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Contents

Two new species of *Deleatidiu*m (*Deleatidium*) (Ephemeroptera: Leptophlebiidae) from the central North Island of New Zealand

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Two new species of mayfly, *Deleatidium* (*Deleatidium*) *crawfordi* sp. nov. and *Deleatidium* (*D.*) *rapidum* sp. nov., are described from the North Island of New Zealand. The larval stages of both species are associated with their respective subimagines and adults. Notes on the ecology of both species are included. One species shows adaptation to relatively fast water flows. Neither species has been identified elsewhere in New Zealand. Diagnostic characters of both species are illustrated.

Keywords: *Deleatidium*, Ephemeroptera, mayflies, mayfly, new species, New Zealand, taxonomy.

Introduction

Deleatidium Eaton, 1899 is the largest genus of the New Zealand Leptophlebiidae with 18 described species, all of which are endemic. The identification of *Deleatidium* can be difficult as finding relatively easily observed morphological features is not easy. The genus has two subgenera, *Deleatidium* (*Deleatidium*) and *Deleatidium* (*Penniketellum*), distinguished in the adult stages by the dissimilarity of the tarsal claws in the case of the former subgenus (Towns and Peters 1996). *Deleatidium* (*Penniketellum*) is restricted to mountainous regions where their gills have adapted to the fast flowing water. This work adds two new species of *Deleatidium* (*Deleatidium*) to the mayfly fauna of New Zealand.

Both species are known only from a single locality in central North Island, which is an area where comparatively little is known of the mayfly fauna.

Materials, methods and conventions

Specimens were collected by William J Crawford from the middle stretches of the Mohaka River between the Ahimanawa and Kaweka ranges in 2001 and 2002. He also reared subimagines and adults, establishing the association.

Larvae were associated by rearing in aquaria. All specimens are stored in 80% ethanol. Body, forewing and hindwing lengths of imagines and larvae are given, with means in parentheses; length ratios of foreleg segments (femur: tibia: tarsomeres 1–5) are based on the length of tibia (absolute measurements in mm, in parentheses). Intraspecific variation was not noted as specimens of both species were collected from small geographic ranges; however, there was no obvious variation in the specimens that we examined. Collection locations were determined from the topographical map series NZGD 2000/WGS 84a. Area codes are given using the system of Crosby et al. (1998). In this instance they are at the boundary of the Taupo and Hawke's Bay regions (TO/HB). All specimens of *D. crawfordi* were collected within 1.5 km, and all *D. rapidum* within 0.5 km, of their respective type locations. All material is held at Canterbury Museum, Christchurch (CMNZ) or the New Zealand

Arthropod Collection, Landcare Research, Auckland (NZAC).

Systematics

Order Ephemeroptera Hyatt & Arms, 1891
Family Leptophlebiidae Banks, 1900
Genus *Deleatidium* Eaton, 1899
As diagnosed by Towns & Peters (1996: 27–29)
Subgenus *Deleatidium* (*Deleatidium*) Towns & Peters, 1996
As diagnosed by Towns & Peters (1996: 30)

***Deleatidium crawfordi* sp. nov.**

Description: Dimensions (mm). Imago male: length of body 9.5–10.5 (10.0); forewings 9.7–10.5 (10.1). Imago female: length of body 9.5–10.5 (10.0); forewings 10.5–10.8 (10.7). Mature (final instar) larva: length of body 8.0–10.0 (9.3).

Male imago: Head yellowish, blackish around base of ocelli and eyes. Antennal scape and pedicel brownish yellow, flagellum whitish yellow; length 1/3 head width. Eyes in contact dorsally; upper parts yellow, lower parts grey-black. Thorax. Pronotum pale yellow, mesonotum and metanotum yellow. Scutum with thin brown margin. Sterna yellow with brownish margins. Dark ganglia prominent on sterna of the prothorax and mesothorax. Legs yellowish white, darker at the femoro-tibial articulatons. Length ratios of foreleg segments 0.75–0.77: 1.0 (3.0–3.3 mm): 0.03–0.06: 0.32–0.35: 0.23–0.26. Tarsal claws dissimilar; pad without apical hook and claw with prominent opposing hook. Wings. Forewing width 0.32–0.34 (0.33) x length. Longitudinal cross-veins brown, fading to light brown and white posteriorly, membrane uniformly whitish (not hyaline). The largest intercalary vein between ICu and CuP attached at its base to ICu. Hindwing length 0.25 x forewing length. Hindwing width 0.50–0.58 (0.53) x length. Hindwing vein Sc 0.92–0.96 (0.95) x wing length; cross-veins variably visible in posterior half of hindwing; longitudinal veins light brown, Sc a little darker; membrane uniformly greyish. Abdomen. Dorsum generally yellowish, a grey-brown transverse band at the posterior margin of segments 2–7; paired paramedian pale maculae anteriorly on terga 2–8, each outlined by grey pigmentation. Sterna pale yellow with faint grey maculae anterolaterally. Ganglia

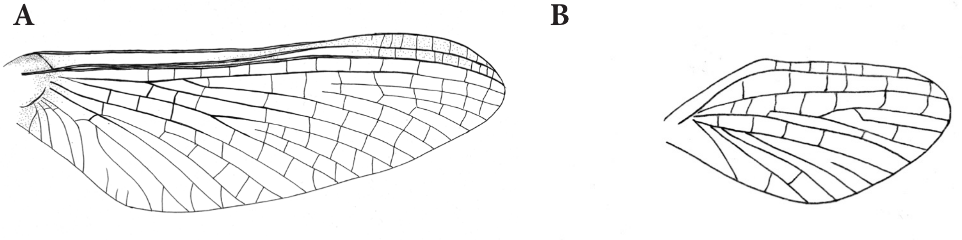

Figure 1. *Deleatidium crawfordi*, male imago. **A,** forewing. **B,** hindwing.

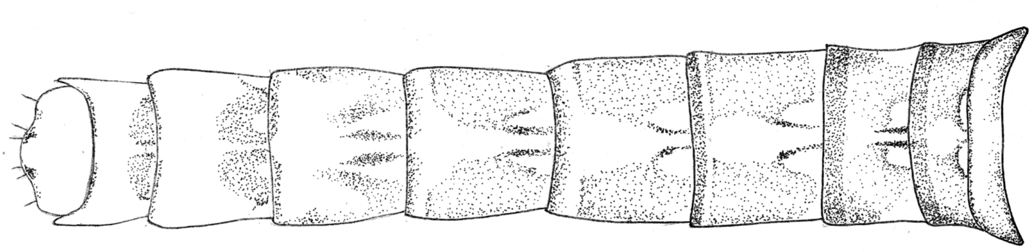

Figure 2. *Deleatidium crawfordi,* male imago, dorsal surface.

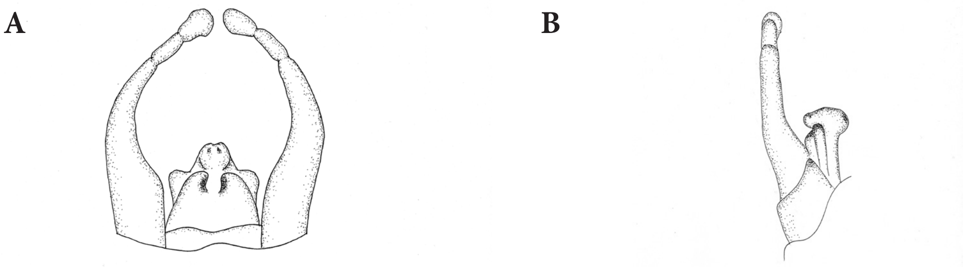

Figure 3. *Deleatidium crawfordi,* male genitalia. **A,** ventral view. **B,** lateral view.

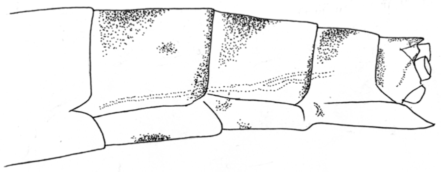

Figure 4. *Deleatidium crawfordi,* female imago, distal abdomen, lateral view.

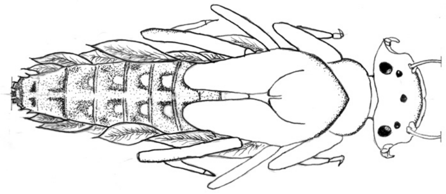

Figure 5. *Deleatidium crawfordi,* mature larva, dorsal view (antennae and caudal filaments truncated).

Figure 6. *Deleatidium crawfordi,* photograph of mature larva, dorsal view (CMNZ 2014.2.24786).

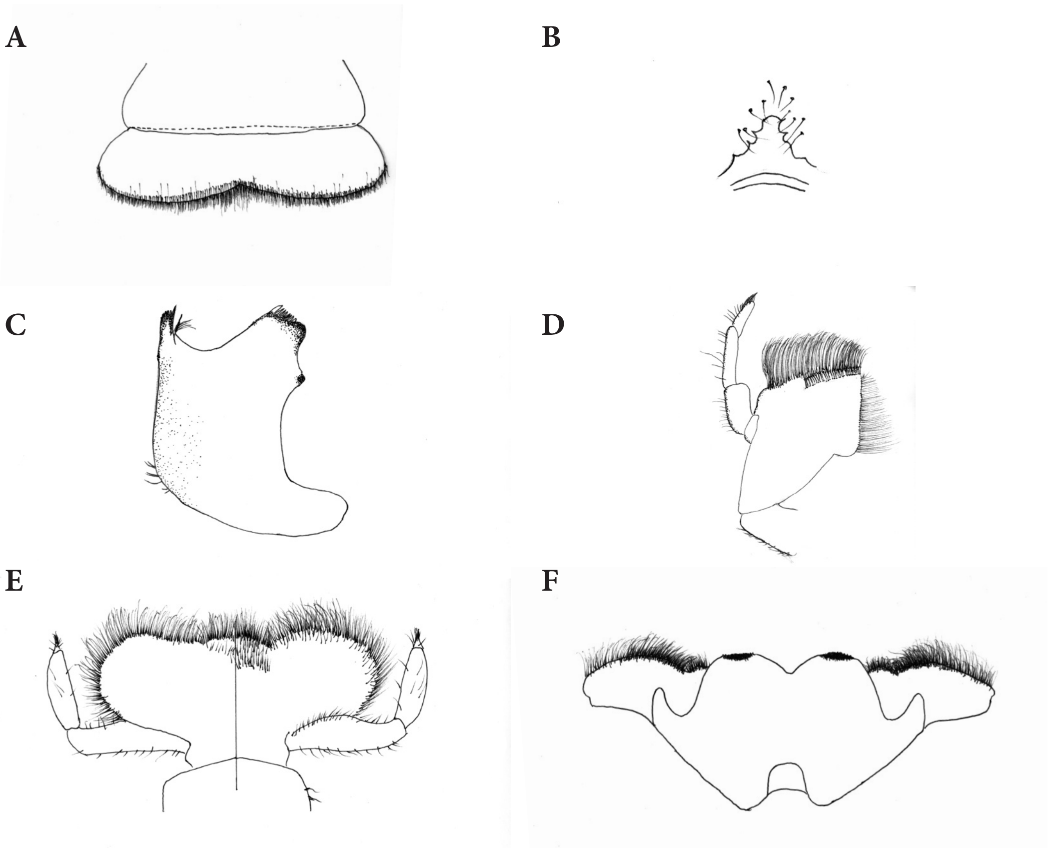

Figure 7. *Deleatidium crawfordi,* larval mouth parts. **A,** clypeus and labrum. **B,** enlarged anteromedian emargination. **C,** left mandible. **D,** right maxilla. **E,** labium, in dorsal (left) and ventral (right) views. **F,** hypopharynx.

dark grey, terminal ganglion sometimes a little darker than the others; connectives usually hyaline, sometimes darker. Genitalia. As illustrated; generally yellowish. In lateral view, penes with a rounded, almost globular upper portion from which paired tapering extensions project, sometimes distally, sometimes curved and directed posteriorly. In ventral view paired tapering apices are separated by a U-shaped indentation. Caudal filaments 12.5–13.0 mm; pale yellow and darker at the articulations.

Female imago: As in the male except as follows: eyes greyish black, separated by 2.5 x diameter of eye. Head whitish yellow, black surrounding the ocelli. Forewing width 0.28 x length. Hindwing width and length as for male. Sternum 7 with small egg guide extending about one tenth the length of sternum 8. Sternum 9 with U-shaped cleft

Subimago: Head, including eyes, as in male imago. Thorax differs from the imago in that the scutum medial to the medioparapsidal suture is whitish and yellowish brown laterally. Medial two thirds of posterior scutal protuberances whitish. Pigmentation of lateral scutal suture strongly dark brown. Pronotum, metanotum and sterna as in the imago. Legs as in the imago. Wings grey with faint whitish clouding in cells across the mid forewing, less apparent in the female. Veins light brown to white. Appearance of dorsal abdomen as in the imago; sterna pale with prominent blackish ganglia; terminal

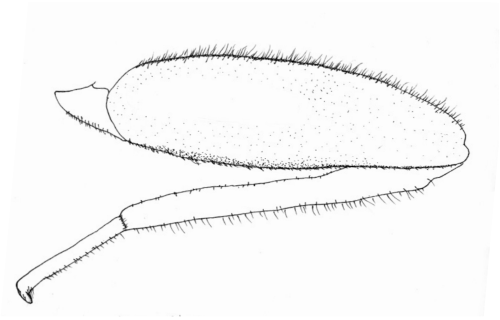

Figure 8. *Deleatidium crawfordi,* larval foreleg.

Figure 9. *Deleatidium crawfordi,* abdominal larval gills 1, 4, 7 (from left to right).

ganglion darkest. Penes whitish, with paired pigmented maculae on mesial surface of ventral appendages. Apical lobe with median cleavage mark more apparent when viewed ventrally.

