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CAPTAIN VANCOUVER'S ASSESSMENT OF KENDALL'S CHRONOMETER K3 1791/1792

Nicholas A. Doe

Summary:

Vancouver's survey of the west coast of North America in the 1790s came at a time of transition in the technology for determining longitude. Cook's pioneering work had established the feasibility of using chronometers for this purpose; but what remained to be done was to establish that the same results could be achieved with instruments that were cheap to produce. The K3 chronometer by Larcum Kendall was one of the first of such instruments.

One of the advantages of the chronometer method for determining longitude over the established method of lunar distances was that the arithmetic needed to reduce observations was much simpler. This was so much so that there is a tendency to take at “face-value” the chronometer longitude determinations reported by Vancouver in his book. However, as shown in this paper, the values that Vancouver reported are not always self-consistent, nor are they always consistent with the correction and calibration figures he claimed he was using. Moreover, Vancouver used longitudes determined by astronomical means to calibrate his instrument, and these calibration longitudes were often not accurate. All of this raises the question of how well the Kendall K3 chronometer really did perform.

CAPTAIN VANCOUVER'S ASSESSMENT OF KENDALL'S CHRONOMETER K3 1791/1792

Nicholas A. Doe

Introduction

Captain George Vancouver's survey of the North Pacific coast of America in the 1790s came at an interesting time of transition in the technology for determining longitude at sea. The lunar-distance method, which relies on measurements of the Moon's position in its monthly orbit in order to establish the time at Greenwich, was increasingly being supplemented and supplanted by the use of chronometers. Both methods had their weaknesses. The lunar-distance method demanded much tedious calculation, and individual determinations were not very accurate. Only by making large numbers of observations of the position of the Moon and averaging the resulting determinations could the required accuracy be attained. Chronometers were easy to use and the mathematical processing was much simpler, but being mechanical devices, there was always a fear that the chronometer would fail. Carrying several chronometers to allay this fear would only be possible if instruments could be manufactured at reasonable cost.[1] They also had to be calibrated on a regular basis, for, as good as their clockwork mechanisms were, they could not be isolated from the ever-changing environment aboard a ship at sea.

The relative merits of the two methods was a topic of lively debate in the latter part of the 18th century—compilers of nautical tables, makers of sextants, manufacturers of watches and timepieces, traders whose skills were often not up to using the lunar-distance method, those responsible for the training of naval officers, and pundits within the scientific and naval establishment—all had an interest in the impact of the new technology.

[1] Davies, Alun. *Vancouver's Chronometers* in From Maps to Metaphors—The Pacific World of George Vancouver. Edited by Fisher R. and Johnston H. University of British Columbia Press, 1993. pp.70–84.

Vancouver used both methods during his survey, both as independent and as complementary methods. On his voyage to the North Pacific coast, he stopped at various points along the way, partly in order to be able to compare the chronometer longitudes with longitudes that he regarded as being well-established by astronomical means. This was a test of the chronometer as a navigational tool rather than a surveying tool. Once he commenced his survey on the coast, the chronometer was used to establish the relative positions of locations along the coastline, a job for which it was highly suited because good time keeping over long periods of time was not required. Astronomical observations were also made and these he "reduced" using the chronometer to a few key locations. At these locations large numbers of determinations were then averaged to provide reference points that determined the longitude of the whole area relative to that of Greenwich.

It is unfortunate that all of Vancouver's personal papers and notes were lost after his death in 1798 and there is almost no record of his observations other than those in his book.[2] As discussed in an earlier paper,[3] the surviving records have been highly "processed" and it is not always a simple matter to trace the source of some of Vancouver's longitude errors. Errors in the astronomical observations were frequent, but because the chronometer method is so relatively simple, the author had always assumed that Vancouver's chronometer determinations were fairly reliable. However, as this paper shows, this is not the case.

Although few of the chronometer longitude errors are of any importance in themselves, there is always a possibility that they may have unduly influenced the opinion of those using Vancouver's results to assess the relative merits of the two methods. This paper sets out to determine how well Vancouver's chronometer, Larcum Kendall's K3, actually did perform from the time he left Portsmouth in March 1791 until his report from Port Discovery in May 1792. This essentially covers the period when the chronometer was being challenged to maintain good time on long voyages devoid of useful landmarks.

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[2] Lamb, W. Kaye, ed. *A Voyage of Discovery to the North Pacific Ocean and Round the World* 1791—1795. George Vancouver. Hakluyt Society 1984.

[3] Doe, Nicholas. *Captain Vancouver's Longitudes 1792* written in 1993 and published in The Journal of Navigation, Vol. 48, No. 3, pp.374–388, Sept. 1995.

Analysis method

The routine procedure for calibrating the chronometer was to establish its error at some place where the longitude was known, and at the same time measure its rate-of-going, i.e. the amount it was gaining or losing per day. A daily record was then kept of the difference between the chronometer's actual reading, and the reading it would have had, had it been keeping perfect time.

Fortunately for us, Vancouver habitually reckoned his longitude according to more than one chronometer calibration, one of which was the reckoning from Portsmouth in England—one of the few places where the longitude relative to the Greenwich meridian was accurately known. Other locations where chronometer calibration occurred were Cape Town in South Africa, King George's Sound in Australia, Dusky Sound in New Zealand, Tahiti, and Port Discovery in the Strait of Juan de Fuca. By quoting the chronometer longitude according to more than one calibration, Vancouver provides the data to check and, if necessary, to correct his calculations as the following analysis shows.

We have for the longitude $C_S(W)$ of place W determined at time t_W from the chronometer calibrated at the rate identified by the subscript s:

$$C_S(W) = G(t_W) - L(t_W) - R_S (t_W - t_S) - K_S \qquad (1)$$

where:

$G(t_W)$ is the actual chronometer reading at time t_W. The chronometer was set to give mean time at Greenwich;

$L(t_W)$ is the local mean time at time $t_{W;}$

R_S is the rate the chronometer was judged to be gaining;

t_S is the time of chronometer calibration;

K_S is the chronometer calibration error at time $t_{S;}$

s is either P (Portsmouth, England)
C (Cape Town, S. Africa)
KG (King George's Sound, Australia)
D (Dusky Sound, New Zealand)

V (Point Venus, Tahiti)

PD (Port Discovery, N. America).

Following the convention of earlier papers longitude is defined as positive in a westerly direction; the conversion factor between time and longitude (1° =4 minutes of time) will not be included explicitly in equations; and the time reference will be taken as noon at Greenwich, Julian Day 2375573.0 (December 30, 1791). Table 1 gives a procedure for calculating relative Julian days (RJD) in 1791/92. All dates will be as given by Vancouver in his book.

TABLE 1 Vancouver's relative Julian Day (RJD) calendar for 1791/1792.

