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Geodetic Research in Finland in the 20th Century

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1. Birth of geodetic tradition in Finland

The Earth was considered to be a sphere until the end of the 17th century. Only then, the concept of an Earth flattened at the poles was beginning to gain support among scientists. A powerful influence in this respect had especially the Englishman *Isaac Newton*, who, in his opus Principia, appearing in 1687, described, based on his theoretical investigations, the Earth as flattened at the poles in a ratio of 1:230.

1.1 Lapponian arc measurement

The genesis and development of a geodetic tradition in Finland was in fact the result of Newton's theoretical investigation mentioned earlier, as it was connected with a scientific disagreement receiving extensive international attention, which was resolved here in our northern country.

The French astronomers did not consider Newton's result correct, because arc measurements performed in 17th and beginning 18th centrury in France had proved the opposite, i.e., the Earth is elongated at the poles. This was quite certain at least in the mind of the famous astronomer *J. Cassini*; he had personally handled the arc measurements and obtained for the amount of elongation as much as 7.5%.

A heated debate took place in the French Academy on the subject "prolate or oblate", and the most renowned cultural personality of the day, the enlightenment writer *Voltaire*, described how in Paris the Earth was considered melon-shaped, whereas in London it was flattened from both "sides".

In order to resolve the disagreement, the Academy equipped two expeditions to perform measurements along a meridian arc: one to the equator, the other to the high North. Each of the expeditions was to determine the length of a meridian arc of one degree in its respective area of measurement. If it were longer in the North than in the equator, Newton was right, in the opposite case Cassini.

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One of the expeditions, led first by *Louis Godin*, but later by *Charles-Maria de La Condamine*, traveled in 1735 to the equator in Perú, and the other, led by *Pierre-Louis Moreau de Maupertuis*, traveled in 1736 to Lapland, the Torne river valley.

The Lapponian arc measurement was carried out mostly on the present Finnish territory – then a Swedish province. The expedition completed its work in 1737. Because the meridian arc of one degree turned out to be clearly longer up in Fennoscandia than the similar arc in France, scientific evidence had been obtained to the effect that the Earth was flattened at the poles. The Peruvian expedition completed its work not before 1744. Its result confirmed that of Maupertuis.

The arc measurement extending from the town of Tornio to the top of the hill Kittisvaara in Pello attracted great attention abroad. Finland, the far away land in the North, came into the focus of international attention, and Maupertuis' work published in 1738: *La Figure de la Terre* attracted an ample readership among the European elite of the day, and no less attention attracted the work *Journal d'un voyage au Nord*, published in 1744 by Maupertuis' travel companion, the abbott *Outhier*. Above all the romantic descriptions of nature in these writings attracted the attention of contemporaries and sparked a longing for magic, far away Lapland.

1.2 Historical triangulations in the North after Maupertuis

The Lapponian arc measurement affected in a positive way also the mapping activities in the then Swedish-Finnish kingdom. It did not just terminate the debate on the figure of the Earth, but was also beneficial to the mapping of the realm: Maupertuis' measurements had provided both Tornio and Kittisvaara with precise latitude values by means of astronomical measurements. Mapping the realm had not been feasible without precise geodetic measurements. Soon such were made throughout the extended territory of the kingdom.

In 1748, a special surveying committee was established in Finland, and as its first observator was named *Jakob Gadolin*. He measured in 1748–1750 and 1752–1753 the Turku-Åland triangle chain, and from there on across the Åland Sea to the Swedish coast at Grisslehamn. In 1754 *Johan Justander* continued the work of Gadolin, who had gone to Turku University to become Professor of Physics, by extending the triangulation eastwards from Turku, along the coast of the Gulf of Finland, arriving in Helsinki in 1774.

In 1801–1803 the Swede *Jöns Svanberg* repeated Maupertuis' measurements along the original triangle chain, at the same time extending it to both North and South. However, the interest of Svanberg was not mapping but a check on the flattening ratio of the Earth.

Also the Russo-Scandinavian arc measurement, planned by one of the great names in the history of astronomy, *Wilhelm Struve*, was done to check the dimensions of the Earth. This measurement started at the Danube delta, ran through Belo-Russia and Estonia to Finland and from here onward into the Norwegian fells and the Arctic Ocean.

It entered Finland from Gogland island and, passing west of Loviisa to the area of Jyväskylä, ran from there on through Kajaani, Oulu, Tornio and Muonio to Hammerfest. The measurements were started in 1816, and the angle observations in the part located in Finland were done in 1830–1845.

Of the triangulations which took place during the 19th century, also the Baltic triangulation must be mentioned. It was done by the Hydrographic Department of the Russian Naval Ministry in 1828–1838. This measurement ran along the coast of the Gulf of Finland from the Eastern border to Åland and from there to Sweden, where it connected to the points Söderarm, Arholm and Grisslehamn determined by Swedish geodesists. All in all 398 triangulation points were measured on the Finnish territory.

Neither of these measurements mentioned above, the Russo-Scandinavian arc measurement and the Baltic triangulation, was very useful to Finnish mapping. In both measurements the triangulation point set was poorly marked in the terrain, as a result of which points were later difficult to find, and a large part of them soon vanished completely.

1.3 H.J. Walbeck and the Dimensions of the Earth

Besides the geodetic measurements summed up above, also original geodetic research was done in Finland during the 19th century, especially by the astronomer *H.J. Walbeck* of the Observatory of Turku. At the age of 25 only, Walbeck published the work *De forma et magnitudine telluris ex dimensis arcubus meridiani definiendis* (Determining the figure and size of the Earth by means of meridian arc measurements). In it he, as one of the first to do so, applied the least squares procedure known from mathematical statistics to the determination of the figure and dimensions of the Earth. He derived the dimensions of the Earth from five different arc measurements, obtaining a = 6 376 896 km and f = 1:302.8, values used in Russian geodetic measurements for almost a century. Through his publication, Walbeck got acquainted with Wilhelm Struve, and planned on Struve's request the course through Southern Finland of the triangulation chain belonging to the Russian-Scandinavian arc measurement.

1.4 The establishment of the Finnish Geodetic Institute

On July 5th, 1918, seven months after Finland had become an independent state, the Government of Finland established the Finnish Geodetic Institute. The main task of the institute was defined as the first order triangulations with the geodetic and astronomical measurements belonging to it. Additionally the institute was to collect and organize geodetic material from elsewhere as well as to take initiatives for completion of the geodetic-astronomical base which directly belonged to its mandate. The second task of the institute was defined as pure scientific research: it was to promote the solution of problems connected with its practical work, investigate geodetic (i.e. geoid-related) elements and follow closely the development of geodesy.

Fig. 1. H.J. Walbeck.

The scientific activity in accordance with the Regulation concerning the Finnish Geodetic Institute was most of all internationally significant, because through it, geoid research was extended to include Finland. This became later of major importance to the development of the institute.

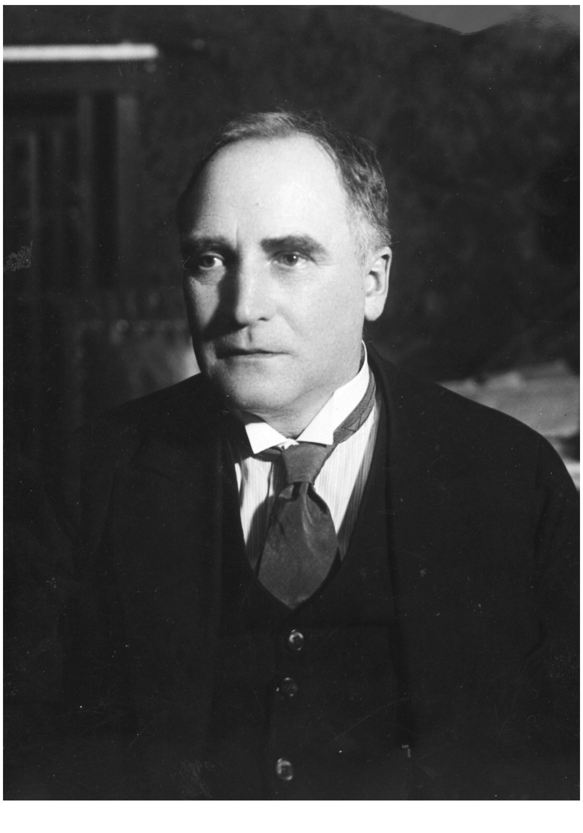

Fig. 2. Professor Ilmari Bonsdorff, director of the Finnish Geodetic Institute from 1918 to 1949. (Finnish Geodetic Institute's Collection.)

2. Primary triangulation of Finland

In its early years the Finnish Geodetic Institute created the material preconditions for performing first order triangulations. This included the procurement of suitable measurement instruments. The director of the newly founded Institute, *Ilmari Bonsdorff*, travelled promptly to Germany in order to personally make up contracts on the purchase of devices and instruments with the factories manufacturing these. As a result of this journey, our country obtained a set of excellent measurement devices, among others three Hildebrand-theodolites for triangulation, two Hildebrand universal instruments and one Bamberg universal instrument for astronomical direction determinations as well as two Bamberg transit instruments for astronomical positioning.

Based on the above, the Institute initially decided to measure only simple triangle chains, with rather large holes in-between. This main network would then later be strengthened by doubling the chains or filling the holes with new triangulations. In order to obtain the greatest possible accuracy, it was decided firstly to make the triangle sides 30–50 km long, the triangle angles at least 40° and the standard errors of the angle measurements as computed from observation series at most 0.3″. Additionally baselines were to be measured in the various parts of the net, 3–6 km long, so precisely and so many of them, that the remaining scale error of the triangle sides would nowhere exceed 5 mm/km. As aiming points, only lighted targets were decided to be used; i.e., no unlit triangulation towers or their signals like in lower order triangulations.

Astronomical latitude and longitude determination was decided to be performed on all points of the main network in order to determine the deflections of the vertical. These “disturbing quantities” had to be known, because angle measured within the true horizontal plane had to be projected, for mapping purposes, onto the tangent plane to the reference ellipsoid. If, in addition to astronomical longitude, also the astronomical azimuth was determined, a triangulation point was called a *Laplace point*. In one point, such a measurement was mandatory in order to orient the triangle network, with multiple Laplace points it became possible to formulate so-called *Laplace equations*, which were used in the adjustment of the triangulation as constraint conditions, in order to minimize the effect of systematic errors.

2.1 Field work of the primary triangulation

One may say that the field works of the Finnish Geodetic Institute commenced officially on May 19th, 1919, when the civil servants employed by the Institute at that time, travelled under the leadership of Ilmari Bonsdorff to a hilltop in the village Paipis in the parish of Sibbo, in order to start the terrain work needed for the construction of the triangulation net. Among these civil servants were, among others, *Yrjö Väisälä*, who was made responsible for the triangulation sites west of Paipis, and *Jaakko Keränen*, who assumed responsibility for the points east of Paipis. The triangulation field crews received assistance from soldiers of the Finnish Armed Forces. Also their work in this field in the service of the fatherland made the triangulation field works possible on the scale that they were planned on.

Fig. 3. Professor V.R. Ölander, who played an essential role in making the triangulation succeed. (Finnish Geodetic Institute's Collection.)

Starting from Mount Paipis, the triangulation expanded to cover the whole of the country. Its central part, the main network with its loops, was completed and published during the 1960's, and its augmentation to its present form by the co-operation of the Finnish Geodetic Institute and the Geodetic Office of the National Board of Survey, was completed in 1987. The net comprised a total of 390 points, of which 63 belonged to the baseline enlargement networks. Astronomical position determinations were performed on all but one of the triangulation points. Until 1936, every point in the main network became a Laplace point. In the later measured chains, only on every third point an azimuth was taken.

The scale of the completed primary triangulation was determined with the aid of 16 baselines. These were measured using invar wires of length 24 metres, the lengths of which were derived from the calibration baseline in Santahamina during 1921–1934, and after 1934, from the normal baseline in Nummela. The lengths of the baselines were from 2.4 to 6.2 km and the precisions from 0.5 to 2 mm. From the baselines, lengths were derived for the corresponding triangulation network sides, and thus for the whole network, through the use of baseline enlargement nets, separate small triangulation networks. The network was tied through the Torne river valley, across the Bothnian channel and over Åland to the Swedish triangulation, and at the location of Helsinki to the Estonian triangulation network. At the southeastern border the network extended onto the territory of the former Soviet Union.

The Finnish primary triangulation is the most precise of its kind in the world, as in it, the relative errors between neighbouring triangulation points are at most a few centimetres. *V.R. Ölander* has played an essential role in making the triangulation succeed. Also the effort of *U. Pesonen* was considerable, as well as that of *E. Hytönen*, *J. Korhonen* and *T.J. Kukkamäki*. Of the younger generation of geodesists especially *R. Konttinen*, *J. Kääriäinen*, *T. Parm* and *M. Poutanen* must be mentioned, on whose shoulders the augmentations of the main network have rested. In addition, T. Parm has measured by geodimeter a traverse extending from Jänhiälä to Kaamanen (Inari), of length 880 km, in order to check the scale of the main network.

