Sitzungsberichte der Leibniz-Sozietät der Wissenschaften zu Berlin *119(2014), 75–90*

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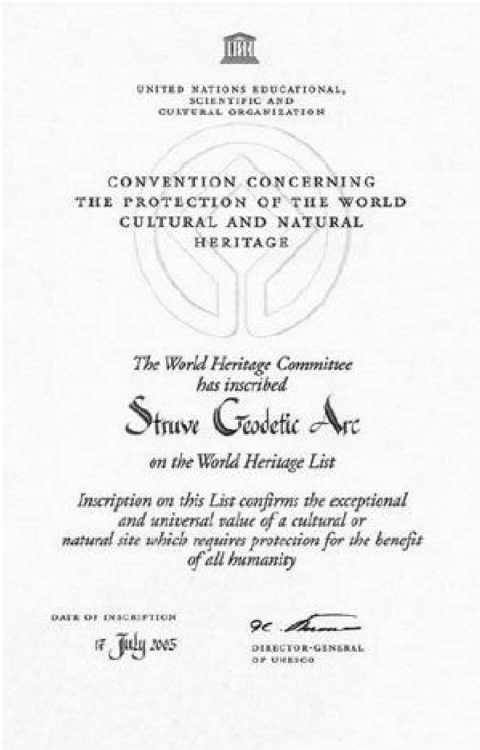
The Russian-Scandinavian Geodetic arc

Abstract. The UNESCO World Heritage List contains about 1,000 names of the world objects – recognized "wonders of the world". Of them, the only geodetic wonder is the Struve Arc known at some time as "the Russian one" and then "the Russian-Scandinavian Meridian Arc". The Struve Arc is the first scientific and technical artifact included in the UNESCO World Heritage List. It is an unusual and very valuable element in the UNESCO World Heritage List. It is written in the resolution of the UNESCO World Heritage Committee that the Struve Geodetic Arc has been included in the list the world heritage as the object of culture of "outstanding universal value" (Resolution No 1187, dated July 15, 2005).

The Struve Arc or the so-called Russian-Scandinavian Arc represents a chain of triangulation points, going from north to south over 2,820 kilometers (which makes 1/14 of the circumference of the Earth) along the 25th meridian of east longitude and is one of the major events of the astronomy, geodesy and geography of the 19th century. Its most northern point is the point of "Fuglenaes" at the coast of the Barents Sea (70 degrees 40 minutes, N), and the most southern one is the point of "Staro-Nekrasovka" at the Black Sea (45 degrees 20 minutes, N).

The triangulation points were established over the period from 1816 to 1855. The work was carried out under the scientific supervision and through personal involvement of the famous Russian astronomer and geodesist of those times – Friedrich Georg Wilhelm (Vasiliy Yakovlevich) Struve, the academician of the St. Petersburg Academy of Sciences, founder and first director of the Pulkovo Observatory.

A military surveyor Charles Friedrich (Karl Ivanovich) Tenner was directly involved in field surveying. Throughout 40 years, employees of V. Ya. Struve and C. F. Tenner as well as their colleagues from Sweden and Norway – surveyors, astronomers, guides, soldiers and fieldwork workers – made measurements in the mountains of Scandinavia, moors of the Belarusian Polesye, flooded areas of the Danube.


UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

CONVENTION CONCERNING THE PROTECTION OF THE WORLD CULTURAL AND NATURAL HERITAGE

The World Heritage Committee has inscribed

Struve Geodetic Arc

on the World Heritage List

Inscription on this List confirms the exceptional and universal value of a cultural or natural site which requires protection for the benefit of all humanity

DATE OF INSCRIPTION

17 July 2005

DIRECTOR-GENERAL OF UNESCO

Figure 1

From the results of the measurements made and after finishing all his calculations, Struve wrote the big work – "The 25°20' Meridian Arc between the Danube and the Arctic Ocean, Measured between 1816 and 1855". Thus, the first authentic measurement of a big segment of the terrestrial meridian arc was performed, which allowed the shape and size of the Earth to be determined. Among the world astronomic and surveying activities of the 19^{th} century, the arc has taken a leading place thanks to its accuracy and extent. F.W. Bessel, while defining the elements of the terrestrial ellipsoid, also used the results of the measurements of the Russian-Scandinavian Arc. The results played an important role in development of scientific investigations into both

the figure of the Earth and practical improvement of Russian and European coordinate networks. The findings of the trigonometric survey performed were applied to adjustment of astronomic-and-geodetic networks for about 130 years, from 1840 until the end of the 1960's.

