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Feature

The first gravity meter designed, built and used in Australia in the late 1890s – and very possibly the first in the world

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Introduction

In October 1893 a gravity meter constructed in the Physics Department of the University of Sydney, and based on the same (fused-quartz balance) principle as some gravity meters in use today, was taken on its first field trip to Armidale, in north-eastern NSW. This trip was the culmination of 5 years of painstaking experimentation and trials in Sydney and I believe that the instrument was not only the first gravimeter built and used in Australia, but the first in the world (evidence for this claim is given below).

The instrument used the same static principle employed in modern gravimeters, as distinct from dynamic measurements such as those made by pendulums. Construction took place in the Department of Physics to a design devised by Dr Richard Threlfall, Professor of Physics, and James Arthur Pollock, a demonstrator in the Department of Physics at the time. Put simply, it was based on measuring the very small movements, due to variations in gravity, of a weighted pointer attached to a stretched wire (if you can't wait to see how the instrument looked, take a peek Figure 5).

A second journey was made to Armidale in February 1894, and another in May 1897 to Bowenfels, near Lithgow. Between June 1897 and December 1898 a more reliable version of the instrument was read in Melbourne, Hobart and Launceston, Armidale (for a third time), Springwood in the Blue Mountains of NSW, Melbourne again, and six times in Hornsby Junction, 34 km by train from Sydney. All this activity took place in the late 19th century, before Australia was a federation and before the arrival in Sydney of motor cars and electricity.

Full details of the gravity meter, including the theory, design, construction, operation and results obtained, are described, in considerable detail, in a paper by Threlfall and Pollock submitted to the Royal Society of London in April 1899 and published in the Philosophical Transactions of the Society (Threlfall and Pollock, 1900)[1]. Because of the historical significance of the instrument this paper is worthy of close study, which I will now attempt to provide. In the following text references to the paper will be abbreviated to the 'T-P paper' and the authors as 'T-P'. All quotations are from this paper unless otherwise indicated. My comments on the form and presentation of the paper itself are given in 'Some observations on the published paper'. Brief biographies of the two physicists are given below (see 'About the authors').

T-P explain, in the introduction to the paper, their desire to have a 'static' measurement using the elastic properties of a spring balance. They knew that this would restrict them to measuring only relative variations but expected that there would be "a smaller expenditure of time and trouble than is incidental to the observations of pendulums". At this time the pendulums that were mostly used to measure absolute gravity in observatories were also being developed to measure relative gravity (see http://en.wikipedia.org/wiki/Pendulum#Later_pendulum_gravimeters. They were intended for geodetic use[2]. However, T-P now planned to build a relative reading instrument better suited to field surveys; a gravimeter[3].

The meter was not given a name in the T-P paper so, in the tradition of gravimeters being named after their inventors (for example, Worden, La Coste and Romberg) I will call it the "Threlfall-Pollock" gravimeter or "T-P meter".

At first T-P considered making accurate measurements in one place where "observations should be of a higher order of accuracy than is necessary during a gravity survey", but after two years they realized they were not going to obtain "sufficient sensitiveness"[*sic*] and turned their attention to a portable instrument. Construction of what was to become the field instrument commenced in August 1892 and by September 1893 it was ready to begin "systematic observing". T-P then understood the consequent need "of such construction that it is not possible to disturb it's mechanism by the shaking inseparable from transport", which required them "to face a mechanical and physical problem of considerable difficulty".

The case for the T-P meter being the 'first'

T-P acknowledge that until the discovery of the unique properties of fused quartz by "Mr Boys" in 1887 (Boys, 1887) no other material had the requisite elastic properties and "….all attempts [*i.e.*, before 1887] at constructing a statical [*sic*] instrument of reasonable accuracy must necessarily have failed – as they all did". The 'all' here must refer to attempts by instrument makers other than T-P, as they declare "Our own attempts to construct a gravity balance began in September, 1889".

This proposition is also strengthened by the disclosure by T-P that "a committee of the British Association, which in 1886 had

[1]The paper, no. A245 in the Philosophical Transactions, was also published as a separate booklet for the Royal Society. A copy is available in the Rare Books section of Fisher Library, University of Sydney.

[2]Specifically, T-P may have been aware of one of the relative reading pendulums developed in 1887 by Von Sterneck who is listed in T-P paper's "Bibliography" with references to him, dated 1885 and 1895.

[3]Gravimeters fall into two classes, 'static' or stable, and 'astatic' or unstable. Both types are still in use today.

invited designs for a gravity meter, reported in 1889 that work had been suspended pending a trial of the fused quartz"[4]. So until then, no other construction was successful, at least via the British Association[5]. This is my basis for supposing that the T-P development is the first successful one of its kind, not only in Australia but in all the world.

I may be not alone in my assertion as Dooley and Barlow (1976) in their review paper of 'Gravimetry in Australia, 1819 –1976', state; "One of the earliest, if not the first, gravity meter in the world was constructed at Sydney University (Threlfall & Pollock, 1900)".

Heiland (1940) is the only textbook I know (that is old enough?) to refer to the T-P meter, where in his discussion on types of static gravimeters, he begins with, "The Threlfall and Pollock gravimeter is one of the earliest examples…" and then gives a brief description with the 1900 reference. As further substantiation of how early this meter is in the development of gravimeters, all the following six meters described by Heiland have references dated 1932 or 1938 including the next one listed, the 'Wright gravimeter' which he claims "closely resembles the Threlfall-Pollock instrument…", but 38 years later![6]

Description of the T-P meter.

Briefly, the principle of operation was one of observing the microscopically small twists of a fused-quartz 'thread' under tension when subjected to changes of gravitational attraction, g, as illustrated by the movement of a pointer or 'lever' attached to the thread. The amount of twist on the thread needed to return the lever to its original position, as determined by a fixed microscope, was read as seconds of arc on a sextant. This angle can be directly related to the value of g (see 'About the theory', following).

