The First Absolute Gravity Observations in Australia and New Zealand

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ABSTRACT

This paper argues that the first absolute gravity measurements in New Zealand were not carried out in 1882 as in H.W. Robertson & R.A. Garrick (1960), but about 100 years earlier in 1773, just like the first absolute gravity measurement in Australia which was not carried out in 1819 (or even 1937) as in A.S. Murray (1997), but much earlier, in 1788. Huygens' Principle of the reversible compound pendulum dating back to 1673 is used in this argument. It is shown that the gravity measurements of 1773 and later represent absolute gravity after Henry Kater clarified one of the variables. Some adventures of these first gravity field parties are outlined, such as the delay of a survey party by inclement weather and near loss of a survey vehicle, stolen survey equipment, a thief shot at, and field hands allegedly eaten by the locals.

KEYWORDS: *Absolute gravity, reversible pendulum, Shelton clock, New Zealand.*

1 INTRODUCTION

Generally the conventional wisdom is that in the 1800s gravity measurements reached an accuracy of 1/10,000 or 100 milliGals (mGals) and that it was not until the 20th century before there was a gain of an order of magnitude to 1/100,000 or 10 mGals. Henderson (2015) claims accuracies around 3 mGal appeared around 1900. Today we are looking at a few microGals. It was also thought by some that pendulum measurements really needed reference to one other gravity measurement for accuracy and thus still represented relative gravity. The author wants to take a closer look at this, especially the last assertion.

It is thought that the first absolute gravity measurement in Australia was carried out in 1937 but there are some earlier determinations on record. In Murray (1997) there is mention of absolute gravity measurements in Australia in 1819. This fact appears to have been sourced from Dooley and Barlow (1976). In the latter there is indeed reference to French expeditions carrying out pendulum gravity observations. There was gravimetry carried out by Freycinet with a pendulum in Sydney City in 1819 and by Duperrey in Sydney Fort (Fort Denison?) in 1824. But a less well known gravity observation from 1788 predates that, observed with a temperature compensated gridiron pendulum. This work was carried out by a first fleeter: by lieutenant William Dawes, the first fleet astronomer. This observation was mentioned in Morrison and Barko (2009).

About 8 years ago, part of this pendulum gravity observation by William Dawes was brought to the author's attention. This brought about a scoping study in order to evaluate what the pendulum length would have been and whether there was any evidence for this length and other data. Using the EGM2008 equation for normal gravity, an estimate was made of the pendulum lengths in use by Dawes and others at the time. The search for supporting evidence led to the rediscovery of explanations by William Wales (of the second Cook expedition) about calibrations of pendulums and common errors which can be made using them. A rather serious but recoverable error was actually once made by Wales in setting his pendulum length, so he was speaking from experience. He refers to this in his introduction, in Wales and Bayly (1777).

William Dawes' gravity measurement data was published by the author in Bosloper (2010) at the FIG2010 congress in Sydney. This not only allowed William Dawes' pendulum length to be recovered but opened the door to an understanding of other gravity measurements of 1773 made during Captain Cook's 2nd expedition, for which pendulum calibration information was available. In Chambers (2016) we find a description of Cook's charting of the east coast of New Holland in 1770 during the 1st expedition, but no gravity work was undertaken on this coast according to Howse (1969).

In Maskelyne (1761), Neville Maskelyne described in a letter to Lord Cavendish how Dr James Bradley explained to him how to set the pendulum length accurately, in connection with his (Maskelyne's) trip to St Helena for the Transit of Venus. In this letter Maskelyne also refers to the communication in Bradley (1733) by Dr Bradley to the Society, wherein Bradley states that the standard isochronal pendulum length is assumed to be 39.126 "English inches" for London. This value is attributed to measurements by George Graham in 1722. This value was only changed to 39.128 by 1790, almost 60 years later. An isochronal pendulum is a seconds pendulum, marking precise "dead seconds" at a location as determined by stellar transit observations (sidereal time) or noon determinations (for mean solar time). Gravity is basically π^2 times the place's isochronal pendulum length plus a non-linearity correction. This means their gravimetry was carried out with what they knew was physically the right pendulum length and thus the result was absolute gravity for the time. Henry Kater's work later was only an enhancement of the quantification of the pendulum length and can be better related to the French "metre" by a full order of magnitude.

