Influence of Chronometer Error Uncertainties on the Longitude of Shackleton's Vessel, *Endurance*

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In 1915 while the Imperial Trans-Antarctic Expedition's vessel, *Endurance*, was icebound in the Weddell Sea, lunar occultation timings were carried out in order to rate the chronometers and thereby find longitude. The original observations have been re-analysed using modern lunar ephemerides and catalogues of star positions. The times derived in this way are found to differ by an average of 20 seconds from those obtained during the expedition using positions given from the Nautical Almanac and introduces an additional offset of the true positions to the east of those recorded in the log.

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1. INTRODUCTION.

The navigational procedures employed by Captain Frank Worsley on the 1914 Imperial Trans-Antarctic Expedition led by Sir Ernest Shackleton have been studied in detail (Bergman et al. 2018, Bergman and Stuart 2018, 2019a, 2019b) by examining his original log and workbook housed at the Canterbury Museum, Christchurch, New Zealand (Worsley 1916b). The majority of these publications were principally concerned with expounding the navigational techniques used in practice and replicating the calculations performed in the workbook. The astronomical data in the analyses was taken from the Nautical Almanacs of the period.

Particularly complex and challenging is the reduction of the occultation timings used to rate the chronometers when the expeditions vessel, *Endurance*, was trapped in the Weddell Sea ice during the southern winter of 1915 (Bergman and Stuart 2018). It was found that both Worsley and expedition physicist Reginald James carried out the necessary calculations accurately and consistently.

One of us (DLM) discovered a paper in the archives of the Scott Polar Research Institute (James 1919) which describes occultation timing reductions carried out by A. D. Crommelin of the Greenwich Observatory based on corrections to the Moon's position from observational data. The occultation times deduced in this manner were found to occur on average 22 seconds earlier than those obtained from tables in the 1915 Nautical Almanac meaning that the chronometers were running around 22 seconds faster than the chronometer errors recorded in the expedition's logs. This displaces the true positions by 5.5′ in longitude to the east and has implications for the location of the wreck of *Endurance* that sank on 21 November, 1915 at a position reported as 68°39′30″S 52°26′30″W.

In this paper the occultation timings are reanalysed using modern ephemerides of the Moon (Folkner et al. 2014) and star positions taken from the Hipparcos catalogue (Perryman et al. 2009). The results are broadly consistent with Crommelin's but produce a much better quality fit to the actual observations recorded in Worsley's workbook.

2. BACKGROUND.

In the navigational procedures that Worsley followed, longitude was found by means of a *time sight*. Using a sextant or theodolite the altitude of a celestial body, normally the Sun, is measured when it lies well off the meridian. After a calculation that incorporates the observer's estimated latitude, Local Mean Time (LMT) is determined. Longitude is the difference between LMT and Greenwich Mean Time (GMT) as read from a chronometer. Ideally the time sight should be made when the body being observed lies on the *prime vertical*, due east or west, as then the longitude obtained is independent of estimated latitude and any uncertainties therein. It is known (Bergman and Stuart 2019b, p.17) that this was the standard procedure adhered to while *Endurance* was underway from Portsmouth to Buenos Aires in 1914. The procedure was relaxed while at *Ocean Camp* on the Weddell Sea ice. Around the time of the sinking time sights were taken at about 9AM local time which may represent a convenient interval in the camp's daily routine. On 22 November, 1915, the day following the sinking of *Endurance*, the AM time sight was taken at 8:52 AM local time. The Sun would have been at an altitude of 34°. On the prime vertical the Sun's altitude was 21° which would be sufficient to allow a time sight to be made.

