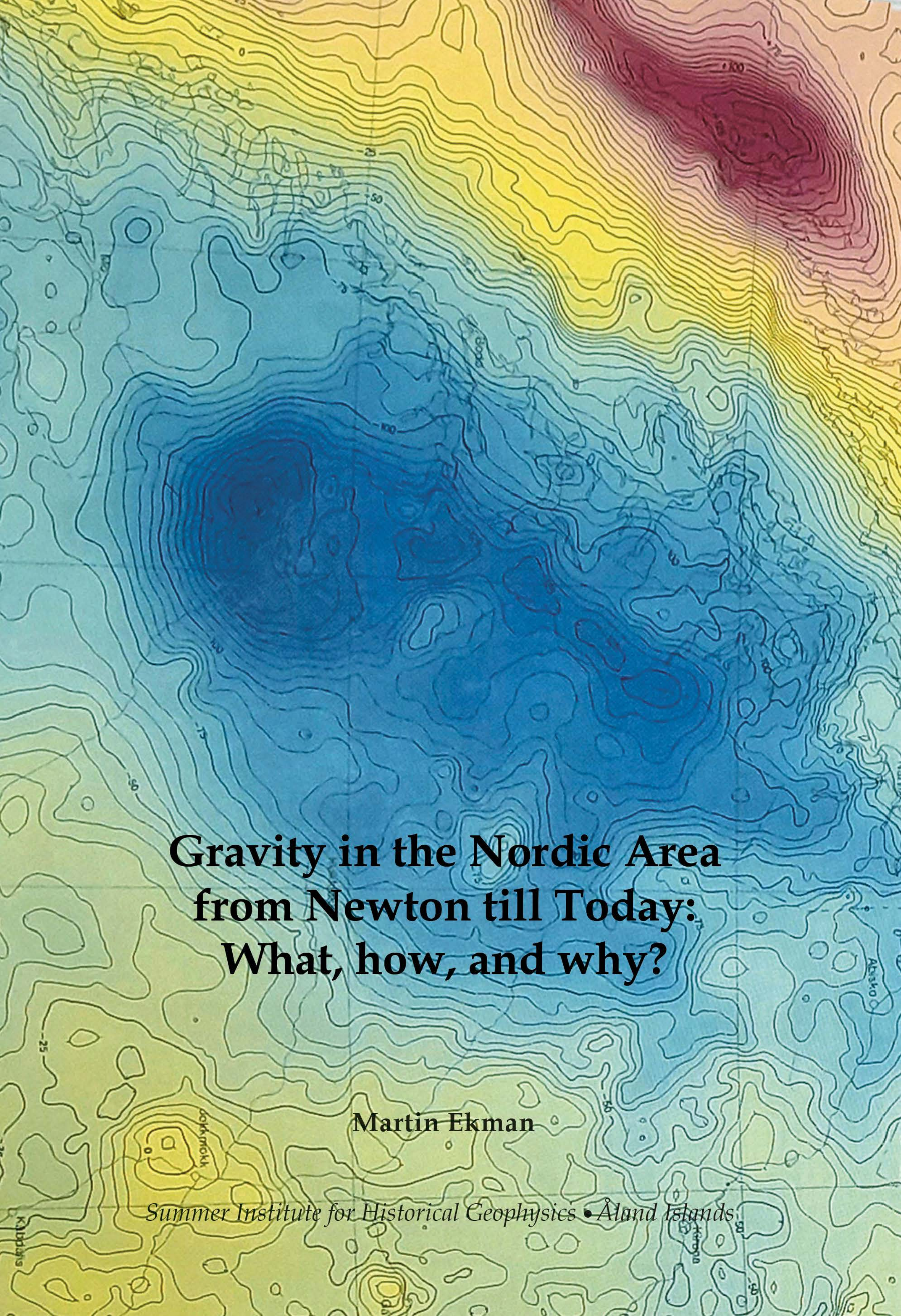

Gravity in the Nordic Area from Newton till Today: What, how, and why?

Martin Ekman

Summer Institute for Historical Geophysics • Åland Islands

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Contents

Preface

This is a book about the Earth's gravity, about what it is, how it has been determined, and why it has been useful to know it. The book has a historical perspective, spanning three centuries, and a northern perspective, dealing mainly with the Nordic area.

The historical perspective of three centuries is quite natural, since it all started with the ideas of Newton a little more than 300 years ago. The Nordic perspective has several reasons (apart from the author being a Nordic scientist): First, early gravity measurements with pendulums were made as far north as possible to try to verify Newton's prediction of a flattening of the Earth at its poles, and to determine the value of the flattening. Second, Nordic scientists later invented spring gravimeters facilitating gravity measurements to search for minerals, and started studying inner parts of the Earth. Third, gravity measurements at sea and on the ice cover of the sea were performed early in the Arctic and the Baltic Seas. Fourth, the postglacial rebound of the Nordic area has been investigated by repeated gravity measurements, lately also involving fall instruments. Fifth, the recently started melting of the Greenland ice sheet due to the ongoing climate warming has been revealed by repeated gravity measurements, in this case using satellites. Finally, the outlook at the end of the book, dealing with Einstein's view on the subject, also has a Nordic flavour, involving interesting problems with his Nobel prize.

The book is intended not only for gravity people, but for a wider audience with an interest in the constitution and the changes of the Earth, or with an interest in the historical development in Earth sciences. A background in elementary physics will be sufficient to understand the text; mathematical formulae (in this field often quite complicated) are completely left out.

References in the text are given by names and years within brackets; when years occur without brackets they relate to historical information. The main reference list at the end is ordered chronologically to give a historical overview of the works used.

A number of people have been helpful during my work on this book. I would first of all like to thank the persons who have read the whole manuscript and given constructive comments on it: Jaakko Mäkinen (Finland), René Forsberg (Denmark), Bjørn Geirr Harsson (Norway), and Holger & Rebekka Steffen (Sweden). I would also like to thank two persons for having answered questions, discussed various matters, and read parts of the manuscript: Per-Anders Olsson and Jonas Ågren (Sweden). In addition I would like to thank a Canadian colleague, Glenn Milne, for having contributed several improvements of the English language.

To get access to the older literature I have benefitted greatly from the Uppsala University Library, the Center for History of Science at the Royal Swedish Academy of Sciences, and the Geodetic Archives at the Land Survey of Sweden. I have also made use of the library of the former Astronomical Observatory of Uppsala and the Umeå University Library. My thanks to all the persons working at these libraries who have assisted me.

Martin Ekman

1. Background: What is gravity? Newton and his idea

In 1687 Isaac Newton, the English mathematician and physicist, published the epoch-making book "Philosophiæ naturalis principia mathematica" (Mathematical principles of natural philosophy). In this book he presented, among other things, the fundamental idea of an attractive force acting between bodies in space: gravitation. This force would be proportional to the masses of the bodies, and inversely proportional to the square of the distance between them. It would govern the motions of celestial bodies as well as the fall of an object on the surface of the Earth. The falling object would be subject to the gravitation of the Earth, slightly modified by the centrifugal force due to the Earth's rotation, the resultant being known as gravity. So, where did Newton's idea of gravitation and gravity come from?

It all started on the Danish island of Hven, today the Swedish island Ven, in the strait of Öresund between Denmark and Sweden. Here the Danish astronomer Tycho Brahe had founded an impressive observatory, Uranienborg, surrounded by a geometrical garden, in 1576. For 20 years, he and his assistants, among them his sister Sophie Brahe, observed the positions of stars and planets from the observatory. This was done with very large instruments designed for the naked eye since the telescope was not yet invented. The apparent motions of the planets against the background of the stars turned out to be very peculiar.

These planetary data came into the hands of the German astronomer Johannes Kepler in Prague. After lengthy calculations they allowed him to formulate two basic laws of planetary motion in 1609, and a third one in 1618. The first law stated that each planet moved around the Sun in an orbit shaped as an ellipse. The second law dealt with the speed of the planet in different parts of the orbit. The third law concerned the orbital period of the planet in relation to its distance from the Sun.

After some time, these laws of planetary motion became the subject of intense thinking by Isaac Newton. In 1665 the plague hit England which made him leave Cambridge and spend two years in the countryside. During this time his brain seems to have been working in an extraordinary manner, allowing him, among other things, to start using Kepler's laws to discover the force of gravitation. However, he did not publish his discoveries. Several years later his friend and colleague Edmund Halley asked him in what orbit a body would move if exerted on by a force inversely proportional to the square of the distance. Newton answered, “an ellipse”. When Halley asked how Newton could know that he simply answered, “I have calculated it”. Since he could not find his calculation, he had to do it once again and then sent it to Halley. This made Halley realize the importance of Newton’s work, and Halley persuaded Newton to publish his findings, finally appearing in his book.

Newton’s (1687) theory of gravitation and gravity was an excellent example of a general theory constructed from careful observations. And it contained one fundamental law capable of explaining several different phenomena; see Figure 1-1 for an example. Yet, it was not received with overall enthusiasm. On the contrary, it was met with a lot of questioning and scepticism for half a century. Why was it so difficult to accept Newton’s theory? Why was it not immediately accepted?

The main problem with Newton’s theory was that the concept of gravitation implied a force acting at a distance, without contact between the bodies involved. This seemed too abstract; in fact, it seemed quite occult and mysterious!

The reactions around 1700 by Swedish scientists who owned a copy of Newton’s book seem to be typical. Petrus Elvius, a predecessor to Anders Celsius as professor of astronomy at Uppsala University, states that Newton’s explanation is beautiful and sharp-witted, but that Newton has “not been able to explain what gravitation is”. He finds that this force “seems to be pure abstraction and no physics”. Also another predecessor to Celsius, his grandfather Anders Spole, did not accept Newton’s gravitation on similar grounds. Similarly, when the renowned technician Christopher Polhem, after having borrowed Elvius’ copy of the book, was asked about his opinion he admits that Newton is a great mathematician – still “he states in several places that the planets and their satellites gravitate, but what is causing such gravitation to occur he does never talk about”.

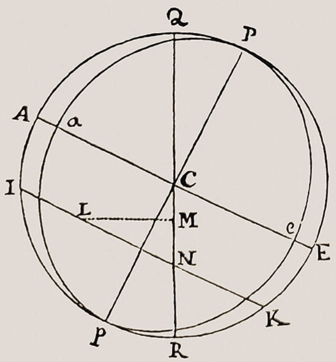
There were more scientists in other countries who reacted in the same way, causing Newton (1713) to add a comment in the second edition of his book:

[470]

Prop. XXXIX. Prob. XIX.

Invenire Præceſſionem Æquinoctiorum.

Motus mediocris horarius Nodorum Lunæ in Orbe circulari, ubi Nodi ſunt in Quadraturis, erat $16''.\ 35'''.\ 16^{iv}.\ 36^{v}$. & hujus dimidium $8''.\ 17'''.\ 38^{iv}.\ 18^{v}$. (ob rationes ſupra explicatas) eſt motus medius horarius Nodorum in tali Orbe; fitque anno toto ſidereo 20 *gr.* 11′. 46″. Quoniam igitur Nodi Lunæ in tali Orbe conficerent annuatim 20 *gr.* 11′. 46″. in antecedentia; & ſi plures eſſent Lunæ motus Nodorum cujuſque, per Corol. 16. Prop. LXVI. Lib. I. forent reciprocè ut tempora periodica; & propterea ſi Luna ſpatio diei ſiderei juxta ſuperficiem Terræ revolveretur, motus annuus Nodorum foret ad 20 *gr.* 11′. 46″. ut dies ſidereus horarum 23. 56′. ad tempus periodicum Lunæ dierum 27. 7 hor. 43′; id eſt ut 1436 ad 39343. Et par eſt ratio Nodorum annuli Lunarum Terram ambientis; ſive Lunæ illæ ſe mutuò non contingant, ſive liqueſcant & in annulum continuum formentur, ſive denique annulus ille rigeſcat & inflexibilis reddatur.



Fingamus igitur quod annulus iſte quoad quantitatem materiæ æqualis ſit Terræ omni *PapAPepE*, quæ globo *PapE* ſuperior eſt; & quoniam globus iſte eſt ad Terram illam ſuperiorem ut *aC qu.* ad *AC qu.* — *aC qu.* id eſt (cum Terræ diameter minor *PC* vel *aC* ſit ad diametrum majorem *AC* ut 689 ad 692) ut 4143 ad 474721 ſeu 1000 ad 114584; ſi annulus iſte Terram ſecundum æquatorem cingeret, & uterque ſimul circa diametrum annuli revolveretur, motus annuli eſſet ad motum globi interioris (per hu-

Figure 1-1. A page from Newton's book on gravitation published in 1687, showing the beginning of his explanation of an important phenomenon in the Earth's rotation (the so-called precession) and its dependence on the flattening of the Earth.

“I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses. … To us it is enough that gravity does really exist, and acts according to the laws which we have explained.”

To many of his readers this was still unsatisfactory.

Moreover, the evidences in favour of Newton could all be questioned in various ways. First, with his theory of gravitation, Newton could explain the way planets moved in orbits around the Sun, and moons around their planets, but this could also be explained reasonably well by older hypotheses. Second, Newton could explain the tides in the oceans, but this explanation to some extent did not agree with the observations. Third, Newton could explain a special characteristic in the Earth’s rotation known as precession, but this was partly dependent on his explanation of the tides which seemed insufficient. Fourth, Newton claimed a flattening of the Earth towards the poles due to its rotation, but this was questioned because of certain measurements in France. So, to those who felt sceptical already because the concept of gravitation seemed strange, there was much evidence that seemed unclear.

On the other hand, it is remarkable how Newton was able to explain a variety of phenomena with one single force; in this respect his opponents had nothing to put up against him. In the end this would be of decisive importance. When it had become sufficiently clear that the Earth must be flattened at the poles, this strengthened other evidences noted above. With the flattening in principle accepted according to Newton, his explanation of the precession of the Earth’s rotation could also be accepted, since it required a flattening of the Earth at its poles. And with the precession accepted according to Newton, his explanation of the tides, although somewhat incomplete, could also be more easily accepted, since it required a gravitational force from the Moon and Sun in the same way as the precession did. (What was incomplete here had to do with oceanographic effects not known at that time.)

One method to test Newton’s gravitational theory and the flattening of the Earth at its poles would be to actually measure gravity on the Earth’s surface at different latitudes. Gravity at that time could be measured using a swinging pendulum since the period of each swing should depend not only on the length of the pendulum, but also on the value of the acceleration of falling bodies, i.e. the value of gravity. To get a useful result one had to send someone with such a pendulum as far north as possible. So, now we turn to the north.

2. Gravity and latitude: The Earth's flattening at the poles

2.1 Trying to prove Newton's theory at the Arctic Circle

Already a decade before the publication of Newton's book, the French astronomer Jean Richer, during a voyage to South America, had found that a pendulum clock close to the equator was slightly slower than in Paris. But it was not until 1731, nearly half a century after Newton's book had appeared, that an English instrument maker, George Graham, succeeded in constructing a pendulum clock with sufficient accuracy that it could be used for studying gravity on the Earth's surface. Only a few years later a young Swedish astronomer and geophysicist, Anders Celsius (later known for his temperature scale), visited Graham in London to order a pendulum for such a purpose. This had to do with a visit of Celsius to Paris just before that.

Celsius, after having been appointed professor at Uppsala University, made a long study tour through Europe. After a few years he arrived in Paris. He happened to be there at the right moment, jumping into a scientific debate on Newton's theories. The head of the Paris Observatory, Jacques Cassini, had, based on measurements across France started by his father, arrived at the conclusion that the Earth must be somewhat flattened at the equator, contradicting Newton. At the same time an opposition against the Cassinis had grown within the French Academy of Sciences, in favour of Newton. This group was led by Pierre Louis Moreau de Maupertuis, a free-thinking physicist.

A method to settle the question would be to make measurements on the Earth at maximally separated latitudes, instead of only within France. In 1735 the Academy sent a scientific expedition of many years' duration to the equator in South America. This expedition included pendulums to determine gravity. Soon after the southern expedition had left, Maupertuis proposed that a similar expedition should be sent as far north as possible. Celsius now suggested that the expedition should go to northern Sweden, to the northern end of the Gulf of Bothnia, close to the Arctic Circle. Maupertuis agreed, and the Academy once again decided to send a scientific expedition to solve the problem, this time to the Arctic Circle, to Sweden (today's Sweden and Finland). Also this expedition was to include pendulums to determine gravity.

Celsius was now charged with the task of ordering some high-quality instruments in London for the expedition, including gravity pendulums. So, he left France for England, going straight to London. There he met scientists at the Greenwich Observatory as well as at the Royal Society of London, the British Academy of Sciences. But perhaps most importantly, on the street where he lived he often visited the home of George Graham, the skilled scientific instrument maker. It was from Graham that Celsius ordered instruments for the French expedition, especially pendulums for finding the value of gravity at the Arctic Circle. Celsius would later also order one for his own use in Uppsala.

In summer 1736, the French expedition including Celsius left by ship for Sweden. Everybody except the expedition leader, Maupertuis, got sea-sick during the North Sea crossing. When arriving in the Baltic Sea and reaching Stockholm they had had enough, and it was decided to continue northwards by horse and carriage. Only the instruments were sent by ship. In the end, both people and instruments arrived at Torneå (Tornio), the tiny town at the northern end of the Gulf of Bothnia, close to the Arctic Circle.

The expedition would perform measurements along a meridian arc of nearly 1° from Torneå northwards, including angle and distance measurements. In some location, gravity was also to be determined. These data were then to be compared with corresponding ones in the south.

An unforeseen language problem soon became apparent that would have consequences for the gravity measurement. The population outside the town did not speak Swedish, but Finnish and Sami, and Celsius did not understand these languages. Fortunately, there happened to be a young educated man in the town, Anders Hellant, who knew all the relevant languages, including French. He was now included in the expedition, not only as an interpreter but also as Celsius' assistant, taking part in the measurements.

The gravity measurement required an arrangement where the special pendulums could be mounted in a sufficiently stable manner. It so happened that Hellant had relatives living in a house close to the northern end point of the meridian arc, in the village of Pello; see Figure 2-1. Hellant, who was born in this house, could explain to its inhabitants what the gravity measurement was about, and what was required to install a pendulum for such a purpose. They now kindly allowed breaking up the floor in one of the rooms to have a stone pillar there as a foundation for the pendulums. Réginald Outhier (1744) notes in his diary:

“One room was designed as observatory for the pendulums, and to have a stationary telescope mounted there for determining the swinging times of the pendulums with the help of the motions of the fixed stars. Mr Camus had, for this purpose, had the floor in this room broken up and a stone pillar constructed, by which one could fix the telescope and have the pendulums suspended.”

Figure 2-1. The building housing the gravity pendulum station in Pello close to the Arctic Circle, established in 1736 by the French expedition for the purpose of testing Newton´s theories. This was the northernmost gravity station in the world for nearly 100 years. (Drawing by Outhier 1744.)

The expedition carried out its various observations from summer 1736 to summer 1737. The gravity observations and their treatment became the speciality of Alexis Claude Clairaut. He also, as probably the only one among the French, learned the Swedish language during this year. When all the measurements had been completed, the French returned to Paris and Celsius returned to Uppsala.

In the following year, the leader Maupertuis (1738) together with the other members of the expedition published a book on their work. Their conclusion from the arc measurement was that the Earth was flattened at the poles in accordance with Newton's theory, although this result, for various reasons, could be questioned. However, a similar result was obtained from the gravity determination, and this was more difficult to question. Maupertuis writes:

"I shall say nothing at present of our experiments upon gravitation, a subject no less important than the other. … Let it suffice to assure whoever has a mind to examine the Earth's figure by the weight of bodies … that they will find all the experiments we made in the north to that purpose … will concur in making the Earth flat towards the poles."

Clairaut himself some years later published a book on gravity; we will comment on that in the next section.

After Celsius had returned to Uppsala he decided to determine gravity there also, at his newly founded Uppsala Observatory; see Celsius (1744) and Figure 2-2. He had a pendulum clock ordered from his old friend Graham in London, for safety´s sake without letting the University Senate know anything so they would not prevent it. (In the end, the University paid for it, but Celsius was prepared to pay out of his own pocket if necessary.) After some time, the pendulum clock arrived and was installed in the Observatory. Celsius writes:

"To make this experiment I could not find a better occasion than in 1741, when Mr Graham for the Uppsala Observatory had constructed an astronomical clock that would be sent from London to Sweden. … I soon started, at the end of July 1741, to compare the swinging of the pendulum with the daily revolution of the stars."

Figure 2-2. Celsius' observatory in Uppsala where he started determining gravity in 1741, five years after he had participated in the gravity determination at the Arctic Circle.

The pendulum was made by iron and brass in such a way that it would not be very sensitive to temperature changes. Celsius used the pendulum for his gravity measurements on several occasions over two years, from the installation to 1743. This pendulum clock is preserved and still functioning! It is shown in Figure 2-3. Celsius' result further supported Newton's theories.