Late instar larva: (Figs 5–6). Head including clypeus and labrum yellowish, margins brown. Region between ocelli darker. Eyes of male yellowish with lower portions black; female black. Antennae 1.04–1.61 (1.32) x as long as head. Mouth parts. Clypeus and labrum (Fig. 7A): labrum length 0.64–0.73 x that of clypeus, width 1.27–1.30 x that of clypeus. Anterior margin of labrum with deep median cleft, otherwise smoothly curved and strongly tapering to rounded lateral margins; dorsally with dense feather-like hairs; the anteromedian cleft with 4–6 irregular emarginations (Fig. 7B). Mandibles (Fig. 7C): an irregular cluster of 8–12 hairs at the centre of the outer margin; outer incisors with 3–4 serrations on the mesial surface. Maxillae (Fig. 7D): galea-lacinia with a sub-apical row of 22–23 spines; palp segment 2, 1.23–1.25 x as long as segment 1; segment 3, 0.60–0.85 x as long as segment 2. Labium (Fig. 7E): one shoulder of the submentum with a group of 2 or 3 long spines at the base, the other shoulder without spines; palp segment 2, 0.75 x as long as segment 1; segment 3, 0.47 x as long as segment 2. Hypopharynx (Fig. 7F): lingua rounded apically, each lobe with a crest of small, dark hairs directed mesially; lobes deeply cleft, the cleavage lined with short, fine spines; anterior margin of the superlingua thickly supplied with long fine hairs. Thorax pale yellowish, darker brown at the margins, pleura and sterna whitish. Legs yellowish, postcoxal plate dark brownish, femur of foreleg (Fig. 8) with a proximal pale whitish macula on the anterior surface. Abdomen yellowish with markings as follows: terga 1–9 with posterior transverse dark brown margins and a pale longitudinal mid-dorsal line. Sterna whitish with a prominent expanded blackish ganglia on segment 7 and smaller, paler, ganglia on the remaining abdominal segments. Gills (Fig. 9) single, plate-like and rounded but drawn out apically to fine thread-like filaments about one-tenth length of the gill. Gill 1 longer than wide and with ventral margin expanded basally as a lobe. Gill 7 sometimes lacking an apical filament. Lamellae translucent with blackish tracheae and branches. Posterolateral projections well developed on segments 4–9. Caudal filaments yellowish white 1.29–1.43 (1.33) x body length. Each segment of the filaments with a distal whorl of small white denticles.

Holotype: Male imago, TO/HB, Mohaka River, McVicar Road, New Zealand. 39°12'S 176°37'E. 320 m. 17 March 2001, WJ Crawford (CMNZ 2014.2.47452).

Allotype: Female imago, TO/HB, Mohaka River, McVicar Road, New Zealand. 39°12'S, 176°37'E. 320 m. 5 April 2001, WJ Crawford (CMNZ 2014.2.47453).

Paratypes: All same locality as holotype and allotype; two male imagines, collected 17 March

2001 (CMNZ 2014.2.47455) and 26 March 2001 (CMNZ 2014.2.24806); two female imagines, collected 17 March 2001 (CMNZ 2014.2.47457) and 15 April 2001 (CMNZ 2014.2.47456); one male subimago, collected 13 March 2001 (2014.2.24789); one female subimago, collected 26 March 2001 (CMNZ 2014.2.24809); four larvae, collected 13 March 2001 (CMNZ 2014.2.47454, CMNZ 2014.2.24786) and 26 March 2001 (CMNZ 2014.2.24796, CMNZ 2014.2.24799); one male imago, collected 17 March 2001 (NZAC); one male subimago, collected 26 March 2001 (NZAC); one larva, collected 26 March 2001 (NZAC).

Distribution and habitat: Deleatidium crawfordi has only been found at closely adjacent locations in the Mohaka River, near the eastern edge of the Kaweka Forest. The collector of all specimens, William J Crawford, has advised that specimens were collected from stable rocks in shallow slow to moderate flows at the river's edge, and had probably moved there in preparation for emergence. As these are the only records of *D. crawfordi*, its geographical range is unknown.

Remarks: In the imago, characteristic features are the uniformly white translucency of the fore and hindwing membranes. The male genitalia most closely resemble those of *D. acerbum* Hitchings & Hitchings, 2016 and *D. atricolor* Hitchings, 2009 in having paired ventral appendages, but the prominent rounded lateral appendages seen in ventral view are distinctive. Forewing venation in the cubital region is similar to that of *D. myzobranchia* Phillips, 1930 and *D. kawatiri* Hitchings & Hitchings, 2016.

In the subimago, *D. crawfordi* is most likely to be confused with *D. branchiola* Hitchings, 2009, but differs in that the cubital margin of the forewing is basally connected with ICu_1.

The larva of *D. crawfordi* is most likely to be confused with that of *D. vernale* Phillips, 1930, but it can be recognised by an absence of strong pigmentation on all of the abdominal ganglia and their connectives. In the case of *D. vernale* the thoracic and abdominal ganglia and connectives are strongly pigmented.

Etymology: Named after William J Crawford in recognition of his contribution to mayfly research in New Zealand, spanning more than thirty years. He has collected specimens, reared life stages and provided much habitat information and advice to research workers. This has been highly valued and much appreciated. Both the species referred to in this paper were first collected by him and he provided all specimens used in its preparation.

Deleatidium rapidum **sp. nov.**

Description: Dimensions (mm). Imago male: length of body 8.8–10.4 (9.7); forewings 9.4–10.6 (10.1). Imago female: length of body 8.7–10.1 (9.5); forewings 9.9–10.2 (10.0). Mature larva: length of body 8.2–9.3 (8.6).

Male imago: Head whitish, brownish at bases of ocelli and around bases of eyes. Antennae; length about ½ width of head; scape, pedicel and flagellum brownish white; antennal length 3.0 mm. Eyes in contact dorsally, upper parts yellow, lower parts grey-black. Thorax. Pronotum, mesonotum and metanotum yellow with brownish margins. Sterna yellow with brownish margins. Legs whitish, dark brown at the femoro-tibial articulation. Length ratios of the foreleg segments 0.74–0.80: 1.00 (2.9–3.1 mm): 0.04–0.06: 0.20–0.32: 0.22–0.29: 0.05–0.09. Tarsal claws dissimilar; pad without apical hook, claw with prominent opposing hook. Wings. Forewing width 0.33 x length; longitudinal veins pale brownish, darkened at the costal brace, cross-veins paler; membranes pale brownish. The largest intercalary vein between ICu and CuP attached at base to ICu. Many cross-veins, particularly in C, Sc, R1 missing or incomplete and faint in the cubital region. Hindwing length 0.26–0.28 (0.27) x forewing length. Hindwing width 0.53–0.61 (0.57) x length. Hindwing vein Sc 0.95 x wing length. Almost without cross-veins in the posterior half of the wing. Abdomen.

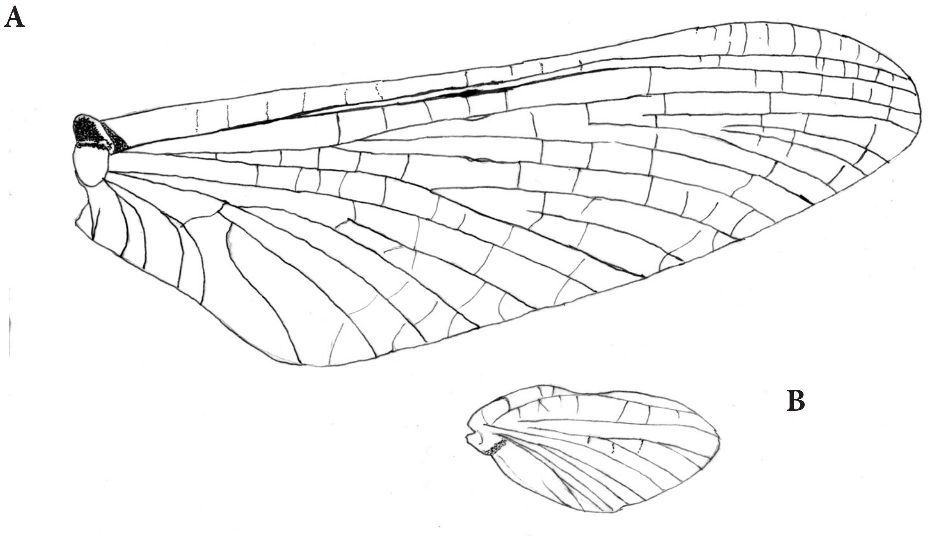

Figure 10. *Deleatidium rapidum,* male imago. **A,** forewing. **B,** hindwing.

Figure 11. *Deleatidium rapidum*, male imago, dorsal surface.

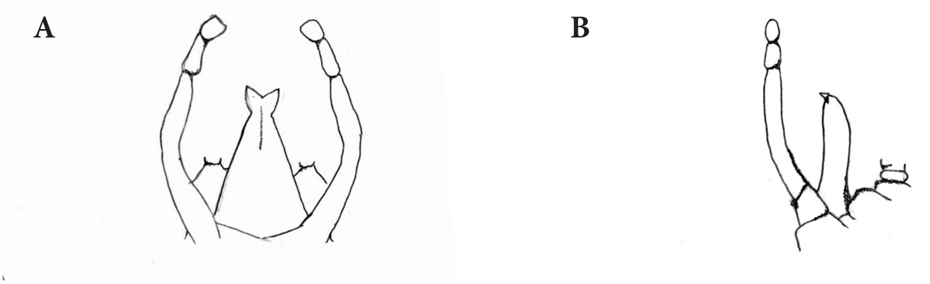

Figure 12. *Deleatidium rapidum,* male genitalia. **A,** ventral view. **B,** lateral view.

Dorsum pale greyish yellow, darker brown mesially and with median whitish longitudinal line. Abdominal segments bounded by whitish transverse lines. Anterior margins of segments 2–4 with paired submedian circular whitish marks. Sterna greyish white becoming yellowish anteriorly. Ganglia strongly marked on sternum 7, but successively less so anteriorly. Genitalia. As illustrated; whitish. Penes in ventral view with tapering bifid apices divided by V-shaped indentation; in lateral view rounded sub-apically, with paired tapered points directed apico-ventrally. Basal third of dorsal surface of forceps with fine hairs. Caudal filaments yellowish with dark brown annulations; length 12.5–12.9 mm.

Female imago: As in the male imago, except as follows: eyes greyish black, separated by 2.8 x

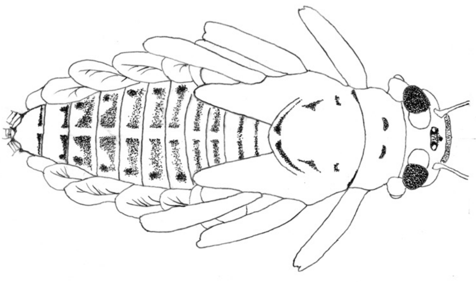

Figure 13. *Deleatidium rapidum,* late instar larva, dorsal view (antennae and caudal filaments truncated).

diameter of eye. Head yellowish white, blackish round the ocelli. Pronotum with two dark brown sub median V-shaped marks. Forewing width 0.31–0.36 (0.34) x length. Hindwing length 0.26–0.28 (0.27) x length of forewing, width 0.50–0.52 (0.51) x length. Hindwing vein Sc length 0.94–0.97 (0.96) x length of wing. Abdominal terga brownish-yellow. Sternum 7 with egg guide undeveloped. Sternum 9 with shallow U-shaped cleft.

Subimago: Head, including eyes, as in the male imago. Thorax. Pronotum whitish with paired submedian brownish U-shaped marks, mesonotum whitish with narrow dark median longitudinal mark and paired wider submedian brown longitudinal marks; metanotum whitish; scutellum brownish; sternum yellowish. Legs as in the imago. Wings whitish, costal brace and pleural wing recess brownish and distinctly darker than the remainder of the forewing. Dorsal abdomen brownish with median whitish longitudinal line, otherwise as for imago. Sterna as for imago. Penes whitish with median cleavage mark and without ventral appendages. Caudal filament 6.0–7.5 mm in length.

Mid and late instar larvae: (Figs 13, 14). Head including clypeus and labrum yellowish with small dark brown marks dispersed across the central region at the posterior boundary of the clypeus; margins brown. Region between ocelli darker blackish. Eyes of male with upper portions yellowish and lower portions black, female eyes black. Antennae 1.30–1.46 (1.38) x as long as the head. Mouth parts. Clypeus and labrum (Fig. 15A): labrum length 0.50–0.72 x and width 1.36–1.55 x that of clypeus. Anterior margin of labrum with a slight central indentation without

Figure 14. *Deleatidium rapidum,* photograph of mid instar larva, dorsal view (CMNZ 2014.2.47471).