1791	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
– E			–244	–213	–183	–152	–121	–91	–60	–30
+ W	–305	–274	–244	–213					–61	–31
1792	Jan	Feb	Mar	Apr	May					
– E										
+ W	0	31	60	91	121					

To find the relative Julian Day (RJD) at local noon of a date in Vancouver's book in 1791 and 1792 add the tabulated figure to the day of the month, and then add or subtract the time-equivalent of his longitude in days as indicated in the column on the left.

For example, Dec 20 1791 at 215°E. Dec 1791 for longitudes east = –30;
215°E = –(215/360) = –0.6 days; hence RJD = –30+20–0.6 = –10.6.

Alternatively, Dec 20 1791 at 145°W. Dec 1791 for longitudes west = –31;
145°W = (145/360) = 0.4 days; hence RJD = –31+20+0.4 = –10.6.

RJD: 0 is December 30, 1791 at noon GMT (now UTC), which is Julian Day: 2375573.0. Vancouver reckoned time as being ahead of GMT even after crossing the 180° meridian from east to west in late November 1791; consequently, RJD: 0 appears in his book as December 31, 1791.

For the purposes of analysis, we re-write eq.(1) in the following form:

$$F(W) = P_S(W) + Q_S \qquad (2)$$

where:

$$F(W) = G(t_W) – L(t_W)$$

$$P_S(W) = C_S(W) + R_S\, t_W$$

$$Q_S = K_S – R_S\, t_S.$$

The term F(W) in eq.(2) has the face-value of the chronometer at local noon mean time[4] and it, of course, should be independent of any chronometer corrections or calibrations i.e. for any place W, $F(W) = F_P(W) = F_C\,(W) = F_{KG}(W)$ etc.

The first objective of the analysis was to arrive at a set of values for $P_S(W)$ and Q_S that gave the same value of F(W) for every calibration rate s. If the set of values for F(W) did not agree, then the source of the error was sought for in $P_S(W)$ if the disagreement was peculiar to the location W, or in Q_S if the same disagreement occurred at adjacent locations. The rationale for this is that the value of $P_S(W)$ varies from location to location, but the value of Q_S does not. Once having narrowed down the source of the disagreement to an error in $P_S(W)$ or Q_S, errors were sought in the values of $C_S(W)$ or t_W for $P_S(W)$, or the values of K_S or t_S for Q_S. Fortunately, it was a relatively easy task to verify that the values for R_S, which occurs in both $P_S(W)$ and Q_S, were at least consistent, if not always correct.

Two examples may make this process clearer.

<u>Example 1:</u>

On September 5, 1791 on the passage between the Cape of Good Hope and the coast of Australia, Vancouver records his longitude by the chronometer at the Portsmouth rate, and the chronometer at

[4] Although longitude was not always determined at noon, it is simpler to assume that it was. No significant error is thereby created because the F(W) of any location varies very little over the course of a day. Local time is most easily fixed at noon, but it can also be calculated at any other time of day, as it would have to be on a moving ship, by measuring the Sun's altitude. The calculation requires the observer's latitude to be known and also the Sun's declination. Early tables for this calculation were called horary tables.

the Cape rate as respectively, 63°46'E, and 64°10'E.[5] The data for this observation is:

t_W = –116.18 (RJD at local noon)

$C_P(W)$ = 63°46'E = –15304.0 sec

R_P = 6.2 sec/day

t_P = –304.00 (RJD at local noon March 1, 1791)

K_P = 90.3 sec

$P_P(W)$ = –16024.3 sec

Q_P = 1975.1 sec

$F_P(W)$ = –14049.2 sec

C_C (W) = 64°10'E = –15400.0 sec

R_C = 9.4667 sec/day

t_C = –144.05 (RJD at local noon August 8, 1791)

K_C = 1086.3 sec

$P_C(W)$ = –16499.8 sec

Q_C = 2450.0 sec

$F_C(W)$ = –14049.9 sec

These results contain no contradiction. On September 5 at local mean noon, the longitudes are consistent with the chronometer showing –14049.6±0.4 sec, i.e. 8:05:50 a.m. GMT.

Example 2:

Eighteen days later, however, on September 23, Vancouver records his longitude by the chronometer at the Portsmouth rate, and the chronometer at the Cape rate as respectively, 113°32'E, and 113°55'E.[6] The data for this observation is:

t_W = –98.32 (RJD at local noon)

$C_P(W)$ = 113°32'E = –27248.0 sec

[5] Lamb, *A Voyage.... (ibid)* p.329.

[6] Lamb, *A Voyage.... (ibid)* p.331.

R_P = 6.2 sec/day

t_P = –304.00 (RJD at local noon March 1, 1791)

K_P = 90.3 sec

$P_P(W)$ = –27857.6 sec

Q_P = 1975.1 sec

$F_P(W)$ = –25882.5 sec

$C_C(W)$ = 113°55'E = –27340.0 sec

R_C = 9.4667 sec/day

t_C = –144.05 (RJD at local noon August 8, 1791)

K_C = 1086.3 sec

$P_C(W)$ = –28270.8 sec

Q_C = 2450.0 sec

$F_C(W)$ = –25820.8 sec

These results contain a contradiction. The values of $F_P(W)$ and $F_C(W)$ differ by 61.7 seconds, even though they supposedly refer to the same chronometer reading. Since the values of Q_P and Q_C have not changed and were previously correct, the figures to suspect are those for $C_P(W)$ and $C_C(W)$. In this particular case, the error occurs again in a later observation and the evidence supports the notion that there is a one minute of time slip in the Cape rate calculation. Vancouver's Cape rate longitude $C_C(W)$, correctly calculated, was probably 114°10'E (–27400.0 sec). At local mean noon, the chronometer would then have shown –25881.7±0.9 sec, i.e. 4:48:38 a.m. GMT.

The number of such errors in Vancouver's data is surprisingly large, and, as the following commentary shows, it is not always easy to identify unequivocally the source of his error.

Tables of results

The results of the analysis are shown in the series of tables. The are two types of table; one recording the best estimate of the chronometer data at the various locations, and one showing the revisions that have been made to make the data at particular locations self-consistent. The data for any location with a version number (row 1) has been altered in some way. In the revision tables, only data that has been changed is shown in the various version columns, i.e. blank entries in these tables indicate that the value to the left should be taken as correct.

The key to the rows of the tables is as follows:

1. Location and version number.
2. Date according to Vancouver.
3. Relative Julian Day (RJD) at local noon. RJD = 0 on December 30, 1791 at noon GMT. This is Julian Day 2375573.0.

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4. Correct longitude of location.
5. Time equivalent of longitude (row 4) in seconds. This is what a chronometer set to GMT should show at local mean noon.

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6. Longitude of location regarded as correct by Vancouver.
7. Time equivalent of longitude (row 6) in seconds.
8. Vancouver's explicit estimate, if any, of the rate-of-going of the chronometer in seconds per day.
9. Vancouver's explicit estimate, if any, of the chronometer error.
10. Chronometer reading at local mean noon in seconds according to Vancouver's estimates. Calculated by adding rows 7 and 9.

