The Waverton long pendulum experiment, 2009–2012

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In 1851 Jean Leon Foucault demonstrated a proof that the Earth turns on its axis. He achieved this by swinging a long (67m) free pendulum from the roof of the Pantheon in Paris. This caused something of a sensation at the time, and led to similar experiments all over Europe. This paper describes attempts started in 2009 in a rural Cheshire church to repeat that experiment, and what those attempts revealed.

Introduction

This paper describes the details of a continuing experiment with a long pendulum hanging in the tower of the church of St Peter, Waverton, near Chester. The author hopes the narrative style in which it is written gives it a greater appeal to the less mathematically minded than it would otherwise have had.

To explain how it came about we need to go back to the coronation of Queen Elizabeth II in 1953, when Chester City Council put on an exhibition of local talent in the Town Hall. My father took his then ten-year-old son for a look round this exhibition; I clearly remember a weight swinging from the ceiling, underneath which a biro inner tube was fastened, drawing shapes on paper below. I was told that this proved the Earth is rotating.

At the time this made no real sense to me; I was just left with a vivid memory of it. Things did not get much clearer even after I had seen the 'Foucault's Pendulum' hanging in the stairwell at the Science Museum in London. That would have been in the 1960s, but it was not then actually in motion and demonstrated nothing at all.

Over the years since, I have come to understand these demonstrations of Foucault's Pendulum:[1] *i.e.* that the pendulum maintains the direction it is set off in, relative to free space, while the floor rotates with the Earth underneath it making the pendulum swing plane appear to move round or precess. When Leon Foucault invited the great and good of Paris to 'see the Earth turning' in 1851 March, his pendulum hanging in the Pantheon was sixty-seven metres in length. In order to leave a record they dragged a spike through a bed of damp sand at either end of each stroke, then made plaster casts of these records which have been kept for posterity.

In 2008 I was involved in the installation of two new bells in the belfry of my local church – St Peter's, Waverton. In the spring of 2009, I put a proposal to the Church Council that a long pendulum be hung in the tower. With the support of one of the churchwardens, a retired secondary school head teacher, approval was given that I was free to use the church (Figure 1) on days it is not required for usual business. Under normal circumstances I can use the building from Monday morning through to Wednesday night.

Ironically, the pendulum's top mounting support is immediately under one of the bells which was cast in 1615, when Galileo was alive. Galileo is credited with being the father of pendulum theory. With this permission granted I set to work on the manufacture of the pendulum and the divided circular scale screen over which it would swing.

The experiment

I had three main aims: the first was to demonstrate the phenomenon of precession to myself and any of the locals interested; the second, more personal, was to determine whether the position of the Moon and Sun in the sky had any measurable effect on the rate of this precession; and the third was simply to witness, and try to understand, what actually was seen to happen – this last aim is the one which keeps the experiment running. I took the view that, as I was extremely unlikely to see anything others had not seen already, I would conduct the experiment from a position of naivety and not read up all that I could find on the subject first. This approach has the result that the problems encountered are solved in a manner unique to oneself; the rights or wrongs of this attitude I leave to the judgement of the reader.

Figure 1. St Peter's Church, Waverton with a sketch schematic cross-section view of the tower showing the pendulum layout.

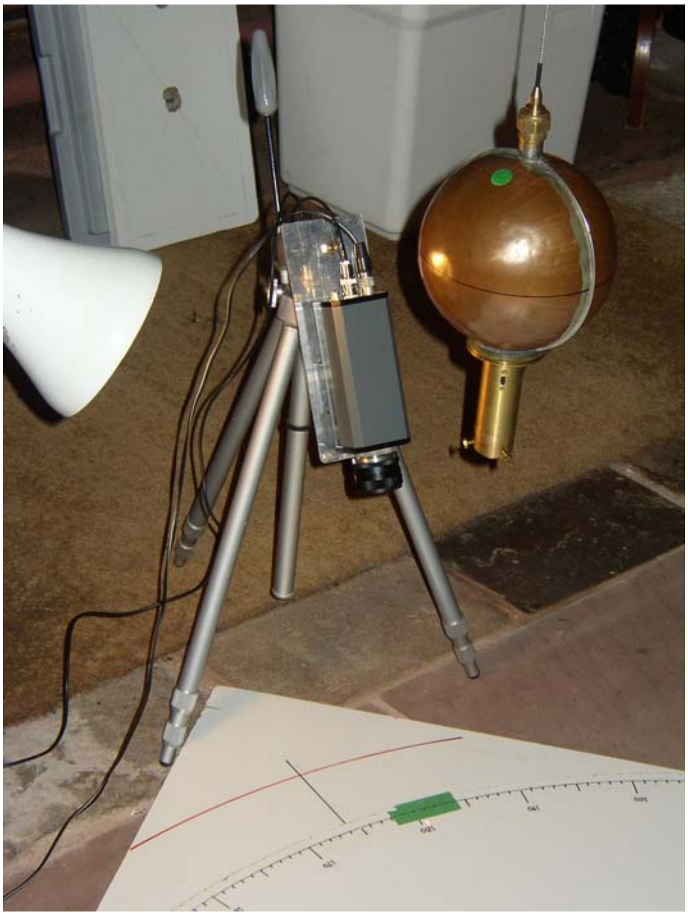

Figure 2. The original bob, laser, camera position and target scale. The anglepoise lamp on the upper left illuminates the area to optimise the image contrast between the target and the red laser trace. The target is green for the same reason. The copper ball-tap float pendulum bob still looks like what it was made from in this picture. The green sticker on the bob identifies the hemisphere.

