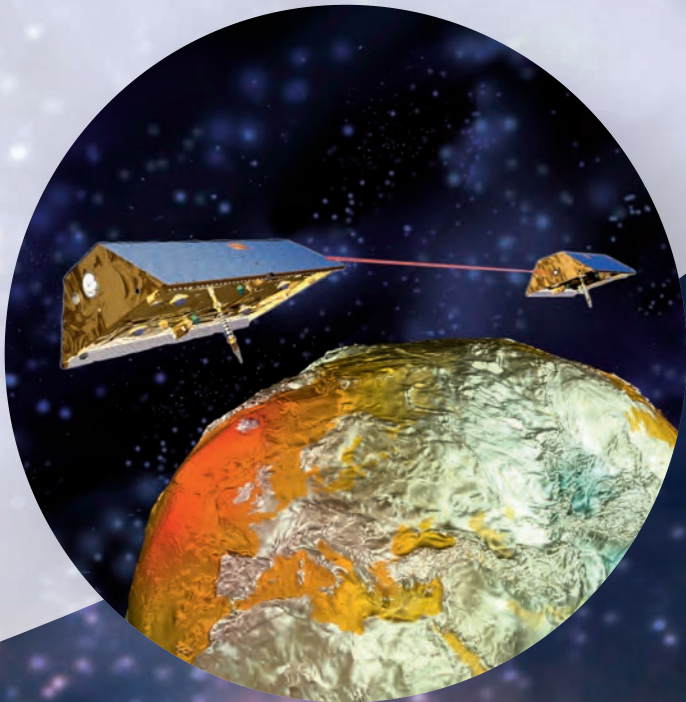
From Pendulum Measurements to the GRACE-Mission

On the history of geodesy on Telegrafenberg Hill in Potsdam

Exhibition on the occasion of the 150th anniversery of the foundation of the „Central European Arc Measurement", forerunner of today's International Association of Geodesy (IAG).



Retrospection on performed works and scientific results of the Geodetic Institute of Potsdam

Booklet for the Exhibition

IAG 150 years

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Topic 1: History of the Institute

Baeyer's idea of a joint arc measurement

In 1857, Lieutenant-General Johann Jakob Baeyer (1794 – 1885) retired from active service as Head of the Trigonometric Department of the Prussian General Staff at the age of 63. Having been put at the disposal (in service) of the Prussian King Friedrich Wilhelm IV (1795-1861) with his previous salary, he dedicated himself to scientific matters. In 1831 to 1834, J.J. Baeyer had already performed arc measurement activities in East Prussia with Friedrich Wilhelm Bessel (1784-1846), Professor of Astronomy and Director of the observatory in Königsberg. Additional surveys in which he participated as a General Staff Officer were: 1837-1842 Baltic Sea coastal survey, 1835 trigonometric astrogeodetic levelling between Swinoujscie and Berlin, 1846/1847 baseline measurements near Berlin and Bonn, 1849 trigonometric astrogeodetic levelling between Berlin-Brocken-Inselsberg. In order to precisely determine the size and shape of the Earth, he submitted his plan to the Prussian Defence Ministry in the memorandum, "Draft on a Central European Arc Measurement", in April 1861. Already on 20 Jun 1861, the King of Prussia Wilhelm I (1797-1888) issued a cabinet order to realise Baeyer's plan "to establish a Central European arc measurement by linking the geodetic measurements in those countries which lie between the same meridians as Germany". Still in the same year, J.J. Baeyer published his detailed, scientifically justified paper "Über die Größe und Figur der Erde. Eine Denkschrift zur Begründung einer mitteleuropäischen Gradmessung" [About the size and shape of the Earth. A memorandum on the justification for a Central European arc measurement], in which he analysed the status at that time in the field of arc measurement and presented the possibilities for continuing the activities. The aim of this was to homogenise and link the national triangulations, compare these results with geodetic-astronomical gravity measurements and investigate the structures of the geoid in this manner.

Formation of the joint arc measurement and the institute

From 24 to 26 April 1862, the founding conference on the Central European arc measurement was held in Berlin. As the Commissioner of the Royal Prussian government, J.J. Baeyer received the government representatives from Austria and Saxony, in order to conduct preliminary discussions on the introduction to the activities for a Central European arc measurement. The goal was consciously pursued of integrating additional countries as soon as possible. At the first General Conference of the Central European Arc Measurement from 15 to 22 October 1864 in Berlin, authorised representatives from 13 countries participated. As the implementing body, a resolution was passed on a central bureau and J.J. Bayer Lieutenant-General in service was elected as President of the central bureau. After funds were provided by the Prussian government in 1866, the central bureau, which was also responsible for contributing the share of activities related to Prussia, was established. In 1867, the second General Conference was held in Berlin with 3 additional European countries, as a conference on the European arc measurement. Due to the high workload in the central bureau with the growing number of participant countries, J.J. Baeyer already applied to the Prussian government for the founding of a scientific institute during this time. This was approved in 1869. With effect from 1 January 1870, the founding of the Royal Prussian Geodetic Institute was completed with its domicile in Berlin and J.J. Baeyer was appointed as its President. The institute was originally housed in private buildings in Lützowstraße 42 and from October 1886, in Genthiner Straße 34.

Due to the limited space in the premises, the construction of a dedicated laboratory was already planned from 1875, but this failed due to a lack of suitable building space in Berlin. The Scientific Advisory Board of the institute (Ch. A. F. Peters, F. R. Helmert, A. Auwers, L. Kronecker, W. Siemens and H. Bruns) therefore made the suggestion in 1878 to build a new institute building on land on the Telegrafenberg near Potsdam, where the main building of the Potsdam Astrophysical Observatory was under construction. But J.J. Baeyer rejected this, “as the institute would enter into scientific isolation at this site far away from Berlin”.

In September 1885, Lieutenant General in service J.J. Baeyer died at the age of 91. From 1 January 1886, Prof. Dr. Friedrich Robert Helmert (1853-1917) took over Baeyer’s functions as Director of the Geodetic Institute and the Central Bureau of International Geodesy. Soon after taking office, he succeeded in putting the construction project for a new main building with a Geodetic-Astronomical Observatory on the Telegrafenberg near Potsdam into motion. On 3 June 1886, the construction site was specified at the location. The building plans that had been drafted by the architect and Senior Construction Director, Paul Emmanuel Spieker (1826-1896) according to suggestions by Helmert, were consulted on in the Prussian Ministry of Culture on 29 September 1886. At the 8th General Conference of International Geodesy at the end of October 1886, F.R. Helmert received support for the plan to relocate the Geodetic Institute outside of Berlin and create sufficient and technically appropriate working conditions with new buildings. After the Prussian Ministry of Finance approved the plans and opinions were available from the President of the Physical-Technical State Institute, Herrmann von Helmholtz (1821-1894), as well as Wilhelm Julius Foerster (1832-1921) and Arthur Auwers (1838-1915) , the project was submitted to the Prussian state parliament for approval in spring of 1888. During the years from 1889 to 1892, the main building of the Geodetic Institute Potsdam (A17) was built on the Telegrafenberg. The associated Geodetic-Astronomical Observatory with observation buildings for the determination of latitudes and time and the tower for angle measurements (now: Helmert Tower, A7) was built from 1892 to 1893. In 1891/1892, the Geodetic Institute and the Central Bureau for International Geodesy relocated from Berlin to Potsdam.

The major scientific results of the institute

Today's accepted definition of geodesy harks back to the statements of Helmert and Bruns, where Helmert describes geodesy as "... the science of surveying and mapping the Earth's surface" (Helmert 1880) and Bruns stated that "... the problem of scientific geodesy is to determine the function of the Earth’s forces "(Bruns 1878), with which the gravity field is meant.

The founding of the IAG and the Geodetic Institute, based on Baeyer’s idea of linking the arc measurement, very soon proved to be fruitful for the scientific field of geodesy. The following summary lists the major results of the first six decades:

- The second General Conference in 1867 had the effect of governments uniformly introducing the metre as the unit of length and an international institution being established for measures and weights.

- The authority of the arc measurement organisation at the Meridian Conference of 1883 was the driving force that chose the Greenwich meridian as the zero meridian.
- Prolonged height measurements were performed, national normal height points were established and the sea level heights were introduced.
- The triangulations of the participating countries were widely homogenised, their accuracy was improved and connected. From 1870 to 1950, the central point of the German main triangulation network was the Berlin / Rauenberg point. In 1950, the European date ED50 was introduced with Potsdam / Helmertturm as a central point.
- The terms “Helmert transformation” for a method of converting coordinates of a point from one coordinate system to another and “Helmert ellipsoid” for the earth's shape, which was already very accurately described by him in 1906, are the central mathematical applications in geodesy.
- The impact of Louis Krüger on the standardisation of the coordinate systems in Central Europe is immortalised in the definition of the Gauss-Krüger projection. Krüger’s continuation of the basic ideas of Gauss led to the mapping rule of the curved surface of the earth on maps, which was named after both of them.
- Close-meshed gravity measurements at various locations were conducted and provided good information about the Earth's gravity field and its anomalies.
- Close-meshed deflections of the plumb line (direction of gravity effect) were determined, so that Baeyer’s goal of being able to conclude the geoid shape was achieved on a large scale.
- Gravity measurements were performed on oceans successfully for the first time.
- Success was achieved in a very accurate measurement of the absolute value of the gravity (Kühnen and Furtwängler 1898 -1904) of 981.274 cm/s² in Potsdam. A measurement pillar of the Geodetic Institute subsequently became the world-gravity reference point in 1909. The "Potsdam Gravity System" served as the world reference system until 1971. Repeated measurements of that type, conducted in the years from 1968 to 1970, were the most accurate pendulum measurements ever performed. They have corrected the systematic error of the origin measurement and resulted in $g = 981.2601$ cm/s².
- Regular water level observations were carried out on coasts.
- Periodic variations of the pole height (geographic latitude) were discovered as a reflection of Earth´s axis movements in the Earth’s body. An International Latitude Service was subsequently established in 1899. Its central office was initially located in the Geodetic Institute in Potsdam. The service still exists today - modernised of course – as the International Earth Rotation and Reference System Service (IERS) in Paris.
- In the measuring chamber of the deep well on Telegrafenberg, the first proof worldwide on the effect of tides on mainland was achieved by measurements of the variations in direction of gravity (O. Hecker) and gravity intensity (W. Schweydar).

Topic 2: Basis measurements, magnification networks and triangulations

Introduction

At the beginning of the 19th century, national triangulations were performed in order to use them as a basis for property tax land registers and topographical maps. A **triangulation** covers an area with a triangulation network. In order to determine the scale, a precisely measured i is used. In 1822, Friedrich Magnus Schwerd (1792-1871) published the important finding that it is purposeful to transfer a small measured baseline to a main side of a triangle with a **basis magnification network**. In 1829, the Russian government, at the instruction of General Carl Friedrich von Tenner (1783-1859) requested the Prussian government for an arc measurement in East Prussia to link Prussian and Russian triangulation chains. The Prussian government was prepared to do this and appointed the Director of the Königsberg Observatory, Friedrich Wilhelm Bessel (1784-1846), to perform this task, with the involvement of Johann Jacob Baeyer. From 1832-1836, the geodetic and astronomical activities were performed and their results were published in the 452-page publication, ***Arc Measurement in East Prussia*.** This work served as a template for arc measurements for many decades.

The measured **triangulation chain** includes 17 stations and the links in the west to the Trunz – Wildenhof line (Tenner Survey) and in the east at Memel - Lepaizi and Lepaizi – Algeberg (Struve Survey) and a link to the Königsberg Observatory. Furthermore, a **baseline** was investigated, which lies in the corridor between the villages of Mednicken and Trenk. The measurement took place with the **Bessel basis apparatus**, twice in each of 2 sub-sections. Length: 935 toises = 1,822.35 m; mean error of a measurement of 1 km in length: ±2.2 mm. The baseline was used to derive the main side of the Galtgarben - Condehnen triangle using the measured basis magnification network.

Measurements using the Bessel basis apparatus

The basis apparatus designed by Bessel in 1830 for the East Prussian arc measurement is comprised of 4 measuring rods with a length of 2 toises (1 toise = 1.949 m). Each measuring rod is an iron rod with a slightly shorter strip of zinc attached to it, which is screwed and soldered onto the rod. The ends of the rods have steel blades. In order to measure the slope of the rod positions, tube spirit levels are used with tilt screws. The measuring rods are mounted on a strong support bar using rollers, in protective boxes made of wood. Only the cutting ends and the spirit level screw protrude from the boxes. With the baseline measurements, the rods are not placed so that they are flush, but on a small void. This is measured with a glass-ground measuring wedge that is approximately 10 cm long. In order to record changes to the length of the measuring rod due to temperature changes, the distances between a blade of the free zinc strip end and a blade on the iron rod (metal thermometer) are measured using a measuring wedge and accordingly taken into account.

Preliminary work for the measurement includes investigating the baseline, a preliminary measurement to define the points for the baseline stands and the erection of so-called alignment gallows for introducing the measuring rods. Around 15 trained observers and 50 assistants were required for performing the basis measurement. The measurement for a position of 4 rods (15.6 m) took around 4 minutes. The following readings needed to be taken: Wedge readings for the rod intervals, readings from the spirit levels and wedge readings from the metal thermometer. For each rod, a precise measurement comparison was necessary, as well as deriving an equation with the relationship between the measurement value and metal thermometer data. With these equations, the individual rod lengths were calculated for each position, reduced according to the spirit level readings on the horizontal, summed up and the wedge readings for the rod intervals were added. The baseline length that was obtained in this way was then also projected to the sea-level surface.

Measurements of baselines, Basismessungen, performed with Bessel´s apparatus

Zeit	Location of baseline	Length of baseline	Mean error at 1 km
1834	Königsberg	1,822 km (935 Toisen)	±2,2 mm
1838	Kopenhagen (Dänemark)		
1840	Upsala (Schweden)		
1846	Berlin	2,337 km (1199 Toisen)	±1,6 mm
1847	Bonn	2,134 km (1095 Toisen)	±1,8 mm
1851	Lommel (Belgien)		
1853	Ostende (Belgien)		
1854	Strehlen bei Breslau	2,763 km (1417 Toisen)	±2,3 mm

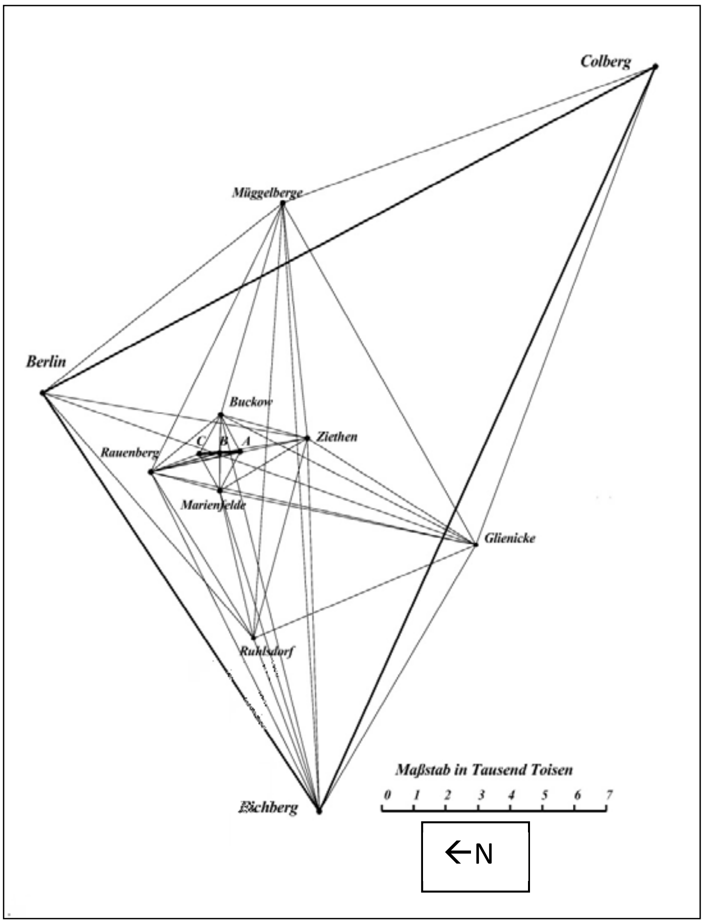
The measurements were conducted in Prussia under the auspices of J.J. Baeyer. The apparatus was also lent out abroad.

Basis measurement and basis magnification network Berlin 1846

The selection for the location of the baseline was the Chaussee of Berlin to Zossen between Mariendorf and Lichtenrade. The baseline of 1199 toises (2,337 km) was measured using the Bessel baseline apparatus in 4 sub-sections that were each measured twice, where the mean error of a measurement of 1 km in length resulted in ±1.6 mm. The basis magnification network Berlin 1846 is shown in the picture. As can be seen, the Buckow - Marienfeld side, then the Rauenberg – Ziethen side were derived, etc. right up to the main triangle Berlin - Colberg Eichberg. With regard to the angle measurements, the mean error of an angle was maintained at ±0.780´´(with 47 condition equations) or ±0.730´´ (with 86 condition equations), also at ±0.339´´ (additional result).

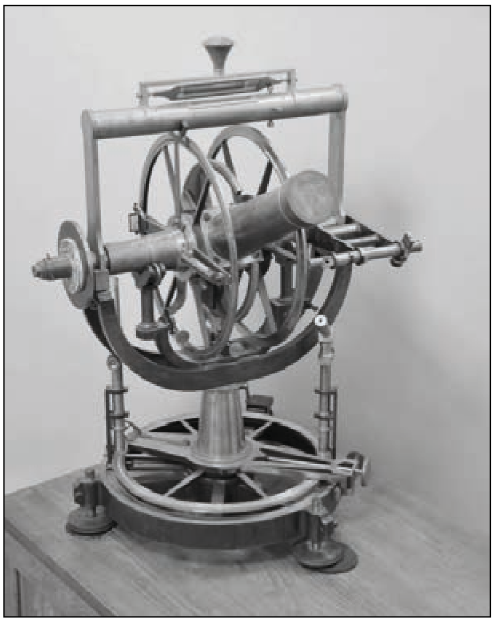
Basis measurements 1879, 1880, 1892 and 1908

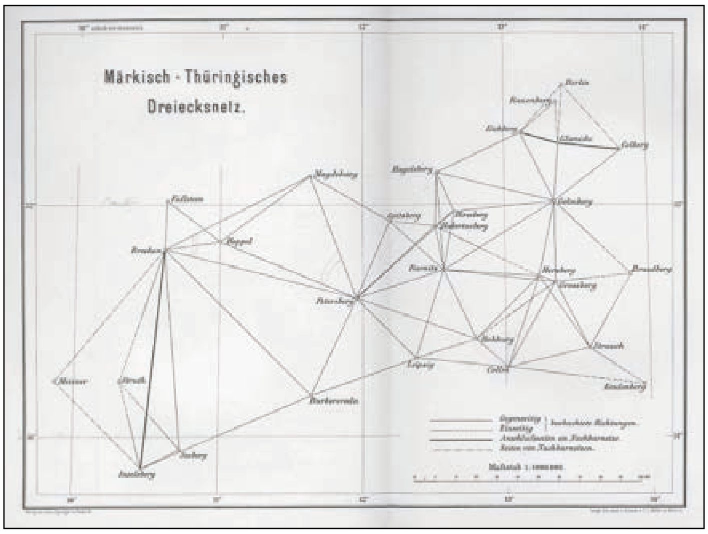
The employees of the institute only conducted few measurements with the basis apparatus of the Brunner brothers, Paris. The material of the 4-metre-long rods was made of platinum-iridium, on the one hand, and brass, on the other hand. In 1879, the follow-up measurement of the baseline took place near Strehlen and in 1880, the baseline near Berlin (as a parallel measurement). This double measurement resulted in a probable error in length of ±0.7 to ±0.8 mm. The Bonn basis measurement was performed in 1892 with Brunner and Bessel apparatus, as was the Berlin basis measurement in 1908. With the measurements using the single-rod Brunner basis apparatus, microscopes are used, while with the four-rod Bessel apparatus, measuring wedges are used. With the Brunner apparatus, the connection of the platinum rod with the bronze rod and with the Bessel apparatus, the connection of the iron rod with the zinc rod, is used as a metal thermometer. The comparative measurements that were performed with both apparatus concluded that the metal thermometers did not function faultlessly with larger temperature changes. After these investigations, baseline measurements with invar wires prevailed.



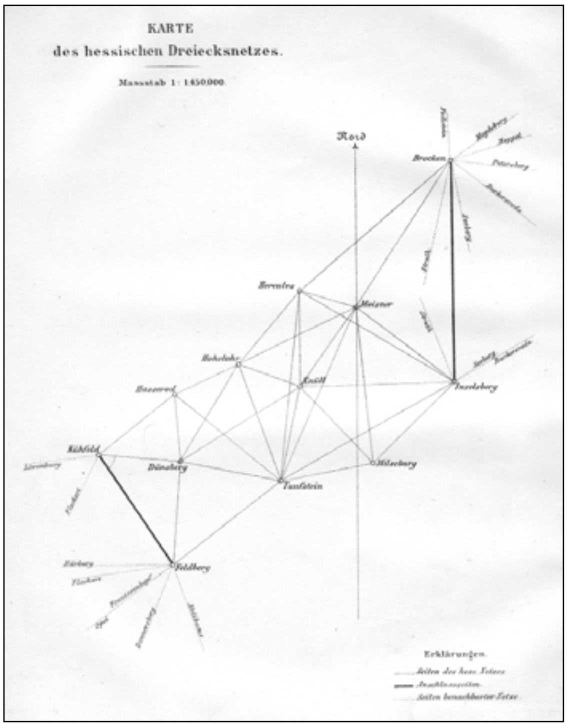
Triangulations

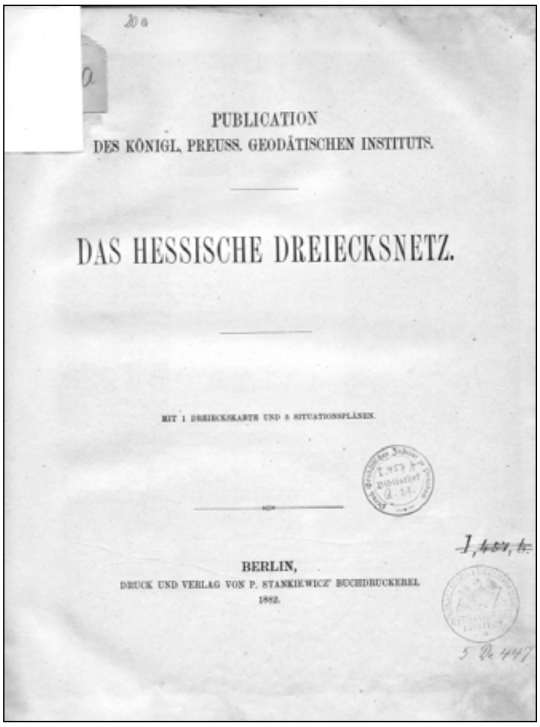
1867 was the start of the *triangulation activities* with 2 identical 10-inch universal instruments from Pistor & Martins, Berlin. The illustration shows a universal instrument, which was used for angle measurements. Three triangulations were performed by institute employees.