2.2 Is the Earth denser towards its centre?

After Clairaut had returned from the expedition to the north, he developed a theory of gravity as a function of latitude on an Earth flattened at the poles; see Clairaut (1743). The gravity stations he had at hand for

Figure 2-3. The pendulum clock used by Celsius for the determination of gravity in Uppsala, especially constructed for the purpose by Graham in London in 1741. This is now one of the oldest preserved gravity meters in the world. (The wooden case is not the original one.)

applying his theory were, from north to south, Pello in Sweden/Finland, with a gravity value (in modern units) of g = 9.82 16 m/s^2, London with 9.80 96 m/s^2, Paris with 9.80 89 m/s^2, and Kingston in Jamaica with 9.78 29 m/s^2; see also Table 2-1. (Results from the French expedition to South America were not yet available.) We note the decreasing gravity values with decreasing latitude, indicating 9.83 m/s^2 at the pole and 9.78 m/s^2 at the equator, in accordance with modern knowledge. London was the first result, obtained through Graham's work with his pendulum clocks, and Kingston was next, by shipping a pendulum from London. Paris, with its observatory, followed, and then Pello due to the French

Table 2-1. Early gravity stations in the world, ordered from north to south, and their observed gravity values in m/s².

Station	Year	Latitude	Gravity
Pello (Sweden/Finland)	1736	66°48′	9.82 16
Uppsala (Sweden)	1741	59 51	9.81 54
London (Great Britain)	1731	51 31	9.80 96
Paris (France)	1735	48 50	9.80 89
Kingston (Jamaica)	1732	18 00	9.78 29

expedition to the Arctic Circle. To this we could add Uppsala after the French expedition, with a gravity value of 9.81 54 m/s², in between those of Pello and London/Paris. This was Celsius' result, but it was not published until the year after Clairaut had published his book. Overall, we find today that the true errors in these values are less than 0.00 5 m/s², indicating a standard uncertainty of about 0.00 2 m/s².

Now, imagine an Earth flattened at the poles, its radius at the equator being a, and the distance from the centre to the pole being b, as shown in Figure 2-4. Thus, at the pole a part of the Earth corresponding to $a - b$ is "missing". The relation of the missing part to the whole radius is the flattening f of the Earth: $f = (a - b)/a$. Clairaut showed how this flattening could be calculated from gravity values at different latitudes. However, the gravity values available at that time – those above – were too few to allow a reliable calculation of the flattening. Nevertheless, he could draw an important conclusion. The differing gravity values implied, in addition to a latitude-dependent centrifugal force, a flattening of the Earth towards its poles.

The numerical value of the flattening was an interesting number, although it was difficult to determine at this early stage. Newton had shown on theoretical grounds that, for a homogeneous Earth, it should amount to $f = 1/230$. (This required that the Earth, in the long run, adapted

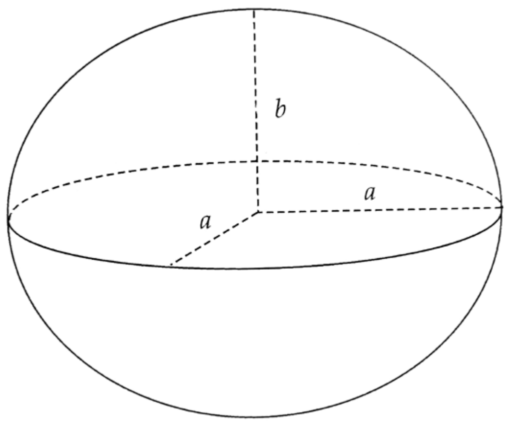


Figure 2-4. The Earth ellipsoid, flattened at the poles, with the equatorial radius *a* and the shorter distance *b* from the centre to the pole.

its shape to the forces applied.) Clairaut took this a step further, showing that the flattening is dependent on the density distribution inside the Earth, and bound by two extreme values. A completely homogeneous Earth would yield the maximum flattening, Newton's value of 1/230. The more the density towards the centre of the Earth increases, the more the flattening decreases. The limiting case of an Earth with all its mass concentrated in the centre would yield the minimum flattening, 1/576. Clairaut noted that the scarce data he had at hand already pointed in the direction of the density increasing towards the centre of the Earth. This was an important message: Gravity on the Earth's surface could give us information on the inner parts of the Earth that are inaccessible to direct observation.

During the following decades more gravity data were collected from different parts of the world. A Swedish mathematician, Fredric Mallet (1772), compiled a list of such data without analysing it properly. Doing so by applying Clairaut's theorem, one finds a flattening of the Earth of about 1/328; this is not too different from today´s value of 1/298. A few decades later the French mathematician and astronomer Pierre Simon de Laplace (1799) used Clairaut´s theorem to calculate the Earth's flattening from gravity data at 15 stations. He found the flattening to be around 1/336, reasonably close to the more uncertain values from contemporary arc measurements based on angles and distances. This was beyond doubt different from the 1/230 for a homogeneous Earth, and thus confirmed a density increase towards the centre of the Earth. Laplace concludes:

"It appears therefore, by observations of the pendulum, that the Earth is much less flattened than in the case of homogeneity."

The northernmost gravity station in the world was still Pello in northern Sweden/Finland, from the Arctic Circle expedition. This was now to be challenged, nearly 100 years later.

2.3 Shipping pendulums to the Arctic coasts

In 1818, the British instrument specialist Henry Kater invented an improved version of the pendulum, allowing gravity to be determined with greater accuracy. This version, known as the reversible pendulum, could account for the difference between a real physical pendulum and an ideal mathematical pendulum. It soon became used for determining gravity at several places, most of them, however, at mid-latitudes.

The importance of determining gravity with the reversible pendulum at more extreme latitudes was recognized by Edward Sabine, an Irish-born British geophysicist. He initiated voyages to other latitudes of the world, bringing pendulums there and making a point to use the same pendulums and the same observer at all stations (to promote consistency). First, in 1822, he made a voyage to more equatorial regions. Then, in 1823, he made a voyage as far north as possible, to the Arctic. This meant bringing gravity pendulums to northern Norway, Svalbard (Spitsbergen) and eastern Greenland; see Sabine (1825). Here, for natural reasons, the expedition had to be confined to the summer months.

The station selected in northern Norway was Hammerfest (Fuglenes), not far from the northernmost tip of Norway, at a latitude of nearly 71°. The main problem here turned out to be the weather: "The weather proved most unfavourable during the greater part of our stay, being almost an incessant gale, with rain, sleet, and heavy fog."

The next stop was at Svalbard (Spitsbergen) where the selected station was a small island to the northwest of the mainland, Inner Norway Island (in the bay of Fair-Haven), at a latitude of close to 80°;

Figure 2-5. The bay of Fair-Haven at Svalbard, at latitude 80°, where Sabine, in 1823, measured gravity with a pendulum to determine the flattening of the Earth. This was the northernmost gravity station in the world for nearly a century.

see Figure 2-5. This was the northernmost point of the expedition and would for a long time be the northernmost gravity station in the world. Here the captain of the ship left the observers on the island for some time: "Captain Clavering, being desirous of employing himself during the experiments in examining the state of the ice to the northward of Spitzbergen, sailed for that purpose on the 4th of July with a boat and crew. … We had, however, the satisfaction of witnessing her return on the 10th."

The third stop was at eastern Greenland, where the selected station was a small island as far north along the coast as they could go with the ship due to the ice conditions: "Captain Clavering, having succeeded in forcing a passage through the barrier of ice, which impedes the access to the shores of East Greenland, in a higher latitude than it is recorded to have been previously traversed, arrived on the coast between the 74th and 75th degrees of latitude." The island for the pendulum observations was the inner one of two islands close to each other, given the names of Inner and Outer Pendulum Islands by the expedition leader; see Figure 2-6. These are the names by which they are still known today.

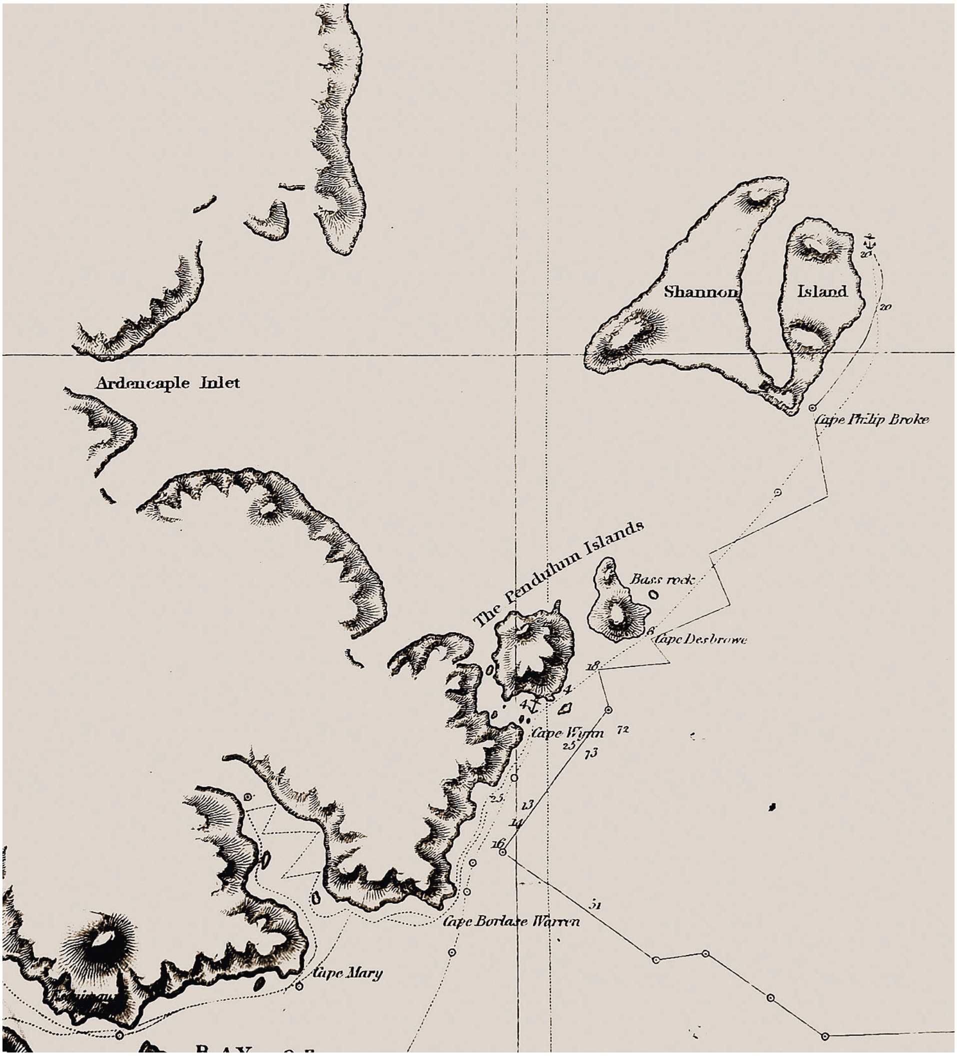


Figure 2-6. Map by Sabine from 1823 showing "The Pendulum Islands" at the Greenland east coast where he measured gravity after his visit to Svalbard. The name of the islands given by him is still in use.

The fourth stop was planned to be at Iceland, but time and weather did not allow that. Instead, they went to the Norwegian west coast and made a final observation in Trondheim at a little more than 63 degrees of latitude.

Now, what was the outcome of these gravity determinations? Sabine calculated the flattening of the Earth from various combinations of gravity values across the latitudes of the globe, using up to 25 stations. He ended up with a flattening of 1/289 and writes:

“The attempt to determine the figure of the earth by the variations of gravity at its surface has thus been carried into full execution, on an arc of meridian of the greatest possible extent [80°]; and the results which it has produced are seen to be consistent with each other.”

He, therefore, considered that his value of 1/289 should be a considerable improvement from that of Laplace, 1/336, mentioned in the foregoing section. We note, based on today’s flattening of 1/298, that this is correct.

Almost at the same time as Sabine made his gravity voyage, the Swedish mathematician and geodesist Jöns Svanberg also ordered a reversible pendulum from Kater in Britain. This was to determine gravity at the Stockholm Observatory, belonging to the Royal Swedish Academy of Sciences, with an additional purpose being to determine more accurately the standards of length, time and mass. Svanberg made a first set of observations in 1825. Being not quite satisfied with the accuracy of these, he made a set of improved observations in 1833; see Svanberg (1825, 1834).

Svanberg’s improved gravity determination can be shown to have had a standard uncertainty of only 0.00 02 m/s^2, apparently somewhat better than Sabine’s. But whereas Sabine’s observations had to be made in provisionally arranged observatories, Svanberg’s observations could be performed in a permanent observatory building. In any case, his result shows a decrease in uncertainty since the 1700s by as much as a factor of 10. (We may remark here that his true error even turns out to be one order of magnitude smaller than his uncertainty, which is rather unusual.)

Soon after Svanberg's contribution, in 1829, the Danish-German astronomer Heinrich Christian Schumacher made a similar gravity determination in southernmost Denmark, at an old palace (now in northernmost Germany). The result, however, was considered uncertain and not published by him, but later by his assistant Christian Peters (1855).

2.4 The Earth's flattening from more gravity data

During most of the 1800s there was no further improvement in the accuracy of gravity observations, but more data were collected, although not north of Sabine's 80° at Svalbard. The German geodesist Friedrich Robert Helmert (1884) used the available data in a more comprehensive analysis, comprising 120 stations. He obtained a flattening of 1/299.3 with a standard uncertainty in the denominator of 1.3. This happened to agree well with the less accurate value earlier obtained by his compatriot Friedrich Wilhelm Bessel from arc measurements based on angles and distances, but Helmert considered this a coincidence.

Soon after that, Helmert was appointed head of the International Earth Measurement Organization ("Internationale Erdmessung") as well as of the Prussian Geodetic Institute at Potsdam, close to Berlin. As such he, among other things, was engaged in trying to determine the optimal ellipsoid of revolution describing the Earth. Due to the invention of a portable pendulum apparatus (see next chapter), the number of gravity stations now could be much increased. Using 1 400 gravity stations spread over the globe, Helmert (1901, 1906) found a flattening of 1/298.3, with a standard uncertainty in the denominator of 1.1; see also Table 2-2 for an overview. He stated that "this should be considerably more accurate than any value that could be deduced from arc measurements".

It is notable that, two decades later, when an international Earth ellipsoid was being agreed upon, Helmert's result based on gravity measurements was not used. Instead, despite Helmert's judgement, an American result based on arc measurements and triangulations was used. In hindsight, it is somewhat ironic that Helmert's result agrees to the decimal with the present value of the flattening, determined from perturbations of satellite orbits (see Chapter 5).

Table 2-2. Historical determinations of the flattening of the Earth from gravity observations. Newton's theoretical value based on a homogenous Earth. (Max. lat. = maximum latitude.)

Author	Year	Stations	Max. lat.	Flattening
Newton	1687	Theory	-	1/230
Laplace	1799	15	67°	1/336
Sabine	1825	25	80	1/289
Helmert	1884	120	80	1/299.3
Helmert	1906	1 400	86	1/298.3

3. Gravity and location: Crustal thickness, northern minerals and the geoid

3.1 Early gravity networks and an experiment in the north

In 1887, the Austrian geodesist Robert von Sterneck constructed a new apparatus for measuring gravity. It was still based on the pendulum principle, but it was a portable instrument. This had obvious consequences. It became possible to bring the instrument more easily on journeys and, thereby, to measure gravity in many more places than before. This would allow investigations on regional deviations in gravity from normal gravity, i.e. from gravity as calculated theoretically for an ellipsoidal Earth. The accuracy, however, was still more or less the same.

The pendulum apparatus was designed for measuring differences in gravity; it was a relative instrument, not an absolute one. Therefore, it was important to also fix an absolute gravity value somewhere as a basis for all the relative measurements. From 1891 this was in Vienna, from 1906 in Potsdam outside Berlin.

Soon after the Vienna absolute gravity value had been established, all the Nordic countries commenced relative gravity measurements, thereby creating early gravity networks in their respective countries. The gravity stations were sparsely distributed; their total number did not reach 100.

First, in 1893, the Geographical Survey of Norway in collaboration with the Norwegian physicist Oskar Emil Schiøtz at Oslo University procured the Sterneck pendulum apparatus. With this, gravity was measured at several stations in Norway, including the Oslo Observatory, forming an early gravity network over the country, mostly along the coasts; see Schiøtz (1894, 1895). At the same time Fridtjof Nansen, the Norwegian polar explorer (and later Nobel peace prize winner), made his scientific expedition to the Arctic Sea, involving the very first gravity measurements on the ocean; we will deal with that towards the end of this section.

At almost the same time, in 1894, a forerunner to the Danish Geodetic Institute started relative gravity measurements in Denmark. Its chief geodesist, Georg Zachariae, determined gravity at the Copenhagen Observatory and several stations on the island of Bornholm; see Zachariae (1897). After that, measurements were continued in other parts of the country, but it turned out that the instrument did not work properly any longer, so it had to be replaced.

At about the same time, the Geographical Survey of Sweden performed relative gravity determinations, but restricted itself to fewer stations. In 1896, its chief geodesist, Per G Rosén, determined gravity at five stations along a north-south line running across the country, including the Uppsala and Stockholm Observatories; see Rosén (1898). Certain measurements, however, had been acquired earlier, and in 1890 he performed a special investigation in an old mine in Sweden, the Sala silver mine. This resulted in a value of the Earth's mean density twice as large as the average density of rocks in the crust, confirming, in Rosén (1895), that the Earth must be much denser towards its centre.

In Finland the astronomer Otto Savander (later Sarvi) started relative gravity determinations in 1897, first at the Helsinki Observatory and also at the Pulkovo Observatory outside St. Petersburg in Russia; see Savander (1899). The measurements were continued at other stations in Finland by his student Ilmari Bonsdorff, as stated in Savander & Bonsdorff (1908). Bonsdorff later became head of the Finnish Geodetic Institute; further measurements were then conducted by this institute.

It should also be noted that gravity measurements were started in Iceland in 1900 by the Danish geodesist Niels Peder Johansen.

We now come back to Nansen's expedition in the Arctic Sea, briefly mentioned above, which lasted 1893 – 1896. The main aim was to let the specially designed ship, Fram, get ice-bound and, thereby, follow the ocean currents, which then could be studied; see Figure 3-1. In connection with this expedition, Nansen planned for possible gravity determinations in case unknown land might turn up in high latitudes; see Figure 3-2. When this did not occur, one switched to an experiment that no one had tried earlier, namely to measure gravity on the sea surface on board the ship, and on the ice. They succeeded and so gravity was measured at

Figure 3-1. The research vessel Fram, used by Nansen 1893 – 1896, ice-bound in the Arctic Sea. This ship carried the new portable pendulum apparatus, thus enabling the first gravity measurements on the ocean and on sea ice.

some 10 places along the route, the northernmost being at 86° latitude. Nansen (1901) concludes:

“Thus the first series of pendulum observations, which, to my knowledge, have ever been made over the sea, were made over the deep North Polar Basin.”

Most of the sea measurements were made on board the ship during winter, when the ship was firmly frozen in the drifting ice. Schiøtz (1901) explains how they were arranged:

“The pendulum apparatus was set up on the iron cross belonging to it, with nothing between it and the solid floor of the saloon, near one long wall; while the coincidence apparatus was placed opposite to it, near the opposite wall, with an underlayer of folios. During the experiments, the observer had to lie upon the floor parallel with the wall. … The observations were taken in the middle of the night, when no one but the

Figure 3-2. The Sterneck pendulum apparatus, the portable gravimeter used by Nansen's Arctic expedition.

observer was up, so that the apparatus was not exposed to any chance of disturbance."

His attached illustration of the scene is shown in Figure 3-3. Furthermore, a few of the sea measurements were made in summer on the ice close to the ship. They were arranged in a snow hut where magnetic observations could also be performed. Schiøtz here comments: "The iron cross for the pendulum apparatus was placed on the ice itself, to which it froze so firmly, that the bubble of the level did not move as much as one division."

Most of the sea measurements were deemed successful. Schiøtz noted from the values obtained that gravity over the sea, somewhat unexpectedly, seemed to be not very different from gravity on land at the same latitude as estimated from a formula by Helmert.