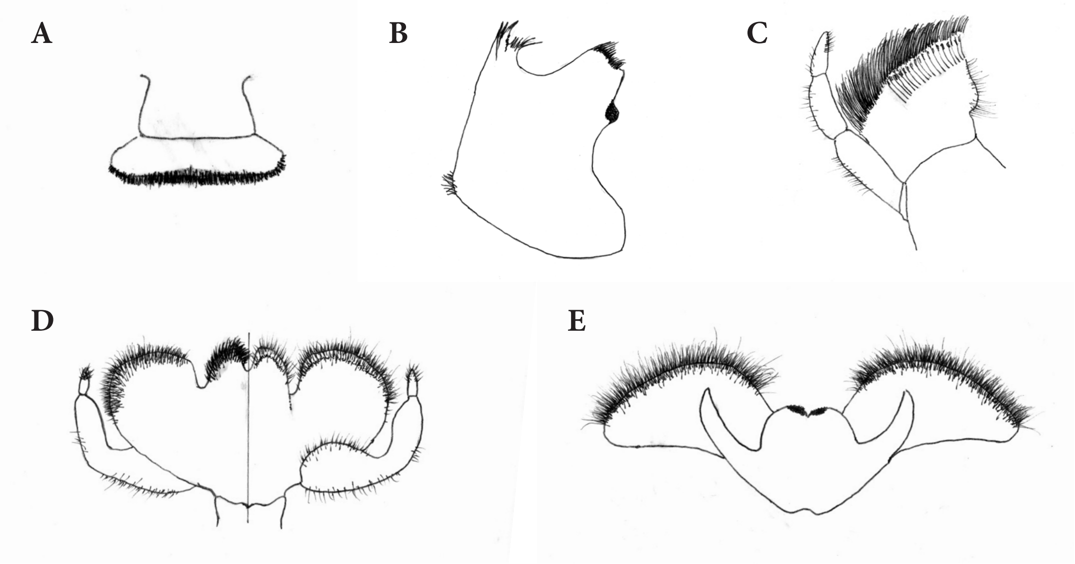

Figure 15. *Deleatidium rapidum,* larval mouth parts. **A,** clypeus and labrum. **B,** left mandible. **C,** right maxilla. **D,** labium, in dorsal (left) and ventral (right) views. **E,** hypopharynx.

denticles; smoothly curved to rounded lateral margins, dorsally with dense feather-like hairs. Mandibles (Fig. 15B): an irregular cluster of 12–20 hairs at the centre of the outer margin, outer incisors with 4 serrations on the mesial surface. Maxillae (Fig. 15C): galea-lacinia with a sub-apical row of 17 spines; palp segment 2, 0.86 x as long as segment 1; segment 3, 0.52 x as long as segment 2. Labium (Fig. 15D): with two paired spines on the shoulder of the submentum; palp segment 2, 0.68 x as long as segment 1; segment 3, 0.46 x as long as segment 2. Hypopharynx (Fig. 15E): lingua with two apical lobes, the crest of each with a small tuft of hairs directed mesially; the anterior margin of the superlingua with mesially directed thick, long hairs. Thorax pale yellowish, dark brown markings at the margins; the pronotum with paired submedian curved brown marks; pleura and sterna whitish. Legs yellowish white with a pale proximal white macula on anterior surface. Abdomen pale yellowish with a pale mid-dorsal longitudinal line, terga1–5 with variable dark brown marks; terga 6–9 with paired submedian dark brown inverted U-shaped marks. Sterna whitish with a faint blackish ganglion visible on sternum 7 only. Gills (Fig. 16) single, plate-like and rounded; gill 1 wider than long (2: 1) with the ventral margin expanded basally as a lobe; gill 7 curved ventrally beneath the abdomen. Lamellae translucent, tracheae and capillaries black. Posterolateral projections developed on segment 9 only. A group of whitish hairs on sternum 5, becoming more plentiful successively on sterna 6–9. Caudal filaments yellowish white 1.03–1.13 (1.08) x body length. Each segment of the filaments with a distal whorl of pale yellowish denticles.

Figure 16. *Deleatidium rapidum,* abdominal gills 1, 4, 7 (from left to right).

Holotype: Male imago, TO/HB, Mohaka River, McVicar Road, New Zealand. 39°12'S, 176°37'E. 320 m. 11 October 2002, WJ Crawford (CMNZ 2014.2.47461).

Allotype: Female imago, TO/HB, Mohaka River, McVicar Road, New Zealand. 39°12'S, 176°37'E.

320 m. 15 November 2002, WJ Crawford (CMNZ 2014.2.47462).

Paratypes: All same locality as holotype and allotype; three male imagines, collected 18 September 2002 (CMNZ 2014.2.24822), 23 October 2002 (CMNZ 2014.2.47464) and 15 November 2002 (CMNZ 2014.2.47463); three female imagines, collected 14 September 2002 (CMNZ 2014.2.24823), 11 October 2002 (CMNZ 2014.2.47469) and 13 November 2002 (CMNZ 2014.2.47466); one male subimago, collected 21 November 2002 (CMNZ 2014.2.47467); one female subimago, collected 15 November 2002 (CMNZ 2014.2.47468); eight larvae, collected 9 September 1998 (CMNZ 2014.2.24815–24818), 14 September 2002 (CMNZ 2014.2.47470), 13 November 2002 (CMNZ 2014.2.47471), 15 November 2002 (CMNZ 2014.2.47472) and 22 November 2006 (CMNZ 2014.2.47473); one male imago, collected 13 November 2002 (NZAC); one female imago, collected 21 November 2002 (NZAC); one larva, collected 9 September 1998 (NZAC).

Distribution and habitat: William J Crawford, the collector of all specimens, described the habitat as fast white-water riffles, runs and rapids. Most larvae were found clinging to large rocks and immoveable boulders from which they were difficult to dislodge and hard to reach. As these are the only records of *D. rapidum*, its geographical range is unknown.

Remarks: The male genitalia of the imago most closely resemble those of *D. kawatiri* and *D. autumnale* Phillips, 1930 in lacking ventral appendages. However, the paired penes are apically rolled ventrally, with a sharp subapical margin. *Deleatidium rapidum* can also be distinguished from *D. kawatiri* by the strongly marked ganglion on sternum 7 and from *D. autumnale* by paired submedian whitish circular marks on the anterior margins of dorsal abdominal segments 2–9. The subimago most closely resembles that of *D. townsi* Hitchings, 2009. Although the wings are also almost uniformly whitish, the costal brace and pleural wing recess is brown and distinctly darker than the remainder of the forewing. The larva most closely resembles *D. myzobranchia*, but differs in the anterior margin of the labrum being without a narrow anteromedian cleft, the submentum having two pairs of spines on the shoulder and prolific whitish hairs on the ventral abdomen sternum 9 and diminishing progressively back to sternum 5. The larval foreleg closely resembles that of *D. crawfordi* (Fig. 8). Many mountain streams in New Zealand are characterised by steep gradients and cool waters (Winterbourn 1997) and are frequently inhabited by *Deleatidium* larvae belonging to the informal '*myzobranchia* group' (Winterbourn 1978), which is characterised by large laminar gills arranged in a ventral ovate pattern. Larvae are believed to maintain their position in swift water primarily by gripping rock surfaces with their tarsal claws, while the large laminar gills assist the body to align itself so that the forces of lift and drag are reduced (Hitchings 2016). Part of this adaptation involves gill 7 being curved mesially and positioned at least partially beneath the posterior abdomen. In addition, the posterior of the abdomen is held slightly above the substratum by the dense, short hairs on sterna 5–9. In *D. rapidum*, these hairs are denser than in the other five described members of the complex and the ovate gill pattern is most strongly developed. Therefore, it appears that *D. rapidum* is particularly well adapted to a fast water habitat.

Etymology: The species name is derived from rapidum (Latin), "rapid" or "fast" from its preferred stream environment

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Thanks are due to members of the staff of Canterbury Museum, Cor Vink and Matthew Shaw for invaluable advice and help, and also to Johnathon Ridden for assistance with the photography. Mike Winterbourn and an anonymous referee are thanked for meticulously removing the worst of the errors and improving the script. In particular we thank Bill Crawford, who not only provided all of the specimens, but also gave us a careful description of the habitat of these two new species. Without his skills and persistence, this paper would not have been produced.

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16 Records of the Canterbury Museum, 2018 Vol. 32: 16–22 © Canterbury Museum 2018

Neocicindela aureata sp. nov. and notes on some congeners (Coleoptera: Carabidae: Cicindelinae)

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Neocicindela aureata sp. nov. is a distinctive tiger beetle from a perched, soggy fen-like habitat within a forested area of the Ngakawau Ecological District near Westport, South Island, New Zealand. Notes on its congeners *N. tuberculata*, *N. spilleri* and *N. dunedensis* are included.

Keywords: Cicindelinae, *Neocicindela*, new species

Introduction

Following the intense collecting activities and publications of Savill (1999), Cassola and Moravec (2010) and Larochelle and Larivière (2013), with the subsequent densely infilled distribution mosaics shown in Pons et al. (2011: fig. 1), another *Neocicindela* species has been found in a habitat that has been rarely examined. Its features add to the putative complex of species centred on *Neocicindela parryi* (White, 1846) (Pons et al. 2011), which has three distinct groups, but *N. garnerae* Larochelle & Larivière, 2013 is not one of them. This latter species was recognised and split from *N. parryi* later and covers most but not all of the southern records south of the Buller River of *N. parryi* shown in Pons et al. (2011: Fig. 1).

Neocicindela aureata sp. nov.

Description: Habitus: size and shape very similar to *N. parryi* figured by Larochelle and Larivière (2013: fig. 143) and below (cf. Figs 1 and 2). Elytral proportions slightly shorter and broader. Length: 9.5–10.5 mm. Holotype measurements (mm): length 10.5; head - narrowest frontal width between eyes 1.4, broadest width between eyes 1.7, greatest width including eyes 2.5; thorax - midline 1.55, width 1.65, elytra-shoulder width at scutellar apex 2.9, greatest width 3.5, sutural length 5.5. Colour: labrum pale; strong blue-green iridescence in corners of clypeus, face of first antennomere, and inner margin of eye; antennomeres 2–4 and very base of 5 pale, others very dark brown; head, thorax and scutellum dark almost black, with coppery iridescence; elytra (Fig. 2) pale areas dull, greatly reduced in comparison with other species, very pale brown or cream, extensively dotted with dark brown to black spots and tubercles in females, less so in the male; humeral lunule narrow in female, slightly wider in male, almost obliterated mesad, completely isolated by a broad, smooth shining black band (Fig. 4), central areas black or dark brown; green foveae reduced, partly to mostly encircled or replaced by golden to bright red almost scarlet maculae also with fine white scales; submedian black velvet areas not extensive, and numerous shining black weakly tuberculate spots (Figs 5 and 6). In bright sunlight the elytra sparkle (N.B. description applies to fresh specimens and colours degrade, especially the white). Undersurface of entire body dark, almost black. Femora dark brown, the profemora with weak subapical/apical pale ring, its anterior and dorsal surfaces all iridescent blue-green; tibiae and tarsi pale

Figure 1. *Neocicindela parryi*, ex Wellington, the published type locality.

Figure 2. *Neocicindela aureata*, holotype female.

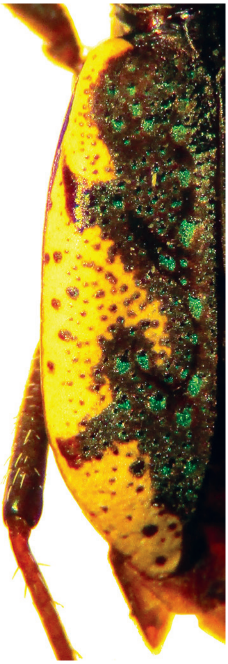

Figure 3. *Neocicindela* cf. *garnerae*, Mount Davy, Paparoa Range

brown, all podomeres with prominent dark brown apices. Labrum with 3 points and a variable straight to rounded lateral margin and corner; first antennomere with single seta; 2 supra-orbital setae (N.B. Larochelle and Larivière 2013: figs 8, 9 show four), no setae on vertex or pronotum; several elytral foveae have very short pale setae; convexity of the elytral lateral margins slightly greater than those of *N. parryi* but not as much as those of *N.* cf. *garnerae* (cf. Figs 1–3). Setation of palps and venter very similar to that of *N. parryi*; proepisternum with 0–2 white setae; mesepisternum with very few or no setae; abdominal ventrites with 2–8 setae near posterior margins and numerous short fine white setae along last ventrite edge. Male aedeagus as for *N. parryi*, but for the single specimen available the arrangement of the sclerites within internal sac appears different. A description of this feature is left until further material of this and other species are available for what is a very difficult dissection technique.

Type material: Holotype female, paratypes one male, four females. Mount Kuha, near Westport (41.8142°S, 171.6877°E, within 20 m radius), alt. 641 m. PM Johns, from 2:30pm 13 February 2018 to 1:00pm 15 February 2018 (Canterbury Museum).

Material of other species examined: Specimens of *N. parryi* group from: Franz Josef river bed, Orowaiti Lagoon, Bullock Creek, Mount Davy, Murchison, Springs Junction, Kohaihai River, Trovatore, Oparara and Haast Pass (Canterbury Museum accession numbers 2007.163.273–280, 2007.163.291, 2007.163.295–304, 2007.163.1243, 2007.163.1244, 2007.163.1265). Also specimens of *N. parryi* from Wiltons Bush, Wellington (=Port Nicholson), its type locality (Canterbury Museum accession numbers 2007.163.1274–1276).

Etymology: aureata (Latin: adorned with gold).

Differential diagnosis: The new species is close morphologically to specimens of the genetically distinct *N. parryi* group PAA6 from sites near site 17 of Pons et al. (2011: table 1, fig. 2, ex Maruia River, sand and stone banks), the only South Island population processed for mtDNA by them. Larochelle and Larivière (2001, 2013) stated that *Neocicindela parryi* could "represent a species complex" or be "variable" in this area. *Neocicindela garneri* was separated from *N. parryi* and described by them in 2013.

The key to species as presented in Larochelle and Larivière (2013: 25) is now modified at couplet 3.

3 Foveae bright blue, green or bronzy-green not encircled or replaced by red to gold sheen; lateral pale areas of elytra extensive, not or only partly obliterated by brown or black spots........................3a

Foveae green, narrowly encircled or replaced by red to golden sheen; pale lateral areas of elytra greatly reduced, obliterated by the extensive, often anastomosing black or coloured spots and extra foveae......................*N. aureata*

3a Humeral and marginal pale areas separated by a broad black bar; extensive spotting over all pale areas but not their obliteration; few or no white setae on the proepisternum or mesepisternum; North Island and Northwest Nelson/Westland north of the Taramakau River valleys.. all populations presently known as *N. parryi*

Humeral and marginal pale areas tenuously separated by a thin triangular black bar; sparse spotting over pale areas; 4–20 white setae on the proepisternum and mesepisternum very rarely fewer or absent; south of the Buller River system.. *N. garnerae* and *N.* cf. *garnerae* possible species complex

The variation in *N. parryi* is a possible basis for future work, which needs to be associated with genetic analysis. Alpine populations of which one, shown as *N.* cf. *garnerae* (Fig. 3), could be of particular interest as it is known only from the southern end of the mountain range aligned south of Mount Te Kuha near Westport where this new species was found. Closer to the form of *N. parryi* (as in the key above) are high mountain populations at Mount Burnett, Northwest Nelson, mountains in the Mount Arthur – Mount Owen massif and further southeast in the Lewis Pass region. These populations show a tendency towards a sharper definition of the antennal pale and dark antennomeres as in *N. aureata* and *N. garnerae*. However, this particular feature may also depend on the length of the teneral stage in colder and wetter climates. Larochelle and Larivière (2001, 2013) made no mention of this possible developmental change.

Figure 4. *Neocicindela aureata* sp. nov., humeral lunule (45˚ angled view), male paratype.