The Märkisch-Thüringisches triangulation network (Illustration) extended from the coastal survey near Berlin to the triangle sides of Saxony and the Ingelsberg-Brocken side of the Gaussian arc measurement. The results are published in: *Das Märkisch-Thüringische Dreiecksnetz. Publisher Kgl. Preuß. G. I. Berlin 1889. 144 p. 1 Kt.. The Hessisches triangulation network surrounded* Brocken, Inselsberg, Meissner, Herkules near Kassel, Taufstein im Vogelsgebirge, Knüll, Milseburg, Haselohr, Hasserod, Dünsberg, Kühfeld right up to Feldberg im Taunus. In the **illustration,** the triangulation network is shown. The Illustration shows the title page of the publication by *Sadebeck, M. Das Hessische Dreiecksnetz. Publ. Kgl. Preuß. G. I. Berlin 1882. VI.*



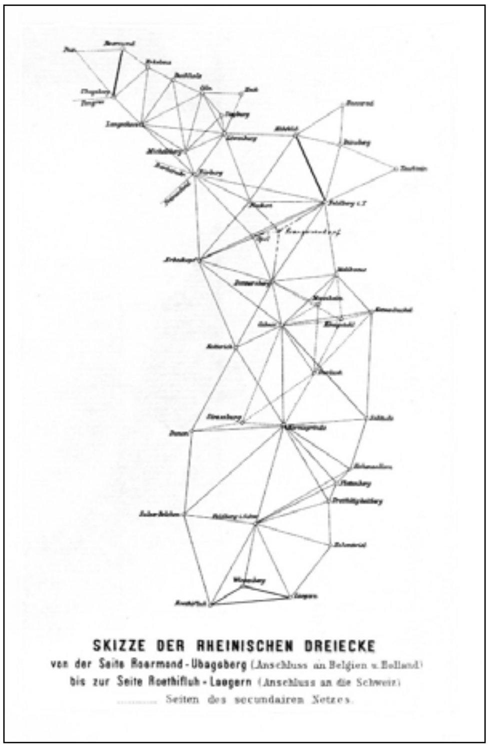

PUBLICATION
DES KÖNIGL. PREUSS. GEODÄTISCHEN INSTITUTS.

DAS HESSISCHE DREIECKSNETZ.

MIT 1 DREIECKSKARTE UND [illegible] SITUATIONSPLÄNEN.

BERLIN,
DRUCK UND VERLAG VON P. STANKIEWICZ' BUCHDRUCKEREI
1882.

The Rheinisches triangulation network extended from the Belgium-Netherlands border up the Rhine as far as the Wiesenberg-Röthifluh-Lägern triangle of the Swiss survey. The illustration shows the Rheinisches triangulation network. The results of the triangulation are published in *Das Rheinische Dreiecksnetz. Volume I-III. Berlin 1876/82. Volume I (1876) by, Bremiker, C. shows: Die Bonner Basis [The Bonn Baseline]. 75 p. the* measurement of the baseline and determination of the azimuth, the angle measurements in the basis magnification network, the equalisation of the triangles, the calculation of the directions and distances and the composition of the results up to the main triangle side Siegburg – Michelsberg. Volume II (*1878) by Fischer, A.: Die Richtungsbeobachtungen [The Direction Observations]. 164 p. shows the* angle measurements on 35 + 4 stations between 1869 and 1877. Volume III (*1882) by Fischer, A.: Die Netzausgleichung [The Network Equalisation]. 207 p. describes the* network equalisation, the links to the neighbouring triangulations (Belgian triangles, Swiss triangulation network and older triangulations in Southern Germany), the geographical coordinates, the comparison of the astronomical results with the geodetic results, the azimuth and pole height determination on the Großer Feldberg in Taunus and the Opel. The following table provides an overview of the triangulation networks observed and processed by the Geodetic Institute Potsdam. Triangulation activities were only performed until 1886.




FORMELN UND HÜLFSTAFELN

FÜR

GEOGRAPHISCHE ORTSBESTIMMUNGEN

VON

PROF. DR. TH. ALBRECHT

DRITTE UMGEARBEITETE UND VERMEHRTE AUFLAGE

LEIPZIG
VERLAG VON WILHELM ENGELMANN
1894.

Period of Observation	Net	Number of Points	Number of opposite views	Arc equations	Length equations	Arc error (after Ferrero)
1867-1877	Rheinisches Haupt-	32	77	46	16	± 0,73"
	+ Nebennetz	36	93	58	24	
1867-1876	Hessisches Netz	12	64	21	11	± 0,84"
1867-1876	Märkisch-Thüring. N.	25	55	33	16	± 0,61"

Geodetic-astronomical specifications for the European arc measurement

In addition to the longitudinal measurements with Bessel and Brunner apparatus, as well as the triangulations, the survey activities included positioning of towns, as well as distance measurements with telegraphy. Baeyer explains the need for the measurements in his paper: Astronomische Bestimmungen für die Europäische Gradmessung aus den Jahren 1857-1866 [Astronomical Specifications for the European Arc Measurement from the Years 1857-1866] (Leipzig, Verlag von Wilhelm Engelmann, 1873. 125 p.). The publication, *Albrecht, Th. - Formeln und Hülfstafeln für geographische Ortsbestimmungen [Formulas and Auxiliary Tables for Geographical Positioning*, the title page of which is shown in illustration, contains a detailed description of the geodetic-astronomical observation procedures for determining time, longitudes, poles and azimths. For this reason and due to the composition of the formulas required for use, as well as the tables, it was very helpful for the astronomical-geodetic activities and already had its 3rd print run in 1894.

Astronomical-geodetic activities from 1869 to 1885

The **determination of the poles** took place by measuring the zenith distances from the North and South Stars and through transit observations through the east-west vertical.

Azimuths were determined with direct angle measurement between a start near the pole and the direction according to an iridescent object with a universal instrument or with measurements according to one or several marks situated in the vertical of the pole stars with a passage instrument. The determination of the pole height and the azimuth took place at 16 stations of the 1st order: Seeberg, Inselsberg, Mannheim, Durlach (direction Mannheim), Rugard (Rügen), Hercules near Kassel, Feldberg in Schwarzwald, Neinstedt, Gollenberg, Thurmberg, Goldaper Berg, Springberg, Moschin, Schönsee, Jauernik, Swinoujscie, Kapellenberg. The determination of the pole height took place at 34 stations: Mühlhausen, Tettenborn, Hohegeis, Ilsenburg, Asse, Löwenburg, Kuhberg, Bornstedter Warte, Gegenstein and Regenstein, Schildberg, Osterode, Hils, Langelsheim, Mansfeld, Morraburg, Dollmar, Heldburg, Harzburg, Dienkopf, Craula, Pfarrsberg, Eckartsberga, Sachsenburg, Kyffhäuser and Lohberg, Neinstedt (also azimuth), Victorshöhe and Josephshöhe, Heligoland, Blankenburg, Hüttenrode, Hasselfelde, Nordhausen. The results are shown in Albrecht, Th.: Instruktion für die Polhöhen- und Azimutbestimmungen [Instruction for Pole Height and Azimuth Determinations] (In: Astron.-Geodätische Arbeiten im Jahre 1875 + [Astronomical-Geodetic Activities in 1875+]) and in Astron.-Geodätische Arbeiten in den Jahren 1881 and 1882 [Astronomical-Geodetic Activities in the years 1881 and 1882].

The **determination of the length of the seconds' pendulum took place** at 10 stations: Bonn, Leiden, Mannheim, Gotha, Seeberg, Inselsberg, Berlin, Königsberg, Güldenstein, as well as at the Saxony pendulum stations in Leipzig, Dresden, Freiberg.

Longitudes determined using telegraphy took place for 28 routes between the stations:

- **Berlin** to Lund, Vienna, Rugard (Rügen), Strasbourg, Paris, Bonn, Altona, Warsaw, Swinoujscie, Göttingen
- **Bonn to** Leiden, Mannheim, Strasbourg, Paris, Altona, Wilhelmshaven
- **Göttingen** to Altona, Leipzig, Brocken
- **Altona** to Helgoland, Wilhelmshaven
- **Leipzig** to Mannheim, Brocken
- **Mannheim** to Strasbourg
- **Königsberg** to **Swinoujscie,** Warsaw
- **Swinoujscie** to Kiel
- **Dangast** to Leiden

The results of this can be found in Albrecht, Th.: Instruktion für die Längenbestimmungen [Instruction for Determining Longitudes] (In: Astron.-Geodätische Arbeiten im Jahre 1876 [Astronomical-Geodetic Activities in 1876]. Berlin 1877) and in Albrecht, Th.: Rectascensionen, Declinationen und Eigenbewegungen von 39 Polsternen [Rectascensions, Declinations and Spontaneous Movements of 39 Pole Stars] (General-Bericht für 1873 [General Report for 1873]. Berlin 1874).

Overview of astronomical-geodetic activities from 1869 to 1885

Determinations	Order	Number of Determinations	Mean Error
Determination of Length (telegraphic)		28	±0,034 s
Determination of Pole height	I. II. III.	16 (both methods) 47 (one method) 3 (for Information)	±0,40“, ±0,26“ ±0,5“
Determination of Azimuth	I. II.	11 (both methods) 16 (one method)	±0,79“, ±0,56“ ±0,8“

Astronomical-geodetic activities from 1863 to 1885 in the Kingdom of Saxony
After Prof. Dr. C. Bruhns, Director of the Leipzig Observatory, died on 25 July 1881, **Prof. Dr. Th. Albrecht took over the performance and evaluation of the measurements regarding the determination of pole** heights and azimuths on the Jauernick and Kapellenberg stations in 1882 and 1884 respectively. The results are described in Bruhns, C, Albrecht, Th. Astronomisch-geodätische Arbeiten für die Europäische Gradmessung im Königreiche Sachsen [Astronomical-Geodetic Activities for the European Arc Measurement in the Kingdom of Saxony], Berlin 1885. 400 p. **Longitudes were determined** on 16 routes between Leipzig and Freiberg, Dresden, Großenhain, Dablitz, Berlin, Breslau, Bonn, Gotha, Vienna (Laaerberg), Leiden, Dangast, Mannheim, Munich, Brocken, Göttingen and Vienna (Türkenschanze). **Pole height and azimuth** determinations were performed at 14 stations, on the baseline intermediate point Großenhain, in Freiberg (Galgenberg), Dresden (Math. Salon), Kahleberg, Fichtelberg, Leipzig (Pleissenburg), Wachauer Denkstein, Grenzhübel, Wachberg, Markstein, Schwarzeberg, Lausche, Jauernick, Kapellenberg. From 22 July until 27 October 1868, Prof. Dr. F.R. Helmert performed observations himself on Pleissenburg and 5 other points.

Furthermore, in the years 1923 to 1937, Mühlig performed and published astronomical-geodetic activities of the 1st order in the publication Preuß. G. I. N. F. No. 109, Potsdam 1938. These activities relate to 34 field stations with 34 longitude, 33 latitude and 25 azimuth determinations. Corrections were applied to the results due to pole fluctuations, which were calculated using the pole coordinates of the International Latitude Service, based on the formulas below. Their amounts only reach 0.001 s for some longitudes, they are between + 0.10” and – 0.16” for the latitudes and between – 0.01” and – 0.33” for the azimuths.

Reduction due to pole motion
Since the pole motions were noticed as latitude changes, the pole path alone was derived from the results of latitude determinations. Therefore, it was sufficient to calculate the mean pole using the definition of mean latitudes.

Due to the fact that the direction of the momentary instantaneous rotational axis is recorded as a pole fluctuation and is ultimately defined in terms of coordinates, it is possible to reduce the results of astronomical-geodetic positioning with interpolated utility values to a mean position of the rotational axis, which is realised by the selected reference system. In the system of coordinates, the positive x-axis points in the direction of the Greenwich meridian and the positive y-axis points in the direction of the meridian +90° west. The momentary instantaneous pole is given by the selected mean reference pole to epoch T through the coordinates (x_T, y_T).

As a result of the influence of the pole fluctuations, the results of astronomical-geodetic latitude, time and azimuth determinations of one station differ from their mean values with the index o as follows:

$$\Delta\phi = \phi_T - \phi_0 = x_T \cos \lambda_0 + y_T \sin \lambda_0,$$
$$\Delta\lambda = \lambda_T - \lambda_0 = (x_T \sin \lambda_0 - y_T \cos \lambda_0) \tan \phi_0,$$
$$\Delta a = a_T - a_0 = -(x_T \sin \lambda_0 - y \cos \lambda_0) \sec \phi_0$$

The deviation for local times occurs through a change of the length of the meridian from the observation site. The relationships above only apply under the assumption that the observation errors and error influences from the environment, star coordinate errors and station changes with a non-polar origin are invalid.

Topic 3: Determination of time and latitude

Time measurements, time unit and time scales

Sidereal time

Sidereal time θ is a unique measurement for the position of the night sky to the meridian of the location. It counts from 0 to 24 hours from the upper culmination of the vernal equinox (or Aries Point). The vernal equinox is defined as the intersection of the rising apparent ecliptic with the equator.

Star coordinates

Analogously to the specifications of a location on the Earth, which are determined with the geographical coordinates of longitude λ and latitude ϕ, the position of a star in the sky is described by its rectascension α and its declination δ. The rectascensions α of the stars are counted from the vernal equinox (seen from the North Pole) counter-clockwise from 0 to 24 hours. They are autonomous from the daily rotation of the Earth.

With the observation of stars, the angle between the star's circle of declination and the local meridian plays a part, i.e. the hour angle t of the star. This is counted in terms of the daily rotation of the night sky from 0 to 24 hours. A relationship exists between the sidereal time θ, the rectascension α and the hour angle t of the star through

$$\theta = \alpha + t \, .$$

In the event that the hour angle $t = 0$, i.e. $\theta = \alpha$, the star is in the meridian in upper culmination.

Solar time

In everyday life, we use the hour angle of the sun as a measurement of time, however, with the addition of 12 hours, because we count the day from midnight onwards.

The true sun moves asymmetrically. It provides the **true solar time** (display on a sun dial). In order to have a symmetrical passage of time, a mean sun is simulated, which moves along the equator at a constant speed. It provides the **mean solar time**.

Equation of time

The difference between true and mean solar time is referred as equation of time g. This includes two parts, namely

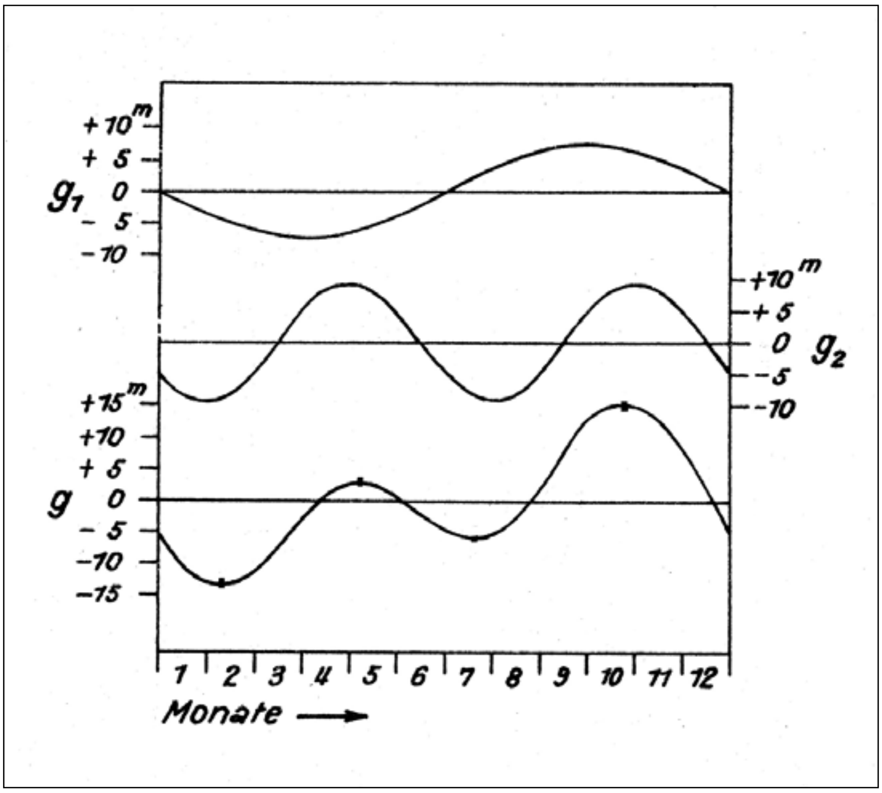
g_1 - from the movement of the sun in the ecliptic (level of the Earth's orbit, which appears as an apparent ecliptic in the sky) and

g_2 - from the projection of this movement on the surface of the equator that is tilted against the ecliptic.

As is evident in the illustration, the course of the time equalisation g shows

- a main minimum of -14 minutes in February,
- an ancillary maximum of +4 minutes in May,
- an ancillary minimum of -6 minutes in July and
- a main maximum of +16 minutes at the end of October.

Four times per year – on 15 April, 14 June, on 1 September and 24 December – the amount is zero. This means that the mean solar time corresponds to the true solar time.



Relationship between sidereal time and mean solar time

The length of a year is defined by the period of time between two consecutive passages of the mean sun through the vernal equinox. It is referred to as the tropical year. As the mean sun increases by a full 24 hours, i.e. 1 day during the course of a year, the year has one more sidereal day than solar days. Therefore, the tropical year has 365 days, 2422 mean solar days or 366.2442 sidereal days. This means that the sidereal time gains by 3 minutes 56.555 seconds compared to the mean solar time each day.

Local time, standard time and zone time

In previous times, every bigger city used its own local time. In order to avoid difficulties because of this, standard times were first introduced in railway traffic. The time to end this intolerable situation finally came at the end of the 19th century. In October 1884, at the International Meridian Conference in Washington, the Greenwich Meridian near London (Royal Greenwich Observatory) as declared as the zero meridian and the relevant applicable time was declared as Universal Time (World Time). The fastest introduction took place in marine navigation. The Central European Time, which relates to the 15th degree of longitude east of Greenwich, was introduced internally for the railway services in Northern Germany on 1 July 1891 and was generally introduced as legal time in the German Empire on 1 April 1893. After a proposal was made by S. Fleming, Chief Engineer of the Canadian Pacific Railway, the 24 time zones have been divided into 15° each since the year 1911.

A very long time before the Greenwich Meridian was introduced as the zero meridian, efforts were made to use a standardised designation of the geographical longitudes and in mapping for the Earth. Claudius Ptolemy (approx. 100-180, Greek mathematician, astronomer and geographer) already used the western tip of the Canary Island of Ferro (today: El Hierro) as the zero meridian around 150. Already used for a long time be European seafarers, in 1634, the Ferro Meridian was declared as the zero meridian by a French congress. This specification became widely prevalent, even in Germany, where the Ferro Meridian was used as the zero meridian in official German mapping until 1884.

Definition of the second

After dividing the hour into seconds, the second was defined as the 86400th part of the mean solar day in around 1500. This took place under the assumption that the mean solar day was a constant time measurement. After irregularities were found in the Earth's rotation in 1935, it was decided to revise the definition of the second. As shown by the time unit and timescales summary, the ephemeris second was defined in 1956.

Zeiteinheit und Zeitskalen

Definition der Sekunde:

A) Sekunde = 86400. Teil des mittleren Sonnentages (um 1500)

B) Ab 1956: Ephemeridensekunde = 31 556 925,9747. Teil des tropischen Jahres bezogen auf 0. Januar 1900, 12 Uhr Ephemeridenzeit (tropisches Jahr = 365,242198781730 mittlere Sonnentage)

C) Ab 1968: Atomsekunde = Dauer von 9 192 631 770 Perioden der Strahlung, die dem Übergang zwischen den Hyperfeinstrukturniveaus des Grundzustandes des Zäsiumatoms 133 entspricht.

Zeitskalen:

TAI Atomzeitskale des BIPM mit Zeitintervallen von 1 SI-Sekunde bei Meeresniveau; UT1-TAI ≈ 0 am 1. Januar 1958

UT1 Universalzeit, d. h. die wegen Polbewegung korrigierte beobachtete Zeit UT0; mittlere Sonnenzeit, gezählt ab Mitternacht

Sie wird für Präzisions-Orts-und Zeitbestimmungen benötigt.

UTC Koordinierte Zeit; sie differiert zur TAI um ganze Sekunden in der Weise, daß |UT1-UTC| kleiner als 0,9 s bleibt.

Ab 1972 werden zur Anpassung Schaltsekunden eingeführt, und zwar Ende Dezember und/oder Ende Juni.

Sie ist die im bürgerlichen Leben benutzte Zeit.

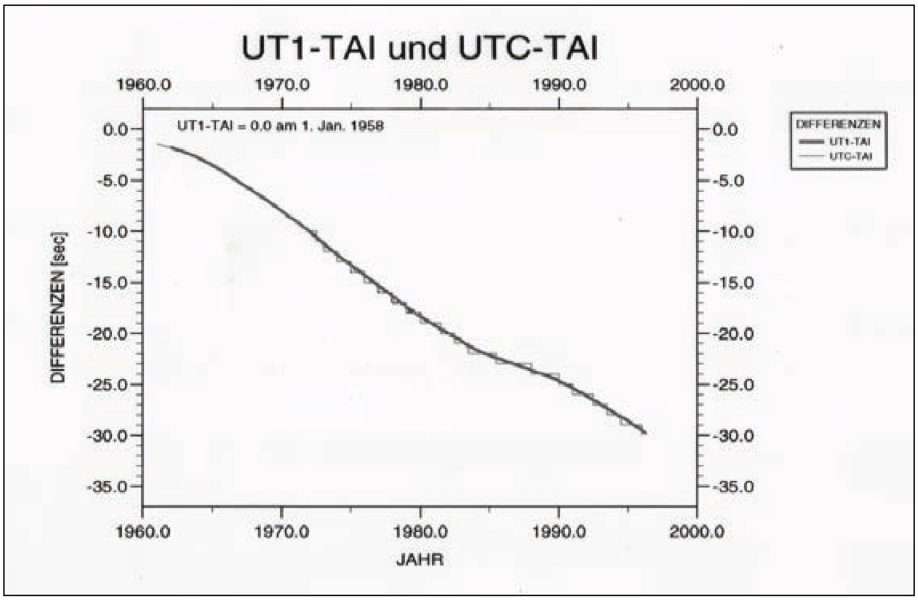
Zeitdifferenzen:

UT1-TAI

UTC-TAI

UT1-UTC

As this did not correspond to the physicists' ideas in any way, the physical time definition was decided in agreement with the previous one. In order to illustrate the different timescales, TAI, UT1 and UTC, they are shown in a chart.



Time service at the Geodetic Institute Potsdam
From 1892 until 1991, geodetic-astronomical time determinations were conducted at the Geodetic Institute Potsdam (from 1969, Central Institute for Physics of the Earth, Potsdam) and a Technical Time Service was operated.

