The “Weigh the World” Challenge 2005

Introduction

A group of Scottish organisations are to mark their response to the G8 summit this year by making a scientific measurement of literally global significance this June 21st.

The “Weigh the World” Challenge is an initiative for raising the public profile of science, in particular physics and astronomy, by determining the mass of the Earth using the mountain Schiehallion in Perthshire. The motivation for this is the thought provoking comparisons that can be drawn between the event and the G8 summit scheduled to take place at Gleneagles nearby in July. The participating organisations are Counting Thoughts, the Glasgow Science Centre, and DJB Microtech, supported by the John Muir Trust, which owns the relevant part of Schiehallion, and the current Astronomer Royal for Scotland, Professor John Brown.

The mass of the Earth was first determined in 1774 by Nevil Maskelyne. He used Schiehallion as a counterweight to the Earth in the set-up of a series of astronomical observations. Having estimated the mass of the mountain, he was then able to determine the mass of the Earth from his observations. The method being employed for the “Weigh the World” Challenge is inspired by this original technique.

This document does not provide a complete technical specification of the proposed project. This can be obtained from Counting Thoughts at the address below.

The organisations involved

Counting Thoughts is a scientific consultancy that develops software for teaching and research. Their products include **SURE***HigherPhysics*, which brings physics alive with interactive simulations, questions, equations, text and graphs.

The Glasgow Science Centre is concerned with the resurrection of Scotland’s proud spirit of innovation and creativity through the establishment of a scientifically aware and technologically capable society as the foundation for renewed and sustainable social, economic and cultural prosperity.

DJB Microtech produce cost effective equipment for the teaching of school Physics, Chemistry and Biology. Their equipment is easy to use and is intended to promote a hands-on approach to learning.

The John Muir Trust was formed in 1983 to protect and conserve wild places and to increase awareness and understanding of the value of such places. The Trust works closely with local communities. It believes that sustainable conservation can only be achieved by recognising special qualities of wild places and understanding the human factors and other aspects which contribute to the landscape we think of - and value - as wild.

The original measurement

In one sense it is straightforward to weigh the Earth. If one determines the acceleration due to gravity by for example measuring the period of a pendulum of a given length, one can derive the mass of the Earth from the Universal Law of Gravitation. However, this requires knowledge of the value of the Universal Constant of Gravitation (conventionally denoted by “G” and not to be confused with “g”, as will be seen later), and this was not known until 1798 when it was measured by Cavendish. Only comparative methods not involving “G” were possible at the time of the original measurement.

One method that had been suggested by Sir Isaac Newton was to measure the extent to which a plumb line is deflected by the gravitational influence of a mountain. The direction of the plumb line depends upon the gravitational pull of the Earth and the much slighter gravitational pull of the mountain were it set up beside one. It would hang in slightly different ways on the north and south side of the mountain since the mountain would pull the plumb bob towards it in a different direction on each side. This difference could be measured by observing the locations of stars relative to the zenith as determined by the plumb line. The same stars would apparently be in slightly different positions in the sky when observed in this way on either side of the mountain. If the mass of the mountain was known its gravitational pull on the plumb bob could be accounted for in subsequent calculations, and the mass of the Earth could then be worked out from the difference in star positions.

Newton dismissed his own idea, as he did not have sufficiently accurate instruments available to him at the time to measure the slight deflection of the plumb line, which he estimated to be about a minute of arc (60 minutes of arc = 1 degree). However, improvements in telescope technology made the method viable. The first significant attempt to perform the measurement was made next to the mountain Chimborazo in what is now Ecuador (but was then Peru) by the French astronomer Bouguer in 1749. It failed due to inadequate instrumentation and poor preparation for working in the harsh conditions on the snow line 15,000 feet up in the Andes. Bouguer measured a deflection of a plumb line of 8 seconds of arc due to Chimborazo, to which he felt he could not attribute any quantitative significance due to the experiment’s shortcomings (60 seconds of arc = 1 minute of arc).

The successful attempt at Schiehallion was funded by the Royal Society using money available to them as a result of underspend on another project. This other project was the observation of the transit of Venus – the project that had involved Captain James Cook’s famous voyage to Tahiti in 1769, where one of the associated measurements was made. This resulted in the first determination of the distance from the Earth to the Sun and hence from Kepler’s laws the size of the orbits of the other planets in the Solar System. The Astronomer Royal, the Reverend Nevil David Maskelyne, had improved and developed the instruments for this project after his own failed attempt to measure the transit of Venus in 1761 in St. Helena, and he was to use the same apparatus and instrumentation developed in association with this project again at Schiehallion.

The motivation behind the original experiment was to test Newton’s Universal Theory of Gravitation, and in addition to demonstrate that the Earth was not hollow, as well as simply to weigh it. If the Earth were found to be as dense or denser than the mountain this would support the hypothesis that it was not hollow. Schiehallion was selected by Charles Mason (who is more famous for contributing his surname to the Mason-Dixon Line in the USA) after having been hired as a surveyor by the Royal Society to find a suitable mountain in 1772.