Management of the chronometers was a crucial task aboard any ship. *Endurance* set out carrying twenty-four (Worsley 1998, p.101). Ideally they would be kept in a temperature controlled environment and wound at the same time each day so as to use the same portion of the spring. Treatises (Shadwell 1861) were written on the methods and procedures that should be followed. From 18 March up until 27 October, 1915 when *Endurance* was abandoned the principal working chronometer used for navigation was a boxed chronometer by Thomas Mercer with serial number 5229. Now in the collection at the National Maritime Museum in Greenwich (Object Id: ZAA0029) it is believed to have been carried on the *James Caird* on the famous voyage from Elephant Island to South Georgia in 1916 (Bergman et al. 2018 p.31). It is usually referred to in the log as *Chronometer X*. Several other chronometers were given similar designations, see Bergman and Stuart (2018, Figure 8). Sometime between 28 October and 2 November, 1915 the role of working chronometer passed to the Smith watch with serial number 192/262, now in the collection of the Scott Polar Research Institute of Cambridge University (Reference number: N: 999a).

The time on chronometers was rarely reset. Instead, careful records were kept of their individual Chronometer Error (CE) fast or slow of GMT and Chronometer Rate (CR) gaining or losing in seconds per day. In this paper the term unaccounted-for chronometer error (UCE) will be adopted to refer to the difference between the true CE and the CE as given in the log.

The CE is generally found by making a time sight from a location of known longitude or by comparison to some authoritative standard time source. When a fixed observing platform was available GMT and hence the CE could be determined from the timing of lunar occultations, meridian passages of Moon-culminating stars or eclipses of Jupiter's moons. It is known that the chronometers were rated on 24 October, 1914 while *Endurance* was in Buenos Aires, Argentina (Bergman and Stuart 2018 p. 86., 2019b p. 13). Upon rating the UCE will be zero.

3. OCCULTATIONS.

The observer's latitude and local mean time (LMT) can be obtained by observation without precise knowledge of GMT, and from them the GMT at immersion or emersion of an occulted star can be computed. Between 24 June and 15 September, 1915 Worsley and physicist Reginald James timed 10 occultations and independently reduced their observations using *Raper's Method* as set out by Close (1905). Close takes the method from *Notes for Traveller's* (Godwin-Austen et al. 1883) which introduced some potential errors of interpretation arising from the somewhat ambiguous description that Raper (1840) provides. These potential errors do not affect Worsley's calculations however. A complete description of the observations has been given by Bergman and Stuart (2018). It was found that Worsley and James correctly carried out the reductions based on the positions of the Moon and stars as tabulated in the Nautical Almanac (1915) where they are quoted to 0.01^s in right ascension and $0.1''$ in declination.

The level of precision to which positions are given in the Nautical Almanac does not reflect the accuracy to which they could be computed in advance. Close (1905, p.190) states

> To get the full benefit from the accuracy of the method, it is necessary to obtain from some fixed observatory the *observed* declination and right ascension of the moon during the night in question, so as to correct the co-ordinates given (by prediction) in the 'Nautical Almanac'; differences even in the second place of decimals of seconds in these quantities appreciably affect the result of the calculation.

James (1919) describes corrections deduced by Crommelin, see also Dyson and Crommelin (1923), aimed at improving the CEs obtained from the occultations.

The CEs for the Mercer 5229 have been calculated using the Jet Propulsion Laboratory's DE430 model for the motion of the Moon (Folkner et al. 2014). The occulted star positions were taken from the Hipparcos catalogue (Perryman et al. 2009) which gave an average difference of $1.3''$ in apparent positions obtained from the Nautical Almanac. The maximum difference was $3.2''$ for the star B.D. -17°4053 (HIP 69792). Calculations were performed using the Skyfield software package (Rhodes 2016) and are summarized in Tables A1 and A2. A comparison of the positions of the Moon given in the Nautical Almanac with those obtained with Skyfield on the hour closest to the occultation finds that the former consistently lag by 0.9^s in right ascension on average and have a root-mean-square difference in declination of 1.7″

There is a complication with regard to the occultations of the star A Ophiuchi (HIP 84405) observed on 23 July and 15 September. It is a binary system consisting of two nearly identical components that at the time of observation were separated by 4.24″ with the B component at position angle (J2000.0) of 184.1° relative to the A star (Hartkopf et al. 2001). The B star is the reference component in the Hipparcos catalogue. To reduce the occultations the position and proper motion of the system's centre of mass (CM) was found by averaging those of the two components. The apparent positions of the A and B stars at immersion were offset from the position of the CM based on the separation and position angle.