Figure 1 as "Fig. 1" from the T-P paper, is a very much a simplified schematic of the assembly where 'H' - 'I' is the fused-quartz thread, 'D' is the wire lever soldered to the thread to reveal the twist due to gravity, 'C' is the sextant arm and 'E' is the microscope to observe the movement of D. This has some similarity to the simplified schematic of modern gravimeters and the T-P meter was clearly the precursor of these. See, for example, Figure 2, which is from Figure G-5 (b) of Sheriff (1991) illustrating the schematic of a Worden gravimeter (in use from 1960) where the 'Hinge beam of fine quartz' is equivalent to the thread H-I and the 'Pointer' is equivalent to the lever at D. The Worden also uses a microscope. For a further comparison of the T-P meter with current meters see 'Comparison with modern gravity meters', below.

A much more detailed scale drawing of the whole assembly is shown as Figure 3 (from 'Plate 1' in the T-P paper) with an index to the lettering given as the last page in the paper. For an idea of scale, the thread, 'OOO', is 30.5 cm long. Additional

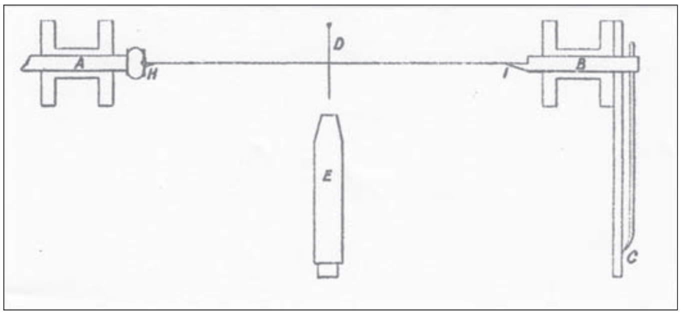

Figure 1. *A simplified drawing of the T-P meter mechanism from "Fig. 1" of the T-P paper showing the 'thread', H to I, the 'lever', D, the microscope, E and on the right side at 'C', the 'sextant' arm.*

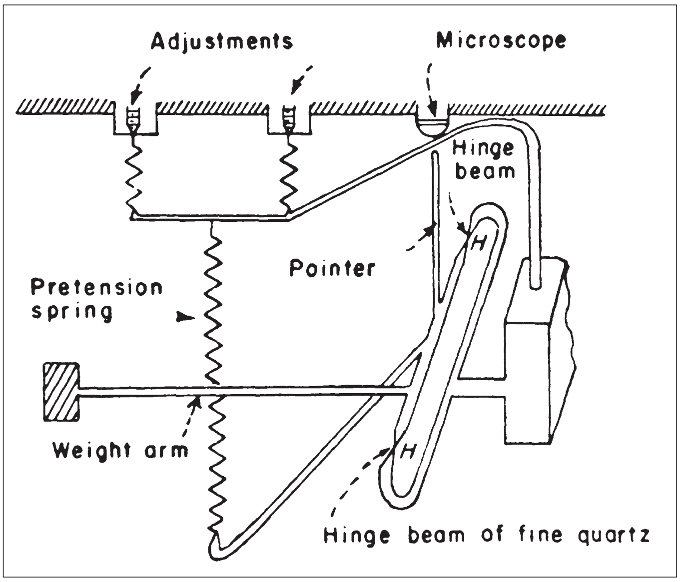

Figure 2. *A schematic of a Worden gravimeter from Figure G-5 (b) of Sheriff (1991) where the "Hinge beam of fine quartz" is equivalent to the thread H-I and the "Pointer" is equivalent to the wire at D. It also uses a microscope.*

elements to those in Figure 1 include the platinum wire thermometer finally chosen to measure the internal temperature and the assembly block attached to the thread, which is the 'arrester', or 'clamp' to the lever.

The whole assembly was contained in a tube of copper, which was thermally insulated to some extent (using paper!) and as air-tight as possible, given the seals employed, to ensure a constant density and humidity of air. Indeed, typical of the detail of T-P's descriptions (of which more later), "The air is passed over potash and through a filter of cotton wool, the object being to have dry dust-free air in the balance case". Constant density ensured no variation resulting from the "flotation of the lever by the air surrounding it", which would affect the moment of the gravitational force. T-P never used a vacuum chamber to solve this problem.

Of the 12 sections in the T-P paper describing individual components of the Instrument in some detail (see "Some observations on the published paper"), the section on the (fused) Quartz Thread acknowledges that it is the most essential part of the instrument and it required "an immense amount of experimenting" to get the right diameter and "the greatest possible uniformity". The T-P paper mentions two main methods of drawing out the quartz thread, as devised by Mr. Boys: the

[4]The British Association was founded in 1831 by persons who, at the time, regarded the Royal Society as elitist and conservative. In 2009 the name was changed to the British Science Association (BSA).

[5]Lorand Eötvös, better known for his development of the pendulum based torsion balance to measure gravity gradient, is reported by Szabo (1998) to have built a "gravimeter" in 1901 but it failed to meet expectations and nothing was published on it.

[6]Heiland includes the T-P meter in the 'static' sub-class but T-P explain that their readings were deliberately made at a point of the lever "upsetting" to be more sensitive, which by Heiland's own definition puts it in the 'astatic' class as he does for the Wright meter.

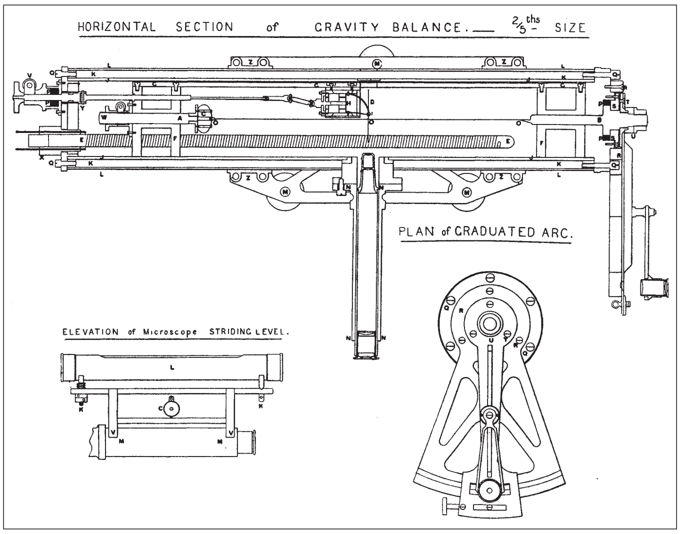

Figure 3. *Scale-drawings of sections of the T-P meter from "Plate 1" of the T-P paper also showing the 'thermometer', E-E, the 'arrester' block on the 'thread', OOO and connected to the 'lever', D. For scale, the thread is 30.5 cm long.*