It is now clear that the first absolute gravity measurements in New Zealand were not carried out in 1882 by the U.S. Coast and Geodetic Survey as in Robertson and Garrick (1960), but about 100 years earlier in 1773 by the gravimetry teams of the 2nd Cook expedition. This was 100 years after Jean Richer determined the pendulum length for a seconds pendulum in Jamaica in 1672 and suggested the earth was flattened at the poles.

William Wales' and William Bayly's gravity determinations at Dusky Bay and at Queen Charlotte Sound in 1773 were determinations of absolute gravity. They had timed the swings of the pendulum in Greenwich against an accurate time base, the rotation of the earth, in order to calibrate the pendulum length and set it precisely, right down to the last thousandth of an inch. For example, William Bayly's pendulum calibration showed his pendulum was within three tenthousandth of an inch of the isochronal length for a seconds pendulum at Greenwich when the regulator nut was set with 9 at the index. The only thing that was not yet actually known was how to accurately measure the effective pendulum length of a physical compound pendulum in a practicable way. The fact that the pendulum rod is not without mass and that the mass distribution in the bob is never uniform at the parts-per-million level complicates the matter. The theory which described how to quantify the pendulum length with a reversible pendulum was developed by Christiaan Huygens 100 years earlier and published in 1673, and a practicable solution came on the scene 40 years after Cook, around 1817 through the work of Henry Kater.

2 THE LENGTH OF THE ISOCHRONAL PENDULUM

In *Horlogium Oscillatorium*, published in Huygens (1673), Huygens developed the “moment of inertia” concept in mathematical terms, and derived an expression for the “reduced length” of a physical (compound) pendulum as a function of the moment of inertia of the oscillating body (Horlogium, Part 4, Proposition VI). It was Leonhard Euler who some 90 years later gave this concept developed by Huygens the name “moment of inertia” in Euler’s Theoria Motus Corporum Solidorum sev Rigidorum in 1765.

The “reduced length” is the length between the point of suspension and the point of oscillation of a conceptualised mathematical pendulum with all the mass represented as a point mass at the end of a rigid rod with no mass at all, which oscillates at the same period as the physical pendulum. In *Horlogium*, Huygens showed that any pendulum with the same reduced length will oscillate with the same period when gravity stays unchanged and gave the equation for this.

In his 1673 *Horlogium*, Huygens also developed the parallel axis theorem (Horlogium, Proposition IX) we alternately know as the Huygens-Steiner theorem with which you can recalculate a body’s moment of inertia relative to a different axis of rotation or oscillation, parallel to the previous axis. More than a century later the Swiss Jakob Steiner did a more elegant mathematical derivation of this theorem, so it now also carries his name.

In *Horlogium* (Part IV, Proposition XX) we also see the discovery by Huygens that the physical pendulum can be reversed, where the point of suspension is interchanged with the point of oscillation, and the so reversed pendulum will show the same period of oscillation if it is suspended from a parallel axis through the right point. The point of suspension and the point of oscillation will be separated exactly by a distance equal to the reduced pendulum length as defined above. It created the missing step between the conceptual mathematical pendulum and the real physical compound pendulum. This opened a path to be able to determine this conceptual “reduced length” by finding the point of oscillation empirically. The acceleration of gravity can then be determined with the pendulum equation, when the “reduced length” is known.

For a while Huygens’ discovery was seen as an academic artefact and other methods of constructing pendulums were tried in order to make the pendulum length more clearly defined and more measurable. Cassini and Borda tried a 12-foot wire pendulum in 1784 with a platinum sphere at the end. Complications arose because the wire flexes laterally during the swings and also stretches and shrinks with temperature and through the changing forces on it.

Then in 1817, Henry Kater found a way to follow Huygens’ suggestion. Henry Kater was a member of a committee tasked to refine the London pendulum length. He created a reversible pendulum which contained two opposing knife edges at some separation from each other, which could be rested alternately on a glass plate (Figure 1). Some weights on this pendulum were adjustable so that you could find a position for the weight where the pendulum would swing with precisely the same period in the reversed position. This allowed the distance between the knife edges to be measured to within a few microns and and the pendulum equation then delivered the absolute value of the acceleration of gravity. In this way, one could now calculate the value for the “reduced length” belonging to any physical pendulum or period.