Zeit– und Breitendienst 1889 bis 1991

Zeitdienst	
Sept. 1892 bis 1991	**Arbeit des Zeitdienstes**
1892 – 1933	4–6 Pendeluhren 10 – 40 ms / d mittl. Gangänderung
1933	Inbetriebnahme der ersten beiden Quarzuhren
1934 – 1963	2–5 Quarzuhren 0,1 – 0,3 ms / d mittl. Gangänderung
1964 – 1991	Quarzuhrenanlage von Rohde & Schwarz 0,01 ms / d
1972 – 1991	Normalzeitanlage mit Atomuhr rel. Unsicherheit $< 5 \times 10^{-13}$
	(Siehe nachfolgende Abbildung)
Breitendienst	
1889 bis 1923	**permanente Breitenbeobachtungen**
Okt. 1957 bis 1991	

In order to save time, 4 to 6 precision pendulum clocks were used with mean speed changes of 10 to 40 milliseconds per day. From 1933, both of the first quartz clocks were used in the Technical Time Service. These had mean speed changes of 0.1 to 0.3 milliseconds per day. Already in 1912, time signals of the Norddeich Coastal Station and the Eifel Tower Station were recorded, in order to determine signal corrections to the Potsdam time system. From 1923, monthly corrections were sent to four institutions for five received time signals and over the years, more and more time signals needed to be monitored and their signal corrections sent to more and more institutions.

Zeitsignale Januar 1942
und Normalfrequenz

Potsdam, Geodätisches Institut, östliches Meridianhaus: Länge $0^h\ 52^m\ 16^s.058$ östl. Gr., Breite $+52°\ 22'\ 54''$

Korrektionen der wissenschaftlichen Zeitsignale von Nauen (DFY 18130 m, 16,55 kHz; DGZ 20,54 m, 14605 kHz; DFC 23,10 m, 12985 kHz), Rugby (GBR 18740 m, 16,00 kHz), Bordeaux (FYL 19100 m, 15,7 kHz), Monte Grande (LQC 17,0 m, 17550 kHz) und der Normalfrequenz 1000 Hz der Phys.-Techn. Reichsanstalt, werktäglich $8^h 45^m$ Weltzeit ausgestrahlt über den Deutschlandsender 1571 m 191 kHz.

1942 Jan.	DFY 12^h	DGZ 12^h	DFC 12^h	GBR 10^h	FYL 8^h	FYL 20^h	LQC $11^h 45^m$	Norm. Frequ. $8^h 45^m$
1	$-^s.024$	—	$-^s.044$	$+^s.025$	—	—	—	—
2	− 25	$-^s.042$	− 42	+ 19	$+^s.054$	$+^s.027$	$-^s.006$	+ 55
3	− 24	− 42	− 45	+ 17	+ 42	—	—	+ 46
4	− 18	− 32	− 34	—	—	+ 31	− 6	—
5	− 19	− 36	− 37	+ 12	+ 32	+ 49	− 15	+ 35
6*	− 16	− 45	− 48	+ 13	+ 54	− 10	+ 2	+ 34
7	− 27	− 44	—	+ 17	+ 42	+ 48	− 2	+ 29
8	− 32	− 47	− 48	+ 18	+ 30	− 98	− 8	+ 25
9	− 34	− 54	− 56	+ 16	+ 34	+ 48	− 58	+ 40
10*	− 41	− 54	− 57	+ 19	+ 238	+ 37	+ 20	+ 28
11	− 26	− 49	− 54	—	+ 52	—	—	—
12*	− 27	− 53	− 54	+ 26	+ 48	+ 40	− 47	+ 47
13*	− 38	− 52	− 56	+ 32	+ 48	—	—	+ 43
14*	− 43	− 57	− 61	+ 30	+ 46	—	0	+ 39
15	− 46	− 61	− 62	+ 30	− 82	+ 58	+ 2	+ 25
16	− 50	− 66	− 67	+ 35	+ 68	+ 40	+ 18	+ 47
17*	− 42	− 58	− 60	+ 31	—	+ 34	—	+ 37
18	− 34	− 50	− 54	—	—	—	—	—
19	− 46	− 60	− 64	+ 18	+ 35	+ 46	+ 73	+ 29
20*	− 52	− 65	− 67	+ 16	+ 44	+ 34	+ 33	+ 10
21	− 49	− 62	− 65	+ 20	+ 32	+ 34	+ 65	+ 19
22*	− 46	− 61	− 65	+ 24	+ 39	+ 34	+ 24	+ 31
23*	− 55	− 72	− 73	+ 16	+ 52	+ 31	—	—
24	− 51	− 69	− 70	+ 20	+ 202	—	—	+ 35
25	− 53	—	—	—	—	—	—	—
26	− 48	− 69	− 71	+ 13	+ 62	—	—	+ 34
27	− 54	—	− 64	+ 3	+ 49	+ 26	—	+ 49
28	− 51	− 69	− 72	− 6	+ 35	+ 27	+ 113	+ 40
29	− 62	− 76	− 79	− 7	+ 31	—	+ 155	+ 16
30	− 48	− 64	− 67	− 4	+ 10	+ 10	+ 202	+ 34
31	− 39	− 55	− 51	− 1	+ 24	+ 24	+ 11	+ 39

* = Tage mit Zeitbestimmungen. Die Zeitangaben sind Weltzeit. + zu spät, — zu früh.

Die Signalkorrektionen gelten für die Mitte der Aussendung und beruhen auf den Angaben der Quarzuhren des Geodätischen Institutes, deren Stände durch Ausgleichung aller Zeitbestimmungen von Ende November 1941 bis Anfang März 1942 erhalten worden sind. — Die Ausbreitungsgeschwindigkeit der Wellen ist nicht berücksichtigt, die mitgeteilten Zeiten sind daher die Ankunftszeiten der Signale in Potsdam. — Die Rektaszensionen der Sterne sind dem dritten Fundamentalkatalog des Berliner Astronomischen Jahrbuches (FK 3) entnommen. Die Korrektionen der Normalfrequenz sind in Einheiten von 10^{-9} gegeben; + Frequenz zu groß, — zu klein.

Die äußere Genauigkeit in der Aufnahme der Normalfrequenz beträgt etwa 7×10^{-9}.

F. Pavel, W. Uhink.

The Potsdam time system on the basis of quartz clocks

The *Potsdam time system* was calculated such that the time determinations obtained in 84 days were subject to a *highly comprehensive parabolic equalisation*. The results for the mean of the period were the equalised clock status, the speed of the quartz clock and a possible speed change.

Prior to equalisation, reductions were applied due to pole fluctuation (= TU1) and annual rotational fluctuations (=TU2) on the clock corrections received on the original geodetic-astronomical time specifications in TU0, which were initially all related to main clock Q3. The equalisation took place in equidistant steps, which continue in seven-day intervals, so that the aforementioned values were received for every 7^{th} day.
As the direct use of the time determinations would not make any equidistant equalisation possible, the mean of each of twenty time specifications are graphically applied to their mean points in time. From the curve that was created in this way, the clock statuses for the equidistant equalisation of the main clock were taken through linear interpolation. The clock statuses for the equalisation of the other clocks were calculated from these values by using seven-day means of the clock status comparisons.
In order to check the quartz clocks, their status differences were compared several times a day using an electronic counter. Status jumps that occasionally occurred could therefore be determined and defined. From the ongoing change of the status differences, the speed difference between two quartz clocks could also be calculated. However, due to its low precision, this procedure was not used. The checking of the speeds of the quartz clocks took place be comparing their frequencies on the cathode ray oscillograph. With this, a precision of approx. $\pm 1 \times 10^{-9}$ was reached, so that relative speed changes of two quartz clocks of approx. 0.1 ms/day can be determined. In addition to this, the speed difference between the main clock of the Time Service and that of the *clock controlling the time signal*, which also provided the normal frequency, was constantly checked using a beat frequency counter. Furthermore, by receiving the normal frequencies of the German Agency for Weights and Measures and the British broadcaster, MSF, over the radio, they were compared with those of its own clocks using the beat frequency method on the oscillograph. Illustration shows the main measurement room of the Technical Time Service.

The time, which was announced using time signals, was an *extrapolated time*, as the *semi-definitive time* was not yet available at the time of transmission. After their determination, signal corrections were calculated which specified the moment of transmission in semi-definitive time. In order to check the time signal transmissions of other time services, 17 different time signals were received per day. The transmission moments of these time signals were based on the *semi-definitive Potsdam system* and sent to the interested parties and the *Bureau International de l'Heure (BIH)* in Paris on a monthly basis through circulars, with details about the own time signal. From the details of the various time services, BIH published the transmission moments of the time signals in the *definitive time system* and in the *Bulletin horaire*. At the same time, the calculations at BIH provided the deviations to the semi-definitive times of the individual time services from the definitive time and therefore made a statement about the quality of the relevant time services. In the BIH annual reports, the absolute difference between the Potsdam time system and the definitive time system of BIH was always < 20 ms, and the annual average error of the Potsdam time system was ± 7 ms. Therefore, the *Potsdam Time Service* was one of the best time systems in the world.

Time determination

Passage instrument for geodetic-astronomical time determination

The passage instrument is a specialist instrument for observing stars passing through the meridian. The device is set up in the meridian. This means that the telescope describes the meridian of the station. With constant use, the instrument is positioned so precisely that the axis azimuth k remains smaller than ±1 s.

A registration micrometer makes it possible to track the star with a movable filament, where the cycle times are registered with a chronograph. The special features of this device are a refractive telescope, a transfer device for the refractive telescope, a hanging spirit level and a registration micrometer on the eyepiece.

Instrument constants

As instrument constants, the scale value p of the hanging spirit level, the contact width KB on the contact drum and the lost motion TG of the micrometer screw must be known.

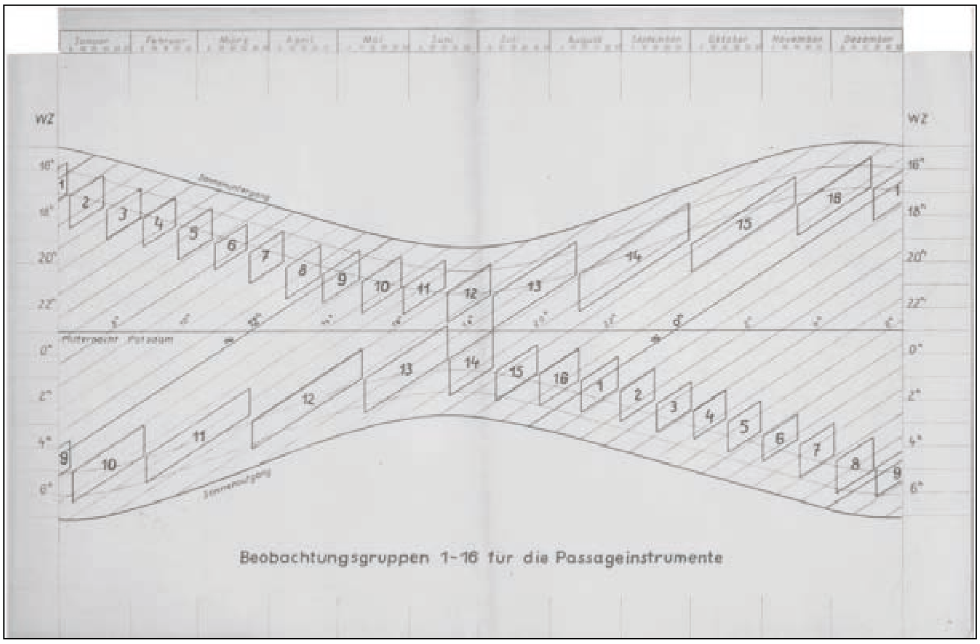
Observing a star

The observation of the star takes place prior to the actual passage of the meridian by recording 10 contact times. Then, the telescope is moved while the star passes the meridian. After passing through the meridian, the observation is again carried out over 10 contact times. The mean of the contact times of both axis positions is the meridian passage time for the observed star.

Prior to starting and after ending each star observation, the bubble positions of the hanging spirit level are registered to calculate the mean axis tilt i. By observing in both axis positions, the influence of the collimation error is eliminated. The observed passages through the meridian must be corrected due to contact width, lost motion and daily aberration. Furthermore, the tilt i of the tilting axis is taken into account. As the axis azimuth k remains unknown, in addition to the clock correction, it must be determined as a second unknown.

Beobachtungsprogramm

Fixed groups with 12 to 15 stars were observed (time stars with a zenith distance between 30° south and 15° north and 2-3 pole stars with declination > 70°), 16 groups over the course of the year. One observation period of a group lasts approx. 1.5 hours. The observation programme was only comprised of stars in the fundamental catalogue (FC). In the table below, the following details of a group from the observation programme are listed: FC4 No. with the comment OK or UK with pole stars, the brightness (Mag), rectascension and declination, the sine of the declination (sec δ), the axis position eyepiece east (E) or west (W) for the start of the start observation and the zenith distance (setting value on the vertical circle).



Group of the observation programme for time determination

Nb.	FC4	Mag	α	δ	sec δ	Axis position	Zenith distance
1	317	3.5	8h27,5m	+60°50′	+2,1	E	8°27′ N
2	323	6.0	8 36,8	52 50	1,7	W	0 27 N
3	915 UK	5.7	8 45,2	82 24	7,6	E	45 13 N
4	335	3.1	8 56,9	48 11	1,5	W	4 12 S
5	340	5.7	9 01,5	54 25	1,7	E	2 02 N
6	346	5.3	9 11,6	43 22	1,4	W	9 01 S
7	358	3.3	9 30,6	51 50	1,6	E	0 33 S
8	363 OK	5.7	9 39,4	69 24	2,8	W	17 01 N
9	368	3.9	9 48,6	59 12	2,0	E	6 49 N
10	374	5.2	9 55,6	41 13	1,3	W	11 10 S
11	1259	5.7	10 02,4	54 03	1,7	E	1 40 N
12	383	3.5	10 15,1	43 05	1,4	W	9 18 S

Note: The zenith distances apply to the Potsdam observation station (φ = 52°23′).

For the evaluation of the meridian time determination, the apparent rectascensions of the observed stars are required. In the Astronomical Yearbook, these are given for every upper culmination Greenwich. The short-periodic nutation terms are not included in the coordinates. For the observation day, the rectascensions of the stars were interpolated with

2. differences on the culminations in the station meridian, taking into account a correction due to the short-period nutation terms.
The true local sidereal times for the epochs of the meridian star passages are the apparent rectascensions α of the stars. The corrected observed meridian passage times differ to these by the clock correction ΔU and by the axis azimuth corrections for the stars. Therefore, the linear correction equation v results as:

$$v = \Delta U + K\,k - l$$

with the expression for the azimuth coefficients

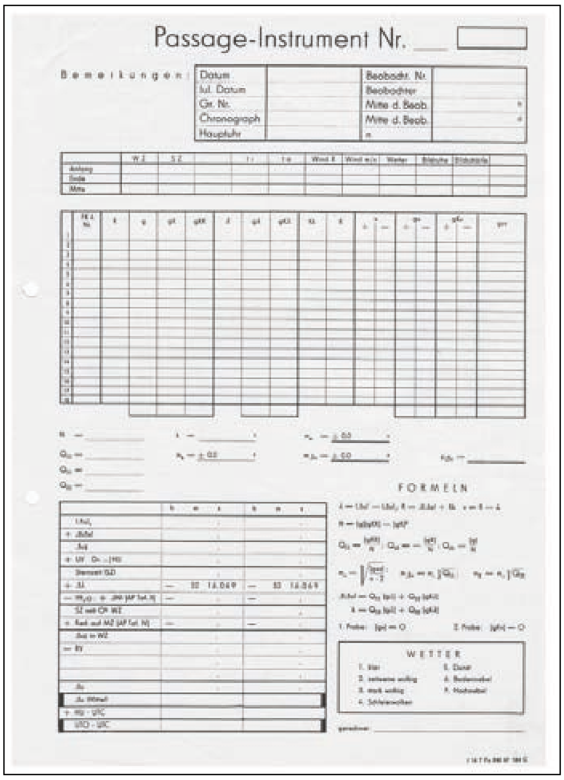
$$K = \sin(\phi - \delta) / \cos\delta$$

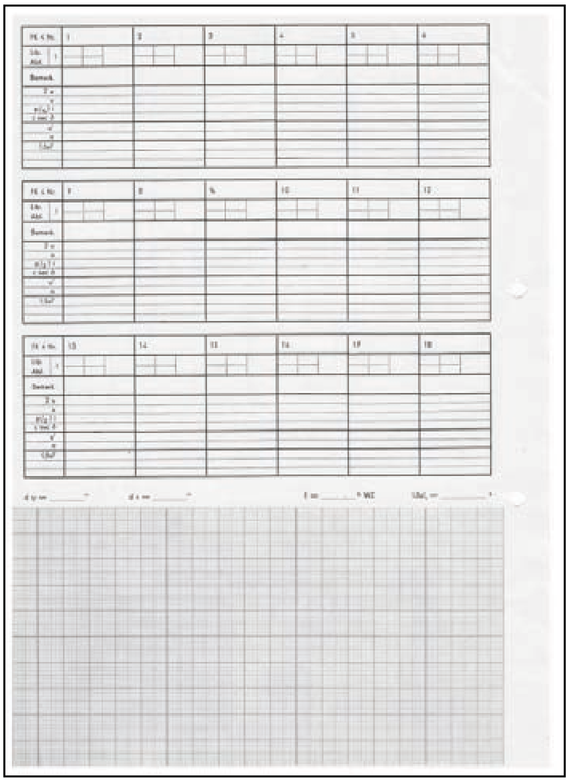
and with the absolute term of the observation

$$-\,l = -\,[\alpha - U_{korr}].$$

Evaluation
The evaluation takes place with an equation according to the method of the smallest squares with 2 unknowns: the time (clock correction) and the axis azimuth (deviation from the meridian).

Imprecision of the time determination
The inner mean error is ± 8 to 10 ms (1 ms = 0.001 s, i.e. approx. 30 cm in east-west direction for the Potsdam latitude of 52° 23´), the outer mean error is approx. ± 15 ms



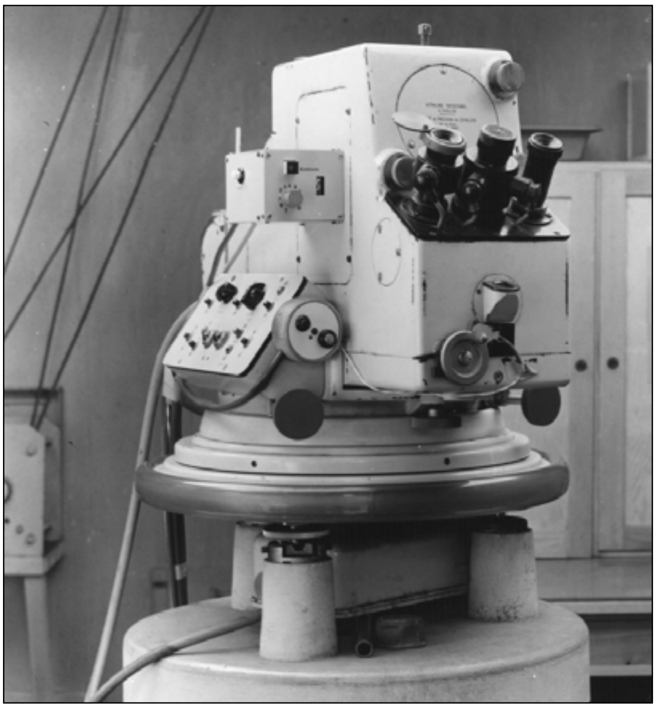


Observation and evaluation forms
For time determinations on the passage instrument, observation and evaluation forms were used, as illustrated by the two-page template. The graphic field had the purpose of showing the absolute term value as a function of the azimuth coefficient K. The straight line drawn through the points then shows if observations are subject to major errors. Approximation values of the unknowns are the sought clock correction through the section on the ordinate axis and the sought axis azimuth through the gradient of the straight lines. The form also summarises the formulas for calculating the unknowns and the mean error.

Determination of time and latitude

Astrolab Danjon for simultaneous time and latitude determination
An Astrolab is a specialist instrument for observing star passages through the almucantar (parallel circle to the horizon of the observation site) with a azimuth distance of 30°. The special features of this device are:

- an apparatus for setting the zenith of the star on the horizontal circle
- the search telescope
- a horizontal telescope with prisms on the same side
- a mercury horizon
- a double symmetric Wollaston prism in the optical path
- a motor with automatic speed control



Preliminary activities
Preliminary activities for the measurement with the Astrolab are the determination of the zero position of the Wollaston prism (with mirrors instead of prisms), the autocollimation, i.e. the vertical alignment of the rear surface of the prism to the optical axis, the mounting of the mercury horizon on the instrument and the readings of temperature, air pressure and relative humidity.

Mode of operation of the device

The starlight runs directly through the prism, on the one hand, and after reflection on the mercury horizon through the prism, on the other hand. Both beams are bundled by the lens in the focal plane and generate 2 images. While the star is approaching the almucantar, the images that are positioned vertically above one another move together. They coincide when the star passes the almucantar. The moment of coincidence is registered as the passage time. By moving a Wollaston prism in the beam of the Astrolab Danjon, the coincidence over an almucantar range of approx. ± 2.5’ coincidence is generated and maintained. Through a contact device, 24 time moments are registered. The rotating micrometer screw and the movement of the Wollaston prism must correspond to the speed of the star’s height movement in the various azimuths, which is provided by a motor-driven device for automatic speed control.

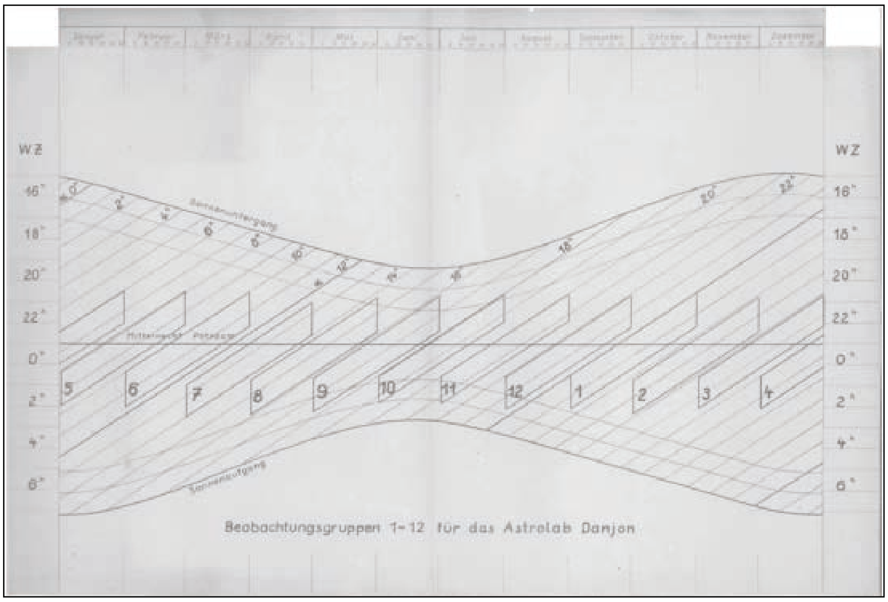
Observing a star

The observer’s task is to first move the Wollaston prism into the relevant final position manually using a crank, depending on whether the observation of the star takes place in an eastern or western passage. When the star has appeared in the finder scope, the moment of coincidence of both constellations is recorded on the main field of vision. This means that the observation process must be started. Therefore, the Wollaston prism is moved automatically. Using a hand wheel, the observer can correct the process and ends it after a signal tone sounds.

Observation programme

Fixed groups with 24 to 29 stars that are distributed as evenly as possible across the azimuths were observed. This was achieved by compiling the groups such that in each group [sin A] < 2, [cos A] < 2, [sin A cos A] < 2 and [$\sin^2$A] ~ [$\cos^2$A] for the stars. 12 groups were observed during the course of the year, one observation term of a group lasts approx. 1.5 hours.