2.2 Coordinate systems and geodetic datum

In order to get a geodetic system, we must have, in addition of the radius a of the equator and flattening f of the reference ellipsoid, a datum point, i.e. its geodetic coordinates: latitude φ and longitude λ, and the azimuth A of some direction at this point. If anyone of these five quantities: a, f, φ, λ, and A changes, the whole geodetic system changes too.

The classical procedure of the terrestrial triangulation is the following: we compute, starting from the datum point, the geodetic coordinates and azimuths φ, λ, and A of the points of the triangulation net on the reference ellipsoid. The astronomically observed corresponding quantities φ', λ' and A' are referred to the geoid. The difference between these quantities gives the known equations for computing the vertical deflection components ξ and η. These equations are

$$\begin{cases} \xi = \varphi' - \varphi \\ \eta = (\lambda' - \lambda)\cos\varphi \\ \eta = (A' - A)\operatorname{ctg}\varphi \end{cases} \tag{1}$$

The last two equations give the famous *Laplace's equation*:

$$A' - A = (\lambda' - \lambda)\sin\varphi \tag{2}$$

Computed values of the vertical deflection components ξ and η at the triangulation points are not absolute (geocentric) but only relative. They depend on the dimensions of the reference ellipsoid, a and f, as well as on how correctly the vertical deflection components of the datum point, ξ_0 and η_0, are known. If anyone of them is wrong, especially ξ_0 and η_0, we get quite "incorrect" components ξ and η (*Heiskanen,* 1951), relating to a non-geocentric reference ellipsoid.

The Finnish Geodetic Institute took in use for its own calculations the so-called Hayford ellipsoid, which in 1924 also was chosen *as the international reference ellipsoid*. Its dimensions are a = 6 378 388 km and f = 1:297.0. In 1922 also the National Board of Survey and the National Board of Navigation decided to use the Hayford ellipsoid as the basis for their own maps. Thus the same ellipsoid was used in Finland as the basis for all maps, and at the same time the trouble that may be caused by using different ellipsoids for the maps of the country was avoided.

The choice of the datum point proved to be a problem, because the coordinate system that had been in use before 1922 was heterogeneous and imprecise, and could not guarantee proper coordinates for a datum point. When the Finnish Geodetic Institute published in 1924 the results of its first triangulation chain (Åland–Helsinki), it chose for the coordinates of the datum point the astronomical coordinates of the point Hjortö, in Korpo. The *Hjortö system* soon proved to be unsuitable and already in 1927 the Institute abandoned it, moving to a new adjusted system partly based on gravimetric measurements. In 1931, the Institute published an improved version of the adjusted system, the so-called second adjusted system. The fourth system used by the Finnish Geodetic Institute was the all-European ED-50, or *European Datum* 1950, the starting coordinates of which were defined thus, that they produced a minimum for the square sum of the plumbline deviations for approximately 100 points all over Europe. The results of the adjustment of the primary triangulation published in 1967 were given in the ED-50 system.

When the National Board of Survey in 1922 moved to using the Hayford reference ellipsoid and *Gauss–Krüger* rectangular coordinates with zones three degrees wide, it chose at the same time as starting coordinates the coordinate values for the Helsinki astronomical observatory at the time, its longitude reckoned from the Greenwich meridian. This choice was mainly dictated by practical considerations, as the works of the Finnish Geodetic Institute had only just started, and precise values for the coordinates of the observatory were not known yet. This so-called *Helsinki System* was used by the National Board until 1970. Not until the network of the primary triangulation had been adjusted by the Finnish Geodetic Institute, did the National Board of Survey move to using, instead of the Helsinki system, the so-called *The National Grid Coordinate System* (*kkj* in Finnish), which it had obtained by translating and rotating the network of the primary triangulation so, that it coincided as precisely as possible, in practice to within a few metres, with the Helsinki system.

The Helsinki System as well as the National Grid Coordinate System differ quite substantially from the system defined by all-European starting points; e.g. from the ED-50 system in the north-south direction 52.3 metres and in the east-west direction 127.8 metres on the average. Even a difference that great has no noticeable effect on the internal accuracy of maps, but if one compares map coordinates to all-European coordinates or coordinates given by positioning satellites in the WGS-84 system, the differences are clearly visible.

On the year of its 75th anniversary, the Finnish Geodetic Institute published the results of the final adjustment of the primary triangulation in the ED87-FIN system. This completed the first-order terrestrial triangulation of Finland (*Jokela*, 1994).

2.3 The Finnish Permanent GPS Network – FinnRef

The Finnish Permanent GPS Network was established in the 1990's mainly for studying the relative crustal movements inside the Finnish territory. The network consists of 12 permanent GPS stations, namely the following: Joensuu, Kevo, Kivetty, Kuusamo, Metsähovi, Olkiluoto, Oulu, Romuvaara, Sodankylä, Tuorla, Vaasa ja Virolahti. Each of them is equipped with an Ashtech Z-12 received, a Dorne Margolin type antenna, and a Vaisala PTU meteorological sensor system. Antenna platforms are either steel grid masts, concrete pillars (Kivetty, Olkiluoto and Romuvaara) or invar stabilized steel masts (Metsähovi and Oulu). All the stations belong also to the Fennoscandian Permanent GPS Network.

The function of the Finnref Net is to act as a basis for the geodetic reference systems and for cadastral surveys in Finland. In addition, the stations take part in the geodetic operations, especially in those, which are aimed at studying crustal motion phenomena such as plate tectonic motions, intraplate crustal deformation, and Fennoscandian postglacial rebound. Some of the stations, namely Joensuu, Metsähovi, Sodankylä and Vaasa, work for the *EUREF-coordinate system* (European Geodetic Reference Frame).

2.4 Astronomical measurements

Astronomical direction and position determinations have from the very beginning belonged to the work program of the Finnish Geodetic Institute. They are the astronomic determinations of latitude, longitude and azimuth, mentioned in the founding regulation, that were to be made "on such points, that the orientation of the triangle system on the mathematical Earth surface can be ensured and that the greatest possible usefulness will accrue for the control of the triangulation and the determination of the elements of the geoid".

2.4.1 Astronomical measurements in 1920

The first triangle chain of the Institute, which was along the coast of the Gulf of Finland, had been reconnoitred in 1919. In the summer of the following year, the expeditions of the Institute built observation towers on the points on the Western side of the chain, in the following order: Lemlaks, Dragsfjärd, Vestlaks, Perniö, Tenala and Degerby. On most triangle points in the Archipelago Sea, it was possible to observe directly "on the rocks", so it sufficed to erect suitable observation pillars out of stone and concrete. Such were built on the following triangle points: Prostvik, Nötö, Hjortö, Jungfruskär, Sälskär, Geta, Toböle, Kumlinge, Kökar, Storskär, Utö, Vänö, Bengtskär and Hanko.

The actual measurements were started in May 1, 1920. The Institute's Director Ilmari Bonsdorff, optimistic as always, had decided to do angle observations and astronomical observations at the same time. For this, the Institute had purchased a Hildebrand universal instrument, with which horizontal and vertical angles, astronomical directions or azimuths, and astronomical latitude, could be easily measured. Longitude, for which precise time signals would be needed, were to be measured separately. It would not be needed at all for the determination of the North component of the deviation of the vertical, and not for the East component either, as these could easily be computed with Eqs. 1: $\xi = \varphi' - \varphi$ and $\eta = (A' - A)\mathrm{ctg}\varphi$, not containing longitude. The measurement works, of which Bonsdorff personally did the lion's share, progressed in the following order: Prostvik, Lemlaks, Hjortö, Nötö, Storskär, Bengtskär, Dragsfjärd, Utö, Kökar and Jungfruskär. Angle observations were done on all these points, similarly astronomical latitude and azimuth observations, with the exception of the Bengtskär and Utö lighthouses.

2.4.2 The Petsamo border survey 1921

During the summer of 1921 no astronomical measurements were done on triangle points at all. The reason was the Petsamo boundary survey. Ilmari Bonsdorff had already in January–February made a three weeks' official journey to Germany and Austria in order to acquire instruments and other equipment for the survey. In June–October he acted on order from the Cabinet as the Finnish chairman of the border survey commission. In April J. Keränen and *Y. Leinberg* performed an astronomical position determination on Mount Korvatunturi, and in May–June U. Pesonen executed similar measurements in the Maattivuono fjord, Petsamo.

2.4.3 Astronomical position determinations in the primary triangulation network

Astronomical measurements were started on the triangle points of the main network again in 1922. In summer 1920 it had been learned from experience, that the execution of astronomical measurements simultaneously with angle measurements was problematic. You see, the triangulations have the best chance of succeeding in overcast weather, whereas the astronomical measurements require a starbright sky. Azimuth measurements were attempted, weather permitting, still in connection with angle measurements, but astronomical position determinations, i.e. both latitude and longitude determinations, were done as separate works. Position determinations were made on the main network up till 1966, when all 293 triangle points had been observed. After that, measurements were made on points of the completion network in Northern Finland. The last observations were done on the Karravaara triangle point in Northern Lapland, September 11, 1990.

Nearly all position determinations were done with a Bamberg portable transit instrument. The latitude of the site, being the same as its polar height, was determined with the *Horrebow-Talcott* method. In it, a star pair is observed, of which one of the stars culminates north of the zenith, and the other south of the zenith. The latitude was obtained after that by the formula

$$\varphi' = \frac{1}{2}(\delta_s + \delta_n) + \frac{1}{2}(z_s - z_n) \tag{3}$$

where δ_s is the declination of the southern star and δ_n that of the northern one. The pair of stars had been chosen such, that the zenith distance of the southern star, z_s, was approximately the same as that of the northern star, z_n, so that the difference $z_s - z_n$ would be small. In this way, the effect of refraction could be eliminated, as the small difference would only contain a vanishingly small part of this error.

The result contained, however, the declination error of the star pair in full. In order to reduce its effect, several star pairs were observed, and furthermore measurements were made on several nights.

Longitude was determined by observing with the aid of international time signals and precision chronometers the times of suitably chosen stars passing through the meridian. A normal observing programme for one night consisted of about 18 stars, of which 15 were time stars and 3 north stars. Time stars, which culminated close to the zenith, were used to determine the local sidereal time, while the north stars, which culminated far from the zenith, were used mainly to determine the meridian plane of the transit instrument. The measurements were tied to the Helsinki meridian using the so-called personal equation. This was obtained from comparison observations made on the eastern pillar in the garden of Helsinki Observatory, immediately before and immediately after the field work. If λ' was the longitude observed on the pillar, the personal equation would be $p = 1^h 39^m 49.200^s - \lambda'$. The constant appearing in the formula is the one derived in the 1930's by the Baltic Geodetic Commission from measurements made in the area of the Baltic Sea.

Astronomical position determinations required special skills in order to succeed. For this reason, such measurements were entrusted in the Finnish Geodetic Institute only to four people: Y. Leinberg, *P. Kalaja*, *E. Kääriäinen* and *M. Ollikainen*.

2.4.4 Azimuth determinations

As remarked earlier, the east component of the deflection of the vertical was determined in summer 1920 by astronomical azimuth measurement. When the measurement of longitudes started in summer 1922, the azimuth measurements made only to determine the east component became superfluous, as this component could be derived from the longitude determination as well, as shown in Eqs. 1. The azimuth had to be measured, however, for Laplace points, and thus was done on every triangle point up to 1936. This changed in 1937, after which the azimuth was measured only on every third triangle point.

Of the older civil servants of the Finnish Geodetic Institute almost everyone has at some point in his career executed an azimuth determination, but most of these by far have fallen to U. Pesonen and V.R. Ölander, 80–90 determinations for each of them.

2.4.5 Stellar triangulation

When Yrjö Väisälä, according to his own account, photographed asteroids in war blacked-out Turku, he had at the same time watched the flak charges explode over Helsinki. Then he had remembered his own rocket tests of already twenty years earlier, that intended to use for aiming, instead of fixed triangulation towers, light signals shot high into the air. If these had been photographed against the starry sky, their astronomical directions would have been obtained by measuring from the photographic plates.

Väisälä presented the principle of his astronomical triangulation on the Session of the Finnish Academy of Sciences and Letters of February 8, 1946. As possible applications of his method he mentioned e.g. intercontinental triangulations, that would be possible if one could use as aiming targets rockets launched to a height of more than 100 km, or satellites orbiting the Earth at even several thousands of kilometres height. The idea was realized quicker than Väisälä perhaps believed himself.

Flash lights suspended under weather balloons were tested by Väisälä for the first time already in 1947, but then further attempts were abandoned. The next time they were used in the late 1950's in tests organized jointly by T.J. Kukkamäki, and Väisälä. The last mentioned, successful tests have been presented in detail in the publication by *Väisälä and Oterma* (1960).

Later, during the late sixties and early seventies, Kukkamäki's Ph.D. student *J. Kakkuri* (1973) measured in Southern Finland a network consisting of five triangle points, the side lengths of which were 150–230 km.