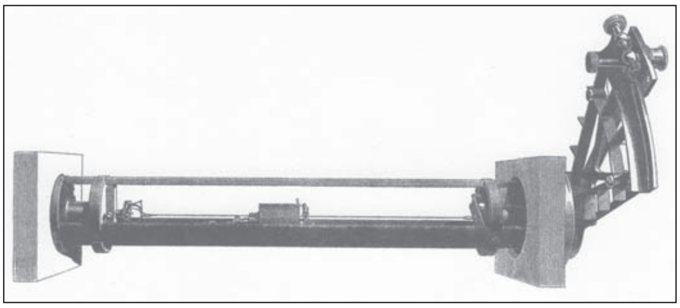

Figure 4. *A "photograph" of the internal assembly of the T-P meter from "Plate 2" of the T-P paper showing the 'thread', the 'arrester' block attached to it and on the right, the 'sextant'.*

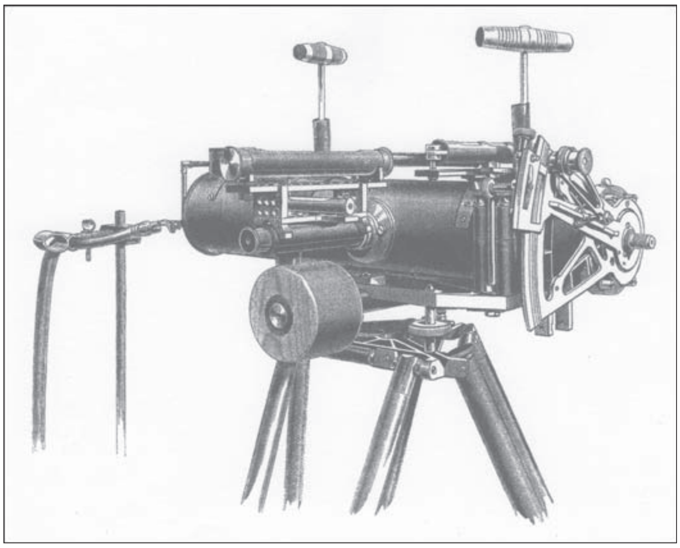

Figure 5. *A "photograph" of the exterior of the T-P meter mounted on a tripod, from "Plate 2" of the T-P paper, showing the 'vernier arm' of the 'sextant', the microscope as the horizontal tube at right angles to the main circular body, and levelling screws.*

"catapult method" and the "shot" or "bow and arrow" method, the latter giving "better threads for our purpose"[7]. However, "the process is so uncertain that we have on occasion got a thread within a few days, and on others we have spent a fortnight over it" (we see in 'Instrumental development' that for the initial threads T-P used, it can actually take months to get a satisfactory thread). Such a 'hit and miss' process of drawing the thread is much as it still is for modern instruments[8]. The thickness of thread they finally found to be reliable was 0.0038 cm in diameter, still very thin and equal to the thickness of a very thin type of human hair.

The next section on the Lever, used to illustrate the twists of the thread, describes the lever finally used, after trying other metals, as "of gilded brass wire of the smallest diameter we could get"; namely 0.013 cm, and with a length of 5.3 cm and weight of 0.018 gm. The center of gravity of the lever is adjusted by applying to it "a small drop of fusible metal, rather larger than a pin's head" (T-P suggested that if making a new instrument they would try using fused quartz for the lever).

Figure 4 (the upper section of 'Plate 2' from the T-P paper) shows the interior assembly with the thin thread just visible and the block attached to it the "arrester" assembly. At the right-hand end is the 'sextant' for measuring the angle of twist of the lever. Figure 5 (the lower section of 'Plate 2' from the T-P paper) shows the exterior view of the full assembly. The arcuate graduated scale on the right-hand end is the "vernier arm" of the sextant. The microscope for aligning the position of the lever is apparent as the horizontal tube at right angles to, and in the centre of, the main body. Various levelling screws are also seen.

The overall dimensions of the instrument alone are not given by T-P, only the outside dimensions of the three transit boxes containing the instrument and accessories. However, from knowing the length of the thread shown in Figure 3 as 30.5 cm, one can scale the overall length to be 65 cm with a width of 30 cm, including the microscope barrel which extends about 18 cm from the main enclosure. The enclosure appears from the "photograph" of the balance (see Figure 5) to be of circular section, about 10 cm in diameter. The overall height of the balance is estimated from the photograph as about 25 cm. These dimensions comply with the outside dimensions of the transit box for the balance, given in the paper as 85 × 48 × 39 cm.

The weight of the 'balance' alone was not given in the T-P paper either, only the combined weight of the balance and it's transit box, a total of 48 kg. The weight of the balance could therefore be as much as 20 kg. Modern meters weigh 8 kg or less. However, "the great weight of the instrument" was found to be a "drawback" and modifications were made to make it lighter. The 48 kg weight of the transit box containing the balance can be appreciated from its description as a "pine box" into which the balance is secured tightly. The box was supported by "a set of sofa springs, which were attached to a false bottom" and then encased in an "iron framework" (!) with "rubber buffers" to prevent sideways movement. Two handles were provided for it to be carried. Whilst elaborate care was taken to prevent any damage during transit, the resulting weight (equal to two heavy suitcases) did render it susceptible to damage in transit (see examples in 'Testing in the field').

[7]The reference given to these methods, namely, 'Laboratory Arts, Threlfall, Macmillan, 1898' has not been investigated by me but one can only imagine how such names can be appropriate!