The observation program was only comprised of stars from the fundamental catalogue (FC3) up to brightness (Mg) 6.2. In total, there are 246 stars, whereas 66 stars were able to be selected for observation in the east and west passage. This means that e.g. the start with FC No. 374 (Mag 5.2) in Gr. 4, No. 20 was observed as an eastern passage (ST =7 h 09.0 min; azimuth = 95.0°) and in Gr. 7, No. 4 was observed as a western passage (ST = 12 h 41.2 min azimuth = 265.0°). The details for observation and evaluation specifically for group 7 are shown in the enclosed table.



Evaluation
The evaluation takes place with an equation according to the method of the smallest squares with 3 unknowns: the time (clock correction) of the latitude correction and the zenith distance correction.

For almucantar passage observations for simultaneous time and latitude determination, the linear correction equation is

$$v = x \sin A + y \cos A - \Delta z + \delta h ,$$

with x, y and Δz for the unknowns, i.e. corrections for the approximation values time, latitude and zenith distance and δh for the observation term.

The observation term is calculated using the formula

$$\delta h = 15 \sin A \cos \phi_0 (T_{obs} - T_{cal}) \text{ (in arcsec)}$$

with T_{obs} = observed passage time and T_{cal} = predicted passage time. In addition to this, there are the following correction terms:

- Correction due to the short-periodic nutation terms $d\psi$ and $d\varepsilon$
- Consideration of the influence of the curve of the star pathway A(X)
- Consideration of the influence of the curve of the almucantar B(A) and
- Correction due to refraction and zero position of the Wollaston prism ε.

The observed passage times T_{obs} are the mean values of the 20 mean registered contact times. The calculation of the passage times T_{cal} must take place with the ephemerides α and δ of the FC stars for the epochs of the almucantar passages in Potsdam. In doing so, the influence of the daily aberration is taken into account, be reducing the conventional value of the geographical longitude, which goes into the calculation of T_{cal}, accordingly.
Based on the example of the observed group 7 dated 19 March 1962, several evaluation formulas are intended to show how an evaluation of Astrolab observations was carried out at the beginning.

7

12^h30^m - 14^h01^m

n = 24
$1^h\ 31^m$
3,8 m/Stern
Bezugszeit 12^h

I. Quadrant 6 Sterne
II. " 6 "
III. " 5 "
IV. " 7 "

[sinA] = -0,15
[cosA] = +1,57
[sinAcosA] = -1,16
[sin²A] = 14,34
[cos²A] = 9,65

Nr.	FK3	Mg	θ	A	15sinA cosφ	J	K	D(A)	dφcosA + ΔFK3R	sinA
1)	595	5,0	$12^h30^m,4$	64°,4	+8,256	-0,30	-0,65	+0,01	+1",67	+0,902
2)	1267	5,8	34,5	245,8	-8,355	+0,31	+0,65	+2	-1,80	-0,912
3)	407	5,4	38,6	235,6	-7,559	+0,19	+0,55	-2	-2,61	-0,826
4)	374	5,2	41,2	265,0	-9,121	+0,47	+0,76	+1	-0,45	-0,996
5)	1380	4,5	44,3	127,8	+7,236	-0,63	-0,73	+2	-2,67	+0,790
6)	619	5,0	49,2	36,1	+5,390	+0,01	-0,30	0	+3,69	+0,589
7)	390	4,4	53,2	253,8	-8,793	+0,36	+0,68	+1	-1,10	-0,960
8)	1432	5,9	55,2	52,0	+7,215	-0,17	-0,42	0	+2,72	+0,788
9)	522	4,8	$13^h00,2$	147,9	+4,861	-0,58	-0,63	+1	-3,82	+0,531
10)	612	5,0	02,7	21,6	+3,376	+0,17	-0,02	+2	+4,14	+0,369
11)	601	4,3	07,8	85,9	+9,123	-0,44	-0,74	+1	+0,28	+0,998
12)	627	4,9	14,1	60,3	+7,950	-0,22	-0,50	+1	+2,22	+0,868
13)	363	5,7	17,0	325,1	-5,241	+0,56	+0,72	0	+3,85	-0,572
14)	368	3,9	22,4	304,6	-7,536	+0,58	+0,81	0	+2,52	-0,823
15)	372	6,0	24,7	332,5	-4,227	+0,55	+0,67	-1	+3,88	-0,462
16)	1414	4,8	27,4	109,4	+8,639	-0,54	-0,82	+1	-1,40	+0,944
17)	576	4,2	32,5	122,4	+7,734	-0,56	-0,83	+2	-2,52	+0,845
18)	1318	4,8	37,2	216,3	-5,416	-0,04	+0,10	+1	-3,72	-0,592
19)	572	3,7	42,4	130,3	+6,986	-0,55	-0,82	+2	-2,84	+0,763
20)	395	5,0	47,1	338,5	-3,351	+0,48	+0,69	-2	+4,16	-0,366
21)	1293	4,8	51,3	257,8	-8,949	+0,33	+0,59	+1	-0,93	-0,977
22)	1262	5,7	55,0	316,9	-6,260	+0,55	+0,82	0	+3,22	-0,684
23)	394	4,8	57,1	298,4	-8,055	+0,52	+0,84	+1	+2,16	-0,880
24)	1396	5,0	$14^h00,2$	149,4	+4,663	-0,50	-0,78	+1	-3,68	+0,509

Nr. 1 62

Astrolab Danjon

Programm Nr. 7

Datum: 19.3.62 / 20.3.62
Beobachter: [illegible]
Beobachtung Nr.: [illegible]

Beobachtungsuhr: [illegible]
Hauptuhr: [illegible]

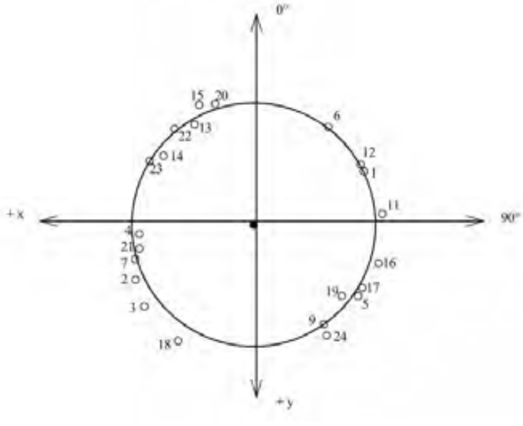
Wetter: [illegible]

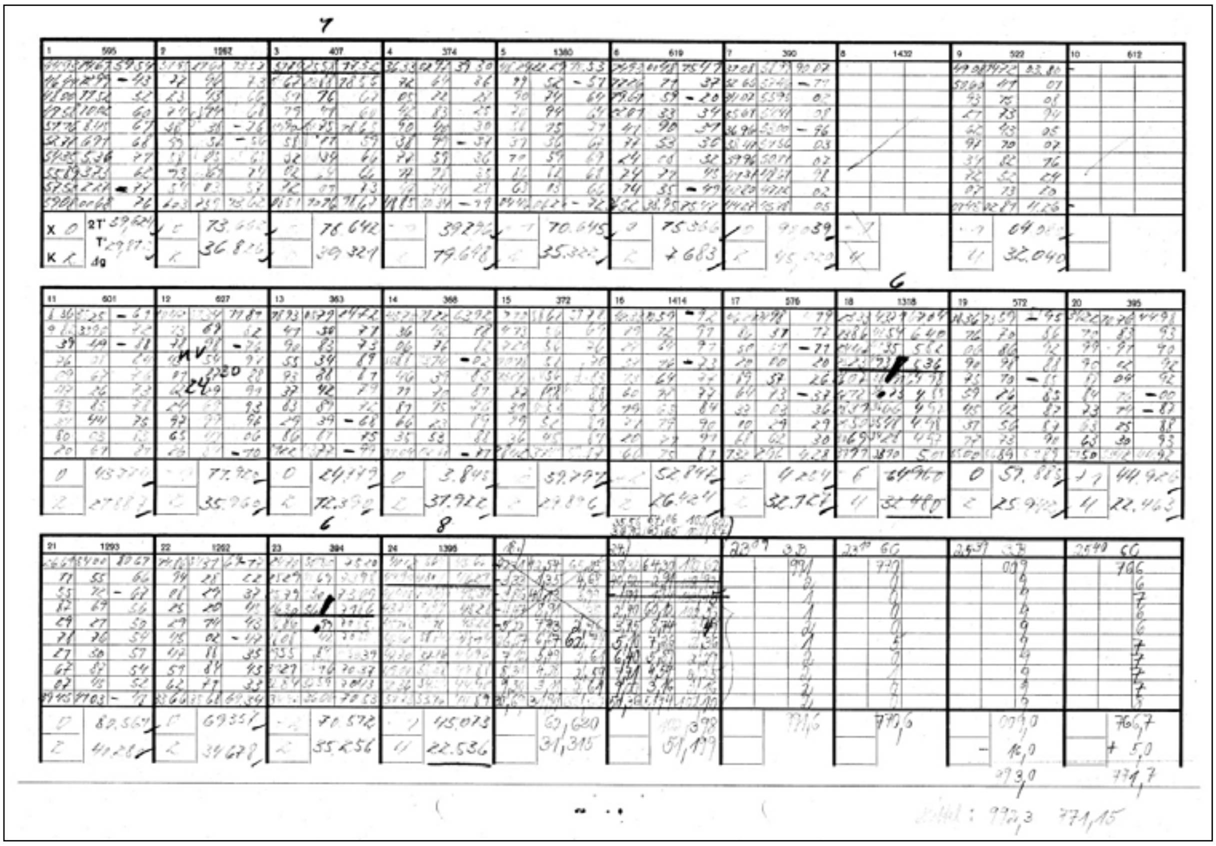
T_u [WZ]	[illegible]	[illegible]
t_i [°C]	[illegible]	[illegible]
t_a [°C]	[illegible]	[illegible]
t_{Instr} [°C]	[illegible]	[illegible]
rel. F. [%]	[illegible]	[illegible]
b' [mmHg]	[illegible]	[illegible]
Θ [°C]	[illegible]	[illegible]

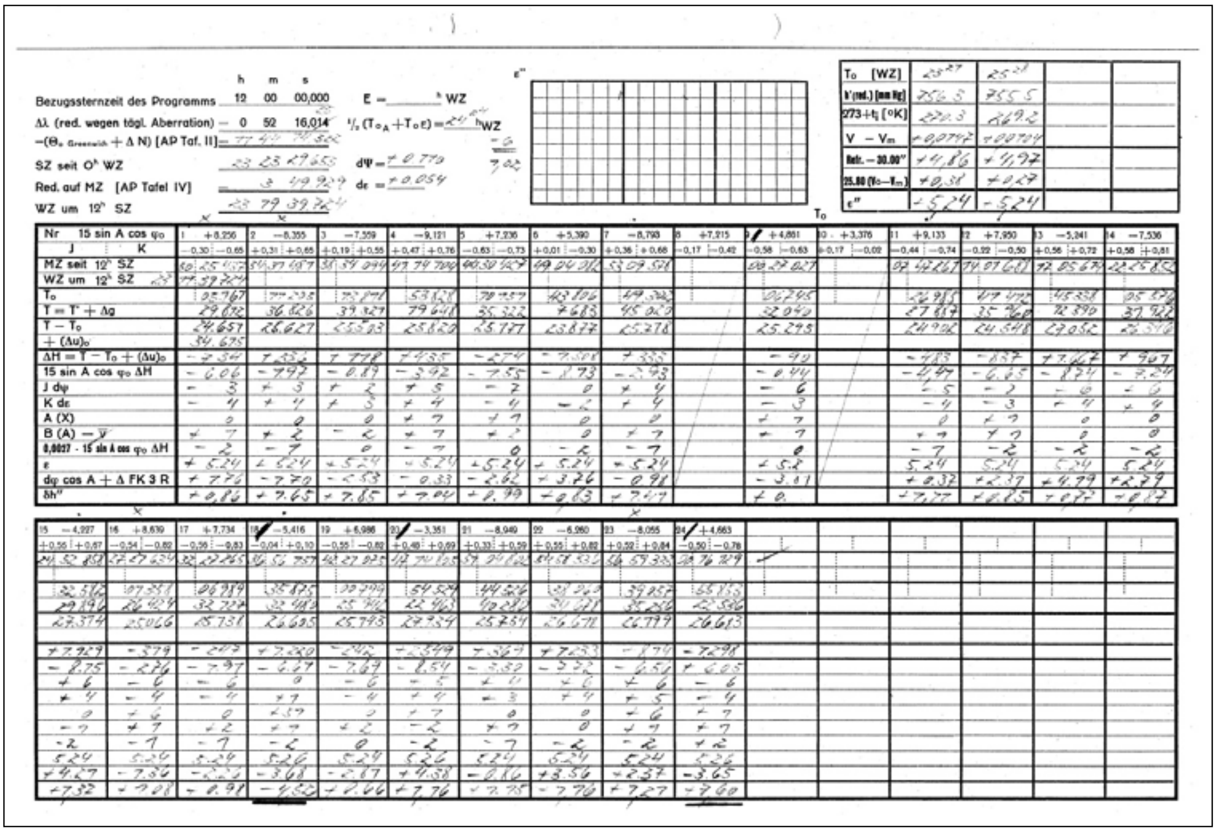
V_{+A}	V_{+E}
[illegible]	[illegible]

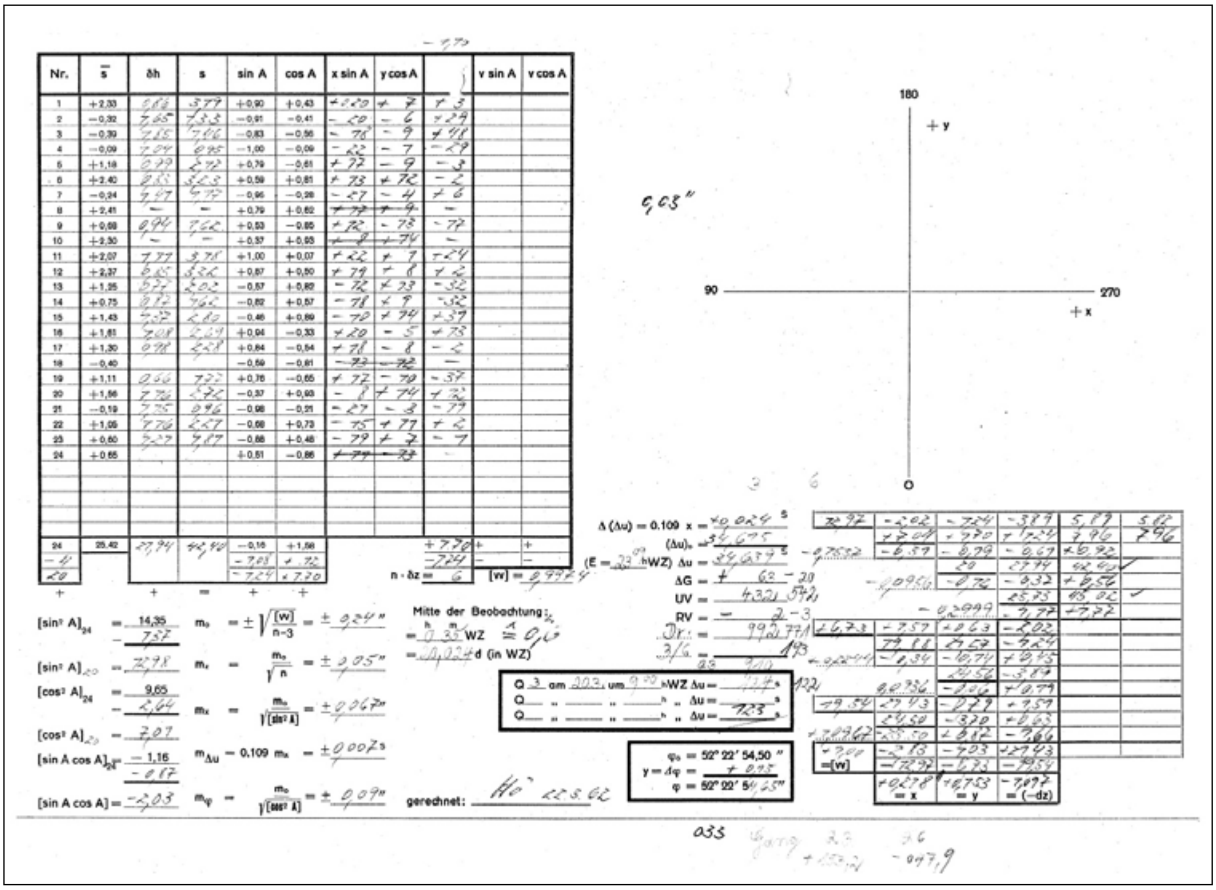
Bemerkungen: [illegible]

Druck: Kartographischer Dienst [illegible]






Bezugssternzeit des Programms h m s 12 00 00,000
Δλ (red. wegen tägl. Aberration) — 0 52 16,014
—(Θ_o Greenwich + Δ N) [AP Taf. II]
SZ seit 0^h WZ
Red. auf MZ [AP Tafel IV]
WZ um 12^h SZ
E = h WZ
½ (T_{oA} + T_{oE}) = h WZ
dψ =
dε =
T_o [WZ]
h'(red.) [mm Hg]
273+t_i [°K]
V — V_m
Refr. — 30.00"
25.00 (V_o—V_m)
ε"
Nr 15 sin A cos φ_o
J K
MZ seit 12^h SZ
WZ um 12^h SZ
T_o
T = T' + Δg
T — T_o
+ $(\Delta u)_o$
ΔH = T — T_o + $(\Delta u)_o$
15 sin A cos φ_o ΔH
J dψ
K dε
A (X)
B (A) — $\overline{y}$
0,0027 · 15 sin A cos φ_o ΔH
ε
dφ cos A + Δ FK 3 R
δh"



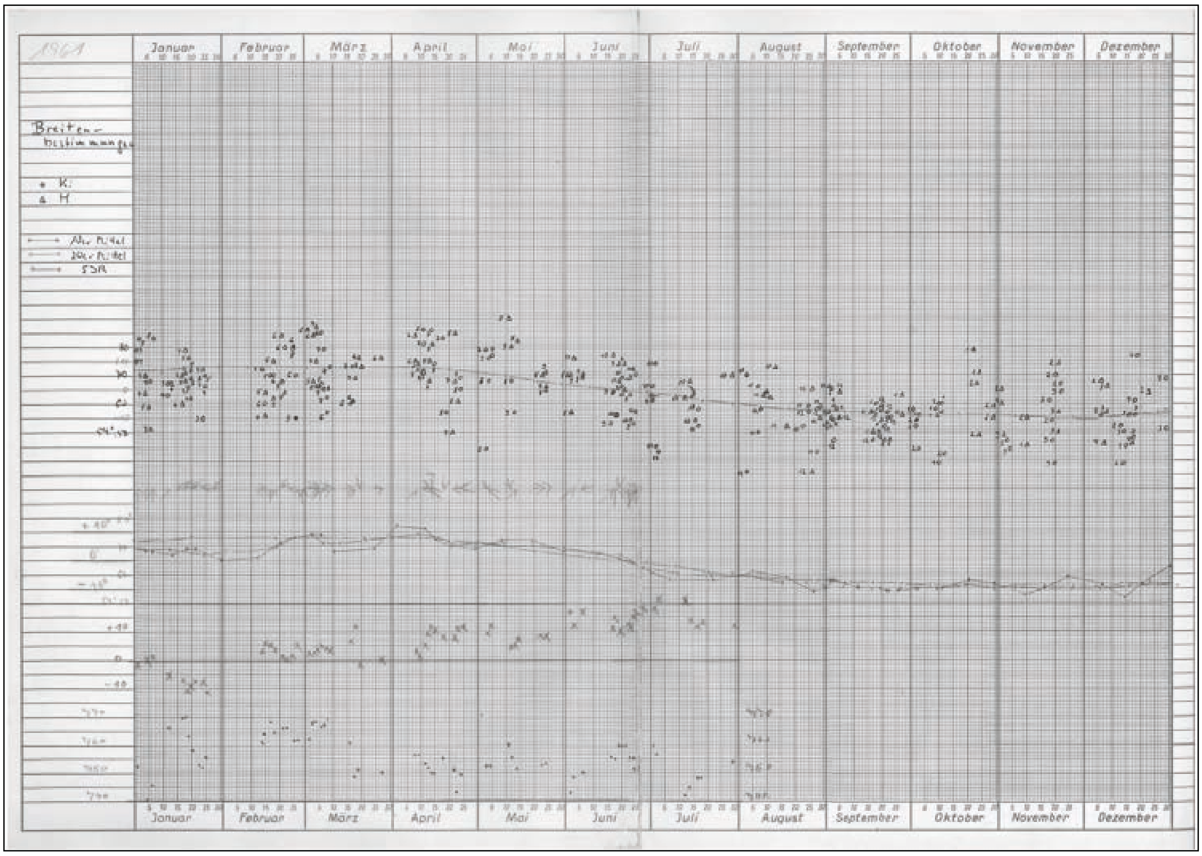
For a graphic solution, the δh values are applied as a function of the azimuth for the observed star. Then, the points of a circle are optimally adapted and with the coordinates of mean, the time correction in x-direction and the latitude correction in y-direction are obtained. The radius of the circle is a parameter for the zenith distance correction.

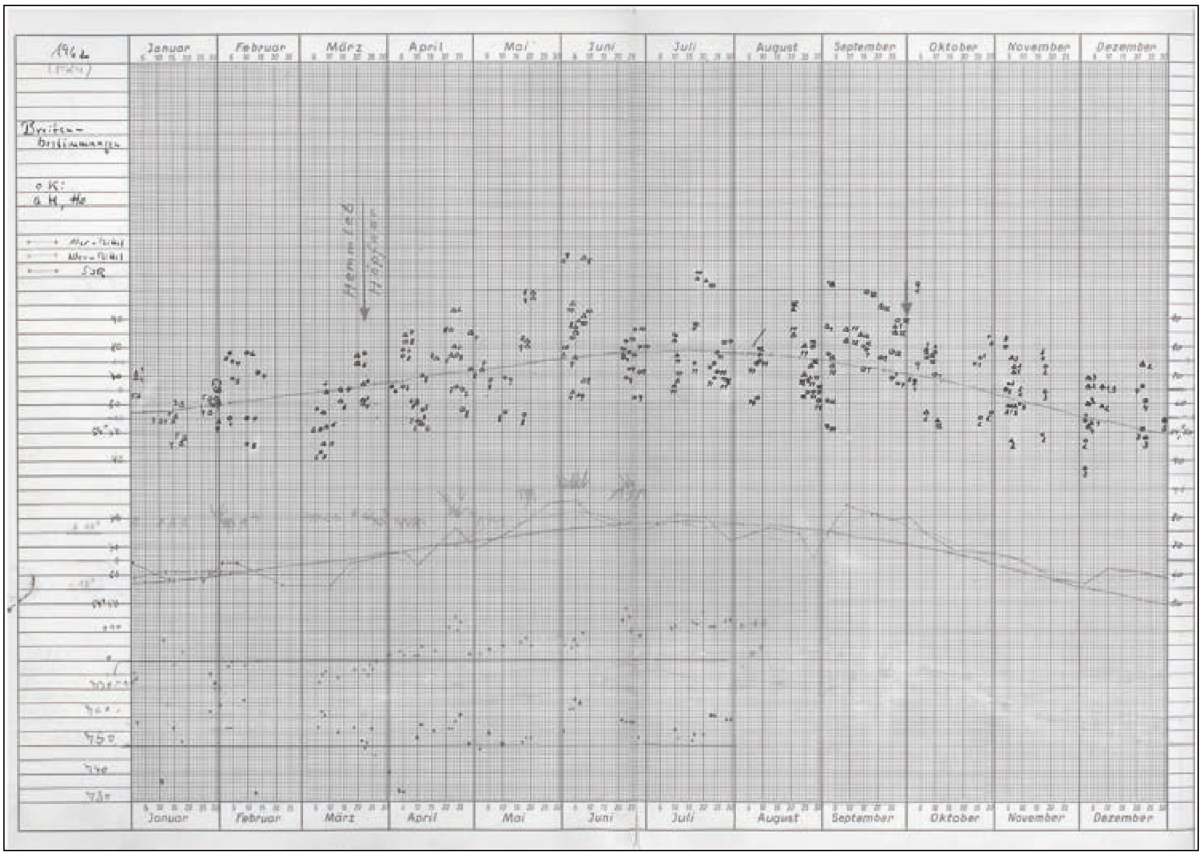
Imprecision of the time and latitude determination

The inner mean error for the time amounts to approx. ± 6 ms (1 ms = 0.001 s, i.e. approx. 30 cm in east-west direction for the Potsdam latitude of 52° 23´), and for the latitude approx. ± 0.1”, the outer mean error for the time is approx. ± 11 ms and for the latitude is approx. ± 0.1”.