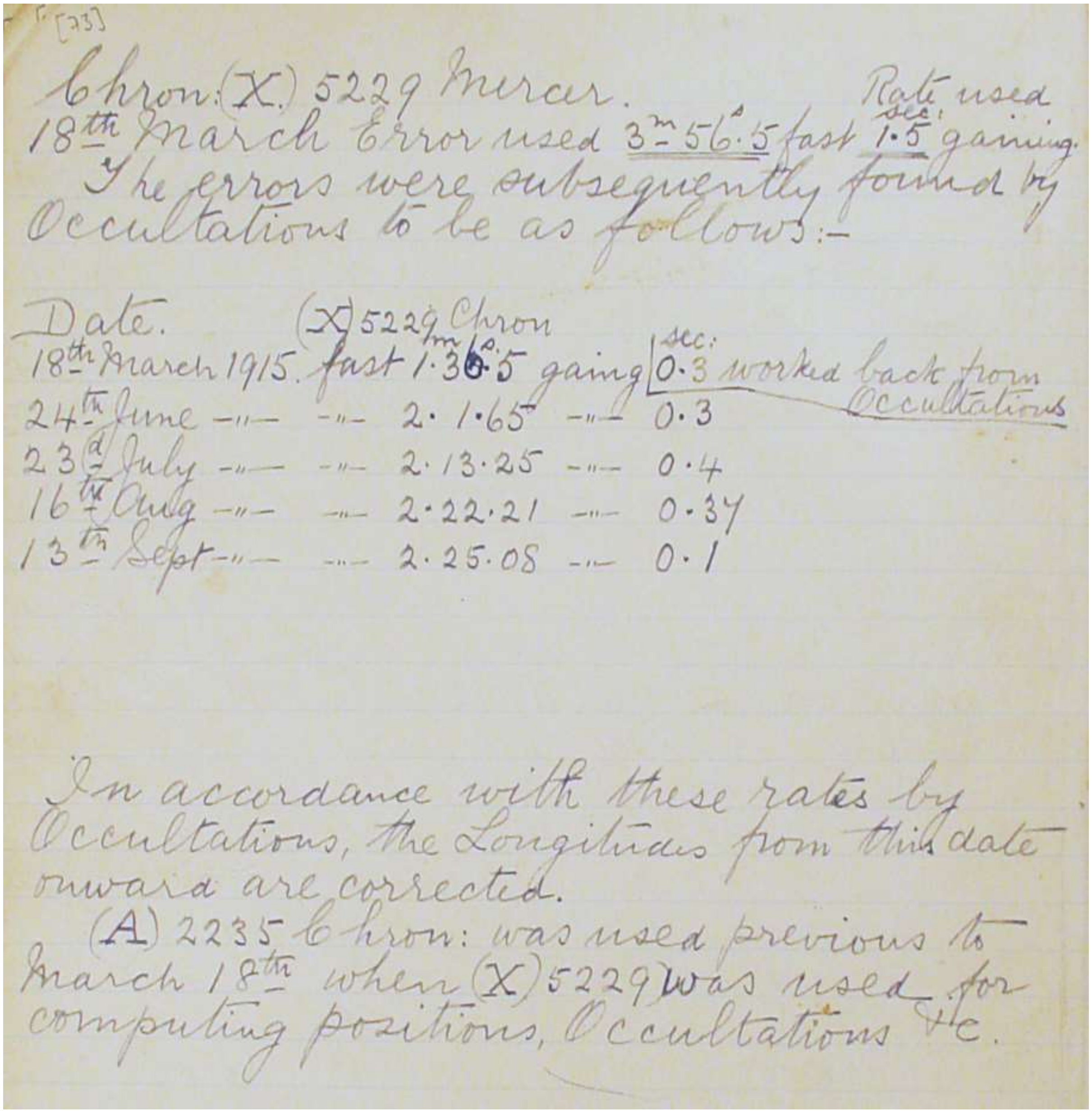
In relation to occultations, the Nautical Almanac (1915) refers to "A Ophiuchi (1st star)". The precise meaning of this term is ambiguous. From the position angle it can be seen that the A star and the B star have very nearly the same right ascension and the one that is occulted first depends on where on the lunar limb the disappearance occurs and that in turn depends on the observer's latitude. For the occultation of 23 July the A star disappeared first with the B star following 0.15^s later. However on 15 September the B star was the first to be occulted and the A star disappeared 4.25^s afterwards. It is assumed that Worsley recorded the time of the first immersion.