The Struve Geodetic Arc (Russian-Scandinavian Geodetic Arc) is the international artifact extending nowadays across the territory of ten countries (Norway, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Byelorussia, Ukraine, and Moldova).
Keywords: Struve Geodetic Arc (Russian-Scandinavian Geodetic Arc).

1. Introduction

The Russian-Scandinavian Arc or, as it is called, the Struve Geodetic Arc (SGA) belongs to a number of historical grade meridian measurements made along in the 19th century and represents a number of triangulation points, stretching from North to South along near the 25th meridian of east longitude. The goal of measuring the SGA and similar grade measurements was to specify the figure and dimensions of the Earth, which required extensive grade measurements. The total length of the arc is equal to 2821.833 km, it is 25 degrees 20 minutes 18 seconds (1/14 part of the circumference of the Earth). SGA consisted of 265 triangulation measurement points that formed 258 triangulation triangles. Thirteen points of 265 were astronomic-geodetic ones, there were defined astronomical latitudes and azimuths in them. Besides, 10 basis sides were also measured. Moreover, 60 auxiliary point were made while making the measuring. The first work was started in 1816, it lasting for almost 40 years until 1855. Then it took more than two years to process the measurement results and another three years to prepare the first two volumes of them for publication. It should be noted that the Anglo-French Arc (22 degrees 9 minutes 44 seconds) and Great Arc of Meridian of India (23 degrees 49 minutes 24 seconds) have comparable lengths, but it took much longer time to measure them. E.g., it took the Great Arc of Meridian of India 72 years to be measured, and the Anglo-French one – 62 years.

The results of this Herculean job were stated in the work "Arc du Méridien de 25° 20' entre le Danube et la Mer Glaciale, mesure depuis 1816 jusqu'en 1855", sous la direction de C. de Tenner, Christopher Hansteen, N. H. Selander, F. G. W. Struve. Ouvrage composé sur les différents materiaux et redige par F. St. Petersbourg: Academie Imperiale. 1857(t.I)-1860(t.II), 970 p. +47 plates. This work was dedicated to his Majesty Alexander II, Tsar of Russia and Charles XV, King of Norway and Sweden [1].

Figure 2

In the 19th century, at the time of its creation, the Arc ran through the territories of two States – the Russian Empire and the Union between Sweden and Norway – that was why its original name was the Russian-Scandinavian one. Later, due to the prominent services of Russian scientist, astronomer, and surveyor V. Ya. Struve to the supervision of the measuring and subsequent processing of the results, the Arc came to be called the Struve Arc. Now, the Struve geodetic arc crosses the territory of 10 States (Norway, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Byelorussia, Ukraine, and Moldova).

In 2005, 34 preserved points of "the Arc of the Meridian at 25°20' " were declared the object of cultural heritage of "outstanding universal value" (Resolution No 1187, dated July 15, 2005) and included in the UNESCO List of World Heritage Sites under the name of "the Struve Arc". In the UNESCO documents, it is noted the important role of the international cooperation of scientists, surveyors, measuring instrument makers, and public figures of many countries that was played in carrying out the Struve Arc measuring.

2. Geographical and historical division of the Struve Arc into parts

There is a geographical and historical division of the Struve Arc into parts. Division into two geographical arcs (the South arc and the North one):

- *the South arc* originates from the point of "Staro-Nekrasovka" in Ukraine near Ismail at 45 degrees 20 minutes N, 26 degrees 45 minutes E and ends on Hogland Island (point "Maki-paalys" at 60 degrees 4 minutes N, 26 degrees 58 minutes E) in the Gulf of Finland (Russia). The total length of the arc is 14 degrees 44 minutes;
- *the Northern arc* originates from point "Maki-paalys" at 60 degrees 4 minutes N, 26 degrees 58 minutes E and ends in point "Fuglenaes" (70 degrees 40 minutes N, 23 degrees 40 minutes E) near Hammerfest at Cape Nordkapp in Norway. The total length of the arc is 10 degrees 36 minutes. As at the moment of its creation, the Struve Geodetic Arc ran through the territories of two States – the Russian Empire and the Union between Sweden and Norway – they also point out
- *the Russian arc.* It has a length of 20 degrees 30 minutes and is located between latitudes 45 degrees 20 minutes N (the southernmost point on the Danube – point "Staro-Nekrasovka") and point "Tornea" in the town of Torneo in Finland (formerly, the garrison town of the Russian Empire "Tornea") with a latitude 65 degrees 50 minutes N;
- *the Scandinavian arc.* This arc has a length of 4 degrees 50 minutes and is located between latitudes of 65 degrees 50 minutes N and 70 degrees 40 minutes N (between point "Tornea" and point "Fuglenaes").