[8]I am aware that the manufacture of LaCoste & Romberg gravimeters used to rely on one particularly skilled person who had the most success in drawing their quartz springs.

The two other boxes of accessories and the tripod made the total weight of the whole assembly 103 kg, which T-P acknowledge could have been halved with some obvious modifications.

About the theory

The development of theory in the paper begins with an "equation of equilibrium" (Equation (1) in the paper) linking the angle of twist, θ (the measurement) to acceleration of gravity, g. This equation is then rewritten taking into account the effect of temperature (t) on the reading by introducing a temperature coefficient (α) to incorporate all the effects of a change of temperature (Equation (2) in the paper). By recognizing that all factors in the equation except θ, g and t are constants (such as the mass of the lever, etc.), T-P produce an equation involving all three variables,

$$\theta = Kg\,(1 - \alpha t) - C,$$

where K and C are constants. (The T-P paper has "$(1 + \alpha t)$", incorrectly). In this case, g can only be a relative value as the constants "can only be approximately determined". By applying this equation to three specific locations (labelled 1, 2 & 3) for one value of 'αt', another relationship is developed linking only the three angles of twist and the three values of 'g', namely,

$$(g1 - g3) = [(g1 - g2) / (\theta 1 - \theta 2)] \times (\theta 1 - \theta 3)$$

If two of the places are chosen where the values of 'g' are known and the meter is read there, say places 1 & 2, then their differences of g and θ are a constant in the above equation, which is a form of sensitivity of the meter giving a value of 'g' equivalent to a value of θ (we learn a specific value of this in 'Results', below). Then the unknown value of 'g' at a third place (g3) can be obtained relative to one of the known values when the meter is read there. This is valid providing 'α' does not change in the meantime. However, there are instances reported in the paper where 'α' has changed, particularly after alterations are made to the meter. Establishment of a new value of the temperature coefficient was "sometimes a lengthy process". Also, as we see below in 'About the results', a different reading can occur at the one place due to a 'daily drift' in the meter, which must also be taken into account.

T-P were given "the most probable" values of 'g' for Sydney and Melbourne observatories as derived by pendulum measurements by "Mr Love" (later expanded in a footnote to "Mr E. F. J. Love") so, to put this theory into practice, T-P needed to make a trip to Melbourne a priority, which they did (see 'About the results')[9]. As these two values are the only absolute values of 'g' mentioned by T-P, apart from published values at the pole and the equator, they may have been the only known values of 'g' in Australia at this time.

Testing in the field

After mounting the first thread in September 1893, the instrument was taken first to Armidale, in north-eastern NSW, in October, 1893. Possibly this was to make use of the biggest elevation-induced gravity difference from Sydney as Armidale is, in fact, the highest city in Australia at 980 m a.s.l. Although the distance from Sydney was 570 km, one can surmise that they thought at this early stage that they needed all the difference in gravity they could get. Presumably T-P knew that the sensitivity of the meter was not nearly enough to make use of the elevation increase in buildings or towers that were no higher than a few storeys in Sydney at the time. As we later learn, the level of sensitivity of the meter would have required a structure at least 30 m high.

While not revealed specifically on this occasion, it is likely that T-P used the train to get to Armidale as the line from Sydney to Armidale opened in 1883. The only other possible land transport at this time was horse and cart (cars not being readily available until the early 1900s), but transport by horse and cart would have been very slow.

Rail transport was not only more suitable for the heavy transit boxes but for T-P it was free. In their acknowledgements, they thank no less than the "Commissioners of the Railways of New South Wales" who through their "enlightened liberality [sic]" provided them with "free passes over the government railways". Furthermore, T- P also gave thanks to the "Secretary for Railways….for the unfailing kindness and courtesy which they showered upon us".

Unfortunately, on this first outing, "the balance was knocked off its stand and practically destroyed". This must have been a huge set-back as 18 months had been spent on its construction. After its restoration, the balance was again taken to Armidale in February 1894 and, unlike the first time when no outcome was mentioned, this time "the results were quite disappointing" and adjustments were needed to be made to the "method of observing". Just as before, however, no actual readings were revealed.

No further field trips were mentioned until May 1897 (three years later) when "the instrument was considered fit to travel" after many experiments with threads (see 'Instrumental development' below) and was taken to Bowenfels (near Lithgow) at an elevation of 900 m a.s.l. and a distance from Sydney by rail of 160 km "… and here we made some promising observations" (but still no details were disclosed). It is puzzling that this site was not chosen for tests before Armidale, being much closer to Sydney and with almost as much elevation difference. One assumption could be that T-P were now, after two unsatisfactory trips to Armidale, no longer as confident that they would get satisfactory results there and chose a location closer to Sydney for better use of their time.

With a new thread, mounted in September 1896, that was thought to be reliable (it lasted for all subsequent readings described in the paper, a period of over two years) a field tour was made in June 1897 from Sydney to Melbourne "by train" and then to Hobart "by steamer", to Launceston by train and then back to Hobart by train, Melbourne by steamer and Sydney by train. It is of interest to know the actual reading sites and in Melbourne the meter was "set up in a cellar of the Physical Laboratory of the University", in Hobart "in a cellar of the Museum and in the University Physical Laboratory" and in Launceston "in the strong room of the Custom House". Such places with solid floors were used, as "Boards…do not form a sufficient inelastic support". Cellars were also favoured, presumably because the temperature was less variable in them during the somewhat lengthy time for a measurement.

[9]According to Home (1986), Mr. E. F. J. Love was, from February 1888, an assistant lecturer in the University of Melbourne and during the 1890s, "undertook precision determinations of the gravitational acceleration at Melbourne and Sydney" (observatories by using pendulums).

In September 1897 yet another (third) sortie was made from Sydney to Armidale. The reason given for choosing Armidale at this time was that "A gravitational survey connecting the towns of the eastern Queensland seaboard with Sydney, was now projected" and Armidale was chosen to be the first station in this survey[10]. In November 1897 the instrument was taken to Springwood in the Blue Mountains (much closer than Bowenfels, at 70 km from Sydney) on three occasions and again to Melbourne in October 1898. From October to December 1898 tests to determine the cause of effects due to travel were made between Sydney and nearby Hornsby Junction on six separate occasions. In all, by now, the meter had travelled over 10,000 km, by horse and cart, train and steamer.