The telescopes used in this work were built and designed by Väisälä himself, and he followed the progress of the measurement up till his last days. When artificial satellites appeared in the heavens toward the end of the fifties, planetary scale triangulations became possible. The United States launched for this purpose several geodetic satellites into Earth orbit, like the satellites Pageos and Geos, the latter equipped with flash lights. By means of these satellite measurements, the dream of all geodesists, a planet-spanning unified triangulation network, was realized in the sixties.

3. Geodetic measurements with solar eclipses

A solar eclipse is created when the Moon comes in front of the Sun. There, where the shadow of the Moon hits the Earth, the eclipse is enjoyed as total. By determining the onset and termination of totality in two different locations, one obtains the time it takes the shadow to travel the distance in-between. As the speed of travel of the shadow is calculable from celestial mechanics, also the inter-location distance can be calculated.

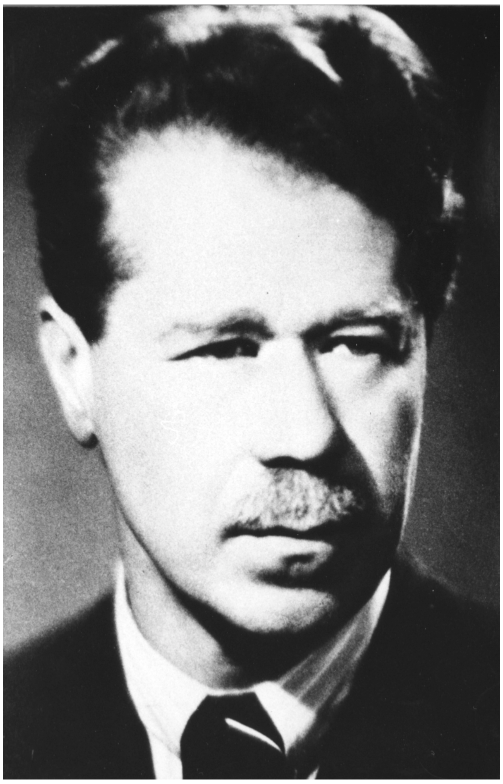

Fig. 4. Professor Yrjö Väisälä. (Finnish Geodetic Institute's Collection.)

3.1 The solar eclipse of 1945

The principles of the grade measurement method explained above based on a solar eclipse was originally proposed by the Swiss-born mathematician *Leonhard Euler*. The famous Polish geodesist *Th. Banachiewicz* experimented with and developed it in connection with the 1927 total eclipse.

When in Finland a total eclipse took place on July 9, 1945, the Director of the Finnish Geodetic Institute Ilmari Bonsdorff decided to exploit it for measuring a large distance. This eclipse started early in the morning on the west coast of North America, the lunar shadow travelled from there to Greenland, Norway, through Sweden and Finland to Russia. The eclipse ended in inner Russia in the Turkestan neighbourhood. In Finland it started about 16 o'clock and totality lasted about 1 minute.

There were in 1945 still theoretical and practical problems in applying the eclipse method. The former ones concerned the movement of the lunar shadow on the Earth surface. The relative motions of Sun, Earth and Moon were known, thanks to long observation series, very precisely, but the distance between Earth and Moon was not known precisely enough. Furthermore the poorly known topography of the limb of the Moon affected the precise determination of the starting and ending times of the eclipse.

Of the practical problems, that of obtaining time was the worst. In order to get a precision of 10–15 metres in the distance, the times of the starting and ending moments of the eclipse had to be determined with an accuracy of approximately 0.01 seconds. In 1945 this was still very much more difficult than today. As quartz clocks in those days were still sizable rarities, one had to be satisfied with measuring time distances using contact micrometers – much less accurate – and radio time signals. The reception quality of time signals left much to be desired.

The determination of the starting and ending times of the eclipse could be done in one of two ways: the contacts of Sun and Moon were filmed with a filmcamera, or, instead of the contacts, the so-called flash spectrum was photographed. There were four contacts: the 1st contact, when the Moon's forward edge touched the Sun, the 2nd contact, when totality started, the 3rd contact, when totality ended and the 4th contact, when the trailing edge of the Moon detached itself completely from the Sun. Of these, the 2nd and 3rd contacts were the most important.

In order to photograph the contacts and flash spectra, two expeditions were equipped, one lead by P. Kalaja in front of Kokkola on the island Poroluoto, and the other lead by U. Pesonen in Kangaslampi, on the shore of Haukivesi. Both expeditions had two cameras, to be installed on identical tripods. One of these had been made by Väisälä, a 206 cm focal length objective, and the other a 50 cm long Zeiss teleobjective equipped with a refracting prism. The times at which every frame was exposed, was obtained from the English Rugby radio station time signals. Both expeditions were lucky with the weather, and the filming with its time taking succeeded excellently.

It was attempted to determine the place of the edges of the zone of totality by photographing the progress of the lunar shadow on the Earth surface from a high flying aeroplane. The father of this idea was T.J. Kukkamäki. With the permission of the Control Commission, four air force planes were assigned to the task, of which three were Blenheims and the fourth a Dornier bomber. These took off from Lake Luonetjärvi thus, that they would be in Pietarsaari, Kalajoki, Juva and Liperi at 6 kilometres altitude approximately half an hour before the onset of totality. The shootings, which lasted only some 45 seconds, were done with RKM aerial cameras.

The photography from the aeroplanes, in spite of painstaking preparation, did not lead to sufficiently accurate results, as T.J. Kukkamäki himself has concluded. In spite of successful observations, the geodetic distances were never calculated or published. Thus the measurements of Poroluoto and Kangaslampi entered the history book of science mainly as dress rehearsals for coming solar eclipses. The most important of these, and the only one producing final results, turned out to be the total solar eclipse of 1947.

3.2 From Gold Coast to Brazil

The 1947 solar eclipse was especially suited for the measurement of the distance between two continents. The lunar shadow touched the Earth surface already in the Pacific. It travelled then across all of the South American continent to the coast of Brazil and from there across the central Atlantic to Gold Coast and after that still across nearly all the African continent's central part to close to the East coast.

The Finnish Geodetic Institute equipped for this eclipse two expeditions, one to Gold Coast, Africa, and one to Brazil. The leader of the Gold Coast expedition was T.J. Kukkamäki and that of the Brazilian one was *R.A. Hirvonen*.

Kukkamäki chose as observation location a hill close to the village of Bana, the coordinates of which are: $\varphi = 6° 9' 56''$ N, $\lambda = 0° 1' 1''$ E, and $H = 220.8$ m. Hirvonen's measurement location again was close to a railway station by the name of Bocaiuva, the coordinates of which are: $\varphi = 17° 14' 2''$ S, $\lambda = 43° 40' 15''$ W, $H = 789$ m.

Several other countries, i.e. Argentina, the Soviet Union, Sweden and the United States, equipped expeditions, but only both Finns succeeded in taking pictures. The others had bad luck due to clouds. The Finns were also concerned about the weather, especially Kukkamäki, who was stressed during the whole shooting due to threatening clouds in the sky. Hirvonen's expedition had to worry about the poor audibility of the time signals and malfunctioning of the camera. Nevertheless a sufficient amount of pictures was obtained. After return home, the films taken by the expeditions were measured. This measurement was complicated, as had been feared, by the unevenness of the lunar limb. The Sun shone through the valleys between mountains on the limb, even though already eclipsed by the mountains, and its crescent was visible as a string of beads. Furthermore the restlessness of the atmosphere and the libration phenomenon of the Moon complicated the determination of the moment of contact. It was tried to diminish the effect of those disturbances using the lunar charts prepared by *Friedrich Hayn*.

Kukkamäki and Hirvonen published the final results of their solar eclipse measurements in 1954 (*Kukkamäki and Hirvonen,* 1954). According to it, the distance between the measurement points in the African Gold Coast and in Brazil, 5458.8 km, was measured with 141 metre accuracy. An accuracy this good was not achieved again until satellites were used.

3.3 At the mercy of the weather, 1954

In 1954 three solar eclipses took place, of which the one on June 30, having the most favourable track, was scientifically the most important. It started in the United States in the area of Omaha, progressed through the Great Lakes to the Southern tip of Greenland, and from there on to Norway, passing over Oslo, on to Öland and continuing from there to Russia and India, where it finally ended.

The Finnish Geodetic Institute equipped two expeditions to observe the eclipse, one led by P. Kalaja to the island Sotra, off the west coast of Norway, and the other led by R.A. Hirvonen to Öland. The U.S. Ohio State University, where V. Heiskanen acted as Professor of Geodesy, equipped four expeditions. Of those, two went to the Labrador peninsula, one to Greenland and one to Iran. As the Greenland expedition's leader the university chose T.J. Kukkamäki.

The Sotra expedition left to station already the 4th of June. In spite of nigh-continuous bad weather they managed to get everything set up for the measurements, but when the eclipse was supposed to start, the sky was overcast and it drizzled, and thus the expedition's work went to waste. The expedition returned home the 4th of July.

The Öland expedition left to station on the 9th of June. On the day of the eclipse the sky was partly overcast, but the photography of the first, second and third contact appeared nevertheless to succeed through the clouds. After developing the film, it was however found that exposure had varied so much, that the pictures could not be measured, and thus also the Öland expedition's work went to waste. It returned home the 6th of July.

The material conditions on the expedition that had left for Greenland were excellent. It had the use of the best measurement tools of the day, a plane to travel within Greenland, and plenty of assistant work force. The only thing lacking was the favour of the weather gods. On eclipse day it rained, and total failure was on the books for that day from the morning onward.

Taking into account that none of the geodetic solar eclipse expeditions obtained results, due to bad weather, it must be said that the weather gods really must have hated global geodetic research.

3.4 Did gravity change?

Isaac Newton, when studying the attraction of spherical bodies, assumed that the exterior layers of the body did not insulate the inner layers from the exterior gravitational field, in other words, no absorption of gravity in obstructing masses is taking place. In most experiments done during the last century, this has been proven to hold within the accuracy of measurement.

During the 20th century the matter has been studied again by many known physicists. The most famous studies and laboratory experiments were done by the Italian *Quirino Majorana* during 1919–1921. In his experiments, he insulated a lead ball of 1.3 kg mass from the Earth's gravity field first by a mercury cylinder of 114 kg, and then by a lead cube of 9 603 kg. He published in total 22 studies on this subject, where he announced having found a small effect. The effect observed by Majorana has not been verified or falsified. Thus, the Frenchman *M.F.C. Allais* and the Americans *E.J. Saxl* and *M. Allen*, who have performed tests with various pendulums during solar eclipses, have announced that they have observed the effect. The Moon coming in front of the Sun has, in their experiments, acted as a mass absorbing the attraction of the Sun.

On the other hand, many geodesists, like *L.B. Slichter*, *M. Caputo* and *C.L. Hager*, that have studied the change of gravity during a total solar eclipse with sensitive gravimeters and horizontal pendulums, have not observed any effect, although in their tests the accuracy of measurement was considerably better than in Majorana's tests.

The total solar eclipse in Finland on July 22, 1990, offered the Finnish Geodetic Institute an excellent opportunity to study the Majorana effect described above. The Sun rose that morning in the North-East already partly eclipsed, and during totality it was only a few degrees above the horizon, so that it would have the strongest possible effect on the plumbline direction.

The instruments needed in the test already existed within the zone of totality in the Lohja mine and the Metsähovi laboratories, so no new purchases were needed. An especially serendipitous device was the long water tube tiltmeter, placed in the Lohja mine, with which the solid Earth tide phenomenon had been studied over many years already. Furthermore the Institute had an absolute gravimeter constructed in the United States, with which the acceleration of free fall could be measured directly during the eclipse.

The measurement programme, in which the Institute's gravimetric department's scientists participated, comprised the following works:

– *Absolute gravimetric measurement in Ilomantsi*. The measurement instrument was the Faller gravimeter, built in the United States, in which the force of gravity was determined from the motion of a freely falling body. The measurements, which were performed by *J. Mäkinen*, started 24 hours before totality and ended 24 hours after it. A measurement series consisting of 50 drops lasted 5 minutes. The standard error of the mean of a series was found to be ±2.5 μGal, after the necessary tide corrections etc. were made. Nothing out of the ordinary in terms of gravity change happened during the phase of totality.
– *The tests done in the Lohja mine.* The measurements were performed by J. Kääriäinen using the long water tube tilt meters. There were two of these, one of 62 metres length in the North-South direction, the angular resolution of which was 0.038 msec of arc, and one of 177 metres length in the East-West direction, with an angular resolution of 0.013 msec of arc. No change in the plumbline direction, above and beyond that caused by the normal lunisolar tide, could be demonstrated.
– *The tests done in the Metsähovi Research Station.* These measurements, which were supervised by *H. Ruotsalainen*, were done with automatically registering instruments. These were a so-called Askania bore hole pendulum, which registered the changes taking place in the direction of the vertical, and a Lacoste-Romberg tidal gravimeter, that registered changes taking place in gravity. Both instruments performed impeccably, and good registrations were obtained, but in spite of the high accuracy of measurement (±0.1 μGal) any absorption effect could not be found from them.