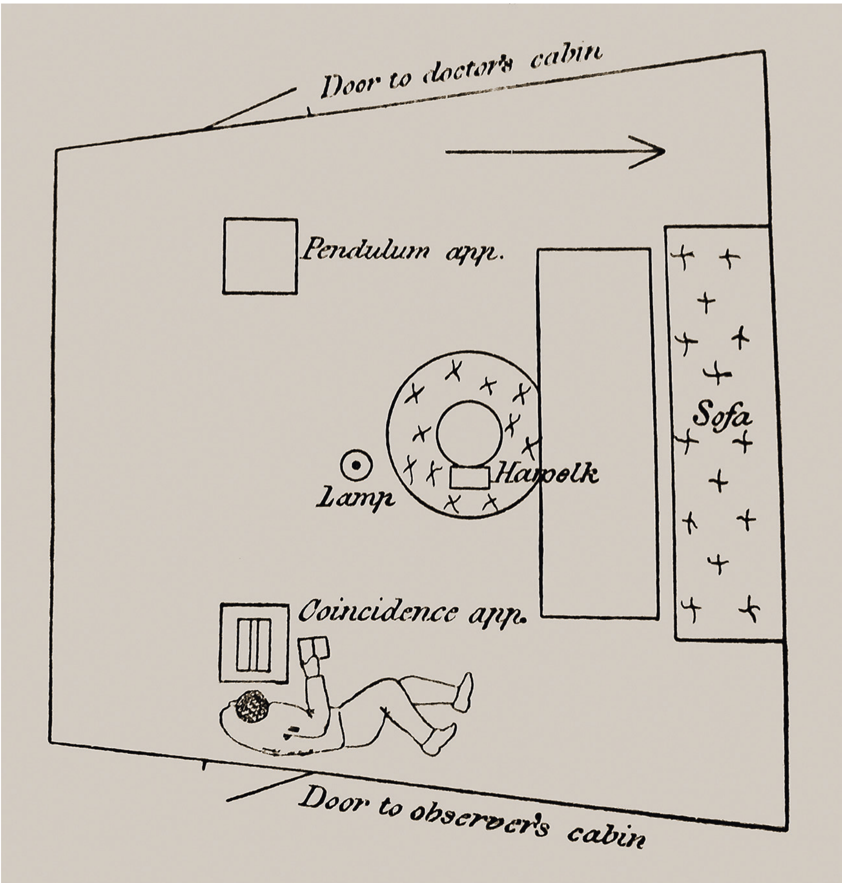


Figure 3-3. A sketch of the gravity room on board Nansen's ship; the observer is Sigurd Scott-Hansen.

As mentioned above, the advantage of the new pendulum instrument was its portability and, thereby, the possibility to start mapping the Earth's gravity field. The accuracy of the gravity measurements, however, was hardly improved. The standard uncertainty in a measured gravity difference was on the order of 0.00 01 m/s^2, not too different from that of an absolute gravity determination at that time (an improved version of the instrument later used in Finland was somewhat better). Nevertheless, this was sufficient to detect deviations in gravity from normal gravity, i.e. from gravity as calculated theoretically for an ellipsoidal Earth. Such deviations, so-called gravity anomalies, were expected to occur due to possible irregularities in the mass distribution in the Earth. It was estimated that such gravity anomalies could be on the order of 0.00 1 m/s^2 and, thus, clearly detectable. (There are different kinds of gravity anomalies depending on how to deal with the height of the gravity station, but we leave that aside here.)

From now on we will also use the gravity unit mGal (milligal), 1 mGal = 10^{-5} $m/s^2 \approx 10^{-6}$ times the value of gravity. This unit (named after Galilei) is commonly applied for small quantities like gravity anomalies or error estimates. Thus, the standard uncertainty above is on the order of 10 mGal, and the gravity anomalies on the order of 100 mGal.

3.2 Investigating the crust and below

Already half a century earlier it had been noticed that the vast Himalayan mountains did not affect the plumb line as much as could be estimated from their total mass. The British-Indian geodesist and archdeacon John Henry Pratt (1855) and the British astronomer George Biddell Airy (1855) tried to explain this by two different models of the Earth's crust. Pratt suggested that the crust under the mountains was less dense. Airy suggested that the crust under the mountains was thicker, reaching deeper into the more dense material below, somewhat like icebergs floating in water.

Measurements of gravity in the early 1900s with the portable pendulum instruments made it possible to try to study these hypotheses. The scientist who contributed considerably here, in 1924, was the Finnish geodesist Weikko Heiskanen. He collected gravity data from a large area in Europe including the mountain ranges of the Alps, the Carpathians and the Caucasus, in total more than 100 gravity stations. Analysing the resulting gravity anomalies, Heiskanen (1924) concluded that the visible masses of the mountain ranges were in some way compensated, known as isostatic compensation, and that Airy's hypothesis seemed to be somewhat more realistic. This was also supported by additional data from North America. Thus, mountains ranges seemed to have "roots" extending into the mantle below; see Figure 3-4. The general thickness of the continental crust could be estimated at exceeding 30 km. The gravity anomalies themselves kept within 0.00 1 m/s^2, or 100 mGal.

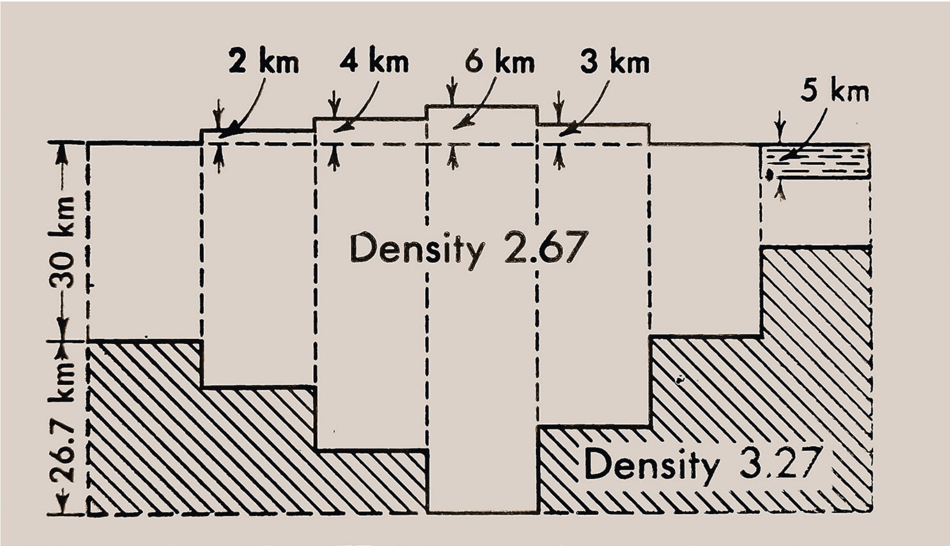


Figure 3-4. Heiskanen's illustration in 1924 of mountain ranges having "roots" into the denser material below, as shown by his calculations of gravity anomalies.

A special form of gravity surveys was the early work performed on the oceans by the Dutch geophysicist Felix Andries Vening Meinesz. He developed a method and a pendulum apparatus for measuring gravity on board a submarine in motion. There are certain problems with measuring gravity from a moving craft like a submarine; its motion causes various disturbing effects on the gravity meter. Vening Meinesz (1934), taking these things into account, carried out several submarine gravity voyages in the world's oceans during several years. (An additional problem was that he was more than 2 m tall, making it difficult for him to move inside the narrow submarine.) Using his own pendulum gravimeter construction, he determined gravity anomalies along profiles across the oceans. They revealed two things. First, the anomalies were in general of a similar size as on the continents, indicating isostatic compensation also for the oceanic crust. This meant a thinner crust, or "antiroots", here. Second, there were considerable anomalies in narrow but long areas of island arcs close to the continental coasts. This led him to develop a hypothesis of convection currents in the Earth's mantle; see also Vening Meinesz (1934a). This idea would later turn out to be very useful in connection with the phenomenon of continental drift.

Heiskanen and Vening Meinesz were pioneers in investigating the Earth's crust and interior by studying its gravity field. This, after some time, led to them publishing a book together on the subject. In their book, Heiskanen & Vening Meinesz (1958) could confirm their earlier findings on isostatic equilibrium of the crust and convection currents in the mantle below.

3.3 A Nordic novelty: Spring gravimeters

In 1918, a meeting for geophysicists from the Nordic countries was arranged. One of the participants was Gustaf Ising, a Swedish geophysicist and instrument specialist at Stockholm University, with a laboratory in his private home. He presented and published an article on a new kind of gravity meter. This was based on a new principle: Instead of using the swinging time of a pendulum it used the elasticity of a spring connected to a weight; see Ising (1918) and Figure 3-5. He expected this to be significantly more accurate.

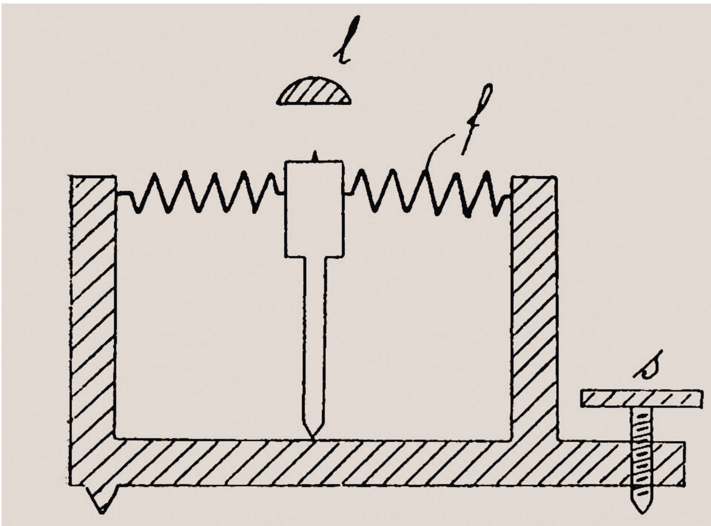


Figure 3-5. Ising's idea in 1918 of a gravimeter based on a new principle, that of an elastic spring instead of a swinging pendulum. After ten years he had developed it into a well-functioning instrument.

Ising got his idea from earlier works with electromagnetic instruments and was also inspired by a recent seismograph. During several years, he developed the idea into a functioning gravimeter, partly together with his collaborator Nils Urelius; see Ising & Urelius (1928) and Ising (1930). The instrument was tested in realistic conditions by, among other things, transporting it in a car between Stockholm and Copenhagen. It worked well, even after having been exposed to ungentle treatment. Ising gives an example: "Once, e.g., the automobile, in which the instrument was transported, got violently stuck into a snow-drift, so that the whole instrument almost overturned." The sensitive instrument was not affected.

A major test of the new gravimeter was made in 1929 by taking it on a journey from Sweden to Switzerland and back again. This meant measuring gravity differences between Stockholm, Copenhagen, Potsdam, München and Bern, and then the same in the opposite direction, with Potsdam being the fundamental absolute station. The results turned out to be successful. Ising concludes:

"Thus the instrument has, in these observations by Urelius, the number of which is certainly small, given quite satisfactory accuracy. This is so although the present version (the result of several reconstructions) mainly is designed for the experimentation of the method. There is still the intention to build, on the basis of the experiences gained, easily handled instruments."

Soon after, Ising's field version of the spring gravimeter reached a standard uncertainty of 0.00 001 m/s^2, or 1 mGal, nearly an order of magnitude better than the older pendulum apparatus. His spring gravimeter proved to be useful for ore and oil prospecting in several parts of the world. Within a few years, during the 1930s, several similar or related versions of spring gravimeters were developed by others, either independently or based on Ising's idea. In addition, spring gravimeters were also developed for more scientific investigations of irregularities in the Earth's gravity field.

3.4 Mineral exploration and geoid determination

The new gravimeters, both more accurate and easily handled, represented a more effective tool for investigating both local and regional gravity anomalies, revealing various kinds of irregularities in the mass distribution in the Earth. More local (spatially restricted) anomalies would reflect density differences in the crust close to the Earth's surface, while more regional (spatially extended) anomalies would reflect density differences deeper inside the Earth.

Local gravity anomalies could indicate the presence of certain useful elements with contrasting densities in the crust. Iron, e.g., has a density nearly three times the average density of the crust, and could thus be searched for through gravity measurements. The interpretation of a gravity anomaly was, however, not easy; in reality, gravity measurements needed to be combined with magnetic, seismic and other measurements.

Sweden has a long tradition of iron and copper mining. In earlier centuries, Sweden was the world's largest iron exporter, and, nowadays, northern Sweden has the world's largest underground iron mines; see Figure 3-6. Other important elements are also present. At one of the mining companies in the northern part of the country two scientifically minded inventors, Axel Lindblad & David Malmqvist (1938), developed their own version of a spring gravimeter for ore and mineral prospecting. It became known as the Boliden gravimeter after the name of the company. After some time, the Geological Surveys in the Nordic countries also engaged in gravity measurements for mapping rocks and minerals.

Mineral exploration through gravimetric methods did not only require a suitable gravimeter, it turned out to require also very dense measurements in the area of interest. It was found that the local measurements had to be performed with the gravity stations at a distance on the order of 100 m or less.

More regional gravity anomalies could indicate deeper and larger structures in the crust, like a varying crustal thickness, or possible processes going on in the mantle beneath the crust. Determining these anomalies would allow, in the longer term, also identifying deviations of the gravity-related mean sea level, or the geoid, from the Earth ellipsoid.

Figure 3-6. Ising's gravimeter and its successors were constructed to enable searching for minerals with deviating densities. This picture shows the world's largest iron mine at Kiruna in northernmost Sweden; most of it is now under ground reaching a depth of more than 1500 m.

Mapping such regional gravity anomalies required considerably better gravity networks at the national (and international) level.

The establishment of useful national gravity networks was much facilitated by a spring gravimeter constructed in 1939 by the Danish geodesist Gunnar Nørgaard; see Nørgaard (1939, 1942) and Figure 3-7. This became used in all the Nordic countries, by their Geographical Surveys and Geodetic Institutes, to create better and denser gravity networks. Nørgaard (1945) noted that the pioneering gravimeter of Ising still had several advantages, but that it was somewhat sensitive to temperature changes. Nørgaard's gravimeter could be used over more extensive areas covering large gravity differences, but still with an equally small uncertainty, i.e. 0.00 001 m/s^2 or 1 mGal.

New national gravity networks benefitted from Nørgaard's improved gravimeter. They were also made denser than the early ones, but of course much less dense than the local networks. The distance between national gravity stations could be on the order of 10 km (see further Section 3.5).

Figure 3-7. Nørgaard's spring gravimeter, invented in 1939 and soon used for mapping the gravity field through extensive national gravity networks.

As mentioned earlier, the mapping of gravity anomalies would allow determination of the geoid, i.e. the level surface in the Earth's gravity field coinciding with mean sea level (undisturbed by tides, winds etc.). Now, imagine standing at a point on the surface of the Earth. On one side, hidden in the crust, is iron ore, and on the other side, also hidden in the crust, is oil. The density difference between the heavier iron and the lighter oil will influence the gravity field and, thereby, the vertical, making it tilt towards the heavier mass, as shown in Figure 3-8. Consequently, the geoid, being everywhere perpendicular to the vertical, will have a high above the mass excess and a low above the mass deficit; this rationale holds also for masses deeper inside the Earth. These deviations of the geoid, or mean sea level, from the ellipsoid could, in principle, be calculated from gravity anomalies, but there were heavy obstacles to achieving this goal.

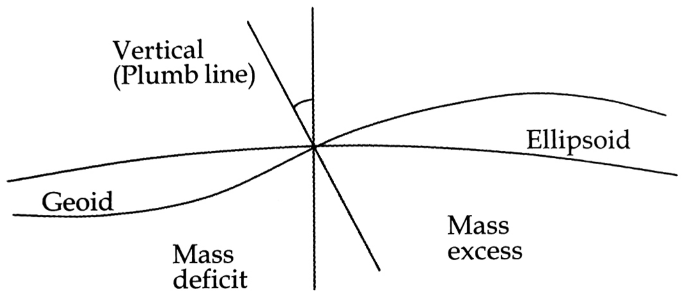


Figure 3-8. Influence of mass excess and mass deficit on the geoid (theoretical mean sea level, perpendicular to the vertical), and its relation to the Earth ellipsoid.

The study of gravity anomalies and the geoid had a theoretical background going back to the work of the British physicist George Gabriel Stokes (1849). He had discovered a formula allowing the height of the geoid above the ellipsoid to be computed from gravity anomalies. However, the method was not possible to apply at that time, since it required that gravity anomalies be known all over the globe to compute the geoid height (with an integral) at one single point. Although the gravity field close to the point was more important, the distant gravity field could not be ignored. In addition, Stokes himself notes that "the calculations indicated, though possible with a sufficient collection of data, would be very laborious".

The first serious attempt to determine the geoid from gravity anomalies was made in 1934 by the Finnish geodesist Reino Hirvonen. He still had to rely on gravity measured by pendulum apparatuses but could use data from more than 4 000 stations with a nearly world-wide distribution. Applying these in Stokes' formula, Hirvonen (1934) arrived at maximum heights of the geoid above (or below) the ellipsoid of about 100 m.

A decade later, Hirvonen's Finnish colleague Lauri Tanni (1948) extended the geoid computation to include five times as many gravity stations, the latest of them now being determined with spring gravimeters.

But the most interesting achievement of Tanni was that he, in 1949, was able to present the first map of the geoid, showing height contours of the geoid above the ellipsoid. It covered central Europe and the southern part of Scandinavia. For Scandinavia he could use a considerable number of gravity values being recently measured with the new Nørgaard gravimeter. This pioneering geoid height map is here reproduced from Tanni (1949) in Figure 3-9. It agrees reasonably well with modern maps of the geoid over this area; notably, the marked inclination of the geoid across Scandinavia, in the east-west direction, is clearly visible here.

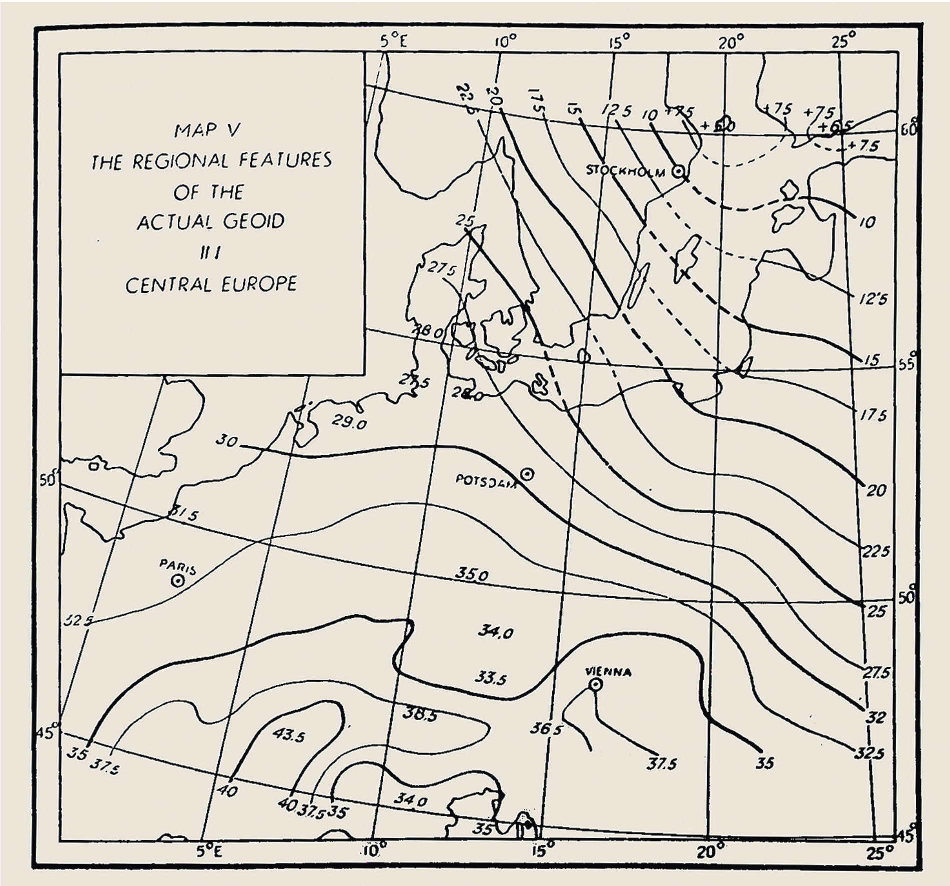


Figure 3-9. The first map of geoid heights above the Earth ellipsoid, covering central Europe and southern Scandinavia, calculated from gravity anomalies by Tanni in 1949.

Tanni himself never saw the printed result of his efforts with the map as he died young of a heart disease before the publication was issued. (His physician had, soon before that, commented that he was unable to understand that a man with such a weak heart could write scientific publications.)

The geoid was also of interest in a somewhat different context: astronomical positioning. When determining latitude and longitude using stars, the instrument was set up with the help of a spirit-level, feeling the direction of the vertical. The vertical, being the normal to the geoid, would deviate from the normal to the ellipsoid. These deflections of the vertical would affect the observed position by a significant amount, on the order of 10″, corresponding to 300 m on the ground. Thus, there was also a practical interest in knowing the shape of the geoid. (This is the case even more so today because of its use in height determination with satellites; we will deal with that in Chapter 5.)

3.5 New gravity networks and a geophysical surprise

The development of the Nørgaard gravimeter in Denmark triggered extensive gravity works in all the Nordic countries. New national gravity networks were established. They were still based on the absolute value observed in Postdam, because the Nørgaard gravimeter was, as all spring gravimeters, a relative instrument. Within a decade or so the number of gravity stations in the Nordic countries increased from the order of 100 to the order of 10 000.

In Denmark, Nørgaard himself already in 1938 made a gravity network over Jutland, the main part of the country; see Nørgaard (1939a). It consisted of gravity stations with approximately 15 km spacing. This allowed him to construct an early map of gravity anomalies, including results from a sea expedition through the Kattegat. The map revealed a surprising structure in northern Öresund between Denmark and Sweden; we will deal with that at the end of this section. (It could also be mentioned here that Nørgaard started measuring gravity in Greenland.) A somewhat denser network covering Denmark was embarked upon a little later by Einar Andersen (1947) and Svend Saxov (1945), at the

Geodetic Institute. Saxov, working as both a geodesist and a geologist, created a network aimed at fulfilling both of these interests.