Throughout this experiment I have enjoyed much support and encouragement from fellow members of Chester Astronomical Society, which holds its monthly meetings in the Church Hall of St Peter's. The experiment has had to be removable because it is a smallish rural church and a pendulum hanging in the middle of the tower floor area seriously gets in the way of church business.

As it has always been in my nature to adapt what I have to hand if at all practicable, the bob was to be a 150mm copper ball tap-float filled with lead; once full it weighed in at 20.87 kg.

The first support cable was chosen after some experimenting with different materials. I settled on a length of government surplus field-telephone wire; its breaking strain was found to be approximately 27 kg. The cable had to be long enough to hang from the floor of the belfry, through the ringing chamber, and down to the floor of the church: a distance of just over 15 metres. That first cable was mounted on a car engine valve spring – this spring would cushion any sudden jerk on the bob, minimising the risk of exceeding the cable's breaking strain. The bottom end of the cable was joined to the bob with a standard conex 15mm water pipe nut screwing onto a brass male threaded stud soldered into the bob.

The plan was to mount a laser pointer under the bob which would project a spot, the position of which could be recorded and measured (Figure 2). The first laser diode was housed in a brass tube stuck to the underside of the bob. This projected a spot, or rather a short bar measuring 0.75 by 3.5 mm. The rectangular nature of the spot had some unexpected advantages by making any torsion rotation of the bob visible.

On the floor under the pendulum I placed a circular white-board screen 121.92 cm in diameter, divided at its edge into 360 equal divisions. At the edge of a circle of these dimensions one degree subtends 10.42 mm. I was already aware that Foucault had launched his pendulum by burning through a thread that supported the pendulum in the drawn-back position. I also employed this method, using a length of fishing line fastened between a solid support post and a loop of soft rope placed around the bob.

All was completed by the end of 2009 September, and the pendulum was ready for its 'first swing'. After a few test runs the first aim was realised: I had witnessed precession of the pendulum caused by the Earth rotating. A ceremonial launch took place on 2009 September 22, attended by the rector and members of the long-suffering church council.

That first arrangement gave a cycle time in the order of 8.01 seconds, and precession was immediately evident. At that time I had not decided how to measure the swing plane's changing position – then I realised that the laser spot could be video recorded as it crossed the graduated circle scale on the edge of the floor screen (Figure 2). This recording would comprise a series of images made up of pixels. The position of the laser trace on these images could then be measured by counting the pixels from the left edge of the image to the centre line of the laser trace; an old version of *Paint Shop Pro* does this quickly and easily, and the count difference on each successive cycle serves as a measure, in pixels, of the precession over the period of that cycle.

Adding a date and time readout to the camera's output allows the time of every event image to be recorded on the images together with the direction of swing (Figure 3). The positional pixel count for each cycle is then entered into a spreadsheet. The

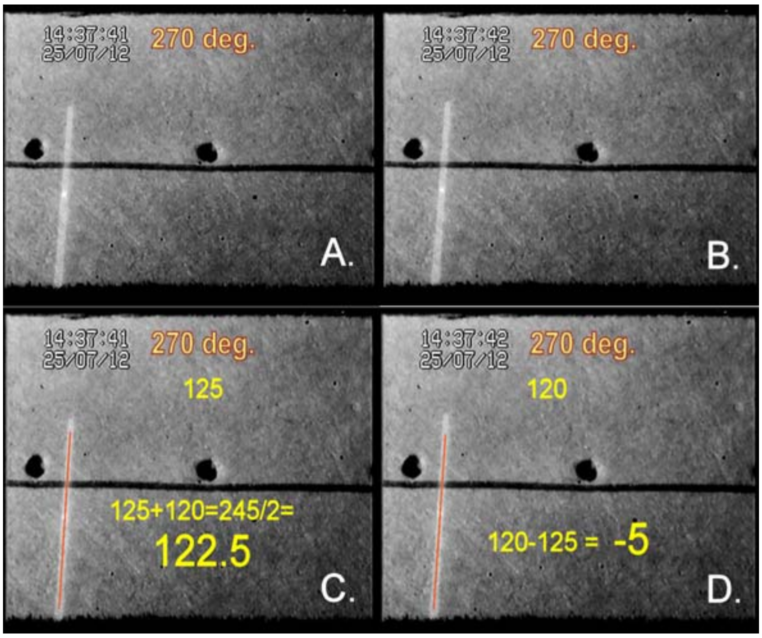

Figure 3. A montage of four captured images illustrating how the data are extracted from the recordings.

A and **B** are the raw frames of one cycle, captured when the laser spot crosses the centre line of the target plate on its way outwards in **A** and a second later on its way back inwards in **B**. The time and date are recorded, as is the swing azimuth (270°). The black spots are approximate degree markers, made bold to make them easier for spectators to see.

Frames **C** and **D** are copies of **A** and **B** with the pixel count from the left side of the image to the red line (marking the middle of the laser trace) shown in yellow (125 for **C** and 120 for **D**). Frame **C** shows the calculation of the position (in pixels) of the average of the traces in the two frames. This average result represents the major axis position of any elliptical motion that has developed. Frame **D** shows the calculation of the difference or spread of the two crossing points, –5 in this instance. The negative sign means the bob is describing an anti-clockwise ellipse, i.e. against the direction of precession due to the Earth's rotation.

spreadsheet is programmed to average each cycle's measurement with the one before it and the one after; this was done to try to minimise seismic interference from the road just outside the church, as well as wind buffeting the tower or the clock chiming.