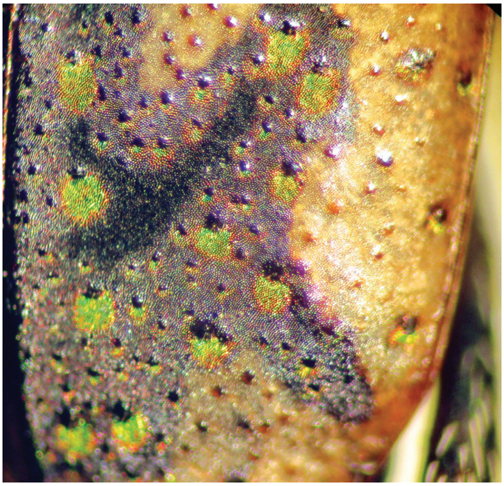

Figure 5. *Neocicindela aureata* sp. nov., posterior region of elytron, male paratype.

Remarks: The type locality, presently the only known site, is a perched soggy fen (Fig. 6) with short sedges and grasses (10 cm) and stunted mānuka (30–50 cm) in an area of mean rainfall of at least 2.2 metres (>170 wet days per year). The bare, crusted soil/mud within the habitat is only a few centimetres above soil water level. This habitat is unlike those for all other species in New Zealand.

In sunlight, individuals quickly run over exposed soil (Fig. 7) dodging the numerous pink sundews and over the very irregular layer of moss, fine twigs, grass leaves and leaf litter and have short (up to 1 minute) stops. They disappear during the many cloudy or foggy periods. They remain active till sunset but were not seen at night. Flights were very short (c.10–30 cm) and did not rise above 20 cm. No other behaviours were observed during a 2 hour period of sun.

The area is within the Ngakawau Ecological District, characterised by its upland forests and shrublands on Buller coalfields and associated rock formations. The district is well known for its endemic fauna, particularly the snail *Powelliphanta augusta* Walker, Trewick & Barker, 2008, which is now confined to a few hectares close to the Stockton coal mine, and *Perionychella ngakawau* Blakemore, 2010, an earthworm, considered critically endangered and again known only from the Stockton mine area. Immediately to the southwest is the Denniston Plateau and its coal mines. These are immediately northeast of the Te Kuha site, which now is also under examination for coal extraction. All these coal bearing areas are aligned over about 24 km and Mount Te Kuha is the only large unmodified area left at the higher altitudes. Mount Davy, where *N.* cf. *garnerae* (Fig. 3) was found, is a site 70 km distant from Te Kuha at 1,000 m on the southern tip of the Paparoa Range. As yet no other cicindelids have been found at similar heights along this range to its northern tip just 15 km from Mount Te Kuha.

Neocicindela tuberculata (Fabricius, 1775)

Cicindela huttoni Broun 1877 synonymy by Horn, 1936
Cicindela huttoni Broun 1880 (?partim)

The holotype of *N. tuberculata* was collected by Banks or his assistants, on James Cook's first voyage, in October–November 1769; thus the type locality could be restricted to one of a few sites where members of the Expedition landed in the North Island or possibly one site in the South Island. All are within the known distribution of the species. However, its synonym *N. huttoni* (Broun, 1877), was possibly described from three specimens. One, considered the holotype, in Broun's collection, came from a "bank of a creek flowing through Hikuwai forest about ten miles inland" from Tairua (Broun, 1877), a place restated by Brouerius van Nidek (1965) and Larochelle and Larivière (2001) as "Hikuwai" [sic] (Hikuai). Hikuai was then a site for kauri log extraction from the forest. Tairua and Hikuai are directly only 20–25 kms to the south of Cooks Beach, Whitianga where Banks spent several days nearby collecting plants and insects, some of which were labelled "Observatory", pertaining to the observation of the Transit of Mercury.

The other two specimens mentioned by Broun (1877, 1880) were collected by Hutton

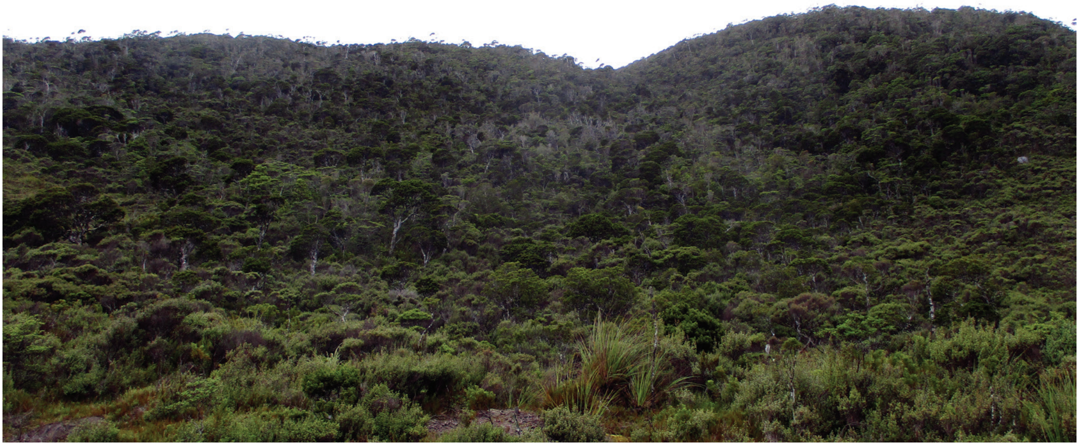

Figure 6. General habitat at Mount Kuha (fog/cloud close to ridgeline).

Figure 7. Bare crusted mud within habitat at Mount Kuha.

from Martin's Bay, western Otago, which is far outside the known distribution of *N. tuberculata*. They had been collected before Hutton shifted in 1873 from Dunedin to Christchurch. There is no direct evidence that Broun or Horn examined them, yet Hutton's handwritten manuscript (c. 1900–1902) of the types etc. in his collection, now in Canterbury Museum, clearly states that a cotype was present. Hutton's early insect collection is still extant and was used in teaching students at what is now Lincoln University. It is still in its original drawers but has been somewhat upgraded over the years by the addition of typed species labels below the specimens. The specimens are in poor condition and still on their original brass pins. Details of the Hutton's specimens are as follows:

One specimen labelled "huttoni", with a small blue paper disc. Two specimens labelled "tuberculata", one with a small pink paper disc and the other with a handwritten label "*Cicindela tuberculata* Fab". Two specimens labelled "parryi", one with a small pink paper disc and the other with a handwritten label "*Cicindela parryi* White". The handwriting on the labels could be Hutton's but is too cramped to be certain.

There are no other labels. The disc colour has no present-day meaning as to the status of these specimens although similar pink discs are on some types present in the later Hutton Collection in Canterbury Museum. It was also usual for Hutton to label his types clearly with "type" or "cotype".

All that can be said at present is that the "huttoni" specimen in his collection is not *N. tuberculata*, the "tuberculata" specimens are *N. tuberculata*, and the "parryi" specimens are possibly *N. parryi*. Thus not one of these specimens could be considered a syntype and the name "huttoni" is based alone on the specimen from Hikuai although it has been labelled subsequent to Broun's death and acquisition by the Natural History Museum, London as "Holotype" rather than "Lectotype".

Neocicindela spilleri **Brouerius van Nidek, 1965**

This species is generally considered rather rare. However, it is certainly active at night as suspected. On Waiheke Island, Auckland, it was abundant for at least 2 hours after sunset on 6 January 2014. There, under a full canopy of 2–3 metre tall kānuka and sparse understory, individuals ran over the very dry (cracked), moderately bare ground, disturbed probably by the strong torchlight. Possible food items were the cockroach *Parellipsidion conjunctum* (Walker, 1868), small spiders and isopods. It was also actively mating. Flight was not seen at all.

Neocicindela dunedensis **(Laporte de Castelnau, 1867)**

Another species whose habitat is poorly known even though it has been recovered, rarely, in large numbers. Collections at two sites point to it being rather reclusive, under shade rather than in open ground. It was seen, and collected in pitfall traps, under the canopy of a single ancient (>200 year old) *Sophora microphylla* tree, a species once very common on river flats near West Melton, Christchurch. That tree is now within a fenced, sloping, revegetated private reserve with planted *Coprosma propinqua*, matagouri, kānuka, *Corokia cotoneasta*, *Meuhlenbeckia astonii* and *Pittosporum* spp. There were no bare areas and no larval holes were found. The tiger beetle was not in any pitfall traps (five) set concurrently, 100–500 m from the revegetation site, across the adjacent relatively flat, lightly grazed grassland towards the Waimakariri River 1 km distant.

Near Fairlie, at the Burkes Pass Scenic Reserve, it was common between the tall tussocks and matagouri but not seen in the dry stream bed within the reserve.

Acknowledgements

All specimens in Canterbury Museum, collected mainly by Anthony Savill, were made available to the author. Rowan Emberson reminded me of the Lincoln Hutton Collection and John Marris provided access and facilities. Helicopter transport to the Mount Te Kuha site was arranged by the Royal Forest and Bird Protection Society. Much appreciated were on-site discussions with Dr Kelvin Lloyd at Mount Te Kuha.

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Navigation of the *James Caird* on the Shackleton Expedition

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In 1916, Frank A Worsley famously navigated the 22½ foot (6.9 m) *James Caird* from Elephant Island to South Georgia Island on a mission to seek rescue for the other 22 men of the Shackleton Expedition. The 800 nautical mile (1,500 km) journey remains one of history's most remarkable feats of seamanship in a small boat on treacherous seas. The contents of the original log book of the voyage, housed at Canterbury Museum in Christchurch, New Zealand, have been interpreted. Photographic images of the navigational log book are provided along with a transcription that allows all characters to be read. The numbers appearing in the log have been independently recomputed and the navigation principles and procedures used to obtain them explained in detail.

Keywords: celestial navigation, chronometer, dead reckoning, Elephant Island, Ernest Shackleton, Frank Worsley, Imperial Trans-Antarctic Expedition, *James Caird*, noon sight, time sight, South Georgia

Introduction

The Imperial Trans-Antarctic Expedition of 1914 under the command of Sir Ernest Shackleton consisted of 28 men and planned to cross the Antarctic continent from the Weddell to the Ross Sea via the South Pole. Their vessel, *Endurance*, captained by New Zealand born Frank Worsley, departed the Grytviken whaling station, South Georgia on 5 December 1914. *Endurance* became trapped in sea ice and was eventually crushed and abandoned on 27 October 1915. Camping on the ice until 9 April 1916, the Expedition launched three small boats from a point 60 nautical miles (110 km) from Elephant Island. They reached Cape Valentine on the eastern tip of Elephant Island on 15 April and relocated to Wild Camp near Cape Belsham on the northern coast on 17 April.

Currents and prevailing winds made reaching Cape Horn or the Falkland Islands an unlikely prospect and favoured South Georgia as a possible destination where help could be sought. With the Antarctic winter approaching, Shackleton, Worsley and four others set off on 24 April in the 22½ foot (6.9 m) *James Caird* that had been modified and heavily ballasted for the journey. Their success in reaching South Georgia was due in no small part to Frank Worsley's superlative skills as a navigator and seaman. Under conditions that were physically challenging and permitted only a limited number of celestial sights to be taken, he was able to navigate to South Georgia and eventually land on 10 May.

The original log book from the voyage resides at Canterbury Museum. Its contents would have been familiar to any practising navigator of the time but generally the numbers that appear are sparsely labelled, which makes their meaning challenging for the modern reader to decipher. Moreover, the methods of celestial navigation employed by Worsley, although common at the time, differ from the standard practice as it is taught today.

The purpose of this paper is to preserve an understanding of the navigational calculations that Frank Worsley performed in order to complete the crossing to South Georgia. The section 'Nautical Navigation – Definitions and Principles' discusses celestial navigation generally and the methods used in computations of distance and course. The section entitled 'Frank Worsley's Navigation' describes in detail how the navigation was done in practice during the voyage. The key component in determining longitude is the maintenance of an accurate time standard which is discussed in the section 'Time Keeping'. The 'Locations' section lists the places mentioned in the log and discusses how their positions were determined. A brief outline of the voyage is then given followed by a description of some of the specifics of the log itself. It was found that with effort all entries in the log could be read and its pages accurately transcribed. The pages from the original log are shown interleaved with their transcription in Appendix A. Using the input information that Worsley had available, the calculations in the log have been labelled and replicated in Appendix B.

Nautical Navigation – Definitions and Principles

This section defines the various navigational quantities used in the computations that appear in the log book. Enough detail is provided to give the reader an accurate understanding of the underlying principles involved. The explanations are expected to be intelligible to someone with a working knowledge of basic trigonometry. No attempt has been made to trace the historical developments leading up to the terms or methods described as this is considered to be beyond the scope of this work.

Celestial Navigation

A navigator can estimate a vessel's position by carefully keeping track of its speed and course from a known starting point by a process known as 'Dead Reckoning' (DR). Over time, errors accumulate and it is necessary to correct the DR position using celestial navigation to obtain a fix. This corrected position will be referred to as an 'Observed Position' (OP), which is consistent with terminology used by Worsley (1916b).

In traditional navigation, numbers are unsigned but have an associated name of N, S, E or W. Rules on when to add or subtract are applied according to whether the values are of the same or contrary name. Following this tradition, values in the formulas that follow are taken to be positive and the arithmetic operations shown are those relevant to the navigation of the *James Caird*, i.e. the observer's latitude and longitude are S and W respectively and the Sun's declination is N.

Celestial navigation uses the measured altitude of a celestial body, such as the Sun, to determine the observer's location on the Earth. The altitude, as measured by a sextant, gets various corrections applied to it and then, along with the time of observation, is used to determine the side lengths and vertex angles of the Navigational or PZX Triangle on the celestial sphere. When that triangle is projected onto the Earth's surface a spherical triangle like the one shown in Figure 1 is created.

The particular navigational triangle in Figure 1 represents a sight made by Worsley on the afternoon of 7 May 1916 when he was located at the point labelled Z nearing South Georgia. The sextant is used to measure the angular distance from the horizon generally to the lower limb of the Sun. The result is commonly denoted as H_s. Sight reduction, however, requires the true altitude of the Sun's centre, H_o, which is obtained by applying various corrections to H_s. Principal amongst these are:

Dip of the horizon: The finite size of the Earth causes the horizon to be depressed from the horizontal direction by an amount that varies as the square root of the height of the observer's eye.