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11. Longitude of location according to the chronometer after calibration at the Portsmouth rate.
12. Time equivalent of longitude (row 11) in seconds.
13. Amount by which the chronometer is fast according to the Portsmouth correction. Equal to the error at Portsmouth (TABLE 2: Portsmouth: row 9) plus elapsed days (Location: row 3 – TABLE 2: Portsmouth: row 3) times the Portsmouth rate (TABLE 2: Portsmouth: row 8).
14. Chronometer reading at local mean noon according to the Portsmouth longitude. Calculated by adding rows 12 and 13. This number should be identical to the number in row 10.

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15. Longitude of location according to the chronometer after calibration at the Cape rate.
16. Time equivalent of longitude (row 15) in seconds.
17. Amount by which the chronometer is fast according to the Cape correction. Equal to the error at the Cape (TABLE 3: Cape *version 2*: row 9) plus elapsed days (Location: row 3 – TABLE 3: Cape *version 2*: row 3) times the Cape rate (TABLE 3: Cape *version 2*: row 8).
18. Chronometer reading at local mean noon according to the Cape longitude. Calculated by adding rows 16 and 17. This number should be identical to the number in rows 10 and 14.

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19. Longitude of location according to the chronometer after calibration at the King George rate.
20. Time equivalent of longitude (row 19) in seconds.
21. Amount by which the chronometer is fast according to the King George correction. Equal to the error at King George's Sound (TABLE 5: King George *version 3*: row 9) plus elapsed days (Location: row 3 – TABLE 5: King George *version 3*: row 3) times the King George rate (TABLE 5: King George *version 3*: row 8).
22. Chronometer reading at local mean noon according to the King George longitude. Calculated by adding rows 20 and 21. This number should be identical to the number in rows 10, 14, and 18.

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23. Longitude of location according to the chronometer after calibration at the Dusky Sound rate.
24. Time equivalent of longitude (row 23) in seconds.
25. Amount by which the chronometer is fast according to the Dusky Sound correction. Equal to the error at Dusky Sound (TABLE 7: Dusky Sound *version 2*: row 9) plus elapsed days (Location: row 3 – TABLE 7: Dusky Sound *version 2*: row 3) times the Dusky Sound rate (TABLE 7: Dusky Sound *version 2*: row 8).
26. Chronometer reading at local mean noon according to the Dusky Sound longitude. Calculated by adding rows 25 and 26. This number should be identical to the number in rows 10, 14, 18, and 22.

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27. Longitude of location according to the chronometer after calibration at the Tahitian rate.
28. Time equivalent of longitude (row 27) in seconds.
29. Amount by which the chronometer is fast according to the Tahitian correction. Equal to the error at Point Venus (TABLE 10: Point Venus *version 4*: row 9) plus elapsed days (Location: row 3 – TABLE 10: Point Venus *version 4*: row 3) times the Tahitian rate (TABLE 10: Point Venus *version 4*: row 8).
30. Chronometer reading at local mean noon according to the Tahitian longitude. Calculated by adding rows 28 and 29. This number should be identical to the number in rows 10, 14, 18, 22, and 26.

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31. Best estimate of the chronometer reading at local mean noon based on available results in rows 10, 14, 18, 22, 26, and 30.

Analysis results

TABLE 2: Passage to Cape of Good Hope

1 W	Portsmouth	Porto Sancto	Santa Cruz	Santo Antao
2 Vancr's date	Mar 1/91	Apr 24/91		May 14/91
3 t_W (RJD)	–304.00	–249.95		–229.93
4 True long.	1°03'W	16°20'W	16°14'W	25°10'W
5 " sec	+252.0	+3920.0	+3896.0	+6040.0
6 Vancr's true	1°03'W	16°23'15"W	16°16'15"W	
7 " sec	+252.0	+3933.0	+3905.0	
8 Vancr's R	+6.2000			
9 Vancr's K	+90.3			
10 Vancr's F	+342.3			
11 C_P(W)	1°03'W	16°24'15"W	16°17'05"W	25°03'22"W
12 " sec	+252.0	+3937.0	+3908.3	+6013.5
13 K_P+R_P $(t_W – t_P)$	+90.3	+425.4		+549.5
14 F_P(W)	+342.3	+4362.4		+6563.0
31 F(W)	+342.3	+4362.4		+6563.0

Note: Santa Cruz observation undated (April 29 to May 7).

Table 2 shows the record on route to the Cape. Only Portsmouth rate longitudes are given so there is no scope for contradiction. Vancouver's remarks in his book indicate that he had a good understanding of the significance of his figures in the Atlantic.

TABLE 3: Cape of Good Hope

1 W	False Bay	Cape - arrival	Cape *version 2*
2 Vancr's date	Jul 10/91	Jul 11/91	Aug 8/91
3 t_W (RJD)	–173.05	–172.05	–144.05
4 True long	18° 39'54"E	18°26'E	18°26'E
5 " sec	–4479.6	–4424.0	–4424.0
6 Vancr's true	18°34'15"E	18°22'E	18°22'E
7 " sec	–4457.0	–4408.0	–4408.0
8 Vancr's R			+9.4667
9 Vancr's K			*+1086.3*
10 Vancr's F			*–3321.7*
11 $C_P(W)$	18°52'45"E	18°39'45"E	*18°20'56"E*
12 " sec	–4531.0	–4479.0	
13 $K_P + R_P (t_W – t_P)$	+902.2	+908.4	+1082.0
14 $F_P(W)$	–3628.8	–3570.6	
31 F(W)	–3628.8	–3570.6	–3321.7

Notes: False Bay longitude (row 4) estimated from compass bearings. This longitude confirms that Vancouver placed False Bay and Simons Bay about 5' west of their true positions. False Bay date evening July 9 or morning July 10.

Cape arrival July 11. Confirmed by Vancouver's remark that False Bay error was 18'30"E (–74 sec) and Cape arrival error was 17'45"E (–71 sec). The chronometer gain was 6.2000+3 = 9.2 sec i.e. one day at the Cape rate.

The Cape arrival and Cape observations indicate a chronometer gain of –3321.7+3570.6 = 248.9 sec over 28 days = 8.8893 sec/day. Vancouver claims a figure of 9.4667 sec/day.

Table 3 shows the record at the Cape. Vancouver's compass bearings give a good fix on his initial anchorage in False Bay, which confirms that the established longitudes (row 6) were somewhat to the west of the true longitudes (row 4).[7] As noted in the comments, the chronometer readings are consistent with his arrival at Cape Town on July 11, as indicated in the text of his book.

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7 Lamb, *A Voyage.... (ibid)* p.318.