Time and latitude determination on the Astrolab Danjon from 1957 to 1986

At the Geodetic Institute Potsdam, observations were performed since the beginning of October 1957 for time and latitude determinations on the Astrolab Danjon. For the years 1961 and 1962, the obtained 231 and 203 latitude values respectively are graphically illustrated. During the period from 1957 to 1986, 6 observers participated, who observed a total of 4045 time and latitude determinations.


1961
Breiten-
bestimmungen
K:
H
Januar
Februar
März
April
Mai
Juni
Juli
August
September
Oktober
November
Dezember


1962
Breiten-
bestimmungen
K:
H, Ho
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Februar
März
April
Mai
Juni
Juli
August
September
Oktober
November
Dezember

Latitude determinations

The visual zenith telescope

For the stations of the International Latitude Service (ILS), the observation instruments were built by Julius Wanschaff in Berlin. The optical parts were produced by Carl Zeiss in Jena and the spirit levels by Carl Reichel in Berlin.

The special features of this device are:

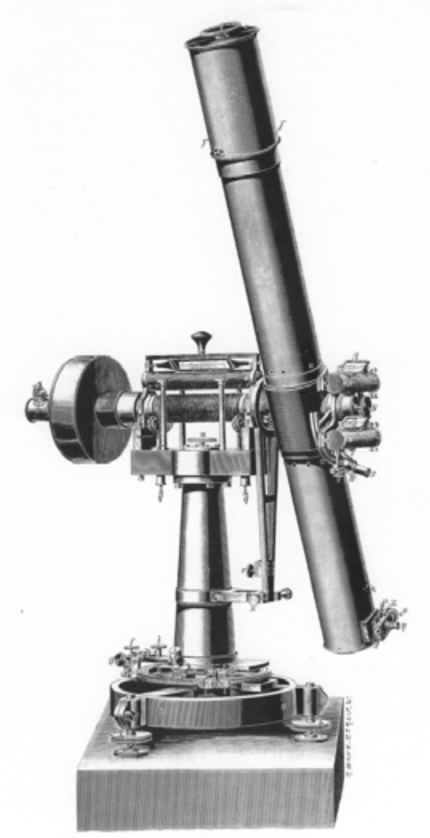
- the eccentric telescope with zenith distance adjustment circle
- a refractive eyepiece extension with an eyepiece micrometer (revolution value 40”)
- a filament mesh with 11 fixed filaments
- 2 Horrebow spirit levels (seconds’ spirit levels)
- a mounting spirit level.

Instrument constants

As instrument constants, the scale values p of the Horrebow spirit levels (in units of the screw revolution), the screw revolution value and the filament distances must be known.

Observation method

According to the report on the preparation of the International Latitude Service by Helmert and Albrecht, the latitude observations were performed according to the Horrebow-Talcott method.



Zenitteleskop
für die Stationen
Mizusawa, Carloforte, Gaithersburg und Ukiah.

Formulas for determining latitude
In the meridian, the following applies, as per the picture,

$\phi = \delta_S + z_S$ for a Southern Star in upper culmination

$\phi = \delta_N - z_N$ for a North Star in upper culmination (between pole and zenith)

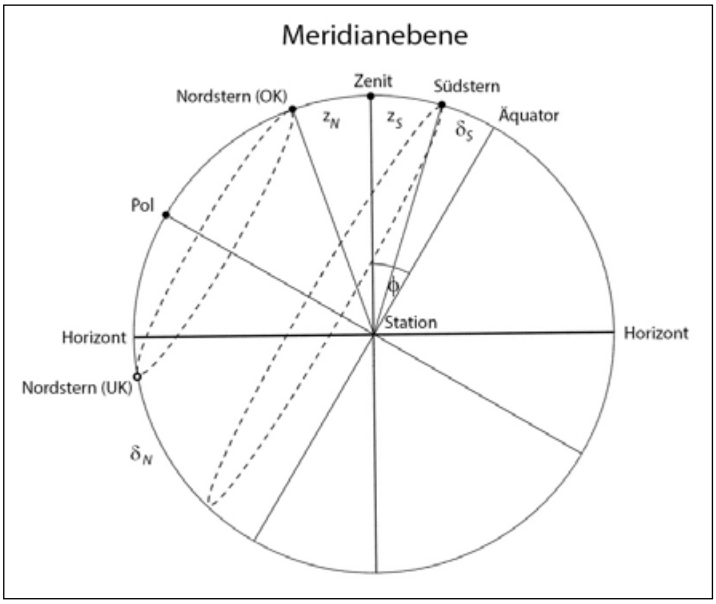
$\phi = 180° - \delta_N - z_N$ for a North Star in lower culmination (circumpolar star).

Horrebow-Talcott method
Pairs of stars are observed, a Southern Star and a North Star consecutively (or in the opposite sequence) in upper culmination in various positions of the tilting axis (rotation of the vertical axis by 180°). From the equations above, this results in:

$$2\phi = \delta_S + z_S + \delta_N - z_N$$

$$\phi = \tfrac{1}{2}(\delta_S + \delta_N) + \tfrac{1}{2}(z_S - z_N).$$

The zenith distance difference $(z_S - z_N)$ can be measured using the eyepiece micrometer attached to the bottom of the telescope, if both stars have been selected such that the difference is smaller than the field of vision of the telescope.



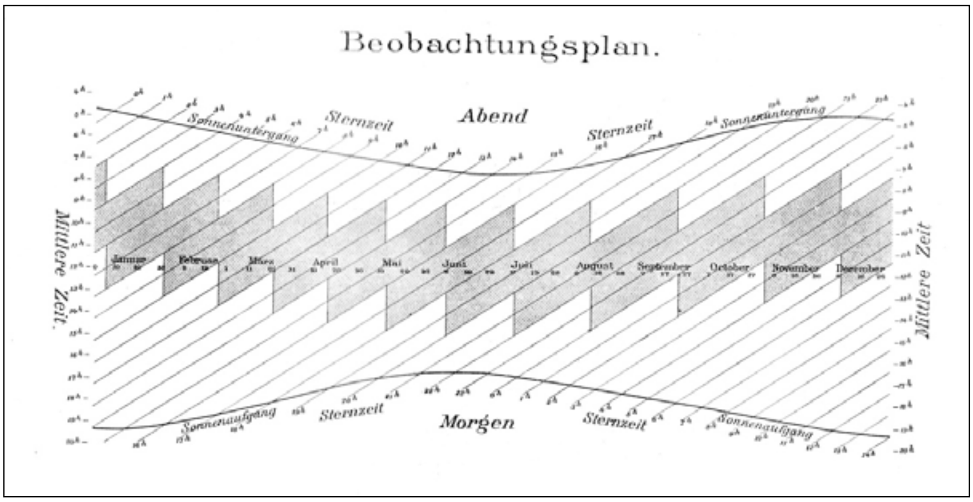
ϕ Latitude of the station, δ , z Declination and zenith distance of a star

Observation programme
The first observation programme on the ILS stations was observed from Sept. 1899 to Dec. 1905. It is comprised of 12 groups with 8 pairs of stars each, specifically 6 latitude pairs (zenith distance to 24°) and according to a suggestion by Helmert, 2 refraction pairs (zenith distance of approx. 60°).

The basis of the star programme is the Bonner Durchmusterung [Bonn Sampling] with

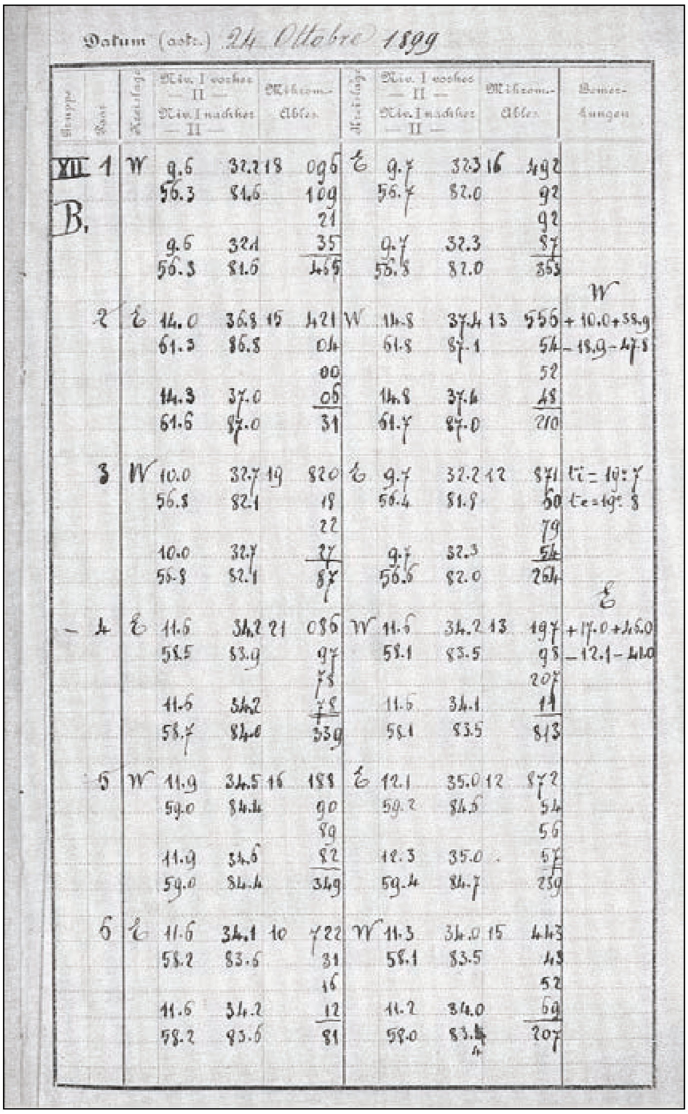
- a time interval between both stars of the pair: 4 to 15 minutes
- a zenith time difference for latitude pairs: 10 to 15 arc minutes
- a brightness (magnitude) of the stars between 4th and 7th magnitude.

The observation programme counts 192 stars. The graphic illustration shows what the observation plan looks like. The declination and spontaneous movements of the stars selected for the ILS were derived from available star catalogues by Dr. Fritz Cohn at the Königsberg Observatory.



Observation of a pair of stars
First of all, the instrument is moved with the envisaged axle position E (or W) into meridian position and the mean zenith distance of the star pair that has been calculated from the declinations is set. The observation of the first star is prepared. Then, the Horrebow spirit levels are set to level. The movable filaments are set approximately to the revolution value on the micrometer in accordance with the zenith distance and the telescope position and the positions of the Horrebow spirit levels are read off. Then, four settings on the micrometer are read off, namely regarding the given positions of the fixed filament mesh. The positions of the Horrebow spirit levels are read off again. Then, the instrument is rotated by 180° and the Horrebow spirit levels are levelled. The observation of the second star is then continued in an analogous manner. The air pressure and temperature readings must be recorded for the observations of a group.

The International Latitutde Service ILS
The observations at different locations in the 19th century showed that there were variations in the determined latitude of a location, probably due to polar movements. The scientists, by now united in International Geodesy, agreed to investigate the problem of polar movement by simultaneous observation of latitude. For this reason, the International Latitude Service (ILS), the first global scientific cooperation, was started in 1899 and at the stations in Cincinnati, Tschardjui, Carloforte, Mizusawa, Ukiah and Gaithersburg, which are located at the same latitude (39° N 08'), the latitude determination based on the same stars was performed using Wanschaff zenith telescopes. The analysis of the results was initially performed in the Central Bureau in Potsdam, before, the headquarters moved to other institutions.
The record of the first observations (observer: Dr. Emilio Bianchi) of 6 pairs of stars (Group XII) on the ILS station Carloforte, Italy on 24 Oct. 1899 (ϕ = +39° 08’ 09”) is shown. For the purpose of completeness, group XII of the star programme is listed.



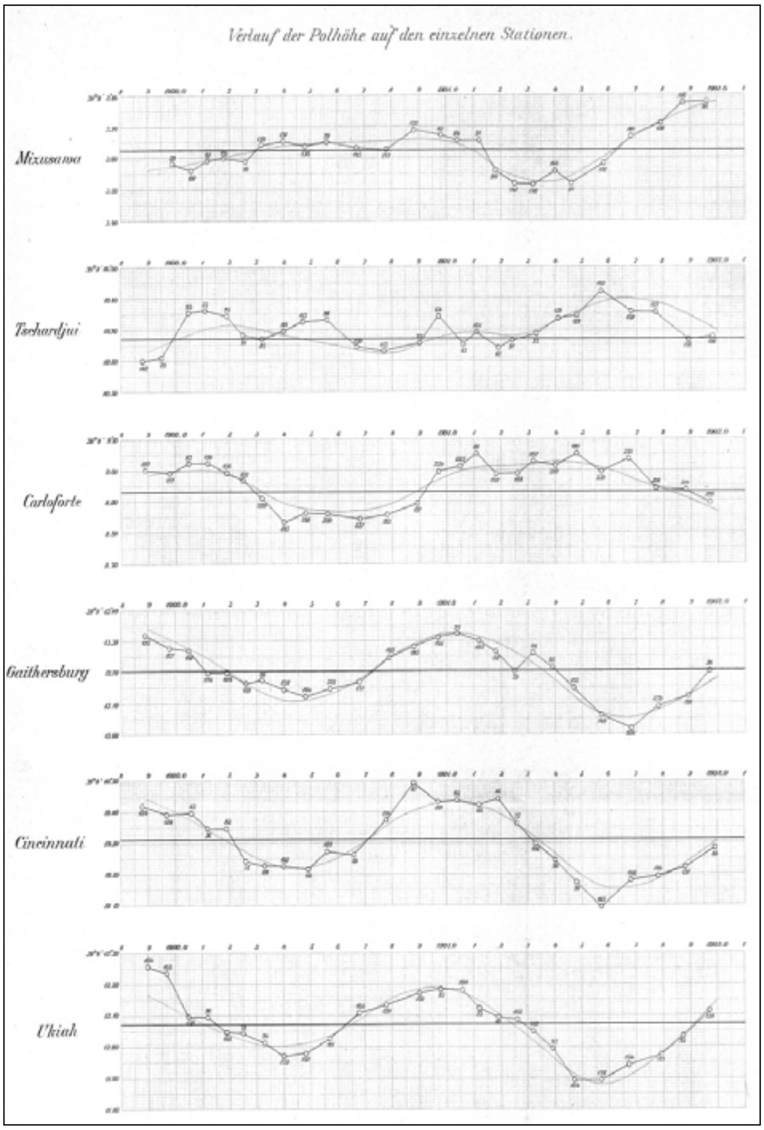
Datum (astr.) 24 Ottobre 1899

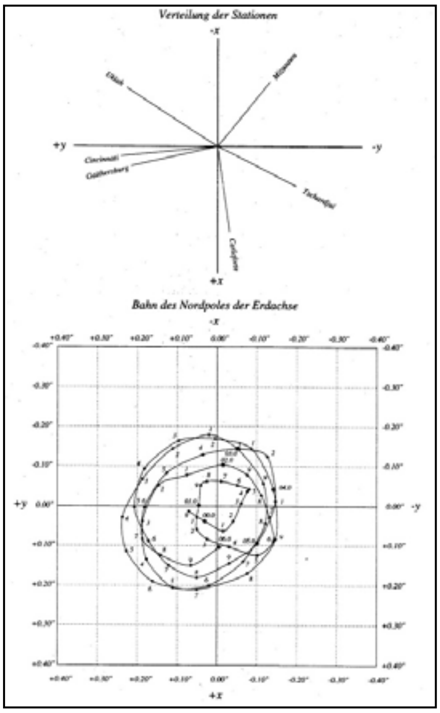
Gruppe	Paar	Kreislage	Niv. I vorher — II — Niv. I nachher — II —	Mikrom.-Ables.	Kreislage	Niv. I vorher — II — Niv. I nachher — II —	Mikrom.-Ables.	Bemerkungen
XII	1	W	9.6 32.2 18	096	E	9.7 32.3 16	492	
			56.3 81.6	109		56.7 82.0	92	
B.				21			92	
			9.6 32.1	35		9.7 32.3	87	
			56.3 81.6	465		55.8 82.0	353	W
	2	E	14.0 36.8 15	421	W	14.8 37.4 13	556	+10.0+38.9
			61.3 86.8	04		61.8 87.1	54	−18.9−47.8
				00			52	
			14.3 37.0	05		14.8 37.6	48	
			61.6 87.0	31		61.7 87.0	210	
	3	W	10.0 32.7 19	820	E	9.7 32.2 12	871	ti = 19.7
			56.8 82.1	18		56.4 81.9	50	te = 19.8
				22			79	
			10.0 32.7	27		9.7 32.3	54	
			56.8 82.1	87		56.6 82.0	264	E
−	4	E	11.6 34.2 21	086	W	11.6 34.2 13	197	+17.0+46.0
			58.5 83.9	97		58.1 83.5	98	−12.1−41.0
				78			207	
			11.6 34.2	78		11.6 34.1	11	
			58.7 84.0	339		58.1 83.5	813	
	5	W	11.9 34.5 16	188	E	12.1 35.0 12	872	
			59.0 84.4	90		59.2 84.5	54	
				89			56	
			11.9 34.6	82		12.3 35.0	57	
			59.0 84.4	349		59.4 84.7	239	
	6	E	11.6 34.1 10	722	W	11.3 34.0 15	443	
			58.2 83.6	31		58.1 83.5	43	
				16			52	
			11.6 34.2	12		11.2 34.0	69	
			58.2 83.6	81		58.0 83.4	207	

Group XII

Paar	Nr.	Mag	$\alpha_{1900.0}$	J.Ä.	$\delta_{1900.0}$	J.Ä.	Zenith distance
89	177N	5.9	$21^h58^m55^s$	+2.4	+44°10′03″	+17.3	5° 02′
	178 S	5.5	22 08 22	+2.6	+34 06 41	+17.7	
90	179 S	7.3	22 20 20	+3.3	-20 44 40	+18.2	59 52
	180 UK	6.3	**10** 25 44	+6.5	+81 00 36	-18.4	
91	181 N	6.5	22 31 44	+2.5	+49 33 10	+18.6	10 23
	182 S	5.0	22 37 04	+2.8	+28 47 08	+18.7	
92	183 N	5.6	22 45 38	+2.5	+55 22 20	+19.0	16 17
	184 S	7.1	22 57 28	+2.9	+22 48 09	+19.4	
93	185 UK	7.0	**11** 02 13	+5.5	+82 16 42	-19.6	58 34
	186 S	7.0	23 11 42	+3.2	-19 25 07	+19.6	
94	187 S	7.2	23 16 33	+2.9	+35 57 11	+19.7	03 12
	188 N	5.9	23 22 18	+2.9	+42 21 40	+19.8	
95	189 S	6.9	23 27 29	+2.9	+34 24 02	+19.8	04 45
	190 N	6.1	23 32 39	+2.9	+43 52 33	+19.9	
96	191 N	6.3	23 42 35	+3.0	+46 16 37	+20.0	07 14
	192 S	6.8	23 53 43	+3.0	+31 49 31	+20.1	

Analysing the similar performed measurements at all stations the polar motion was detectable. The illustration shows the trend´s comparison of the pole height determination. at the different observatories. Resulting the polar motion is remarkable for the years 1899 to 1906 (right illustration). Above the locations of observatories is shown, below the motion of earth axis pole.





Topic 4: Gravity measurements

Absolute gravity measurements with reversion pendulums

Terms and physical bases
Pendulum
The pendulum is a rotatable, suspended body that oscillates around its resting positions under the influence of gravity.

Mathematical pendulum
The mathematical pendulum is an ideal, where the total oscillating mass is imagined to by in one point, which is fastened to the end of a non-extendable thread without mass (thread pendulum).

Pendulum laws
The pendulum laws can be formulated as follows:

1. The oscillation time T is independent from the mass of the pendulum body.
2. For small oscillations, it is independent from the largest deflection from the resting position of the oscillation width or amplitude.
3. The oscillation time T, which means the time of a back-and-forth movement, is

$$T = 2\pi \sqrt{\frac{l}{g}}$$

where l is the pendulum length and g is the gravitational acceleration.

Physical pendulum
With the physical pendulum the volume expansion of the oscillating body must be taken into account. The oscillation centre point to the distance from the pivot point: This is the reduced pendulum length:

The seconds' pendulum
The half-oscillation of a seconds' pendulum takes one second. It pendulum length *l* is approx. 99.4 cm. The formula that has been transformed for this is:

$$l = T^2 \frac{g}{4\pi^2}$$

with T = 2s and g = 9.81m/s^2.

The half-second pendulum
The half-oscillation of a half-second pendulum takes half a second. With the oscillation time T = 1s, its pendulum length *l* is approx. 24.9 cm.

The reversion pendulum
The special feature of reversion pendulums is that the *two suspension points* are set so that they have exactly the same oscillation period. This avoids the serious problem of

determining the pendulum's centre of gravity in order to precisely determine the length of the pendulum. *The task is reduced to the measurement of the distance between both blades, the value of which is the pendulum length to be entered into the oscillation formula.*

Gravitational acceleration or gravity
The formula for calculating the gravitational acceleration is:

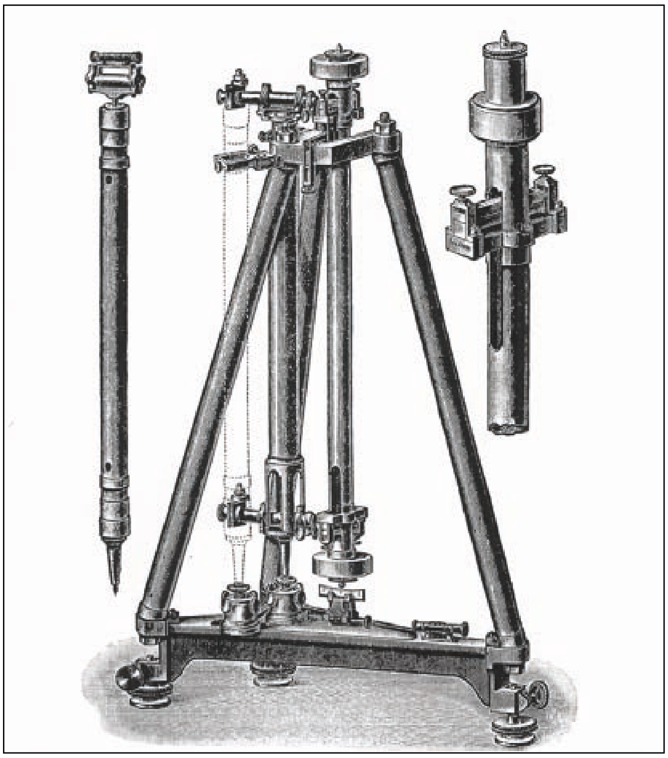
$$g = 4\pi^2 \frac{l}{T^2}$$

The gravitational acceleration is also called force of gravity acceleration or in short, gravity. Units of measurement for gravity are:

m/s^2, 1 Gal = 10^{-2} m/s^2, 1 mGal = 10^{-5} m/s^2, 1 µGal = 10^{-8} m/s^2.

