Small Publications in Historical Geophysics

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A Partial Reanalysis of the French Arc Measurement at the Arctic Circle to Prove Newton's Theories

Martin Ekman & Jonas Ågren

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Åland Islands

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1. Was Newton right or wrong?

In the 1730s an international scientific controversy with wide implications arose concerning the shape of the Earth. In England Newton had, based on his theories of gravitational and centrifugal forces, arrived at the conclusion that the Earth must be a body somewhat flattened at the poles. In France Cassini at the Paris observatory had, based on his geodetic measurements across the country, arrived at the conclusion that the Earth must be a body somewhat flattened at the equator, thus contradicting Newton's theories. The shape of the Earth seemed to be a key to accepting or rejecting the theories of Newton. In order to solve the problem the French Academy of Sciences decided to organize two scientific expeditions, one to the south, close to the equator, and one to the north, as far north as possible.

By the time the matter was being discussed in France, Celsius happened to arrive there from Sweden; he was making a study tour to European universities and observatories. Following a proposal from Celsius, the French Academy of Sciences decided to send the northern expedition to northern Sweden (now Sweden and Finland), more specifically to the area of Torneå (Tornio) at the end of the Gulf of Bothnia, close to the Arctic Circle. Celsius became a member of the expedition, which was headed by Maupertuis.

The main task for Maupertuis' expedition was to perform a meridian arc measurement, i.e. to determine the distance as well as the latitude difference between the end points of a meridian arc. A comparison of such a result in the north with a corresponding result from an arc in the south, in France or at the equator, would give information on the flattening of the Earth. For an Earth flattened at the poles a meridian arc of a certain latitude difference, say 1°, will be longer, in metres, closer to the pole, because of the smaller curvature there, and shorter closer to the equator, because of the larger curvature there. For an Earth flattened at the equator the relation will be the opposite.

The main result, based on the meridian arcs at the Arctic Circle and in France, was published by Maupertuis et al (1738): The Earth was flattened at the poles, in accordance with Newton. This conclusion was later confirmed by the gravity measurements also made by the expedition, analyzed by Clairaut (1743). But Maupertuis' result was questioned for several reasons; see e.g. Widmalm (1990). Perhaps the greatest problem with Maupertuis' result was the following.

In finding the shape of the Earth from gravitation and centrifugal force Newton had assumed that the Earth behaved as a rotating fluid. This was uncertain at that time, but today we know that it does. Newton also assumed that the Earth was homogeneous, having a constant density throughout. This could definitely be questioned, and today we know that the density increases towards the centre. When Newton claimed that the Earth was flattened at the poles he also gave a numerical value of the flattening based on his fluid and homogeneous Earth: $f = 1/230$. This was the value that Maupertuis' expedition expected to find. If the Earth is denser towards its centre the flattening becomes smaller; today we know that the flattening is 1/298. In the extreme case of all mass concentrated to the Earth's centre the flattening would be 1/576. Thus Newton's value may be considered as a theoretical maximum, as shown by Clairaut (1743). The value obtained by Maupertuis from the meridian arcs in Sweden and France was 1/178; see also Celsius (1741). It was larger than Newton's. Something was not quite correct. (In fact, this would indicate an Earth denser towards its surface; in the extreme case of all mass concentrated to the Earth's surface the flattening would be 1/115.)

We will here make an analysis of the French arc measurement at the Arctic Circle, dealing with the latitude difference and the distance. In particular we will investigate the deflections of the vertical, an error source that was unkown at that time. We will also compare our findings with earlier error studies.

2. The arc measurement and its result

The arc measurement at the Arctic Circle was carried out during the years 1736 – 1737. The southern end point of the meridian arc was Torneå church, on the coast of the Gulf of Bothnia, and the northern end point was the mountain Kittisvaara, almost 1° (100 km) to the north. Near both end points there are now memorials (see Tobé, 1986).

The latitude difference between these end points was found by determining the latitudes of the end points through star observations. What was observed was basically the altitude or height angle of the star above the horizon. In reality, however, the latitude difference was determined through a somewhat more special procedure.

