

THE DEVELOPMENT OF SURVEY INSTRUMENTS

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ABSTRACT

The paper gives a short review of the development of survey instruments. Some highlights in the development are emphasized: — The realization of Heinrich WILD's ideas in the early twenties — the geodimeter 1947, the tellurometer 1957 — electronic tacheometers in the seventies — doppler satellite receivers and inertial surveying systems, also in the seventies.

The surveyor and his instrument have been integrated parts in the process of measurements. Will, however, future survey instruments be more or less "black boxes" and consequently the surveyor's role be reduced to pushing buttons? What effect will it have on the surveyor's professional practice?

IN OLDEN TIMES

The development of survey equipment and survey instruments goes far back in history. The oldest instruments served in the determination of distances needed in house building, water supply, the dividing of land property, and in the determination of land property areas.

The construction of roads, canals, monumental buildings and the like needed rather accurate measurements and therefore contributed to the development of instruments and methods of measuring.

In Babylon and Egypt, distance measuring equipment such as ells, rods and cords were known 3 000 years before Christ. Similar equipment was also known in

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China 3100 years ago. The plumb bob and the water-level were used by the Sumerians, the Chinese, and the Egyptians. The plumb bob and the water-level automatically introduce the direction of the gravity force as reference direction, a direction which plays a decisive role in most cases of survey measurements.

The plumb rule was known by the Egyptians and the magnetic compass was already known by the Chinese. The accuracy of levelling at that time is estimated to have been 8 cm/200 m. The Gnomon, a high column in an open place (the pointer of a sun-dial), was used by Meton 2420 years ago to determine the northern direction.

Erathostenes, 2200 years ago in Alexandria, determined the circumference of the earth by measuring the length of an arc on the earth's surface and the corresponding angle at the earth's centre. This angle was measured indirectly by means of the Gnomon.

Heron of Alexandria wrote a text-book on practical field surveying 2100 years ago. In this book he described an instrument called a Dioptra (fig. 1).

Figure 1 shows a reconstruction built in accordance with Heron's description. For sighting there is a sight rule with a water-tube level attached to it. Among other things, one could measure angles between directions to stars with the Dioptra. In principle, it acts like a theodolite, and it is equipped with clamps and slow motion screws. Heron mentions the various purposes the instrument can serve and points out that it will be no problem to align a tunnel from both ends with such an accurate instrument. Heron also constructed a half-automatic measuring wheel for distances.

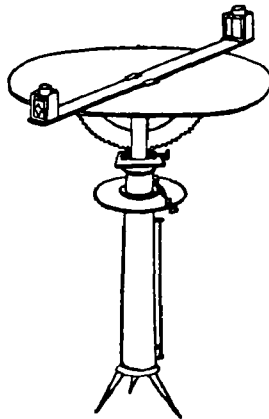


FIG. 1

About 50 years earlier, Hipparch of Nikea, known for his extensive and accurate star observations, had invented the astrolabium which is considered to be the forerunner of the theodolite. Approximately 300 years later, Ptolemy described the quadrant, a graduated quarter of a circle. The Romans contributed little to the development of survey instruments, but they transferred knowledge of the instruments from the Middle East to Europe.

The Arabs, who advanced as far as to France, took care of the earlier knowledge of geodesy and astronomy and developed it further.

IN THE MIDDLE AGES

During the Middle Ages there was little progress in creating new and better instruments. The magnetic compass, however, had become known in Europe and it is known that a water compass was used in mining surveying in Harz, Germany, in 1168 AD.

THE PERIOD 1500-1920

The instruments of the 16th and 17th centuries were very much like those used 1700 years before. They included rods, usually made of wood, for the measuring of distances, cross staffs for setting out right angles, water-tube levels, quadrants and astrolabiums.

Snellius (Netherlands), the inventor of triangulation (1615), measured angles with a quadrant and so did Picard (France) when he accomplished the triangulation along the Paris meridian from Sourdon, south of Amiens, to Malvoisine, south of Paris. Picard's quadrant (fig. 2) was equipped with a telescope for accurate sighting (1669-70).