The time calculated for an occultation depends somewhat on the assumed value of the constant, k. This is the ratio of the Moon's radius to the equatorial radius of the Earth but is adjusted in an attempt to account for observational effects such as irradiance. In these calculations $k = 0.272550$ is used as recommended in the Nautical Almanac (1915, p.641).

Table A1 gives the latitude and local mean time of immersion for the 10 occultations observed on the expedition. The Universal Time (UT1) deduced from these observations is given. This modern timescale is 12 hours ahead of GMT as it was recorded in the log. The CEs listed come from Worsley (1916b) and James (1919). The UCEs represent the corrections that must be added to the CEs in order to be consistent with the DE430 model and Hipparcos catalogue. They range around an average value of 20^s. The UCEs computed by Crommelin are deduced from James (1919) and have an average of 22^s.

Table A2 gives the observer's latitude and longitude at the time of the occultation based on the UT1 listed in Table A1. Also given are the apparent topocentric positions for the equator of date of the Moon and occulted stars along with the Moon's semidiameter.

As seen in Figure 1, Worsley computed CEs for the Mercer 5229 chronometer from the occultations. Those of 24 June and 16 August are averaged over the multiple stars observed. From these the chronometer rate (CR) over the intervals between occultations is obtained. The occultation of 15 September is omitted. It gives CR of gaining 3.9 s/day from 13 September which is far larger than the other values and Worsley apparently rejected it. The average CR for the three intervals between listed occultations is gaining 0.3 s/day which is extrapolated backwards to estimate the CE on 18 March. However, perhaps motivated by the smaller than average CR of gaining 0.l s/day obtained for 13 September, Worsley adopts a CR of gaining 0.2 s/day from 17 September until *Endurance* was abandoned on 27 October.



[73]

Chron: (X) 5229 Mercer. Rate used

18th March Error used 3m 56s.5 fast sec: 1.5 gaining.

The errors were subsequently found by Occultations to be as follows:–

Date.	(X) 5229 Chron		
18th March 1915.	fast 1m 36s.5	gaining	sec: 0.3 worked back from Occultations
24th June –"–	–"– 2. 1.65	–"–	0.3
23rd July –"–	–"– 2.13.25	–"–	0.4
16th Aug –"–	–"– 2.22.21	–"–	0.37
13th Sept –"–	–"– 2.25.08	–"–	0.1

In accordance with these rates by Occultations, the Longitudes from this date onward are corrected.

(A) 2235 Chron: was used previous to March 18th when (X) 5229 was used for computing positions, Occultations &c.

Figure 1: Chronometer Errors deduced by Worsley for the Mercer 5229 (chronometer X) from the occultations. The occultation of 15 September has been rejected. Canterbury Museum 2001.177.1-pg 73.

A least-squares linear regression can be performed on the CEs and corrected CEs (CE + UCE) in Table A1 against the tabulated UT1. The results are shown in Table 1. James (1919) suggests that Crommelin's UCE for the star B.A.C. 5253 on 24 June seems to be wrong and it is therefore omitted from the regression. The fit yields an estimate of the CR. R^2 for Worsley and James' initial CEs indicates a fair fit. Correction by the DE430/Hipparcos UCEs produce an excellent fit with $R^2 = 99.2\%$ and give a CR of gaining 0.365 s/day. The fit residuals are plotted in Figure 2. For clarity James' original values are not included because they lie very close to those of Worsley. Although the average of the UCEs derived from modern calculations is close to the average for Crommelin's, the former produces a considerably better fit.

