



Constructional details of the lower left corner of square frame that supports the upper telescope include a cramp (screw), a setting screw and an eye piece for reading the circle.

MEASURING ANGLE

Behind the construction of the repetition circle is an idea of the German surveyor and astronomer Tobie Mayer. He imagined around 1752 repeating the same observation several times without returning to zero on the circle. Finally the accumulated angle has to be divided by the number of repetitions. The resulting angle is far more precise than a single interpolation of the circle's graduation allows. An additional advantage of this method is a decrease of uncertainties that are inherent to any angle-measurement. Errors due to the instrument itself, such as irregularities in the graduation of the circle, have less influence on the result. The method is specifically effective when an instrument can be aimed with a better angular precision than a single interpolation of the circle's graduation can provide. This problem occurs when an optical telescope is used instead of an ordinary sight.

Unlike a theodolite, a repetition circle has only one circle, as explained in another side bar. The instrument's construction therefore excludes the direct measurement of horizontal angles. Before an angle between two targets can be measured, the circle must be oriented parallel to the inclined plane through the instrument's station (C) and the positions of two targets (G) and (D); see Fig. 1. For measuring zenith angles, the circle is oriented in a vertical position. One of the two telescopes

doing a local system therefore means that its built-in protection of local markets disappears as well. These markets are then susceptible to takeover by outside parties, which are often more powerful. In short, the introduction of uniform standards to support a national economy at the macro level can create an economic boomerang at the micro level. The WTO is currently discussing these trends.

In many of today's less-developed countries, agriculture is still the dominant economic activity. Measures are directly derived from, or related to, human needs and activities. Alder calls such measures

anthropomorphic, or shaped towards man. The metric system, on the contrary, comprises scientifically based abstract units, purposely designed for measuring the world. When in France the 'hectare' had to replace local measures for area that related to what a man can plow, surveyors were the first to discover that such an abstract measure gives rise to numerous problems.

Precision vs. Accuracy

In addition to Jefferson, Adams and Napoleon, Alder spotlights many other world-famous scientists and politicians