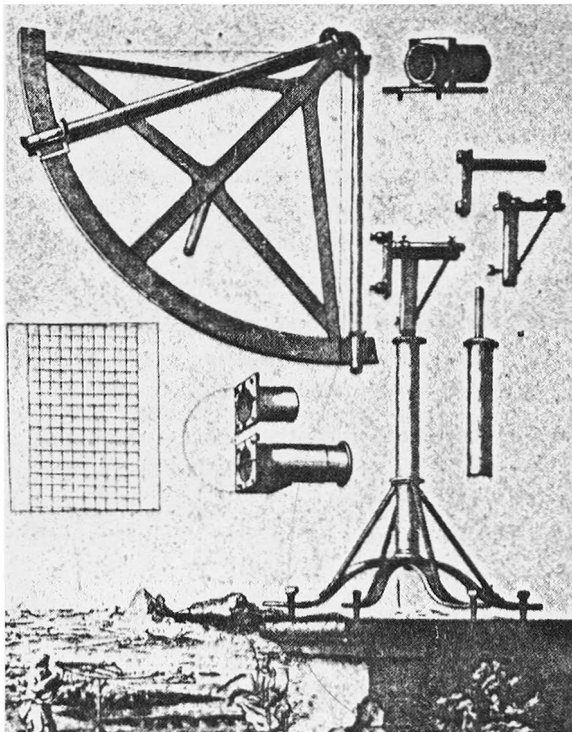


FIG. 2

On two geodetic expeditions, one to Lapland, Sweden, 1736-37, and the other to Peru, 1735-41, quadrants were the angle-measuring equipment, and rods approximately 9.74 m long (5 toises) (1 toise = 1.949036 m) were used for base line measurement.

The expeditions were organized and sent out by the French Academy of Sciences. They aimed at solving the dispute between the Newtonians and the Cassinians. The Newtonians maintained that according to the co-effect of gravitational and centrifugal force the rotational ellipsoid was flattened at its poles. Contrary to that, the Cassinians had derived from geodetic measurement that the major axis of the ellipsoid was coincident with the rotational axis of the earth. Thus, the dispute was caused due to the lack of sufficient measuring accuracy at that time.

Gemma Frisius (1508-1555), from the Netherlands, invented the plane table. It was through the German professor, J. Praetorius (1537-1616), that it became generally known. The sight rule was replaced by a telescopic alidade in the 19th century. Surveying by use of the plane table was the main method for mapping for a long time. From the middle of the 19th century, tacheometry came more and more into use for large scale mapping. Today, photogrammetry is almost the sole method used for the production of basic maps.

Table I is a list of some important inventions which contributed to the development of theodolites, tacheometers, and levels.

Some inventions were already of an old date when they were first applied to survey instruments. The screw microscope had been known for a hundred years when it was built into a theodolite as a reading device.

Other ideas for improvement were refused because they were considered impossible to realize. That was the case when Wild originally proposed the optical transfer of diametrical circle images.

The first known optical distance measurement was carried out by Geminiano (1674) in Italy, with a telescope equipped with a reticule containing 12-15 horizontal wires. James Watt built a distance-measuring telescope with one vertical and two horizontal wires in the plane of the reticule.

Georg Reichenbach (1812) built distance-measuring cross-wires into a telescopic alidade for cadastral survey in Bavaria. From that time on, a broader application of this method of measuring distances evolved.

The increasing need for maps and other surveying data as a base for planning and construction of railways, roads, canals, etc., led to an increasing use of optical distance measurement. Many types of tacheometers, and especially various kinds of self-reducing tacheometers, were built during the 19th and the first half of the 20th centuries.

The subtense bar has been used since about 1880. The first bars were made of wood, later of steel (1906) and invar (1923).

In Mollet's papers (1702) a telescopic level is described. The telescope was equipped with a focusing device, a tilting screw and screws for adjustment. But it was not until one hundred and fifty years later that telescopic levels became more

TABLE I

| INVENTION | INVENTOR | COUNTRY | YEAR | REMARKS |
|---------------------------|-----------------|---------|------|-----------------------|
| Telescopes | Hans Lipperhey | N | 1608 | |
| | Galileo Galilei | I | 1609 | Improvements |
| | J. Kepler | G | 1611 | Upright image |
| Cross-hair (reticules) | Generini | | 1630 | Eyepiece diopter |
| | Gascoigne | GB | 1640 | Cross-hair |
| Objective | Moor Hall | GB | 1729 | Achromatic |
| Eyepieces | Huygens | N | 1684 | |
| | Ramsden | GB | 1783 | |
| | Kellner | | 1849 | |
| Bubble tubes | Thevenot | F | 1662 | |
| | Sturm | G | 1715 | |
| | Amsler-Laffon | Swi | 1857 | Revolving tube |
| | Wild | Swi | 1908 | Coincidence reading |
| Circular bubbles | Mayer | G | 1770 | |
| | Mollenkopf | | 1904 | Improvements |
| Reading devices | Clavius | | 1593 | Vernier |
| | Ramsden | GB | 1780 | Microscope |
| | Ramsden | | | Screw microscope |
| Circle graduation | Wild | Swi | 1918 | Optical micrometer |
| | Hooke | GB | 1684 | Half automatic |
| | Hidley | GB | 1760 | Graduation machine |
| | Ramsden | GB | 1763 | Graduation machine |
| | Reichenbach | G | 1803 | Copying method |
| | Oertling | | 1840 | Automatic machine |
| Theodolites | Heyde | G | 1895 | |
| | Heron | | 100 | b. Chr. |
| | Sisson | GB | 1730 | |
| | Ramsden | GB | 1735 | With screw microscope |
| | Reichenbach | G | 1804 | Analytic telescope |
| | Wild | Swi | 1923 | Many improvements |