Excel draws a bar graph (Figure 4), adds the total precession and produces a numerical result for the entire swing in the form of the actual measured precession divided by the theoretical. The graph shows any precession variance cycle by cycle, alongside a trace of the theoretical, in green. As aim no.2 involved the Moon and Sun they are added to a compass roundel on the graph, with a blue marker for the Moon and a red one for the Sun; also the azimuth direction of the swing in question. This, along with the quotient of the actual and theoretical numerical results, gives a good pictorial representation of what has occurred in the course of each swing (Figure 4).

The following terminology has been adopted to describe aspects of these experiments: a 'swing' denotes the recorded result of a complete number of cycles of pendulum oscillation (initially 35, finally 38); a 'run' refers to all swings done, one after the other, continuously at one time (usually at least one set of four); a 'session' is all those runs executed with the pendulum's mounting undisturbed; and finally, a 'series' refers to all those runs executed with a particular cable length.

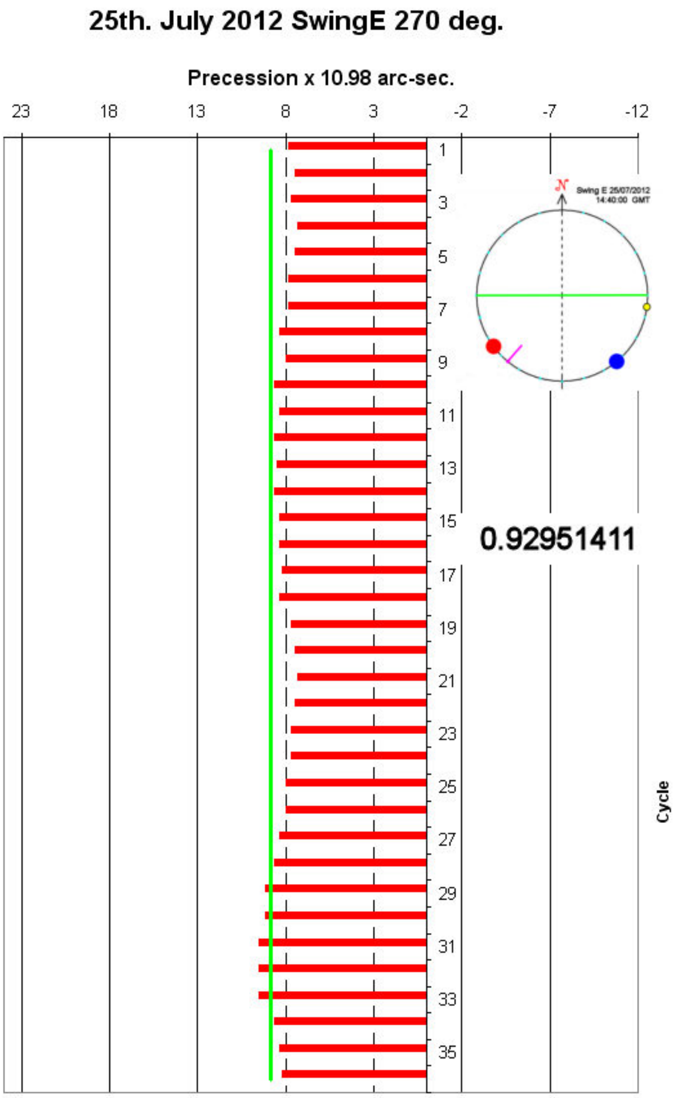

Figure 4. Bar chart of one complete swing of 38 cycles. The length of each red bar corresponds to the amount of precession on that cycle; the green line is what theory predicts. There are only 36 bars due to the averaging of each with the one before and the one after. On the compass roundel the green line is the swing azimuth, and the red and blue spots are the Sun and Moon at their appropriate azimuths.

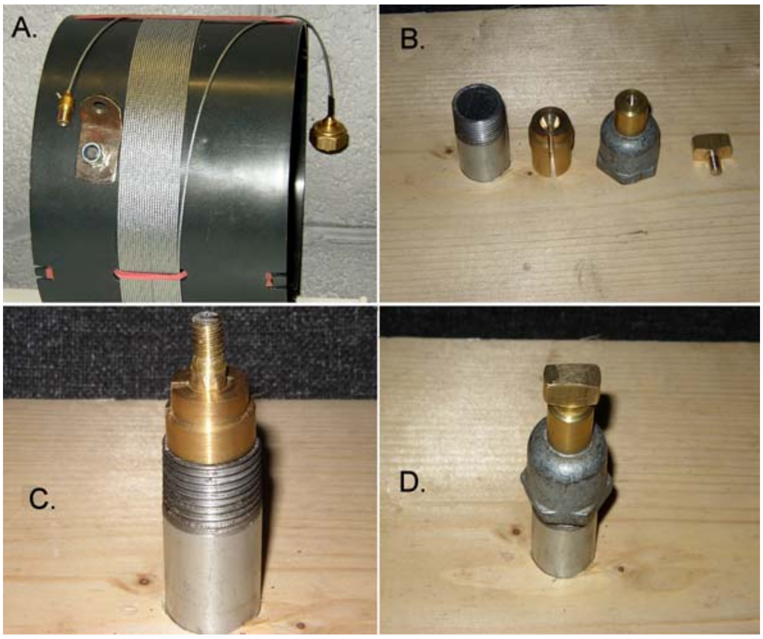

Figure 5. Montage of the suspension parts.
A. The support cable wound on its storage drum. The top conical anchor with locating pin is on the left, the bottom 15 mm hexagonal pipe fitting on the right.
B. The different parts of the top mounting. The ¾ BSP pipe passes through the wooden board.
C. Shows the assembled mounting with the cable in place.
D. Shows the locking cap and top thumb screw tightened down on the cable end.

