HISTORICAL REVIEW OF PRECISE LENGTH MEASUREMENTS

Siniša Delčev[1]
Vukan Ogrizović[2]
Jelena Gučević[3]
Stefan Miljković[4]

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Summary: *Precise measurement of long distances for scale determination, especially in 1st order trigonometric networks, was a problem for years. Thanks to Snellius and his work, a shorter distance on a flat field could be measured, and then its scale could be transferred by angle measurements to a distance between two 1st order trigonometric points. However, even measuring those short distances could not be measured with high accuracy. Lengths were measured by wooden or metal levers, until the invention of invar, which allowed precise distance measurements. Furthermore, electro-optical and, later, laser distance meters, involved direct precise measurements of long distances.*

Keywords: *invar wires, Jäderin basis apparatus, distance meter, pulse, phase, frequency*

1. INTRODUCTION

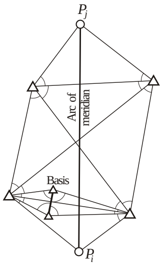

Figure 1: Meridian arc measurement

Snellius has performed measurements that placed the foundations of the horizontal networks, by invented triangulation, with angles measured with accuracy of few arc minutes. In 1615, he gave the basics of meridian arc measurements, including a short, but directly measured, baseline in his triangulation. His work, but also Piccard's and French expeditions, during the meridian arc measurement campaign, showed that terrestrial angle and length measurements are convenient for trigonometric networks establi-shment. The instruments have become

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[1] V. prof. dr Siniša Delčev, dipl. geod. inž., University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, Subotica, Serbia, tel: ++381 24 554 300, e-mail: delcevs@gf.uns.ac.rs

[2] V. prof. dr Vukan Ogrizović, dipl. geod. inž., University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, Subotica, Serbia, tel: ++381 24 554 300, e-mail: vukan@gf.uns.ac.rs

[3] V. prof. dr Jelena Gučević, dipl. geod. inž., University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, Subotica, Serbia, tel: ++381 24 554 300, e-mail: jgucevic@gf.uns.ac.rs

[4] Stefan Miljković, mast. geod. inž., University of Belgrade, Faculty of Civil Engineering, Bul. kralja Aleksandra 73, Belgrade, Serbia, e-mail: skiljk@live.com

more precise and simpler for work, which initiated development of the trigonometric networks in all parts of Europe.

The main problem during the development of the national 1st order trigonometric networks was how to measure a distance - a baseline. The national networks were developed in this way from beginning of 19th century, up to mid 20th century, when electro-optical distance measurement replaced the classical way.

2. MECHANICAL LENGTH MEASUREMENT

In the beginning, length measuring was performed by measuring tapes, metal chains (Fig. 2) or wooden rods. The chain for the length measuring consisted of more pieces 1 m long, joined with special pieces which were, in the same time, used for mark meters – 2, 5, or 10 m. At the ends, there were larger links with wedges placed inside them, which were used for strain the chain. The accuracy of such distances was around several cm, which was enough only for topographic surveying, i.e. cadastre.

Figure 2: Chain for length measurement

For precise length measurements, special wooden (Fig. 3) or metal rods were used. The wooden rods were made of good and dry wood, and then they were cooked in oil and protected from moisture in a special way. The rods were 4 m long, with metal shackles several centimetres long on the ends. A half-cylinder was soldered to one end and it represents the beginning of the rod division. The other end had a knee-shaped mechanism (*d* in Fig. 3), that could be precisely moved. It served for reading parts of mm. Putting the rod in horizontal position was performed by iron sticks (*E* and *F*, Fig. 3), which went through the rollers (*C* and *D*) on the rod. Some, mainly iron rods, had microscope-micrometres, to achieve better accuracy. During the measurements, the temperature was measured, to calculate changes in length due to temperature coefficient of the material. This equipment was able to measure distances with cm accuracy level. The productivity was about 300 m per day. Later on, after some improvements, the crew could measure up to 800 m per day.

A huge progress in precise length measurements was made with Jäderin basis apparatus in 1880 (Fig. 4). In a way, it is an improvement of using the chains where there is only one wire, instead of more pieces. Also, the straining system is reconstructed. The wires were metal, 24 m long and they were strained by 1 kg weights on both sides. The reading system for special – there were rules on each side, for precise reading of the lengths. Tripods for hanging the wires were about 60 cm tall.