TABLE 4: Cape of Good Hope Revisions

1 W	Cape	Cape *version 2*	Cape *version 3*
2 Vancr's date	Aug 8/91		
3 t_W (RJD)	–144.05		
4 True long	18°26'E		
5 " sec	–4424.0		
6 Vancr's true	18°22'E		18°26'18"E
7 " sec	–4408.0		–4425.2
8 Vancr's R	+9.4667	(+8.8893)	(+8.2750)
9 Vancr's K	+1069.1	+1086.3	
10 Vancr's F	–3338.9	–3321.7	–3338.9
11 C_P(W)	18°25'13"E	18°20'56"E	18°25'13"E
12 " sec	–4420.9	–4403.7	–4420.9
13 K_P+R_P (t_W – t_P)	+1082.0		
14 F_P(W)			
31 F(W)	–3338.9	–3321.7	–3338.9

Notes: Vancouver's claim that he considered the chronometer to be $17^m49.1^s$ (+1069.1 sec) fast (row 9) is not confirmed in subsequent calculations. All of these indicate that his assumed error at the Cape was $18^m06.3^s$ (+1086.3 sec) fast.

The change (row 9) requires a change either to the calculated chronometer reading (row 31) and hence the Portsmouth longitude (version 2), or to the longitude that Vancouver regarded as true (row 6) (version 3).

Version 2 is preferred to version 3 because the False Bay observations indicate that Vancouver regarded the Cape as being somewhat west of true (row 6 compared to row 4). Version 2 supports this. Also if the version 3 calculated chronometer reading (row 31) were accepted the Cape arrival and Cape observations would indicate a chronometer gain of –3338.9+3570.6 = 231.7 sec over 28 days = 8.2750 sec/day. This is well over one second per day less than what Vancouver says he measured.

Cape Town was Vancouver's first calibration location and immediately there are problems. He states that he found the K3 to be 17'49"06"' (1069.1 sec) fast, yet all of his subsequent calculations show that the value he actually used for K_C was

18'06"18"' (1086.3 sec) fast.[8] This is corrected in *version 2* (row 9).

Vancouver identifies what he regards as his true longitude as 18°39'45"E less 17'45" i.e. 18°22'E. In *version 2*, we accept that this was true and deduce a face-value for the chronometer (rows 10 and 31) and from this deduce that the Portsmouth longitude (row 11) was 18°20'56"E (row 31 – row 13).

In *version 3*, instead of re-calculating the face-value of the chronometer (row 10), we accept that there is instead an error in what Vancouver regarded as the true longitude (row 6), and deduce that the Portsmouth longitude (row 11) was 18°25'13"E (row 31 – row 13). Vancouver's longitude in this version (row 6) is almost correct (row 4).

Now comes the problem. Given the chronometer readings at noon (row 31) on August 8 and on arrival (TABLE 3: July 11: row 31) we can calculate the rate-of-going of the chronometer as Vancouver did. Unfortunately neither *version 2* nor *version 3* give Vancouver's figure of 9"28"'/day (9.4667 sec/day). For *version 2*, the result is 8"53.4"'/day (8.8893 sec/day) and for *version 3* it is 8"16.5"'/day (8.2750 sec/day).

Version 2 is closer than *version 3*, which would be reason enough to prefer the *version 2* interpretation. However there is one more clue. If the *version 2* elapsed days are taken to be exactly 23.0 days instead of the correct 28.0 days, and the rate is calculated from the difference in the Portsmouth longitudes (TABLE 3: Cape arrival: row 11 – TABLE 4: Cape *version 2*: row 11), then the deduced rate is 6.2 + 3.2725 = 9.4725 i.e. 9"28.3"'/day, almost exactly Vancouver's rate.

Since, as noted in the remarks for Table 3, the False Bay and arrival at the Cape observations support each other, it is not possible to bring the arrival date forward five days to July 16 as required by Vancouver's calculation, without disrupting both. It is therefore difficult to avoid the conclusion that *version 2* is correct and Vancouver incorrectly calculated the K3 rate-of-going at the Cape by averaging over 23 days instead of 28.

[8] Lamb, *A Voyage.... (ibid)* p.324.

TABLE 5: Passage to Australia

1 W	At sea	At sea	At sea	At sea	At sea *version 2*	King George Sound *version 3*
2 Vancr's date	Aug 23/91	Aug 24/91	Sep 5/91	Sep 8/91	Sep 23/91	*Oct 9/91*
3 t_W (RJD)	–129.09	–128.09	–116.18	–113.20	–98.32	*–82.33*
4 True long						117°57'E
5 " sec						–28308.0
6 Vancr's true						118°14'13"E
7 " sec						–28376.9
8 Vancr's R						+6.0000
9 Vancr's K						*+1574.0*
10 Vancr's F						*–26802.9*
11 C_P(W)	31°29'E	33°55'E	63°46'E	73°01'E	113°32'E	117°46'E
12 " sec	–7556.0	–8120.0	–15304.0	–17524.0	–27248.0	–28264.0
13 K_P+R_P (t_W – t_P)	+1174.7	+1180.9	+1254.8	+1273.3	+1365.5	*+1464.7*
14 F_P(W)	–6381.3	–6939.1	–14049.2	–16250.7	–25882.5	*–26799.3*
15 C_C(W)	31°42'E	34°05'E	64°10'E	73°27'E	*114°10'E*	*118°38'E*
16 " sec	–7608.0	–8180.0	–15400.0	–17628.0	*–27400.0*	*–28472.0*
17 K_C+R_C (t_W – t_C)	+1227.9	+1237.4	+1350.1	+1378.3	+1519.2	*+1670.6*
18 F_C(W)	–6380.1	–6942.6	–14049.9	–16249.7	*–25880.8*	*–26801.4*
31 F(W)	–6380.7	–6940.9	–14049.6	–16250.2	–25881.7	–26801.2

Table 5 shows the record across the southern Indian Ocean on route to Australia. Portsmouth and Cape rate longitudes are in good agreement except, as described above, on September 23. Unfortunately, the paucity of known locations make it impossible to check the chronometers true rate-of-going for this section of the voyage.

The average rate-of-going between the Cape and King George's Sound is 6.5538 sec/day which is closer to the King George rate of 6.0000 sec/day than the claimed Cape rate of 9.4667 sec/day.