So the method was born: a high-resolution monochrome video camera was positioned with the field of view encompassing five or so degrees of the divided circle where the laser spot would pass (Figure 2), care being taken to avoid the pendulum colliding with the camera. Six-minute recordings were made with a VHS cassette video recorder; these were later captured in digital MPEG2 format. A recording period of six minutes was chosen on account of the theoretical precession of one degree taking about five minutes at the latitude of St Peter's Church. With due regard to this latitude of 53.15° North, and the difference between sidereal and solar time, theory predicts a precession rate of 0°.0033433 or 0.2006 arc-minutes per second of solar time, in a clockwise direction (see appendix A). So for the first series of swings the standard became a swing of 35 cycles taking very close to 280.35 seconds, or 4 minutes and 40.35 seconds.

The first measurements using this method were made on 2009 October 19. These first results were somewhat ragged, showing both precession and occasional recession. The inconsistency was probably due to insufficient care, and drawing the bob back too far causing the support wire to contact the side of the hole in the ringing chamber floor.

Most advice I was given when discussing this experiment was that the pendulum should be made to swing for as long a period as possible, in order to allow the small effects to build up. However the pendulum's swing amplitude decays due to entropy and the maximum time available before the laser trace no longer crosses the measuring line is about ten minutes. I have therefore decided to measure the precession with increasingly greater precision: currently, three years on in series 4, this simple apparatus achieves a resolution where one image pixel represents 0.0304mm, or 11 arcseconds around the precession scale, a cycle period of 8.0678 seconds, and a swing of 38 cycles lasting just over 306 seconds, or 5 minutes and 6 seconds (see appendix B).

After several runs in 2009 with the setup as described above, the results were not very regular; and acting on the advice of a clockmaker friend, I abandoned the spring mounting in favour of a dead solid conical mounting and a stronger cable. The galvanised twisted steel cable of seven strands, in use now, has an overall diameter of 1.5mm and a breaking strain far in excess of what is required; it is also cheap and easily soldered. At the top end of the pendulum the wire passes axially through a short 10mm brass bar, which has a male 60° cone turned on the down-pointing end (see Figure 5A); this mates with a female conical hole drilled using a 10mm centre drill in the top of a short length of 19mm brass bar (see Figure 5B). The central hole in this is drilled right through with a 3mm drill bit, and widens sufficiently so as not to interfere with the cable as it swings through a total of 4°.5 of swing angle.

Also, a 2mm slot is cut on one side from top to bottom right through to the central hole of the 19mm bar, allowing the cable to pass in. This bar is then held in a short length of externally threaded ¾-inch BSP pipe fastened through the belfry floor, and screwed down solid with a modified ¾-inch BSP end cap (Figure 5D).

Run series 2 began in January 2010, again with swings of 35 cycles each and in different azimuth directions for comparison. As stated earlier, a second aim of the experiment was to investigate whether the positions of the Moon and Sun have any effect on the precession rate measurable with this setup; to this end, the precession on each cycle of each swing was plotted on a vertical bar graph using the counted pixel as the unit. It was very obvious from the beginning that the cycle could develop into an ellipse, and the position of the major axis of this ellipse was what was required.

The spot overshoots the graduated scale throughout all the cycles of each swing recording and in order to determine where the major axis of the ellipse is, the spot's position on the edge scale on both the out-bound and in-bound half cycles must be measured and averaged. For the original 35 cycles this meant capturing, counting, adding and then dividing the results of 35 pairs of image readings: a total of 70 images for each swing, and matters became worse when later changes were made, first to 36, and then to 38 cycles in each swing.

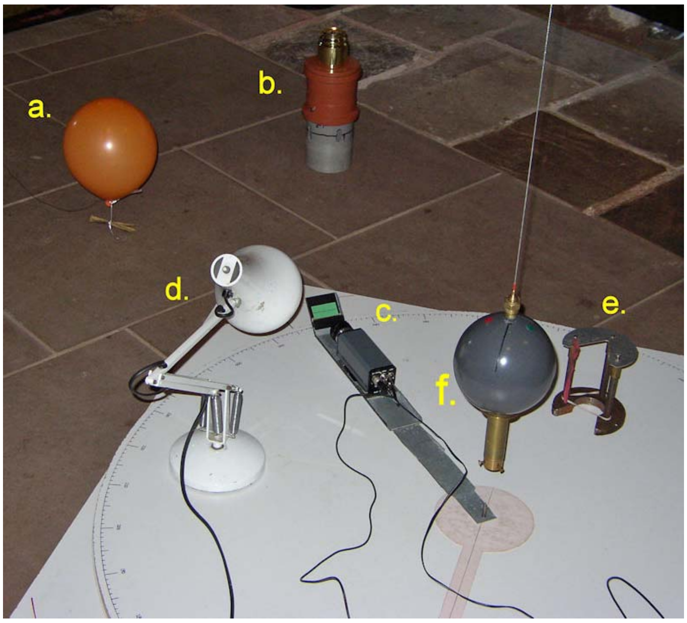

Figure 6. Items used in the experiment.
a) Tethered helium balloon and **b)** Candle, used to monitor any air unsteadiness in the swing area.
c) Video camera.
d) Floodlight, to balance the contrast of the laser light on the target scale.
e) Cradle for holding the bob steady while the launch procedure is prepared.
f) The smoothed pendulum bob with attached laser.