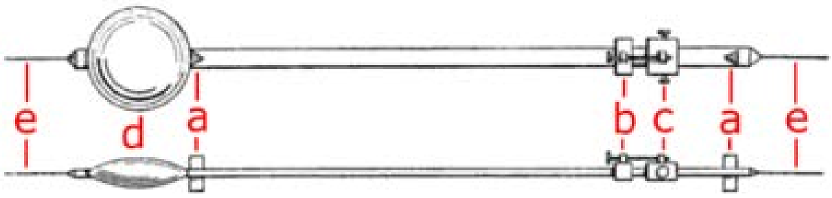


Figure 1: Henry Kater’s pendulum (after Watson’s physics textbook of 1920). The knife edges are shown as a. The adjustable weights are b & c. The amplitude scale can be read with the pointers shown as e.

It was often thought until now that the earlier period in the late 18th century only produced relative gravity measurements. What one forgets is that the variable (the Greenwich length of the seconds pendulum) which Henry Kater solved in 1817 by constructing a reversible pendulum as described in principle by Huygens, is exactly the length of the pendulums which were used in the previous century. The lengths of the older pendulums were calibrated at Greenwich in the 1700s by the use of astronomy. They were made to swing exactly 86,400 seconds in a 24-hour day by adjusting a regulator nut supporting the pendulum bob – this created an “isochronal” pendulum for that location. Before Kater, the pendulum length itself was *set* at an order of magnitude more accurate than the accuracy with which one could *quantify* the length. This is because the definitions of the point of suspension and the point of oscillation were hard to realise in practice until then. The knife edges now solved this problem.

The 18th century astronomers like Neville Maskelyne at Greenwich were not only able to create and calibrate seconds pendulums empirically, but these bi-metallic gridiron pendulums were also of an intrinsically higher quality than Kater’s. This is because of John Harrison’s accurate temperature compensation of the body of these pendulums used by Maskelyne. Although Kater later measured the reduced pendulum length to a precision of 2.5 microns, he had to read representative temperatures and calculate the compensation for expansion throughout the duration of the oscillation tests. John Harrison’s bi-metallic pendulums of a century earlier were self-compensating for temperature changes in real time.

By inference this means we can use Huygens’ conclusions regarding equal periods and say that Maskelyne’s pendulums built by John Harrison must have the same reduced pendulum lengths as later determined by Henry Kater if both are made to swing with the same period and have been calibrated against the same time base (the rotation of the earth). Once Captain Cook’s pendulum lengths are regarded as known, his astronomers’ gravity observations become determinations of absolute gravity at the 10 parts-per-million or 10 mGal level – this is the same order of accuracy with which time could be measured. This means (with 2020 vision) that his determinations in Dusky Bay, New Zealand and Queen Charlotte Sound, New Zealand, and his determinations on Shag Island in Tierra del Fuego, are the very earliest and veritably the *first* absolute gravity determinations in New Zealand and in Chile!

Neville Maskelyne set down some specifications for a clock (or actually a frequency counter) that allowed one to use it as a gravimeter. Before his trip to St Helena in 1761 for a Transit of Venus observation, he made the following list of requirements for an accurate astronomical clock, as mentioned in Higgit (2014): The clock had to have a hand to distinguish seconds and this had to be not only clearly visible but also audible. This already meant it had to include an approximately 39-inch pendulum so it would swing exactly once every second and cause the "tick". The clock had to experience no loss of time when the once-monthly moment came to wind it up, i.e. it had to maintain 'power'. The pendulum also had to be of a temperature compensated type.

John Harrison had constructed the temperature compensated grid iron pendulum in 1725 as mentioned in Hellman (1931), and had later said he could easily temperature compensate the pendulum clock to not lose more than one second in 100 days if given sufficient funds to enable this. This would have been a phenomenal accuracy of 0.1 parts per million or 100 nanoseconds per second as the accuracy of a time base in the middle of the 18th century, using then current state-of-the-art technology. Even 200 years later the rotation of the earth was still one of the most accurate and reliable time bases. But John Harrison was obviously only allowed sufficient funds to make the astronomical regulator clock pendulum temperature compensated to perform to slightly better than a second per few days or, say, less than 10 parts per million or 10 microseconds per second.

So the gravimeter which these first absolute gravimetry field parties carried was a Shelton astronomical regulator clock. This was basically a very accurate and tall "grandfather clock" with a specially calibrated temperature compensated pendulum which could be given a "reduced length" of g/π^2 metres with g being the gravity at Greenwich, by just adjusting a nut when at Greenwich. This would make it a "seconds pendulum". In order to realise this length, the pendulum was calibrated in Greenwich against the rotation of the earth in such a way that the hands of the clock precisely recorded 86,400 seconds in a mean solar day. This could be accurately fine-tuned with the regulator nut at the bottom of the pendulum.