Earth scientists in Sweden, already acquainted with spring gravimeters because of Ising's contributions, were eager to employ the new gravimeter on a large scale. In 1943 the geodesist Bror Wideland at the Geographical Survey of Sweden started creating a gravity network, using the Nørgaard gravimeter, to cover the whole country; see Wideland (1946, 1951). In the beginning Nørgaard himself took part in the work, acting as a kind of instructor. The distance between the stations in the network was some 20 km (although less than that in the mountains), allowing the construction of gravity anomaly maps for the entire country. As with the Danish anomaly map, a special feature was evident in the area close to Öresund.

Finland switched to the Nørgaard spring gravimeter in 1945. From then on, Tauno Honkasalo at the Finnish Geodetic Institute measured a quite dense national gravity network, the distance between the stations being some 5 km in the south but less than that in the north; see Honkasalo (1962). This resulted in quite detailed gravity anomaly maps over much of the country.

In Norway, the Nørgaard spring gravimeter was introduced in 1948 when the geodesists Ole Trovaag and Gunnar Jelstrup at the Geographical Survey of Norway started using it for their national network and anomaly maps. They first travelled with the gravimeter to Teddington in Great Britain, for a special reason. At that location a new absolute determination of gravity had recently been made, considered to be more reliable than the old one at Potsdam in Germany. Trovaag & Jelstrup (1950), connecting their network to both absolute stations, could confirm that the international Potsdam value was in error by more than 10 mGal.

Now to the surprising structure in northern Öresund between Denmark and Sweden, briefly mentioned above. Nørgaard (1939a) found a very steep gradient in the gravity anomaly there, i.e. a large difference in the gravity anomaly over a short distance, as shown in Figure 3-10a. He writes:

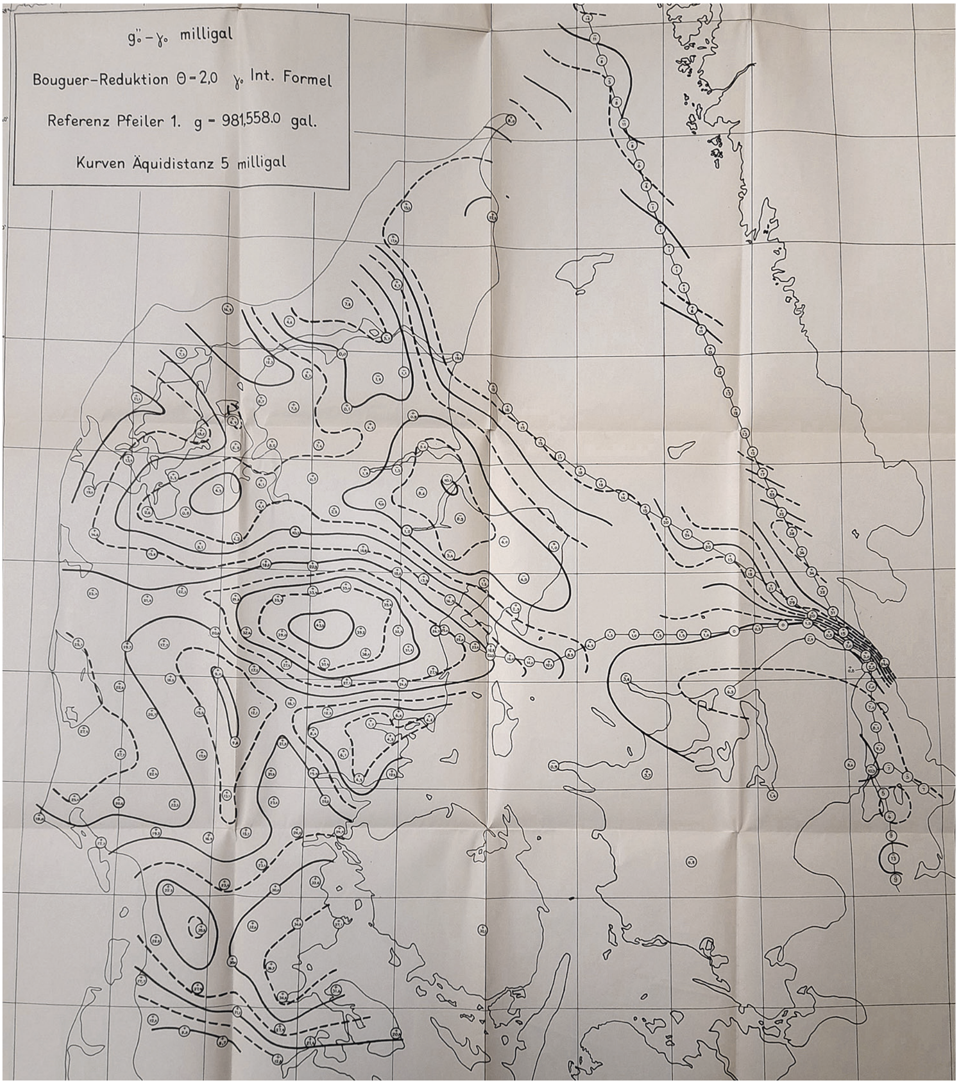


Figure 3-10a. Gravity anomaly map over much of Denmark by Nørgaard in 1939, revealing a remarkably steep gradient in the anomalies at Öresund in the east.

“The compression [of gravity anomaly curves] in northern Öresund was found during the sea measurements in 1933 – 1935, but seemed at that time extremely surprising due to its unusually large gradient. However, it has turned out that this perturbation is quite real, since land measurements in the harbours of Helsingör and Hälsingborg, also straight across the northern Öresund, have yielded the considerable anomaly increase of 23.6 mGal over this distance of only 5 km. Such large gravity differences obviously have their origin in corresponding large differences in the mass distribution."

Nørgaard was also in contact with the Swedes who provided preliminary results from the southernmost part of the country, the province of Skåne just to the east of Öresund; see Figure 3-10b. Here he notes, with great interest, a continuation of the narrow zone with the large gravity difference:

"One finds a very beautiful and further confirmation of the curve compression, as regards intensity as well as location and direction."

The Swedish measurements had been performed as a regional investigation by the Geological Survey, inspired by a first investigation there by Ising & Eeg-Olofsson (1936). Tryggve Eeg-Olofsson was a geophysicist cooperating with Ising, the gravimeter pioneer (he later measured gravity with Ising´s gravimeter also in Asia for oil prospecting). Ising and Eeg-Olofsson had measured gravity along two profiles across south-western Skåne, already indicating a considerable gradient there; these observations were then continued by the Geological Survey, using both the Ising and the Boliden gravimeter.

Inspired by the Danish-Swedish results revealing a zone with a steep gravity gradient, Nørgaard (1942) turned his interest towards the island of Bornholm, the Danish island south of Sweden. This island was situated in the direction of a possible continuation of the mysterious zone. The gravity anomaly map he could construct from his measurements there, shown in Figure 3-10c, clearly confirms his expectations:

"The extremely strong density of the gravity curves at Rønne and at Hasle [along the west coast] form the continuation to the south-east of the concentration of curves established earlier at Helsingør [northern Öresund]."

Gravity observations had, through the discovery of this remarkable zone, proven to be a powerful tool for detecting interesting structures in the Earth´s crust. The gradient in the gravity anomaly across the zone

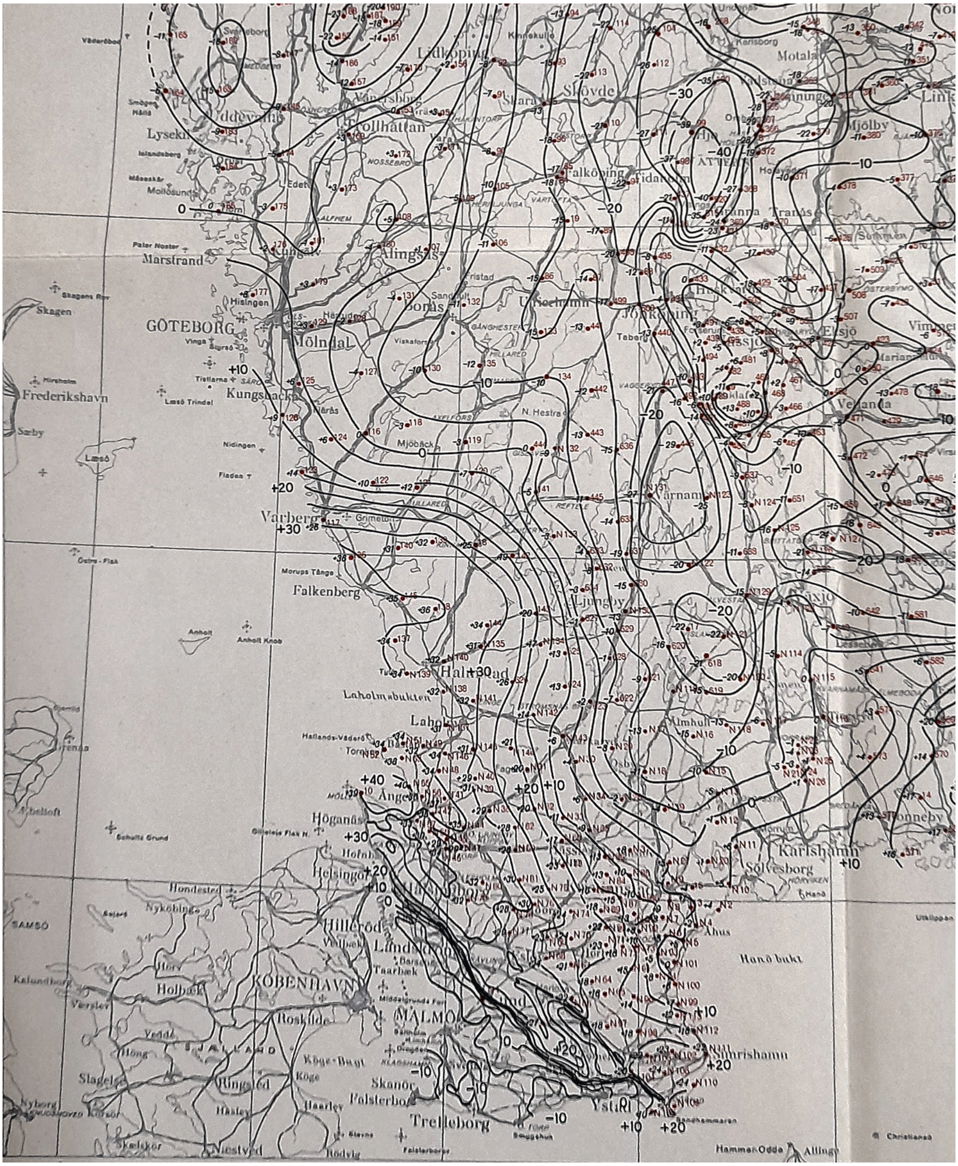


Figure 3-10b. Gravity anomaly map over southernmost Sweden by Wideland in 1946, showing a continuation of the steep anomaly gradient appearing in the preceding figure. Nørgaard had got information on this beforehand.

amounted to about 5 mGal/km, with the zone being about 5 km wide. The length of the zone was at least 200 km. This zone has since then been the subject of a lot of investigations; today it is known to be part of a

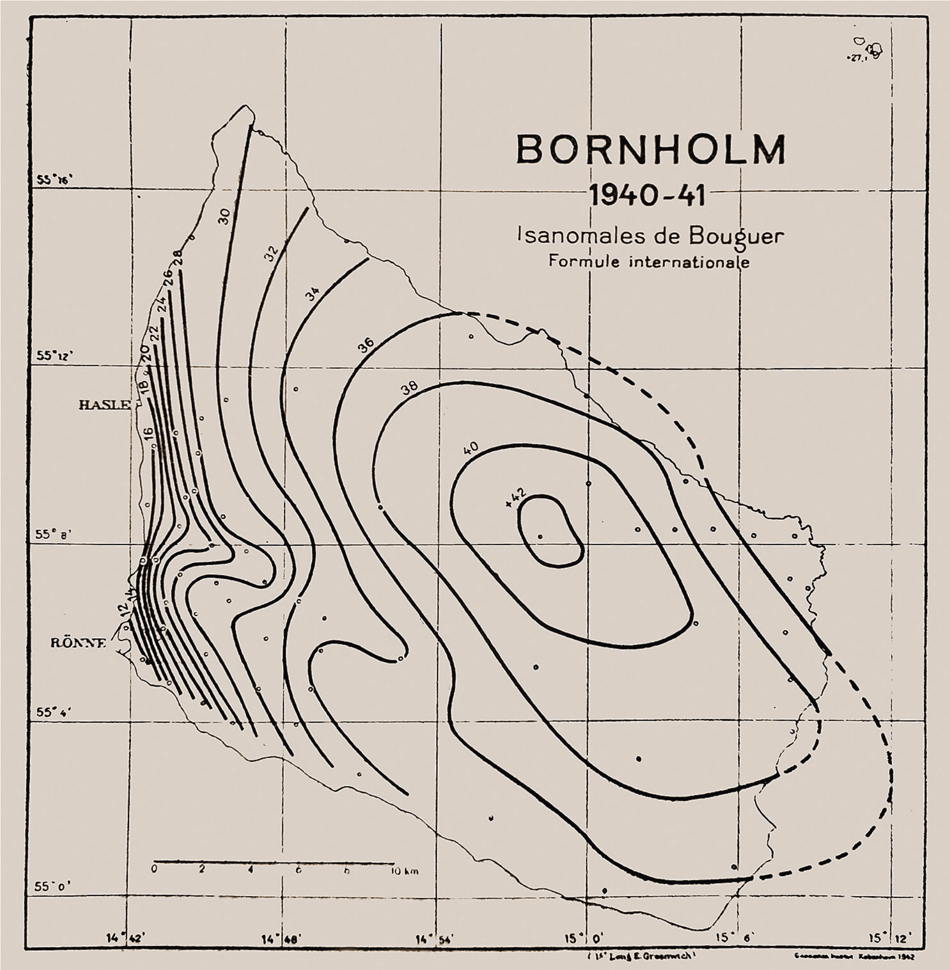


Figure 3-10c. Gravity anomaly map over the island of Bornholm by Nørgaard in 1942, showing a further continuation of the steep anomaly gradient appearing in the two preceding figures. The gravity feature illustrated in the three figures is nowadays believed to reflect an ancient plate boundary.

much longer zone, known as the Trans-European Suture Zone (Tornquist zone), and the character of the zone is interesting: It is believed to be the remnant of an ancient plate boundary.

Nørgaard's gravimetric work on the island of Bornholm also seems to have inspired him to make a rather unusual action: At the end of the

Second World War he wrote, together with a geologist also involved on the island, a letter to the Prime Minister of Denmark. The letter was sent immediately after the American attack with the first atomic bombs on Japan, bombs based on the fission of uranium. In the letter, Nørgaard and his colleague pointed out two things making it possible for Denmark to act for a peaceful use of the nuclear power of uranium as a new source of energy. The first was the expected presence of uranium in the bedrock of Bornholm, the other was the fact that Denmark had the world's leading atom physicist, Niels Bohr. However, in the end it did not lead to any action by the Prime Minister. Nevertheless, it is interesting to note the role of a gravity specialist behind this early attempt to persuade a state to introduce uranium as an energy source.

A few decades later an improved gravimeter, of American construction and known as the Worden gravimeter, tended to replace the earlier instruments for making measurements in gravity networks. The standard uncertainty of this instrument was on the order of 0.1 mGal, one order of magnitude smaller than before. It was introduced in the Nordic countries around 1960. Also, the number of stations now increased; the average station distance one aimed at was some 5 km in most areas, although the mountain areas formed a severe obstacle in this respect. There was also a need to measure a separate, less dense, network, a "fundamental network" of high accuracy (simplified versions of which had also been measured earlier), and then tie all the other and somewhat less accurate measurements to this fundamental network. However, the international reference absolute gravity value in Potsdam was still in use, although it was now known to be in error by more than 10 mGal; the rare newer absolute gravity determinations were not yet considered reliable enough to replace it. This had the strange consequence that official gravity values at this time had a systematic error in the absolute sense that was 100 times larger than the uncertainties in the gravity differences. For local practical applications, like mineral exploration, this was, however, not a problem.

By this time, a young student in geophysics had moved all the way from India, via Britain, to northernmost Sweden with its important mining companies. This geophysicist, Dattatray Parasnis, thus moved from an equatorial region to the Arctic circle. He concentrated on mineral exploration using geophysical methods. After ten years in Sweden

Parasnis (1962) published a book, “Principles of applied geophysics”, including gravimetric as well as electric, magnetic and seismic methods. This book was so well received that it was repeatedly issued in new and expanded editions; the fifth and last edition was published 35 years after the first edition. As stated earlier, interpreting local gravity anomalies in terms of density differences in the upper crust was not easy. It was often necessary to combine gravity observations with those from other geophysical methods. Parasnis’ book spanned the whole field. His chapter on gravity methods included theory and useful examples of the connection between density deviations in the crust and the resulting gravity anomalies at the Earth’s surface.

3.6 A Baltic venture: Gravity on sea ice

As stated in Section 3.1, Nansen’s Norwegian expedition to the Arctic Sea in the 1890s was the first to measure gravity from a ship, and also the first to measure gravity on sea ice. To determine gravity not only on land but also at sea, a watercraft was normally necessary. However, in the Baltic Sea, as in the Arctic Sea, a quite special method might be worth trying: to measure gravity on the frozen sea surface during winter, i.e. on the ice cover. This question was raised in the 1960s, at the Finnish Geodetic Institute, soon after a ship-borne gravity survey had been made in the Baltic.

The ship-borne gravity survey was made by Honkasalo (1959) using a research vessel with several commissions. From this ship a sea gravimeter was put down on the bottom of the sea in a sparse net of selected points, resulting in a preliminary anomaly map. He also had in mind testing gravity measurements on the sea ice, but this was made a little later by his colleague Aimo Kiviniemi (1966). He made experiments on the ice in the Gulf of Finland off Helsinki, the ice having a thickness of ½ m and the distance to open water being 500 km. The main problem turned out to be wave motions in the ice.

Once one had learned how to handle this problem, gravity could be measured on the ice cover quite successfully. Such observations started in the northern part of the Gulf of Bothnia on a small scale in 1976 by Kiviniemi, and were continued in full the following year by his colleagues Pekka Lehmuskoski and Jaakko Mäkinen (1978). They achieved a standard uncertainty of 0.1 mGal, not very different from ordinary land-based measurements. This kind of measurement was then performed during every winter of normal or severe character, partly in cooperation with Sweden. Eventually, almost the whole Gulf of Bothnia, as well as parts of the area around the Åland Islands, were covered with gravity observations, i.e. the whole northern half of the Baltic Sea. Thus, the ice conditions in the Baltic Sea made it possible to achieve much more accurate determinations of gravity on the sea surface than would have been possible using ships.

For other sea areas, not normally covered by ice in winter, gravity had to be measured from ships or from aeroplanes. Also one special land area could only be covered by gravity measurements from an aeroplane: Greenland with its vast ice sheet. That project was carried out as an American-Danish cooperation in 1991 – 1992, involving the Danish geodesist René Forsberg (1994). He later continued coastal air-borne gravity surveys to complete the coverage of Greenland, which later on went into an international gravity mapping of the Arctic.

3.7 Gravity from fall and adherent gravity networks

We noted earlier the clear indications that the fundamental absolute gravity value at Potsdam was in error by more than 10 mGal, two orders of magnitude larger than the random errors of accurate relative gravity measurements. This unsatisfactory situation was now about to be rectified by introducing a new principle for determining gravity.

Hitherto gravity had been determined, both absolutely and relatively, by using the swinging time of a pendulum, and then, relatively, by using the elasticity of a spring. Now a third principle was introduced, an absolute method that might seem quite natural: using the acceleration of a freely falling object. This, however, required extremely accurate measurements of length and time.

The first successful experiments of this kind were performed by the British physicist Arthur Herbert Cook in 1965. Soon after, in 1967, a transportable absolute gravity meter was developed by the American physicists James Hammond and James Faller; see Figure 3-11. They used laser interferometry to handle the delicate measuring of length and time.