	CR (s/day) gaining	R^2
Worsley	0.347	0.901
Worsley (DE430)	0.365	0.992
James	0.343	0.925
James (DE430)	0.365	0.992
Crommelin	0.271	0.863

Table 1: Chronometer rate and R^2 obtained by a linear least-squares best fit to the CEs and corrected CEs (CE + UCE) in Table A1 omitting Crommelin's C.E. for BAC 5253.

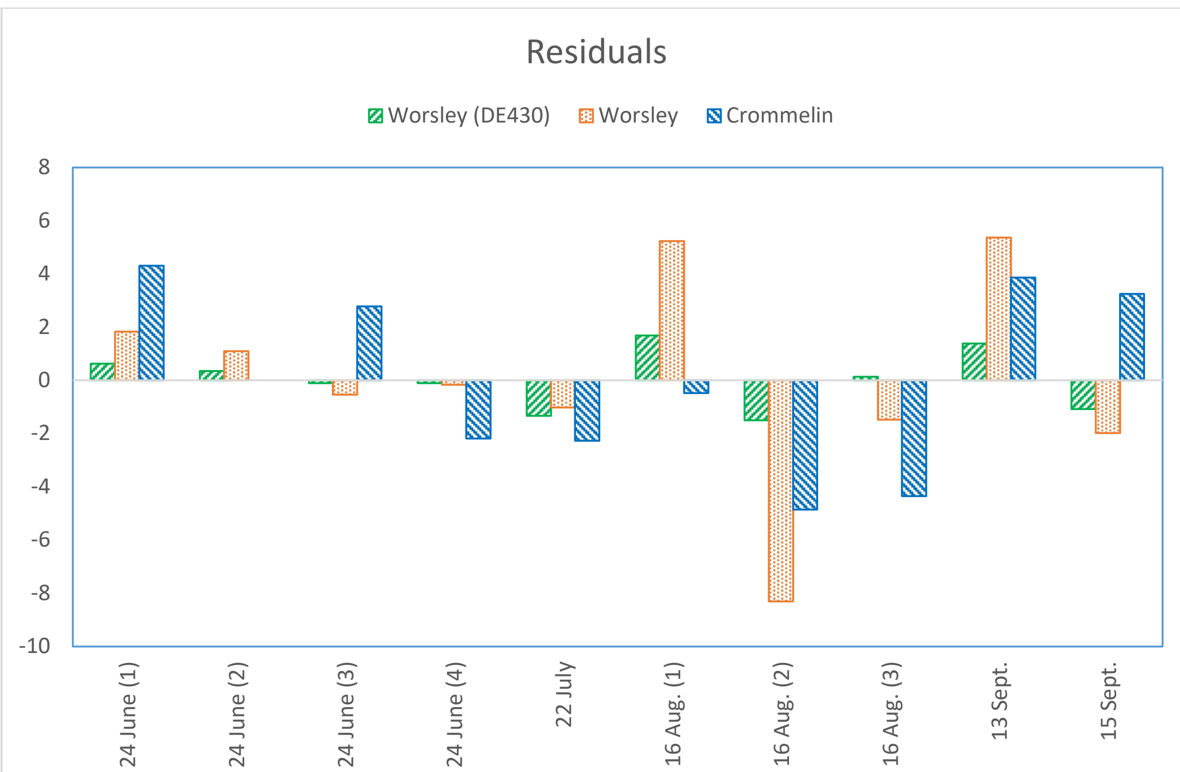


Figure 2: Residuals to the linear least-squares best fit of chronometer errors and corrected chronometer errors. James' CEs fall very close to Worsley's and are not plotted.