3. Who was involved with the Struve Geodetic arc?

The Russian arc

The experience of the war between Russia and Napoleonic France clearly confirmed the need for an early and detailed topographic study of border regions that could become a new theatre of war. Therefore, in 1816, the Main Headquarters of the Russian army set a task "to cover Western Russia with a continuous triangulation network and then survey it in as many details as possible" [2] with the purpose of preparing the territory for defense.

The work on the first determination of the Meridian arc length in Russia started on the initiative of two outstanding surveyors – the famous astronomer and surveyor Friedrich Georg Wilhelm (Vasiliy Yakovlevich) Struve (15.04.1793-23.11.1864) and the outstanding military surveyor Charles Friedrich (Karl Ivanovich) Tenner (22.06.1783-28.12.1859).

Figure 3: Friedrich Georg Wilhelm Struwe (Vassili Yakovlevich)

In 1816, they began work on laying out a triangulation chain in the Vilnius province, Russia. The military surveyor C. F. Tenner supervised the work [3]. He personally took part in the reconnaissance activity of points, establishing monuments, performing angular measurements, preparing and measuring basis lines, as well as in astronomical definitions.

Around the same time, in the Baltic provinces of Russia, grade meridian arc measurements were headed by the famous astronomer V. Ya. Struve. In 1830, the triangulation chains of C. F. Tenner and V. Ya. Struve were joined together, they forming a grade measurement of an 8 degree meridian arc. Then measurements were extended north- and southward.

Figure 4: Charles Friedrich (Karl Ivanowich) Tenner

V. Ya. Struve headed the activities in the Northern direction. In large, measurements were taken between the Zapadnaya Dvina River and Torneo under his direct supervision, the total length was about 9 degrees 20 minutes, there were laid 100 first-order triangles and measured 3 base lines [4].

The Southern direction arc was measured under the leadership of C. F. Tenner, it having a total length of 11 degrees 10 minutes, from the Danube River (point “Staro-Nekrasovka”) to the Zapadnaya Dvina River. There were laid 125 first-order triangles and measured five base lines (the Tashbunar, Romankautsky, Staro-Konstantinovsky, Osovnitsky, and Ponedel’sky ones) and defined 6 astronomical points (Ismail, Vadullui, Suprunkivtsi, Kremenets, Belin, Nemezh).

The Scandinavian arc

Work on the Scandinavian arc was performed, with an approval of King Oscar I of Sweden and Norway, by joint efforts of Swedish and Norwegian surveyors with the assistance of astronomers of the Pulkovo Observatory.

Under the leadership of Swedish astronomer Nils Hagvin Selander (20.03.1804-18.06.1870), Director of the Stockholm Observatory and with his direct participation, there was measured a part of the Scandinavian arc from "Tornea" to "Baljatz-vaara" with a length of 3 degrees 13 minutes. Along this arc there were laid out 21 first-order triangles, measured 1 base line and defined one astronomical point.

The meridian arc measurements in the Norwegian territory were conducted under the guidance of Director of the Oslo Observatory and Chief of Geographic Services in Norway Christopher Hansteen (26.09.1784-15.04.1873). Under his leadership there was measured the northernmost part of the arc from point" Baljatz-vaara" to point "Fuglenaes", its length being 1 degree 37 minutes. Along this part of the arc there were laid out 12 first-order triangles, measured 1 base line and defined the latitude and azimuth at point "Fuglenaes" (astronomical definitions were performed by V.YA. Struve himself). Nils H. Selander and Christopher Hansteen as well as C. F. Tenner were co-authors of V. YA. Struve's report that he presented at a meeting of the Paris Academy of Sciences on October 12, 1857.