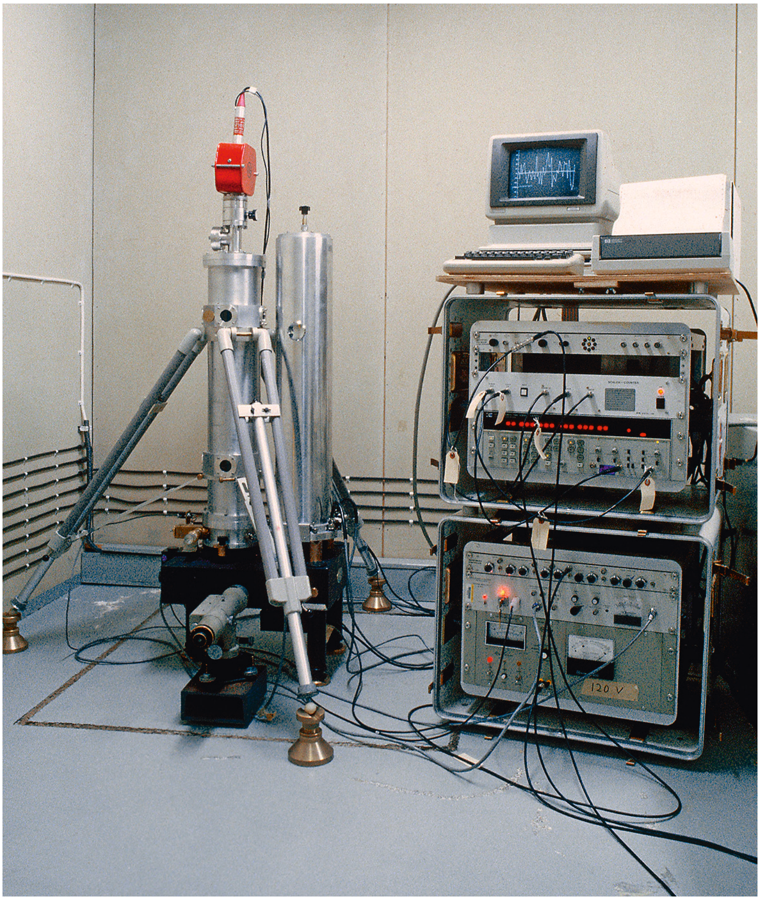


Figure 3-11. Gravimeter based on a new principle, that of a falling object, originally constructed by Hammond and Faller in 1967. The gravimeter shown here was a somewhat later improved version (known as JILAg).

A somewhat different version of this transportable absolute gravimeter was later developed through a cooperation between the International Bureau of Weights and Measures in France and a group of Italian scientists. This instrument went on a journey to measure absolute gravity in parts of Europe in 1976; see Cannizzo et al (1978). The tour included the Nordic countries where gravity was measured at 6 stations. The stations, selected by the Nordic Geodetic Commission, after discussing with the Italian measuring team, were from north to south: Hammerfest in northern Norway, Sodankylä and Vaasa in Finland, Mårtsbo (near Gävle) and Göteborg in Sweden and København (Copenhagen) in

Denmark. This was the first time since the 1800s that absolute gravity was measured in the Nordic countries. And the accuracy was impressive: The standard uncertainty turned out to be on the order of 0.01 mGal.

With such an increased accuracy, however, new problems emerged. These problems are connected to geodynamical phenomena and raise a quite fundamental question: How to define gravity on the Earth, when the Earth is constantly deformed by the Moon and the Sun, and in the Nordic area also continuously deformed by postglacial rebound after the Ice Age? The absolute gravity values were later recomputed taking such things into account, according to principles by the author; see Ekman (1989). On the other hand, gravity could also be used to study these interesting phenomena. We will deal with these new subjects in the following chapter.

At about the same time an improved relative spring gravimeter became much used, in the Nordic countries and elsewhere. It was the American LaCoste & Romberg gravimeter, enabling gravity differences to be measured with a standard uncertainty of about 0.01 mGal. It was thus, so to speak, in phase with the new absolute gravimeters. This new generation of instruments allowed new fundamental gravity networks of high accuracy and reliability to be established. Moreover, the large amount of gravity values in lower accuracy gravity networks could be recalculated to fit into the high accuracy networks and, thereby, be improved. In addition, the gravity networks were densified to an average distance between gravity stations of a few km. In combination with satellites this would turn out to be very useful; we will deal with that aspect in chapter 5.

An example of using the more accurate and densified gravity networks for improved mapping of gravity anomalies is given in Figure 3-12. This gravity anomaly map, covering the area around and north of the Arctic Circle, was the result of a special cooperation between the Geodetic Institutes and the Geological Surveys of Norway, Sweden and Finland; see Nordkalottprojektet (1986). The map reveals a considerable difference in gravity anomaly across a part of the Scandinavian Mountains, from well below - 100 mGal along the eastern side (dark blue area) to more than + 100 mGal immediately to the west (dark red area), indicating a corresponding contrast in crustal density.

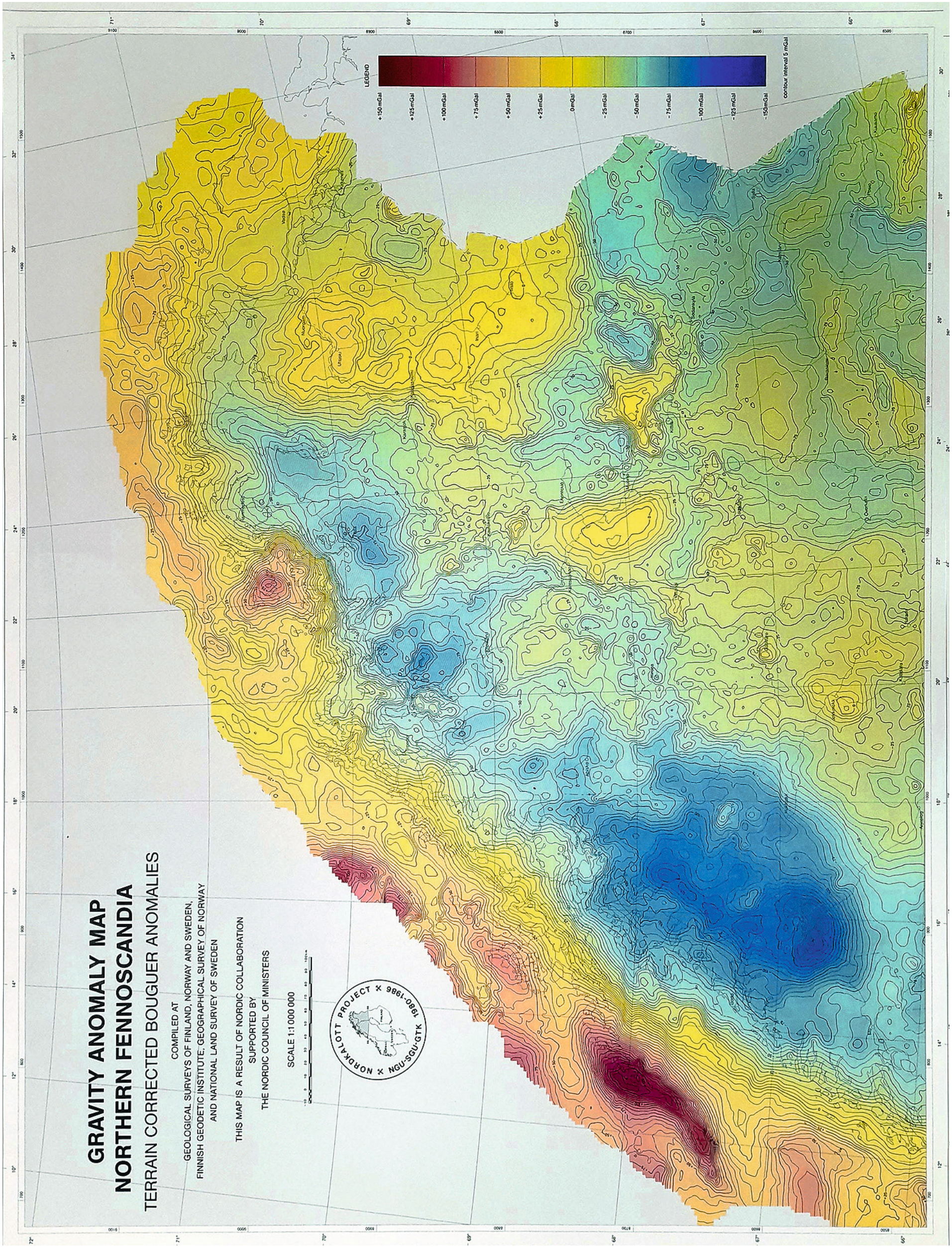


Figure 3-12. Gravity anomaly map of the northern parts of Norway, Sweden and Finland, produced in 1986 as a cooperation between the three countries. The map shows, among other things, a considerable gravity difference – between red and blue areas – across the Scandinavian Mountains.

Toward the end of the 1900s, an improved version of the absolute fall gravimeter appeared (the one in Figure 3-11), allowing improved gravity networks. However, its main importance will be revealed in connection with postglacial rebound in the following chapter.

4. Gravity and time: Postglacial rebound and mass flow

4.1 Missing mass in the mantle?

A remarkable phenomenon in the Nordic area is the continuous land uplift since the Ice Age, known as postglacial rebound or glacial isostatic adjustment. Its origin had been known, since the late 1800s, to be the unloading of a thick ice sheet a long time ago. It was also known that the land had risen by nearly 300 m since the melting of the ice, and that the process was still going on; see Figure 4-1. However, the character of the uplift process was still not known. More specifically: What happened beneath the crust when it was rising?

When Vening Meinesz (1934, 1937) was working with his gravity determinations at sea and developing his hypothesis of convection currents in the Earth (Section 3.2), he also reflected on the land uplift in the north. From his Finnish colleagues he had some information on

Figure 4-1. Continuously uplifted shore lines due to postglacial rebound.

gravity anomalies close to the land uplift maximum at the Gulf of Bothnia, the northern part of the Baltic Sea. The gravity anomalies there were clearly negative, with values down to about - 40 mGal. Such a deficit in gravity would indicate a lack of mass in some sense. Vening Meinesz interpreted this as a remaining (still to be completed) inflow of mass in the mantle beneath the crust connected to a remaining uplift of the crust. He also, based on this gravity deficit, made a rough estimate of the remaining uplift, arriving at some 180 m. Moreover, he used this quantity to make a first estimate of the viscosity of the slowly flowing mantle mass.

However, admitted by Vening Meinesz, there was a basic problem of ambiguity: The negative gravity anomaly could also be interpreted in other ways, related to various kinds of density differences rather than a lack of mass not yet arrived. Furthermore, the uplift process might not necessarily relate to an inflow of mass, as originally suggested by Nansen (1921), but instead maybe to a kind of decompression of the material below the crust. This ambiguity was not easy to resolve.

An additional problem was that the correlation between the land uplift area and the area of negative gravity anomalies was not as strong as expected. This, however, was studied closer by the Japanese geophysicists Hitoshi Takeuchi and K Yamashina (1973). They showed that by eliminating less relevant parts of the Earth's gravity field (using a series expansion in spherical harmonic functions), the remaining, more relevant, parts did correlate quite well with the uplift area. Still, the basic problem above remained: Was this deficit in gravity related to the postglacial rebound? In other words: What was actually going on below the crust when it was rising?

4.2 The Nordic land uplift gravity lines

In the 1960s, when relative gravimeters reached an accuracy of 0.1 – 0.01 mGal, it became relevant to start thinking about using repeated gravity measurements for studying the process of the ongoing land uplift. Obviously, if the uplift of the crust was accompanied by an inflow of mantle mass below, gravity as observed on the surface of the Earth would decrease due to the uplift and, at the same time, increase due to the inflow of mass. If, on the other hand, the uplift of the crust was accompanied by some kind of decompression of the mantle below, gravity as observed on the Earth would only decrease due to the uplift, without any increase due to an influx of mass.

It was fairly easy to calculate theoretically the gravity change for the two different models. In the first case, with an inflow of mass, gravity on the rising surface of the Earth would change by - 0.17 mGal/m. In the second case, with no additional mass, gravity on the rising surface of the Earth would change by - 0.31 mGal/m. The uplift rate in the centre of the uplift area was known to be 1 m per century. With sufficiently accurate gravimeters it would thus be possible to judge, from repeated gravity measurements during enough decades, which of the two models was the most realistic one.

An idea along these lines was presented by Tauno Honkasalo & Tauno Kukkamäki (1964), Honkasalo having worked with gravity in Finland for many years (Sections 3.5 and 3.6) and Kukkamäki being a colleague of his. The idea itself was not new; it had been speculated on earlier with the possibility of pursuing such a project when instrumentation made it feasible. A special line was now established for this purpose, in cooperation with the Nordic neighbours, allowing repeated observations of gravity differences across the land uplift area. The line ran in an east-west direction, crossing Finland, Sweden and Norway at approximately 63° latitude, just to the south of the land uplift maximum; see Figure 4-2. Gravity observations along this profile began in 1966, using the new LaCoste & Romberg spring gravimeters.

Some special arrangements had to be made to ensure the highest possible accuracy in these gravity observations. First, the gravity stations were chosen so they would have as equal gravity values as possible. This was important because spring gravimeters could handle small gravity differences better than large ones. Thus, the gravity line had to more or less follow a certain latitude. In the Scandinavian Mountains, however, the gravity line had to be drawn somewhat more to the north to compensate for the greater heights there, as shown in Figure 4-2. Second, as many gravimeters as possible were used. This was important because of instrument bias, not uncommon in spring gravimeters. Averaging results from several gravimeters would minimize errors of this kind. Hence, up to 10 gravimeters were used to measure the gravity line about every 5th year.

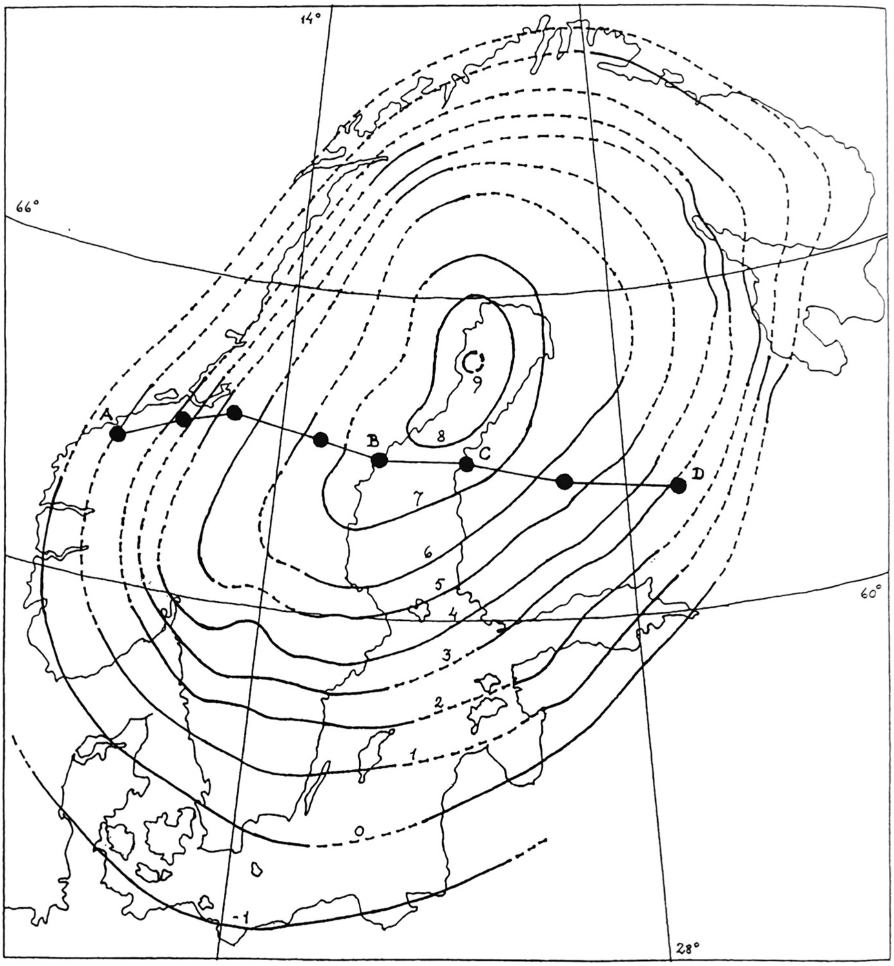


Figure 4-2. The Nordic land uplift gravity line running, approximately, along latitude 63° and crossing the land uplift area just to the south of its maximum; this line was established in 1966 through Nordic cooperation. Contours show land uplift relative to sea level during the 1900s in mm/yr.

The observations also had to be corrected for various disturbing effects, the most important one being the tidal effect caused by the Moon and the Sun. This effect was composed of two parts. One part was the direct effect of the attraction of the Moon and Sun, the other part was the indirect effect due to the tidal deformation of the Earth. We will return to this phenomenon in Section 4.4.

Most of the gravity measurements along the 63° line were, in the beginning, made by Aimo Kiviniemi (Finland), Lennart Pettersson and Lars Åke Haller (Sweden), and Bjørn Geirr Harsson (Norway). The first results from these measurements were published by Kiviniemi (1974) and Pettersson (1974). This was of course too early to allow any conclusions about gravity change, but the results indicated a standard uncertainty in the gravity differences of only 0.01 – 0.001 mGal. The whole long-term project was planned and discussed within the Nordic Geodetic Commission, an organization where geodesists from the Nordic countries cooperate in a spirit of friendly competition.

Soon a computational group took care of designing and performing the calculations of the gravity measurements, including physical corrections, instrumental corrections, and adjustment computations. This work was carried out by Jaakko Mäkinen (Finland), Martin Ekman (Sweden), Åge Midtsundstad (Norway), and Ole Remmer (Denmark); Midtsundstad, after some years, sadly died in a helicopter accident while measuring gravity in Svalbard. Their results were published by Mäkinen et al. (1986). By then, a few additional lines had been established, one at 65°, one at 61°, and one at 56°. However, the 63° line remained the primary one, with observations taken more often compared to the other lines. Although the results hitherto indicated a decrease in gravity, it was still too early to draw any conclusions about possible mass changes in connection with the uplift.

The question whether the present land uplift was associated with an inflow of mantle mass or not was considered by many geophysicists to have an expected answer: Yes, it was. Nevertheless, the problem could not be solved without rigorously investigating the matter via continued observations and theoretical considerations.

Moreover, some geologists favoured another view, claiming there was no inflow of mass but rather some kind of decompression. This was strongly advocated by the Swedish geologist Nils-Axel Mörner. He claimed, in several papers, that the postglacial rebound was composed of two separate mechanisms: the glacial isostatic one which, according to him, had already faded out, and another one that remained active and could be observed today. This latter mechanism, according to him, was related to a phase boundary displacement due to decompression, his arguments being based on a number of geological observations of ancient shore lines. In Mörner (1991) he summarized this view, pointing out that the present mechanism "no longer involves any interchange of mass". At the end he concludes:

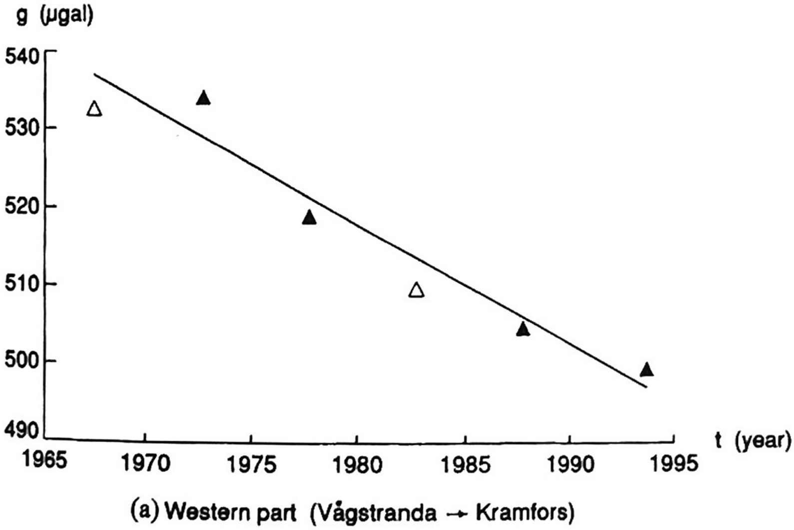
"It is true – though quite surprising to me – that it has been hard to convince people about this two-factor uplift. Naturally, it complicates and hampers geophysical calculations and modelling. On the other hand, it is the product of detailed and well dated observations: observations that must guide the models and not vice versa."

So, would it be possible to decide what was actually occurring inside the Earth in connection with the uplift of the crust? Could the repeated gravity determinations give an answer?

A first, preliminary, answer was given nearly 30 years after the establishment of the first Nordic land uplift gravity line, by Ekman & Mäkinen (1996). They could conclude, from repeated gravity along the 63° line, that at least some inflow of mass had to occur beneath the crust; see Figure 4-3. This was statistically significant at the 99% level. The uplift rates required in their calculations were derived from long sea level records and repeated levellings (see the map in Figure 4-2). They write:

"Even allowing for things like linearization errors in the uncertainty estimation, outliers in the gravimeter data, and eventual unmodelled errors in the land uplift differences, the evidence is strongly against a model of the type c = 0 [no additional mass]. We conclude that Mörner's model in this respect has to be ruled out, and that a viscous inflow of mass is a necessary part of the ongoing uplift process. On the other hand, this process might be more complicated than a pure viscous flow."