In Springwood, readings were made in the cellar of the Oriental Hotel. In Bowenfels they were made in the house of a Mr Flint (who was thanked for "allowing us to use his house as an observing station") and at Hornsby Junction it was read "at night in the lamp room of the station"[11]. The location in Armidale was never mentioned but quite possibly that was also in some similar place at the station.

Many of these trips resulted in damage to the instrument (let alone being "practically destroyed" as reported in 1893) that then necessitated changes and repairs to many of the components. On return from Springwood for the third time, in November 1897, one of the handles of the (transit) box broke allowing the box to fall 60 cm to the road. The thread was not broken but it resulted in a shift in readings of 60 sextant minutes (as we learn later, equivalent to the difference in gravity between Sydney and Melbourne).

Manner and duration of reading

The method of reading is described in detail in the T-P paper. The variables to be observed were the temperature of the interior of the meter and the amount of twist of the thread to bring the image of the lever "coincident with a cross wire in the eyepiece of the microscope" which was then read on the sextant arm. Readings over periods of temperature change (in one case a rapid change due to the infamous Sydney "southerly buster") show in T-P's "Plot 1" that the platinum wire thermometer reacted more quickly to changes in temperature than did the lever. Also, the sextant reading varied greatly depending on whether the temperature was rising or falling as well as the rate of change. This gave different readings for the same temperature and led to the procedure of making readings just when the temperature reversed, such as in the early afternoon when a maximum temperature is reached. A reading could also be made at minimum temperature, especially if they chose to read in the evenings when the falling temperature of the evening was reversed by the heat of the gas lamps. A disadvantage of this procedure was the extra time needed to observe the temperature long enough to detect its natural reversal.

Figure 6 is one example of three tables of observations given in the T-P paper as "Specimen Observations". The observations were made in Sydney on December 20, 1898 (the fifth last reading ever shown in the T-P paper, as it happens). It is one for a 'natural maximum', the others being a 'natural minimum' and

Natural Maximum. December 20th, 1898.

Time. P.M.	Temperature of instrument.	Readings of end of level.	Circle reading.	Remarks.
h. m. s.	°C.		° ′ ″	
1 1 0	21·509	...	...	Air temperature 22°·1
2 12 0	21·779	...	...	" " 22°·4
2 42 0	21·890	...	...	" " 22°·5
3 53 20	22·033	6·1 41·1	81 26 50	
3 57 30	22·033	6·2 41·1	81 26 50	
4 2 30	22·033	6·2 41·1	81 27 0	Lever continues to rise, but temperature is steady
4 21 0	22·033	6·2 41·1	81 27 20	
4 24 0	Begins to fall			
4 26 0	22·31	6·2 41·1	...	Lever turned, air temperature 21°·6

Aneroid 28·2. Lever clamped at 85°
Level reversed. B end to eye-piece. Readings of bubble 6·2 41·1
" " A " " " " 6·2 41·1
" " B " " " " 6·1 41·1

Figure 6. *A table from the T-P paper shows the "Circle", or sextant, readings, in degrees to 10s of seconds, rising to a maximum while the instrument temperature is read to a precision of 0.001°C for 3.5 hrs.*

an 'artificial maximum'. Here the temperature reading began nearly three hours before it was observed to level out and the first reading of the Sextant began. In that case, the temperature was the same (to within 0.001 of a degree) for 28 minutes while the lever reading continued to rise. The sextant was read over a period of 28 minutes.

Readings were quicker when the balance was artificially heated with a gas burner or lamp. This meant the observer(s) controlled the temperature change and could read at a maximum temperature in less time than for natural changes. However this procedure led to some erratic readings at the same place over one month. T-P also believed this to be "barbarous treatment" of the instrument and chose in future to only read at natural changes. Also, it was noted that the temperature could be "disturbed considerably by the presence of the observer".

Thus, a complete reading of sextant angle, pressure and temperature, with the levels checked, could take several hours and the shortest time overall was 90 minutes. This is still a quicker than the time to read the Eötvös pendulum, the instrument most in use in the 1920s. A modern meter is read in one minute or less.

About the results

T-P proposed "two conditions which a balance of this kind must fulfil for it to be a working instrument – firstly, it must give accordant readings at any one place from day to day; and secondly, the readings must not be affected by the vibration inseparable from transport". At any one place, the readings will differ due to two causes: temperature changes, which, for comparisons, are reduced to a common temperature by the application of the temperature coefficient, and "the slow elastic after-working of the thread and its supports". The latter produced a daily drift, not uncommon to modern instruments, which at first was too high but was later improved by changes to the instrument to be, finally, less than the repeatability value (see 'Specifications').

The results of the latest surveys (from June 1897 to December 1898) are illustrated in 'Plots' 2-9 in the T-P paper, as grids of time in days on the abscissa and sextant angles in minutes on the ordinate[12]. Figure 7, as "Plot 4" from the paper, is an example (one of the better ones) of the eight plots of results. It

[10] Such a bold project may have proved too difficult to achieve given the modes of transport available and, possibly, the departure of Threlfall to England in the following year (see 'About the authors').

[11] "Lamp room" reminds us that electricity was not yet available even in Sydney until 1904. Until then, light was by gas lamp.

[12] These plots may be viewed at the URL listed in References for the T-P paper.

shows readings taken in Sydney and Springwood in the period October – November, 1897. The readings at Sydney shown here are almost one per day, a density that ensures that the daily drift at this time is well determined, in this case 2.3 sextant minutes (in the following, 'sextant minutes' is abbreviated to "sm" which also avoids confusion with minutes of time).