The distance between the end points was found using triangulation. First, a comparatively short distance, a baseline, was measured with rods on the ice of the Torne river. Next, horizontal angles were measured in a network of triangles, the sides of the triangles being sight lines between stations on hills and mountains along the Torne river, all the way from the southern end point to the northern one. Included in this network were the end points of the baseline. Finally, using (spherical) trigonometry, the distance between the southern and the northern end points of the meridian arc could be computed from the length of the baseline and the angles in the triangulation network.

Knowing now the distance as well as the latitude difference of the meridian arc, its curvature could be computed. Comparing this result of the Arctic expedition with a corresponding result in France (and later on with the result from the equatorial expedition), Maupertuis et al (1738) found that the meridional curvature of the Earth is smaller closer to the pole and larger closer to the equator. From this they concluded that the Earth is flattened at the poles; in the words of Maupertuis et al (1738):

"We shall then take for the true amplitude of the arc of the meridian between the parallels of Kittis and Torneå 57′28.67″. … And this amplitude, compared with the length of the arc, which is 55 023.47 toises [107 241 m], gives for the length of the degree of the meridian which cuts the Polar Circle 57 437.9 toises [111 946 m]. … The degree of the meridian which cuts the Polar Circle being longer than a degree of the meridian in France, the Earth is a spheroid flattened towards the poles."

As mentioned in Section 1 this result was questioned. This caused an interest in trying to check it by remeasurements. The first partial check of Maupertuis' result was made by Svanberg (1805), performing a renewed arc measurement in the area. This new arc measurement was longer; hence its astronomical end points did not coincide with the original ones. Thus the latitude difference was not checked. However, the distance could be checked, since the original end points were included as triangulation stations also in the new triangulation network. This yielded an error in the distance of only about 50 m, indicating that a larger error might be expected in the latitude difference.

Later Struve (1857 & 1860) made a very long arc measurement through Europe. It included some of Svanberg's triangulation stations. This allowed checking the length scale of Svanberg's triangulation, showing that his distance error estimate had to be reduced somewhat. The distance between Maupertuis' end points was now found to have an error of 45 m, corresponding to 1.43″, as shown by Leinberg (1928).

There was still a need to repeat the astronomical latitude determinations of the end points, to check the latitude difference. This was performed by Leinberg (1928). He made new star observations at Maupertuis' end points. These yielded an error in the latitude difference of 8.83″. (Of this 0.96″ could be ascribed to Maupertuis ignoring the refraction; accordingly the error in the astronomical observations themselves amounted to 7.87″.)

In addition to the above errors there is an error source that was unknown at the time of the French expedition: the deflections of the vertical. This will be explained in more detail in the next section. Leinberg (1928) made an estimate of this error by comparing his astronomical latitude difference with the geodetic latitude difference he obtained on Hayford's ellipsoid from the distance according to Struve's triangulation. He found an error of this kind of 2.42".

Today it is possible to make a partial reanalysis of Maupertuis' arc measurement with new methods; this is what we will do here. We first will make a determination of the deflections of the vertical through gravimetric methods, thereby referring to the global and geocentric ellipsoid GRS 1980. Combining deflections and astronomical latitudes we then can find the latitudes referring to this ellipsoid. From that, finally, we also may find the distance on the same ellipsoid. We now first turn to the deflections of the vertical, thereby adopting the same method as in Ekman & Ågren (2010, 2012), from where much of the following section is taken.

3. The deflections of the vertical

Determining a latitude by astronomical positioning means measuring vertical angles towards a star. When putting up the instrument for measuring angles it is adjusted with a spirit level. The spirit level "feels" the direction of the plumb line, or the vertical. The vertical, being the normal to the geoid, deviates from the normal to the ellipsoid. This deviation, known as the deflection of the vertical, directly affects the astronomically determined latitude.

Determining a latitude by modern satellite positioning means measuring distances through timekeeping of radio waves emitted from the satellites. This procedure is independent of any spirit level and, hence, does not depend on the direction of the vertical. Thus the latitude so determined is unaffected by the deflection of the vertical. (The same arguments go for longitudes.)

Denoting the star-derived or astronomical latitude by Φ, and a satellite-derived or geodetic latitude by φ, we may write

$$\Phi = \varphi + \xi \qquad (1)$$

Here ξ is the deflection of the vertical in the south-north direction; Φ may be said to refer to the geoid and φ to the ellipsoid.