Immediately after the completion of field measurements, due to a high scientific importance and a great amount of labor required, memorial obelisks with a text on cast-iron plaques were erected at the Northern ("Fuglenaes") and Southern ("Staro-Nekrasovka") ends of the arc. The inscription on the obelisk in the village of Staraya Nekrasovka says: "*The Southern end of the Meridian arc at* 25°20' *from the Danube River to the Arctic Ocean, through Russia, Norway, and Sweden, by the Order of August Monarchs of Emperors Alexander I, Nicholas I, and King Oscar I. Surveyors of the three peoples worked continuously from 1816 until 1852 to measure it. Latitude* 45°20'28"". At the Northern end, in Hammerfest town, the following text in Latin and Swedish is inscribed: "*The Northern end of the Meridian arc measured from the Arctic Ocean to the Danube River, through Norway, Sweden, and Russia, by Imperial order and maintenance of August King Oscar I and August Monarchs Emperors Alexander I and Nicholas I ; performed by continuous work of astronomers of three generations from 1816 until 1852. Latitude* 70°40'11.3"".

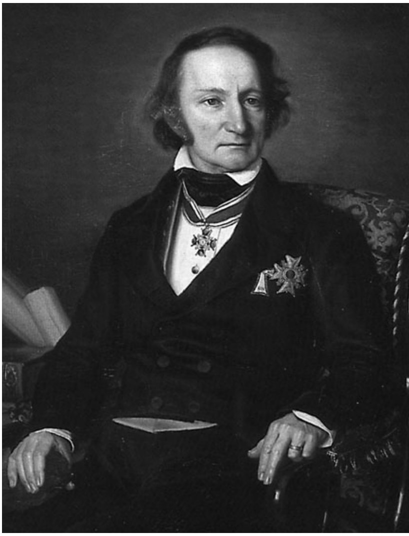


Figure 5a: Christopher Hansteen

Figure 5b: Nils Hagvin Selander

4. Point on Hogland Island

Only two points of all the points of the Struve Arc are currently situated in the territory of Russia due to a number of geopolitical transformations: one is the original point of the Struve Arc – point "Maki-paalys" and the other one is an auxiliary point – "Point Z". Both are in good conditions and situated on Hogland Island, in the Gulf of Finland in the eastern Baltic Sea, about 180 km west of Saint Petersburg and 35 km from the coast of Finland (near Kotka). Hogland has an area of approximately 21 km^2 (8.1 sq mi); its highest point is 173 m (568 ft). It is part of Russian's Leningrad Oblast. Point "Maki-paalys" plays a special role in the Struve Arc. Thanks to its insular situation, it made it possible to link two continental parts of the Arc, separated by a large water body. Astronomic-geodetic work was conducted on Hogland Island in 1826-27, 1833, and 1843 and described by V. Ya. Struve in his reports in 1831[5] and 1861 [6]. It took a lot of time to do work on the island because the physical geographical factors of the island were very difficult, with very limited visibility to conduct astronomical and geodetic observations. Therefore, V. Ya. Struve established an astronomic-geodetic point on the island as a network of points, two of them being the main ones, and ten were auxiliary ones.

Figure 6: Astronomical point "Z" on Gogland Island in the Gulf of Finland

V. Ya. Struve chose the location of one of the main points on the top of Mountain Maki-paalys, where a metal rod of 23 mm in diameter was set in the rock surface using lead filler. Nevertheless, it was impossible to set the instrument at this point. Therefore, to conduct astronomic-geodetic work, there was chosen another point, about 1.4 km northward off this mountain, it being linked with point "Maki-paalys". And although it was an auxiliary point, however, it was also included in the final report of Struve under the name "Point Z". V. Ya. Struve used ten auxiliary points. Four of them were various objects on the ground – a beacon, a light-keeper's house, a church, and the bell tower next to it; two points were the ends of a 250-meter base line, its length was measured with a bar; another three points were specially built wooden towers, without any permanent monuments as centers; a tenth point was the center of the universal instrument set not far from point "Maki-paalys". Throughout 1998 – 2000 period, an expedition arranged by the Russian Geographical Society found and restored five of the twelve points. In 2000, at "Point Z" a DKM theodolite was used to measure the latitude of the point by the Talcott method, its value was $60^0 05' 10.4'' \pm 0.1''$ [7,8]. For comparison, the latitude of the point obtained by Struve in 1826 was $60^0 05' 09.8'' \pm 0.1''$. The measurements were made with an J. Dollond's astronomical transit in the first vertical, by the Bessel-Struve method. The instrument had a 2.6-meter telescope, its horizontal axle resting on two pillars – massive brick pillars built at a distance of one meter from each other in a North-South direction (the telescope rotated in the plane of the first vertical). A pendulum clock and barometer were located on a small "clock" column. To determine the latitude they also used two identical Reichenbach-Ertel vertical circles which were set on massive tripods 48 meters away from the main instrument and aligned along one meridian.