3 THE FIRST ABSOLUTE GRAVIMETRY IN NEW ZEALAND

In the following story, the mode of transport for the first gravimetry field parties of New Zealand were of course not vehicles but 400-ton 3-masted colliers or coal barks sailing around the world with about a hundred mouths to feed aboard. Maintenance of sails or repairs of a mast or a hull was an often returning occurrence for barks like the Resolution and the Adventure. Gales and fog could separate you, reefs and uncharted rocks were a mortal danger so you mapped them. When some trigonometrical mapping or charting of baselines of a few miles on nearby land were required to help with this, they were not unknown to have been sometimes measured by the "timed gunshot-and-smoke interval" after climbing some of the mountains.

It is amazing that 250 years ago two survey parties could be so confident of their own positioning capabilities to agree that if losing sight of each other they would wait for the other in a bay of a far away island 9,000 km away. Sure enough, they did loose sight of each other after heading north again from the Antarctic South latitude of about 59º, south-east of Cape Town. Somewhere between the Crozet Islands and the Kerguelen Islands two parties were separated by fog, so they stayed in the area for three days as arranged, tacking back and forth and firing a gun into the fog at hourly intervals. The fall back position was to meet at Queen Charlotte Sound in New Zealand, a quarter of a world away. Captain Furneaux, after experiencing frozen sails and brittle rigging and more, headed north with the Adventure after stopping at Van Diemen's Land (i.e. Tasmania) for wood and water and continued on to the Cook Strait of New Zealand. Captain Cook headed for Dusky Bay in the south of the South Island for astronomical work and gravity surveys first, to then also proceed to Queen

Charlotte Sound later.

When the gravimeter had to be deployed, one had to drag a tall grandfather clock, the Shelton astronomical regulator clock, onto a row boat, land it safely after passing through the surf and carry it up to a high and dry spot near the shore. Cook's astronomer William Wales described the Dusky Bay site preparation effort for the gravimetry work in his observations logbook of the Resolution (Cambridge University Library, 2017):

> Thu 25 May 1773. Sailed into Dusky Bay.
> Fri 26. Anchored in 50 fathoms and headed to the place. Found a better Anchoring Place & in the morning moved the ship to it and Anchored there.
> Sat 27. Went in with Capt Cook to look for an observing place & found one; but in the Morning met with Natives, which rendered it improper. Showers.
> Sun 28. Made choice of another. Clearing away the Trees, which grow everywhere here down to the Water's Edge. Heavy Rain.
> Mon 29. Employed as above. Frequent Showers, Wind at North.
> Tue 30. Still Employed cutting down Trees & levelling the Ground. Strong Gales, Northerly & heavy Rain.
> Wed 31. Cutting down Trees and erecting the Observatory. First part Showers: the latter clear & fine weather.
> April 1. Got up the Clock and Quadrant but found they would not do, the Ground was so loose. First part Clear, Latter, showers as usual.
> Apr 2. Cut down two large trees which stood close together, on the stump of one set my Clock, on the other the Quadrant and Erected the Observatory over them.

The Bird quadrant referred to above, as well as delivering latitude and longitude, was for determinations of mean noon by equal altitudes of the sun in order to determine the clock rate of the astronomical regulator clock which was the actual gravimeter.

This site preparation for New Zealand's first absolute gravity measurement had taken the first seven days after their arrival. The preparations for stabilising the regulator clock were once described in Dixon (1769) and Bayley (1769). Generally, a 3-foot deep hole would be dug in which a 14-inch wide board or oak plank, possibly at least 6-foot long and almost 5-inch thick would be inserted, standing up perfectly vertical. This is almost as massive as two railway sleepers shoulder to shoulder and almost one and a half times as thick as normal sleepers. The hole would then be backfilled with dirt and rocks and rammed tightly so the plank was not moving. The back of the Shelton regulator clock would be screwed to this and the clock would be chocked as well. Obviously this or a Smeaton iron frame were not firm enough in the case of Dusky Bay, and Wales decided to set the astronomical regulator clock case up on a sawn off tree trunk (Figure 2).