Now, the deflection of the vertical at a certain point is nothing but the inclination of the geoid relative to the ellipsoid at that point. Thus the deflection of the vertical ξ can be computed as the derivative of the geoid height N in the south-north direction,

$$\xi = -\frac{\partial N}{R\ \partial\varphi} \qquad (2)$$

R being the mean radius of the Earth.

The geoid and, thereby, the deflections of the vertical are due to the irregular mass distribution within the Earth. Hence the geoid can be computed from a detailed and global knowledge of the Earth's gravity field. Such a knowledge has only been achieved during the last decades. Modern geoid computations are based on a combination of satellite orbit perturbations, surface gravity anomalies, and digital terrain models. The most recent global geoid model is EGM 2008 of Pavlis et al (2008). This is given as a spherical harmonic series expansion up to degree and order 2160, corresponding to a minimum resolution (half wave-length) of 0.08°. We also have the recent geoid model SWEN08_RH2000 over Sweden and some adjacent areas by Ågren (2009), based on KTH08 by Ågren et al (2009). This is computed as a grid with density 0.02°. Over land areas this regional model can be considered slightly more accurate than the global one; it is illustrated as a geoid height map in Figure 1.

According to these geoid models we obtain the following deflections of the vertical in the south-north direction at Torneå and Kittisvaara, relative to the global and geocentric ellipsoid GRS 1980:

	Regional model	Global model
Torneå	ξ = - 3.2″	ξ = - 3.4″
Kittisvaara	ξ = - 5.6″	ξ = - 5.7″

The models differ by up to 0.2″; this is within the estimated uncertainty of 0.2″ of the deflections. We will use the regional model which, according to our judgement, in this case is slightly better.

From the values above we obtain a difference in deflections of the vertical between Torneå and Kittisvaara of