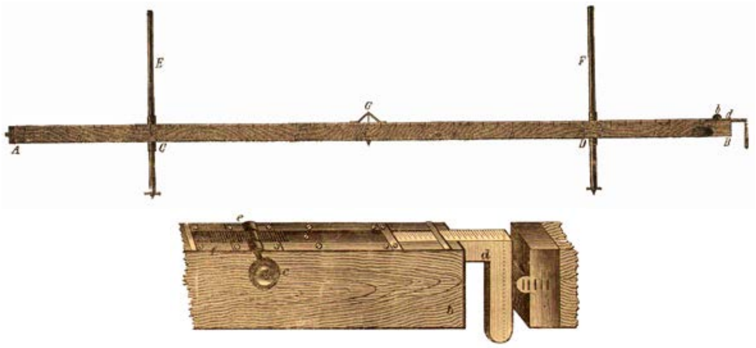

Figure 3: Precise wooden rod and nonius for reading

The main drawback of Jäderin basis apparatus was the same as with previous instruments – a huge temperature coefficient of the material, which requested precise temperature measurement. This problem was overcome in 1896, when J.-René Benoît and Charles Édouard Guillaume (from International Bureau of Weights and Measures) found invar - a nickel (36%) steel (63,5%) alloy, with trails of Manganese (0,4%) i Carbon (0,1%), which is often, due to its content, written as FeNi36. This alloy has uniquely low coefficient of thermal expansion of about 1.2×10^{-6} K^{-1} (1.2 ppm/°C).

Figure 4: Jäderin apparatus

After the invention of invar, the production of precise length measurements based ofn Jäderin apparatus has begun. Some changes were made, specifically in design of the wires and accessories. The radius of the wires remain the same, 1,65 mm. At the ends, there were special rulers with triangle-shaped cross-section, for reading parts of millimetre. The rulers (Fig. 5) were placed near specially designed benchmarks (Fig. 6), placed on stands. They were used for precise centring above the point. The wires were strained by the rollers (Fig. 7). A rope, which was pulled over them, was fixed with one side to the invar wire, while on the other end was fixed to the 10 kg weight.

Figure 5: ruler for reading

Figure 6: Tribrach with benchmark

This tool was the first one that made available precise measurement of the long distances. The accuracy was better than 1 mm/km, while the distances up to several km can be measured. There were two drawbacks: the first is related to the location – the terrain has to be flat, and second – the measured length has to be a multiplication of 24 m, due to the length of the wires themselves.

Figure 7: Tripod for straining wires and cover box

Length measurements with invar-basis rods (Fig. 8) are indirect – an angle is measured, while the distance is calculated. In practice, the instrument and the accessories are called a tool for paralactic polygonometry. The tool consists of a 1“ accurate theodolite, the invar-basis rod, four aiming targets, and four to five tripods. Some tools have a special optical plumb bob (Zeiss). The targets, the theodolite, and the rod have the tribrach for forced centring using the optical plumb bob.

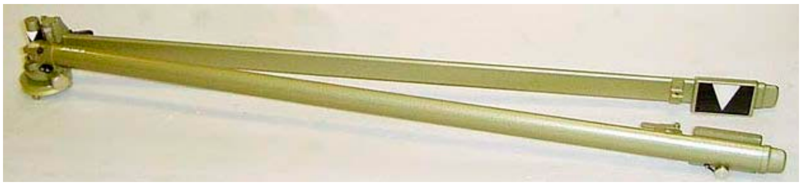

Figure 8: Invar-basis rod Wild (1921)

The lengths are measured indirectly, by the links consisted of the set of the triangles, which are used to obtain the measured distance *d*, from the base length *b*. It means that the measured values are always the angles. Basically, there are tri link types mostly used, and one based on measuring the distances in segments (Fig. 9). Only the distances up to 70 m can be measured with this tool. Increasing the length, the paralactic angle above the rod becomes smaller, which decreases the accuracy of the measured distance. Measuring the angles between the targets on the rod, at the distances shorter than 70 m, one can achieve submillimetre accuracy of the measured distance.