4. Standard baselines

The career of Yrjö Väisälä as a civil servant at the Finnish Geodetic Institute lasted from 1918 to 1925, i.e., 7 years. This very short time he used to plan the triangulation, to do research and to do practical field work. From this time originates the first publication of the Institute written by him, namely *Tafeln für geodätische Berechnungen* *nach den Erddimensionen von Hayford*. In it, he presented logarithmic tables for the computation of geographic coordinates of triangulation points (*Väisälä*, 1923). Of considerably greater value, however, was his second publication *Die Anwendung der Lichtinterferenz zu Längenmessungen auf grösseren Distanzen*. It was about a new procedure to measure baselines using the interference phenomenon of light (*Väisälä*, 1923).

Yrjö Väisälä moved from the Finnish Geodetic Institute to the University of Turku as a Professor of Physics, on March 1, 1925. This transfer to a new position did not cut short his geodetic career, however, because in Turku he could continue the research work he had started at the Finnish Geodetic Institute, and he preserved his active connection with the Institute until the end of his days. Soon, his workstead gave birth to the interference comparator and the quartz metre system belonging to it. This innovative laboratory device, suitable for outside measurements, can be used to measure, and has been thus used, standard baselines of nearly 1 km length, to be used for calibrating invar wires and electro-optical distance measuring instruments. Väisälä's excellent publication describing the comparator, *Anwendung der Lichtinterferenz bei Basismessungen*, appeared in the series of the Finnish Geodetic Institute in 1930 (*Väisälä*, 1930).

4.1 Nummela Standard baseline

The Finnish Geodetic Institute's comparison baseline had been built in Santahamina in 1921. The permanency of this 720 m long baseline was put in jeopardy, however, especially when in 1930 construction of an airfield was started. In 1932 the Institute started to look for a suitable location for a new comparison baseline. Such a place was found in the village Nummela, parish Vihti, on top of the Lohja esker. The place, a sandy soil under thin pine vegetation, its ground hard sand and its ground water deep, was such that movements of the earth layers were not to be feared. The new baseline, the standard baseline, was built to a length of 36×24 m = 864 m, so that invar wires of length 24 m could be calibrated there. In measuring the baseline, up to 1946 only invar wires were used. The baseline was measured with the interference comparator for the first time in 1947. After that, the permanency of the baseline has been monitored only using interference measurements.

As can be seen from Table 1, the length of the Nummela baseline has during forty years varied only very little, if at all. The baseline is the most precise in the world. The standard errors of the measurements are one ten millionth part of the total length of the line. A precision that high cannot be achieved by any other means on a baseline of this length, only with the Väisälä interferometer; not even modern laser interferometers can do this.

Table 1. Interference measurements on the Nummela standard baseline.

Year	Length (mm)	Error (mm)
1947	864 122.78	±0.07
1952	864 122.47	±0.08
1955	864 122.41	±0.09
1958	864 122.25	±0.08
1958	864 122.33	±0.08
1961	864 122.31	±0.06
1968	864 122.37	±0.07
1975	864 122.33	±0.07
1977	864 122.70	±0.08
1984	864 122.40	±0.09
1991	864 122.32	±0.08
1996	864 122.75	±0.07

4.2 International Standard baselines

Following a proposal by the Finnish Geodetic Institute, the International Association of Geodesy recommended in 1951 at its General Assembly in Brussels, that the interference method be used also in other countries for standard baseline measurements. This recommendation has been followed up by Argentina, The Netherlands, Portugal, Germany, The United States, South Africa, Spain, China and Hungary, where *T. Honkasalo,* E. Hytönen, *J. Jokela, R. Konttinen,* T.J. Kukkamäki, J. Kääriäinen, and M. Poutanen – each in his turn – have measured baselines. In Germany, two baselines have been measured: in Munich and in Potsdam, and three in China: in Beijing, in Chengdu and on Taiwan.

5. Precise levellings and vertical datum definitions

A large part of the benchmarks of the Finnish first precise levelling performed by the Supreme Board of Road and Water Works in 1892–1910 disappeared within a few decades due to construction and improvement of the road network. Furthermore the land uplift changed the heights of the benchmarks so much, that it caused practical trouble to road and water construction work. Because of this, a new national precise levelling was felt to be necessary already in the early 1930's.

5.1 The second precise levelling

The Finnish Geodetic Institute was commissioned to execute the Finnish second precise levelling in 1932. The actual field work started in 1935, when the state budgeted funds to acquire measurement instruments, employ personnel and cover the expences of field work. Before this, already in summer 1932, V.R. Ölander had done preliminary measurements on the Carelian isthmus. Partly based on Ölander's, partly on his own research, T.J. Kukkamäki, who was hired to lead the precise levelling, developed during the 1930's almost all of the measurement methods used in the second precise levelling. He became famous for his method to correct for the error caused by the refraction of a ray of light (*Kukkamäki,* 1938, 1939).

Fig. 5. Professor T.J. Kukkamäki, director of the Finnish Geodetic Institute from 1963 to 1977. (Finnish Geodetic Institute's Collection.)

The levelling works, which had started off so well, were interrupted for the duration of the war. After the war, they continued, and principally T.J. Kukkamäki, E.Kääriäinen, J.Korhonen and E. Hytönen measured Southern Finland up to the line Aavasaksa–Rovaniemi–Kemijärvi, a measurement which was completed in 1955. It comprised 18 closed loops and ties to 12 tide gauges. The total length of the lines measured by spirit level was 6 236 km, of which 5 928 km belonged to the loops. Of it, 490 km was located on territory ceded to the Soviet Union. The precision, obtained from statistical treatment of the loops, was ± 0.64 mm/$\sqrt{\text{km}}$.

The Northern part of Finland was levelled twice during the years 1953–1975. The net, measured mainly by J.Kakkuri, J.Kääriäinen and *M.Takalo*, comprised 3 closed loops and was tied to the corresponding networks in Norway and Sweden. The total length of the lines was 1 615 km, of which 1 079 km belonged to the loops. The precision obtained from the network adjustment was in Northern Finland ± 0.86 mm/$\sqrt{\text{km}}$.

5.2 The levelling of Åland

Åland, hundreds of islands separated by straits, required its own levelling. This was started in 1962, when J. Kääriäinen levelled on the main island the line Eckerö–Gölby–Bomarsund.

The line connecting the mainland and Åland, which ran from Mynämäki over Kustavi to Bomarsund, was measured during the years 1963–1966. The line Gölby–Degerby tide gauge was measured in 1975, and the line, containing overly long water crossings, from Eckerö to the lighthouse islet of Märket, in the years 1967–1972.

The levelling of Åland comprised land and island lines 233 km and water crossings 55 km. The levelling, mainly done by J. Kakkuri and J. Kääriäinen, contained even water crossings over 4 km in length, which required observations over long periods with special instruments. Also the levelling of the islands covered with steep cliffs and mires was demanding, and asked much time and patience from the workers. Nevertheless, the Åland levelling succeeded well, as the error in the height difference calculated from the starting point No. 51008, located in Mynämäki, amounted in Bomarsund only to ±9.1 mm, in Eckerö to ±9.2 mm, in Degerby to ±10.3 mm and even on Märket still to a satisfactory ±26 mm. From this we obtain for the precision of the Åland levelling, if we leave the Eckerö–Märket connection out: $\pm 0.64\ \mathrm{mm}/\sqrt{\mathrm{km}}$, and taking Märket along: $\pm 1.53\ \mathrm{mm}/\sqrt{\mathrm{km}}$, which is in itself still quite good.

5.3 The third precise levelling

The land uplift taking place in Finland changes continually the heights of benchmarks. Because of this, the useful lifetime of heights based on levelling is limited. In order for these heights to be up to date and the height differences between benchmarks correct, it is necessary to revise the height system with several decades interval. The current, third precise levelling aims at a height system tied to the year 2010.

The third precise levelling was started in 1978. Its network covers completely that of the second levelling. Furthermore it contains new lines, which were not present in the second levelling due to lacking roads. The points common to the first and second levellings are naturally along, so that we can obtain an understanding of the speed and continuity of land uplift, which is as correct as possible.

The third levelling, mainly executed by *P. Lehmuskoski, P. Rouhiainen, V. Saaranen* and M. Takalo, has progressed to Northern part of Lappland, and it is expected to be completed in 2002.

5.4 The reference surface for height systems

During the present century, three height systems have been in use in Finland, namely the NN, the N43 and the N60 system. Of these, the NN system is the oldest. It was created as a result of the first precise levelling. Its reference level was defined to go through the zero point of the footstock at Katajanokka Bridge, Helsinki, i.e. a point attached to the Earth's crust. It was apparently intended to make the reference level coincide with mean sea level in Helsinki. Later it was found, that it remained 10.9 cm below the level representing the mean sea level over the period 1904–1909. The reference level moved up more and more because of the land uplift, and around the beginning of 1943 it was on the same level as the mean sea level over the period 1935–1954. The reference level of the NN system coincides thus in 1943 with the mean sea level computed over the period mentioned above, whereas the differences in benchmark heights again correspond approximately to the situation for the mean epoch of the first precise levelling, the year 1900.

During the second precise levelling, the second height system for Finland was taken into use, the temporary N43 system, so that the results of the new levelling could be published to satisfy practical needs. As the starting point, a certain benchmark located in Pasila and its NN height was used. This point was tied to the fundamental bench mark located in Helsinki on Observatory Hill, which is located 30.4652 m above the zero point of the Katajanokka footstock. When the levelling loop started from the Pasila point closed, its closing error was adjusted without changing its height. A new loop was measured by its side, which was adjusted without changing the heights of the common part, etc. The end result was a height system that had the same reference level as the NN system. The heights of the benchmarks, on the other hand, are larger than the NN values there, where the land uplift is faster than in Helsinki, and smaller there, where the land uplift is slower.

When the main network of the second levelling was completed in 1955, it was adjusted, taking the land uplift into account. In 1960 a negotiation was arranged at the Finnish Geodetic Institute's premises, aimed at being able to choose the new reference level and reference epoch in a way that would satisfy the offices and agencies using the height values. At this meeting, the reference level Helsinki mean sea level and the epoch 1960.0 were chosen.

The choice of Helsinki was influenced by the finding, from the levellings, that there sea level was lower than in any other coastal municipality in Finland and that the tide gauge there had operated long and its location by the open sea was good.

6. Gravimetric measurements

The first gravity measurement was made in Finland in connection with the Laponian arc measurement, when Maupertuis measured gravity in Pello with the aid of a pendulum. *Planman* did similar measurements in central Finland in 1761 and *Sawitz* in Tornio and Vaasa in 1865. In 1896–1897 *O. Savander* measured the differences between Potsdam and Helsinki as well as between Pulkova and Helsinki with a Stückrath's twin pendulum device. Ilmari Bonsdorff used the same instrument in 1901 when doing gravity measurements in South and Central Finland. During 1907–1908 he measured the gravity difference between Helsinki and Pulkova using a Stückrath's three pendulum device.

6.1 Pendulums and gravimeters

The Finnish Geodetic Institute started gravity measurements in 1924. They were done initially only for geoid determination, but later on, when the number of gravity points grew, came the study of the structure of the Earth's crust and geophysics along into the picture.

During 1924–1937 U. Pesonen and R.A. Hirvonen measured in total 186 gravity points with a so-called Sterneck's four pendulum instrument. These points formed a sparse network, covering the south of Finland up to the polar circle. The precision of gravity differences measured with the pendulum instrument was as good as ±1.3 mGal.

The gravity measurements done by the pendulum instrument lasted 2–3 days on each point, and the processing of the observations lasted several hours. Because of this, the national gravimetric mapping progressed slowly. This improved essentially by the end of the 1930's, when a device suitable for gravity measurement was successfully developed based on a spring balance. With these so-called gravimeters one could measure gravity differences rapidly and precisely. The first useable instrument was an Askania gravimeter, where the extension of the spring was measured initially photoelectrically and later capacitively. The whole instrument was placed inside a thermostat to minimize the effect of temperature. Just as useable was the Danish Nørgaard's gravimeter, which came into the use of the Finnish Geodetic Institute in 1945. Its reading accuracy was 0.05 mGal, but here, like in all gravimeters, the reading changed a little due to stretching of the spring. The most precise gravimeters were built in the United States. There, the large oil companies developed and built these to facilitate their search for the black gold. The best of these were the Worden- and LaCoste-Romberg gravimeters. These were (and are) compact and light instruments, with which one can achieve within a small area a measurement accuracy of even 0.01 milligals.

The Institute acquired a Worden gravimeter in 1955. Four years later a thermostat was added to it in connection with its servicing, changing it into a Worden-Master gravimeter. In 1967 the United States gave the Institute in loan four LaCoste-Romberg gravimeters, of which one remained permanently in Finland. In 1981 the Institute got to buy its own LaCoste-Romberg gravimeter from the U.S. manufacturer.