4. CONNECTING THE MERCER AND SMITH CHRONOMETERS

As previously noted, to function reliably chronometers should be kept in a temperature controlled environment. After *Endurance* was abandoned and the expedition took up residence in *Ocean Camp* on the ice floe this would not be possible for a boxed chronometer like the Mercer 5229. The log entry for 2 November shows that the role of working chronometer had passed to the Smith 192/262 with a CE of "$40^{m}26^{s}$ slow". As it takes the form of a large pocket watch it could be worn close to the body to maintain it at a constant temperature. Worsley (1998, p.191) mentions that "I carried… the chronometer…slung around my neck by lampwick, inside my sweater, to keep it warm". Similar watches were apparently placed in the care of Hudson (192/232) and Wild (192/231). The exact procedures followed remain uncertain however the Smith 192/262 would have inherited the UCE from the Mercer 5229 when it became the working chronometer. On 7 November the Smith 192/262 is recorded as having a CE "fast $3^{m}28.5^{s}$ Cor" indicating that it had been reset.

Little information is available to pin down the behaviour of the UCE for the Smith chronometer between 2 and 22 November. Long term averages can be obtained from sights taken in March and April of 1916 but these may not reliably reflect short term variations that could have occurred in the period.

Mount Percy on Joinville Island was sighted on 24 March, 1916 from *Patience Camp* on the Weddell Sea pack ice and an attempt was made to rate the chronometers by triangulation on its changing bearing over a 3 day period (Bergman et al. 2018 p.54, Bergman and Stuart 2018 p.87–88). From these observations it was determined that Mount Percy was "23′W of Chron:" (Worsley 1916b p.80). Worsley did not have sufficient confidence in the observations to allow the CE to be adjusted based on them. In fact Mount Percy lies at 55°49′W or 11′ further west than the position that Worsley had for it. This implies a UCE of $2^{m}16^{s}$ slow.

On 24 April, 1916 immediately prior to departure from Elephant Island for South Georgia, Worsley was able to take a time sight from Cape Wild (now Point Wild). A detailed analysis can be found in Bergman et al. (2018). Geographical constraints mean that the location where the sight was taken is quite well determined at 61°6′S 54°51′30″W giving a UCE of $2^{m}25^{s}$ slow.

5. SCENARIOS AND UNKOWNS

5.1 Effects of Chronometer Error The foregoing information can be used to estimate ranges by which the true longitude differs from that given in the log. Each 1 second of UCE fast (slow) moves the true position 0.25′ of longitude or at the latitude at which *Endurance* sank, 0.09NM east (west) of the position given in the log.

For 27 October, 1915, the day that *Endurance* was abandoned Worsley (Worsley 1916b p.39) gives a CE as $2^{m}38^{s}$ fast. However taking the sum of the values for "Worsley CE" and "Worsley UCE" in Table A1 and regressing them in time predicts a true CE for the Mercer 5229, Chronometer X, of $3^{m}6.8^{s}$ fast on that date and suggests that the working chronometer was actually fast by an additional 28.8 seconds. On that date the expedition's true position would then be 7.2′ of longitude east of where the log entries put it.

Worsley may have begun using the Smith 192/262 immediately after *Endurance* was abandoned or alternatively, since it makes its first appearance on 2 November, the CE for the Mercer 5229 may have been carried forward at CR of 0.2s/day gaining until this date by which time the UCE would be 29.8s fast. Exactly what transpired, how the role of working chronometer was transferred from the Mercer to the Smith and what errors may have been introduced in the process is unknown.

If the Smith was the working chronometer from 27 October, 1915 then its UCE on that date would be 28.8s fast. Taking the observation of Mount Percy on 24 March, 1916 for which the UCE was 2m16s slow and performing simple linear interpolation gives a UCE on 22 November of zero. In this scenario the positions as stated in the log are correct.

If the Mercer was the working chronometer until 2 November the UCE inherited by the Smith on that date would be 29.8s fast. If it were to keep perfect time then true positions would be 7.5′ (2.7 NM) east of those given in the log. If it began to drift immediately at a rate determined by the time sight from Elephant Island taken on 24 April, 1916 and for which the UCE was 2m25s slow then the UCE on 22 November would be 9.7s fast. This corresponds to the true position of the sinking being 2.4′ (0.9NM) of longitude east of that given in the log.