A somewhat more definite answer was given ten years later by Mäkinen et al. (2004), after nearly 40 years of repeated gravity measurements. They could now state that the process was even closer to a full inflow of mantle mass, but there was also some inconsistency in parts of the data. They also concluded that absolute gravity measurements had now become more accurate and less laborious than relative ones and so



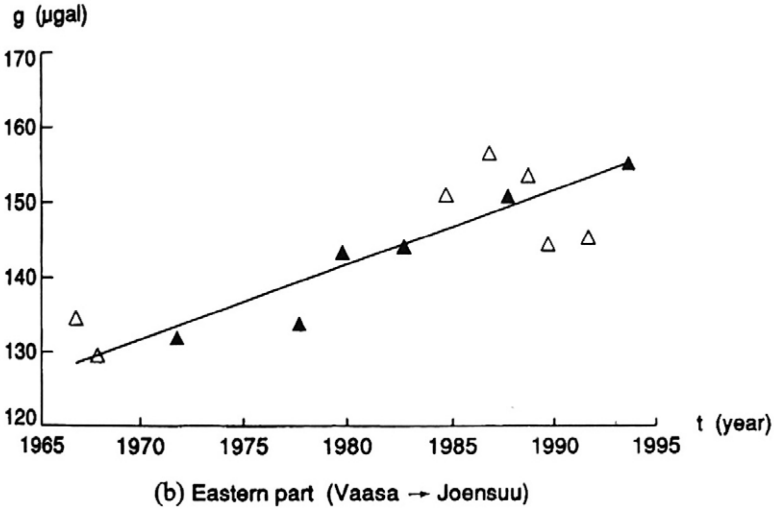


Figure 4-3. Evidence of mass flow beneath the rising crust in connection with postglacial rebound, according to Ekman & Mäkinen 1996. The inclined straight lines show the change of gravity (g) with time (t) for the western and eastern parts of the land uplift gravity line (A → B and C → D in Figure 4-2). The obtained inclination turned out to require, in addition to the uplift of the crust, an inflow of mass beneath it.

recommended a continuation with absolute gravimeters instead of the relative instruments.

4.3 Repeated absolute gravity and land uplift

In the 1980s Faller and his colleagues in America developed his transportable absolute fall gravimeter, introduced in Section 3.7, into a version that was produced in a small series. It became known as the JILAg gravimeter (JILA = Joint Institute for Laboratory Astrophysics, and g = gravity). One such gravimeter was acquired by the Finnish Geodetic Institute in 1987. During the following decade an improved successor to this instrument (FG5) became available. This was used early in the Nordic area by one American and one German institute, and then a little later by the geodetic and mapping institutes in Finland, Sweden, and Norway, as well as a different instrument by Denmark. With these instruments, repeated absolute gravity measurements started to be made in the postglacial rebound area, in 1993 with the American and German instruments, and then continuing with the Nordic ones. The standard uncertainty in an absolute gravity determination approached a level as low as 0.001 mGal. It may be noted here that promising versions of fall gravimeters, of the same accuracy but using falling atoms, are being developed at the time of writing.

As before, the Nordic Geodetic Commission took care of planning and coordinating this long-term project of repeated observations. In contrast to the gravity lines, gravity could now be observed at stations spread over the entire land uplift area. Observations were in general made with an interval of a few years. Also, land uplift rates could now be determined from continuous satellite positioning (GPS).

Preliminary results, supporting the findings from the gravity lines, were reported by the German geodesist Olga Gitlein (2009). A decade later, after nearly 30 years of repeated absolute gravity observations, a conclusive result was presented by the Swedish geodesist Per-Anders Olsson and his group (2019). This group included scientists from Finland (Mirjam Bilker-Koivula), Norway (Kristian Breili, Vegard Ophaug), Denmark (Emil Nielsen), Germany (Ludger Timmen) and Estonia (Tõnis Oja) as well as an additional one from Sweden (Holger Steffen). They used in total 59 stations and then selected 21 stations considered the most reliable ones. It turned out that the two data sets – the complete set and the most reliable set - yielded almost the same results. Their main result can be summarized as: Yes, there is a full inflow of mantle mass below the rising crust. The obtained relation between gravity change and land uplift clearly confirmed this; see Figure 4-4. In addition, if needed for other purposes, a gravity change could now be reliably estimated anywhere within the uplift area from known uplift values, simply by using the obtained relation between gravity change and land uplift.

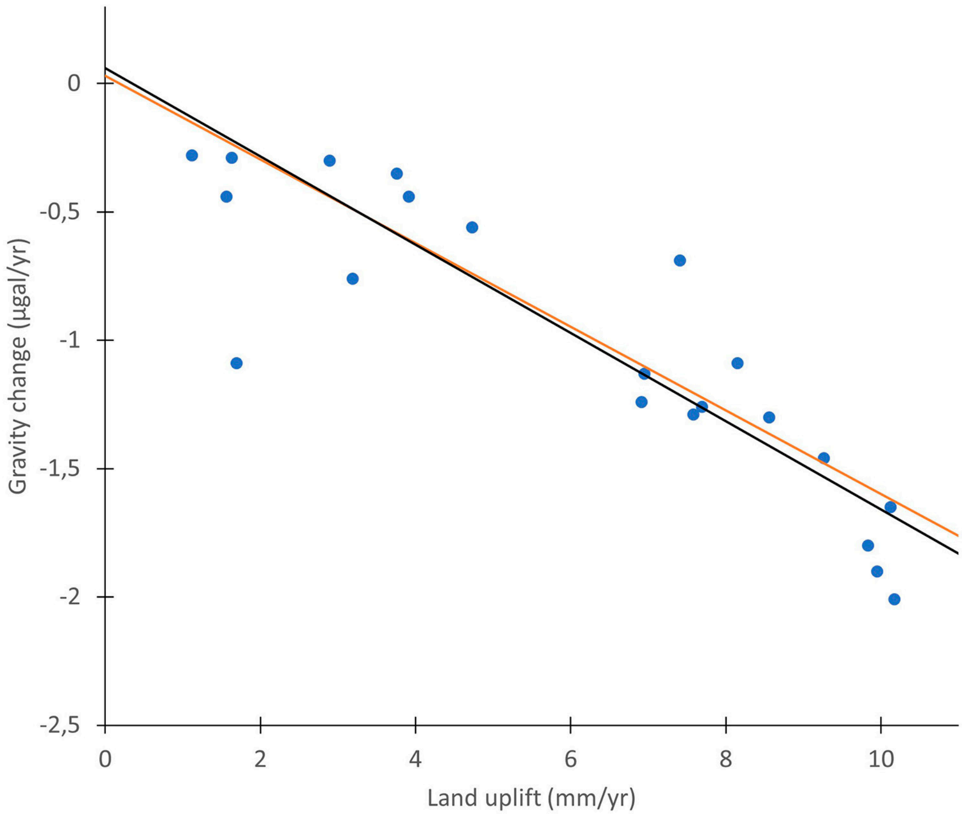


Figure 4-4. Evidence of full inflow of mass beneath the crust in connection with postglacial rebound, according to Olsson et al 2019. The coloured straight line represents the theoretical relation between gravity change and land uplift in the case of full inflow of mass. The corresponding black line represents the result of the observations, agreeing very well with the full inflow theory.

An illustrative picture of what had been found to go on inside the Earth may be given by a visit to the breakfast table in the family of the author. The author usually eats muesli with milk and something else for breakfast. His wife, on the other hand, usually eats a thicker fluid, sour milk. The author's wife now pours a suitable amount of sour milk into a plate. On the surface of the sour milk, she puts a heap of solid material like muesli, raisins etc. Then she leaves to spend some minutes doing a few other things. During this time the muesli gradually sinks down into the underlying sour milk, whereby the sour milk to a corresponding degree flows outwards; see Figure 4-5. This leads to a rising of the sour milk level close to the brim of the plate. Finally, just before she returns, the sour milk flows out over the brim and down onto the table, where it creates a decorative ring around the plate.

This process is almost identical to the one going on in the Earth when loading it with an ice sheet. The muesli corresponds to the ice, the sour milk to the Earth. When you load the Earth with the ice it sinks, together with the thin crust, down into an inner part of the Earth, the mantle, then flowing outwards. The difference is that the Earth is more viscous than the sour milk; what the sour milk takes minutes to do requires thousands of years for the Earth.

If you would now lift most of the muesli away from the sour milk again, the sour milk will gradually flow back into the more central parts of the plate. This leads to the sour milk level again rising in the middle of the plate. This process corresponds to the land uplift going on since the deglaciation of the ice sheet. And it was the inflow part of this process, the inflow of sour milk, i.e. mantle mass, that had now been conclusively verified, through repeated gravity observations, to still be going on.

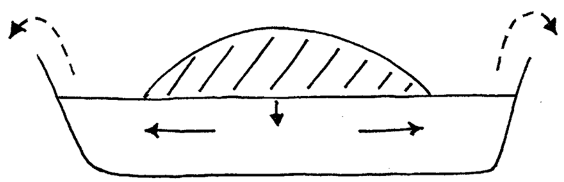


Figure 4-5. Mass flow in a plate with sour milk after adding a load of muesli. This corresponds to the mass flow in the Earth after adding the load of ice. The reverse flow will then occur in both cases upon removing the load.

4.4 Influence of Moon and Sun: Earth tides

There is also another change of gravity on the Earth's surface with time, but due to a completely different process. This is the variation in gravity caused by the gravitation of the Moon and the Sun, the tidal effect. It can be calculated theoretically and shown to be at most 0.3 mGal. As we know, this effect is responsible for the tides in the world's oceans, although the ocean tides are here and there magnified by resonance phenomena; see Figure 4-6 a & b.

When spring gravimeters were introduced, it became possible to record tidal variations in gravity. Actually, such variations were recorded already before the use of spring gravimeters, by the German geophysicist Wilhelm Schweydar (1914). He constructed a special instrument for this purpose, based on the spring principle but a stationary one and so only recording variations with time. Schweydar also found that the observed tidal variations in gravity were somewhat larger than those calculated theoretically. The theoretical calculations were based on a rigid Earth, while the real Earth yielded slightly to the tidal forces. The Earth turned out to be somewhat elastic. This produced tides in the Earth's body itself, Earth tides, of up to ½ m, responsible for the additional variation in gravity measured by Schweydar.

The Earth tides meant not only that the Earth's surface moved up and down twice every day, as could later be recorded by an ordinary gravimeter, but also that the Earth's surface was periodically tilted. This effect could be measured by a horizontal pendulum, as was done already by a colleague of Schweydar, Oskar Hecker (1907).

In Finland, instead of a horizontal pendulum, an extremely long tilt meter was later installed for the purpose of recording the Earth tides. This was a 180 m long horizontal tube filled with water, oriented in the east-west direction, combined with a 60 m long similar tube oriented in the north-south direction; the whole thing was placed in an abandoned mine at Lohja. The construction of this unusual tidal instrument was overseen by Jussi Kääriäinen (1979), who also analysed the recordings for studying the elastic properties of the Earth.

Figure 4-6 a & b. Tidal effect due to the gravitation of the Moon and the Sun: Road at the British North Sea coast, possible to use only during low tide, completely flooded during high tide.

For recording the vertical component of the Earth tides, tidal gravimeters had been tested in Sweden, at Uppsala, since 1963. They revealed, as in other places, the elastic tidal deformation of the Earth, increasing the gravity variation by about 15 %, but also a small resonance effect in the liquid core of the Earth. Careful methods to investigate these variations in tidal gravity observations were developed by Hans-Georg Scherneck (1986).

Now, given that the tidal effect on gravity is up to 0.3 mGal, it was clear that this effect had to be considered when making accurate determinations of gravity values, both absolute and relative ones. Noting that the standard uncertainty in the absolute gravity determinations approached 0.001 mGal in the early 2000s, it was also clear that the tidal effect had to be calculated with considerable accuracy. This obviously required that the elastic tidal deformation be taken into account as well. Hence, the results from tidal gravity observations of the elasticity of the Earth were necessary for correcting absolute (and relative) gravity determinations.

When making tidal corrections to accurate gravity determinations it turned out that a quite strange problem appeared, affecting the very definition of the concept of gravity on the Earth. The problem had to do with the fact that the Moon and Sun are always fairly close to the equator, thereby causing, on average, a kind of constant high tide close to the equator and a corresponding constant low tide closer to the poles; see Figure 4-7. This phenomenon became known as the permanent tide, upon which the "normal" periodical tides are superimposed. The permanent tide was of a similar magnitude as the periodical tides and, hence, of importance. This led to the question: What to do with this permanent signal in the definition of gravity?

To start with, tidal corrections were simply applied in such a way that the whole effect of the Moon and Sun – periodical and permanent together – was eliminated from gravity, without much further ado. However, Honkasalo (1964) claimed that this was, in a way, artificial, and proposed only eliminating the periodical effects in gravity, not the permanent one. To this, his colleague Markku Heikkinen (1979) objected that gravity in that case would include gravitation from masses outside the Earth, causing obstacles when computing the geoid from gravity

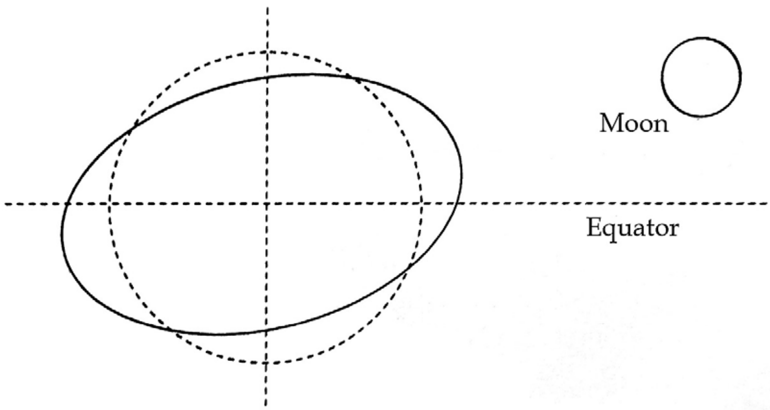


Figure 4-7. Tidal deformation of the Earth caused by the Moon being always close to the Earth's equatorial plane, leading to an average low tide at the poles and an average high tide at the equator. This permanent tide caused problems in handling the concept of gravity on the Earth, the present solution of this being according to Ekman 1989.

anomalies, and so he recommended returning to the original way of removing both tide contributions.

Now a third person, the author, interfered, pointing out that neither of these two solutions was without tricky problems: The original one (later called non-tidal or tide-free gravity) would cause trouble because changing the shape of the Earth, the other one (later called mean gravity) would cause obstacles when performing computations based on gravity data. He, therefore, put forward a third solution (later termed zero gravity): The permanent tide should be divided into two parts, the direct permanent tidal attraction of the Moon and Sun, and the resulting permanent tidal deformation of the Earth. The permanent attraction should be eliminated whereas the permanent deformation should be retained. This meant that the shape of the Earth was kept as it is, at the same time as gravitational forces from other celestial bodies were done away with; see Ekman (1989).

On the international level, recognizing the need for a global agreement on the concept of gravity, the three solutions above were all, one after the other, accepted, the third one being the final one. Ekman

(1989) argued that this kind of tidal solution should be applied generally, also for defining global (GPS) coordinates on the Earth:

“How to do: Use zero gravity, zero geoid and zero crust (= mean crust). This … should be extended to all gravity networks, levelling networks, and GPS. The exception that proves the rule: The mean sea level must be related to the mean geoid to give oceanographically relevant information.”

Although later decided internationally, the practical implementation of this on the international GPS level failed, illustrating that handling the effects of fundamental details of gravity is not always an easy task. A further discussion on the international handling of the permanent tide was later given by Mäkinen (2021).

4.5 Smaller gravity changes

To record very small changes in gravity at a certain point, a special stationary instrument was invented by the American physicist John Goodkind, and further developed by his group in the 1990s. In this instrument, known as a superconducting gravimeter, a spherical superconducting mass is levitated using a magnetic force balancing the force of gravity. The magnetic force here, so to speak, replaces the spring in spring gravimeters, although this instrument is for recording changes in time only. The sensitivity of the instrument is extreme, a couple of orders higher than that of the transportable fall instruments.

Such a superconducting instrument recording gravity change was used at Ny-Ålesund in Svalbard to start studying recent ice melting and land uplift there during the early 2000s, by the Norwegian geodesists Ove Omang and Halfdan Kierulf (2011). Such an instrument could also be used for studying other kinds of mass changes, like ground water changes, and it even reacts to changes in snow cover (especially on the roof of the instrument building!), as reported by the Finnish geodesist Heikki Virtanen (2006) from Metsähovi close to Helsinki. A similar instrument was later also installed in Sweden, at Onsala close to Göteborg. It should be noted here that since then a moveable version of this instrument has also been developed.

5. Gravity and satellites: The Earth from space and climate effects

5.1 The Earth's gravity field and perturbations of satellite orbits

Through most of the centuries gravity, with its irregularities and its changes with time, had been studied by observing it on the surface of the Earth. To start with, as we have seen, pendulums were used for this purpose, later spring devices, and more recently fall instruments.

Around 1960, however, a completely new method of studying the Earth's gravity field emerged – by observing the orbits of satellites. Had the Earth been a perfectly spherical body with a homogeneous (or laterally uniform) mass distribution, a satellite would have moved in a constant orbit around the Earth. In reality, as we know, the Earth is not that simple, and any deviation from this idealized state will cause the satellite to move in an orbit that changes with time. Hence, to turn it the other way around: Observing perturbations of a satellite orbit will allow information to be obtained on the irregularities of the Earth's gravity field.

The primary deviation from spherical symmetry is the flattening of the Earth at its poles, discussed in connection with the early gravity measurements in Chapter 2. What effect will this have on a satellite orbit? A satellite normally orbits the Earth at some inclination to the Earth's equator. Now, the Earth's flattening will make the inclined orbital plane slowly revolve relative to the equatorial plane so that the intersection between them gradually moves along the equator (backwards with respect to the motion of the satellite); see Figure 5-1. The resultant orbit will be that of a spiral. The speed at which this regression of the orbital plane occurs gives information on the flattening of the Earth.

The first to develop the theory behind this was, in fact, Laplace in 1802, long before the era of satellites. How come? Well, in addition to the artificial (man-made) satellites of our time, we also have a natural satellite since long ago, the Moon! Laplace developed this kind of theory

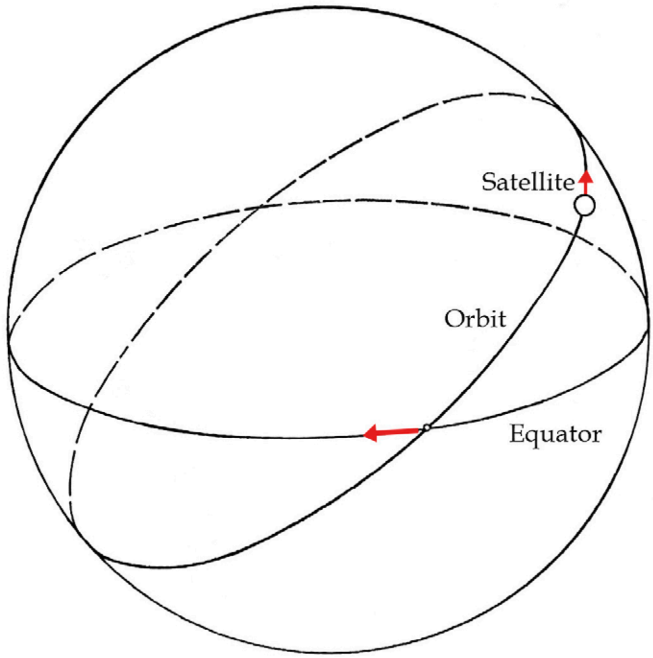


Figure 5-1. A satellite orbit and its intersection with the equator. The flattening of the Earth, and its effect on the Earth's gravity field, will cause this intersection to gradually move "backwards", making the satellite move in a kind of spiral around the Earth.

for the lunar orbit, and in 1884 Helmert applied it to find an approximate value of the flattening, close to the modern one.

The Moon, however, is quite far away from the Earth, a distance of about 60 Earth radii. This makes the Moon quite insensitive to deviations in the Earth's gravity field. Artificial satellites, on the other hand, orbit much closer to the Earth, most of them at distances less than one Earth radius from the surface. Application of this technique led rapidly, in 1960, to the modern value of the Earth's flattening of 1/298.3, by the Austrian-American geodesist Irene Fischer and others.

The method could now quickly be widened. The closeness of the artificial satellites makes them considerably more sensitive also to other gravitational irregularities in the Earth. Consequently, a much more extensive theory of the relation between satellite orbits and the Earth's gravity field had to be elaborated. This was done primarily by the Australian-American geophysicist William Kaula (1962), but also by Arthur Herbert Cook (1963), mentioned in connection with absolute gravity in Section 3.7, and others.

To define and deal with an elliptic satellite orbit, five quantities are needed. The size of the orbit is determined by its semi-major axis, and the shape of the orbit by its eccentricity. The tilt of the orbit is determined by its inclination to the equator, and the orientation of the orbit by its intersection (ascending node) with the equator. The position of the orbit in its plane is determined by its closest point (perigee) to the Earth. These quantities, known as the orbital elements, would, according to Kaula, all change with time, gradually or periodically, due to the various irregularities in the Earth's gravity field. Observing the changes in the orbital elements with time, through tracking a satellite, would reveal the irregularities in the gravity field.