TABLE 6: Coast of Australia Revisions

1 W	At sea	At sea *version 2*	King George Sound	King George Sound *version 2*	King George Sound *version 3*
2 Vancr's date	Sep 23/91		Sep 29/91	Oct 9/91	
3 t_W (RJD)	–98.32		–92.33	–82.33	
4 True long			117°57'E		
5 " sec			–28308.0		
6 Vancr's true			118°14'13"E		
7 " sec			–28376.9		
8 Vancr's R			+6.0000		
9 Vancr's K			+1514.0	+1574.0	
10 Vancr's F			–26862.9	–26802.9	
11 C_P(W)	113°32'E		117°46'E		
12 " sec	–27248.0		–28264.0		
13 $K_P+R_P (t_W – t_P)$	+1365.5		+1402.7	+1464.7	
14 F_P(W)	–25882.5		–26861.3	–26799.3	
15 C_C(W)	113°55'E	114°10'E	118°23'E		118°38'E
16 " sec	–27340.0	–27400.0	–28412.0		–28472.0
17 $K_C+R_C (t_W – t_C)$	+1519.2		+1575.9	+1670.6	
18 F_C(W)	–25820.8	–25880.8	–26836.1	–26741.4	–26801.4
31 F(W)	?	–25881.7	?	?	–26801.2

Notes: On Sept. 23, the chronometer reading calculated from the Cape rate observation (row 18) is 61.7 sec faster than that calculated from the Portsmouth rate observation (row 14). In version 2, the Cape rate chronometer longitude is moved –60 seconds to correct this.

At King George's Sound the chronometer reading calculated from the Portsmouth rate observation (row 14) is in agreement with that calculated from what Vancouver considered to be correct (row 10), but is 25.2 sec slower than that calculated from the Cape rate observation (row 18).

In King George version 2, Vancouver's date has been changed from "arrival" to Oct. 9 when he concluded his chronometer rate observations. This slightly degrades the agreement between the chronometer reading calculated from the Portsmouth rate observation (row 14) and that calculated from what Vancouver considered to be correct (row 10), but the Cape rate disagreement becomes 59.7 sec which is identical to the Sept. 23 error. Moved –60 seconds in version 3.

Table 6 shows the revisions made to the September 23 observation. To bring the chronometer reading according to the Portsmouth longitude (row 14) into line with that according to the Cape longitude (row 18), the Cape longitude has been moved east by the equivalent of one minute of time.[9] This correction is also made in *version 3* to the *version 2* Cape rate longitude at King George's Sound.

Vancouver marks his King George's Sound chronometer longitudes as being calculated "on arrival" i.e. about September 29.[10] The figures are however consistent with them having been calculated for October 9, as in *version 2* when he reported his chronometer rate-of-going estimates.

[9] The 18th-century astronomer William Wales once experienced a mysterious one minute discrepancy in his chronometer readings which he attributed to some *witty* gentleman on board having found a way to unlock the box in which the chronometer was kept and turning it back to see if he would notice. In this case, however, such mischief would have affected both the Portsmouth and Cape rate longitudes and nobody would have been any the wiser. Taylor, E.G.R. *Navigation in the Days of Captain Cook.* Journal of the Institute of Navigation. Vol. 21:3. July 1968. pp.256—276.

[10] Lamb, *A Voyage.... (ibid)* p.356.

TABLE 7: Tasmania and New Zealand

1 W	SW Cape *version 2*	Swilly Rock *version 2*	Dusky Sound *version 2*
2 Vancr's date	Oct 27/91	Oct 27/91	Nov 16/91
3 t_W (RJD)	–64.41	–64.41	–44.46
4 True long	146°02'E	146°58'E	166°31'E
5 " sec	–35048.0	–35272.0	–39964.0
6 Vancr's true	146°07'E	147°06'E	166°15'54"E
7 " sec	–35068.0	–35304.0	–39903.6
8 Vancr's R			+3.0000
9 Vancr's K			+1594.0
10 Vancr's F			–38309.6
11 C_P(W)	*146°00'52"E*	*146°57'23"E*	166°42'23"E
12 " sec	*–35043.5*	*–35269.5*	–40009.5
13 K_P+R_P (t_W – t_P)	+1575.8	+1575.8	+1699.4
14 F_P(W)	*–33467.7*	*–33693.7*	–38310.1
15 C_C(W)	147°07'15"E	148°03'45"E	*168°04'42"E*
16 " sec	–35309.0	–35535.0	*–40338.8*
17 K_C+R_C (t_W – t_C)	+1840.2	+1840.2	+2029.1
18 F_C(W)	–33468.8	–33694.8	*–38309.7*
19 C_{KG}(W)	146°27'E	147°23'30"E	167°07'40"E
20 " sec	–35148.0	–35374.0	–40110.7
21 $K_{KG}+R_{KG}$ (t_W – t_{KG})	+1681.5	+1681.5	+1801.2
22 F_{KG}(W)	–33466.5	–33692.5	–38309.5
31 F(W)	–33467.7	–33693.7	–38309.7

The average rate-of-going between King George's Sound and Dusky Sound is 3.9002 sec/day which is comfortably between the King George rate of 6.0000 sec/day and the Dusky Sound rate of 3.0000 sec/day.

TABLE 8: Tasmanian Revisions

1 W	SW Cape	SW Cape *version 2*	Swilly Rock	Swilly Rock *version 2*
2 Vancr's date	Oct 27/91		Oct 27/91	
3 t_W (RJD)	–64.41		–64.41	
4 True long	146°02'E		146°58'E	
5 " sec	–35048.0		–35272.0	
6 Vancr's true	146°07'E		147°06'E	
7 " sec	–35068.0		–35304.0	
8 Vancr's R				
9 Vancr's K				
10 Vancr's F				
11 C_P(W)	146°08'E	146°00'52"E	147°02'E	146°57'23"E
12 " sec	–35072.0	–35043.5	–35288.0	–35269.5
13 $K_P + R_P (t_W – t_P)$	+1575.8		+1575.8	
14 F_P(W)	–33496.2	–33467.7	–33712.2	–33693.7
15 C_C(W)	147°07'15"E		148°03'45"E	
16 " sec	–35309.0		–35535.0	
17 $K_C + R_C (t_W – t_C)$	+1840.2		+1840.2	
18 F_C(W)	–33468.8		–33694.8	
19 C_{KG}(W)	146°27'E		147°23'30"E	
20 " sec	–35148.0		–35374.0	
21 $K_{KG} + R_{KG} (t_W – t_{KG})$	+1681.5		+1681.5	
22 F_{KG}(W)	–33466.5		–33692.5	
31 F(W)	?	–33467.7	?	–33693.7

Notes: At the SW Cape the Portsmouth longitude has been calculated from a reading 28.5 sec slow (row 14) compared with the Cape and King George readings. Corrected in version 2.

SW Cape figure supports date change at King George Sound (4.1 sec/day compared to 2.6 sec/day)

The true longitude of Swilly Rock (Pedra Branca) is incorrect in Lamb 1984.

At Swilly Rock the Portsmouth longitude has been calculated from a reading 18.5 sec slow (row 14) compared with the Cape and King George readings. Corrected in version 2.

The observations on October 27 contain two errors in the Portsmouth rate longitude. Since the two observations were made on the same day, it is difficult to account for the errors.

At the SW Cape, the Portsmouth longitude is the equivalent of 28.5 seconds of time too far east. At Swilly Rock (or Island, now Pedra Branca), the Portsmouth longitude is the equivalent of 18.5 seconds of time too far east. Thereafter it is correct.