Such was not the case for the first trip to Melbourne, in June 1897, where only single readings are shown in each place of observation (in T-P's "Plot 2"). The differences between Sydney and Melbourne, going and on return, were 78 sm and 58 sm respectively (see below where the mean of 68 sm is used). For the last trip to Armidale, in September 1897, (T-P "Plot 3") only three readings at Sydney over five days produced a doubtful daily drift value that was then applied across the only two readings over two consecutive days shown at Armidale, thus making the difference between the two stations very uncertain. This would consequently make any determination of 'g' at Armidale uncertain too.

Also illustrated in Figure 7 is an offset, or 'tare', on 6 November 1897 of 5 sm. Such offsets of more than 2 sm were attributed to "when the instrument was travelled [sic]" and in one case in particular, "to the looseness in the joint fixing the lever to the thread". It can also be noted from Figure 7 that the repeat readings on the same days in Springwood differ by 2-3 sm. This same difference is also shown on other plots on the rare times when repeat readings on the same day are shown which is contrary to T-P's claim of no more than 1 sm for repeats. The much smaller difference in readings between Springwood and Sydney on the third occasion in late November 1897 compared to the other two earlier times, which give a consistent difference of 35 sm, was attributed to "a permanent change taking place due to the travelling".

"Satisfactory observations were made in Melbourne" on the second trip in October 1898 "with a view to finding the sensitiveness [sic] of the instrument". Single readings on each of three days in Melbourne (T-P "Plot 5") gave the difference to Sydney at the same time (as extrapolated from an uncertain drift line) as a doubtful average of 63 sm. Together with the (only) other value of 68 sm (itself the mean of two differences) obtained before, in June 1897, T-P chose to use a somewhat arbitrary value of 60 sm as the final difference "until the difference has been more accurately determined". Maybe T-P believed that since readings were becoming more reliable, any subsequent differences would trend to this lower amount. However, no further trips to Melbourne were reported in the paper to provide more confidence in this value. With the difference in gravity between Sydney and Melbourne given by Love (see 'About the theory') as 277 mGals, using 60 sm meant that one sm equalled 4.6 mGal, or as T-P have "a change in the value of g of 1 part in 100,000 would be represented by a change in reading of 2.12 sextant minutes"[13]. Here then is the ratio from theory of 277/60 (see 'About the theory') as the sensitivity constant to be used for relating the reading in Sydney to that of an unknown place. It is unfortunate that this important constant was not established with more assurance.

Providing the constant was unchanged and readings were generally reliable, T-P claimed that eventually "we may say that the value of g at any station may be determined relatively to that at some standard station by a single observation… with certainty to one part in 100 000". Given their results, I believe this to be optimistic. No new values of 'g' at an unknown place were attempted to be determined by applying the theory other than in the case of Hornsby, the last location for field measurements and after "the readings are not now affected by travelling". Also, by then the daily drift was the lowest ever at ~0.2 sm/day. Using differences from Sydney from three separate trips, T-P claimed "a maximum difference [between the three readings] of 0.4 sextant minute, or to less than 1 part in 500 000 in the value of g"[14]. However, I dispute this accuracy as one of the three values is itself a mean of two readings on the same day and the difference could therefore be as much as 0.6 sm giving an accuracy of more like one part in 300 000 or < 3 mGals (it was not unusual for T-P to be somewhat relaxed with their conclusions from the results, as seen elsewhere).

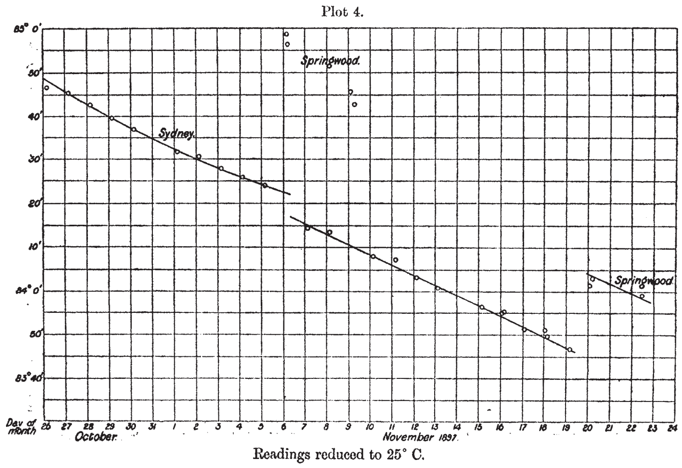

Figure 7. *An example of the method of plotting the results from 'Plot 4' of the T-P paper, a plot of the readings in Sydney and Springwood from Oct. 26 to Nov. 24, 1897. It shows a near-linear daily drift and a 'tare' on Nov. 6.*

At no time was any attempt made to correct gravity readings for latitude, elevation, density or terrain. The accuracy of the determination of 'g', at an unknown site, was not sufficient to justify any further such processing.

Specifications

A list of specifications of the instrument and its performance, as we have with modern gravity meters, is not provided and apart from the weight and the overall dimensions being inferred as above by me, such performance factors as resolution, accuracy and drift are scattered throughout the paper. For the factors given in the following, the equivalent values for a Scintrex CG-5 gravimeter (see 'References') are in brackets.

T-P consider the error of the final reading as made up of the error in measuring the temperature, the angle of twist and the levelling. "If all these three maximum errors conspire, we shall obtain a value of g in error by one part in about 300 000". That translates to about 3 mGal in Sydney. T-P state that the "accuracy of a determination of g … depends on the possible deviation of a single observation from the mean".

Only at the end of the discussion of results did T-P address the sensitivity of the meter and a relationship between readings and

[13]The value of gravity at Sydney Observatory from Love was "979.639" and "979.916" at Melbourne Observatory.

[14]It was this accuracy that McCaughan (1988) claims of Pollock that "astonished his contemporaries" (see 'About the authors').

values of gravity suggested as, 1 sm equal to 4.6 mGal. Therefore, the best resolution of 10 seconds of angle represents 0.77 mGal (CG-5: 0.001mGal). The repeatability of readings in the same place was generally, from their plots of results, about 1 -2 sm, equivalent to less than <10 mGals. (< 5 microGals).