Refraction: The bending of light by the Earth's atmosphere causes objects to appear higher than

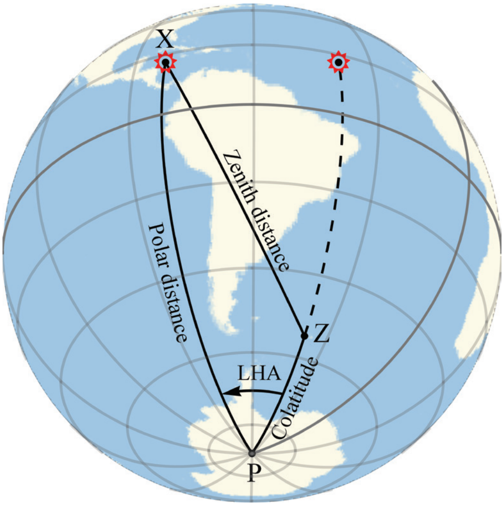

Figure 1. The navigational or PZX triangle for the time sight of 7 May 1916 when the *James Caird* was at the point Z, nearing South Georgia on its voyage from Elephant Island. The dashed line shows the triangle at Local Apparent Noon (LAN) when the Sun is on the observer's meridian and LHA = 0.

they actually are. The effect is greater the closer the object is to the horizon.

Semi-diameter: If H_s is measured to the Sun's lower limb it must be increased by half the Sun's angular diameter to get to the centre.

The value of H_o provides a direct measurement of the angular side length of the navigational triangle labelled Zenith Distance, which will be denoted ZD. The zenith is the point directly overhead at the observer's position and hence ZD = 90° – H_o.

The point labelled X is the sub-solar point or the location on the Earth where the Sun appears directly overhead at the time the sight was made. It is determined by calculation from information in the *Nautical Almanac* and by reading Greenwich Mean Time (GMT) from a ship's chronometer. The angular distance of the sub-solar point, X, from the South Pole, P, is the Polar Distance (p.d.) and is related to the Sun's declination, δ, by p.d. = 90° + δ.

If the observer's latitude at the point Z is denoted L then the length of the remaining side of the triangle is the colatitude, 90° – L.

The angle LHA at the South Pole vertex of the navigational triangle is the Local Hour Angle. It is the angle measured from the observer's meridian in a westerly direction to the meridian through the Sun.

At Local Apparent Noon (LAN), the Sun is on the observer's meridian making LHA = 0 and the navigational triangle collapses into a line shown dashed in Figure 1. In that case it is evident that p.d. = ZD + colatitude, which may be rearranged to $L = \text{ZD} - \delta$. Thus measuring the Sun's altitude as it crosses the meridian allows the observer's latitude to be directly determined. This is the 'noon sight', which is the simplest sight to make and reduce.

Greenwich Mean Time is a uniform time scale determined by the average or mean motion of the Sun and is read from clocks and chronometers synchronised with those at Greenwich. Apparent Time is the time measured by a sundial or sextant with noon occurring when the Sun crosses the observer's meridian. The elapsed time between successive meridian passages can differ over 24 hours by up to 30 seconds. The cumulative effect is that the Apparent Time will lead or lag the Mean Time by up to 15 minutes approximately, depending on the time of year. The difference is called the Equation of Time: EqT = Apparent Time – Mean Time. It was a key quantity in the navigation of the time and was tabulated in detail along with the Sun's coordinates in the *Nautical Almanac*.

Measuring the angle LHA gives the Local Apparent Time (LAT) elapsed since LAN. Greenwich Apparent Time (GAT) is obtained by adding EqT to the GMT determined by means of a chronometer. The difference between GAT and LAT, when converted to angular measure, gives the ship's longitude.

Note that the LHA is not measured directly. Rather the Sun's true altitude, H_o, its declination, δ, and the observer's latitude, L, are combined to compute the LHA. This procedure is known as taking a time sight.

Conversely if the observer is at a position of known longitude, its difference from the longitude obtained from the time sight allows the chronometer error to be determined. This process is called rating the chronometer.

Distance and Course

Although generally not the shortest route, for practical convenience ships tend to follow rhumb line courses in which a constant compass bearing is maintained along the track. On the spherical Earth, calculations of rhumb line distances and bearings are achieved by introducing varying degrees of approximation.

A nautical mile (approximately 1.85 km) in the north-south direction along a meridian subtends 1 arc minute of latitude anywhere on the Earth's surface, however a nautical mile along a parallel of latitude, L, spans $\sec(L)$ minutes of longitude. Equivalently a 1 arc minute track along the same parallel is $\cos(L)$ nautical miles in length. As a ship traverses a track with a north-south component, the ratio of the length of a minute of longitude to a minute of latitude changes continuously but in many situations rhumb line distances and courses can be computed with adequate accuracy by treating the Earth's surface as if it were a plane rectangular grid with fixed spacing between the lines of latitude and longitude.

If a rhumb line track begins at latitude L_1, and ends at latitude L_2, then under so-called middle-latitude sailing, the ratio of length of a minute of latitude to length of a minute of longitude is taken to be $\sec(M)$ where $M = ½ (L_1 + L_2)$ is the average of the beginning and ending latitudes.

Frank Worsley's Navigation

Worsley performed a combination of noon sights for latitude and time sights for longitude. He used traverse tables to adjust the longitude to account for the vessel's run until or since noon and obtained a noon position that was entered into the log book. Today this would not be considered modern navigation but was the method still in widespread practical use at the time. The modern approach relies on plotting a line of position (LoP) on which the observer is located. It is tempting to speculate on how feasible it would have been to perform this technique in the wet and violently moving environment of the *James Caird*.

Sight Reduction

The reduction of a celestial sight to obtain a position on the Earth requires:

- corrections for dip of the horizon, refraction, semi-diameter and possibly others to obtain the true altitude of the body above the horizontal or equivalently its true zenith distance
- coordinates in the sky of the body observed
- a means of performing calculations involving trigonometric functions.

For these purposes Worsley had his navigation books of which he says:

> *My navigation books had to be half-opened, page by page, till the right one was reached, then opened carefully to prevent utter destruction. The epitome had had the cover, front and back pages washed away, while the Nautical Almanac shed its pages so rapidly before the onslaught of the seas that it was a race whether or not the month of May would last to South Georgia* (Worsley 1998: 116).

The epitome here refers to a navigational text providing the altitude correction and containing logarithm and trigonometric tables. The position of the Sun is taken from the monthly pages of the *Nautical Almanac*[1].

Noon Sights

Weather permitting, noon sights are the easiest sights to perform. Near the time of LAN the Sun's altitude is watched until it peaks. As it approaches maximum, it slows and the altitude remains fairly constant over the course of several minutes and accurate timing is not required.

Noon Sights appear in the log on 26 and 29 April. As discussed in the section on celestial navigation, the reduction is a simple arithmetic evaluation of

$$L = \mathrm{ZD} - \delta \qquad (1)$$

and is laid out in the form

Observed altitude of Sun's lower limb	H_s
True altitude of Sun's centre	H_o
Sun's true zenith distance	$\mathrm{ZD}=90°-H_o$
Sun's declination	δ
Latitude	$L=\mathrm{ZD}-\delta$

The boxed quantities are to be entered.

On 4 May, the log shows the inverse of this calculation being performed in preparation for a noon sight that is unrecorded. The DR latitude and Sun's declination are used to compute the altitude at which the Sun's lower limb is expected to be observed. This would then be used to preset the sextant to simplify taking the sight.

Logarithms

Long multiplications by hand are converted into addition by the use of logarithm tables, which considerably reduces the time and effort required and was the standard method used to perform such calculations.

The logarithm of a positive number less than 1 is negative and to avoid the need for subtractions such values are represented with 10 added to them, which effectively serves to track the sign. If the addition of logarithms results in a value greater than 10, then the rule is to reject the 10 and take only the first digit to the left of the decimal point.

Considerable effort was made to arrange calculations in a form that could be efficiently evaluated using logarithms. Equation (2), in which the right hand side is a product of trigonometric functions, is an example of this.

Time Sights

The ideal time sight is taken when the Sun is due east or west. The reason for this is that in these configurations errors in latitude have no influence on the resulting longitude. As the Sun moves nearer the meridian the time sight becomes a less sensitive measure of longitude and more susceptible to errors in latitude. Sights taken when the Sun is low to the horizon are subject to increased uncertainties in refraction. Weather or latitude and time of year may limit how far off the meridian the Sun can be usefully observed. During the *James Caird*'s voyage in latitudes between 61°S and 54°S during late April and early May, the Sun rose above the horizon a little north of NNE. A time sight was taken on 26 April at just 56 minutes time from LAN which is far from the ideal geometry, but was the only sight made.

On Elephant Island a time sight was taken to rate the chronometer on 24 April just prior to departure. Time sights underway were made on 26 and 29 April, 3 and 4 May and three on 7 May. With one exception, all used the Sun's lower limb, which is indicated in the log by the symbol $\underline{O}$. One of the sights on 7 May was made through cloud with no clearly defined limb visible. The estimated position of the centre of the Sun was brought down to the horizon and the sight recorded with symbol $\ominus$. Worsley wrote:

> *… the conditions for observing were most unfavourable. It was misty, the boat was jumping like a flea, shipping seas fore and aft, and there was no "limb" to the sun, so I had to observe the centre by guesswork. Astronomically, the limb is the edge of the sun or moon. If blurred by cloud or fog, it cannot be accurately "brought down" to the horizon. The centre of the spot is required, so when the limb is too blurred you bring the centre of the bright spot behind the clouds down to the horizon. By practice, and taking a series of "sights", you can obtain an average that has no bigger error than one minute of arc.* (Worsley 1998:137)

To determine longitude, the observer takes a time sight in which the Sun's altitude is measured when it is well off the meridian and obtains the LHA by evaluating the formula

$$\begin{aligned}\operatorname{hav}(\mathrm{LHA}) &= \sec L \csc(\mathrm{p.d.}) \\ &\quad \times \cos\frac{S}{2}\sin\left(\frac{S}{2}-H_o\right)\end{aligned} \qquad (2)$$

where $S = H_o + L + \mathrm{p.d.}$

The product of trigonometric functions on the right hand side of equation (2) is an arrangement that can be efficiently evaluated using logarithms. The function hav θ is the haversine (half versed sine) and is defined as

$$\operatorname{hav}\theta \equiv \frac{1}{2}\left(1-\cos\theta\right) = \sin^2\frac{\theta}{2}$$

The LHA was then extracted by inverse look up in a table of the logarithms of haversines. When haversine tables are not available, the trigonometric identity to the right allows the LHA to be extracted from tables of logarithms of sines. This introduces additional steps and is not the procedure followed in the log.

Time sight reductions all follow a standard layout shown in Table 1 and is an evaluation of equation (2) using logarithms with the boxed quantities to be entered.

In the course of the calculation, longitudes are expressed both in terms of angles and in time. These are distinguished here by the use of the degree symbol '°' and superscript 'h'.

In the log book the leading digit is suppressed in logarithms in time sight reductions.

Distance and Course

For a rhumb line course from a position with latitude, longitude (L_1, λ_1) to position (L_2, λ_2) lying at a distance D and course direction C measured eastward from north the fundamental equations of middle-latitude sailing are:

$$\text{D.Lat.} = L_2 - L_1 = D\cos C \quad (3a)$$

$$\text{Dep.} = D\sin C \quad (3b)$$

$$M = \tfrac{1}{2}(L_1 + L_2) \quad (3c)$$

$$\text{D.Lon.} = \lambda_2 - \lambda_1 = \text{Dep.}\sec M \quad (3d)$$

D.Lat. and D.Lon. are the changes in latitude and longitude over the track respectively. The quantity Dep. is the distance over ground of the track in the east-west direction along a parallel of latitude. It is the departure from the initial meridian and is confusingly known simply as the 'departure'. The relationship between these quantities is illustrated graphically in Figure 2 along with the units, nautical miles (NM) and/or minutes of arc, in which they are specified. The notation and conventions employed here are later used in the discussion of traverse tables.

Sun's true altitude	H_o		
Latitude	L	sec.	$\log_{10}\sec L$
Polar distance	p.d.=90°+ δ	cosec.	$\log_{10}\csc$ p.d.
Sum	$S = H_o + L$ + p.d.		
Half-sum	½S	cos.	10 + $\log_{10}\cos$ ½S
Remainder	½S − H_o	sin.	10 + $\log_{10}\sin$(½S − H_o)
		hav.	Σ =10 + $\log_{10}$hav(LHA)
			reject the 10!
Mean time at Greenwich	GMT		
Equation of time	EqT		
Apparent time at Greenwich	GAT = GMT + EqT		
Apparent time at ship	LAT		
Longitude in time	λ^{h}= GAT − LAT		
Longitude	$\lambda° = 15\,\lambda^{h}$		

Table 1. Standard layout of time sight reductions, which is an evaluation of equation (2).

Traverse Tables

Traverse Tables are essentially look up tables used to solve the unknown parts of plane right triangles such as the one shown in Figure 2. For a given angle, *C*, and distance, *D*, traverse tables list *D*, *D* cos *C* and *D* sin *C* in columns typically labelled Dist., D.Lat. and Dep. respectively. Tabulated values for *D* extend up to a few hundred nautical miles. The tables are shown stylistically below

Traverse **C °** Table

Dist.	D.Lat.	Dep.
-	-	-
-	-	-
-	-	-
D →	*D* cos *C*	*D* sin *C*
-	-	-
-	-	-
-	-	-

From equation (3d), D.Lon. = Dep. / cos *M*. This calculation may be done by reverse look up of the value of Dep. in the D.Lat. column of the traverse table for course, *M*, and reading D.Lon. from the Dist. column.

Traverse **M °** Table

Dist.	D.Lat.	Dep.
-	-	-
-	-	-
-	-	-
D.Lon.	← Dep.	-
-	-	-
-	-	-
-	-	-

In practice this may require interpolation in one or both of *M* and Dep.

When the required distances exceed the tabulated range in the tables, the values for some fraction of the required distance can be looked up and the final results scaled up accordingly. This technique was used in the log book with a scale factor of ½ to compute the remaining distance and course to the destination on 29 April and 3 May but not on 4 May or subsequently as the remaining distance then fell within the range covered by the tables.