common. For a long time, the main method for levelling was based on the hydrostatic principle. It is known that G. Branca (Rome, 1629) built a water-tube level, where the tube was made of leather. Geiger (Germany, 1849) made a water-tube level using a hose of rubber.

AFTER 1920

There was a rapid development of new types of instruments beginning in the early 1920's. At the beginning of this century, surveying instruments already had

a high degree of precision, but they were, compared to today's instruments, large in form and heavy. They were very inconvenient, especially when the instrument and its accessories had to be transported on the surveyor's and aide's backs. The limited precision of circle graduation and reading devices had to be compensated for by suitable, often time consuming, measuring routines. The effort for improvement concentrated on building instruments of lighter weight and more compact form, and to introduce more accurate reading devices, and to exploit the optical possibilities of reading the vertical and horizontal circle in the same microscope. Besides, it was aimed at making the instruments more stable with respect to adjustment and to have the sensitive parts of the instruments better protected against dust and humidity.

Essential contributions to the modernization of surveying instruments was made by the Swiss instrument designer Heinrich WILD (1877-1951). In cooperation with the firm Carl Zeiss, Jena, he introduced in 1908 inner focusing, first using a positive lens and later a negative lens, which made it possible to build high precision sighting telescopes of short length. The most important common features of the new types of theodolites are :

- Cylindrical azimuth axis
- Inner focusing lens
- Coincidence reading bubble
- Tripods without clamping screws
- Parallel-glassplate micrometer
- Mean-reading optical micrometers
- Graduated circles made of glass.

Other optical and mechanical improvements introduced are :

- Optical plummet
- Better optics for one thing by coating optical surfaces
- Invar subtense bar
- High precision tacheometers with self-reducing optical wedge system for distance and height difference measurements
- Self-levelling levels

TABLE II

| | YEAR | STANDARD DEVIATION OF A | |
|--|---------|-------------------------|-------------|
| | | DIRECTION | LEVELLING |
| <u>Angle measurement</u> | | | |
| Triangulation — Peru | 1736-44 | 2.6" | |
| First order triangulation in Europe | 1892 | 1.2" | |
| High precision | Today | 0.2"-0.5" | |
| <u>Levelling</u> | | | |
| Switzerland | 1867 | | ≤ 3 mm/km |
| Europe | 1912 | | ≤ 1.5 mm/km |
| High precision | Today | | 0.3 mm/km |

- Automatic index for vertical circle reading
- Gyrotheodolites
- Digital circle reading
- Electronic tacheometers
- Levels with a rotating laser beam.

Most of the theodolites of today are strongly influenced by WILD'S main ideas and the various types have a standardized shape and accuracy characteristics for the type concerned.

On the average, the weight of a modern theodolite including tripod and packing is reduced by 60 percent of the weight of the old ones, and the time taken for measuring is also reduced by 60 percent.

Table II gives a review of accuracies of angle measurement and levelling.

PROBLEMS OF DISTANCE MEASUREMENT

Distance measurement on the terrain has, until recent decades, been far more problematic than measuring angles. In addition, there has been the long-lasting problem of defining an unambiguous unit of length along with the lack of some reliable standard with which the measuring tool could be compared.

The units of length have been related to some natural standard, for example the fathom, ell, foot and inch. But these units were, for long periods, not properly defined. This caused problems, not only for surveying and geodesy, but for other sciences as well.

In the year 1791, the "Commission Générale des Poids et Mesures" of France decided to introduce a new unit of length which, it was hoped, would eliminate this troublesome ambiguity. The new unit, the meter, was to be one part in 10 million of the length of a meridian quadrant. To obtain a reliable value of the length of the quadrant, a new triangulation along the meridian of Paris, from Dunkirk to Barcelona, was carried out. The calibration problem of distance measuring tools, however, lasted until the last decades of the 19th century. In geodesy, the problem became acute when triangulation networks of various countries had to be fitted together. This was a special task for the Internationale Erdmessung, the forerunner of IAG, founded in 1862.