6.2 The gravity survey of Finland

With the new, precise gravimeters, the national gravimetric mapping proceeded rapidly, and in 1967 gravity had been determined already in over 13 000 points, and in 1978 in approximately 22 500 points. Their foundation was the primary gravimetric base network measured in 1962, comprising 41 carefully built measurement stations. Together these 22 500 points form Finland's national gravity net, where the point density is

1/15 km^2. It covers the Finnish mainland completely as well as parts of the sea area, where measurements have been mainly done upon the ice in winter.

The densification of the national gravity network was started in 1980. The network was intended to become so dense, that there would be 1–2 points within every square of one km^2 size. A network this dense is useful in many ways. With it, one can study and find out about e.g. the structure of the upper part of the Earth's crust, connected to ore and mineral deposits of significance to the national economy. Because of this, the densification was co-ordinated with the Finnish Geological Survey.

The measurement of the national gravity net was for the greater part done by T. Honkasalo and *A. Kiviniemi*. The gravity data collected were delivered to the international use through the International Gravity Bureau and applied, for example, to computation of the Bouguer anomaly map for the Nord Kalott as well as to the gravimetric geoid modelling for the Nordic Countries.

6.3 Absolute gravimetry

The absolute value of gravity can be determined either by a pendulum, as was done in work by the Finnish Geodetic Institute in 1924–1937 or with the aid of a freely falling body, like *Galileo Galilei* did. If we use a pendulum, we get the absolute value with the formula $g = 4\pi^2 b / T^2$, where b is the length of the pendulum and T the observed swing time. If the measurement is done with the aid of a freely falling body, the formula $g = 2s / t^2$ is used, where t is the time it takes the body to fall a distance s.

Table 2. Absolute gravimetric measurements by the Finnish Geodetic Institute at home and abroad.

Country	Place of the measurement
Antarctica	Aboa
Belgium	Brussels, Membach
China	Beijing, Guangzhou, Harbin, Kunming, Lhasa, Nanning, Shanghai, Xi'an
Czech Republic	Pecný
Estonia	Suurupi, Kuressaar, Toravere
Finland	Kirkkonummi, Joensuu, Sodankylä, Vaasa, Virolahti
France	Sévres, Strasbourg
Germany	Clausthal, Moxa, Wettzell
Island	Höfn, Reykjavik
Latvia	Riga, Popé, Viški
Lithuania	Klaipeda, Panevežys, Vilnius
Luxemburg	Luxemburg
Norway	Ny Ålesund, Stavanger, Tromsö, Trysil
Poland	Borowa Góra, Jozefoslav, Konopnika, Pivnice
Portugal	Faial, Flores, Mertola, Porto, St. Miguel
Slovenia	Bogensberg, Gotenica
South Africa	Paarl, Pretoria
Spain	Madrid
Sweden	Furuögrund, Gävle, Göteborg, Onsala

Absolute values were measured up to the sixties almost exclusively by means of pendulums, and the best instruments achieved accuracies of 2–3 milligals. In 1957 T.J. Kukkamäki proposed on the Toronto General Assembly of the International Union of Geodesy and Geophysics the absolute measurement of gravity using a 220 metre long wire pendulum. If such a pendulum were only to be suspended in a deep mine shaft inside a vertical vacuum tube, it would according to him be possible to measure absolute gravity better than 1 mGal.

E. Hytönen undertook to implement Kukkamäki's idea. He quickly found out that there were almost insuperable theoretical and practical problems, and because of these, the original plan of Kukkamäki had to be abandoned. As the place of measurement was chosen instead of a mine shaft, an elevator shaft in the power utility building in Vallila, Helsinki. The wire used in the measurements was only 7.77 m long. At its end a bob was dangling made of pure gold, weighing 17.8 kg. The precision of the absolute measurement published in 1972 was ±2.1 mGal, which was not bad result for a pendulum measurement.

E. Hytönen's measurement will probably remain as the last attempt in the whole world to determine absolute gravity by means of a pendulum. The laser interferometer had namely made the Galileo's method a superior one for determining absolute values of gravity rapidly and effectively, and already in the 1970's ballistic devices achieved hundred-fold accuracies compared to pendulum devices. The Finnish Geodetic Institute decided in the early 1980's to acquire its own ballistic (falling-body) instrument for absolute gravity measurements. Because one does not buy such super-precise equipment "off the shelf", it had to be built. This was possible at the University of Colorado in the United States, where Professor *J. Faller* was just in the process of building six falling-body instruments for research use.

The Institute offered to pay for one, and when agreement was reached on the price and the research contract connected with the instrument, the construction contract was signed. The Faller's falling-body device, a so-called absolute gravimeter, was completed and delivered to the Institute in 1986. J. Mäkinen, which Faller trained as user of the instrument, has from then on made many measurement journeys both at home and abroad. On those, it was tried to measure, following the principles of the International Association of Geodesy, precise absolute points in different parts of the globe, so that the gravity measurements all over the Earth would be of the same scale. This was of great benefit for geodetic-geophysical research in the whole world.

6.4 Studying the Solid Earth's tides

On the shallow ocean shores the sea floor is at times exposed, at times under water, and the difference between low and high water may be many metres. Here we have a periodic fluctuation in water level caused by Moon and Sun, the tidal phenomenon or flood and ebb, which generally repeat twice a day.

To some extent it is surprising, that the tidal phenomenon can also be observed in the solid Earth crust, even so strongly that its effect must be taken into account in the most precise geodetic measurements, like gravity measurements and precise levellings. If the Earth had been a completely rigid body, then the effect of the tides could have been precisely calculated given the apparent motions of Moon and Sun, and no observations would have been needed. In reality the Earth is somewhat elastic, so that its shape changes under the influence of the tidal force, and precise gravimeters observe the amplitudes and phases of the tidal waves, which differ from what the calculated corresponding values for a rigid Earth would be. When we observe gravity changes, the observed amplitudes are some 16 % greater than the theoretically computed ones. This is caused by the vertical motion of the Earth's crust, which changes the distance of the measurement instrument from the centre of the Earth. Thus the attraction acting upon the instrument changes, and the effect works in the same direction as the original effect of the tidal force. The amplitudes of the changes in the direction of the vertical, on the other hand, are smaller than the á priori calculated ones. Also this is caused by the change in shape of the globe, which compensates about 30 % of the change in vertical direction calculated for a rigid Earth.

The Finnish Geodetic Institute acquired a tidal gravimeter manufactured by the Askania factories, in 1964, in order to be able to participate in the international research program for solid Earth tides. Participation in this was considered important abroad, because there were too few observing stations north of latitude 60° in the international observing network.

T. Honkasalo installed the tidal gravimeter acquired for the Institute in Helsinki in a cellar located in the Sinebrychoff park. In 1967 he moved it to a tunnel in the bedrock in Pasila, where the water utility of Helsinki built suitable rooms. That same year the Institute acquired two Verbaandert-Melchior horizontal pendulums in order to register changes in the direction of the vertical. These devices Honkasalo placed in the Ojamo mine in Lohja. Later these were moved to the Tytyri mine. The observations produced by the tidal gravimeter and the horizontal pendulums are transmitted to Brussels, where the International Centre of Earth Tides (ICET) processes them and derives from them, using harmonic analysis, amplitude and phase coefficient values for the various waves present in the tide.

In 1971, a Geodynamics gravimeter in excellent state of functioning was received in loan from the United States. The Finnish Geodetic Institute used it to determine tidal coefficients in seven Finnish, four Swedish and one Norwegian municipalities. Of other tidal observations made with registering gravimeters we should mention those of the German *G. Jentzsch* in Vaajakoski, Virojoki and Kirkkonummi during the 1970's and 1980's, which have produced valuable additional knowledge on the elasticity properties of the Earth's crust in our northern country.

A mention all of its own also deserves the long water tube tiltmeter built into the Tytyri mine in Lohja. In a meeting in 1965 in Aulanko (*Kukkamäki,* 1966) on recent movements in the Earth's crust, T.J. Kukkamäki proposed that the continual tilting of the Earth's crust caused by the land uplift could be monitored by means of a horizontal, approximately one kilometre long, U-tube, if 1) such a tube were to be placed under the Earth's surface at a depth of at least 50 m, 2) it were to be filled with a suitable fluid, e.g. mercury, and 3) the fluid surface level relative to a fixed reference point would be determined with the aid of the light interference phenomenon.

J. Kääriäinen, disciple of Kukkamäki, implemented the idea of his teacher nearly completely. In a tunnel no longer in use in the Tytyri mine he built a 177 m long horizontal tube in the east-west direction, which was filled half way up with water. On both its ends was a low terminating vessel, and inside these, just barely covered by water, a lens, convex on top, mounted to the rock. When the terminating vessel was illuminated with monochromatic light, a reflection was created from both the water surface and the lens surface, and the reflected beams interfered with each other, producing concentric rings. Under the influence of the tidal force, the separation between lens and water surface was continually changing. Thus also the radii of the rings were changing. When these changes were recorded with a film camera using a diametrically fitted slit diaphragm, a figure was obtained on the slowly advancing film of the changes in direction of the plumbline caused by the tide, which could be measured with great precision (*J. Kääriäinen,* 1979).

In the mine corridor, which was some 150 m under the surface of Lake Lohja, conditions for measurement were almost ideal, as the yearly variation in temperature (+9° C) was only 0.4° C. No wonder, that beautiful results were obtained with the water tube. In fact it was never used, as Kukkamäki intended, for the study of the land uplift, but instead it was used from 1977 onward to determine tidal wave coefficients reliably and with great precision. The resolution of the instrument is so high, that it reacts to even small deformations of cavities in the Tytyri mine, as well as to the changes that the variation in atmospheric pressure caused in the solid Earth's crust. The device has as the first in the whole world observed the response of the Earth's fluid core to the horizontal component of the tidal force.

In 1983, a second water tube was installed in the Tytyri mine, in the north-south direction, length 62 m. It was placed in a side tunnel perpendicular to the water tube tunnel. Also this instrument has yielded precise results.

6.6 Measurements on Antarctica

Finland joined the Antarctic Treaty in 1984. The signatory states are obliged to organize on the continent, and the areas surrounding it, scientific research activity, aimed at furthering the peaceful use of the ice covered continent. The Finnish Geodetic Institute participated in research on the Southern continent during 1989–1994 by executing in the area of Dronning Maud Land works belonging to a gravity survey.

In autumn 1989, the first expedition was sent by the Institute to Antarctica in the framework of the so-called FINNARP-89 project. The expedition consisted of two members, M. Ollikainen and P. Rouhiainen. During the measurement period, which lasted one and a half months, it measured in the surroundings of the station Aboa – the base of the Finnish Antarctic researchers – some 100 gravity points and determined their geographic coordinates using a GPS satellite receiver. Additionally the expedition gathered experiences on working in antarctic conditions with an eye on expeditions later to be equipped.

In November 1991 the Institute sent a second expedition to Antarctica in the frame of the FINNARP-91 project. Also this expedition consisted of two members, J. Jokela and *H. Virtanen*. During the time of the measurement period, about two months, it established in Dronning Maud Land 300 new gravity points and determined their geographical coordinates with GPS receivers like the previous expedition. Furthermore it made two tie measurements to Montevideo, where the nearest international gravity network base point was to be found.

In 1993 J. Mäkinen took part in FINNARP-93 project and determined the absolute gravity at a rocky hill close to the station Aboa. The measurement was repeated in 2001.

7. Geoid studies

The famous mathematician *K.F. Gauss* defined the Earth as having the figure of the geoid (later known as so-called *Gauss-Listing geoid*), i.e. of the equipotential surface of the gravity potential, which at the coasts coincides as precisely as possible with the mean level of the oceans. From the geoid, the topographic heights and the depths of the seas are reckoned.

Because one of the objectives of geodetic research is the determination of the figure of the Earth, geoid research has a central place within the science of geodesy.

7.1 The astrogeodetic geoid

Astronomical position determinations and azimuth determinations produced as visible results numerical values for the plumbline deviation components in the North and East directions, and with their aid one can draw the contours of a so-called astrogeodetic geoid on a map. Such a geoid is on the whole of similar shape as the true geoid. It contains however less detail than a gravimetric geoid based on gravity measurements, and furthermore it is tilted with respect to a truly geocentric coordinate system, if the system for the geodetic reference points is chosen wrongly.

At the Finnish Geodetic Institute the astrogeodetic geoid has been calculated many times. The version displayed in Figure 6 is based on the most extensive observational material available.