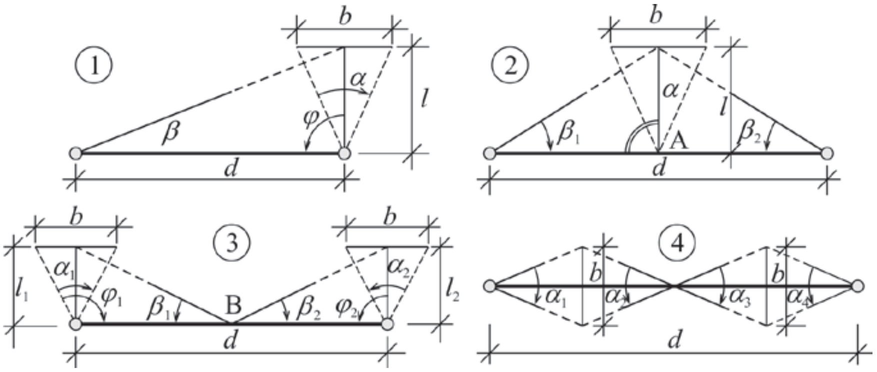

Figure 9: Link types

3. ELECTRONIC DISTANCE MEASUREMENTS

Radio distance meters, which were developed first (Fig. 10), appeared to be not practic and not economic, because two same distance meters should be at both sides of the measured distance – one to send a signal, the other to receive it, amplify it, and send back. The reason was scattering of the radio-waves during their way through the atmosphere. The radio-waves lose their power and only the small amount arrives to the targeting point, so it has to be amplifies in order to send it back to the distance meter that transmitted it.

After the invention of electro-optical distance meters, which use the optical waves for the information carrier, the problem of waves dimming was overcome, so a passive reflector – a prism could be used.

The working principle of electronic (radio and electro-optical) distance meters is based on measuring the time of propagation of an electro-magnetic oscillation. Depending on how the time is measured, there were three types of distance meters:

- Pulse,
- frequency and
- phase.

Beside measuring the time of the signal propagation, other methods of distance measurements and developed. They use:

- light interference,

- electrical quantities,
- Doppler effect, or
- Newton Gravity Law.

Figure 10: Tellurometer MRA1 (1957) – the first radio distance meter

Pulse method

By this method of distance measurement, the distance meter transmitter transmits the high frequency electromagnetic oscillations in the form of very short pulses, which are periodically repeated. During the period between two consecutive pulses, the oscillations propagate to the reflector and back, when they are received by the receiver. The measured length is calculated according to the measured time interval between the start of emitting the pulse, and its receiving after the reflection from the reflector.

Frequency method

This method uses the continuous beaming. Its characteristic is to measure the distance by using dependence of frequency change (frequency modulated oscillations) of the distance. The distance meter transmits the oscillations of the frequency that constantly changes in time. The current frequency of the reflected oscillations received into the receiver depends on the distance between the receiver and the reflector. That frequency is modulated after a predefined rule, which is most often, sinusoidal.

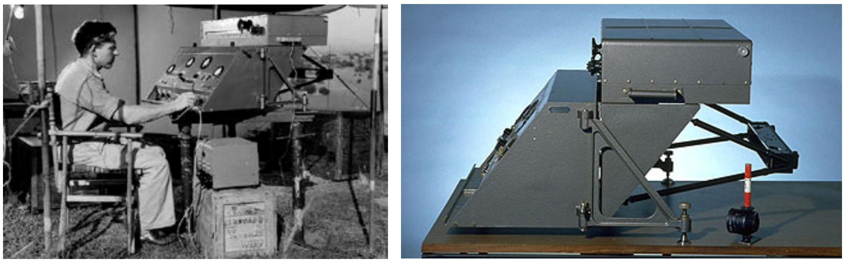

Figure 11: AGA Geodimeter NASM-2A (1959.) – first electro-optical distance meter

Phase method

All phase distance meters (both radio- and electro-optical) share the same principles, although their constructions differ, which makes their theory general. The time interval of signal travel with phase distance meters is measured indirectly.

Figure 12: AGA Geodimeter Model 8 (1968) – laser distance meter

The electromagnetic signal is transmitted and received continually, but its oscillations change periodically, following some rule, for example, the law of harmonic oscillations (sinusoidal). This method introduces a principal issue that is solved indirectly – determination of the integer number of phase differences *N*. There are two types of phase distance meters, according to the method to resolve that issue. The first method is determination of *N* by changing the frequency during the measurement. The second method is measuring by the oscillations onto two different frequencies.