5.2. Effects of Ice Drift *Endurance* sank at around 5pm local time on 21 November, 1915 but sights to fix the position could not be taken until the following day. As noted elsewhere (Bergman and Stuart 2019a) Shackleton's journal entries as well as those from other expedition members indicate that the wind blew with a persistent southerly component during that period. The position of the sinking reported in the log is consistent with the noon position of *Ocean Camp* on 22 November plus an offset of 1.2NM S 33° E (1′S 1′45″E) to account for the distance and bearing of *Endurance* from *Ocean Camp* at the time of the sinking and is consistent with accounts by Worsley and others. On 10 November Worsley (1916a) records, "…our camp is roughly 2 m NW of the position of the ship..." In his diary entry of 21 November Orde-Lees (1916) writes "…there was our poor ship a mile and a half away breathing her last". If indeed the reported position of the wreck is simply based on the noon position as determined the following day then the influence of the wind and ice drift in the intervening 19 hour period needs to be considered. There is very little quantitative guidance available here.

On 21 November Shackleton (1915) reports, "… a SSE fair wind all day" and "The wind veered later to the west, and the sun came out at 9 p.m." (Shackleton 1920. Ch. V, P.98). For the same day Orde-Lees (1916) writes "wind S. to S.W. increasing about 6pm".

As noted previously (Bergman and Stuart 2019a, p.263) the difference in longitude that Worsley obtained in the AM and PM time sights on 22 November show a roughly north-westerly drift with a westward component of 0.9NM in 6^h47^m giving an average speed of 0.13 knots. If maintained over 19 hours that would push the true position of the wreck a further 2.6 NM east of the noon position given in the log. However since the AM and PM time sights were not made when the Sun was on the prime vertical the longitude difference has some dependency on the latitudes that were assumed in the sight reduction and is therefore open to question. Moreover the westward drift on 22 November suggests an easterly component to the wind and a reversal of direction since the evening before. Which direction predominated over the period is unknown.

6. CONCLUSIONS

The occultation timings made over the winter of 1915 by the Imperial Trans-Antarctic Expedition in order to rate their chronometers and thereby fix longitude have been re-analysed using modern lunar ephemerides and star positions. This shows that previous estimates of chronometer errors based on positions from the 1915 Nautical Almanac are too slow by an average of 20 seconds. It was noted elsewhere (Bergman and Stuart 2019a) that Captain Frank Worsley had an apparent tendency to underestimate how slow the Smith 192/262 chronometer was running in the period following the sinking of *Endurance* which would favour a wreck site to west of the position in the log. The new correction examined here more than compensates for that bias and pushes the wreck site back toward the east. As previously noted, a westerly component of ice drift would tend to offset the position still further to the east.

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APPENDIX A

Star	Latitude				LMT (Astro.)			UT1 (DE430)			Worsley CE fast		Worsley UCE (DE430) fast	James Preliminary CE fast		James UCE (DE430) fast	Crommelin UCE fast
	°	′	″		h	m	s	h	m	s	m	s	s	m	s	s	s
June 24, 1915																	
42 Libræ	74	0	0	S.	1	34	5.5	16	43	45.23	2	0.40	20.37	2	0.4	20.37	20.7
B.A.C. 5253	73	58	0	S.	6	40	5	21	49	37.87	2	1.20	19.93	2	1.3	19.83	36.7
B.A.C. 5286	73	57	45	S.	8	34	55	23	44	27.38	2	2.875	18.74	2	2.6	19.02	20.1
σ Scorpii	73	57	0	S.	17	22	18	8	31	38.62	2	2.27	19.11	2	2.6	18.78	24.9
July 23, 1915																	
A Ophiuchi	73	14	30	S.	21	24	8	12	35	31.56	2	13.25	20.01	2	13.4	19.86	22.1
16 August, 1915																	
B.A.C. 4722	70	41	43	S.	5	15	51	20	35	43.87	2	15.45	23.68	2	16.0	23.13	24.3
B.D. -17°4053	70	41	43	S.	6	13	23.5	21	33	13.18	2	29.00	13.32	2	26.7	15.62	18.0
B.A.C. 4739	70	41	43	S.	6	59	2.5	22	18	53.81	2	22.18	18.51	2	22.1	18.59	22.1
13 September, 1915																	
B.D. -21°4030	69	45	0	S.	8	35	51.5	23	57	25.8	2	25.08	24.62	2	25.1	24.60	18.5
15 September, 1915																	
A Ophiuchi	69	32	0	S.	10	19	52	1	42	45.44	2	32.81	19.75	2	32.8	19.76	11.7