$\Delta\xi$ = 2.4″

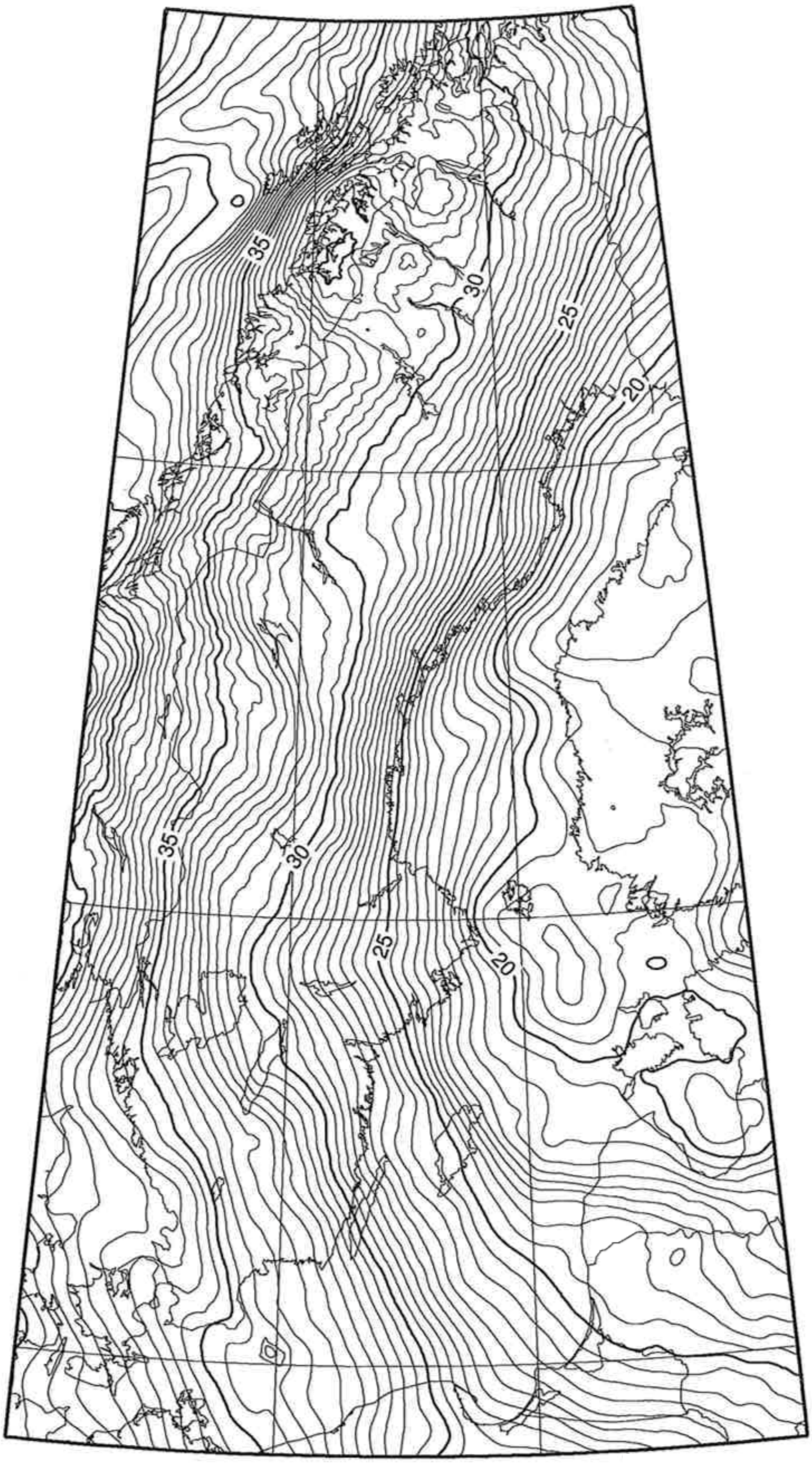

Figure 1. Map of geoid heights (m) over Sweden and adjacent areas (Ågren, 2009).

This is identical with the difference found by Leinberg (1928) in a completely different way. His difference, however, was related to a deviating and non-geocentric ellipsoid (Hayford's). There is also a kind of ambiguity in his value. These things will be discussed at the end of Section 5. The deflections themselves were not possible to determine for Leinberg at that time.

4. The latitudes

As mentioned in Section 2, Leinberg (1928) made careful redeterminations of the astronomical latitudes. His results were

Torneå $\Phi = 65°50'51.78''$
Kittisvaara $\Phi = 66°48'29.28''$

with a standard deviation of 0.1″. These coordinates refer to the locations of Maupertuis' temporary astronomical observatories; we will comment further on that below.

Rearranging (1) we can now find the geodetic latitudes, i.e. the latitudes on the ellipsoid GRS 1980. This is achieved by subtracting the gravimetric deflections of the vertical calculated in Section 3 from the astronomical latitudes above,

$$\varphi = \Phi - \xi \tag{3}$$

We obtain

Torneå $\varphi = 65°50'55.0''$
Kittisvaara $\varphi = 66°48'34.9''$

From these values we obtain a geodetic latitude difference between Torneå and Kittisvaara of

$$\Delta\varphi = 57'39.9''$$

This is identical with the difference found by Leinberg (1928), in a completely different way. That is not surprising, since our difference in deflections according to Section 3 happens to be identical to Leinberg's, and the astronomical latitudes used here are his own. His geodetic latitude difference, however, was related to a deviating and non-geocentric ellipsoid (Hayford's). Moreover, there is also in this case an ambiguity in his value. As above, these things will be discussed at the end of Section 5.

What we have obtained here are also the absolute latitudes on the ellipsoid. These quantities were outside the reach of Leinberg at that time. This gives us some further possibilities.

In the case of Torneå our latitude can be compared with the latitude in a modern satellite-based reference system closely related to the global systems ITRF 89 and WGS 84, the European system known as ETRS 89 (or rather its Finnish and Swedish versions EUREF-FIN and SWEREF 99; see Ollikainen et al (1999) and Jivall & Lidberg (2000)). For our purposes all the mentioned systems can be considered more or less identical. In this system we have φ = 65°50′55.2″, as calculated from Finnish as well as Swedish positioning data. The agreement is very good; it is within the estimated uncertainty of 0.2″ of the deflections of the vertical.