TABLE 9: New Zealand Revisions

1 W	Dusky Sound	Dusky Sound *version 2*
2 Vancr's date	Nov 16/91	
3 t_W (RJD)	–44.46	
4 True long	166°31'E	
5 " sec	–39964.0	
6 Vancr's true	166°15'54"E	
7 " sec	–39903.6	
8 Vancr's R	+3.0000	
9 Vancr's K	+1594.0	
10 Vancr's F	–38309.6	
11 C_P(W)	166°42'23"E	
12 " sec	–40009.5	
13 $K_P + R_P (t_W – t_P)$	+1699.4	
14 F_P(W)	–38310.1	
15 C_C(W)	167°55'12"E	168°04'42"E
16 " sec	–40300.8	–40338.8
17 $K_C + R_C (t_W – t_C)$	+2029.1	
18 F_C(W)	–38271.7	–38309.7
19 C_{KG}(W)	167°07'40"E	
20 " sec	–40110.7	
21 $K_{KG} + R_{KG} (t_W – t_{KG})$	+1801.2	
22 F_{KG}(W)	–38309.5	
31 F(W)	?	–38309.7

Note: The Cape longitude has been calculated from a reading 38.0 sec fast (row 18) compared with the Portsmouth (row 14) and King George (row 22) readings. Corrected in version 2.

The “only” revision necessary to the Dusky Sound data is to move the Cape rate longitude east the equivalent of 38 seconds of time to bring it into line with the Portsmouth and King George's Sound rate chronometer readings. There is no obvious explanation for this error; presumably it is the result of some faulty arithmetic.

TABLE 10: South Pacific

1 W	Snares	Point Venus *version 4*
2 Vancr's date	Nov 24/91	*Jan 18/92*
3 t_W (RJD)	–36.46	*+18.42*
4 True long	166°35'E	149°29'30"W
5 " sec	–39980.0	–50522.0
6 Vancr's true		149°35'45"W
7 " sec		–50497.0
8 Vancr's R		+4.0333
9 Vancr's K		+1874.1
10 Vancr's F		–48622.9
11 $C_P(W)$		148°42'W
12 " sec		–50712.0
13 $K_P + R_P (t_W – t_P)$		+2089.3
14 $F_P(W)$		–48622.7
23 $C_{DS}(W)$	166°20'E	*149°58'39"W*
24 " sec	–39920.0	*–50405.4*
25 $K_{DS} + R_{DS} (t_W – t_{DS})$	+1618.0	+1782.6
26 $F_{DS}(W)$	–38302.0	*–48622.8*
31 F(W)	–38302.0	–48622.8

The average rate-of-going between Dusky Sound and the Snares is 2.9625 sec/day which agrees well with the Dusky Sound rate of 3.0000 sec/day. Between the Snares and Point Venus it is 4.0306 sec/day.

TABLE 11: Tahiti Revisions

1 W	Point Venus	Point Venus *version 2*	Point Venus *version 3*	Point Venus *version 4*
2 Vancr's date	Jan 19/92		Jan 18/92	
3 t_W (RJD)	+19.42		+18.42	
4 True long	149°29'30"W			
5 " sec	–50522.0			
6 Vancr's true	149°35'45"W			
7 " sec	–50497.0			
8 Vancr's R	+4.0333			
9 Vancr's K	+1898.7	+1878.1	+1874.1	
10 Vancr's F	–48598.3	–48618.9	–48622.9	
11 C_P(W)	148°42'W			
12 " sec	–50712.0			
13 $K_P + R_P (t_W – t_P)$	+2095.5		+2089.3	
14 F_P(W)	–48616.5		–48622.7	
23 C_{DS}(W)	150°02'W			*149°58'39" W*
24 " sec	–50392.0			*–50405.4*
25 $K_{DS} + R_{DS} (t_W – t_{DS})$	+1785.6		+1782.6	
26 F_{DS}(W)	–48606.4		–48609.4	*–48622.8*
31 F(W)	?	?	?	–48622.8

Notes: Vancouver's claim that the chronometer was $31^m38.7^s$ ($31^m42.7^s – 4.0^s$ = 1898.7) fast (row 9) on Jan.19 is not confirmed in subsequent calculations. All of these indicate that his assumed error at Tahiti on Jan.19 was +1878.1 seconds fast. Corrected in version 2.

In version 3, the date has been moved back one day (this was the first major observation after crossing the 180° meridian) bringing the chronometer readings for Vancouver's estimates (row 10) and the Cape rate (row 14) into agreement.

In version 4, the Dusky Sound reading has been moved back 13.4 sec. For a possible explanation of this error see text.

Point Venus, Tahiti was Vancouver's final calibration before beginning his survey of the North American coast. Its location was regarded as being well-established for it was here that Cook and the astronomer Charles Green observed the transit of Venus in 1769. Cook also visited the island during his second and third voyages.

The problems with the Tahiti observations begin with Vancouver's remark that he found the K3 to be 31'42"46"' fast on January 20, which would be 31'42"46"' – 4"2"' = 31'38"44"' (1898.7 sec) on the 19th when his longitudes are recorded.[11] All of his subsequent calculations show that the value he actually used for K_V was 31'18"06"' (1878.1 sec) fast. This is corrected in *version 2* (row 9).

The next problem is that the calculated values for the chronometer reading on January 19, (row 10, 14, and 26) all disagree. However, the Portsmouth figure (row 14) can be brought into alignment with the figure derived from Vancouver's estimates (row 10) by moving the date of the observations back one day, as in *version 3*. Point Venus was the first major observation point after crossing the international date line, not then established, so some confusion over dates would be understandable.

There is a second reason for suspecting that the chronometer reading (row 26) based on the Dusky Sound longitude is at fault. Vancouver records that at the Dusky Sound rate the longitude was 209°55'45"E (150°04'15"W) on the 7th and 209°58'E (150°02'W) on the 19th.[12] Since the apparent longitude was moving east, the correct conclusion was that the chronometer was losing on the Dusky Sound rate of 3.0000 sec/day. Vancouver, however, concludes the opposite. Taking his longitudes at face-value gives a Point Venus rate of 3.0000 – 0.7500 = 2.2500 (2"15"') sec/day. It would seem that Vancouver may have incorrectly calculated 3.0000 + 0.7500 = 3.7500 (3"45"') sec/day; although this mistake is not the only one he made as his result was even higher at 4.0333 (4"02"') sec/day.

In *version 4*, the chronometer reading for the Dusky Sound longitude (row 26) is brought into line with the Portsmouth (row 14) and the estimated readings (row 10). Now, using the new Dusky Sound longitude of 210°01'21"E (149°58'39"W) (row 23), and noting the change in date, the chronometer rate becomes 3.0000 – 2.0364 = 0.9636 (57.8"') sec/day, or calculated incorrectly

[11] Lamb, *A Voyage.... (ibid)* p.441.