Run series 2 continued until 2010 June 15, by which time I had a total of 57 bar-graphs, and several more questions that needed answers. By the end of series 2 the launching mechanism had been upgraded to a ratchet, winding in the fishing line which was fastened to the stainless steel yoke of a small plastic marine pulley wheel – the latter carrying the cord which surrounded the bob prior to launch.

The bob, once in its launch position, can be left with its laser shining on a small bright ball-bearing on the floor; the reflection off this ball greatly magnifies any unsteadiness, and as soon as none is seen the fishing line is burnt through. The cord and pulley drop off leaving the pendulum swinging. At this point a stopwatch is started simultaneously with the video recorder, which is left to record for six minutes. Records are also made of the outside weather conditions during each run, the wind strength and direction, barometric pressure and temperature inside and outside the church, along with an evaluation of draughts inside the church (Figure 6).

During the early swings it became obvious that some either noticeably exceeded or fell short of the theoretical precession rate: as time passed and method improved, it appeared that over-precession in any one swing direction (azimuth) tended to be balanced by under-precession in the direction at right angles to it.

Run series 3 started with a new cable 22.86cm longer than the previous, with the camera lying flat underneath the swinging pendulum and focused on a 45° inclined target plate (c in Figure 6) – this again being marked with one degree markings. This lengthening of the cable resulted in the cycle time increasing from 8.01 to 8.08 seconds, and allowed the camera to get closer to the target screen, thus increasing the number of pixels in each degree in the recorded images, typically from 77 to around 203 pixels. This yielded an improvement in resolution from 46 to 18 seconds of arc on each captured frame. Another addition was a steady to hold the bob pre-launch, with the cable in a position of balanced torsion (e in Figure 6).

When the pendulum is first hung it tends to unwind the twisted cable, rotating many times, overshooting equilibrium, then rotating back and forth until it settles in balance several hours later. In fact it takes very little force indeed to cause the bob to rotate. This rotation is highly undesirable, since any departure of the bob's laser beam from a linear continuation of the support wire and the centre of gravity of the bob will give a false variation in spot position.

With this in mind, in 2010 August the number of cycles per swing was increased from 35 to 36, because when the bob rotation was timed it was found to have a torsion frequency of one complete cycle in close to 2 minutes 30 seconds. A swing time was therefore needed to fit two complete torsion cycles into the total swing time; this adjustment made, even if the bob did rotate, having two complete twist cycles would cancel out any effect on the end result. Launching with the bob in its most relaxed position is now easily achievable; and carelessness aside, bob rotation (due to the cable untwisting) during the swing is greatly reduced, if not eliminated.

With smoother graphs and more accurate measuring, confidence

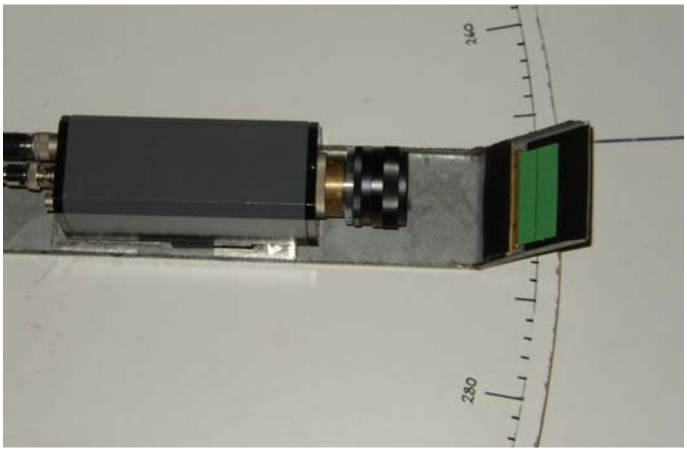

Figure 7. Close-up of the video camera and the target screen. The circumference scale divided into degrees is visible under the camera cradle, set in position for an east/west swing.

in the results was building; but no evidence of any relationship between precession and the positions of the Sun and Moon had yet come to light, despite careful selection of swing timing with direction relative to Sun/Moon positions. However, as mentioned above, there was a regular variation tendency in precession rate with direction of swing, apparently independent of the Sun and Moon's positions. Efforts were therefore then concentrated on examining this more closely.

The first few runs of series 3, starting from 2010 July 26, were conducted simply swinging the pendulum first in a north-west/south-east direction, followed immediately by a swing south-west/north-east. These were still timed to coincide with the Moon's azimuth being either at right angles to the swing azimuth or in line with it. But still no regular influences showed up.

The west door of St Peter's is in the tower, and does not fit the masonry of the doorway very closely, so prevailing draughts could be having some influence on the behaviour of the pendulum. Thin sheet steel shields, placed around the swinging area standing well above bob height, did not make any obvious difference to what was seen. The steadiness of the air in the church is monitored with the help of a candle flame and a tethered helium balloon containing just enough gas to cause it to hover; these are placed close to the bob (a & b in Figure 6) and show up even the slightest gust or draught.

From 2010 November 10 a run comprised one or more sets of four swings: starting east/west, then north-west/south-east, then north/south, finishing with north-east/south-west. With swings being done in groups of four, the cost in time to measure every cycle became too great, and a different method of presenting the results had to be devised.