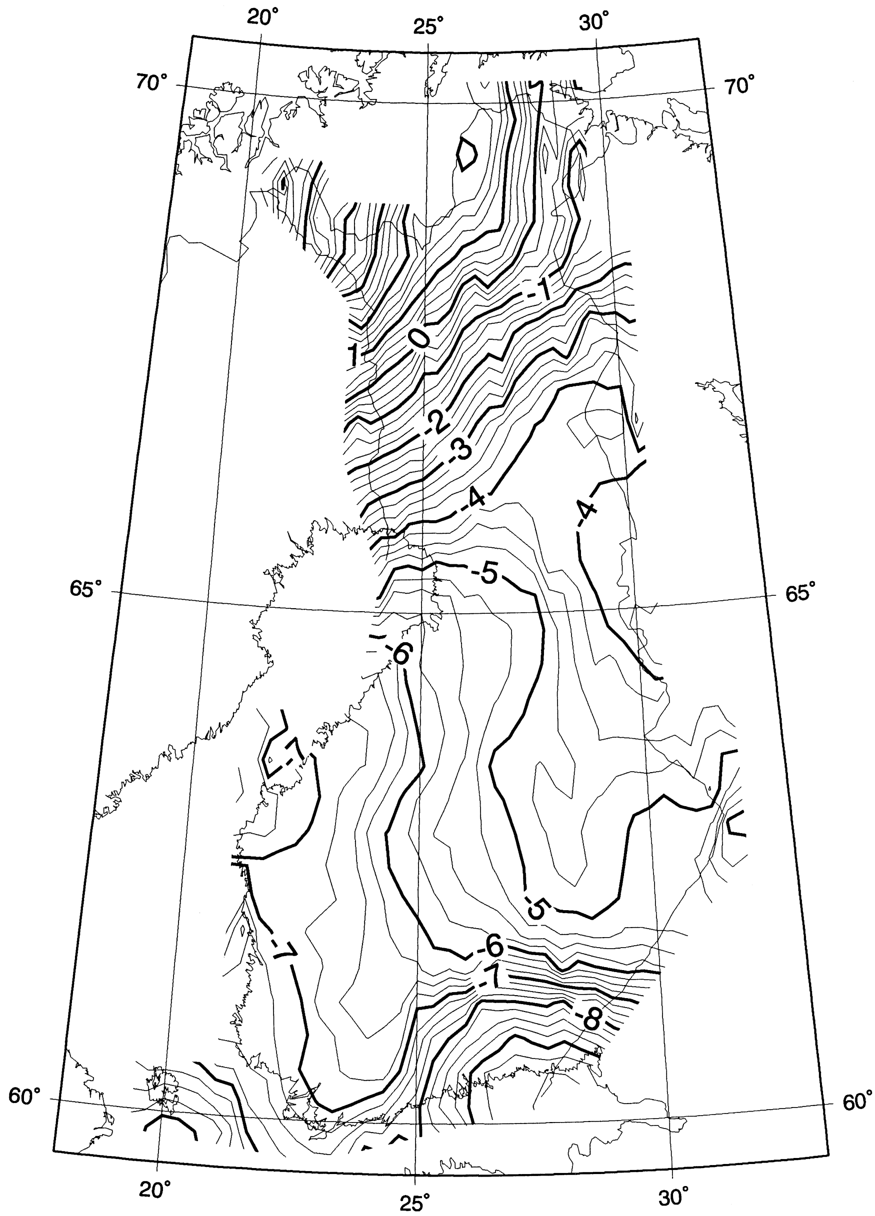

Fig. 6. The astrogeoid of Finland according to M. Ollikainen. Starting point is Korkatti and system is Bomford 70.

7.2 The man who dedicated his life to physical geodesy

Immediately after the foundation of the Finnish Geodetic Institute, its appointed Director, Ilmari Bonsdorff, started searching young talents for his Institute, and he succeeded excellently in this, as he managed to catch e.g. Yrjö Väisälä. Soon also M.Sc. Veikko Heiskanen wandered in, becoming in September 1921 a civil servant at the Institute. Ilmari Bonsdorff had written his own doctoral dissertation in the field, which studied the isostatic balance of the Earth's crust, and so perhaps he gave the young Heiskanen the stimulus to start studying isostasy.

Fig. 7. Professor V.A. Heiskanen, director of the Finnish Geodetic Institute from 1949 to 1961. Portrait by E. Tilvis. (Finnish Geodetic Institute's Collection.)

In 1922, the Hayford reference ellipsoid had been chosen as the basis for map-making in Finland; a couple of years later it was chosen also as the international reference ellipsoid, as told earlier. The Hayford reference system lacked a normal gravity formula. To find one, it was necessary to collect gravity measurements made around the Earth at that time, and remove from them the local irregularities caused by mountains and seas. Already in the middle of the 19th century it had been shown, that these were compensated by invisible mass distributions inside the Earth, but no reliable model had as yet been found for this distribution. There were two alternatives, either the mountains had risen from their substrate like dough, in which case the density of the mountains would be inversely proportional to their height (*Pratt's model*), or the continents floated on top of fluid internal matter like ice floes on the ocean, in which case the mountains had roots extending the deeper, the higher the mountain was (*Airy's model*). Heiskanen considered the Airy model more natural and started developing it. Soon he could demonstrate, that, provided one chose a suitable value for the thickness of the crust, the Airy theory would be at least as useable as the Pratt theory.

The first research results Heiskanen used as the subject for his dissertation. His research results were internationally noted for the first time in 1930, when the international geodetic congress in Stockholm canonized as a gravity formula an expression which read like this:

$$\gamma = 978{,}049\left(1 + 0{,}0052884\sin 2\varphi - 0{,}0000059\sin^2 2\varphi\right) \quad (4)$$

Here, φ is latitude and γ the acceleration due to normal gravity. The leading term of this equation Heiskanen had derived from his isostatic studies.

In 1931 Heiskanen moved to the Helsinki University of Technology as Professor of Geodesy. He returned to the Finnish Geodetic Institute in 1949, this time as Director. The handling of responsible official duties at the Technical University had in no way interrupted Heiskanen's research programme, which featured, in addition to the study of isostatic problems, also prominently research belonging to the field of physical geodesy. Around his research assistants and young people living on grants, an actively functioning research institute was formed, that in 1936 received from the International Association of Geodesy the official status and name of Isostatic Institute. In the name of this Institute, until 1965, 49 publications appeared.

In 1951 Heiskanen was appointed as a research professor and supervisor of the global gravimetric mapping project to Ohio State University, in connection with which there functioned a separate Research Center, and there, a Mapping and Charting Research Laboratory, the work of which was close to Heiskanen's other activities. The same year, a geodetic, photogrammetric and cartographic institute was founded within the Ohio State University. As the scientific leader and, since 1953, also executive director, Heiskanen acted up till 1961, when the institute was merged with the just founded geodetic faculty.

At the start of the American part of his career, Heiskanen presented his views and plans to solve the fundamental problems of geodesy in his publication *The World Geodetic System*. In order to realize this, a worldwide project was started, aiming at collecting to Ohio gravity material from everywhere on Earth in order to compute a global geoid and deflections of the vertical. Material was received from 35 countries, but the international situation caused it to be collected slowly, and holes remained in the global gravimetric map, which would not be filled during Heiskanen's lifetime.

7.3 The gravimetric geoid

According to his own narrative, V. Heiskanen became convinced in 1931, that the figure of the Earth could be pictured in detail with the aid of a gravimetric geoid. Therefore he proposed to his assistant of that day, R.A. Hirvonen, that he would write his dissertation on gravimetric methods for determining the geoid. Hirvonen followed the advice of his superior, and when the dissertation *The Continental Undulations of the Geoid* became ready in 1934, Heiskanen was satisfied, as the results of the work were both important and promising. Hirvonen was the first to apply the *Stokes' formula* to the calculation of the gravimetric geoid.

This famous formula in its basic form is as follows

$$N = \frac{R}{4\pi G} \iint_{\sigma} \Delta g S(\psi) d\sigma \tag{5}$$

where N is a geoid undulation to be calculated, R is the radius of curvature of the Earth, G is mean value of gravity over the Earth, Δg is a gravity anomaly, $d\sigma$ is a surface element, and $S(\psi)$ is so-called Stokes' function (shown in all textbooks of physical geodesy). In spite of incomplete global coverage of the gravity material used, Hirvonen was able to show, that the geoid can deviate from the reference ellipsoid only little, on average ±50 m.

Heiskanen's other assistant, *L. Tanni*, who had worked at the isostatic institute, continued Hirvonen's studies. In 1948 he published a study that came into widespread use: *On the Continental Undulations of the Geoid as determined from the present gravity material*. The gravity material available to Tanni consisted of some 13 000 pendulum points and several thousand gravimeter points. Most of these were done on land. In spite of the deficient global coverage of the material, the main features of the figure of the Earth were clearly visible in Tanni's geoid and in their right places.

When Heiskanen moved to the United States in 1951, also the focus of gravimetric geoid research shifted with him, like told before. In Finland this was continued by R.A. Hirvonen, who succeeded Heiskanen in 1950 as Professor of Geodesy at the Helsinki University of Technology.

7.4 The point mass method

The geoid research at the Finnish Geodetic Institute had diminished after Heiskanen had left. This did not change until 1974, when the Finnish gravimetric geoid computed by T. Honkasalo was published. It was based on gravimetric measurements made in the 1950's and 1960's in approximately 20 000 points, and it was computed using the Stokes' formula.

After this, geoid studies at the Institute moved into an upward curve again. *M. Heikkinen*, who had come to the Institute as Honkasalo's assistant, gave up the use of the Stokes' formula for gravimetric geoid determination at the end of the 1970's and developed instead a computing method based on the straight application of Newton's attraction law, the so-called point mass method. In 1981 he published the significant work *Solving the Shape of the Earth by using Digital Density Models*. In it, he presented both the theory and maps of the global geoid, which he had computed using over 40 000 mass points. Later the Dutch *M. Vermeer* developed the computational aspects of Heikkinen's method and computed both the Finnish and the Nordic gravimetric geoids using it (*Vermeer,* 1984). In 1992 Vermeer was appointed to the position of department head and professor at the Finnish Geodetic Institute.

7.5 New methods applied to determination of the geoid

Geoid studies were continued in Finland also in the 1990's, this time by applying completely new methods to the study. One of the methods was to derive the geoid undulations from the GPS satellite measurements performed along levelling lines. Geoid undulations are, as is well-known, the differences between the ellipsoidal heights from GPS measurements and orthometric heights from the levelling. High accuracy for the geoid undulations can be obtained with this method as shown by *Ollikainen* (1998).

In the other new method the geoid undulations were derived from the deep seismic sounding data (*Wang,* 1998*, Kakkuri and Wang,* 1998). This is possible because the data obtained from DSS can be used to construct a 3-D velocity structure model for the Earth's crust. The velocity model can further be converted to a 3-D density model using the empirical relationship that holds between the seismic velocities and crustal mass densities. This relationship is a linear relation known as Birch's law

$$v_p = \alpha(m) + b\rho \tag{6}$$

where v_p is velocity of the seismic P-waves known from the DSS, ρ is density to be calculated, α is a coefficient which depends on the mean atomic weight m of the rock material only, and b is a constant. For plutonic and metamorphic rocks, which are the main types of rocks in the shield areas, the mean atomic weight plays an insignificant role and can be safely neglected from the density-velocity relation. In the sedimentary rock areas, where the p-velocities depend on the burial and geologic age of the rock, the use of Birch's law is, however, questionable. Density data, for example, from drilling holes should be used instead of DSS-data.

As soon as observed velocities have been converted into densities and 3-D density model developed for the crust, the geoid can be calculated using well-known computing techniques.

8. The Fennoscandian land uplift

Land uplift studies have a long and respectable history in Finland and Sweden. For this, both countries can thank Mother Earth, who has blessed both her children with a powerful land uplift, so powerful, that already the changes happening during a human lifetime can be easily observed. The writer Zachris Topelius depicted late last century the land uplift thus:

"Most noticeable are the effects of this partly still unexplained phenomenon. The land rises from the sea, the sea flees, shores are exposed, the slope is moving forward. Where in old days the ships were sailing, now hardly a ship can travel; where once the fisherman cast his net, now his cows go grazing on the coastal meadow. Banks and rocks appear out of the water, of which no sea chart has had knowledge before; banks expand into islets, these grow together and connect with the mainland. Beaches expand,

harbours dry up, sea ports must move after the fleeing sea. Every generation of men, new areable land rises from the sea, every century grants Finland a principality."

(Finland in the 19th Century as presented by Finnish writers and artists in words and pictures (in Finnish). Helsinki, 1893. G.W. Edlund, publisher.)

One encounters many a renowned scientist's name in the field of land uplift research, like the Swede *Gerard de Geer,* who proved the land uplift to be a residual rebound phenomenon from the ice age, or the Finnish geologist *Wilhelm Ramsay*, who separated conceptually the isostatic land uplift and the eustatic change of sea level from each other.

8.1 Determining the land uplift

The speed of land uplift can be measured on the shores by using water level meters also called tide gauges, and inland by precise levellings, repeated with 40–50 years interval.