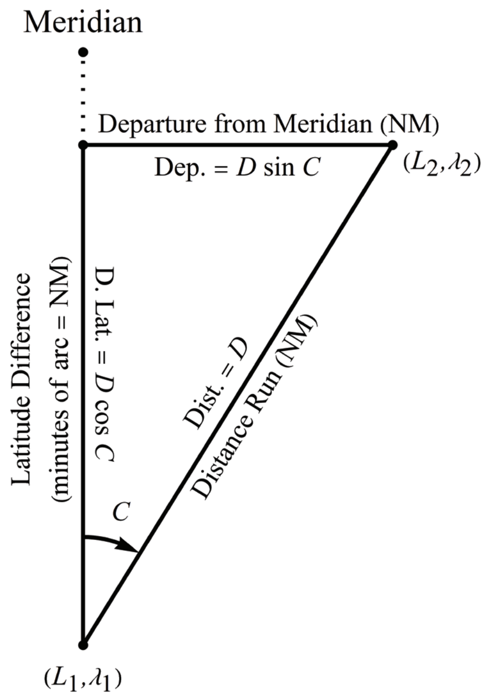

Figure 2. Graphical representation of quantities used in rhumb line course and distance calculations. NM indicates that a value is expressed in units of nautical miles

Dead Reckoning by Traverse Table

For a known course, *C*, and distance run, *D*, the traverse table immediately gives D.Lat. and Dep. For an initial position with latitude, longitude (L_1, λ_1) the middle latitude is then:

$$M = L_1 + \tfrac{1}{2}\,\text{D.Lat.} \tag{4}$$

The longitude difference, D.Lon., is then obtained by reverse look up of Dep. in the traverse table for latitude, *M*. The DR position, (L_2, λ_2), is

$$L_2 = L_1 + \text{D.Lat.}$$

$$\lambda_2 = \lambda_1 + \text{D.Lon.}$$

In the log this calculation is used in two ways:

1. The boat's position at noon on the previous day is advanced by the distance and course of the day's run to give the boat's DR position at noon for the current day.
2. The estimated latitude and observed longitude from a time sight is advanced or retarded by the distance and course run to noon.

Distance and Course to Destination by Traverse Table

Before setting out on the voyage of the *James Caird*, Worsley performed a direct calculation of the course and distance from Cape Belsham to a point 46' of longitude or 27 nautical miles (50 km) west of Wallis Island off South Georgia using rearrangements of equations (3).

On the voyage he made use of traverse tables. From the boat's current position (L_1, λ_1) the distance and course to the destination (L_2, λ_2) is required.

D.Lat. and D.Lon. are obtained by equation (3a) and (3d) with the middle latitude, *M*, being computed by equation (4). Looking up the value of D.Lon. in the column labelled "Dist." of the traverse table for latitude, *M*, allows the corresponding departure value to be read from the column labelled "D.Lat." because, from equation (3d), Dep. = D.Lon. cos *M*.

In practice when the middle latitude, *M*, is not close to an integer the procedure may be performed for adjacent values, one above and one below, and the value of Dep. computed by interpolation.

The distance, *D*, and course, *C*, to the destination are then extracted from the traverse table by a reverse look up in two variables. The traverse table is searched for a location where the values obtained for D.Lat. and Dep. are found together in their respective columns. The distance is then read from the Dist. column and the course from the angle at the top of the table in which the values are found.

The Navigator's Daily Work

Weather permitting, the navigator took an ante-meridian (A.M.) time sight when the Sun lay sufficiently far off the meridian. The altitude was measured, and the chronometer time noted, but the observation was not reduced at that time, because the knowledge of the actual latitude was lacking. The latitude by dead reckoning from the previous noon was maybe 21 hours old, and therefore less reliable. It was better to wait until noon, only a few hours ahead, to get a latitude determination that was nearer in time to the longitude observation.

At noon, the navigator determined his latitude as the Sun culminated, i.e. reached its greatest altitude, bearing due north. This noon latitude was then moved backwards to the time of the A.M. observation. The course and distance sailed between the A.M. observation and noon were estimated and with the aid of the traverse tables, D.Lat. was found and combined with the noon latitude to get the latitude to insert into the time sight formula, equation (2). The A.M. longitude was calculated as described earlier and then moved forward to noon using the D.Lon. Thus the day's noon position by observation was determined.

If no A.M. sight was possible for any reason, then a post-meridian (P.M.) sight for longitude could be used together with the noon latitude, to determine the noon position. The work involved is analogous to that already described, the difference was only that the noon latitude was moved forward to the time of the P.M. sight and the resulting longitude moved backwards to noon.

The dead reckoning position at noon was also noted. If no celestial observations were possible on a particular day, dead reckoning was continued until an observed position was available. That observed position was then used as the starting point for next day's dead reckoning.

A day in this context is the interval between two successive LAN's. If sailing eastwards, the day's length was less than 24 hours; if sailing westwards a little more than 24 hours.

Time Keeping

The LHA of the Sun is measured westwards from the observer's meridian and gives LAT directly. It is therefore quite natural and convenient that in nautical time keeping for the purposes of celestial navigation, a new day was taken to begin at noon. The zero hour in time then occurs when LHA = 0. In 1916, the *Nautical Almanac*, in common with *Astronomical Ephemeris*, tabulated positions for Greenwich noon. This is the 0 hour in the Julian Day system, which continues to be used in astronomical applications today. Worsley records his chronometer times using this astronomical time convention. Dates given in the log, however, follow common civil reckoning. In some cases in the log, 24 hours is added to the time to facilitate the calculation of longitude.

The Chronometer

The determination of longitude requires GMT as read from the ship's chronometer and it is crucial that its error and rate be accurately determined. Writing approximately 7 years after the voyage, Worsley gave the following description: 'This English chronometer, an excellent one of Smith's, was the sole survivor, in good going order, of the twenty-four with which we set out in the *Endurance*.' (Worsley 1998: 101). In the log it is referred to by the serial number 192/262 and takes the form of a large pocket watch that is now in the collection of the Scott Polar Research Institute of Cambridge University, United Kingdom (Reference number: N: 999a)[3]. Worsley describes how in the trek across South Georgia, 'I carried…the chronometer, with which I had navigated the boat. This was slung around my neck by lampwick, inside my sweater, to keep it warm.' (Worsley 1998: 191).

Although Worsley never mentions it directly there is some evidence for a second chronometer aboard the *James Caird*. The National Maritime Museum in Greenwich, United Kingdom houses a chronometer by Thomas Mercer (Object Id: ZAA0029)[4] that is 'Believed to have been used on Shackleton's 800-mile open boat journey to South Georgia on the *James Caird*, after his ship the *Endurance* was crushed in ice'. This is a boxed chronometer and in its lid there is a note stating: 'Punta Arenas, 14th Sept 1916, Watchmaker Fallor No. 985 Calle Roca has overhauled & placed in repair to my satisfaction, the chronometer used by me in the relief of my men on Elephant I^{d}, E. H. Shackleton'.

Even if not in full working order, it may have been used for timing short intervals such as when sight times are averaged as in the log on 26 April where a correction given as 'Fast 29' is applied and again on 3 May where 'Slow 46' appears. Neither value is consistent with the known error for the Smith chronometer. The correction is thus most probably the difference between the Mercer and the Smith, a comparison between the two being made either immediately before or after the sights were taken.

Rating the Chronometer

In the early twentieth century marine chronometers were mechanical devices, essentially a spring clock. The chronometer was wound each day at the same time, in the same way, so as to use the same portion of the spring. Extraordinary care was taken to not expose the chronometer to variations in temperature in order to minimise the drift. Nevertheless mechanical chronometers of the time were subject to certain systematic errors. Chronometer Error (CE) is the difference, fast or slow, between the chronometer's time and GMT. Chronometer Rate (CR) is the rate of change of the CE and stated as the number of seconds gained or lost per day. The determination of the CE and CR was a critical task of the celestial navigator and they would be measured and recorded as the opportunity arose. This procedure is known as rating the chronometer. It was the norm for any given chronometer to have an associated CE as they would almost never be reset to GMT. Rather the recorded CE was updated by the CR daily. A CR of zero seconds per day indicates that the chronometer is running at a constant rate and acting as a perfect clock. On 24 April 1916 the Smith chronometer was determined to have a

CE of $11^{m}55^{s}$ slow and a CR losing 5^{s} per day.

As noted earlier rating the chronometer can be performed by comparing the longitude of a known position with the longitude obtained by a time sight but a number of other methods exist. In particular the timing of the disappearance and/or reappearance of stars in lunar occultations provides a means of determining CE. This method was also used by Worsley and Reginald James, expedition physicist, to rate the chronometers.

In March 1916, while camped on the drifting ice of the Weddell Sea, Mount Percy on Joinville Island off the tip of the Antarctic Peninsula came into view. James wrote: 'After the crushing of the ship on October 27, 1915, no further occultations were observed, but the calculated rates for the watches were employed, and the longitude deduced, using these rates on March 23, 1916, was only about 10' of arc in error, judging by the observations of Joinville Land made on that day.' (Shackleton 1920 Appendix 1).

In the log entry for 24 March, Worsley makes several notes that show he was using Nordenskjöld's book (Nordenskjöld and Andersson 1905) as his chart reference for latitudes and longitudes of known headlands. However, he describes the charts as 'evidently only intended for the general public thus not the close accuracy of [position] for Mt Percy necessary to correct [chronometer]' and consequently 'will not allow any change to [chronometer] in [the] meantime.' (Worsley 1916a: 86).

The original page from the log and its full transcript can be found in Appendix A.

New opportunities to rate the chronometers arose when Clarence Island was sighted on 7 April, 1916 (Shackleton 1920) as their entrapment in the ice was coming to an end. The navigational log book (Worsley 1916a: 88) states: 'of Clarence Pk [to] be 61°12' S + 53° 40' W [would] make my [chronometer] 192/262 [too] far East, or in other words it is 50 seconds slower than I had'. This conclusion is based on the observation that on 9 April, while under way to Elephant Island, their dead reckoning position fell 12.5' west of expectations.

Amongst the materials housed at Canterbury Museum is the detached page of the log containing entries from 4–8 September, 1915. On its back (Worsley 1916a: 12) a table can be faintly seen listing the daily anticipated CE from 10 to 26 April 1916 based on a CR of losing 5 seconds per day. These values cover the period of the Expedition's passage from the icepack to Elephant Island. They show the adjustment of 50 seconds slower being applied to the CE on 18 April which is the day following the Expedition's arrival at the relative safety of Wild Camp on Elephant Island. The CE for 24 April is given as $10^{m}51^{s}$ slow.

On Elephant Island on 24 April 1916, the morning of departure of the *James Caird* for South Georgia weather conditions permitted a time sight to be made. Worsley (1916b) wrote 'I jubilantly welcomed this opportune appearance of the sun for without it we should have been placed in a still more difficult & dangerous position making S. Georgia than we were.' and in (Worsley 1998: 101) 'Immediately after breakfast the sun came out obligingly. The first sunny day with a clear enough horizon for rating my chronometer.' No noon sight for latitude was possible.

Using the CE of $10^{m}51^{s}$ the log entry for 24 April gives the longitude from the time sight as 54°19'45"W. Comparing this to the assumed longitude for Cape Belsham of 54°50'W indicates that the chronometer had lost an additional $2^{m}1^{s}$ and gives a CE of $12^{m}52^{s}$. Worsley apparently rejected this result as being too large and chose instead to 'allow 1minute+4sec more slow' yielding a CE of '$\underline{11^{min}55^{sec}}$ slow' with the justification that the longitude of Cape Belsham is 'only approximately known'. The CE of $11^{m}55^{s}$ slow is underlined in the log and the CR is taken to be losing 5 seconds per day. The log entry for 25 April shows a table of the anticipated CE for each day based on these values.

Longitude of Cape Belsham	54 °	50 ′	0 ″	
Longitude by Time Sight	54	19	45	
Difference		30 ′	15 ″	
Difference in time		2^{m}	1^{s}	more slow
Chronometer Error		10^{m}	51^{s}	Slow
"allow"		1	4	more slow
Adjusted CE		11^{m}	55^{s}	Slow

The adjustment effectively moves Cape Belsham 14'25" or 7 nautical miles to the east of its previously assumed position and provides some safety margin against overshooting South Georgia. In the log entries for 26 and 28 April, Worsley corrects his longitude by 16' to the west. The reason for this is unclear but it effectively undoes the earlier easterly adjustment. It is not done subsequently and the time sights on 4 and 7 May were reduced using a CE of $12^{m}45^{s}$ and 13^{m} slow respectively without further correction.

On sighting South Georgia on 8 May Worsley (1916a) in his log concludes that '[Latitude] proved to be correct within about 2 [miles. Longitude] ditto but [chronometer] was much slower than I had allowed which made us about 20 [miles or] so distance further astern than [observation] showed'.

At that time the course was roughly easterly and at 54°S latitude the distance of 20 miles translates into an additional CE of around 2¼ minutes slow. Of this 57 seconds is accounted for by the adjustment made to the time sight on 24 April and the remainder is consistent with a CR of 10 seconds per day rather than 5.

It should be noted that numbers in the diary (Worsley 1916b), which was likely written sometime after the voyage took place, differ from those in the log. For 24 April a CE of 12^{m} 52^{s} slow is given with a CR losing 7 seconds per day. The stated CE is as it was obtained from the time sight at Cape Belsham without adjustment and the CR may have been inferred from it.

Locations

The log lists a number of locations and the positions that Worsley had for them.

Cape Belsham	61 °	4' S	54 °	50' W
46' or 27^{m} West of Wallis Island	54	4	39	0
Wallis Island	54	4	38	14
Bird Island	54	0	38	0

Cape Belsham is a prominent headland to the west across the bay from the small Cape Wild (now Point Wild). This is where the Expedition finally encamped after their initial landing on Cape Valentine on the eastern tip of Elephant Island. The bay was given the name West or Glacier Bay and has the Furness Glacier at its head. A survey map of the area by expedition member Reginald James (Wordie 1921: 24, fig. 4; Burley 1972: 307, fig.3) is shown in Figure 3. The landforms are distinctive and leave no doubt as to the location of the camp or the geographic feature that the Expedition identified as Cape Belsham. In his diary, Worsley (1916b) uses the phrase 'Cape Belsham (where our camp was situated)' and both he and James adopt the same longitude for Wild Camp and Cape Belsham.