Figure 7: Geodetic point "Maki-paalys" on Gogland Island in the Gulf of Finland

5. The instruments used

While performing grade measurements on the Northern part of the Arc, V. Ya. Struve applied a theodolite made by G. Reichenbach from Munich, it was equipped with a 13-inch horizontal circle and an 11- inch vertical one, which were divided into 5 min – divisions, and readings were taken with a vernier to an accuracy of up to 4 sec.

On the Southern arc, C.F. Tenner had at his disposal 7 instruments by different manufacturers. They were: two repeating circles, one of them was a 13-inch circle made by Baumann of Stuttgart and reading with a vernier scale 4 sec, the other one was a 14.3-inch circle by Troughton, a British instrument maker, vernier 10 sec; a repetition theodolite by Reichenbach of diameter 12 inches, vernier 4 sec; an 8-inch Ertel astronomical theodolite, vernier 10 sec; a repetition theodolite with a 10-inch circle manufactured by État-Major, vernier 5 sec; besides, an universal instrument of T.E. Ertel and a 12-inch Ertel theodolite. The first two of them gave the opportunity to measure vertical angles; Tenner and Struve measured horizontal angles with the help of the rest of them.

To measure base lines they applied base-line apparatuses with three different units of length – two French: ones *toise* (approximately equal to 1.95 m) and *metre* ("decree", "archive"), and a Russian *sagene* (approximately equal to 2.13 m). There were manufactured standards of the units to calibrate the working tools to be applied to field measurements. The sagene (Russian origin and of a local length) was used to expressed each linear value of all Russian triangulations in the 19th century. C. F. Tenner himself made twice the normal measure (physical length standard) of the sagene: the first "sagene № 1" and the second "sagene № 10" or the Tenner's sagene. The toise value and that of the sagene were applied to "sagene No1" at 14 degrees Réaumur (1 °C = 0.8 °R). When applying divisions of "sagene № 1" to "sagene № 10" C. F. Tenner used the Ramsden's lever divider. Three of the ten base lines of the arc were measured in sagenes.

V. Ya. Struve had the iron standard etalon "F", which was a copy of the Peruvian toise. This bar was made by J. Fortin in Paris. In 1821, French scientist and surveyor J.F.D. Arago certified this bar for V. Ya. Struve by comparing it with the Peruvian toise. In 1827, in Dorpat, by the order of V. Ya. Struve there was made a new normal measure of a double length – "double toise N" equal to two J. Fortin's standard etalons. The design of this base-line apparatus was invented by V. Ya. Struve himself. Seven base lines were determined with the help of working measures that were copies of the "double toise N". To bring the measurements to one unit of length V. Ya. Struve and C. F. Tenner calculated conversion factors: 1 toise = 1.949052 m, 1 toise = 0.9135152 sagene [1].

6. Development of measurement methods and improvement of the equipment

The work of C. F. Tenner and V. Ya. Struve played a great role in the development of the theory of geodesy and methods of geodetic engineering. V. Ya. Struve personally analyzed the results of field measurements. In the first half of the 19th century, triangulation used the method of repetitions while measuring angles. The method contained systematic errors and was very time consuming. V. Ya. Struve counted that 8674 repetitions were performed while determining 174 angles of the Lithuanian arc of the Meridian, i.e., 50 repetitions per an average angle measured. In some cases, to measure one angle it was performed up to 100 repetitions. In 1823, V. Ya. Struve offered his own measuring method called the "method of direction observations". While introducing this method, C. F. Tenner and Friedrich Theodor Schubert (Fedor F. Schubert) introduced the procedure for closing the horizon. Struve's improved closing the horizon method was widely used and since 1889, it has become known as the method of rounds. This method allows angles in the 1^{st} – order triangulation to be measured by 6-12 observations. Besides, V. Ya. Struve studied the influence of refraction on the results of angular measurements, created a precision base-line apparatus for measuring baselines to an accuracy of 1:1 000 000, which was used in Russia till the 20th century. The Struve's base-line apparatus included 4 bars, each of 2 toises in length. The temperature of each of the bars was measured by 2 mercury thermometers. At their ends, the bars were provided with special devices that permitted two neighboring bars to make a touch without a slightest shock. This apparatus was applied to measure all important base lines in Russia. For a detailed description, one can resort to V. Ya. Struve's writing [1].