Observed discontinuities (or offsets) can be of the order of 5 sm, equal to about 20 mGals. ('Tares" are less than 5 microGals). The daily drift, was finally 0.2 sm in December 1898, or about 1 mGal. (<0.02 mGals).

Instrumental development

"Appendix B" of the T-P paper titled, "Notes on experiments made with various forms of gravity balances" is 6 pages of a very detailed chronology of all the challenges and trials T-P experienced from September 1888 to June 1897 together with the innovations they devised to overcome them.

At first T-P made calculations as to the "sensitiveness" of the balance and then made "several" experimental balances 'on the bench' (in this case "on an old watchmaker's lathe-bed"). "The thread and levers were massive [then] compared with those we now employ". "By May, 1891, [after 2 plus years] we had sufficient experience to hope to detect the lunar disturbance of gravity" (the 'tidal effect'). At this time a mirror was mounted on the lever and the balance was read in a cellar on a stand weighted down "with sand and stones". During the latter part of 1891 T-P used a "Michelson's arrangement of interference mirrors" (see more on Michelson in 'Famous names'). This system "presented no advantages in practice" and "By March, 1892 [another ten months later] we became convinced that it was hopeless to attempt to disentangle the lunar effect from the instrumental irregularities…" and "The research was therefore abandoned".

Investigations into constructing a portable instrument started in May 1892. This led to the present form of the instrument, which was ready in July 1893, and a thread, made by the 'catapult method', was mounted in September 1893. In October, 1893, while the instrument that was "practically destroyed" in Armidale was repaired, another instrument "intended as a trial instrument" was built "in which the whole of the working parts were immersed in mineral sperm [whale] oil", presumably to test the oil's damping ability. This in itself led to two years of "subsidiary" experiments testing the resistance of different cements when immersed in oils. In order to see whether it would be possible to observe at sea, the instrument was mounted in a swing whereupon they satisfied themselves "that no amount of damping would enable accurate measurements under such circumstances".

When the repaired instrument was deemed to be "worse than the one that had been broken…an experimental thread was mounted on "yet another balance", in January 1894. Then for "two months of incessant work we struggled with fine threads" leading to "a separate experiment on another balance" with the realisation, in August 1894, that "The very fine threads have not been a success". Initially they were too thin, often only 0.001 cm in diameter, with many breaking, and "it was not till March 1895, that we succeeded in obtaining a thread to satisfy us". However, this was broken in November 1895 while making other repairs and two more months were spent getting another satisfactory one, until July 1896 "when it was pleased to break" (no reason was given in this instance).

After the bad experience with very fine threads, in August 1894, "we abandoned the lever and mirror in favour of a microscope, and also brought the arrester to its present form". In September 1895 the theodolite, given to T-P by the Surveyor-General of NSW was replaced "by a sextant arc".

Yet another "new thread was got in September 1896, after some weeks of shooting. This thread is still in use and is the best we ever got [sic]". Then, after "a great deal of trouble in stopping leaks in the apparatus" and effects due to "wear in the bearings", the instrument was again "considered to be fit to travel" to Bowenfels in May 1897. This was after two years spent drawing more ideal threads and after five years altogether developing the portable instrument, admittedly with some subsidiary distractions along the way.

Many of the difficulties they faced would now be solved easily in other ways. For example, when an air-tight seal was required on the turning shaft they used 'tallow' (animal fat) and mercury, and because of the different air pressure the mercury drove the tallow through the joint. This was the basis of the "stuffing boxes" (see 'Some observations on the published paper').

Comparison with modern gravity meters (see for example the Scintrex CG-5 "Autograv" Gravimeter)

Some of the elements that T-P devised in building a meter for the first time have carried through to modern meters. As we have seen in 'Description of the T-P meter', some current meters still use fused quartz material, a pointer ('lever'), a microscope and a clamp ("arrester"). Many of the technicalities that T-P had to overcome to obtain reliable readings are still present in modern gravity meters. For example, temperature effects were dealt with by accurate measurements of the ambient temperature and the temperature inside the chamber by a sophisticated platinum thermometer involving an electrical circuit of resistors able to measure 0.001 0C. However, modern meters have electronic temperature compensation and, if necessary, separate heaters, and have solved T-P's effects due to varying air pressure by employing vacuum-sealed chambers. Drift, which T-P finally improved to an acceptable level, is almost eliminated today. Modern meters no longer suffer 'tares' as did T-P through rough handling. They are much more rugged and smaller (e.g. 30 × 22 × 21 cm) and lighter (8 kg or less). The T-P meter lacked the modern attributes of digital reading displays, digital storage or remote control.

About the authors

Threlfall, Sir Richard (1861–1932)

According to Home (1990), Threlfall was born in Lancashire, England in 1861 and before coming to Australia in 1886 worked as a demonstrator in the Cavendish Laboratory under his friend J. J. Thomson (see 'Famous names') who regarded him as "one of the best experimenters I ever met". In 1886 he was appointed to the Chair of Physics at the University of Sydney whereupon, according to Home, "his research developed along three separate lines", one of which was to develop "a quartz thread torsion balance…gravity meter" with "his [then] student and friend, J. A. Pollock". Two publications by Threlfall are referenced in the T-P paper, both in relation to the drawing of the quartz thread and its characteristics. One, "to refer the reader to" is a book entitled "Laboratory Arts". According to Home (1990), Threlfall left Australia in 1898 to work as Director of Research at Albright & Wilson in Oldbury, England and was elected a Fellow of the Royal Society, London in 1899 (before the T-P paper was submitted). Also, it can be noted from the T-P paper that the meter was being used up to December 22, 1898.

Pollock, James Arthur (1865–1922)

According to McCaughan (1988), Pollock was born in Cork, Ireland in 1865 and migrated to Sydney in 1885. Specialising in physics and mathematics, he graduated from the University of Sydney in 1889 with a B.A. and University Medal and in 1890 was appointed demonstrator in physics assisting Professor Threlfall. McCaughan (1988) states that "he published jointly with Threlfall and worked independently in optics, using the Michelson-Morley technique". This expertise was made use of in early trials of the balance (see 'Instrumental development'). McCaughan (1988) also states "an accuracy of 1 part in 500 000 achieved for the relative value of the acceleration due to gravity astonished his contemporaries". This order of accuracy is indeed claimed in the paper but only in the second last paragraph and is doubtful in my opinion (see 'About the results').