At a conference in Paris in 1875, 18 nations signed the International Meter Convention and the participating nations decided to found the "Bureau International des Poids et Mesures". A meter prototype is kept in Breteuil outside Paris. In the year 1889, 30 copies of the prototype were distributed to the nations which had signed the Convention. Tools used for base line measurement could now be compared to proper standards and corrections applied accordingly. The result appeared to be surprisingly good when the various triangulation networks were fitted together.

Essential improvements of base line measurements were achieved when JÄDERIN, in Sweden, introduced tapes and wires during the eighteen eighties. By making wires of invar, an alloy invented by the Swiss-French physicist, Ch. GUIL-

LAUME, 1897, the accuracy of base line measurements could now be further enhanced. But it was not until EDM instruments came into general use that distance measuring became a surveying method on a level with angle measurement and for many purposes surpassed it with respect to applicability and accuracy.

EDM-INSTRUMENTS USING VISIBLE AND INFRARED LIGHT

The history of EDM does not go very far back in time and is, to a certain degree, connected to the experiments carried out to estimate the speed of light. The working principle of electro-optical instruments is, in essence, given by FIZEAU, 1849. To determine the speed of light FIZEAU used a rotating toothed wheel to chop up a light beam, directed at the toothed perimeter, into light pulses. Thus, the wheel acted as a mechanical modulator producing approximately square waves.

In 1920, JONES, the director of the U.S. Coast and Geodetic Survey, during his discussion with the physicist MICHELSON, advanced the idea of using modulated light waves for distance measuring. MICHELSON wanted an accurate base line for the estimation of the light velocity. With the velocity known, JONES proposed to reverse the method concerned.

At the IUGG congress in Madrid (1924) the Norwegian astronomer JELSTRUP outlined a proposal similar to JONES'. During the 1930's more scientists were working at developing electro-optical distance meters. Prototypes were made, but it wasn't until the geodimeter was built by the Swedish firm AGA that an instrument applicable for practical use became commercially available. The geodimeter was a result of the research work of the Swedish physicist and geodesist, BERGSTRAND, who estimated the light velocity by high frequency light signals. This was a continuation of the work of KAROLUS, MITTELSTADT and HÜTTEL. By intensive research AGA developed, in the following years, new geodimeter types of lighter weight which were easier to handle and to operate.

From the end of the nineteen sixties a number of new instruments have been introduced. Most of them make use of luminescent diodes for direct modulation of infra-red light. Theodolite and distance meter are jointly built into a self-reducing high precision electronic tacheometer with electro-optical reading of circles and automatic storing of data in some coded form. The built-in microprocessor of the tacheometer ELTA 2 (Zeiss, FRG), for example, does not only control the whole measuring process, but can compute, if desired, the station coordinates, coordinate transformation and set out data on the spot.

Most of the electro-optical distance meters commonly used render an accuracy of :

$$(5 - 10) \text{ mm} + (1 - 5) \text{ p.p.m.}$$

High precision distance meters such as :

the Mekometer Me 3000 : 0.3 mm + 0.3 p.p.m.

and the Tellurometer MA 100 : 1.5 mm + 1 p.p.m.

The atmospheric influence on electro-optical distance measurement can be almost completely eliminated by using simultaneously two carrier frequencies, for example red and blue laser light.

INSTRUMENTS USING RADIOWAVES AND MICROWAVES

Since the 1930's there has been more and more research in the field of using radiowaves for positioning and navigation. Some of the systems developed had an accuracy also sufficient for geodetic purposes. That was true for the Shoran and Hiran systems. The latter is an improvement of the first one with respect to accuracy. To maintain a sufficiently high relative accuracy, the application of these systems was limited to distances of 100 km or more. In geodesy, they were mainly used for special purposes, such as establishing geodetic connections between islands and between islands and continents.

An instrument more appropriate for the general surveyor's need, the Tellurometer, became commercially available in 1957. The Tellurometer, which uses microwaves and which is based on the principle of phase comparison, was developed by WADLEY, FEJER and HEWITT of South Africa. The working range of the first Tellurometer had an upper limit of 80 km and rendered an accuracy of 10 cm. Compared to the available geodimeters at that time, the Tellurometer was of lighter weight, easier to handle, simpler to operate, and it functioned independently of daytime and weather conditions. Improved models of the Tellurometer with some wider working ranges were produced the following years.