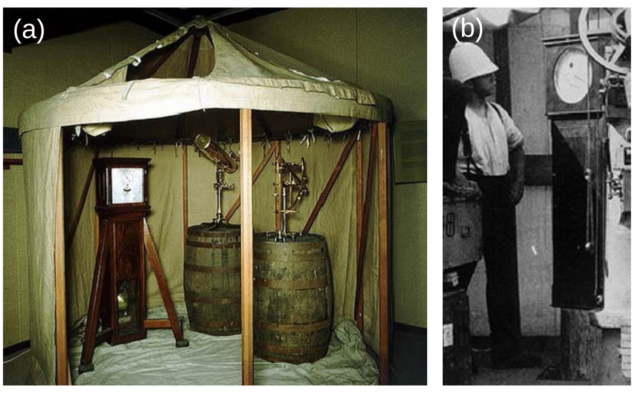
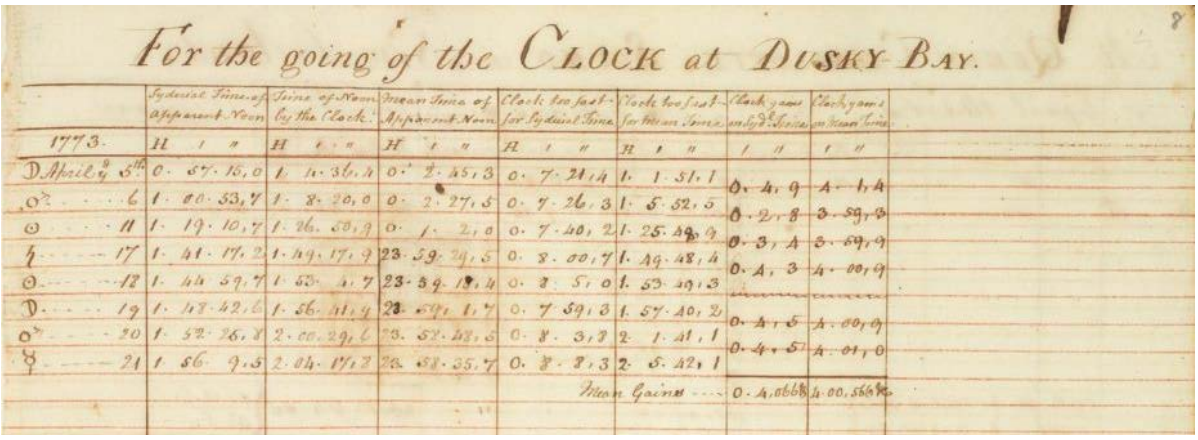


Figure 2: (a) Clock on the ground (National Maritime Museum, Greenwich) and (b) clock on sawn off tree trunk (Jimbour, Queensland, 1882).

He started his 16-day series of gravity observations on Monday, 5 April 1773. This long run of observations allowed the Shelton clock rate to be averaged for higher accuracy, by rating it against equal solar altitudes carried out daily with the quadrant. The gravity observations at Dusky Bay started about the same time as when the lost ship, the Adventure, arrived in Queen Charlotte Sound 800 km to the north of them, after having lost sight of Cook's ship two months earlier.

Wales summarised the Dusky Bay results of his 16-day observation run of gravity observations as follows (Figure 3):

> At Duskey Bay in New Zealand, latitude 45º 47' 5/12 S, longitude 166º 18' E., Clock B gained 4' 0.56" on sidereal time, from April 5th to 21st, 1773; and its mean vibrations were 1º 35' each way.



For the going of the CLOCK at DUSKY BAY.

1773	Sydereal Time of Apparent Noon	Time of Noon by the Clock	Mean Time of Apparent Noon	Clock too fast for Sydereal Time	Clock too fast for Mean Time	Clock gains on Syd. Time	Clock gains on Mean Time
	H ' "	H ' "	H ' "	H ' "	H ' "	' "	' "
☽ April 5th	0. 57. 15,0	1. 4. 36,4	0. 2. 45,3	0. 7. 21,4	1. 1. 51,1		
♂ 6	1. 00. 53,7	1. 8. 20,0	0. 2. 27,5	0. 7. 26,3	1. 5. 52,5	0. 4, 9	4. 1,4
☉ 11	1. 19. 10,7	1. 26. 50,9	0. 1. 2,0	0. 7. 40,2	1. 25. 49,9	0. 2, 8	3. 59,3
♄ 17	1. 41. 17,2	1. 49. 17,9	23. 59. 29,5	0. 8. 00,7	1. 49. 48,4	0. 3, 4	3. 59,9
☉ 18	1. 44. 59,7	1. 53. 4,7	23. 59. 18,4	0. 8. 5,0	1. 53. 49,3	0. 4, 3	4. 00,9
☽ 19	1. 48. 42,6	1. 56. 41,9	23. 59. 1,7	0. 7. 59,3	1. 57. 40,2		
♂ 20	1. 52. 26,8	2. 00. 29,6	23. 58. 48,5	0. 8. 3,3	2. 1. 41,1	0. 4, 5	4. 00,9
☿ 21	1. 56. 9,5	2. 04. 17,2	23. 58. 35,7	0. 8. 8,3	2. 5. 42,1	0. 4, 5	4. 01,0
				Mean Gains		0. 4,0666	4. 00,566