In 1774 Maskelyne obtained a leave of absence from the Royal Observatory at Greenwich from his employer, the King, George III, so that he could proceed to Perthshire to make the measurements. He spent 17 weeks of a very poor summer trying to make astronomical observations in the vicinity of Schiehallion with a view to employing the comparative method outlined above to determine the mass of the Earth for the first time in history. He started at the beginning of July, employing local labour to level a platform on the south side of the mountain and build a small observatory to house his instruments and a bothy to house himself. After six weeks and 169 measurements of the zenith distances of 39 stars he moved to an observatory he had had built on the north side of the mountain. Another 168 observations of 37 stars later, on the 24th of October, he had completed his measurements. The deflection of the plumb line due to the gravitational pull of Schiehallion was found to be 11.6 seconds of arc. After successfully completing the measurements Maskelyne hosted a party in the north observatory where the local fiddler, Duncan Robertson, entertained the guests. During the party the observatory burnt down, destroying Duncan's fiddle – Maskelyne sent him a replacement from London.

Maskelyne's measurements were published the following year, but it was not until a further two seasons had passed that the mass of Schiehallion had been determined. This was necessary to calculate the mass of the Earth, as described above. The surveyor who mapped Schiehallion so as to work out its volume and hence mass was Charles Hutton. In the course of performing his survey he invented contour lines. In 1778 he completed the calculation of the mean density of the Earth, reaching the conclusion that it is 4.5 times the density of water. From this and the size of the Earth the mass of the Earth was computed for the first time. This could be used along with the sizes and periods of the orbits of the planets made available by measurements such as the observation of the transit of Venus mentioned earlier to derive the weights of the other planets in the Solar System. Schiehallion had proved central to process of weighing not just the Earth, but every planet in the sky.

Schiehallion

Schiehallion was chosen historically for this measurement because it is a regular shape, approximately conical, which allowed its mass and centre of mass to be more easily calculated. It is appealing from the point of view of a modern measurement inspired by Maskelyne's work due to its proximity to Gleneagles and the comparisons one might draw between determining the Earth's weight and determining its worth, as will be done at the G8 summit in Gleneagles this July.

Schiehallion lies approximately in the centre of Scotland, and its name means "fairy hill of the Caledonians" which indicates that it was considered to be a sacred mountain, a sort of large Scottish Omphalos. It is likely that it is the "Caer Sidi" referred to in the earliest Arthurian literature such as the poem "Pa gur." More recently the Glasgow based NVA organisation staged the innovative installation and performance "The Path" in the area.

It is a Munro, standing 1083m (3547 ft) above sea level, and lies within the Loch Rannoch and Glen Lyon National Scenic Area. It receives around 20,000 visitors a year and is a Site of Special Scientific Interest (SSSI). The John Muir Trust owns the eastern part including the summit.

The new measurement

The modern method is based on measuring the variation in the acceleration due to gravity (conventionally denoted by "g") at the top and bottom of Schiehallion by measuring the variation in the period of a pendulum. This provides the basis of a similar comparative method to that used in 1774 without needing to make difficult astronomical observations and making it easier to involve the public.

The length of time it takes for a pendulum to swing back and forth depends upon the value of "g". This varies by about 1 part in 2000 over the surface of the Earth due to the variation in the distance from the surface to the centre of the Earth. For the same reason the period of a pendulum will be different at the top and bottom of a mountain like Schiehallion due to the difference in elevation. The gravitational influence of the mountain serves to reduce this difference. If the mass of the mountain is known and the variation in the period of the pendulum and hence in the value of "g" is measured, the Earth's mass can be calculated.

The experiment will detect variations of one part in a million in the period of the pendulum to achieve the required accuracy. This is possible by using apparatus specially assembled by DJB Microtech. The components are however standard and available to schools from DJB Microtech. The method involves measuring the time taken for a number of swings at the bottom of the mountain and repeating the measurement at the top using the same apparatus to minimise sources of systematic error. The amount of time needed to accumulate enough data to sufficiently minimise the random errors is typically only a few hours.

This method has been chosen because it does not rely on making measurements at night, or rely on the weather, as the original method did. This modern method was not originally adopted because devices for making sufficiently accurate timing measurements were not available in the 18th century. The necessary apparatus can be assembled today with little expense.

Local schools in Perthshire will be involved in this initiative in three ways:

1. The measurement of the period of a pendulum in the class can be made following a simple worksheet issued by Counting Thoughts. A value for the mass of the Earth can be deduced from this using the known value of "G". The values obtained by schools in this way will be compared to the value obtained using the mountain.
2. Pupils can participate in the measurements at the foot of the mountain on the afternoon of June 21st, after the measurements have been made at the top of the mountain. Two pupils can obtain a run of data over 30 minutes, with one pupil operating the pendulum and the other operating a laptop.
3. Pupils can join the measurement party at the top of the mountain to obtain data. The measurement party will ascend the mountain very early to begin data collection so it is suggested that school parties join them at the top of the mountain when it is convenient for them.

The downloadable worksheet describing how to "weigh" the Earth in class using a pendulum will be made available for schools. The results will be presented at a special public lecture given at the Glasgow Science Centre on July 28th.