It should be pointed out here that the astronomical station of Maupertuis in Torneå was not identical with his triangulation station. The triangulation station was the tower of Torneå church (Figure 2), while the astronomical station was a temporary observatory building, situated 143.7 m = 4.64″ to the south of the church tower; see Maupertuis et al (1738) and Leinberg (1928). The church tower is still there, while there are no longer any traces of the observatory. The observatory latitude in ETRS 89 above has been calculated starting from the church tower, for which "modern" coordinates are available.

In the case of Kittisvaara our latitude cannot be accurately compared with a latitude in ETRS 89. Also here the astronomical station was not identical with the triangulation station. Both were situated on the top of the Kittisvaara mountain (Figure 3); the triangulation station was a small temporary observatory building there, while the astronomical station was a larger temporary observatory, situated 7.3 m = 0.24″ to the north of the small one; see Maupertuis et al (1738) and Leinberg (1928). Today there are no longer any traces of these observatories, and the rather flat top is fairly undefined within a few tenths of meters, or more than half a second. Our latitude in any case agrees with this top.

When Leinberg made his astronomical latitude determinations in 1928 he could indentify Maupertuis' observatories by two piles of stones, separated by an adequate distance. These piles also contained what was probably remnants of foundations of the observatories. According to people he met, the piles had been erected by two Swedish-speaking men some 40 years ago, i.e. around 1888. This seems reasonable, because just in that year there was a Swedish-Finnish (Swedish-Russian) border commission working in the area, containing Swedish geodesists. Moreover, according to a very old man he met, there had been foundations of two buildings there in his youth nearly 80 years

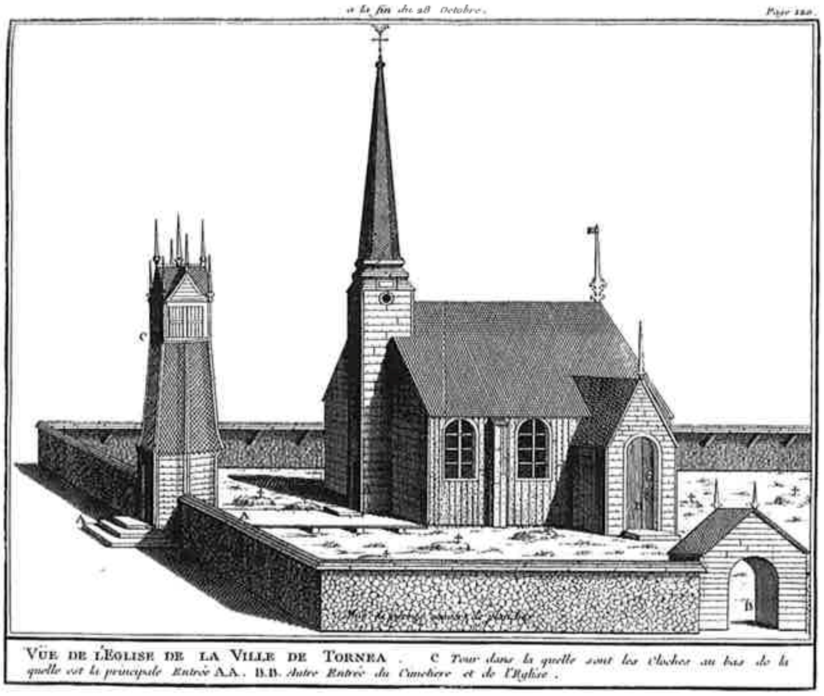

Figure 2. Torneå church, the southern end point of the arc measurement; the astronomical station was situated just to the south of this church (Outhier, 1744).