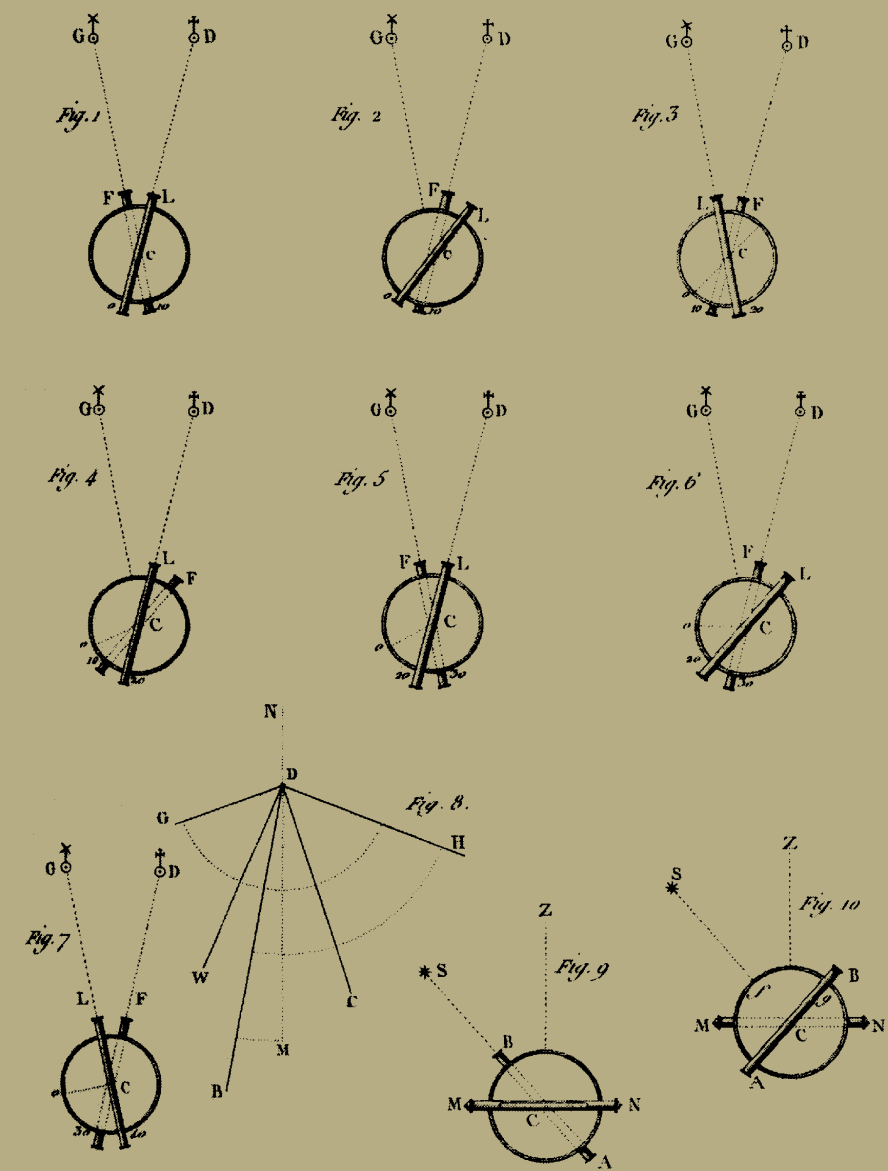
ES BY REPETITION

(MN) is accurately leveled to provide a reference perpendicular to zenith (Z). The other telescope (AB) is aimed at the celestial body (S) for which the zenith angle has to be measured; see Fig. 9.

Measuring an angle between two targets (Fig. 1-7)

In the example, the two targets G and D, which stand for Gauch (left) and Droit (right), are about ten degrees apart, as can be seen from the readings shown for the two telescopes F and L. Initially, both telescopes are fixed to the circle. In Fig. 2, telescope F is rotated clockwise until it is aimed at target D. Consequently, the upper telescope L has been shifted clockwise over the identical angle. In Fig. 3 the upper telescope is released from the circle and independently aimed at target G again. With respect to its starting point in Fig. 1 the angle to be read now is twice ten degrees. In Fig. 4 the upper telescope L is fixed to the circle again, so that when aiming L at target D the lower telescope F rotates over an identical angle.

In Fig. 5 the lower telescope F is aimed at target G independently of the upper telescope L. This adds another ten degrees to the sum of angles from the starting position. The circle is in its initial position again. Fig. 6 & 7 show a repetition of the process, which can be carried on as many times as needed for achieving a specified precision.



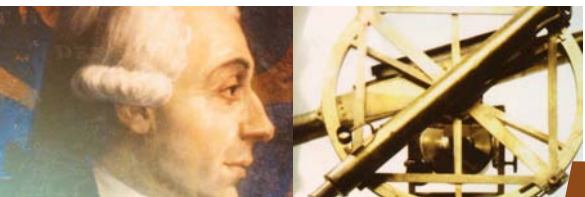
This illustration, adopted from *The Measure of All Things*, originates from a French publication about connecting the astronomical observatories in Greenwich, England and Paris, France via triangulation in 1787. Courtesy Houghton Library, Harvard University, Cambridge MA.

Measuring a zenith angle (Fig. 9 and 10)

The side-view in Fig. 9 & 10 demonstrate how the same repetition process should be used to measure the zenith-angle of a celestial body S. The bubble fixed to telescope MN is accurately set level.