Of the various chart options built into Microsoft *Excel* – the spreadsheet application used for this experiment – the 'radar chart' was considered the most suitable, and has been used ever since. The software plots the value of a result as the length of a radial line from the centre, providing a very convenient element of directional information in addition to the quantity plotted. Precession over a complete swing is calculated by subtracting the pixel count of the first cycle from that of the last of the 38 cycles now used. The increase in the number of cycles per swing from 36 to 38 was again made in order to include two complete bob torsion cycles within the whole swing: examination of the bar graphs showed the bob's torsion period to be very close to 19 complete pendulum cycles.

Run series 4 started when the bob was smoothed into a more regular sphere and the laser was changed to produce a beam focused to a small round spot, rather than the short bar. The camera was placed still closer to the target screen (Figure 7), such that one degree division in the images contained 328 image pixels, and one pixel now represented just under 11 arcseconds. The support cable had to be a little shorter for the smallest spot to be achieved, giving a cycle time of just over 8.06 seconds. The elongated nature of the spot was now lost; it had been useful in the images and bar graphs by making bob rotation visible.

Radar graphs are now compiled to demonstrate precession through eight sections of the 360° of possible swing direction. The eight steps are made up from the four measured swings being duplicated – this assumes that swinging east/west is the same as swinging west/east etc. (That assumption was tested and found to be sound.) These radar graphs show up quantitative variation in the actual precession, for each of the four azimuth directions the pendulum is swung in to complete the run.

The Sun and Moon azimuths are also included on these graphs, even though no effects from their differing positions have been noted. Figure 8 is a theoretical, Figure 9 an actual example.

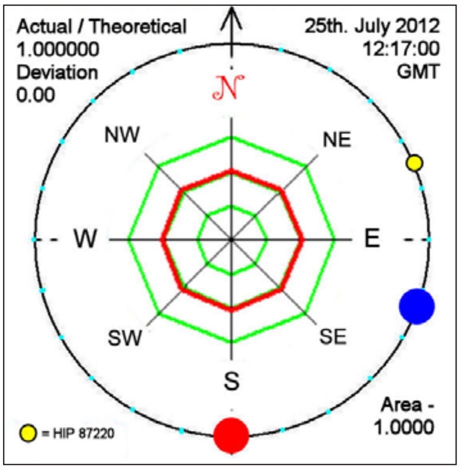

Figure 8. A theoretical 'radar' chart where the precession is equal to what theory would predict. It has been drawn for 12:17 GMT on 2012 July 25 when the Sun was due south of St Peter's. The Sun, Moon and star HIP 87220 (which is close to the galactic centre) are included at their correct azimuth for that time.

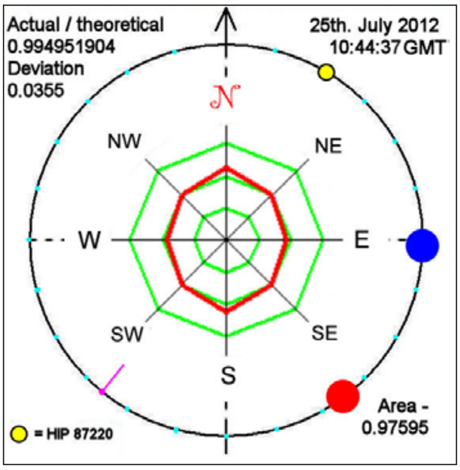

Figure 9. The actual radar chart from 2012 July 25 at 10:44:37 GMT, showing over-theory precession along the north/south direction and under-theory along the east/west. The Sun, Moon and HIP 87220 are included at their correct azimuth for that time.

Ellipticity

The tendency for the bob to describe an ellipse has been examined; this elliptical motion has now been measured and recorded, using the method described above, for every swing since 2010 July 26. While not being a true measure of the ellipse minor axis, which would have to be measured at the centre, it is still a good guide to its development.

This has presented one of the most intriguing outcomes of the experiment, in that when the bob does develop an ellipse it appears to 'orbit' the centre point, vertically below the point of suspension. It can adopt an orbit in either direction *i.e.* either clockwise or anti-clockwise as seen from above. The precession of the pendulum swing plane due to the Earth's rotation is always clockwise in the northern hemisphere, and the minor axis of the bob's elliptical orbit appears to build in either a prograde with precession (clockwise) or retro-grade (anti-clockwise) direction.

This rate of ellipse minor axis increase seems always to be at a linear rate, but varies in magnitude from swing to swing in a random fashion. However the orbital direction does not, being always retrograde when swinging NW/SE and, on all except one occasion, prograde when swinging NE/SW, and showing no great preference when swung in the E/W or N/S directions. This is so even when the bob is accidentally launched with an orbit of the wrong direction; that ellipse will decay then continue to build again in a direction in agreement with the above. Neither the magnitude nor the direction of the bob's elliptical motion have shown any influence on the general precession rate of the pendulum swing plane (Figure 11).