Determination of absolute gravity in Potsdam by F. Kühnen and Ph. Furtwängler

Introduction
Gravity measurements are of fundamental importance for determining the structure of the Earth. Therefore, absolute gravity determinations were already performed from 1869 to 1871 with the *Repsold pendulum apparatus* at 10 stations in Prussia and Saxony by the Central Bureau of European Arc Measurement and the Geodetic Institute. Such an apparatus is shown in the illustration. The reversion pendulum is a hollow brass cylinder with a diameter of approx. 4 cm and a length of 1.25 m. Between the weights that are attached to the ends, the rod has two notches for holding the blades.



As there were major difficulties in transporting the large pendulum apparatus to the field stations, at the 4th General Conference of the European Arc Measurements in Dresden in 1874, a Pendulum Committee was formed under the chairmanship of J.J. Baeyer. Its task was to investigate a secure and rational process for measuring in gravity nets. Important findings and recommendations were provided in the committee report by Baeyer. The best solution for the measurements was seen as initially only determining the absolute gravity at a few stations with an improved reversion pendulum. At these stations, the additional stations would then be linked through relative measurements using an invariable pendulum.

In 1885, J.J. Baeyer died and in 1886, Friedrich Robert Helmert (1843-1917, geodesist and originator of the mathematical and physical theories of modern geodesy) became his successor as Director of the Geodetic Institute. From 1889 to 1892, the *main building of the Geodetic Institute Potsdam (GIP)*, now Helmert-Haus of the GeoForschungszentrum (GFZ) was built. F.R. Helmert had a considerable influence on how the construction project was to be carried out in accordance with the future requirements, particularly the *Pendulum Hall* as a temperature-stabilised room in the interior of the building with a double pier for absolute reversion pendulum measurements and three additional piers for measurements with relative pendulum devices.

Preliminary studies

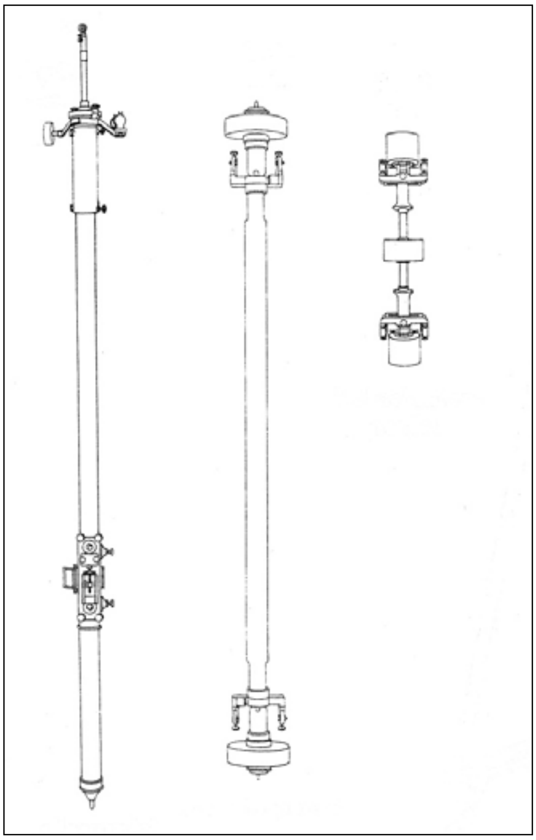
F. R. Helmert and Richard Schumann (1864-1945, astronomer, geodesist and geophysicist), later also Friedrich J. Kühnen (1858-1940, mathematician, physicist and geodesist) and Philipp Furtwängler (1869-1940, mathematician and physicist) conducted studies on the improvement of the reversion pendulum method. In 1898, the publication "Beiträge zur Theorie des Reversionspendels" [Contributions on the Theory of the Reversion Pendulum] by F.R. Helmert was published. In 1902, Ph. Furtwängler developed fundamental formulas on resonance of the stand.

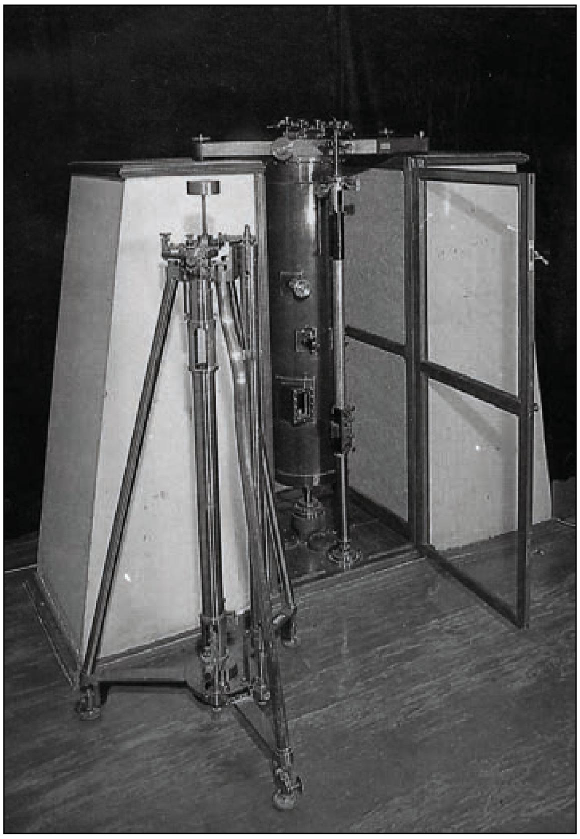
Main measurements

From 1898-1904, the absolute value of gravity was determined with reversion pendulums in the Pendulum Hall of the Geodetic Institute Potsdam by Friedrich Kühnen and Philipp Furtwängler. For the measurements, *5 brass reversion pendulums* produced by Repsold were used:

1. An old *seconds' pendulum* of the GIP (acquired 1869, mass of 5.57 kg)
2. A seconds' pendulum of the Osservatorio astronomico Padua (5.87 kg)
3. A heavy seconds' pendulum of the K. und K. Militärgeographisches Institut Vienna (6.23 kg).
4. A lightweight seconds' pendulum of the K. und K. Militärgeographisches Institut Vienna (2.86 kg).
5. A *half-second* pendulum of the GIP (acquired 1892, 3.53 kg).

A *thread pendulum* was used to check the resonance of the stand and pier. Its thread is a brass wire with a thickness of 0.04 mm and its pendulum body has a brass weight of 40 g. The thread pendulum oscillates in a brass tube. To observe the oscillation movement, the tube has notches on the relevant points. The illustration on the left shows the thread pendulum, a seconds' pendulum and the half-second pendulum.





The *reversion pendulum apparatus* is shown in the illustration on the right. In addition to this, the pendulum equipment included a *Sterneck coincidence apparatus* and a *new scale*.
The coincidence apparatus functions such that a movable gap, in which the excitation current is closed and opened in second intervals of the clock using electromagnets, is passed by a fixed gap and returned again with a spring. Through the fixed gap, the light beam of an observation lamp falls in the beat of the clock pendulum. The reflection of the beam is observed in a mirror on the pendulum and the coincidence moments of the clock pendulum and observation pendulum.
The coincidence observations to determine the oscillation term took place according to the following schematic:

- *for a heavy weight at the bottom,* twice 16 coincidences, namely with a large amplitude 9approx. 26' to 15') and then with a small amplitude (approx. 9' to 6') and
- *for heavy weight at the top,* (the amplitude fell twice as quickly) twice 8 coincidences, again with large amplitude and then with small amplitude.

The *oscillation time measurements* were performed for two long series, in which respective blades and bearings were exchanged. With this, 3 blade-bearing pairs were available, partially made of agate and partially made of steel. In the *first series*, in which the pendulum oscillated with blades on an flat surface, the *coincidences were observed according to the Sterneck electrical method*. In the *second series*, in which the pendulums oscillated with flat surfaces on a fixed blade, an *optical coincidence method* was used. The observations were reduced according to the Helmert methods, which are published in his "Beiträgen zur Theorie des Reversionspendels" [Contributions on the Theory of the Reversion Pendulum]. *From the derived coincidence intervals c, the unreduced oscillation terms T were calculated.*

For the second pendulum used, the formula is

$$T = 1 + 1 / (c - 1)$$

and for the half-second pendulum

$$T = ½ + 1 / 2 (2c - 1) .$$

The following reductions were applied to the results:

- due to suspension
- amplitude reduction (deflection)
- temperature reduction
- reduction due to variable air density
- reduction on the sidereal time seconds (clock speed)
- due to the resonance of the pendulum base (formulas according to Furtwängler)
- due to elastic curvature and expansion of the pendulum and
- reduction due to asymmetry of the pendulum.

After reduction of the observations, an equation was carried out according to the Helmert approach. The final result is:

Length of the basic seconds' pendulum (994.239 ± 0.003) mm and thus the gravity value

$$g = (981274 \pm 3)\ \text{mGal},$$

relating to the absolute pillar S0 with the geographic coordinates 52° 22.86' northern latitude and 13° 04.06' eastern length and the height of 87.00 m in the Pendulum Hall.

In 1906, "Bestimmung der absoluten Größe der Schwerkraft zu Potsdam mit Reversionspendeln" [Determination of Absolute Gravity in Potsdam with Reversion Pendulums] by F. Kühnen and Ph. Furtwängler was published. From 1909 to 1971, the derived gravity value was used worldwide as an international reference value of the Potsdam gravity system.

Other measurements and further development

Other measurements showed that the Potsdam gravity value has a systematic error of between -20.0 and -12.8 mGal. After the Second World War, intense activity started in the area of absolute gravity measurements. In doing so, the pendulum and fall methods were initially applied alongside one another. However, due to the development of the short-term measurement technology, the fall methods were ultimately given priority. AT the GIP, the preliminary activities were performed for the new determination of absolute gravity when the initial tests and plans with fall methods were reported on, but an evaluation of this method was not yet possible.

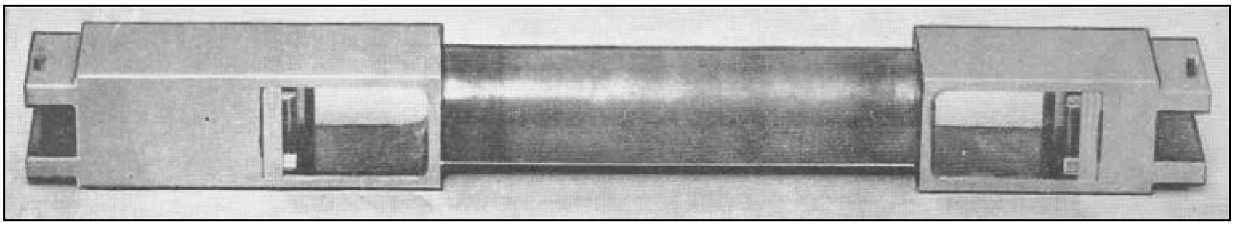
Determination of absolute gravity in Potsdam by R. Schüler, G. Harnisch, H. Fischer and R. Frey

In 1956, *preliminary activities* began for the measurements at the initiative and under the management of Karl Reicheneder (1903-1981, physicist). The scientists, Rudi Schüler (1925-2004, physician), Günter Harnisch (born 1936, geophysicist), Harald Fischer (born 1939, physician) and Reiner Frey (born 1938, geodesist), were involved in the activities of absolute gravity measurements. *Two measuring instruments with reversion pendulums* were developed:

- a reversion pendulum device with 25-cm-long measuring pendulums and
- a quartz pendulum device with three pairs of pendulums in different lengths

With both instruments, the *two-pendulum process* was used.

The 25-cm reversion pendulum device
It was specifically set up for a pair of measuring pendulums with fixed-pendulum blades and a reduced pendulum length of 25 cm. The mass of the pendulum is 4 kg. The illustration shows how both brass pendulums are set up.



The 25-cm reversion pendulum has a double T-shaped stand with four bearing surfaces that are allocated to the pendulum blades. With regard to the reversion, the rotation of the pendulums took place in a vacuum container together with the stand, where a vacuum of approx. 1 x 10^{-4} Torr is maintained. Blades and bearing surfaces are exchangeable for different material pairings of agate and steel.

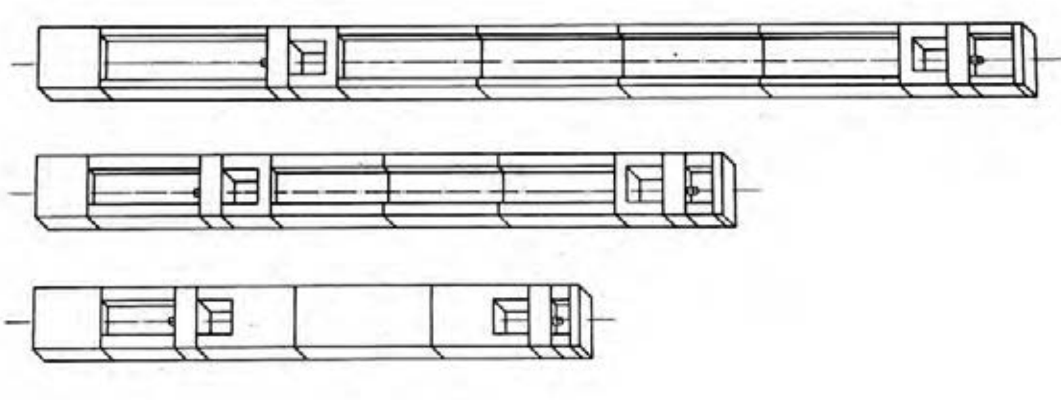
The *measurement of oscillation times* for both pendulums was performed with two separate *electronic counters*, whereas the pre-selection of the number of pendulum oscillations was 1000 oscillations. The oscillation time measurements started when the oscillation process was triggered electromagnetically; the oscillation amplitudes amounted to approximately 14' and were photographically registered. The phase difference between both pendulums did not differ by more than 4° from the target value at the start. The oscillation time measurements were implementable in a least two blade lengths due to the different curvature radii of the blades.

The *determination of the pendulum length* (distance between the blade edges facing one another) took place

- through the *interferometric comparison* of the rear blade surfaces with two quarzetalons, which are arranged in the vacuum container next to the pendulums,
- and by measuring the blade heights on an interference comparator outside of the pendulum device, length in working position; no ventilation was necessary for the length comparison.

The resonance of the stand due to high resonance coefficients (low mechanical stability due to revertability) was taken into account.   Oscillation time and length measurements due to the high temperature coefficients of brass are very highly temperature-dependent; therefore a thermometer pendulum was used in the device. A temperature change of 0.02 degrees Celsius causes a length change of 0.1 µm.

The quartz pendulum device
The measurements on the quartz pendulum device were performed with three pairs of reversion pendulums of different lengths, but the same mass. The reduce pendulum lengths amount to 75 cm, 50 cm and 37.5 cm. The illustration shows a schematic diagram of the pendulum.



Details on the material and form of the pendulums are listed below:

- optical quartz glass apart from small conductive screws
- double T profile (high bending rigidity!)
- even, parallel oscillation surfaces with which they oscillate on fixed blades (measurement of the pendulum lengths with high precision)
- damping of the pendulums with an aluminium layer to avoid electrostatic charging

The pendulum apparatus rests on a massive double pier made of granite. This is pier S12 in the NO cellar of the institute building (no resonance effects need to be taken into account). For both sides of the pendulum apparatus, there was an autocollimation device to adjust the pendulum and to determine the pendulum amplitude (approx. 20’). With the reversion, the pendulums need to be removed and readjusted in the new position.

The oscillation time measuring system included an autocollimation device arranged under the pendulum apparatus and several electronic counters and measuring value printers. The *oscillation time measurements* were performed with each of two pendulums of the same length, which oscillate with a phase difference of 180°, in an evacuated pendulum apparatus at 10^{-4} to 10^{-5} Torr. With regard to the precision of the oscillation time, it is stated that with a measurement time of 1000 pendulum oscillations, the oscillation time was precisely maintained at 10^{-8}. Quartz only has low heat expansion, so that the temperature influence is low and can be recorded with certainty.

Length measurement of the pendulum
A vacuum interferometer was used with a beam according to Dowell, where the distance of the oscillation surfaces of the pendulum are compared with quartz end measurements of a relevant length (necessary to use plane mirrors). The achieved comparative precision was 0.01 to 0.02 µm.

The results of the measurements are:

g_1 = (981 260, 89 ± 0.83) mGal for the 25 cm reversion pendulum device and
g_2 = (981 259, 86 ± 0.29) mGal for the quartz pendulum device and from this

g = (981 260, 1 ± 0.3) mGal as the overall result of the measurements with both devices.

The gravity values relate to double pier S0 in the Pendulum Hall and the reference height 87.00 m. In 1971, "Absolute Schweremessungen mit Reversionspendeln in Potsdam 1968 – 1969" [Absolute Gravity Measurements with Reversion Pendulums in Potsdam 1968 – 1069] was published.

Comparison of results
The new absolute measurements of gravity in Potsdam are the most precise reversion pendulum measurements ever conducted:

g = (981 260, 1 ± 0,3) mGal as the overall result of the measurements 1968 – 1969.

The comparison with the results of other modern absolute gravimeters shows that the new gravity value does not contain any systematic error within the achieved precision.

The gravitational acceleration is dependent on location and time. The location dependency results from the centrifugal acceleration, the flatting of the Earth due to its rotation, the height and the mass distribution in the Earth (with mGal units, these are the variations at 1 to 4 places before the decimal). The time dependency results from the tides of the solid Earth, the air pressure, the pole movement, ground water and soil moisture changes and height changes (with mGal units, these are the variations at 1 to 4 places after the decimal).

New devices for such measurements are transportable absolute gravimeters, which operate according to the principle of free fall or vertical throw. These achieve precisions in the magnitude of a few microgal.

Relative gravity measurements

Basics
The gravity g_A of a station A is calculated from the pendulum measurements according to the formula

$$g_A = 4\,\pi^2\, l / T_A^2$$

with l = reduced pendulum length (distance between the axis and the oscillation centre point) and T_A = oscillation time.

With relative pendulum measurements, the oscillation time T_A and T_B of the same pendulum is determined at stations A and B, where the reduced pendulum length must remain unchanged. This then provides the ratio of gravity values at:

$$g_A / g_B = T_B^2 / T_A^2 .$$

Furthermore, the gravity difference between A and B with the formula resulting from the series development can be calculated:

$$g_B - g_A = -2\, g_A (T_B - T_A)/ T_B + 3\, g_A (T_B - T_A / T_B)^2 - \dots$$

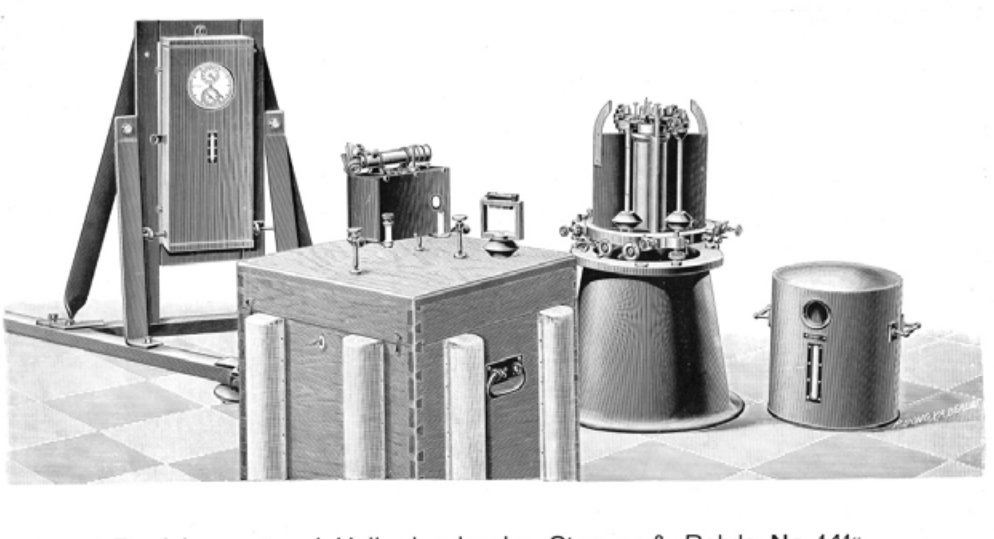
However, the 2nd term only reaches a half unit of the 5th decimal in g_B for $(T_B - T_A) = 2071$ units of the 5th decimal in g_B.In order to check the non-changeability of the pendulum length, the measurements are conducted with several pendulums. Usually, four pendulums are used. The observed oscillation times must be reduced to constant external conditions, by applying reductions for

- influence of the finite amplitude
- air density
- temperature
- elastic stand movement
- magnetic field and
- clock speed

Then, the mean reduced oscillation times will provide the gravitational differences.

Relative pendulum measurements from 1892

From 1892, relative gravity measurements were conducted at the institute with two Sterneck pendulums as testing and follow-up measurements. These were followed in 1908 with newly designed three-pendulum and four-pendulum apparatus, specifically, a three-pendulum apparatus, built by Stückrath, Friedenau, with 3 brass pendulums and with 3 nickel-steel pendulums (invar pendulums) and one four-pendulum apparatus (illustration below), built by Fechner in the institute.



Pendelapparat und Halbsekundenuhr „Strasser & Rohde No. 141“

Related time measurements
First of all, astronomical time determinations were performed at the stations until 1913 in order to determine the speed of the clock. Since 1923, radio-telegraphic time signals have been used for checking the station clock. For the measurements of oscillation time, the electro-optical coincidence observation was used. From 1936, a photographic registration device, designed and tested by H. Schmehl, was used for oscillation time measurements and signal recording.

Geodetic-astronomical time determinations at field stations in 1897
A 10-inch universal instrument by Pistor & Martins or a small Bamberg passage instrument is used to determine time. The usual method for passage observations of stars was used when using a passage instrument in the meridian.
Under normal conditions, two time determinations were observed in the evening according to the scheme of 2 time stars with eyepiece east, 1 polestar with eyepiece east and west, 2 time stars with eyepiece west. With few exceptions, easily determinable stars were used as pole stars of + 82.2°, + 86.6° and 87.2° declination. All of the stars were included in the Berlin Astronomical Yearbook. With the evaluation of a time determination, the collimation was first from the each pole star observation, the azimuth of the instrument from the linking of the observations of pole stars with sidereal stars and finally, the clock correction from the passage times of the sidereal starts, according to the well-known Mayer Formula.