Figure 3: Clock rate summary.

The clock rate results had a standard deviation of the mean of about 1/3 of a second of time which is at the level of 4 parts per million of the length of a day. The amount of time the clock gains per day is a measure of the local gravity when considered together with the pendulum length and after allowing a correction resulting from the swing amplitude. Wales also listed his seconds pendulum calibration data from which the pendulum's reduced length can be determined:

> The clock B gained 5.03" a day on sidereal time from March 28th to April 1st, 1772, when fixed up at the Royal Observatory in Greenwich Park, to pieces of wood let into the wall of the Observatory; that is, in the manner whch the Transit Clock at that place is fixed up.

From Henry Kater's work we know the reduced length of the seconds pendulum beating 86,400 seconds in a mean solar day in Greenwich is 39.13858 inches in today's definition of the international inch of 25.4 mm. From the above calibration data we can see that Wales' pendulum, as set (the index of the bob was set at 13 on the nut, according to him), was slightly shorter so that it gained 5.03 seconds.

We can calculate the relevant length from this with the pendulum equation – this is what the calibration data allows us to do. From the pendulum equation we see that at a given value of the gravity, if we slightly change a pendulum's length it will swing at a different period, and the ratio of the squares of these two periods is the same as the ratio of the two slightly different pendulum lengths. This means Wales' pendulum length when set at 13 properly, was slightly too short as it gained against the astronomically determined value. The pendulum length is the square of 86,400/86,405.03 times Kater's "London pendulum length" of

39.13858 inches, resulting in 39.1340 inches. This was for Clock B carried on the Resolution, with Captain Cook and William Wales. Note that this is independent of the local gravity, which cancels in the comparison of the two periods. We get a relation between two lengths and two periods.

The full pendulum equation as in Giancoli (1988) is:

$$T = 2\pi \sqrt{\frac{L}{g}} \left(1 + \frac{1}{2^2} \sin^2 \frac{\theta_M}{2} + \frac{1}{2^2} \frac{3^2}{4^2} \sin^4 \frac{\theta_M}{2} + \cdots \right) \tag{1}$$

where θ_M is the "arc from the vertical" or half amplitude of the swing, L is the length of the pendulum in metres, g is the acceleration of gravity in m/s^2, and T is the period of a full swing and return of the pendulum in seconds.

However, Wales describes a mistake he made at Dusky, in his words: "as the difference corresponds nearly to that which would arise from a whole revolution of the nut which supports the ball of the pendulum". William Wales explains most of this in his introduction of the printed version of his and William Bayly's observations in Wales and Bayly (1777). Bosloper (2010) found this had also happened to William Dawes and he calculated the change to the pendulum length as 0.0258 inches for a full turn of the nut. This means that the effective length for the pendulum used by William Wales at Dusky Bay was 39.1340 minus 0.0258, i.e. 39.1082 inches. This allows us to calculate his absolute gravity measurement at Dusky Bay as all the other necessary variables are given.

In a similar way, we can accurately determine the pendulum length of Clock C of William Bayly's pendulum in Queen Charlotte Sound as mentioned earlier. It was only three tenthousandth of an inch shorter than its intended length, according to its calibration data as shown in Howse (1969) and Wales and Bayly (1777). So it was 39.1383 inches. This gives us the result of the month-long second absolute gravity determination in New Zealand, carried out by the gravimetry field party of the Adventure. The gravimetry here was carried out between 20 April and 20 May 1773, just after William Wales' gravimetry in Dusky Bay. The references to Clock B and C are also explained in Howse and Hutchinson (1969).