On the shores of Finland there are 13 tide gauges maintained by the Finnish Institute of Marine Research, namely the tide gauges in Kemi, Oulu, Raahe, Pietarsaari, Vaasa, Kaskinen, Mäntyluoto, Rauma, Turku, Degerby, Hanko, Helsinki, and Hamina. Of these, the Hanko tide gauge is the oldest; it has been in use since 1887. The youngest is the tide gauge of Rauma, which started operation in 1933. Because even the youngest tide gauge has already operated for 67 years, one can determine with their aid the land uplift on the coast extremely well. Such determinations have been done; e.g. the civil servants of the Finnish Institute of Marine Research *I. Hela* and *E. Lisitzin* have published extensively used values for the land uplift. The up till now most precise values for the tide gauges were determined by a working group established jointly in 1988 by the Finnish Institute of Marine Research and the Finnish Geodetic Institute, to which belonged *P. Mälkki, H. Boman, Kimmo K. Kahma* and *M. Leppäranta* from the Finnish Institute of Marine Research, and M. Vermeer and J. Kakkuri from the Finnish Geodetic Institute. In their work, the sea level values were treated as monthly means, whereas in earlier determinations they were yearly means.

The Finnish Geodetic Institute has tied all the tide gauges to the precise levelling network. By this means, a datum or reference level was obtained for the precise levelling, and starting values for the relative land uplift values given by the successive levellings. The reference level of the precise levellings is, as mentioned earlier, mean sea level in Helsinki at the start of 1960.

In the Finnish Geodetic Institute, several land uplift studies have been published. The most well-known of these is probably the determination of uplift figures by E. Kääriäinen (1953), in which the differences in yearly land uplift values between benchmarks were derived using the material of the first and second precise levellings. The relative land uplift values thus obtained were then anchored to the values for the tide gauges, which I. Hela had determined. Thus, final land uplift values were obtained for about a thousand benchmarks measured in both levellings. When to these was added still the eustatic rise of sea level – estimated to be 0.8 mm/yr, the land uplift velocities relative to the geoid were obtained. Using these point values for the land uplift, that were considered reliable, a map was drawn with contours of the same land uplift value, or isobases. Their precision has been estimated at ±0.3 mm/yr.

Of the other land uplift maps produced at the Finnish Geodetic Institute, one must mention the one by T.J. Kukkamäki of 1975, which pictures the rising Earth's crust in Sweden, Southern Finland, East Carelia and the Baltic states, as well as O. Suutarinen's map from 1983, covering Finland in its entirety. Among the latest versions is the map published by Mäkinen and Saaranen (1998).

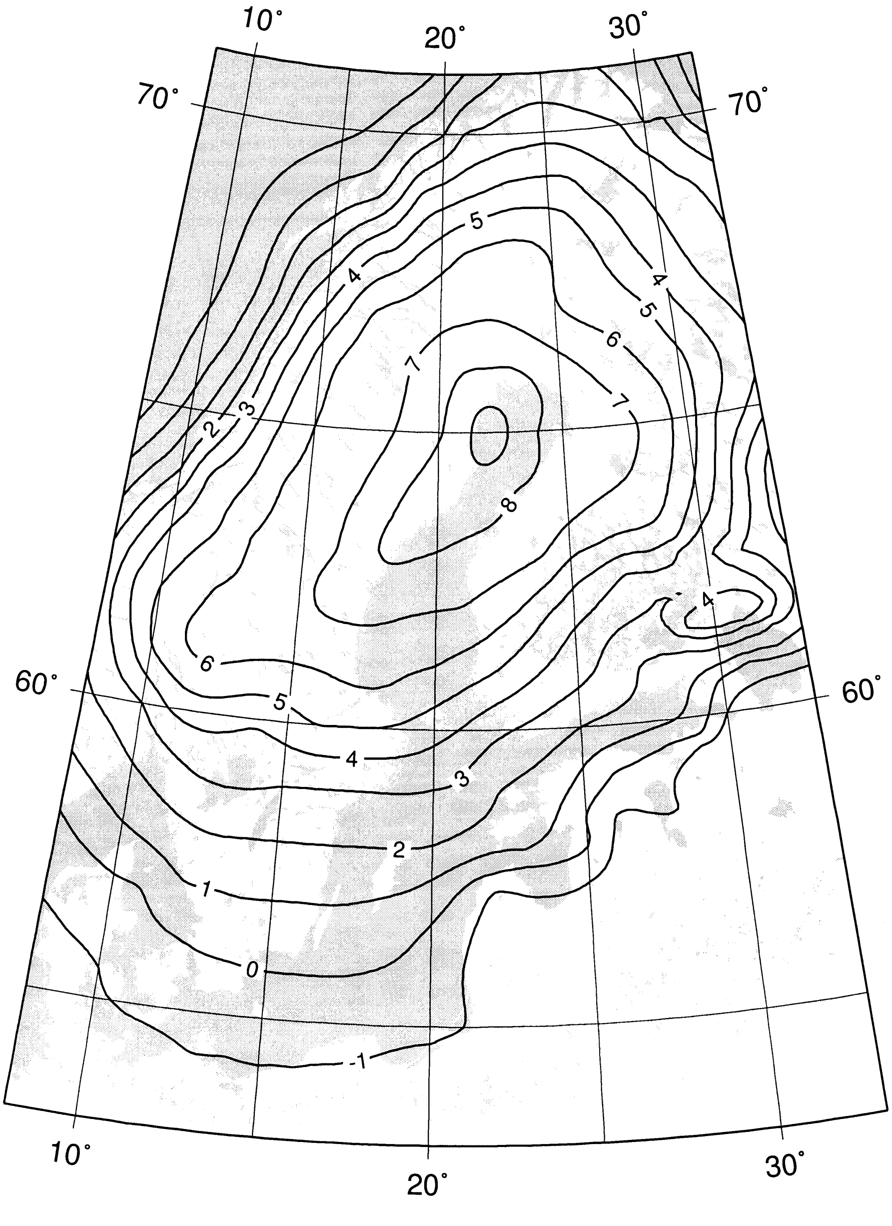

Fig. 8. The land uplift map of J. Kakkuri. It depicts the land uplift in the Fennoscandian Shield area. The map is based on two precise levellings and sea level observations. The isobases depict the land uplift relative to the mean sea level in millimetres per year (*Kakkuri,* 1997).

8.2 Land uplift and gravity

When the land rises, the land surface is moving away from the centre of the Earth. At the same time, mass is flowing in under the crust from outside the uplift area. This phenomenon makes gravity diminish on the Earth's surface as a result of land uplift. If the diminishing is slower than what Newton's law of attraction would require, then the mass flowing in within a thin layer under the crust is partly compensating for this. There are, for this simplified model, two extreme values for the rate of gravity diminishing: if it is –0.17 μGal/mm, then the inflow of mass is total, if on the other hand it is –0.31μGal/mm, there is no mass flow at all (*Mäkinen,* 2000).

The Finnish Geodetic Institute started its research on the foregoing phenomenon in 1967, when four instruments needed for the measurements were received on loan from the United States. Eight observation stations were constructed for the measurements, located in Joensuu, Äänekoski, Vaasa, Kramforss, Stugun, Kopperå, Meldal and Vågstranda. The line formed by them followed the 63rd parallel. Later three other lines were built, one along the 65th parallel, one along the 60th parallel and the third one along the 56th parallel. Most of the measurements performed by A. Kiviniemi and his foreign colleagues almost yearly have been done on the line running from Joensuu to Vågstranda.

Over 30 years have passed since these measurements were started. Has gravity changed during this quarter century? We can answer this question in the affirmative. J. Mäkinen and his Swedish colleague *M. Ekman* have analyzed all the measurements made up to 1990 on the line from Joensuu to Vågstranda and obtained a value for the rate of diminishing of gravity of –0.22 μGal/mm. On the basis of this it may be concluded, that the Fennoscandian land uplift is associated with almost total mass flow. When e.g. the land uplift in the Vaasa area in relative to the centre of the Earth approximately 10 mm/y, gravity has diminished there in 26 years 0.22×10×26 microgals, i.e. about 0.06 milligals. Even a change this small can be observed with an absolute gravimeter.

8.3 Horizontal component of the land uplift

The complicated upward motion in the area of Fennoscandia once covered by the continental glacier has been characterized according to research, by changes in time, and the land has risen in blocks bounded by fault zones.

Also the recent land uplift has these features. According to the land uplift map presented above the land rises in some places "too" quickly, in other again too slowly. This may be caused by horizontal stress induced by the continental plate motion, which speeds up the uplift, or extension, which slows it down. The land uplift may in that case also have a horizontal component. Successive precise levellings cannot detect possible horizontal motions of the Earth's crust – that requires successive triangulations. Fortunately these have been done in Finland.

As mentioned earlier, the main network chains of the national triangulation form loops. The areas inside them have been filled with younger triangulations and electromagnetic distance (EDM) measurements. The distances between the triangle points may thus be derived from two different measurement sets, namely the measurements of the main network and the later performed triangulation and EDM measurements, and crustal movements that change distances, may in this way be detected.

The Finnish Geodetic Institute started an investigation on the horizontal motions in the Finnish bedrock in the beginning of the 1980's. Preliminary results of investigations by J. Kakkuri indicated already the possibility of such motions, and his student *R. Chen'*s (1991) final analysis confirmed their existence.

8.4 Determining the horizontal crustal movements in Central Asia

The Finnish Geodetic Institute performed short-range EDM measurements also in Central Asia, more precisely in Tadžikistan, in 1980–1983. These measurements were aimed at studying surface deformations caused by tectonic plate motion in the Garm area, which is located on the northern side of the Pamir mountains (*Konttinen,* 1985*, Kakkuri and Konttinen,* 1986).

The measurement location in Garm, the *Saripul* network, extended across a beautiful valley between the Pamir and Alai mountains. A deep crustal fault ran through the valley, i.e. along a river called the Surchob. There were five bechmarks in the Saripul network. Three of them were located in the foot of Mindalul mountain, which belongs to the Alai. Two other benchmarks were located to the foothills of the Pamirs.

According to the measurements performed mostly by R. Konttinen, the Pamirs moved slowly ($\vec{v}$ = 1.5 cm/yr) to the north. The direction of the motion was 349° (north is 0°).

9. Baltic Geodetic Commission

Early spring 1924 the Finnish government organized in Helsinki at the request of I. Bonsdorff a geodetic conference, in which participated delegates appointed by their governments from Sweden, Germany, Poland, Lithuania, Latvia, Estonia and Finland. As the Finnish representative acted Bonsdorff and Professor *A. Donner*, then Chancellor of Helsinki University. The conference decided to propose the founding of a permanent Baltic Geodetic Commission for the states in the Baltic Sea region.

9.1 The Baltic triangulation ring

When the Helsinki conference was over, I. Bonsdorff drafted a treaty for founding the Commission, and the Finnish government forwarded this to the governments of the Baltic Sea states. In it, it was proposed in conformity with the resolutions of the conference, that the signatory states would be bound to establish a Baltic Geodetic Commission and to cover its expences. The task of the Commission would be to further the execution of triangulation measurements of first order, measurements of baselines, astronomical position determinations and gravimetric measurements on a uniform basis and using uniform methodologies within the area of the Baltic Sea, and to derive from the measurements results in a uniform way. The measurements were to serve both practical and scientific purposes. Every state were to appoint one voting member and an arbitrary number of other, non-voting members. The running affairs of the Commission were to be handled by a Presidium consisting of a president, a vice-president and a secretary-general. They were to be elected by the voting members for three years at a time. The president and vice-president would not be re-electable. The Commission were to meet generally once a year, in a place and time of its own choosing. The treaty was to be in force for 12 years starting January 1st, 1925.

The proposed treaty received a positive response in the participating countries, and it was signed at the end of 1925 and beginning of 1926. In 1926, also Denmark and the free city of Danzig joined it, and the Soviet Union was a member from 1929 to 1937. The duration of the treaty was set to 12 years, but later the duration was extended with another 12 years, i.e. up till 1948.

Already in Helsinki a presidium and officers had been elected for the Commission: the Swedish Professor *Rosén* had been elected president and the Polish Professor Banachiewiez became vice-president. As the permanent secretary-general was chosen I. Bonsdorff, and the Commission's office was located in Helsinki, on the premises of the Finnish Geodetic Institute. The presidium decided to organize a new conference in Stockholm already August 1926, in order for the main task of the Commission, the measurement of the Baltic triangulation ring, to get started as soon as possible.

From the national activity reports presented at the Stockholm conference it became apparent, that many of the planned measurements had already started. Thus, Estonia had reconnoitred the Tallinn baseline, and the network connecting Estonia and Finland had been measured. In Latvia, all signals on the triangulation network had been built, a part of the network had even been measured already and the baselines of Libau and Mittau had been measured. In Lithuania, organizational work had been done, on the basis of which the measurements could start. In Germany, the Berlin-Strahlsund triangulation network had been reconnoitred. In Sweden, the triangulation had progressed from the South to the level of Norrköping. The Uppsala baseline had been reconnoitred, as well as the connecting network with Finland. For the Finnish part, the field observations of the common part had already been completed.