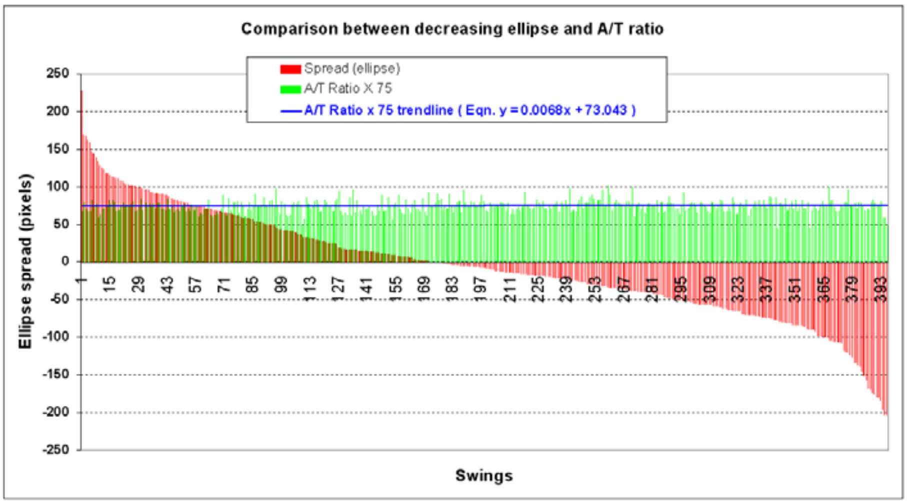

Figure 11. Graph compiled to demonstrate the relationship between the cycles' elliptical developments and their overall effect on the major axis precession rates. The 400 swings are sorted by ellipse spread magnitude (in pixels) and plotted on the x axis in red, from greatest positive or prograde to greatest negative or retrograde. The actual/theoretical (A/T) ratio of precession of each swing (multiplied by 75 to make it stand out more clearly) is plotted in green next to its red ellipse spread plot. Then a linear trend line of these plotted A/T precession values along with their equation (y = 0.0068 × +73.043) is added in blue. The close to zero slope of this trend line is testimony to the independence of major axis precession from any ellipse development.

Conclusions

There has been an extensive investigation into possible sources of disturbance carried out among the experiments discussed above without any clear picture emerging to explain the findings. More needs to be done in this area before any definite links can be established.

It *has* been established that with due regard to the latitude of St Peter's and the difference between sidereal time and Greenwich mean time, the actual precession divided by the theoretical (A/T) precession of the swing planes of this particular pendulum setup is as follows:

Swung in a N/S direction, averaged over 86 swings of 38 cycles each, A/T = 0.9814
NE/SW direction, averaged over 102 swings of 38 cycles each, A/T = 0.9613
E/W direction, averaged over 86 swings of 38 cycles each, A/T = 0.9995
NW/SE direction, averaged over 102 swings of 38 cycles each, A/T = 1.0246

From the results of an overall average of 376 swings with St Peter's Long Pendulum, the actual precession recorded is 0.9917 of what theory would predict.

As of 2012 October this continuing experiment has shown that a run's swing precession rates can vary with azimuth, while maintaining the tendency for over-theory to be balanced by under-theory in the direction at right angles to it (even when the air in the building is completely steady). From all the radar charts of four swings each, there is a slight overall excess in the NW/SE direction and deficits in the NE/SW and N/S directions. E/W swings show precession very close to the theoretical (Figure 12).

These conclusions form the basis for future experiments with a view to finding out why this happens.

Extract from William Tobin quoting Leon Foucault: 'Passing from theory to practice, the physicist must expect disappointments; and, in the present case, he must think himself very happy if with a real pendulum he is able to obtain an unequivocal deviation in the expected direction.'[1]

I have communicated with Dr Albert Prinn, of Cork in southern Ireland, whose understanding of pendulum theory far outstrips my own. We differ in that he is using a much shorter pendulum support wire, to encourage elliptical motion, and has focused on solving the equations for precession due to elliptical motion. It has been very interesting to have an insight into an experienced mathematical approach.[2]

Discussions with Dr Prinn and others have convinced me that pendulums of different weights and different lengths will behave very differently, and comparing results will lead to confusion. The Waverton experiment has compared results derived from the same general setup, in the same place, changed only to test for possible sources of error, or interference; so as long as the measuring procedure is sound something outside of the pendulum's physical setup must be leading to these anomalies.

I have found it very difficult to convey the majestic spectacle of a slowly swinging long pendulum. Seeing is appreciating with this.

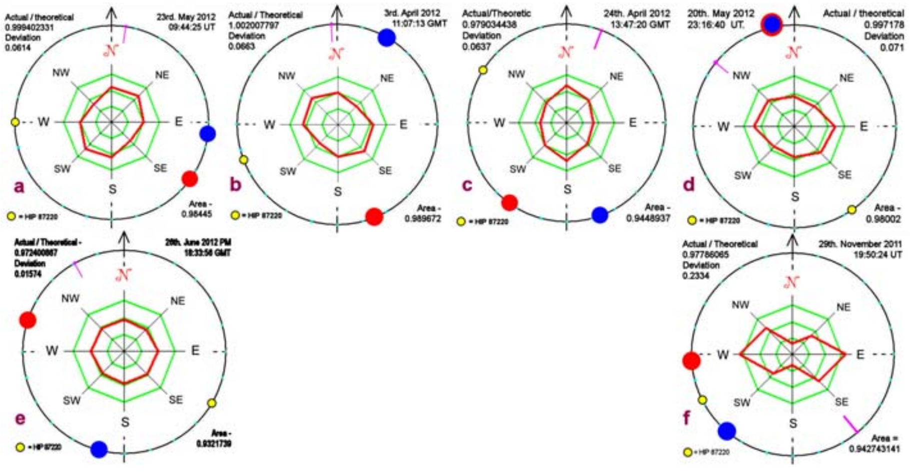

Figure 10. A selection of radar charts typical of those recorded. **a, b, c, d** show enhanced precession along different directions. **d** was recorded at the time of an annular solar eclipse.
e is the chart with the closest fit with theory, while **f** is the most disturbed run recorded.
Note in chart **e** the A/T precession ratio = 0.9724, while in **f** A/T = 0.9779. Also in **f** the extreme precession along the E–W direction is balanced by the shortfall along N–S.