EDM supplemented and to a certain degree replaced angle measurement which earlier was the main method for higher order control nets.

For shorter distances of up to about 10 km, electro-optical distance meters are most commonly used. This is due to the fact that for short and medium ranges they render a higher accuracy than the microwave instruments and because they only need a simple, passive signal reflector, a mirror or a reflecting prism. The microwave method, however, needs two active instruments, one at either end of the line to be measured.

In figure 3 new and old instruments are placed together. The plane table and its accessories, still in use at the beginning of this century, are very much like those of Praetorius which were designed about three hundred and fifty years ago.

The developments of modern equipment for aircraft and ship navigation were, during the 1970's, leading to significant improvement of survey technology. The new systems are mainly based on the application of satellite and inertial technology. The surveyors have got new tools for point positioning and establishing of control nets. These tools are Doppler satellite receivers, inertial survey instruments, and instruments for the exploitation of the satellite NAVSTAR GPS system currently being developed. These types of instruments are totally different from the conventional and all of them have automated measuring processes. The surveyor is no longer an integral part in the measuring process itself, as he is when he uses

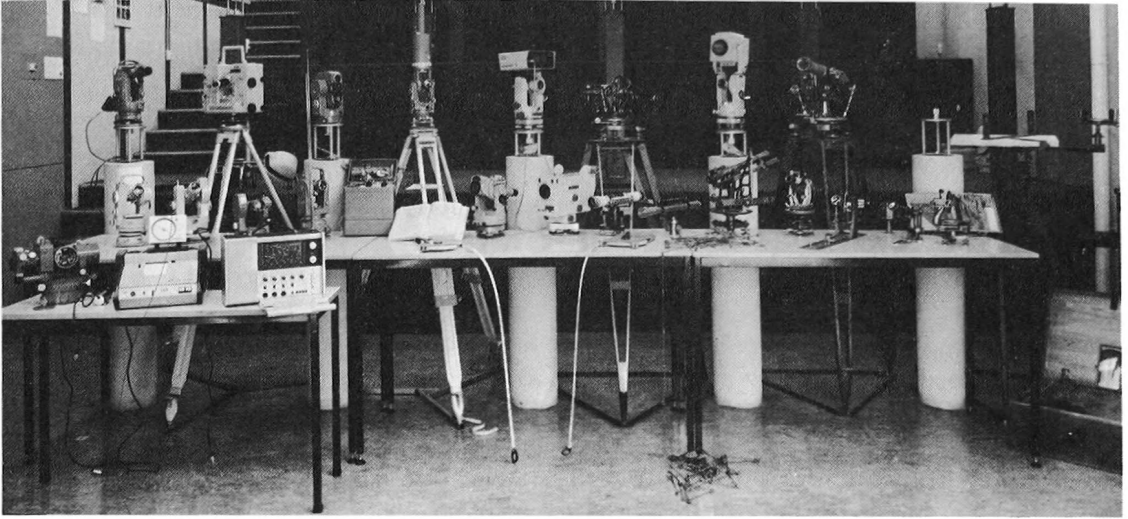


FIG. 3

a theodolite or a level. The quality of the measurement, when one uses the conventional type of instrument, depends just as much on the skill of the surveyor as an observer as on the precision of the instrument itself. With a fully automated instrument, his role is reduced to operating the instrument in accordance with a written instruction. There is not much challenge to the surveyor in collecting data by automated instruments. The challenge is shifted more to analysis of the measurement process, evaluation of data, often large amounts of these, adjustment procedure, and computation.

Table III gives examples of today's achievable accuracy by application of inertial instruments and satellite signal receiving instruments.

TABLE III

| SYSTEM | INSTRUMENT | σ ABSOLUTE | σ RELATIVE | DISTANCE | REMARKS |
|----------|-----------------------------|----------------------|----------------------|----------------|------------------------|
| NNSS | Doppler receivers | 0.5-1.0 m | 0.5-1.0 m | | Several days |
| NAVSTAR | Multiplex receiver | 5-7 m | | | 6s |
| NAVSTAR | Macrometer (interferometry) | | < 0.01 m | 1 km | 1982, 1 hour |
| | | | < 0.05 m | 10 km | Expected : 1 hour |
| NAVSTAR | Series (interferometry) | | < 0.07 m | 1 km | 1.5 hour |
| INERTIAL | Various types | | 0.2-0.5 m | 60 km traverse | Flat terrain about 1 h |

It can be anticipated that the precision of such instruments as are listed in table III, will be improved in the future. The conventional instruments and point positioning by conventional triangulation and traversing will probably become wholly or partially obsolete.

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