In 1899, Pollock succeeded Threlfall as Professor of Physics and in 1916 was elected Fellow of the Royal Society, London. His enlisting in the Australian Imperial Force in 1916 at the age of 51 (!) is particularly interesting for geoscientists, as he served in France with Professor (Sir) Edgeworth David in the Mining Corps, where he helped to design listening apparatus to foil German countermining measures. Pollock died in office in Sydney in 1922.

Famous names in the T-P paper

Some idea of the scientific atmosphere of the times in which the gravity meter development took place is provided by the famous physicists listed in the T-P paper's "Bibliography". Here names are listed with references to specific papers and reports, some from the British Association, dated 1886 and 1887. In the following text the underlined names are just as they appear in the T-P paper. First is Herschel (with a reference, "Outlines of Astronomy" not dated), is presumably Sir John Herschel (1792-1871), the English polymath who, in 1849, proposed the possibility of measuring gravity using a mass on a string (Garland, 1965); Siemens, C. W. (with a reference dated 1876) is presumably Carl Wilhelm Siemens (1823–1883), the German engineer whose brother, Werner von Siemens lent his name to the S.I. unit of conductance; Poynting (with a reference dated 1886) is presumably, John Henry Poynting (1852–1914), the English physicist who published on the determination of the universal gravitational constant; and Lord Kelvin (with a reference dated 1886) is the British physicist (1824–1907) of thermodynamics and absolute temperature fame.

Also discussed in the paper is an early system T-P tried using "Michelson's arrangement of interference mirrors" no doubt the Michelson (1852-1931) of the famous Michelson-Morley pair. This is confirmed by McCaughan (1988). In addition, the paper was "Communicated" to the Royal Society by Professor J. J. Thomson, F.R.S. (1857–1940). Professor Thomson discovered electrons and Threlfall worked under him in the Cavendish Laboratory (Home, 1990).

Epilogue

Information on any subsequent use of the balance after publication of the T-P paper is provided in another paper co-authored by Threlfall, when he was in England, and titled "Further History of a Quartz Thread Gravity Balance" (Threlfall and Dawson, 1933). In that paper it is revealed that, on the departure of Threlfall to England in 1898, the instrument was to be left in the charge of Professor Pollock "and that he should continue the work in so far as his duties as Professor of Physics enabled him to do so. Unfortunately, an opportunity never occurred, and the balance was stored in one of the cellars of the Physics Laboratory of the University till 1923." We may excuse Professor Pollock from making any further use of it, particularly as he did service in WWI during that period and died in 1922 (see 'About the authors'). Nevertheless, this meant that further use of the instrument was delayed for 25 years.

Threlfall and Dawson (1933), also reveal that it was suggested by the then Director of Research at the British Admiralty, Sir Frank Edward Smith, that the balance be sent to England for possible further use. Accordingly, in 1923, it was "mounted in the Magnetic Annexe of the National Physical Laboratory" at Teddington, near London. Threlfall and Dawson (1933) then describe how, after 25 years had elapsed, there was some deterioration of parts and oils, etc., requiring a virtual reconstruction of the instrument. I would expect that the 'tallow' would need replacing for one thing. Observations were made in 1928 in Teddington and Kew Observatory with results tabled in the paper. Finally they conclude with a discussion "on the design of a new instrument", listing all the improvements that 25 years of advancement could provide. However, as it was now approaching the 1930s, other more sensitive rivals were beginning to appear.

Some observations on the published paper by Threlfall & Pollock

The paper consists of 44 pages including 2 figures, 3 tables of sample observations, 9 "Plots" of results and 2 separate "Plates"[15]. The latter consist of scale drawings of parts of the assembly including a horizontal section of the balance (see Figure 3) and two "photographs" of the interior and exterior of the meter (see Figures 4 and 5). Overall, the paper would have benefited from some editing.

The first three pages start without a sub-heading, and are a combination of a brief introduction to the parameters of the design, a very brief summary of aspects of the construction and field operations and finally, acknowledgements of assistance. One acknowledgement recognizes the value to the meter's existence of Mr James Cook F.R.A.S. "mechanical assistant … who made the whole instrument, except the thermometric appliances" and without "his great mechanical skill and accuracy we should in all probability have failed in our undertaking". T-P also gave thanks to the Surveyor-General of New South Wales for "having placed a disused theodolite at our disposal".

The first sub-heading, starting at the bottom of the third page, is "Bibliography" (referred to above for its famous names), then "General Description of the Instrument and Preliminary Remarks" followed by "Instrument Details", where 11 pages are devoted to 12 individual components of the meter. Each has its own section including the most important Thread and Lever sections but also extensive details on the Microscope, Thermometry (consisting finally of a platinum wire thermometer and its associated Resistance box), The Arrester (which we now

[15]The "Plates" in the paper are numbered 1 & 2 (p. 258) but in the published paper they are Plates 13 & 14, respectively.

call a ‘clamp’), the Stuffing Boxes (a type of air-tight seal on the rotating shaft), Thermal Insulation and finally, Packing and Transport. Even though I was a very interested reader of the T-P paper, I found some of this section in particular to be too detailed in the technicalities, making it hard to retain interest.

The following sub-headings in the T-P paper are, “Theory of the Balance”, “Observations” (including the method of observing), “Discussion of Results” and finally “Appendix B” (despite there being no Appendix A included). A summary of Appendix B, is in ‘Instrumental development’. As perhaps is usual for the time, references are not in a separate list at the end but at the bottom of the relevant page using an asterisk or other such symbol.

Because of some differences with dates between the main paper and Appendix B of the same events, some parts may have been written by only one of the authors. The language is often quaint with literary tendencies. For example, a thread doesn’t just break but “it was pleased to break”, and overheating of the instrument was “barbarous treatment”.

Acknowledgements

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