Other Foucault pendulums

There is a permanently mounted Foucault Pendulum in The Harlow Hill Tower, Harrogate, under the care of David Cook of Harrogate Astronomical Society. Liverpool University has one in its Chemistry building; this is driven and swings continuously. Manchester University has one in the Manchester Conference Centre, Sackville Street, and there is still an example in the Science Museum, South Kensington, London.

None of these four is used for high precision experiments.

Acknowledgments

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Also Peter Williams, church warden of St Peter's, and David Andrews, tower captain, without whose support obtaining the freedom to use the church would have been much more difficult.

Many members of the Chester Astronomical Society, particularly the late Bill Jones, Tom Green, Jennifer Robinson and her father Martin, for their enthusiasm and the support they have given me.

Dr Jeremy Shears, who has searched through the results for patterns against the months and years after the style of the variable star observer, and given me much help with the preparation of this paper.

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David Cook, Harrogate Astronomical Society, who has mounted a permanent pendulum in the Harlow Hill observation tower overlooking Harrogate.

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2 **https://sites.google.com/site/bertgroup/**

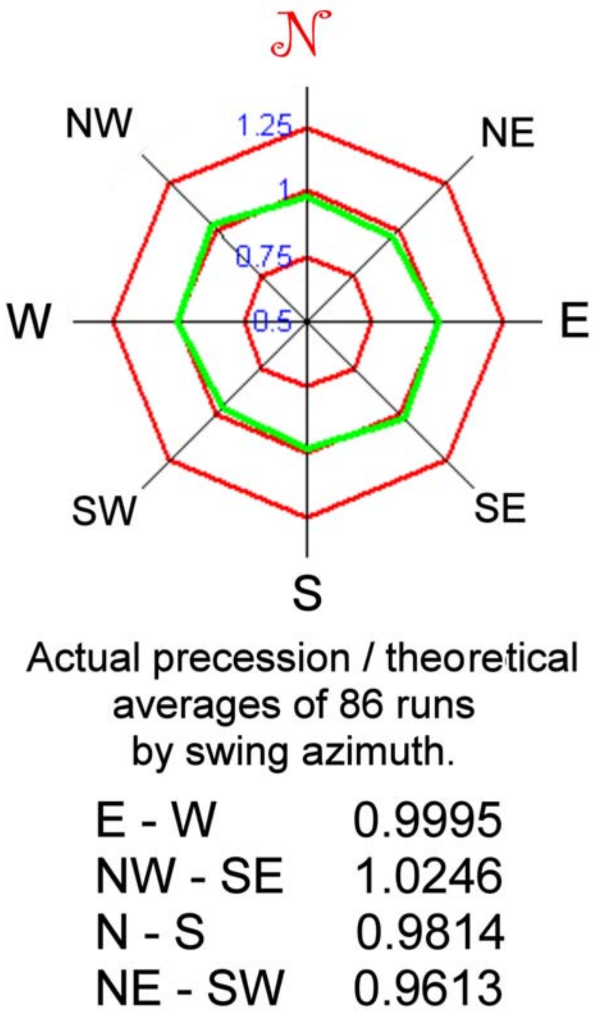

Figure 12. A radar chart showing the overall average precession along each of the four swing directions, compiled from the averages of 88 runs. The excesses and shortfalls of actual precession divided by the theoretical (A/T) are demonstrated.

Appendix A. Calculation of theoretical precession

In one solar day Earth rotates through 360° in 24h 0m 0s, or 86,400.00 sec. of solar time.

So in one solar hour Earth rotates through (360/24) = 15°.

In one sidereal day Earth rotates through 360° in 23h 56m 4.09s, or 86,164.09 sec. of solar time.

Solar day/sidereal day = (86400.00/86164.09) = 1.002738.

Therefore in one solar day free space appears to rotate through 360°×1.002738 = 360°.98568,
and in one solar hour 15°×1.002738 = 15°.04107.

Precession is clockwise in the northern hemisphere, anti-clockwise in the southern hemisphere and zero on the equator.

Precession = angular rotation × sin ϕ, where ϕ = latitude.

Latitude (ϕ) of St Peter's = 53°.15 N

Sin 53.15 = 0.8002

Therefore a pendulum at St Peter's latitude maintaining its swing azimuth relative to free space should appear to precess at 15°.04107 per (solar) hour × 0.8002

= 12°.03586 per hour (solar)
= 0°.2005977 per minute (solar)
= 0°.0033433 per second (solar).

Appendix B. Derivation of the cycle times

The cycle times are derived in the following manner.

Each individual swing lasts for 38 complete oscillation cycles, which for this pendulum is just over 5 minutes, starting when the laser trace crosses the scale on the first image, and ending when the trace crosses the scale 38 cycles later.

The scale is recorded in standard composite video with 25 full frames per second. Each full frame is made up of two sequential frames of 1/50 sec interlaced. Figure 3 shows examples of these.

The start frame time is calculated by identifying the second during which the laser trace crosses the target screen. Then, starting at the beginning of that second (where the seconds on the clock in the top left hand corner of the image increase by one), counting the frames until the frame with the laser trace on it is reached, that number multiplied by 0.04 is the decimal part of the second, thus identifying the event time to within ±0.02 sec, which is noted.

The same procedure is then carried out on the 38th cycle to give the end time. This yields a total time for a swing of 38 cycles to an accuracy of ±0.04 sec.

Since the swing comprises 38 cycles and assuming all cycles are equal, each cycle time will be 1/38 of the total swing time, to an accuracy of ±0.04 divided by 38, or ±0.0011 seconds.

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