[12] Lamb, *A Voyage.... (ibid)* p.441.

3.0000 + 2.0364 = 5.0364 (5"02"') sec/day. These values are rather extreme, which casts doubt on the January 7 longitude.

If we accept both *version 4* and that Vancouver's rate-of-going calculation was correct, then on January 7, the Dusky Sound longitude should have been 149°55'48"W which is suspiciously related to the claimed 209°55'45"E. If Vancouver actually observed 149°55'45"W then the rate was 4.0545 (4"3.3"') sec/day which is almost what he says it was; if he really observed 209 55'45"E then the rate was only 0.9636 (57.8"') sec/day.

My guess is that over a period of 12 days he observed the chronometer go from 149°55'45"W, not 209°55'45"E, to 149°58'51"W, not 209°58'??"E, and his rate is correct. Again crossing the 180° meridian has caused trouble! This is however, just a guess.

A further note is that based on the *version 4* chronometer reading (row 31) and the original estimated error (row 9), the Vancouver's true longitude (row 6) would be on January 18, 149°30'37"W, which is where Cook puts Point Venus in his 1769 chart, and in his observations with Lieutenant King in 1777. Quite possibly Vancouver was not sure which of two illustrious authorities (Cook or Green) he should rely on for his true longitude and the error (row 9) is evidence that at one point he changed his mind.

TABLE 12: North Pacific

1 W	Kealakekua	Waikiki	Walmea	Kaumuhon u	Port Discovery
2 Vancr's date	Mar 3/92	Mar 8/92	Mar 9/92	Mar 16/92	May 4/92
3 t_W (RJD)	+63.43	+68.44	+69.44	+76.45	125.34
4 True long	155°55'46" W	157°49'15"W	159°40'W	160°13'W	122°52'30"W
5 " sec	–48976.9	–48523.0	–48080.0	–47948.0	–56910.0
6 Vancr's true	156°00'W ?		159°40/47'W	160°12'W	122°37'41"W
7 " sec					–56969.3
8 Vancr's R					+11.9167
9 Vancr's K					+2638.7
10 Van.r's F					–54330.6
11 C_P(W)	A°–1°18'W	156°30'10"W	158°19'15"W	158°55'W	122°09'W
12 " sec	Y–312.0	–48839.3	–48403.0	–48260.0	–57084
13 $K_P + R_P (t_W – t_P)$	+2368.4	+2399.4	+2405.7	+2449.1	+2752.2
14 F_P(W)	Y+2056.4	–46439.9	–45997.3	–45810.9	–54331.8
27 C_V(W)	A°	157°50'23"W	159°41'45"W	160°20'W	124°01'W
28 " sec	Y	–48518.5	–48073.0	–47920.0	–56636.0
29 $K_V + R_V (t_W – t_V)$	+2055.6	+2075.8	+2079.9	+2108.1	+2305.3
30 F_V(W)	Y+2055.6	–46442.7	–45993.1	–45811.9	–54330.7
31 F(W)	Y+2056.0	–46441.3	–45995.2	–45811.4	–54331.3

Notes: Between March 26 (RJD:+86) and April 17 (RJD:+108) Vancouver increased the Tahitian rate R of 4.0333 sec/day to 8.0000 sec/day (row 8). Between April 18 (RJD:+109) and May 4 (RJD:+125) it was further increased to 11.5000 sec/day.

Vancouver's Hawaiian true longitudes (row 6) are Cook and King's figures. No re-calibration was made in Hawaii.

Between Hawaii and Port Discovery the chronometer face value F(W) (row 31) is closely approximated by the expression: True(row 5)+1841.2+0.6293 RJD+0.042253 RJD^2.

Table 12 shows the record for Hawaii and Port Discovery. Both Portsmouth and Point Venus longitudes are given, and remarkably, in the light of previous results, none require correction. This may be an indication that the figures were checked with extra care by Vancouver, possibly as a result of his problem with the Port Discovery longitude which was crucial to his determination of accurate longitudes throughout 1792.[13]

The average rate-of-going between Point Venus and Waikiki is 3.6485 sec/day, which shows that it must have, at some time during the voyage from Tahiti to Hawaii, been significantly less than Vancouver's 4.0333 sec/day.

The performance of the K3

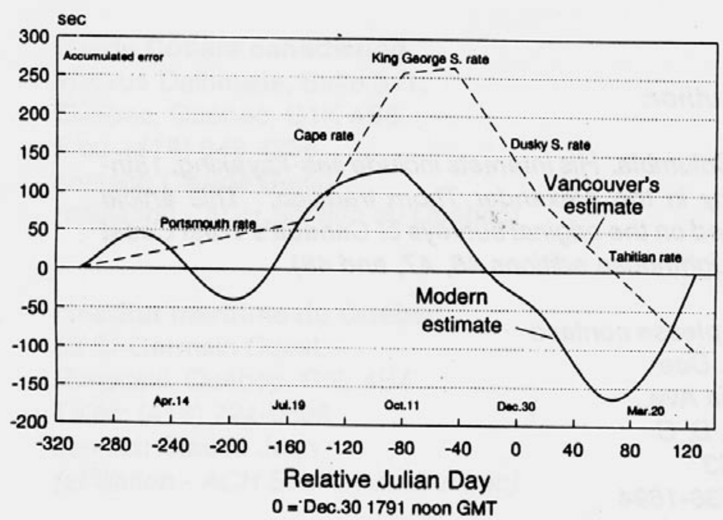

Figure 1: Estimated Error (Relative to 5.7959 s/day mean)

Figure 1 shows the accumulated error of the K3 chronometer over the period March 1, 1791 (RJD:–304) to May 4, 1792 (RJD:125). The error curve has been normalized to a mean daily rate of gaining of 5.7959 (5"47.8"') sec/day, which, fortuitously, is quite close to the Portsmouth rate of 6.2 (6"12"')sec/day. The curve has been obtained by interpolation between values of F(W) (row 31) true longitudes (row 5) in the tables described above. It represents the author's best estimate of the actual performance of the K3 based on the evidence in Vancouver's book.

[13] Doe, *Captain Vancouver's Longitudes 1792.... (ibid)*

Had the mean rate-of-going been known, then the K3 could have been relied on an accuracy of about ±150 seconds (±37.5' of longitude) without re-calibration over this portion of Vancouver's voyage.[14]

Also shown in Figure 1 is the error curve generated from Vancouver's measurements of the rate-of-going of the chronometer. The curve does not track the error closely, but it does approximate it, albeit with a delay of roughly 50 days. This is a clear indication, as many previous commentators have noted, that Vancouver's difficulty was having so few opportunities to establish the chronometer's rate-of-going. The rate changed more rapidly than it was possible for him to track.