In Worsley's own words, the longitude of Cape Belsham is 'only approximately known to us' (Worsely 1916a). This introduced a potential uncertainty for navigation as its position was used to rate the chronometer. In his diary, Worsley states that he 'assumed' the position of Cape Belsham, an uncertainty that surely bedevilled him.

It is known that Worsley based his estimate for the position of Cape Belsham on 'doubtful little chartlets in Nordenskjöld's book, Antarctica' (Worsely 1916b). The reference here is to Nordenskjöld and Andersson (1905) and the chartlet on page 77 of that volume[2] bears the caption 'The latest map of W. Antarctica before the Belgian [1897-1898] and [Nordenskjöld's] Swedish [1901-1904] expeditions (after Fricker)'

Neither of the referenced expeditions visited Elephant Island. As indicated it is an English relabelling of a chart appearing in Antarktis

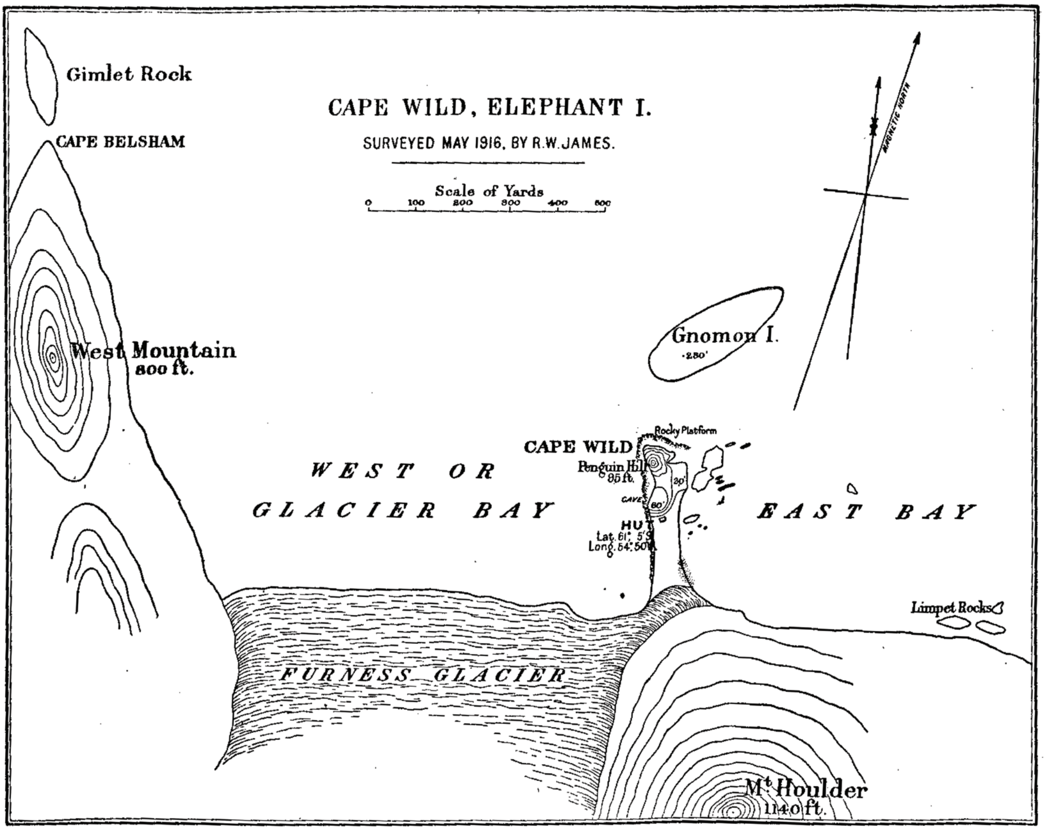

Figure 3. Survey map by Reginald James from May 1916 showing the location of and area surrounding Wild Camp where 22 members of the Shackleton Expedition spent 4½ months awaiting their eventual rescue on 30 August 1916. Reproduced by permission of The Royal Society of Edinburgh from Wordie (1921). All rights reserved.

(Fricker 1898: 122), which in turn was taken from Stieler's Hand-Atlas (Stieler 1891 No. 7). The area of the chartlet around Elephant Island is shown at twice actual size in Figure 4. Given its small scale of 1:8,000,000, it is remarkable that the position Worsley obtained for Cape Belsham is within 2¼ nautical miles of the position as it is known today.

Leith Harbour, on the northern shore of South Georgia where the Stromness whaling station was located, is mentioned as being 62 nautical miles (115 km) from Wallis Island and 53 nautical miles (98 km) from Bird Island, which both lie to the west of South Georgia.

Figure 4. Section of the chartlet from Nordenskjöld and Andersson (1905: 77) used for the estimation of the longitude of Cape Belsham on Elephant Island. Shown twice actual size. All rights reserved

The Voyage to South Georgia

Despite the obvious perils that the voyage to South Georgia in a small boat entailed, Worsley was confident in his abilities while also being aware of Shackleton's unvoiced concerns: 'For me, used to boat work, surf landings and every kind of craft, this passage was an adventure - a too uncomfortable and dangerous one - but still an adventure. To him [Shackleton]…it must have been more menacing, even appalling.' (Worsely 1998: 107).

The *James Caird* was prepared for the journey but in Worsley's opinion was over ballasted by about five hundredweight (250 kg), which made it slow, stiff and jerky: 'It kept us constantly wet all passage, so causing much unnecessary misery.' (Worsley 1998: 103).

Shackleton, Worsley, McNish the carpenter and three others set sail around noon on 24 April 1916. After battling gale force winds and being struck by what would today be recognised as a rogue wave (Worsley 1998: 130), on 8 May the presence of seaweed and increasing bird life indicated that land was near. The DR position at noon fell at a point in the interior of South Georgia and within about half an hour land was sighted almost exactly 14 days since their departure. Hurricane force winds from a south westerly direction forced them to beat off the lee shore until they subsided and the crew were only able to land in King Haakon Sound after nightfall on the 10th.

Figure 5 shows a sketch map in the collection of Canterbury Museum of the area surrounding King Haakon Bay signed by F A Worsley.

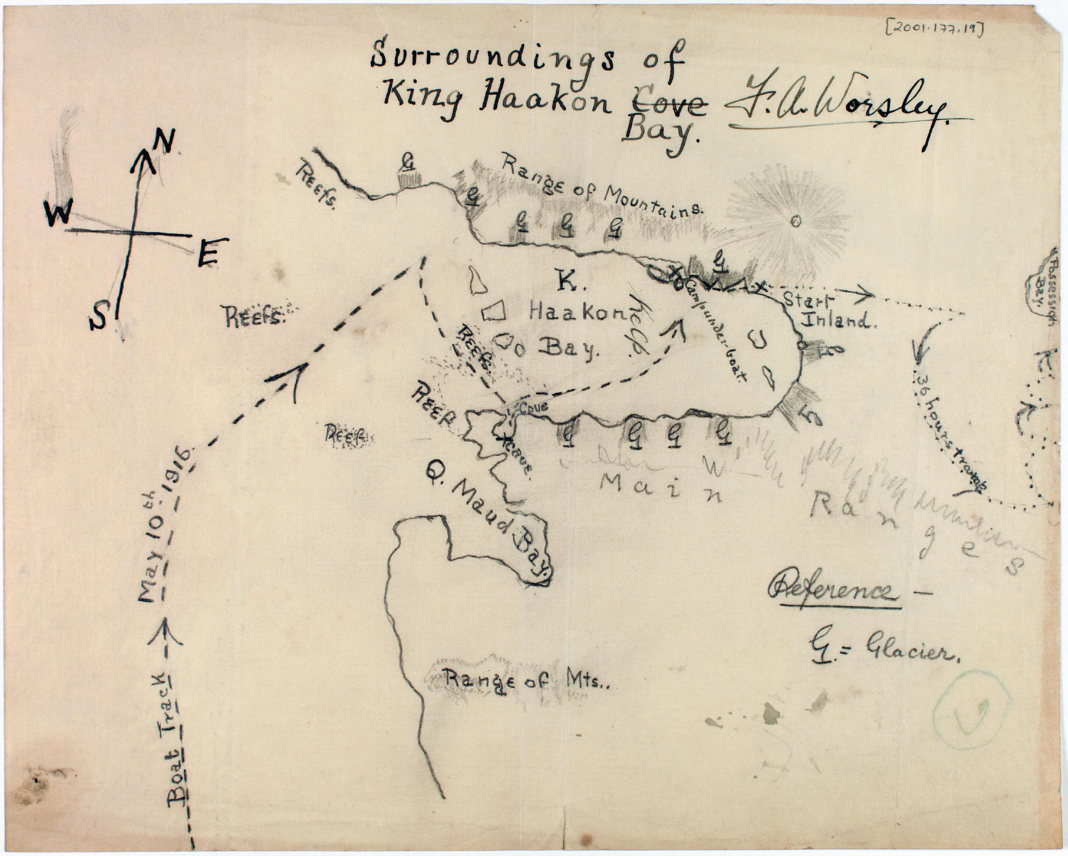

Figure 5. Frank Worsley's sketch map of King Haakon Bay and its surroundings. Canterbury Museum 2001.177.19

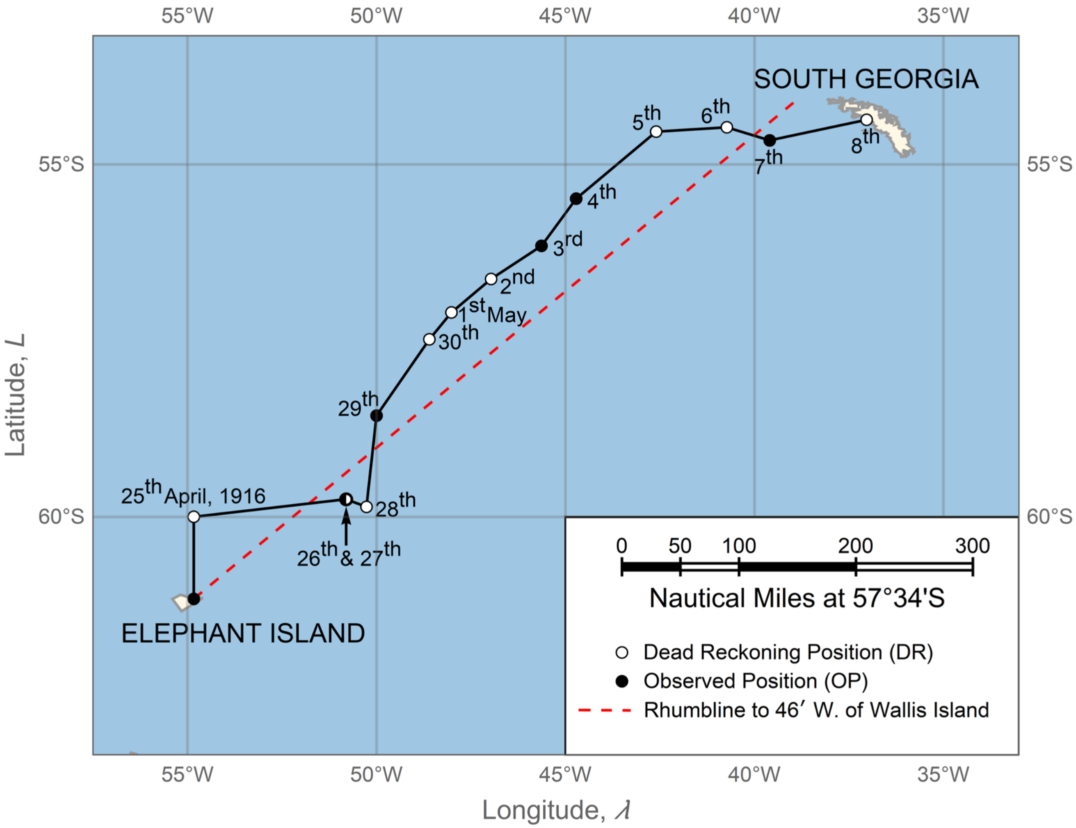

Figure 6. Track of the *James Caird* from Elephant Island to South Georgia showing positions from the log book at noon each day. Dead reckoning (DR) positions are shown as open circles, ○, and observed positions (OP) as solid dots, ●. The dotted line is the rhumb line course from Cape Belsham on Elephant Island to a point 27 nautical miles west of Wallis Island.

Figure 6 shows the track of the *James Caird* from Elephant Island to South Georgia. The plotted positions are those given in the log at noon each day. Dead reckoning positions are denoted by open circles and observed positions that have been corrected by noon or time sights are shown as solid dots. The observed position on 26 April and dead reckoning position on 27 April lie only half a nautical mile apart and are shown as half solid and half open dots. The dotted line is the rhumb line from Cape Belsham on Elephant Island to the point 27 nautical miles (50 km) or 46' of longitude west of Wallis Island. In this Mercator projection the length scale in the legend is drawn for latitude 57°34' S, which is the rhumb line's middle latitude. The track made good is generally held to windward of the direct rhumb line and begins to turn east when the parallel of South Georgia is reached some 150 nautical miles (250 km) west of the island. This is a seaman-like approach that gives margin for uncertainties in longitude.

On 7 May, Worsley recounted: 'I told Sir Ernest that I could not be sure of our position to 10 miles, so he would not agree to my trying to weather the northwest end of South Georgia, for fear of missing it. We then steered a little more easterly, to make landfall on the west coast.' (Worsley 1998: 138).

The Log Book of the *James Caird*

Pages of the original log book of the *James Caird* (Worsley 1916a) are reproduced in Appendix A along with their transcripts keeping as close as possible to the format of the original. The numbers in the log have been used to replicate, annotate and explain the calculations as shown in Appendix B.

In both the log and the transcript, noon positions by Dead Reckoning are underlined while Observed Positions are double underlined. In some cases the D.Lat or D.Lon. used to obtain these positions are seen faintly nearby in the log book pages.

Throughout the log Worsley records the wind speed using terms such as 'moderate breeze' and 'gale' that are associated with well-defined ranges on the Beaufort Wind Force Scale. On 7 and 8 May, Beaufort Weather Codes are used to record the conditions: 'BC[partly cloudy] to 6 A[M] when it became foggy' and 'wind NxE [Beaufort] 5–6 O[vercast]M[ist]R[ain]' (Worsely 1916a).