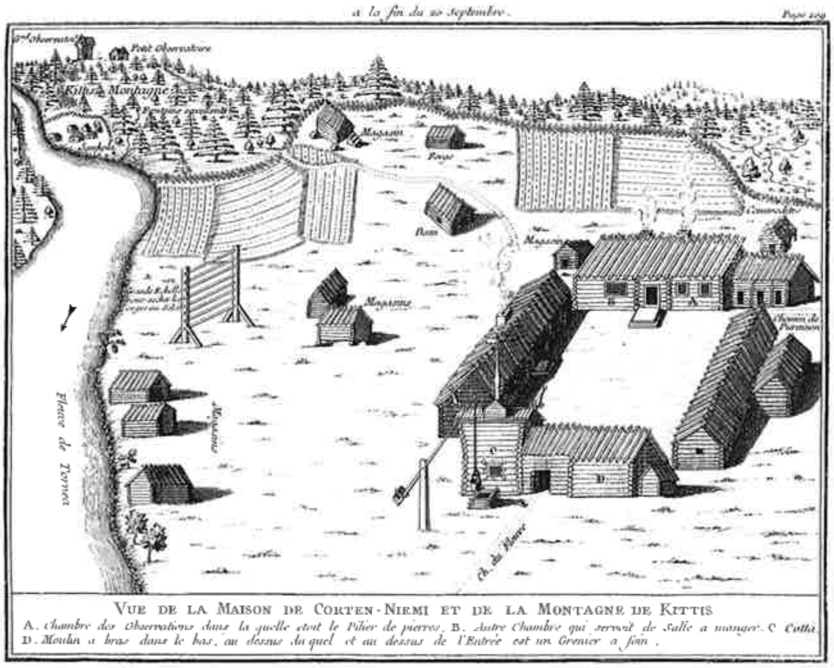

Figure 3. Kittisvaara, the northern end point of the arc measurement (upper left corner); the astronomical station was the larger of the two observatory buildings there (Outhier, 1744).

ago, i.e. about 1850. This also seems reasonable, because Svanberg (1805) in his arc measurement obviously could identify Maupertuis' stations without problems. As mentioned, however, there are no longer any traces left, neither of the foundations themselves nor of the piles of stones. And most unfortunately, neither does Leinberg seem to have made any permanent mark showing his astronomical observation point. Thereby we seem to have lost the possibility of accurately identifying Maupertuis' stations on Kittisvaara. What we might do instead is the opposite: Maupertuis' astronomical station on the top of Kittisvaara might be located through our geodetic latitude calculated above.

Finally, what about the latitude difference between Torneå and Kittisvaara found by Maupertuis and his colleagues? At the time of Maupertuis, deflections of the vertical were unknown phenomena. Thus he simply took it for granted that his astronomically determined latitude difference was identical to the geodetic latitude difference on the ellipsoid. The latitude difference found by Maupertuis et al (1738) was 57'28.7". This is too small by 11.2", of which 2.4" is due to the deflections of the vertical. Our results here agree with those of Leinberg (1928); note, however, the ambiguity discussion of Leinberg's values later on. The error in Maupertuis' latitude difference is of the same order as in other accurate latitude determinations of that time, although somewhat increased by the deflections of the vertical; see Ekman (2011).

To present an overview, all values of latitudes and deflections of the vertical given above are collected in Table 1.

5. The distance

Based on the geodetic latitudes obtained in Section 4 we can now compute the distance on the GRS 1980 ellipsoid between the astronomical stations at Torneå and Kittisvaara. The distance is given by

$$\Delta s = \int_{T}^{K} M(\varphi)\, d\varphi \qquad (4)$$

where M is the meridional radius of curvature and φ as earlier the geodetic latitude. The radius of curvature is a function of latitude according to

$$M = \frac{a(1-e^2)}{(1-e^2 \sin^2 \varphi)^{3/2}} \qquad (5)$$

Table 1. Astronomical latitudes (Φ), deflections of the vertical (ξ), geodetic latitudes (φ), and distances (Δs) for Torneå/Kittisvaara: a comparison between our results (referring to the GRS 1980 ellipsoid), Leinberg (1928) and Maupertuis (1738). Stars denote independent values, obtained by measurements (or, in our case, by computations from independent measurements), the other values are calculated from the starred ones.

Station	Our results	Leinberg (1928)	Maupertuis (1738)
Torneå		Φ = 65°50′51.8″ *	
Kittisvaara		Φ = 66°48′29.3″ *	
Difference, Φ		$\Delta\Phi$ = 57′37.5″	$\Delta\Phi$ = 57′28.7″ *
Torneå	ξ = - 3.2″ *		
Kittisvaara	ξ = - 5.6″ *		
Difference, ξ	$\Delta\xi$ = 2.4″	$\Delta\xi$ = 2.4″/2.9″	
Torneå	φ = 65°50′55.0″		
Kittisvaara	φ = 66°48′34.9″		
Difference, φ	$\Delta\varphi$ = 57′39.9″	$\Delta\varphi$ = 57′39.9″/40.4″	$\Delta\varphi$ = 57′28.7″ (*)
Difference, s	Δs = 107 176 m	Δs = 107 196 m *	Δs = 107 241 m *

where a is the semi-major axis and e the eccentricity of the ellipsoid. This integral does not have a closed solution, but can be solved either through a series expansion of the integrand or by a numerical method.