After Stockholm, conferences were held almost yearly, namely in Riga, 1927, in Berlin, 1928, in Copenhagen, 1930, in Warsaw, 1932, in Leningrad and Moscow in 1934, in Tallinn and Tartto in 1935, in Helsinki, 1936 and in Kaunas, 1938. During the Second World War, conferences were not held, and not after it either. The Presidium however met 11 times during 1939–1948.

The Baltic triangulation ring measurement, which had started with so much energy, continued also to progress rapidly, and it in spite of the restless political situation in the world it was even brought to a successful conclusion. The ring counted 317 triangulation points, and its total length was approximately 2 500 km. The closure error of the whole ring amounted to ±2.5 m, the mean error of a triangle point to ±0.37″, the mean error of longitude differences $\pm 0.010^{r}$ and the relative mean error of the comparison baselines 1:3 850 000. Gravity differences were measured by two different expeditions. The mean error of both measurements was ±0.45 mGal. The measurement work of the Baltic triangulation ring was thus an excellent success and of high quality accuracy-wise.

The activities of the Baltic Geodetic Commission were in reality led by its originator an secretary-general I. Bonsdorff. As his assistant acted V.R. Ölander, who was also responsible for the treatment of observations and for the final adjustment of the whole triangulation ring. The personnel of the Finnish Geodetic Institute participated in many international measurements of the ring, e.g. P. Kalaja, U. Pesonen and V.R. Ölander participated in the baseline measurements and Y. Leinberg in the astronomical measurements.

9.2 Recovery of collaboration

In 1989, the International Association of Geodesy established an ad hoc working group led by J. Kakkuri to plan the unification of the height systems of the countries around the Baltic Sea using satellite measurements. The initiator of the idea, the Pole Professor *J.B. Zielinski*, was appointed secretary of the working group, and the Swede Professor *L. Sjöberg* vice-president (*Poutanen and Kakkuri,* 1999).

The working group organized in October 1990 a two weeks' GPS observation campaign, called the *First Campaign*, in which 26 tide gauge stations on the coast of the Baltic Sea were tied to the same height system. Measurement teams from Poland, Sweden, Germany, Finland and Denmark participated in the campaign.

As the First Campaign took place at a time of political unrest in the Baltic States and Russia, these countries were not able to take part in it. As soon as it was politically possible, contacts were made with the authorities of the newly independent states in order to plan and organize the Second Baltic Sea Level Campaign which was agreed to be carried out in the period June 7–13, 1993. The *Second Campaign* was then performed under more favourable measurement conditions than the First Campaign, and plenty of good data was collected.

The Third Campaign was performed in the period May 21–29, 1997 simultaneously with the EUVN (European Vertical GPS Reference Network) Campaign. The reason of combining these two campaigns was that most of the points on the Baltic Sea area were common to both networks.

The working group collected from the above mentioned three campaigns a large volume of accurate GPS data. In addition, tide gauge observation series as well as gravimetric data from the Baltic States and Russia were collected. All the data collected were then applied to calculating the gravimetric geoid for the Baltic Sea and to determination of the sea surface topography of the Baltic. The data was also used for calculating the gravity potential, W_0, and its temporal variation, $\dot{W}_0$, on the Baltic Sea.

In fact, geodetic determination of the sea surface topography of the Baltic was performed in 1990's many times using various techniques. The first of them (*Ekman and Mäkinen,* 1996) was based on the levelling height system NH60 used to derive mean sea surface topography at Finnish, Swedish, Danish and Norwegian tide gauges in Baltic and its transition area to the North Sea. The next determination (*Kakkuri and Poutanen,* 1997) was based on the Baltic Sea Level GPS Campaign of 1993 at tide gauges and on a modified BSL95A geoid of *Vermeer* (1995). The GPS/geoid technique used made it possible to use tide gauges on islands, not connected to the Nordic levelling network. A later GPS/geoid determination at tide gauges (*Poutanen and Kakkuri,* 2000) used the Baltic Sea Level GPS Campaign of 1997 and the NKG96 geoid (*Forsberg et al.,* 1997). Also altimetry/geoid technique was successfully applied to the determination of the sea surface topography (*Poutanen,* 2000).

10. The Metsähovi observatory

The observatory site Metsähovi, located in Kirkkonummi, counts research and observation stations belonging to three institutes, namely the Finnish Geodetic Institute, Helsinki University of Technology and Helsinki University. Of these, the activity of the Finnish Geodetic Institute is concentrated on geodetic measurements with the aid of satellites, aimed at investigating the shape and size of the Earth, researching various motions taking place in the Earth's crust, and developing measurement methods. Furthermore the Institute participates in the international tracking and orbit determination programmes.

10.1 The story of the satellite laser

At the beginning of 1972 is was completely clear, that the Finnish Geodetic Institute should undertake to develop a satellite observation technique based on the use of electronics and the use of computers, if it intended to stay along in the international development of its field. The precision of the stellar triangulation was no longer sufficient for international triangulations, as one could perform considerably more precise measurements with "radars" based on the use of laser light and radio waves.

Of the new measurement instruments, the satellite lasers were the most precise, but also the most expensive. There was no market for these devices, so they had to be made on order in electronics factories, or to be home-built. The Finnish Geodetic Institute chose the latter alternative and started up a collaboration with Professor *M. Tiuri* of Helsinki University of Technology. He again handed the planning tasks for the instrument down to Professor *S. Halme*, and when the Academy of Finland had agreed to act as the main financier of the project, the working group led by Halme and consisting of J. Kakkuri*, Kalevi Kalliomäki, Kari Kalliomäki, M. Paunonen, O. Ojanen* and *A.B.*

Sharma started the construction work on the Finnish version of the satellite laser (e.g. *Paunonen,* 1982).

The group decided to build a so-called ruby laser. This was a pulsed radar. It developed inside a ruby crystal a giant, short light pulse, which was fired up to a geodetic satellite orbiting at several thousand kilometers height. The reflections were received in a reflector telescope, which tracked the satellite's motion. When the pulse's back-and-forth travel time had been measured using a nanosecond counter, the instantaneous distance to the satellite was obtained, using a formula describing the propagation of light, to within a fraction of a metre. From successive shots, one could derive parameters describing the satellite motion and orbital elements, and from those again elements of the Earth's gravity field and intercontinental distances, with great accuracy.

The construction work on the satellite laser was started in 1973, and the first reflections were obtained from the Geos-satellite in 1978. The planning and construction work, which lasted some five years, confronted lots of difficulties. When the work was started, the precision of the time signals transmitted by international radio stations was at best 0.001 seconds. This was not even close to being sufficient, as Universal Time was needed a hundred times more precisely, i.e., with a precision of 0.000 01 seconds. In order to improve the precision of time signals, a quartz crystal clock was purchased by the Institute, and Kalevi Kalliomäki connected it through a LORAN-C receiver built by him to the international atomic clock time system. The quartz clock locked to the LORAN-signals soon proved to be sufficiently precise, and the time signal problem had found a successful solution.

There were other problems to be solved. One of these had to do with the high power laser pulses. The duration of one pulse was approximately 0.000 000 02 seconds, and the instantaneous power was 50 million watts! This caused technical problems, because especially the optical parts of the instruments came under heavy load, and they had to be cooled; and safety problems, as the powerful light pulses were dangerously bright. Every pulse had to hit its target, a satellite moving at great speed (6–7 km/s). Its orbit had to be computed in advance, and the laser was to be fired with a precision of several millionth parts of a second, in order for the pulse to hit its target.

The so-called return pulse reflecting from the satellite was extremely weak, especially compared to the powerful outgoing pulse. In fact it contained only a few photons, which the receiving telescope collected onto the cathode of a photomultiplier tube. The telescope with which the return pulse was received, was entirely hand-built in Finland, as its mount was made in the State Technical Research Centre's fine mechanical workshop, the optical parts at Tuorla Observatory and the guidance electronics in the Institute's own workshop. The diameter of the primary mirror was 63 cm.

All the problems, mentioned above and left unmentioned, were solved in satisfactory ways, and in 1978 the satellite laser started producing observational material, from which it has been possible to determine e.g. the geocentric coordinates of Metsähovi with a precision of approximately 2 centimetres. As a result of the development effort, two doctoral dissertations were born (M. Paunonen and A.B. Sharma) as well as two licentiate theses (Kari Kalliomäki and O. Ojanen). Also the Finnish people benefitted from the development work, as the Finnish National Broadcasting Company (Yleisradio) took as the basis of its own time signal transmissions the signals of the quartz clock locked to the LORAN signals, and soon all the clocks in the nation could be compared with a precision of a few millionths of a second with international atomic clocks.

10.2 American Doppler and GPS; French Doris

In spring 1982 the Finnish Geodetic Institute acquired from England a so-called Doppler satellite receiver. It could be used to determine the coordinates of the observation site relative to the Earth's centre with a precision of a few metres. The operation of the instrument was based on the use of the American Transit satellite system. It consisted of some ten satellites in polar orbits, that transmitted stabilized 150 MHz and 400 MHz frequency signals. On the Earth's surface, the Doppler receiver "heard" the transmitted frequency as higher or lower, depending on whether the satellite was approaching or moving away. From this so-called Doppler shift, the coordinates of the receiver could be calculated, if the satellite orbital elements were known. These were contained in the signal transmitted by the satellite (Broadcast Ephemerides) or were added to the coordinate calculation process later on (Precise Ephemerides). Using its Doppler receiver, the Institute determined Metsähovi's geocentric coordinates during many years and collected an observational material from which the polar motion of the Earth may be calculated actually more precisely than from astronomical zenith observations.

The Transit satellite system became quickly obsolete, and halfway into the 1980's it was replaced by the more advanced GPS system, i.e. the Global Positioning System. This all-weather satellite system developed by the United states comprises 24 satellites organized in circular orbits, a permanent network of tracking stations, and a large international community of users. The satellites, which are orbiting at a height of approximately 20 200 kilometres, transmit radio waves on two different frequencies, i.e. 1 575.42 and 1 227.6 MHz. Both waves have modulated upon them information on the satellite's orbital elements and time signals. They are observed on the Earth's surface using the user community's GPS receivers, which have an antenna and a precise clock, and the receiver's "smart" computer calculates from these the location of the antenna with great accuracy. The tracking network consists of numerous permanent observartion stations, the coordinates of which are precisely known and that monitor all GPS satellites day in day out. Also Metsähovi belongs nowadays to this set of tracking stations. The GPS observations in Metsähovi are fed into the storage of computers in the United States and Europe once a day over electronic communication lines, to be used for computing and updating orbital elements. In 1992 Metsähovi joined the so-called IGS network (International GPS Service for geodynamics), which produces observational material for research into crustal movements.

North of Metsähovi, at a distance of some kilometres, is located the Sjökulla training centre, and close to it, on a low lying field, a small hut and an antenna mast of some 3 metres height. In spite of its modest looks, the mast is one link in the Doris measurement system spanning the globe. This measurement system, maintained by the French mapping agency (Institut Géographique National), consists of fifty fixed stations, which form a global triangulation network. The operations are based on radio waves, which the ground stations transmit at frequencies of 401.25 MHz and 2 036.25 MHz, and with the aid of which the small Doris receivers mounted on satellites can determine their position to within a fraction of a metre in a geocentric coordinate system defined by the ground stations.

When the Sjökulla Doris station started operations early 1989, its coordinates were based upon the satellite laser's coordinates. In 1989 the German mapping agency Institut für Angewandte Geodäsie (IfAG) brought from the United States to Europe a high precision radio telescope in order to measure the base points of the European EUREF coordinate system. Metsähovi had been chosen as one of the base points, and that is why the radio telescope was brought in summer 1989 also to Finland, and with it, a precise reference point was established in Sjökulla.

10.3 The future of Metsähovi

At the Metsähovi Research Station, satellite observations have been performed since 1978, i.e. over a period of 20 years. During these years, the station has established a firm position among the geodetic fundamental stations of the world. In addition to satellite observations, gravimetric measurements have been made in Metsähovi, and it is the location of the reference point of the Finnish gravimetric network. Also Earth tidal registrations have been made in Metsähovi over many years, as told earlier.

In the 1994 the Metsähovi Observatory was equipped with a superconducting gravimeter SG T020. In this instrument mechanical spring suspension is replaced by a magnetic levitation. Due to that, the instrument has superior sensitivity as well as smooth and small instrumental drift. Since August 1994 it has sampled every 1 second the gravity field with a precision better than $10^{-12} g$ (i.e. 1 nGal). The analyses of the data have shown that the superconducting gravimeter is useable for studies in all bands of gravity spectrum. It can monitor the noise level at the microseismicity band and retrieve seismic eigenmodes. E.g., microseismic vibration of the Fennoscandian Shied due to storms in northern Atlantic Ocean is observable. Tracks of moderate (M > 4.5) distant earthquakes are found from the data (*Virtanen,* 1998), and free oscillations triggered by major earthquakes are visible several days (*Virtanen and Kääriäinen,* 1997).

The Metsähovi Observatory is participating to Global Geodynamics Project, which started in 1997. Among scientific aims of this project are, for example, a study of weak core effects on gravity as well as silent and slow earthquakes.

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