Table A1: UT1of immersion computed from the latitude and local mean time (LMT) given in the log using the DE430 model (Folkner 2014) and Hipparcos star positions. LMT is given here as astronomical time in the way it was recorded in the log with 0^h at local mean noon. This is 12 hours behind clocktimes ascurrently understood. The column Worsley CE gives the chronometer error computed from tables in the Nautical Almanac (1915) in Antarctica. James' Preliminary CE gives the same results as computed independently by James (1919). The columns headed UCE give the unaccounted-for chronometer error (UCE) that must be added to the CE to be consistent with UT1. Crommelin UCE is the adjustment for inaccuracies in the Nautical Almanac positions as known in the early 20^{th} century.

Star	HIP	Latitude	Longitude	Apparent Topocentric				
				Moon R.A.	Moon Declination	SD k = 0.272550	Star R.A.	Star Declination
		° ′ ″	° ′ ″	h m s	° ′ ″	°	h m s	° ′ ″
24 June, 1915								
42 Libræ	76742	74 0 0 S.	47 24 56 W.	15 34 10.39	23 27 11.2 S.	0.277493	15 35 18.67	23 32 51.6 S.
B.A.C. 5253	77858	73 58 0 S.	47 23 13 W.	15 47 39.18	24 16 21.6 S.	0.279388	15 48 52.66	24 17 7.6 S.
B.A.C. 5286	78246	73 57 45 S.	47 23 6 W.	15 52 19.94	24 32 21.4 S.	0.279836	15 53 32.47	24 35 31.0 S.
σ Scorpii	80112	73 57 0 S.	47 20 9 W.	16 14 53.03	25 19 37.4 S.	0.278749	16 16 4.90	25 23 38.7 S.
23 July, 1915								
A Ophiuchi	84405 A	73 14 30 S.	47 50 53 W.	17 8 57.93	26 27 12.2 S.	0.274804	17 10 11.22	26 28 52.3 S.
16 August, 1915								
B.A.C. 4722	69658	70 41 43 S.	49 58 13 W.	14 9 37.41	17 50 14.3 S.	0.270124	14 10 45.15	17 48 34.6 S.
B.D. -17°4053	69792	70 41 43 S.	49 57 25 W.	14 11 30.66	18 1 40.7 S.	0.270089	14 12 23.93	18 11 47.9 S.
B.A.C. 4739	69929	70 41 43 S.	49 57 50 W.	14 13 2.29	18 10 27.7 S.	0.270004	14 13 58.39	18 19 41.1 S.
13 September, 1915								
B.D. -21°4030	73927	69 45 0 S.	50 23 34 W.	15 0 26.17	21 45 36.1 S.	0.271644	15 1 34.97	21 42 23.1 S.
15 September, 1915								
A Ophiuchi	84405 B	69 32 0 S.	50 43 22 W.	17 9 5.34	26 36 15.8 S.	0.271729	17 10 10.49	26 28 56.9 S.

Table A2: Latitude from the log and Longitude derived from the occultation observations given in Table A2. The apparent topocentric positions for the equator of date are given for the Moon and star at the computed UT1 of immersion along with lunar semidiameter.