Obviously, what could be revealed were not individual (local) gravity anomalies but a more or less global description of the gravity field. So, what could be deduced from the satellite orbits was the general shape of the geoid, i.e. the level surface (equipotential surface) of the gravity field being everywhere perpendicular to the plumb line and coinciding, in principle, with mean sea level. The geoid was characterized by its height above and below the Earth ellipsoid. From the perturbations of the satellite orbits a global pattern of geoid heights could thus be computed. It indicated geoid heights of up to ± 100 m.

Now, geoid heights could also, as we have seen in Section 3.4, be calculated from gravity measurements on the Earth's surface, which yielded geoid heights of similar magnitude. In the beginning of the satellite era, however, there was an annoying gap between these two methods. Geoid heights from surface gravity mainly reflected mass distribution of a more regional character, while geoid heights from satellite orbits mainly reflected mass distribution of a more global character. The gap between these scales was difficult to handle. When, in 1967, Weikko Heiskanen, the author of the gravity book mentioned in Section 3.2, wrote a new gravity book together with the Austrian geodesist Helmut Moritz, satellite gravity was still treated as a separate topic at the end of the book; see Heiskanen & Moritz (1967).

5.2 The Nordic geoid from satellite orbits and surface gravity

After a few decades, the resolution of the geoid as determined from satellite orbits improved to the point at which it could start being combined with geoid determinations from surface gravity. This combination turned out to be very useful, as shown by the American geodesist Richard Rapp (1973), applying mathematical ideas from Moritz. As was mentioned in Section 3.4, determining the geoid from surface gravity measurements required gravity not only from around the point of computation but in principle from all over the world, not a very easy requirement to fulfil. With the introduction of satellites this problem of global coverage could be handled, or rather, circumvented. The perturbations of satellite orbits provided the global coverage of gravity needed as a background for the more accurate and spatially resolved contributions to the geoid from surface gravity measurements.

After cooperation with Rapp, work along these new lines was started in the Nordic countries by the Danish geodesists Carl Christian Tscherning and René Forsberg. Their first result of practical importance was an accurate geoid over the Nordic area, related to the recently internationally adopted satellite-based Earth ellipsoid; see Tscherning & Forsberg (1986). This geoid, as well as subsequent determinations, was based on a combination of geoid heights from three different sources. First, the global contribution stemmed from perturbations of satellite orbits (in the mathematical form of a series expansion in spherical harmonic functions). Second, the regional contribution stemmed from Nordic gravity data. Third, the local contribution stemmed from a digital terrain model. Data were treated in a gridded format.

The resultant map of the Nordic geoid is shown in Figure 5-2. The standard uncertainty in geoid height was estimated at only a quarter of a metre. Behind this map was a considerable effort to include the Nordic gravity data, coordinated through the Nordic Geodetic Commission. In total more than 100 000 gravity stations were used; see Figure 5-3. The gravity measurements taken on the ice within the Gulf of Bothnia (Section 3.6) were also included.

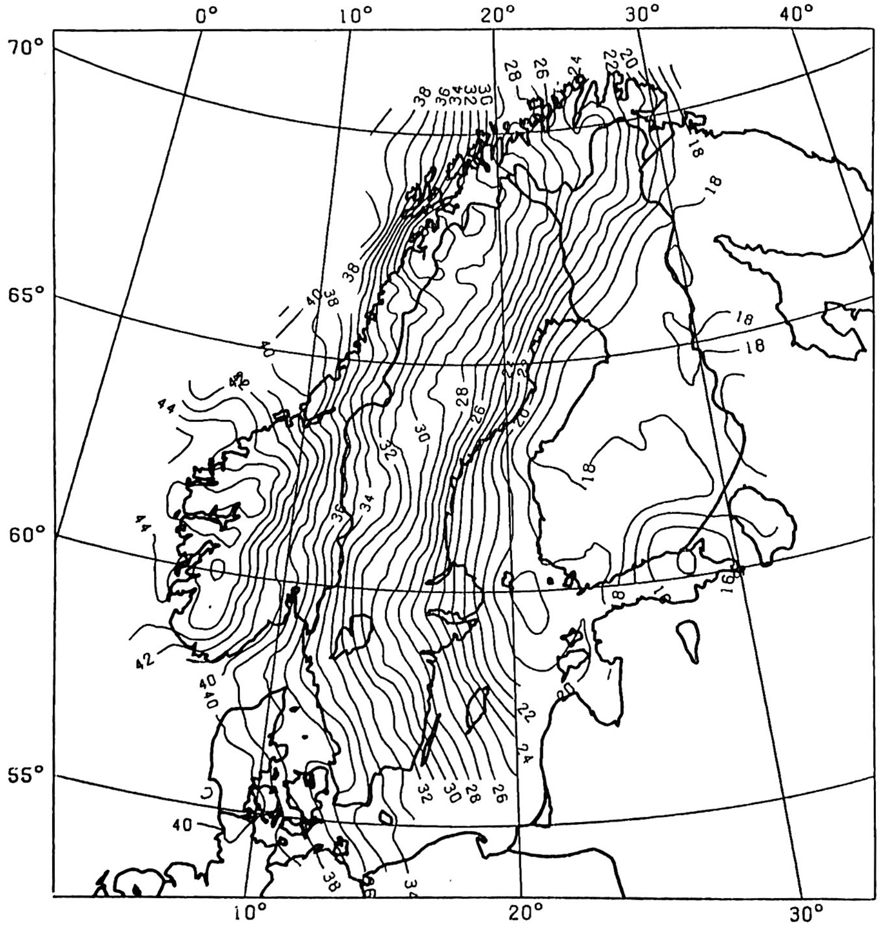


Figure 5-2. The first Nordic geoid height map calculated from a combination of satellite orbit perturbations and surface gravity measurements, by Tscherning & Forsberg 1986.

Tscherning & Forsberg's (1986) map in Figure 5-2 may be compared with the old pioneering map of Tanni (1949), shown in Figure 3-8. We note the east-west tilt of the geoid over Scandinavia occurring in both maps, but also the considerable difference between the maps as far as geoid heights in metres are concerned. The new map was a huge step forward, mainly due to satellite orbits but also to the large amount of Nordic gravity data.

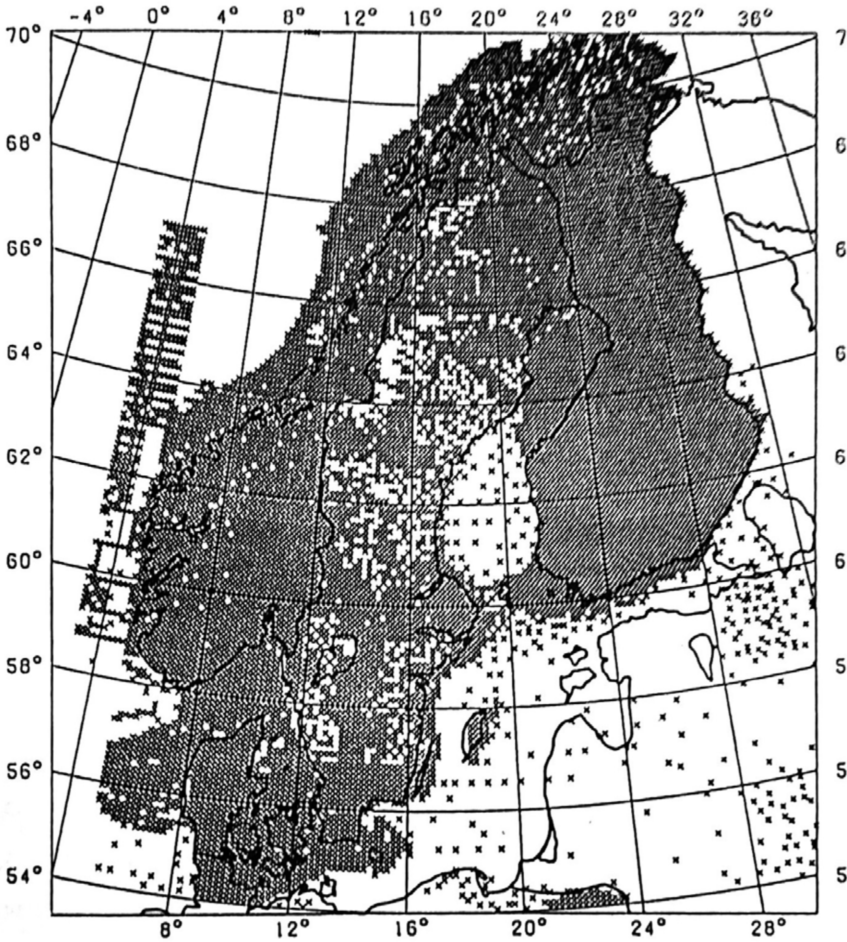


Figure 5-3. Surface gravity data coverage for the Nordic geoid in Figure 5-2.

Only four years later Forsberg (1990) could present an updated version of the Nordic geoid, but the most interesting news here was its connection to height determination with satellite positioning (GPS) and levelling. The connection entered because of a fundamental difference between these two methods for height determination.

The traditional way of measuring heights by levelling is based on the use of a spirit level; thus there is a dependence on the plumb line of the gravity field. It results in heights above the geoid. The new possibility of finding heights by satellite positioning does not involve any spirit level and is, therefore, independent of the plumb line. It results in heights above the ellipsoid. If at a certain point heights are determined by both methods, the difference between them will reveal the geoid height there. This was now used by Forsberg to check his geoid heights obtained from the gravity field of the Earth, and the outcome was highly satisfactory. The agreement was on the order of a decimetre, and Forsberg (1990) states:

"In the future updated geoid solutions are planned, especially when more GPS/levelling control is available."

This also opened up a future prospect of turning the whole approach "upside-down", so to speak: using the geoid for transforming heights from GPS (above the ellipsoid) to traditional heights (above the geoid) needed for most practical applications. This was first tried using the subsequent geoid determination by Forsberg together with the Norwegian colleague Dag Solheim and the Latvian colleague Jānis Kaminskis; see Forsberg et al (1996).

In the early 2000s, increased efforts within the Nordic Geodetic Commission were put into new and better geoid solutions, partly because of their expected use for height determination with GPS. The main improvements were the following. First, there were special gravity satellites launched (see next section), allowing more detailed surveys of the gravity field. Second, the Nordic gravity data base was densified, supplemented by ship-borne and air-borne data, and cleaned from remaining systematic defects. Third, height determinations involved were modified to be in a common reference system. Fourth, the combination of satellite gravity data and surface gravity data was made in a more optimal way. For this last item use could be made of works by the Swedish geodesist Lars Sjöberg, also included in his book together with his Iranian-Swedish co-author, Mohammad Bagherbandi; see Sjöberg & Bagherbandi (2017).

The work behind a considerably improved Nordic geoid was led by Jonas Ågren, a Swedish geodesist, who headed a quite large group of gravity researchers from all of the Nordic and Baltic countries. In the end this resulted in a Nordic geoid clearly superseding the earlier ones;

see Ågren et al (2016). The agreement between these gravimetric geoid heights and the corresponding geometric differences GPS/levelling was on the centimetre level (after a 1-parameter fit). This was extremely good; the authors found the result to be directly usable for height determination with GPS (GNSS). After that, an effort was also put into a cooperation around the Baltic Sea to densify the ship-borne gravity measurements in the Baltic in order to improve the geoid there for navigational depth purposes.

5.3 Special gravity satellites and the Greenland ice sheet

As mentioned earlier, to be sensitive to the irregularities in the Earth's gravity field, satellites need to move in orbits close to the Earth. That is why a special satellite for gravity and other geophysical purposes (called CHAMP) was launched by a German institute in 2000 to orbit the Earth at a distance of less than 500 km.

This was replaced in 2009 by a more sophisticated satellite called GOCE (Gravity field and Ocean Circulation Explorer), which was launched by the European Space Agency and moved in an orbit at a distance of only 250 km. This satellite was equipped with a gradiometer sensitive also to small differences in gravity in all three dimensions. Although active for only four years, it produced much more detailed satellite gravity data than had been possible before. These data were used in the latest Nordic geoid solution described above.

Gravity data from this satellite were particularly useful when collected over areas not easily covered by earlier gravity measurements. Such an area was Greenland with its vast ice sheet, although there had been air-borne gravity measurements made there (as mentioned in Section 3.6). Here the German-Swedish geophysicist Rebekka Steffen, with the Danish and Swedish colleagues Gabriel Strykowski and Björn Lund, made use of the gravity results from GOCE (together with other gravity data) to model the crustal depth below Greenland; see Steffen et al (2017).

A different kind of gravity satellite was the American-German mission called GRACE (Gravity Recovery And Climate Experiment), launched in 2002. This was a "double satellite" moving in an orbit around the Earth at a distance from its surface of 500 km. This meant that there were actually two satellites following each other in the orbit, as shown by Figure 5-4. As it appears that one satellite is chasing the other one, the pair got the nickname Tom and Jerry. Although at a mutual distance of a little more than 200 km, the distance between them could be determined with an accuracy of a fraction of a mm. This had the great advantage of not only revealing density differences within the Earth but also density changes in time, i.e. movement of masses. Such mass changes could be melting of land ice into sea water, changes of ground water distribution, and motions in the Earth's viscous mantle, including postglacial rebound. These important twin satellites continued to be in action for 15 years and have, since, been followed by a successor.

A simple illustration of the way the twin satellites work may be given by Figure 5-4. Suppose that the first satellite approaches an area with a mass excess inside the Earth or at its surface. This satellite, thereby, is somewhat accelerated compared to the second one, making the distance

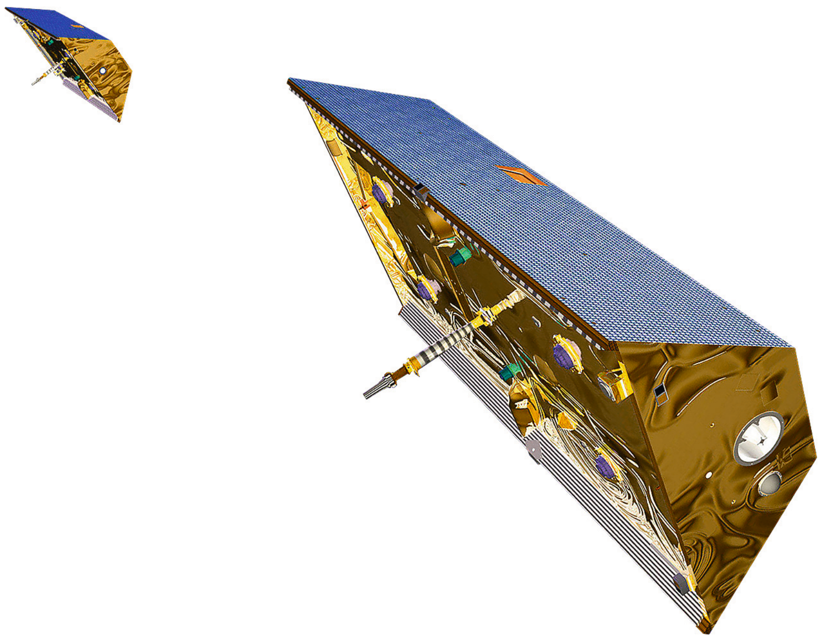


Figure 5-4. The GRACE twin gravity satellites, launched in 2002, with the purpose of observing changes in gravity due to mass changes on or in the Earth.

between them increase. After having passed over the area in question the first satellite is instead somewhat retarded while the second one is now accelerated, making the distance between them decrease. When both satellites have clearly passed, the distance between them will be restored to its original value. If there occurs some change in the mass distribution before the next passage of the two satellites, there will also be a corresponding change in the motions of the satellites when they pass the next time.

An early application of these twin gravity satellites was a confirmation of mass changes in connection with the postglacial rebound (cf. Sections 4.2 and 4.3). This was made by the German-Swedish geophysicist Holger Steffen with a group of German colleagues; see Steffen et al (2009).

A completely new field of study made possible by the GRACE mission was monitoring mass changes of ice sheets; see Figure 5-5 for the case of Greenland. Due to global climate warming, the Greenland ice sheet

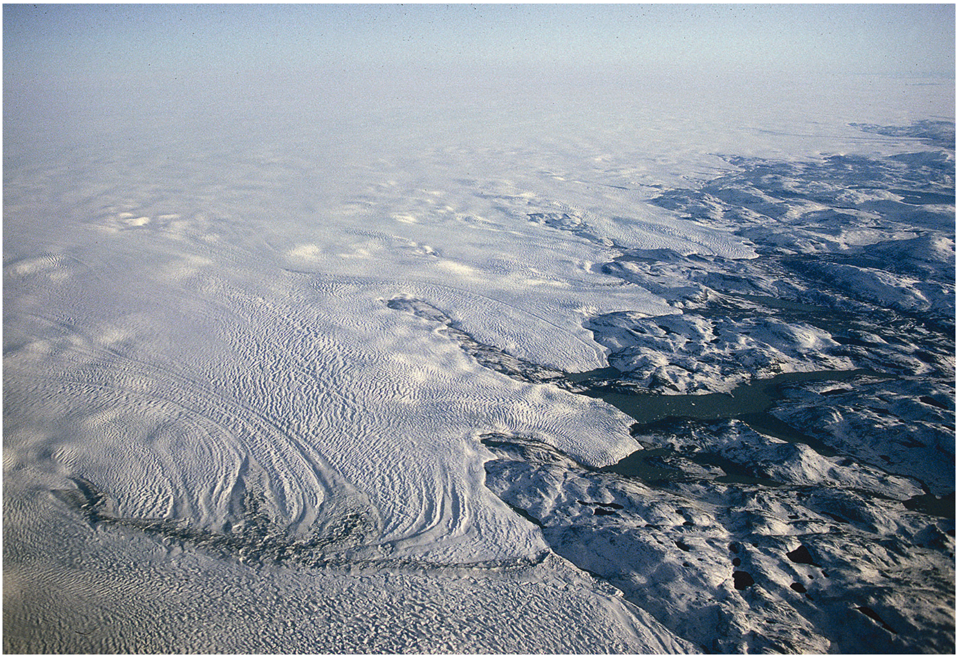


Figure 5-5. A view of the Greenland ice sheet, now melting due to climate warming.

had started melting, and this melting process could be studied through the GRACE twin gravity satellites, attracting several research groups. In an early investigation three Danes, the geodesist René Forsberg and the glaciologists Louise Sørensen and Niels Reeh (2006) found evidence of ice mass disappearing. In a following investigation, by Sørensen and Forsberg (2008), this could be confirmed, the mass loss being strongest near the ice margins.

A decade later the two last-mentioned authors above, together with the glaciologist Sebastian Simonsen, could make a considerably improved calculation of the loss of ice mass, based on the twin gravity satellites. They now found more than 200 gigatons ($2 \cdot 10^{12}$ kg) of Greenland ice turning into sea water per year; see Forsberg et al (2017) and Figure 5-6. In addition, they found a similar but smaller effect in West Antarctica. They conclude:

"Thirteen years of GRACE data provide an excellent picture of the current mass changes of Greenland and Antarctica, with mass loss in the GRACE period 2002 – 2015 amounting to 265 ± 25 GT/year for

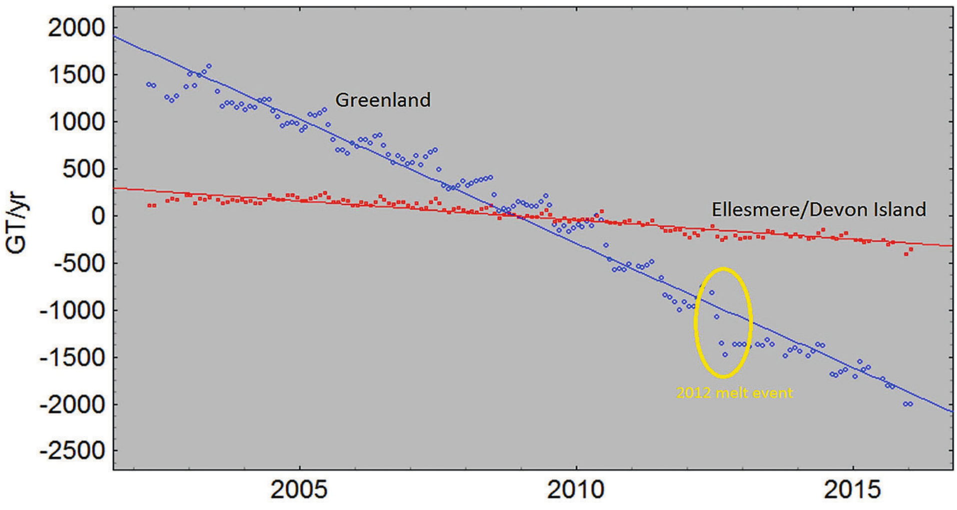


Figure 5-6. Mass loss of the Greenland ice sheet, in blue colour, as revealed by the twin gravity satellites according to Forsberg et al 2017. Dots denote monthly results, with the straight line indicating the linear trend. (Included, in red colour, is also a corresponding result for the smaller islands close to northwestern Greenland.)

Greenland (including peripheral ice caps), and 95 ± 50 GT/year for Antarctica, corresponding to 0.72 and 0.26 mm/year average global sea level change."