Figure 13: Kern Mekometer ME5000 (1972) – the most accurate distance meter

The accuracy of the radio distance meters was several cm/km. After the improvements in the instrumentation and technology, nowadays it is common to use distance meters with

2 mm + 2 mm/km accuracy. At present, the most accurate electro-optical distance meter is Kern Mekometer ME5000 with nominal accuracy 0,2 mm + 0,2 mm/km (Fig. 13).

3.1. INTERFEROMETRIC DISTANCE MEASUREMENT

The most recent technique of distance measurement is based on light interferometry. Currently, this method is used in surveying only for laboratory measurements (mostly for calibrating levelling rods), due to interferometer measuring range (up to 150 m).

The most known and applied interferometer is Michelson interferometer. It consists of the laser, beam splitter, two mirrors, and a detector (Fig. 14). The first beam travels to the beam splitter where is reflects, goes to the prism which serves as the mirror, returns to the beam splitter and arrives to the detector. The other beam passes through the microscopic glass, reflects from the prism, and come to the beam splitter, where it is reflected to the detector. There, a constructive interference happens, when the paths of two beams differ for one whole wavelength. When the path difference equals to ½ of the wavelength, the destructive interference happen. Application of the interferometers is limited, due to the fact that moving of the mirror should keep the paths of the input and the output beam parallel, which is extremely hard to perform on longer distances.

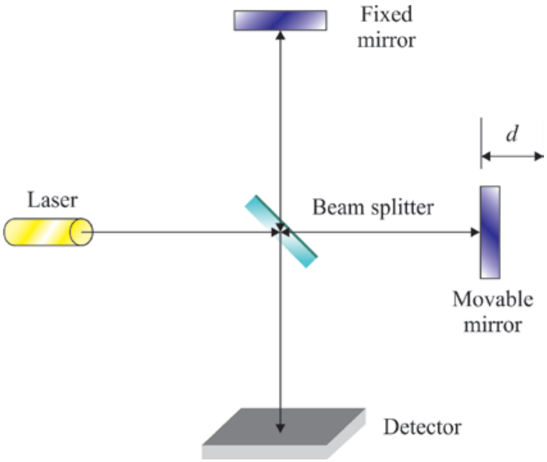

Figure 14: Scheme of the Michelson interferometer

4. CONCLUSIONS AND REMARKS

Precise measurement of the long distances was a huge problem to the surveyors for years. The distances were measured by various means: chains, sticks,... Yet, the appearance of Jäderin basis apparatus and the invar wires increased the accuracy. Thanks to that, based on Snellius paper: *Snellius*-a "*Eratosthenes batavus, de terrae ambitus vera quantitate*", the distances needed for scale definition in the trigonometric networks could be determined indirectly – from the baseline networks. Technology development enabled the construction of radio- and electro-optical distance meters, which could suffice the requirements for the geodetic networks in the sense of accuracy.

However, all distance measurements, despite of the method or technology, have to be performed respecting the metrological support of the instruments and the accessories. If this is not done, the accuracy cannot be guaranteed.

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ИСТОРИЈСКИ ПРЕГЛЕД ПРЕЦИЗНИХ ГЕОДЕТСКИХ МЕРЕЊА ДУЖИНА

Резиме: *Прецизно мерење великих дужина, због дефинисања размере, нарочито у тригонометријским мрежама 1. реда, геодетама је дуго година представлајало проблем. Захваљујући Снеллиус-у и његовим радовима могла је бити измерена нека краћа дужина на равном терену, а затим пренета њена размера угловним мерењима на дужину између две тригонометријске тачке 1. реда. Но, мерење и таквих, краћих, дужина није могло бити извршено са великом тачношћу. Мерења су вршена полугама, дрвеним или металним, али тек је појава инвара и инварских жица омогућила прецизна мерење дужина. Појавом радио и електро-оптичких, а после и ласерских, даљиномера је постало могуће директно прецизно мерење великих дужина.*

Кључне речи: *инварске жице, Једеринов базисни апарат, даљиномер, импулсно, фазно, фреквентно*