Example for the determination of the oscillation time of a pendulum
A pendulum observation was started when the pendulum, which set put into oscillation with an amplitude of 15’, had been oscillating in the workbox already for a minimum of 30 minutes. At the beginning and end of the observation, the following items were noted: pendulum deflection, air pressure and humidity, as well as temperatures. In order to determine the oscillation term of a pendulum, two rows of 8 consecutive coincidences each were observed with the clock. The time distance between both rows was equal to 20 times the coincidence interval (20 c) and amounted to between 30 and 35 minutes for the 4 pendulums used. The example below illustrates the procedure.

First of all, the oscillation time s of the pendulum in seconds of the coincidence clock is calculated from the observed coincidences period c. As the clock was always regulated according to sidereal time and the oscillation time of the half-second pendulums was always greater than half a sidereal second, the clock and pendulum completed c and 2c – 1 oscillations respectively after the end of a period. Therefore, the formula for calculating the oscillation time is

$$s = c / (2c - 1) = ½ + 1 / (4c - 2) .$$

The reduction of s provides the reduced oscillation time

$$S = s - s \cdot (\mathrm{arc}^2\alpha / 16) - (571^s D + 48^s T) 10^{-7} - \sigma + (s \cdot U) / 86400^s ,$$

where
α-pendulum deflection, D-relative air density, T-pendulum temperature, σ-influence of the resonating pendulum bearing and U-speed of the coincidence clock against sidereal time in 24 hours of clock time are.

Station *Potsdam*. Datum *19. Juni 1900*. Beobachter Borrass. Pendel *No. 5*.

Uhrzeit		Luftdruck und Feuchtigkeit			Ausschlag		Luft-temperatur		Pendel-temperatur	
		Barom.	Temp.	Hygrom.	oben	unten	Beob.-Raum	Arbeits-Kasten	Arbeits-Kasten	Ruhe-Kasten
		mm		%						
Anfang	$2^h\ 15^m$	760.6	18°9	87.5	$7^p.8$	$7^p.8$	14°0	14°14	13°80	13°84
Ende	3 3	760.5	17.1	87.5	5.9	5.9	14.2	14.15	13.84	13.94
Mittel	2 39	760.6	18.0	87.5	6.85	6.85	14.1	14.15	13.82	13.89
Korrekt.		− 5.8 + 0.2		10.4 − 3.9	13′.7			− 19	+ 9	0
		755.0						13.96	13.91	13.89

1	$2^h\ 16^m\ 24^s.4$	21	$2^h\ 50^m\ 12^s.6$	$20\,c = 33^m\ 48^s.2$	$c = 101^s.421$
2	18 3.9	22	51 52.2	48.3	$s = 0^s.5024772$
3	19 46.8	23	53 35.2	48.4	Ausschl. − 5
4	21 27.2	24	55 15.4	48.2	Luftdr. − 537
5	23 10.0	25	56 58.8	48.8	Temp. − 668
6	24 49.9	26	58 38.0	48.1	Mitschw. − 64
7	26 32.8	27	3 0 21.3	48.5	Uhrgang + 4
8	28 12.2	28	2 1.0	48.8	$S = 0.5023502$
				48.41	

Entfernung Spiegel-Skala *1.72 m*. Wert eines Skalenteils (*2 mm*) = *2′*.

The second expression in brackets in the reduction formula contains the pendulum constants with the air density coefficients and the temperature coefficients. These depend on the form and material of the pendulum. They were determined using specific studies.

Development activities

The Geodetic Institute Potsdam performs major development activities for the measuring methods and multi-pendulum apparatus. Extensive studies related to the resonance of the stand, the influence of magnetic fields on invar pendulums and the material and form of the pendulums. First of all, several pendulums were used consecutively in a single-pendulum apparatus in order to identify erratic changes to the pendulum length. The two-pendulum method required a stand with a minimum of two bearings to determine the resonance. Already in 1910, L. Haasemann used a four-pendulum apparatus for pendulum measurements, which was built by Max Fechner in the institute's mechanical workshop. For the measurements with the four-pendulum apparatus, each of two pendulums oscillated simultaneously in vertical levels that faced vertically towards one another. In the 1920s, a four-pendulum hood apparatus and a four-pendulum pan apparatus were produced in the institute workshop. The pan apparatus had a more stable set-up that the hood apparatus. Its special feature is that 4 small consoles fastened to the wall of the pan hold the pendulum bearings. Both apparatus were evacuable to approx. 4 mb. Therefore, the observation period was extended significantly, due to which the influence of the uncertainty of the clock speed was reduced. The simultaneous observation of all four pendulums became possible because an optical bridge came into use, which was developed by H. Schmehl in 1928. Four-pendulum apparatus were built in series production by Askania, Berlin, which are based on the Potsdam pendulum apparatus designs.

Relative pendulum measurements after 1945

In the Geodetic Institute Potsdam, two devices were used with each of two pendulum sets after 1945: a 4-pendulum pot apparatus, built by M. Fechner and a 4-pendulum hood apparatus from Jena. The pendulum sets are half-second pendulums made of invar or quartz. With the gravity measurement, they oscillate against one another in pairs in two levels that are vertical to one another with the same amplitude. The observation of the pendulum oscillation times took place with a photographic registration device or an electronic time measurement system. The measurement precision of the relative pendulum measurements was at approx. ± 0. 2 mGal, which corresponds to a precision of the oscillation time measurement of $\pm 5 \cdot 10^{-8}$ s.

The pendulum devices were used to create a gravimeter calibration line, which was used for checking the scale factors of gravimeters. Furthermore, the gravity differences were determined to Sofia (1958/59), Rome (1964), Mirny and Molodjoshnaja, Antarctica (1964/65), Helsinki and Ivalo (1966). Both of the Askania GS-12 gravimeters were also used for relative gravity measurements in Central Europe and the Antarctic, which were otherwise mainly used for the registration of periodic gravitational changes over time at the Gravimetric Observatory.

Relative pendulum measurements, performed by employees of the Geodetic Institute Potsdam

Time period	**Number of Stations**	**Apparatus**	**Determination of clock´s rate**	**Determination of Resonance**	**Mean error (rate)**	**Mean Error Ø**
1894–1901	114	1-Pendulum apparatus with 4 brass pendulums	Astronomical time determination	Rocker method	± 1,0 mGal	± 3,0 mGal
1902–1907	73	1-Pendulum apparatus with 4 brass or Invar pendulums, 3-Pendulum apparatus with 3 brass and Invar pendulums each	Astronomical time determination	2-pendulum method	± 1,3 mGal	± 2,3 mGal
1908–1913	50	4- Pendulum apparatus with 4 Invar pendulums	Astronomical time determination	2-pendulum method	± 1,0 mGal	± 2,0 mGal
1923–1925	121	4- Pendulum apparatus with 4 Invar pendulums	3-6 time signals of 3-4 Stationsn	2-pendulum method	± 0,8 mGal	± 1,4 mGal
1930 (Ostsee-ring)	8	4-Pendelum pan apparatus with 4 Invar- and 4 bronze pendulums each	4 time signals of 2 Stations, writing chronograph	2-pendulum method	± 0,3 mGal	± 0,5 mGal
1934–1943	293	4- Pendelum pan apparatus and 4-Pendelum hood apparatus with 4 Invar pendulums each	Time signals of 3 Stations , photogr. registr.	2-pendulum method	?	± 0,3-0,4 mGal
1958/59	1	4- Pendelum pan apparatus with 2x 4Invar pendulums	Time signals, photogr. registr., Quartz clocks	2-pendulum method	± 0,03 mGal	± 0,2 mGal
1963–1966 (1963)	3	4- Pendelum pan apparatus with 2x 4 Invar pendulums (+ 1x4 Quartz pendulums), 4-Pendulum hood apparatus with 2x4 Invar pendulums	Time signals, photogr. registr., Quartz clocks	2-pendulum method	± 0,02 mGal	± 0,2 mGal

Observers and processors: Borrass, E., Haasemann, L., Schumann, R., Schmehl, H., Weiken, K., Elstner, C.

The resonance of the pendulum base

From experience, an oscillating pendulum puts the system with which it is connected through the rotational axis, i.e. the stand, the pier and within a certain range, also the ground, into isochronous resonance, the influence of which is identified by an enlargement of the oscillation time in proportion to the weight of the pendulum.
Therefore, the derived oscillation times require a correction due to the small movements of the rotational axis generated by the pendulum movement.

In order to determine this influence, two different methods were used. The **first** method is the so-called *rocking method.* It is comprised of artificially putting the pier into oscillations, which the ground and the main pendulum impart by using a traction dynamometer. When the deflection of the pendulum is observed in the oscillation beat of the pendulum after a number of tractive movements of a given intensity, a measurement has been obtained for the elasticity of the pier and the ground. With the relative pendulum measurements, the piers were investigated regarding their resonance. For this, rocking took place around the piers at distances of 45° each. From the values, the rocking constant was determined for each pier (= 12 for transportable piers, = 8 for pier no. 31 in the Pendulum Hall). This indicates by how many units of the 7th decimal place the oscillation time for a deflection of 1" needs to be corrected with an impact of 1 kg.
The **second** method (2-pendulum method) is based on the *use of a thread pendulum*, which has a suspension point that is firmly connected to the stand heads and is therefore forced to participate in the movements of the same. The ratio of the amplitudes of the thread pendulum to those of the main pendulum provides a direct measurement for the enlargement of the oscillation time of the main pendulum due to the resonance.
The correction of the length of the main pendulum due to resonance was calculated according to the formula

$$\gamma \;=\; \beta_{max} \,/\, \alpha \quad (l - L) \,/\, (\, 1 + e^{(\zeta - z)\, t}\,)$$

where

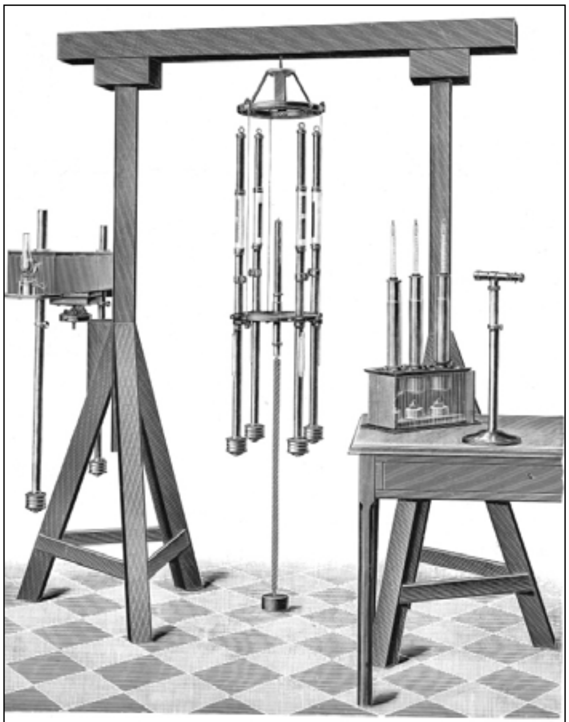
- β - amplitude of the thread pendulum,
- α - amplitude of the main pendulum,
- l - length of the main pendulum,
- L - length of the thread pendulum,
- $e^{-\zeta t}$ - damping coefficient of the main pendulum
- $e^{-z t}$ - damping coefficient of the thread pendulum.

Relative determinations of gravity at foreign stations

Year	**Country**	**Station**	**Observer**
1894	Austria	Vienna, M.-G. I.	Kühnen, F. u. a.
1898	Denmark	Copenhagen, Obs.	Schumann, R.
1898	Norway	Cristiana	Schumann, R.
1900	Austria	Vienna, Obs.	Borrass, E.
1900	Romania	Bucharest	Borrass, E.
1900	Romania	Tiglina	Borrass, E.
1901	Russia	Pulkovo, Obs.	Borrass, E.

First significant gravity measurements on oceans

In 1901, the *first measuring expedition* took place to determine the gravity on the Atlantic Ocean, as well as in Rio de Janeiro, Lisbon and Madrid, by Oscar Hecker. His baro-thermometric g-measurements achieved a precision of ±30 mGal. The apparatus used as an ocean gravimeter is shown in the picture, on the left, there are two photographic-registration mercury sea barometers, in the centre, there are four mercury sea barometers that can be read off visually and on the right, the hypsoapparatus with three hypsometers and the telescope for reading them off. The intensity of the gravity was determined by calculating the gravity correction with the difference between the gravity-dependent air pressure values of the mercury barometer and the gravity-independent steam current values, which were taken from the hypsometer readings using the Wiebe tables. At the locations on the continent, the gravity determinations were performed using relative pendulum measurements.



Barometer und Siedeapparat.

ZENTRALBUREAU DER INTERNATIONALEN ERDMESSUNG
NEUE FOLGE DER VERÖFFENTLICHUNGEN, No. 16

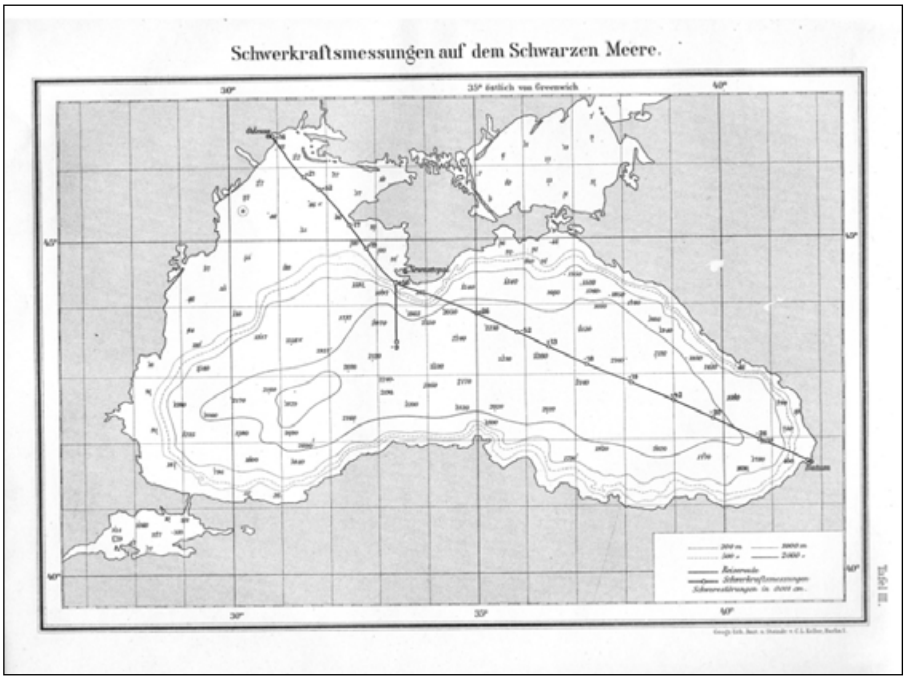
BESTIMMUNG DER SCHWERKRAFT
AUF DEM
INDISCHEN UND GROSZEN OZEAN
UND
AN DEREN KÜSTEN
SOWIE ERDMAGNETISCHE MESSUNGEN
MIT ZWÖLF TAFELN

VON
PROF. DR. O. HECKER

BERLIN 1908
VERLAG VON GEORG REIMER
DRUCK VON P. STANKIEWICZ' BUCHDRUCKEREI

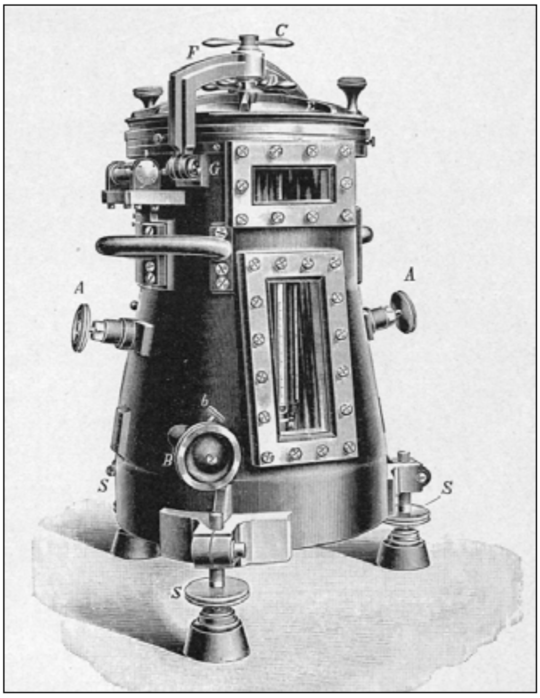
In 1904/1095, the second measuring expedition took place on the Indian Ocean and the Great Ocean and on their coasts. Baro-thermometric g-measurements were performed. Determinations of gravity resulted from relative pendulum measurements on 9 sites: Melbourne, Sydney, San Francisco, Tokyo, Zi-ka-wei, Hong Kong, Bangkok, Rangoon and Jalpaiguri with pendulums no. 16, no. 21, no. 5, no. 7 and no. 8.

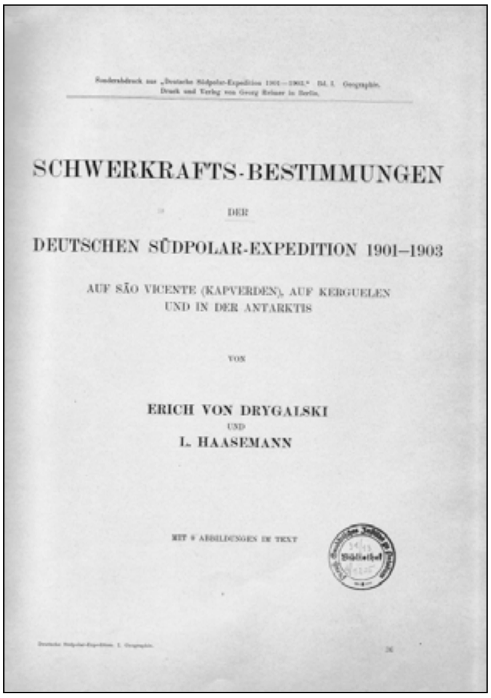
The *third measuring expedition* in 1909 on the Black Sea, led to baro-thermometric g-measurements. In addition to this, there were gravity determinations with the new Potsdam four-pendulum apparatus on land at the Odessa, Tiflis and Bucharest stations. The following pendulums were used for this: pendulum no. 5 made of phosphorous bronze, pendulum no. 7 made of brass and produced in the institute, both with a period of coincidences of approx. 30 seconds; pendulum no. 6 and no. 8 made of brass from Stückrath in Friedenau with the coincidence interval of nearly 100 seconds. The results of the measurements support the theory of isostasy.



Relative gravity measurements of the German South Polar Expedition

From 1901 until 1903, the German South Polar Expedition took place under the leadership of Erich von Drygalski and performed relative gravity measurements with an airtight, sealable two-pendulum apparatus, built according to the specifications of F.R. Helmert by the mechanic, M. Fechner, in the Geodetic Institute Potsdam, with four Stückrath *half-second pendulums.* The processor, L. Haasemann, operated the apparatus at the Porto Grande station on the Cape Verde island of Sao Vicente, at the station on the Kerguelen Islands and in the winter camp in the Antarctic.





SCHWERKRAFTS-BESTIMMUNGEN

DER

DEUTSCHEN SÜDPOLAR-EXPEDITION 1901–1903

AUF SÃO VICENTE (KAPVERDEN), AUF KERGUELEN
UND IN DER ANTARKTIS

VON

ERICH VON DRYGALSKI

UND

L. HAASEMANN

MIT 8 ABBILDUNGEN IM TEXT

Relative gravity measurements with gravimeters

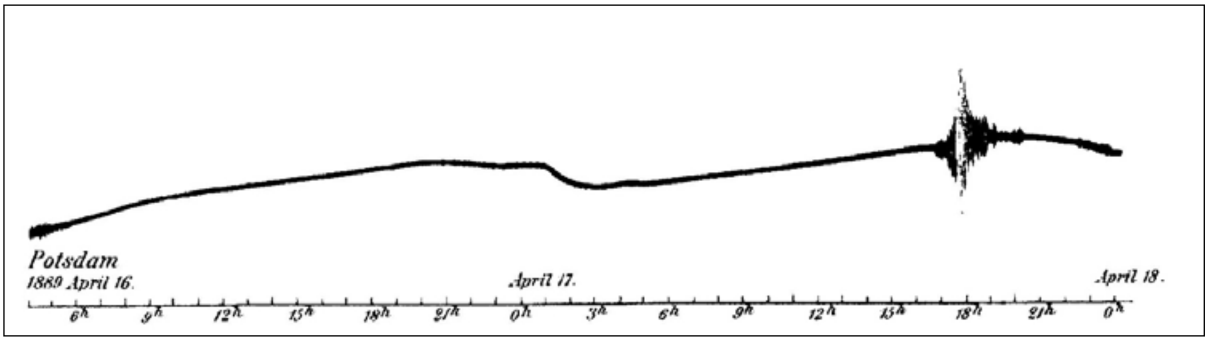
Prinziple of a relative gravimeter
In terms of the principle, the relative gravimeter is a very precise and sensitive spring scale, which is protected from temperature and air pressure fluctuations. It has a spring with a constant mass. During a measurement, the mass expands the spring according to the gravity at the station. The measurements at two different stations provide different length expansions of the spring, if the gravity does not correspond. Therefore, the measured length difference is a measurement for the gravity difference. In order to be able to use the gravimeter for measurements, it must first be calibrated, which takes place on a gravimeter calibration track. A calibration table or a gravimeter factor and a specific calibration function is available from the manufacturer.
Measured, relative gravity differences must be reduced due to various influences, namely due to the effect of tides, the gravimeter speed (gravimeter drift), the effect of air pressure (possibly with several µGal) and possibly different instrument heights.

Tidal gravimetry

The phenomenon of tides
At every location, the amount and direction of gravity are periodically changed by the gravitational pull of the moon and sun. This means that because of this tidal effect, the gravity can vary by approx. $\pm 25 \cdot 10^{-8}$ from 9.81 m/s^2 or up to ± 245 µGal. The tidal wave results from a sum of several hundred partial tides with periods between eight hours and 18.6 years and with amplitudes that depend on the geographical latitude. Specifically for Potsdam, there are only 27 partial tides with amplitudes that are greater than 1 µGal.

In order to measure fluctuations of gravity (gravity intensity) over time, gravimeters are used at gravimetric observatories. For recording the time fluctuations of the direction of the gravity (pole fluctuations), horizontal pendulums and inclinometers are used.

First evidence and recordings of tidal pole and gravity fluctuations
In 1889, the first experimental evidence was found of tidal pole fluctuations with horizontal pendulums by Ernst von Rebeur-Paschwitz (1861-1895) in the cellar under the east dome of the Astrophysical Observatory. This also provided the 1st recording of a remote earthquake (Japan earthquake on 17 April 1889).