In this situation, the repetition process starts by rotating the instrument over 180° around its first (vertical) axis; see Fig. 10. The indications M and N do not change between Fig. 9 and Fig. 10, because M and N stand for the French words Meridional and

Nord, which mean South and North. Subsequently the clamp screw of telescope MN is released and telescope AB is aimed at S again. (This is not illustrated with an additional figure, neither is the next step.) This cycle adds two times the zenith angle to the initial value of the zenith angle. To add a next cycle, the instrument is rotated over 180° again; the clamp screw of telescope MN is released, and telescope AB is aimed at S once more. This second cycle again adds two times the zenith angle.



Really?

whose efforts resulted in the ‘international meter.’ Amongst these are Cassini, Fourier, Benjamin Franklin, Gauss, Herschel, Lagrange, Laplace, Lavoisier, Legendre, Talleyrand, and George Washington. The leading roles, however, are held by two astronomers who led the triangulation between Dunkirk and Barcelona, Pierre-François-André Méchain and Jean-Baptiste-Joseph Delambre. Méchain was obsessed with precision; he regarded errors as a token of personal failure. Distrustful of any assistant, he performed all instrument observations in his part of the triangulation. More importantly, in Barcelona he did far more astronomical observations than needed to achieve the required precision. His observations were tremendously supernumerary (over-determined). Due to his extreme precision, Méchain discovered discrepancies that he could not explain. He decided to hide the ‘ghost error’ by manipulating his results, risking mortal shame when his fraud would be detected. This secret became a vexation that killed him. He died of malaria during an attempt to extend his part of the triangulation from Barcelona to the Balearic Islands in the Mediterranean Sea for the sole reason to unravel the ghost error. Delambre discovered the fraud, but not until after Méchain’s death. Fortunately, Delambre also discovered that Méchain had manipulated his results in such a way that the triangulation was not corrupted. Delambre documented and published all original data. At the time, nobody could clarify the contradictions in Méchain’s astronomical observations in Barcelona. For that purpose, a mathematical theory on errors and error propagation had to be formulated. The scientific giants Laplace, Legendre and Gauss laid the ground for this theory. Not until twenty-five years after Méchain’s death, did a pupil of Laplace apply this theory on the Barcelona observations, proving that instrument error had caused the unexplainable contradictions in Méchain’s data. In order to get observations from as many stars as possible, Méchain had included stars both South and North of

zenith, where Delambre in Dunkerque and Paris had restricted his observations to stars South of zenith. Nicollet, by applying the recently developed error theory to Méchain’s two-sided star observations, discovered a systematic error that could not appear in Delambre’s one-sided observations. Mechanical wear in the rotation axis of the repetition circle had caused Méchain’s hidden ghost error. If this discovery had occurred when Méchain was still alive, what may have been his reaction? Alder emphasizes that accepting the new concept of ‘error’ requires a shift in scientific attitude, thus a mental shift. It is a matter of human ‘values’ and ‘virtues,’ which defy measurement within a rigid and abstract universe.

The Measure of All Things is a title that expresses an ancient wisdom; it is a tribute. Its meaning remained hidden from me until I had read the last sentence of the epilogue (see sidebar “The Shape of All Things”) From that perspective, the book is a detective story. Alder’s story provides hope to ordinary mortals like me and furnishes food for thought to inspired “reformers” of our world.

An intriguing detail with respect to the various editions of Alder’s book is that a reference to the “hidden error” is mentioned in the subtitle of the American edition but not in the British and Dutch editions. Even more intriguing, at least to me, is why Méchain himself could not detect the error’s cause. In this respect, Alder’s explanation has not convinced me. That, however, is a story in itself.



This map, adopted from *The Measure of All Things*, is from an original map in Paris. It shows the original arc of triangulation from Barcelona to Dunkirk as performed by Méchain and Delambre.

Janhein Loedeman is a professional engineer, a life-long teacher of surveying, aerial photo-interpretation and photogrammetry, and GIS. He has the equivalent of a MSc in agricultural engineering and has specialized in surveying as well as land & water conservation. He currently teaches at Wageningen University’s Centre for Geo-Information.