These Greenland gravity investigations were then continued as a key element in internationally organized studies of climate change. Moreover, results from Greenland could be used to correct GRACE-derived ice mass changes in Iceland, as shown in a cooperation between Danish and Icelandic scientists; see Sørensen et al (2017).

Clearly, the above findings show the great ability of twin satellites to record changes of gravity, and thereby changes of mass, especially over larger areas.

5.4 A brief review

Let us now look back and make a few brief reflections on the development of the determination and use of gravity during the past 300 years. We have collected some information and data on gravity determinations in Tables 5-1, 5-2 and 5-3, and on gravity applications in Table 5-4.

From Table 5-1 we note that pendulum methods were the only means to determine gravity for two centuries, both absolutely and relatively, from the first half of the 1700s to the first half of the 1900s. In the first half of the 1900s, spring methods were introduced, strongly facilitating relative gravity measurements. And in the second half of the 1900s, fall methods completely took over when making absolute gravity measurements. The decades around 2000 have seen the addition of satellite methods, allowing the study of the Earth's gravity field over larger areas and in a more global sense.

Table 5-2 shows that the number of gravity stations in the Nordic countries increased fairly slowly for two centuries, during the pendulum era from the early 1700s to the early 1900s. This period saw an increase from the first stations to the order of 100 stations around 1900. Since then, the increase has been much faster, mainly due to the introduction of the more easily handled spring gravimeters, with the number of gravity stations reaching the order of 10 000 around 1950 and 1 000 000 around 2000.

Table 5-1. Principle methods of gravity determination through history with years of invention.

Method	Main inventor	Year
Pendulum	Graham	1731
Reversible pendulum	Kater	1818
Portable pendulum	Sterneck	1887
Spring	Ising	1928
Fall	Cook	1965
Transportable fall	Hammond	1967
Satellite	-	1980s
Twin satellites	-	2002

Table 5-2. Number of gravity stations in the Nordic countries through history, orders of magnitude.

Year (approx.)	Number
1740	1
1830	10
1900	100
1940	1 000
1950	10 000
1980	100 000
2000	1 000 000

Table 5-3 reveals an interesting development in the accuracy of gravity determinations. From the early 1700s well into the 1900s there was a fairly slow decrease, i.e. improvement, in the measurement uncertainty, by two orders of magnitude in two centuries. In contrast, since somewhat after the middle of the 1900s until around 2000, the uncertainty has decreased rapidly, by as much as three orders of magnitude in only half a century, mainly due to the introduction of the advanced fall gravimeters.

Table 5-3. Uncertainty in gravity in m/s² through history, for absolute gravity as well as relative gravity, orders of magnitude.

Years	Abs. grav.	Rel. grav.
1700s	10^{-3}	
1800s	10^{-4}	
1900s, 1st half	10^{-4}	10^{-4}
1900s, middle	10^{-4}	10^{-5}
1900s, 2nd half, early	10^{-5}	10^{-6}
1900s, 2nd half, late	10^{-7}	10^{-7}
2000	10^{-8}	10^{-7} - 10^{-8}

Table 5-4. Applications of gravity determinations through history with years of introduction.

Application	Year of intr.
Earth's flattening	1738
Crustal thickness (deflected verticals)	1855
Crustal thickness (gravity anomalies)	1924
Mineral exploration	1930s
Mantle convection currents	1934
Geoid heights	1949
Postglacial rebound	1966
Ground water changes	1980s
Ice sheet melting	2002

Now over to Table 5-4, which lists the various applications of the knowledge of gravity. During the 1700s and the 1800s the main objective for making gravity measurements was finding the flattening of the Earth at its poles, which was also a clue to the radial density structure inside the Earth. In the middle of the 1800s there was also an awakening interest to study the thickness of the crust, at that time only using the direction of gravity and its deviations. In the first half of the 1900s, however, there was an explosion in new applications of gravity measurements: crustal thickness, mineral explorations, mantle convection and the shape of the geoid. This was mainly due to the introduction of spring gravimeters. And in the second half of the 1900s and around 2000 the opportunity arose to study geodynamic and climate effects through changes in gravity with time: postglacial rebound as well as ground water changes and ice sheet melting. This was partly due to the introduction of fall gravimeters, and partly due to the introduction of satellites for gravity purposes.

In total, the uncertainty in gravity determinations has decreased by five orders of magnitude during the past 300 years, from 10^{-3} m/s^2 to 10^{-8} m/s^2. This means an increase in the knowledge of gravity values – g = 9.8… m/s^2 – from 4 digits to 9 digits. Furthermore, this increase in accuracy as well as the new possibilities of using satellites have allowed not only an improved understanding of the Earth's structure, but also the ability to monitor and understand mass redistribution on and within the Earth.

6. Outlook: What is gravity? Einstein and the Nobel prize

As we have seen in the previous chapters, scientific development over the past few centuries has made it possible to determine gravity on the Earth's surface with an accuracy of up to 9 digits. This has allowed insights into the structure of the Earth as well as into geodynamic phenomena.

But what is it actually that we measure and study? According to Newton it is an attractive force exerted by all masses in the Universe. In Chapter 1 we noted that the concept of such a force was not well accepted, even though Newton had several good arguments. A main objection concentrated on the idea of action at a distance: How could there be a force acting at a distance between bodies in space without any contact between them? There was no answer to that – not until more than 200 years later.

The answer was a revolutionary one: There is no gravitational force – it is all about the character of space itself! Space is not linear but curved, and this curved space governs the motions of bodies. The man behind this remarkable theory was Albert Einstein, the German-American physicist. He presented it in portions in 1915 and then in a comprehensive final paper the following year, in 1916. His theory was not only a different way of looking at the problem, it also contained new effects not predicted by Newton's theory. On the other hand, for many purposes, Newton's theory could be considered as an excellent approximation to that of Einstein.

It should be noted here that a predecessor to Einstein's theory of gravitation was given by Gunnar Nordström (1913), a Finnish-Swedish physicist. This led Einstein to discuss Nordström's theory in a special paper the year after; see Einstein & Fokker (1914). Nordström seems to have made the very first attempt to construct a theory of gravitation involving the geometry of space, although it turned out to contain some flaws. Immediately after Einstein's final paper Nordström, in a letter to the Royal Swedish Academy of Sciences, nominated him for the Nobel prize; we will return to that later.

Einstein started his thinking from two fundamental observations. One was that the speed of light seemed to be a constant, independent of the velocity of the observer. This was apparent from the fact that the speed of light always turned out to be the same relative to the Earth irrespective of the Earth's motion around the Sun. The other fundamental observation was that gravitation and acceleration seemed to be inseparable quantities. This was apparent from imagining a person in a box: The person inside the box would not be able to tell, by any kind of measurement, whether standing on its floor was caused by the box accelerating in space or by the box being on the Earth acting on it with its gravitation.

After a lot of calculations, based on these two observations, Einstein (1916) ended up with a new world: Space must be curved. Although our brains cannot imagine a curved space but only a curved surface, the mathematics of curved surfaces (differential geometry) could be expanded to curved spaces, i.e. from two dimensions to three dimensions. (In reality Einstein worked in four dimensions, including time to create a four-dimensional "space-time", but we keep to the ordinary three-dimensional space as it is the curvature itself that is the point here.) Space, according to Einstein, was curved by the presence of a mass, i.e. a celestial body or the Earth. Another body would then move along the shortest path (a geodesic) in this curved space. Thus, Einstein's theory of gravitation – mostly known as the general theory of relativity – may be summarized as follows: Matter tells space how to curve, the curved space tells matter how to move.

There are two ways of making this more understandable in spite of our inability to imagine a curved space. One way is imagining a surface in the form of an elastic cloth mounted horizontally. Putting a mass there, say a heavy ball, will make the elastic cloth curve. Sending another ball across the cloth, its motion will be influenced by the curvature of the cloth, especially in the vicinity of the heavy ball; see Figure 6-1. The influence of the curved cloth on the motion of the second ball may be looked upon as a two-dimensional analogy for the case of the curved space.

The other way of trying to understand the thing is to imagine a small flat animal living on a flat map of the Earth, say a map in the Mercator projection. To this animal the world is a linear surface. To us humans

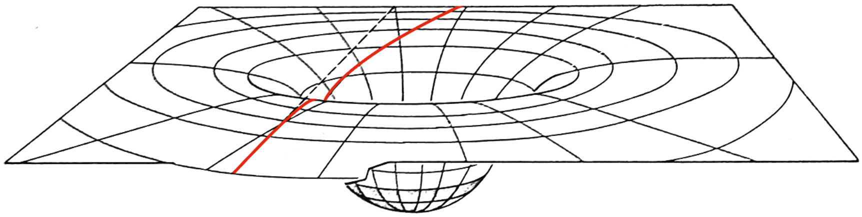


Figure 6-1. A surface analogue to Einstein's curved space. A mass on an elastic cloth will curve the surface in a similar way as a mass in Einstein's universe will curve the space, thereby influencing the path of a moving body.

the Earth is a curved surface. Now, between two places on either side of the North Atlantic a ship (or an aeroplane) is travelling along the shortest path on the Earth, i.e. along a great circle, with constant speed. The animal would observe, in its flat map projection, that the object is moving along a curved path with changing speed; see Figure 6-2. From this observation, the map animal would draw the conclusion that the object is influenced by a force of some kind, constantly making the object change its direction as well as its speed. As humans, we realize that the object is not affected by any force at all in this respect – it just moves straight ahead along a great circle on the curved surface of the Earth with constant speed. Our inability as humans to imagine a curved space is similar to the inability of the map animal to imagine a curved surface. That is why we have to introduce a force if we apply the concept of a linear space, but why we do not need a force any longer if we adopt the concept of a curved space.

Thus, gravitation is a fictitious force introduced by Newton since he considered space to be linear, while gravitation as a force is unnecessary according to Einstein since he accepted space to be curved. Einstein, so to speak, turned gravitation from the physics of moving bodies into geometry of space.

We noted in Chapter 1 that Newton could explain or predict several phenomena with his gravitational theory, even though his concept of action at a distance was questioned. Einstein could also explain or predict certain phenomena. One of these had been an unsolved problem for a long time: the motion of the planet Mercury. Its orbit around the Sun is

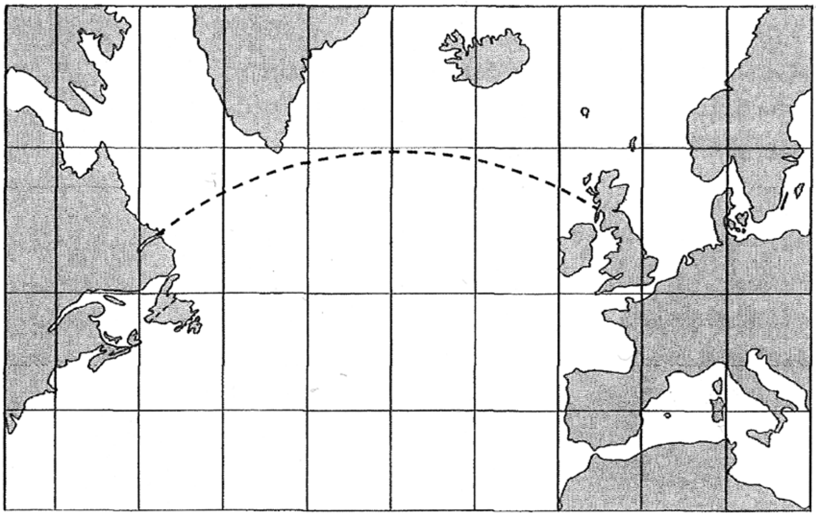


Figure 6-2. A projection analogue to Einstein's curved space. A linear (flat) map projection of the Earth will distort the curved Earth in a similar way as our perception of a linear (flat) space will distort the curved space. A ship's route along the shortest path across the North Atlantic will be a curved route in the map projection, and in a similar way the shortest path in Einstein's space will be a curved path in our "ordinary" space. Gravitation is the force we need to introduce to explain such curved paths if we do not treat space itself as curved.

not stable, due to perturbations from other planets. The point closest to the Sun (perihelion) gradually moves so that the orbit slowly rotates in the orbital plane. The influence of the other planets on the orbit could be calculated according to Newton's theory, but the result did not agree with the observations. In contrast, Einstein could now suddenly explain the observations, as a curvature of space caused by the Sun. Einstein (1916) thus concludes his new theory of gravitation by a successful numerical application:

"Calculation gives for the planet Mercury a rotation of the orbit of 43" per century, corresponding exactly to astronomical observation; for the astronomers have discovered in the motion of the perihelion of this planet, after allowing for disturbances by other planets, an inexplicable remainder of this magnitude."

The fact that Einstein had been able to use his strange theory to explain an unsolved problem made a strong impression. Nevertheless, this was only one piece of evidence. More was needed, and more would come. A second prediction by Einstein was that a light ray passing close to the mass of the Sun would be deflected by a certain amount. According to Newton, however, light, having no mass, could not be attracted by the Sun. In 1919 a total solar eclipse showed that stars observed close to the Sun were displaced by the amount predicted by Einstein. This was a great success for his theory.

As a consequence of this second successful test of his theory, the Royal Swedish Academy of Sciences received several letters nominating Einstein for a Nobel prize in physics. One of the early nominators was, as mentioned, his "gravitational colleague" Nordström. The main argument from the nominators was the new theory of gravitation. This turned out to be a problem. Einstein's concept of a curved space appeared mysterious. This seemed to be philosophy rather than physics. The Nobel committee evaluating the various nominees for the prize in physics were dominated by experimentalists with limited understanding of strange theories. Hence, there was considerable scepticism within the committee and, thereby, an opinion against awarding Einstein the prize for his gravitational theory. On the other hand, there was also a considerable opinion from outside to award him the prize for this. The solution became an act of balancing different views: He was awarded the prize, but not for his gravitational theory! Instead, an early achievement related to quantum physics (the so-called photoelectric effect) was put forward as the reason for the prize.

It is interesting to note that this dilemma was actually documented in the official motivation of the prize by the Swedish Academy of Sciences. There it says "regardless of the value that, after any confirmation, could be attributed to the theories of relativity and gravity" Einstein was awarded the 1921 prize "for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect."

The controversy over Einstein's Nobel prize would return in 1923. A Nobel laureate will receive the diploma and the medal whether he or she can attend the solemn Nobel ceremony or not. To receive the money, however, the laureate has to give a Nobel lecture on the subject for which

Figure 6-3. Einstein giving his Nobel lecture before a large audience, with the King of Sweden in the first row. This Nobel lecture was contrary to the rules – it was about his theory of gravitation, which was not the subject for which he got the prize.

he or she has been awarded the prize. When Einstein gave his Nobel lecture, in front of the King of Sweden and large number of people – see Figure 6-3 – it was not on the theory for which he got his prize. It was on the theory for which he, as especially stated in the motivation, did not get the prize! Thus, he talked about relativity and gravitation. This fact was controversial; it caused complaints within the Academy, but also from abroad. (More about the Nobel prize problems may be found in Grandin (2021).)

Looking back, we may notice a similarity between Newton and Einstein: Newton's attractive force between bodies without contact was initially considered mysterious. Now Einstein's curved space appeared equally mysterious. This caused difficulties in awarding Einstein the Nobel prize. Had the Nobel prize existed 200 years earlier there probably would have been similar difficulties in awarding Newton the prize. A summarizing comparison between the gravitational theories of Newton and Einstein is given in Table 6-1. What, in the end, made their strange theories successful was their ability to explain observations on the Earth and in the Universe.

It is easy to think of the differences between Einstein's and Newton's theories of gravitation as something of importance only close to heavy masses in the Universe and not for people on the Earth. A relevant counter-example to this is satellite navigation with GPS (GNSS). These satellites orbit the Earth at a distance of three Earth radii. According to Einstein's theory, as mentioned earlier, not only three-dimensional space but also four-dimensional space-time is curved. This means that also time is affected: Time runs slower close to masses. In the case of the navigational satellites, where exact timing of radio signals plays a fundamental role, time runs slightly faster at three Earth radii than at the surface of the Earth. This has to be taken into account, otherwise the navigational system would go astray!

Table 6-1. Comparison between Newton's and Einstein's theories of gravitation.

Newton	Einstein
Attractive force	No force
Linear space	Curved space
Curved orbits	"Straight" orbits
Problems with acceptance	Problems with Nobel prize

Appendix A: Gravity determinations at the Uppsala Observatory during three centuries

From Chapter 2 we know that Celsius (1744) made a very early determination of gravity at the Uppsala Observatory. Since then, some renewed gravity determinations have been made following the development of improved observation methods. The results are collected here, in Table A-1. They form an illustrative example of the steadily increasing accuracy in gravity determination. The last value is correct to within some units in the last digit; accordingly, it may serve as a reference when considering the older values.

The first value is from 1744. It was determined with a pendulum especially constructed for the purpose and yielded an absolute value for Uppsala.

The 1898 value is a combination of the then absolute value of Vienna transferred to Potsdam (close to Berlin) and a relative determination between Potsdam and Uppsala. The absolute value was observed with a reversible pendulum and the relative one with a portable pendulum apparatus.

The 1946 value is a combination of the then absolute value of Potsdam and a relative determination between Potsdam and Uppsala. The absolute value was observed with a reversible pendulum and the relative one mainly with a spring gravimeter.

The 1967 value is a combination of a corrected absolute value of Potsdam and a relative determination between Potsdam and Uppsala. The corrected absolute value was based mainly on observations with a fall apparatus in Teddington (London) and then transferred to Potsdam, and the relative one on observations with spring gravimeters.

The last value from 2017 is a combination of an absolute determination at Mårtsbo geodetic observatory outside Gävle north of Uppsala and a relative determination between that location and Uppsala. The absolute determination was made with a transportable fall apparatus and the relative one with spring gravimeters. This value is of such an accuracy that the handling of the permanent tide as well as the postglacial rebound

Table A-1. Gravity determinations at the Uppsala Observatory in m/s^2 during three centuries.

Observer	Year	Gravity
Celsius	1744	9.81 54
Rosén	1898	9.81 924
Wideland	1946	9.81 899 4
Pettersson	1967	9.81 885 85
Ekman & Olsson	2017	9.81 883 801

has to be specified. In the former case zero tide gravity is used, in the latter case gravity is reduced to the year 2000 (Chapter 4).

The gravity values refer to the uppermost step at the main entrance of the observatory building in the so-called observatory park. The original value of Celsius was observed in his older observatory in the city centre but, due to its limited accuracy, it is equally valid for the observatory building in the park. (More about the gravity determinations at the Uppsala Observatory may be found in Ekman & Olsson (2017).)

Appendix B: Gravity and the size of large animals

In the far north, in the Arctic Sea and around Svalbard, the blue whale likes to spend its summers. The blue whale reaches a length of 30 m and a weight of 150 tons. It is the largest animal in the world, and also the largest that has ever existed.

The world's largest animal on land is the African elephant. It reaches a length and a height of 5 m and a weight of 5 tons. It is not quite as large as the largest dinosaur, but they are of a somewhat similar construction.

Neither the elephant nor the extinct dinosaur can compete with the blue whale. The blue whale is 6 times longer than an elephant and weighs 30 times as much as an elephant. It is also considerably larger than a large dinosaur. How come?

The answer is: gravity. To be able to stand upright an animal needs bones and a skeleton to counteract the effect of gravity. This effect is proportional to the mass of the animal and, therefore, approximately to its volume. The ability to keep the animal upright, on the other hand, is proportional to the area of the cross-section of the bones. The former effect is proportional to the length scale raised to the third power, while the latter is proportional to the length scale raised to the second power. Hence, the larger the animal is the more of the animal has to be made up of bone.

This leads to an upper limit of the size of land-living animals, otherwise too much of the animal would have to consist of bone. This maximum size seems to be roughly that of an elephant or a large dinosaur. But what then about the enormous size of the blue whale? Well, the whale lives and floats in the sea water – thus it does not have to bother too much about gravity!

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This is a book about the Earth's gravity, about what it is, how it has been determined, and why it has been useful to know it. The book has a historical perspective, spanning three centuries, and a northern perspective, dealing mainly with the Nordic area.

The historical perspective of three centuries is quite natural, since it all started with the ideas of Newton a little more than 300 years ago. The Nordic perspective has several reasons: First, early gravity measurements with pendulums were made as far north as possible to try to verify Newton's prediction of a flattening of the Earth at its poles, and to determine the value of the flattening. Second, Nordic scientists later invented spring gravimeters facilitating gravity measurements to search for minerals, and started studying inner parts of the Earth. Third, gravity measurements at sea and on the ice cover of the sea were performed early in the Arctic and the Baltic Seas. Fourth, the postglacial rebound of the Nordic area has been investigated by repeated gravity measurements, lately also involving fall instruments. Fifth, the recently started melting of the Greenland ice sheet due to the ongoing climate warming has been revealed by repeated gravity measurements, in this case using satellites. Finally, the outlook at the end of the book, dealing with Einstein's view on the subject, also has a Nordic flavour, involving interesting problems with his Nobel prize.

This book is intended not only for gravity people, but for a wider audience with an interest in the constitution and the changes of the Earth, or with an interest in the historical development in Earth sciences.

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