C. F. Tenner was the first who introduced the division of triangulation into orders and set out the scientific principles of its establishment. This marked the beginning of the implication of the principle "from the general to the special", that became mandatory in the organization of all topographic and geodetic activities in Russia. He designed one type of base-line apparatuses that allowed base lines to be measured to an accuracy of 1:300 000. The Tenner base-line apparatus was used to define the Ponedel'sky (1820), Osovnitsky (1827) and Staro-Konstantinovsky (1838) base lines.

In the early 19th century, barometric leveling was mainly used to determine the elevation of ground points. Barometric leveling, quite simple for these measurements, could not provide the required accuracy. Therefore, C. F. Tenner, beginning with his first observations, started the application of trigonometric leveling that although more time consuming provided him with a fairly high accuracy. From processing the results of trigonometric leveling, it was established for the first time ever that the difference in the levels of the Baltic and Black seas was equal to 0.53 sagenes (1.13 m).

To increase the accuracy of astronomo-geodetic observations, C. F. Tenner and V. Ya. Struve introduced verification telescopes that were used only for Russian measurements because of the landscape features. V. Ya. Struve performed an accuracy assessment of the angular measurements of the Lithuanian arc. The studies showed that the mean squared error of a horizontal angle was equal to 0.99 sec, the average error was 0.995 sec, and the probable one equaled – 0.672 sec.

Due to the fact that the terrain where the southern part of the Russian arc was laid was swampy and forested, triangulation chains could be established only with construction of high signal towers and pyramids. C. F. Tenner designed simple towers (up to 10 meters high) and complex signal towers (of a height up to 50 meters). It was necessary to determine carefully the position of the instrument center relative to the projections of the tops of the signal towers and pyramids when observing from towers. Therefore, C. F. Tenner developed a methodology for determining the position of the instrument center relative to the projections of the tops of the signal towers and pyramids. Considering a possible loss of the tower or its top shifting from the initial position over time, C. F. Tenner fixed tower top projections not only on the ground surface but also in some depth in the ground by stone foundations.

Until 1816, triangulation points in Russia were fixed by temporary benchmarks as they were used only in surveying. C. F. Tenner was the first who placed the centers of all signal towers in solid stone foundations along the Russian part of the Arc from the Dvina River to the Danube. This approach to secure the centers and the accuracy of measurements executed made it possible to use the C. F. Tenner chains when establishing new triangular chains in 1910-1916, and later in 1926.

It should also be noted that, despite the very difficult terrain where they had to establish the Southern part of the Russian arc, C. F. Tenner managed to build amazingly correct equilateral triangles.

The triangulation chain of the Northern part of the Russian arc passed through the area not requiring any high signal towers, that was why only small wooden signal pyramids were constructed. V. Ya. Struve as a Head of the work believed that the pyramids would stand quite long and the preservation of the pyramid centers would not be important. However, the pyramids did not last long, which reduced the value of the Struve triangulation chain and did not allow it to be used in the future.

7. Conclusion

The measuring of the Struve Arc is one of the most important events in the development of astronomy, geodesy, and cartography. The measurement data played an essential role in developing correct ideas about the figure of the Earth.

The measurement results were used by C.F. Gauss for specification of cartographic projections. Partial or complete results of the Russian-Scandinavian arc measurement were used by many scientists in their works on determining the figure of the Earth, including Airy (1830), Everest (1830,1847), Schmidt (1831), Bessel (1834,1837,1841), Paucker (1853), Struve (1854), Clarke(1856, 1858, 1860, 1866, 1878,1880), Schubert (1859, 1860, 1861), Pratt (1863, 1871), Villarceau (1866), Ph. Fischer (1868), Zhdanov (1892), Krasovsky (1901, 1936), Helmert (1906, 1913), Heiskanen (1926, 1929), Izotov (1940), and others.

The Struve Arc is an important evidence of the interaction between scientists of different countries, as well as the cooperation of rulers and monarchs in the name of scientific purposes.

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