The rate-of-going

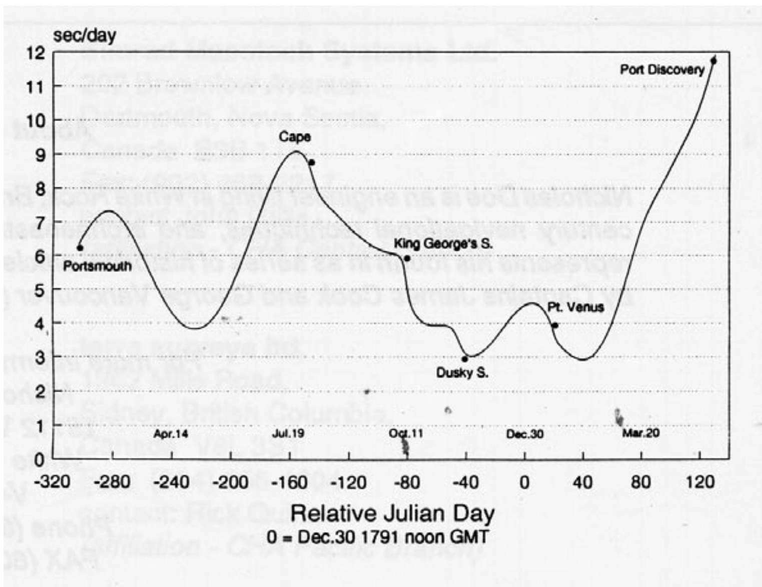

Figure 2: Estimated Rate-of-Going

Figure 2 shows a modern estimate of the rate-of-going of the K3 obtained by differentiating the error curve in Figure 1. It shows the chronometer rate varying between 3 sec/day, rising to nearly 12 sec/day at Port Discovery.

The singlemost important characteristic of the chronometer from the 18th-century navigators' point-of-view was not the rate-of-

[14] The standard deviation of the error curve is 85 seconds (21' of longitude).

going, but the rate of change of the rate-of-going, i.e. its acceleration. There is nothing magical in the 24 hour mean solar day; determinations of time made by observations of the Sun always had to take into consideration variations in the length of the solar day resulting from the Earth's non-circular orbit.[15] Some early chronometers were even set to show sidereal time, so their day was $23^h56^m4.1^s$ long which is the time between transits of any selected star across the local meridian.[16] What was important was that the rate-of-going be constant i.e. the acceleration be zero.

Figure 2 shows that the Kendall K3 did at times have a fairly high acceleration. On the approach to the Cape in the spring of 1791, and a year later during the passage from Hawaii to North America, the rate was changing by 0.1 sec/day/day. If the aim was to keep the chronometer accurate to say 30' of longitude, which is 120 seconds of time, it was essential to calibrate such an instrument at least once every 50 days.

It is interesting to note in the light of speculation that Vancouver's Point Venus estimate of the rate-of-going (Table 11) was too high, that there would be no difficulty in reconciling a lower value with the downward trend starting at the Cape. Also, a lower value would make it unnecessary to surmise that short-term fluctuations occurred at Tahiti in December and January.

[15] The variation peaks in December each year when successive solar days differ in duration by as much as 29 seconds.

[16] Even the length of a sidereal day is not constant, principally because of lunar nutation, but the effect is too small to concern navigators.

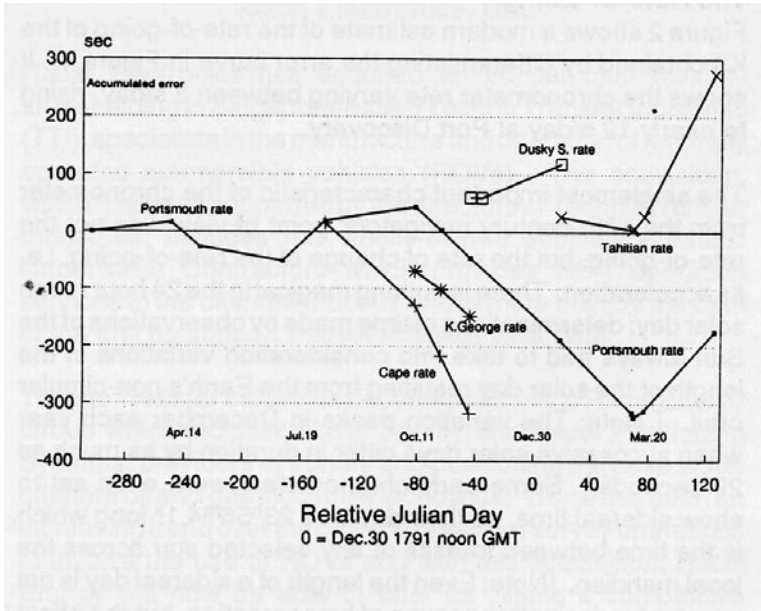

Figure 3: Calibrated Error

Figure 3 shows the error in the chronometer reading after calibration by Vancouver at various rates. The figure shows the Cape rate calibration to have been fairly useless, largely because the chronometer rate at the Cape had deviated considerably from its mean rate-of-going. At King George's Sound and Dusky Sound the chronometer was set over a minute slow and fast respectively due to the uncertainty in the longitude of these locations. Ironically the K3 Portsmouth rate error at the two locations was only 44 and 46 seconds respectively. Only at Tahiti and again at Port Discovery did the re-calibration become worthwhile.

Conclusions

One of the surprising facts to emerge from this study of Vancouver's observations over a short period of 14 months is how unreliable by modern standards his chronometer data is. One third of the 21 reports examined require some correction. In addition, there are serious doubts about the accuracy of his arithmetic at two of the five locations at which the all-important rate-of-going of the chronometer was established. This could be taken as evidence that Vancouver's records were in poor shape when he came to writing his book[17], or that he was under a great deal of stress to complete

[17] Poor record keeping may also have been the reason why Vancouver seriously misrepresents several of his astronomical observations on his way from Tahiti to the coast of America in 1792. Doe, Nicholas. *Captain Vancouver's Longitudes 1792.... (ibid)*

his book and he had no time to edit the numerical information it contained.[18]

The K3 performed well, particularly for such an early "affordable" instrument. Even without re-calibration, it was almost a year after leaving Portsmouth before its error reached one degree (4 minutes). Larcum Kendall would no doubt have derived pleasure from the observation that at King George's Sound and Dusky Sound, locations where the chronometer was re-calibrated to longitudes established astronomically, the calibration was not as accurate as the K3 Portsmouth rate longitude. Admittedly this was largely due to the fact that the Portsmouth rate was close to the mean rate for the selected portion of the voyage, and by the time Vancouver reached Port Discovery the Portsmouth rate longitudes were no longer accurate; nevertheless, it indicates the seriousness of the challenge of the chronometer method to the older lunar-distance method, even over extended periods of time.

[18] There is of course no evidence that Vancouver himself made the mistakes that have been identified. They may have been made by Joseph Whidbey, master of the *Discovery*, who was responsible for the ship's position, or by any of the others assisting Vancouver in his work.