As a debrief later, William Wales described how the gravimeter was deployed with large intervals and spent the rest of the time in a damp and improper place in the ship. It should be stored in a more fit and proper place. This would be upright in the middle of the ship, which was to be lined with painted canvas overlain with thick baize. Often the pendulum spring would accumulate rust and even possibly bend at a different place which could affect the effective pendulum length. Thick baize might help with keeping moisture from accumulating.

4 ADVENTURES OF THE EARLY GRAVIMETRY FIELD PARTIES

In Rickard (2015) an interesting incident is described. During this second gravity determination, which lasted a full month, the party on the shore was met by a number of native New Zealander warriors who had been sent towards them. They had possibly become impatient by this long stay of the strangers in Queen Charlotte Sound and tried to intimidate them with a haka. James Burney, one of the crew of the Adventure describes it as follows in a May 1773 entry in his diary of the journey: "They all get in a row & jump & put themselves in many different strange attitudes, sometimes rolling their eyes about frightfully. One of them speaks a number of short sentences, at every one of which they change their posture, keeping exact time and very regularly through all their motions…".

In Henry and Marra (1775) a description can be found of theft of survey material in December 1773 during the next gravity observation series. It appears based on the journal of John Marra, another member of the crew. This happened after the return of the Adventure from Tonga, a trip during which the lighter bark Adventure again lost sight of the heavier Resolution for more than a month. During a fierce northerly gale they last sighted each other, trying to round Cape Pallisier of the North Island. The lighter bark could not turn West in this gale without the risk of capsizing and had to return 300 km to the north to Tolago Bay twice to find refuge from the gale, before it could return south and enter the Cook Strait in a third attempt more than a month later. When they arrived in Queen Charlotte Sound, the Resolution had already left a week earlier, but Cook had left a message for them confirming that they had been there. This message made no mention of having encountered any hostilities.

The crew of the Adventure prepared for more observations. After the seventh day of the gravity observations, survey equipment had disappeared in the night of 13 December out of the astronomer William Bayly's tent observatory. According to John Marra's journal, William Bayly was about to do observations when he saw that his quadrant had disappeared together with other equipment, and while he was mouthing off the guard he saw a native New Zealander sneaking out of the tent observatory. The astronomer fired a gun in his direction and wounded him but he got away into the bush. This alarmed the New Zealander's companions and they ran off into the bush as well, leaving their boat behind on the beach with the stolen goods. The wounding of the thief had severe consequences a few days later.

It rained the next day, but William Bayly did one more day of clock comparisons on 15 December 1773 so the retrieved quadrant appeared still to be in working order. Two days later everything was back on board in the afternoon for departure the next day. But a party of seven men who had been sent in a boat to gather some greens and wild celery from Grass Cove, had not returned yet. This included a midshipman, a carpenter's assistant and a first mate, possibly some of the crew who had helped the astronomer with his site preparation and such and were comfortable with being on shore in unknown and possibly hostile territory. At day break another party of seven was sent to look for them, among which was James Burney, the second lieutenant. His journal and John Mara's tells the story. It was not till five in the afternoon that they came upon some locals who fled from a canoe they were hauling onto a beach. In this canoe they found the first remains of their mates. This was followed by a battle with more New Zealanders which they encountered at arrival at Grass Cove, after finding more remains of four of their crew there, described as "heads, hearts and livers". They gathered the remains they could find and returned to their ship by midnight, unable to find the lost row boat. Tied in a hammock and cast overboard with "ballast and shot", the unfortunate men were later given a seaman's grave with the usual solemnity of the occasion. When the Adventure got clear of land, the clothes and effects of the lost men were sold before the mast as is a sea custom.

During his third journey, Captain Cook was told by the New Zealanders that the thief of the quadrant had succumbed to the wound inflicted by the astronomer's or guard's gun and this brought about the anger of the New Zealanders. These were the dangers of gravimetry field work in uncontrolled surroundings.

5 CONCLUDING REMARKS

John Harrison's isochronal temperature compensated gridiron pendulums have the same "reduced length" as later determined by Kater, because they have the same period. In hindsight, using Kater's value for the London isochronal pendulum, one can recalculate the results of Cook's absolute gravimetry to an accuracy of 10 mGals when using their pendulum calibration information, equalling accuracy levels not obtained again until the middle of the 20th century. This and their adventures leaves the author with tremendous respect for the gravimetric crews, astronomers and clockmakers of that period.

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