Using both ways to solve the integral we obtain a distance between Torneå and Kittisvaara of

$$\Delta s = 107\,176 \text{ m}$$

This distance differs by 20 m = 0.7″ from the distance found by Leinberg (1928), 107 196 m, in a completely different way. The discrepancy is in reasonable accordance with the uncertainty in the triangulations of the 1800s used by him (cf. Ekman, 2011).

The distance found by Maupertuis et al (1738) was 55 023 ½ French toises = 107 241 m (where we have used 1 toise = 1.9490 m). This is too large by 65 m = 2.1″ according to our result (while Leinberg found it to be too large by 45 m = 1.4″). We may note that the error in Maupertuis' triangulated distance is of the same order as in the triangulation of the Åland Islands, performed only a decade later and with one of the angle instruments from the arc measurement; see Ekman (2009, 2011).

All the distances given here are also included in the overview shown in Table 1.

We now come to a certain ambiguity in Leinberg's (1928) values. Leinberg, although quite detailed in some respects, does not really state his distance. He only says that it is 45 m shorter than that of Maupertuis et al (1738). Thus we have calculated it that way; this is the value 107 196 m given in Table 1. Then Leinberg goes on by saying that his distance corresponds to a geodetic latitude difference on Hayford's ellipsoid of 57′39.9″; this value is also given in Table 1. However, making this calculation on the said ellipsoid ourselves we obtain 57′40.4″, which is 0.5″ larger. As Leinberg is so brief on this matter, it is not possible to judge whether there is some misunderstanding concerning the distance or whether there is some error in his calculation of the latitude difference. In the latter case also his difference in deflections of the vertical will be influenced by the same amount; it should then be 2.9″. These possible alternative values have also been included in Table 1.

Finally we should mention that if Leinberg had had exactly the same distance as ours he would still have obtained from that a geodetic latitude difference 0.2″ smaller than ours, because of using Hayford's ellipsoid instead of the optimal GRS 1980 available to us. The same thing then holds for the deflection difference.

6. Conclusions

In this partial reanalysis of the French arc measurement at the Arctic Circle by Maupertuis et al (1738) we have determined the gravimetric deflections of the vertical at the two end points. Using the astronomical latitudes of Leinberg (1928) we have then determined the geodetic latitudes of the end points. From these we have also calculated the distance between the end points. All these results refer to the global and geocentric ellipsoid GRS 1980 and are shown in Table 1.

Comparing these results with those of Maupertuis et al (1738) we find that their latitude difference is 11.2″ too small, of which 2.4″ is due to the deflections of the vertical, and that their distance is 65 m too long, corresponding to 2.1″. These error figures agree with those of Leinberg (1928), obtained in a different way, except that his figure for the distance error is 20 m or 0.7″ smaller than ours. However, there is also a certain ambiguity in Leinberg's values, where his differences in geodetic latitude and deflection of the vertical might be 0.5″ larger than stated by himself.

The purpose of the French arc measurement at the Arctic Circle was to prove Newton's theories by showing that the Earth was flattened at the poles. Because of the errors, all going in the same direction, the flattening became too large, even somewhat larger than theoretically allowed. In that situation the support of the gravity measurements made by the expedition was useful. This is not too surprising. On the whole, as shown by Ekman & Mäkinen (1998), the arc measurements in the middle of the 1700s yield more uncertain values of the flattening than the gravity measurements.

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Addresses of the authors

Jonas Ågren, Geodetic Research Division, National Land Survey, SE – 801 82 Gävle, Sweden, and Royal Institute of Technology (KTH), SE – 100 44 Stockholm, Sweden; jonas.agren@lm.se

Martin Ekman, Summer Institute for Historical Geophysics, Äppelträdgården E, Haraldsby, AX – 22 410 Godby, Åland; martin.ekman@ha.ax

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