Initial recordings of tidal pole fluctuations with horizontal pendulums over a longer time period in the measuring chamber from a depth of 26 m in the deep well on the Telegraphenberg succeeded in 1902-1909 by Oskar Hecker (1864-1938). During the years 1910 to 1920, measurements were conducted with two horizontal pendulums in Reiche Zeche in Freiberg/Saxony at a depth of 189 m by Wilhelm Schweydar (1877-1959). The recordings of the gravity intensity with a bifilar gravimeter in the measuring chamber of the deep well by W. Schweydar from 1913-1914 are prominent. The period of the M_2 tide amounts to 12.4206 h in mean solar time. In order to find the half-day M_2 tide from the one-year measurements, the hourly readings were grouped by M_2 hours. After eliminating the zero point and deducting a constant (reduction to the airless void), the sums formed over 295 days resulted in the mean values for the dg/g of the M_2 tide in units 10^{-8}. The **illustration** graphically shows the M_2 tide derived from the observations made with the bifilar gravimeter. With the applied method, the amplitude is multiplied by a factor of 1.0115, so that the following expression results for the M2 tide:

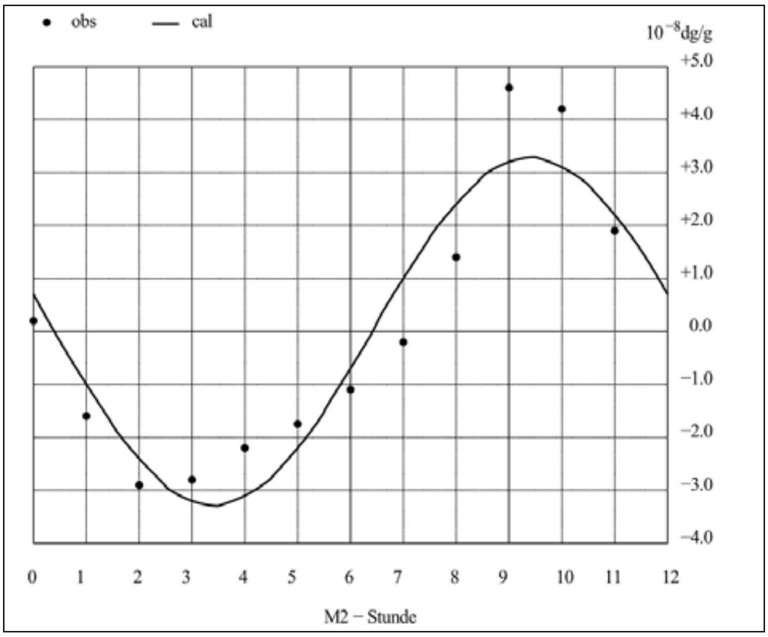
$$dg/g = 3.32 \times 10^{-8} \cos(2t + 77.5°)$$

with t – mean solar time

For a rigid Earth, the expression is:

$$dg/g = 2.76 \times 10^{-8} \cos(2t + 74.7°).$$

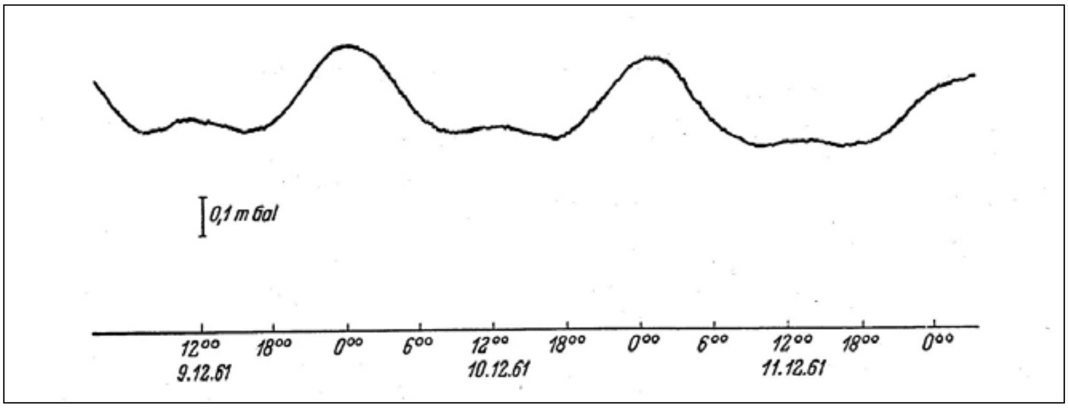
This means that the calculated amplitude factor is 1.20. Schweydar’s determination of the amplitude of the M2 tide from one-year measurements was precise, down to a few percent.



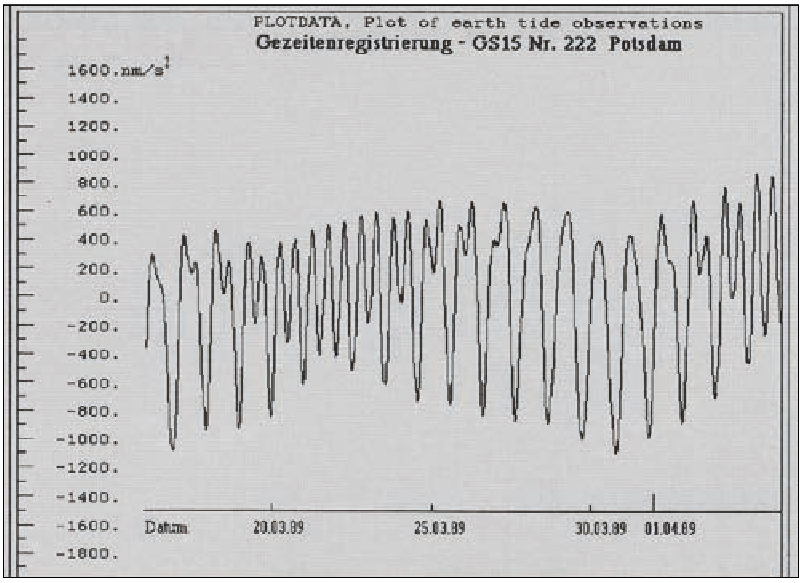
Continuous registration of tides at the Gravimetric Observatory

In order to measure tidal changes in gravity over time, a gravimeter station was set up at the Geodetic Institute Potsdam by Jörg Byl in a cellar room on the south side of the main building, which was operated from 1957 to 1965 with the *Askania GS-12 gravimeter* no. 137. The device is a non-static gravimeter which is not protected from external forces, the design of which is based on the principle of the torsion spring scale. In order to illustrate the tidal registration obtained at that time, the picture shows a recording from December 1961. From

1969 onwards, the devices were set up in two neighbouring cellar rooms, in the previous cellar room as a gravimeter room, with the gravimeter on its own and in the other as a registration room, with the equipment for the electrical supply, the measurement amplifiers and the compensation strip chart recorder.



Since 1973, tidal registrations have continuously been performed with the *Askania GS-15 gravimeter* no. 222 by Hans-Jürgen Dittfeld (1938-2004). As the noise of the registration only accounts for approx. ±1 µGal, hourly readings are significantly more precise that those received with the Askania GS 12 gravimeter. To compare with the recording from December 1961, a plot of the tide times is given, as measured in March 1989 with the Askania GS-15 gravimeter. In Potsdam, the measurement series became the longest registration of tides with this gravimeter.



The studies on the observation material according to the analysis methods developed by Pertzev and Venedikov concluded that homogeneous measurement series over more than a year with the older device of the type Askania GS-12 can be used for exact determination of the parameters of the main tides, M_2, S_2, O_1 und K_1, but not for studying the space-time microstructure of the spectrum gravity variations.

For the first four measurement series registered with the Askania GS-15 gravimeter, which only covered 1.5 to 2 months, i.e. are relatively short, sufficiently significant results were able to be derived from the full-day partial tides, Q_1, O_1 and $P_1S_1K_1$, and half-day partial tides

N_2, M_2 and S_2K_2 (table 1). The mean errors of the amplitudes are up to a magnitude smaller in comparison to those from the older gravimeter registrations. It is worth mentioning that the meteorologically influenced wave groups $P_1S_1K_1$ and S_2K_2 were easier to determine. After this, there was an analysis of the measurement series from 17 years, which provided the amplitudes and phases of 73 of the more than 1200 partial tides. Very long measurement series not only make a further resolution of closely neighbouring waves possible, but also the study of long-period changes in gravity and the effect of external mass redistributions of a meteorological and hydraulic nature.

Tafel 1. **Harmonische Konstanten nach *Venedikov*-Analyse**

Serie	17. 11. 73 bis 30. 12. 73 (44 Tage)		31. 12. 73 bis 14. 02. 74 (46 Tage)		16. 02. 74 bis 15. 04. 74 (59 Tage)		17. 04. 74 bis 06. 06. 74 (50 Tage)	
Partialtide	Amplitudenfaktor	Phase [°]	Amplitudenfaktor	Phase [°]	Amplitudenfaktor	Phase [°]	Amplitudenfaktor	Phase [°]
Q_1	$1{,}223 \pm 0{,}097$	$-1{,}0 \pm 4{,}6$	$1{,}153 \pm 0{,}030$	$1{,}5 \pm 1{,}5$	$1{,}149 \pm 0{,}026$	$1{,}2 \pm 1{,}3$	$1{,}134 \pm 0{,}017$	$-0{,}5 \pm 0{,}9$
O_1	$1{,}165 \pm 0{,}021$	$-0{,}6 \pm 1{,}0$	$1{,}155 \pm 0{,}007$	$0{,}1 \pm 0{,}4$	$1{,}158 \pm 0{,}005$	$0{,}1 \pm 0{,}2$	$1{,}155 \pm 0{,}003$	$-0{,}2 \pm 0{,}1$
$P_1S_1K_1$	$1{,}144 \pm 0{,}011$	$0{,}5 \pm 0{,}6$	$1{,}135 \pm 0{,}004$	$0{,}4 \pm 0{,}2$	$1{,}135 \pm 0{,}004$	$0{,}4 \pm 0{,}2$	$1{,}144 \pm 0{,}002$	$0{,}4 \pm 0{,}1$
N_2	$1{,}175 \pm 0{,}034$	$0{,}3 \pm 1{,}7$	$1{,}167 \pm 0{,}018$	$2{,}4 \pm 0{,}9$	$1{,}145 \pm 0{,}013$	$2{,}2 \pm 0{,}7$	$1{,}164 \pm 0{,}008$	$1{,}2 \pm 0{,}4$
M_2	$1{,}182 \pm 0{,}008$	$1{,}2 \pm 0{,}4$	$1{,}178 \pm 0{,}004$	$1{,}4 \pm 0{,}2$	$1{,}188 \pm 0{,}003$	$1{,}0 \pm 0{,}1$	$1{,}189 \pm 0{,}002$	$0{,}8 \pm 0{,}1$
S_2K_2	$1{,}164 \pm 0{,}020$	$-1{,}0 \pm 1{,}0$	$1{,}182 \pm 0{,}008$	$-0{,}3 \pm 0{,}4$	$1{,}174 \pm 0{,}004$	$0{,}0 \pm 0{,}2$	$1{,}179 \pm 0{,}004$	$-0{,}2 \pm 0{,}2$
Fehler der Ordinate								
ganztägig:	8,75 µGal		3,18 µGal		2,35 µGal		1,38 µGal	
halbtägig:	3,00 µGal		1,66 µGal		1,18 µGal		0,66 µGal	

Topic 5: Accuracy checks

Initial activities

The initial activities of the Central Bureau of the European Arc Measurement and in the Geodetic Institute included comparing all of the scales used with the triangulations to be linked together with *Bessel's Toise*, which was to be used as a unit. In 1866 and 1867, Baeyer, Albrecht and Sadebeck performed the *measurement comparisons* listed below on the Bessel comparator: Copy no. 10 of the Bessel Toise with copy no. 18, produced for the North American government, copies no. 12 and 12, produced for the Brazilian government, and the Italian toise by Spano.

The problem that the *expansion coefficient* changes over time was investigated by Baeyer from specifications of the Bessel basis apparatus for iron and zinc rods from 1834, 1846 and 1854. As the expansion coefficients had reduced, it was to be investigated whether the ageing of the material could be responsible for this. A comparison of Ancient Roman bronze rods with newly produced rods was envisaged for this, but was not done. Another problem that was identified related to the lagging-behind of the temperature of the measuring rods compared to the display on the mercury thermometer.

In the years 1907 to 1910, O. Toepfer & Sohn, Potsdam built a *comparator for 4-m baseline measuring rods* according to a design by Kühnen. In the years 1918 to 1921, this served to compare the measuring rods of the Austrian, Bessel and Brunner baseline apparatus with normal metres. As a result, the achieved precision was at $\pm 0.2 \times 10^{-6}$ to $\pm 0.8 \times 10^{-6}$, where the normal metre is approx. $\pm 1 \times 10^{-6}$ precise. After this, the device was no longer used, because in the 1930s, *invar wires from a length of 24 m* were virtually exclusively used *for baseline measurements.*

In 1891, a *horizontal baseline of 240 m in length* was set up to the south of the Potsdam main building, divided by intermediate points at a distance of 80 m. The end fixed points were to be solidly grounded. In addition to this, each one had a second point at a 1 m distance in the direction of the baseline, which has extra grounding and lies 1 m deeper. These points were covered with iron plates. In each of August 1924 and in January 1926, this baseline was measured 8 times, in order to study the Brunner rod at high and low temperatures. There were differences in the sub-sections, which originated from changes of the fixed points and/or imprecisely determined expansion coefficients for the temperature intervals.

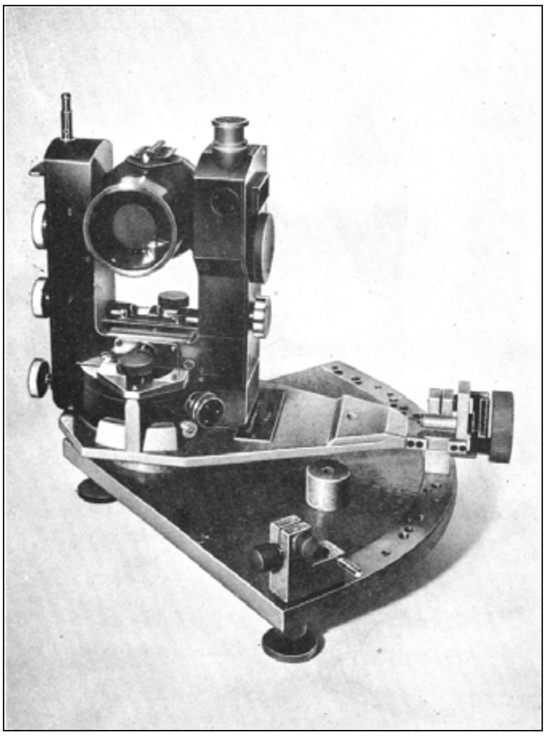
In order to test the 24-metre-long invar wires for baseline measurements, Mühlig, Picht and G. Förster performed *initial tests* from 1925 to 1930, in order to use light interferences for longitude measurements with the highest precision. From 1937 to 1943, the activities of Mühlig and Ritter were continued according to a Japanese principle, however, they were not able to be completed due to the war and post-war events.

Developments after 1945

The previous activities were continued at the Geodetic Institute Potsdam. These initially related to tests of circular graduations, seconds' spirit levels and length measuring instruments, before these activities were limited to the geodetic length measuring instruments from 1970.

In order to *test seconds' spirit levels*, the institute had the large Hildebrand spirit level tester until 1945. This allowed instruments of up to 20 kg to be recorded. There was an urgent requirement for a new, equivalent spirit level tester. Therefore, a device was built in the institute workshop according to W. Uhink, which permitted the examination of a suspended spirit level with an attached support arm or two unmounted spirit levels together with a box. The *new spirit level tester* proved to be a fully-fledged replacement for the large Hildebrand spirit level tester.

For *testing unmounted circular graduations*, a circular graduation testing device was available from Askania. Examinations of graduations could specifically take place, which are found on a graduation carrier with a diameter of up to 500 mm made of glass or metal. The results are line and diameter errors, where the measuring uncertainty is approx. $\pm 2 \times 10^{-6}$. In order to also test *circular graduations that are installed in* instruments, a limit stop testing device was built (see illustration). The testing procedure is partially automated.



In order to *test geodetic length measurement instruments,* the following could be used:

- the International Standard Baseline Potsdam
- an interference comparator with a length of 24 m
- a partial-length comparator with a length of up to 24 m
- a dilatometer from a length of 24 m and
- a longitudinal comparator with a length of up to 2m.

The table on the next page provides a compilation of which testing options exists and were offered as a service.

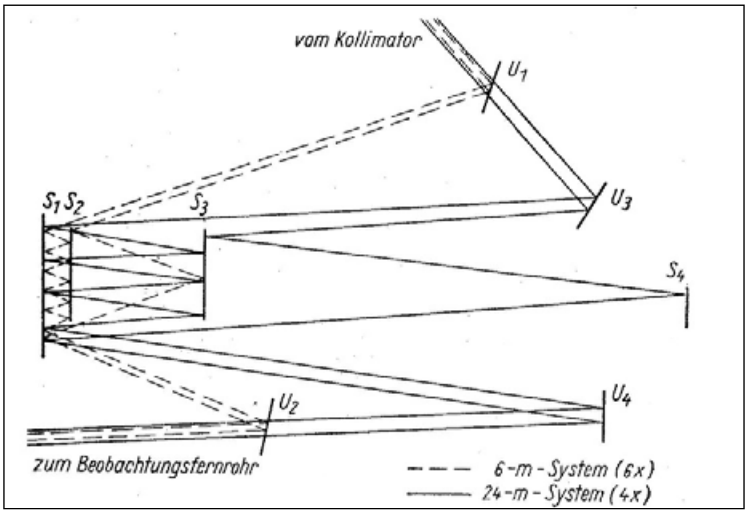
Längenmeßmittel	Länge (m)	Art der Prüfung	Meßunsicherheit (WECC-Norm)
EDM-Geräte	960	Prüfung durch den Interessenten	
Invarmeßdrähte	24	Gesamtlänge	$u = 20 \mu m$
		Längen-Temperatur-Koeffizienten	$u_\alpha = 2 \times 10^{-8} K^{-1}$ $u_\beta = 1 \times 10^{-9} K^{-2}$
Invarmeßband	24	Gesamtlänge frei durchhängend, aufliegend	$u = 20 \mu m$
		Meterteilung aufliegend	$u = 50 \mu m$
		Längen-Temperatur-Koeffizienten	$u_\alpha = 2 \times 10^{-8} K^{-1}$ $u_\beta = 1 \times 10^{-9} K^{-2}$
Strichmaßstab	1 2	Gesamtlänge	$u = 20 \mu m$
Maßstab mit schneidenförmigen Enden	1	Gesamtlänge	$u = 10 \mu m$
Basislatte	2	Gesamtlänge	$u = 20 \mu m$
		Markenexzentrizität	$u = 0{,}2 mm$
Nivellierlatten mit Teilung auf Invarband	bis 3	jede Marke	$u = 5{,}5 \mu m + 1{,}6 \times 10^{-6} \times l$

International Standard Baseline Potsdam

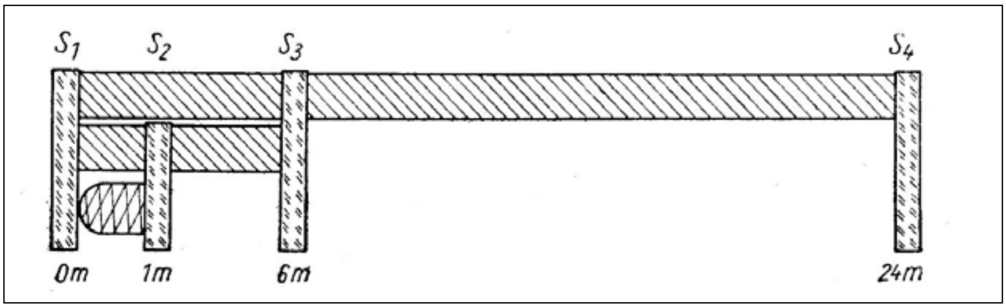
As the 240-metre baseline for the comparison of geodetic length measuring instruments set up on the institute grounds in 1891, e.g. invar wires from a length of 24 m under field conditions, proved to be too short, a new baseline with a length of 960 m was set up in 1931 in a forest area on Michendorfer Chaussee on the outskirts of Potsdam. Its baseline points, beginning, middle and end, are securely marked underground and above ground. The baseline length is 40 times 24 m. Measuring marks are stationed on concrete piers at a height of approx. 0.8 above ground at a distance of 24 m. According to the Jäder method, the baseline was measured several times with 24-metre invar measuring wires, also in international cooperation. In 1964, the virtually horizontal southern half was determined with the Finnish Väisälä interference comparator. With this, the baseline was linked to the standardised scale worldwide and it became an international standard baseline. The somewhat tilted northern half was determined by Kühne and Rauhut with a specifically developed interference comparator and both halves were compared with one another using a specific interference method.

The 24-metre interference comparator

The measuring principle of the comparator lies in the optical distance multiplication using light inferences, which are generated by Frauenhofer diffraction on the double-slit. The 24-metre interference comparator is a modification of the well-known Väisälä interference comparator. The illustration shows the beam in the 24-metre interference comparator. With this: S_1, S_2, S_3 and S_4 - are distance reflectors and U_1, U_2, U_3 and U_4 – are passive reflectors.



A basic distance of 1 metre in length, which was determined with the quarzetalon, is enlarged to 24 m in two multiplication stages. In each stage, the path lengths of two light bundles are compared with one another. One is reflected multiple times in a smaller, known track section, but the other, in the larger track section to be determined, is only reflected once. The illustration shows the arrangement of the 1-metre quarzetalon between S_1 and S_2 **a**nd the position of both multiplication systems.



The comparator was set up in a purpose-built comparator building at the International Standard Baseline Potsdam. Its elements are arranged on a pier, which was grounded independently from the building foundation. The 24-metre distance can be reproduced with an uncertainty of approx. 8 µm. The length of an invar measuring tape can only be determined with an uncertainty of 20 µm.

The partial-length comparator
In order to determine the position deviations of the metre marks of measuring tapes, a basic optical-mechanical comparator was built. A 25-metre-long invar rod is movably mounted on 52 ball bearings. At a distance of one metre, measuring marks are attached. The invar rod is locked in at one end. A 24-metre invar measuring tape to be tested can be applied and tightened. At each metre mark, coincidence can be set by moving the measuring tape. The small movement distances are displayed by a dial gauge and evaluated accordingly. The uncertainty of the calculated position deviations amounts to 50 µm.

The dilatometer
In order to determine the length-temperature coefficients of invar measuring wires and tapes, a dilatometer was developed and built. In a temperature range of 40 K, the values for the length change are measured based on the temperature. The tempering optionally takes place by heating the air surrounding the test piece in a tube system or directly using electric current. The temperature is derived integratively from the electrical resistance of the measuring object. The change in length is recorded with spiral microscopes. The uncertainties for the calculated coefficient for the linear term α are: $u_\alpha \leq 2 \times 10^{-8}\ K^{-1}$ and for the quadratic term β: $u_\beta \leq 1 \times 10^{-9}\ K^{-2}$

The longitudinal comparator
For geodetic measuring instruments with a length of up to 2 m and precision levelling bars of up to a length of 3 m, there has been a longitudinal comparator since 1964. This comparator was constantly enhanced and fulfilled the current requirements of geodetic practice. It was set up in an air-conditioned cellar room and guarantees low measurement uncertainties with high constancy of temperature in the measuring space. It is equipped with a sensor for automatic measurements and with several microscopes for visual measurements. For the length measurements, an incremental incidental light measurement system and a laser measurement system are available. A personal computer is connected for entry, evaluation, documentation and archiving of all measurement data. With this comparator, testing particularly takes place on:

- 2-metre subtense bars: total length and mark eccentricity
- graduated scales up to a length of 2 m: total length and errors of the marks
- measuring standards with blade-shaped ends: total length
- invar levelling bars up to a length of 3m: errors of all marks.