The log ends on 13 May, 1916 with a noon sight taken near a small cove on the south side of King Haakon Bay, as shown in Figure 5, where they had landed a few days earlier. Shackleton (1920, Ch. IX: 190) writes, 'A noon observation on this day gave our latitude as 54°10'47" S., but according to the German chart the position should have been 54˚12' S. Probably Worsley's observation was the more accurate.'

Shackleton is correct in his assessment but as it turns out the outcome is largely fortuitous. In the log the correction of 9'20" applied to the Sun's lower limb is consistent with incorporating the dip of a sea horizon. From the cove, the north shore of King Haakon Bay lies at a distance of around 2 nautical miles and for the stated height of eye of 12 feet no sea horizon is visible. The Sun's altitude would be measured from the far waterline, which requires that the dip short of the horizon be used and for which the appropriate total altitude correction is 8'30". However, in addition the Sun's declination was entered in the noon sight reduction as 18°22'53" N. This is obtained by interpolating values tabulated daily in the *Nautical Almanac* (1916:51) but should actually be 18°23'53" N. Astoundingly, this is the only such error made during the voyage of the *James Caird* and it almost exactly cancels the error in the dip leading to the stated latitude of 54°10'47" S being very close the true value.

Acknowledgements

This project began with an obscure listing to Worsley's navigational logbook at Canterbury Museum. The information contained therein was cryptic, washed out and smudged. Instead of a great read of a heroic journey, it turned out to be a grand puzzle. I (Brad Morris) mentioned that I had a copy of the log in passing and George Huxtable leaped forward, playing the critical role in cracking the code. George has passed, but we could not have done this without him. Thank you again George! Other members of NavList (www.fer3.com/navlist) have contributed over the years, until nearly every character has been decided. It may be impossible for us to recall each individual, yet Henry Halboth stands out as a major contributor in helping to decipher the chronometer issue. The authors also thank David Castle for locating and making available information in Worsley's diary (Worsley 1916b).

Endnotes

1. In its modern incarnation the *Nautical Almanac* also gives the altitude corrections along with sight reduction tables for line of position navigation.
2. In addition to the chartlet on page 77 (Nordenskjöld and Andersson 1905), there is a fold-out chart at a scale of 1:5,000,000 attached to its back cover. This chart shows Elephant Island displaced to the east and it is unlikely that it was used as the source of Cape Belsham's longitude.
3. http://www.spri.cam.ac.uk/archives/shackleton/articles/N:_999a.html
4. http://collections.rmg.co.uk/collections/objects/79134.html

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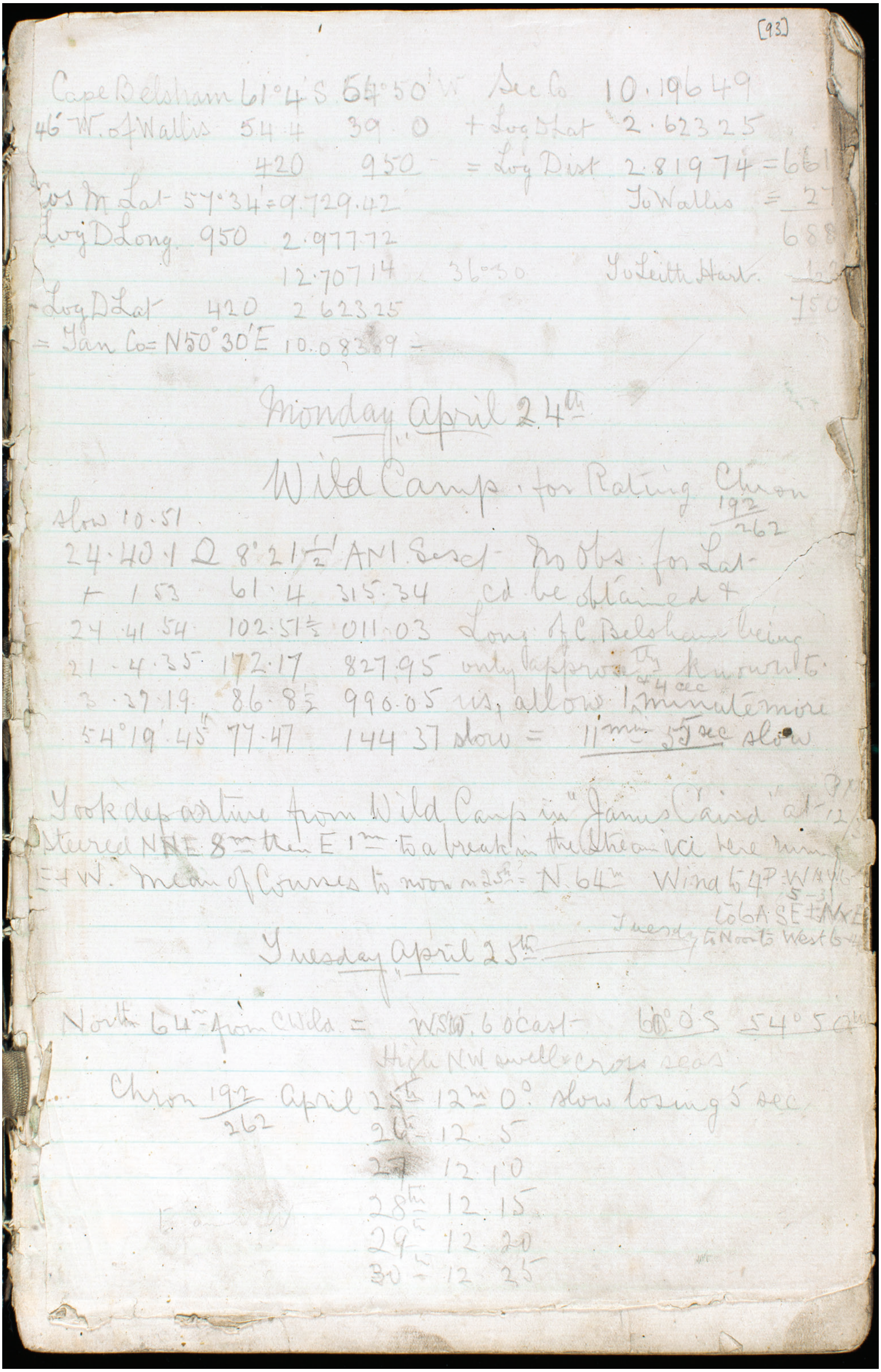
Appendix A

Images of pages from Frank Worsley's Navigational Log Book (Worsley 1916a) that relate to the navigation of the *James Caird* from Elephant Island to South Georgia over the period 24 April to 13 May 1916 are shown here along with their transcriptions. The log book is damaged with rips, smudges and water immersion. In the process of transcription every effort has been made to preserve the spacing and actual characters used by Worsley.

Also shown is the log entry and its transcript for 24 March 1916 when Worsley attempted to rate his chronometers using Mount Percy on Joinville Island while camped on the Weddell Sea ice.



[93]

Cape Belsham 61°4'S 54°50'W Sec Co 10.19649
46' W. of Wallis 54 4 39 0 + Log D Lat 2.62325
420 950 = Log Dist 2.81974 = 661
Cos M Lat 57°34' = 9.729.42 To Wallis = 27
Log D Long. 950 2.977.72 688
12.70714 36°30 To Leith Hart. [illegible]
Log D Lat 420 2 62325 750
= Tan Co = N50°30'E 10.08389 =

Monday April 24th

Wild Camp. for Rating Chron 192/262

Slow 10.51
24.40.1 ☉ 8°21½' AN1 Sexd - No Obs. for Lat
+ 1 53 61 4 315.34 cd be obtained &
24 41 54 102.51½ 011.03 Long of C. Belsham being
21.4.35 172.17 827.95 only approx^ty known to
3.37.19 86.8½ 990.05 us, allow 1 & 4 sec minute more
54°19'45" 77.47 144 37 slow = 11 min 55 sec slow

Took departure from Wild Camp in "James Caird" at 12 PM
Steered NNE 8m then E 1m to a break in the stream ice here running
E & W. Mean of Courses to noon on 25th = N. 64m Wind to 4P W x N 6 5-3
to 6A SE & NxE

Tuesday April 25th — Tuesday to Noon to West 6-4

North 64m from C Wild = WSW. 6 0 cast 60°0'S 54°50'W
High NW swell & cross seas
Chron 192/262 April 25th 12m 0s slow losing 5 sec
26th 12 5
27 12 10
28th 12 15
29th 12 20
30th 12 25

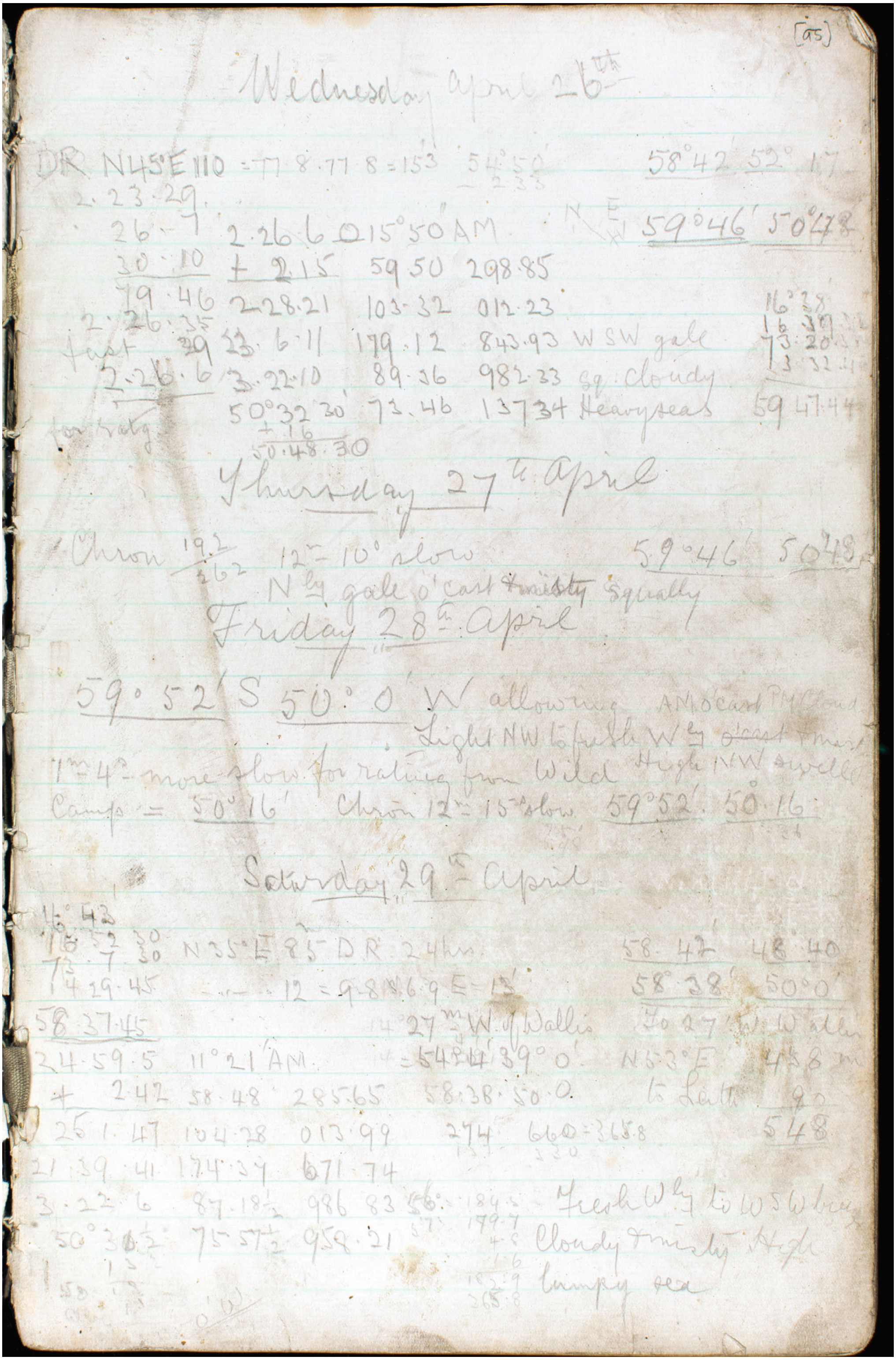
Cape Belsham 61°4′S 54°50′W Sec Co 10.19649
46′W. of Wallis 54 4 39 0 +Log Dlat 2.62325
420 950 = Log Dist 2.81974 = 661
Cos M Lat 57°34′= 9.729.42 To Wallis = 27
Log DLong 950 2.977 72 688
12.707 14 36°30 To Leith Harb 62
-Log DLat 420 2.623 25 750
=Tan Co=N50°30′E 10.083 89 -

Monday April 24th
Wild Camp for Rating Chron
192
slow 10.51 262
24.40.1 O 8°21 ½′ AM Sext No Obs for Lat
+ 1 53 61 . 4 315.34 cd be obtained +
24 41 54 102.51 ½ 011.03 Long. of C. Belsham being
21. 4.35 172.17 827.95 only approx^{tly} known to
3.37.19 86. 8 ½ 990.05 us, allow 1minute+4sec more
54°19′.45″ 77.47 144 37 slow = $11^{min}55^{sec}$ slow

PM
Took departure from Wild Camp in "James Caird" at 12/30
Steered NNE 8^{m} then E1^{m} to a break in the stream ice here being
E+W. Mean of Courses to noon on 25th = N64^{m} Wind to 4^{P} WNW6-
to 6A·SE to NxE
Tuesday to Noon to West 6-4

Tuesday April 25th

North 64^{m} from CWild = WSW 6 o'cast 60°0′S 54°50′W
High NW swell + cross seas
Chron 192 April 25th 12^{m}0^{s} slow losing 5 sec
262 26th 12 5
27 12 10
28th 12 15
29th 12 20
30th 12 25



[95]

Wednesday April 26th

DR N45°E 110 = 77.8 . 77.8 = 153 54°50 − 2 35 58°42 52° 17
2.23.29
26 . 7 2.26.6 ⊙ 15°50" AM N E W 59°46′ 50°47.8
30 . 10 + 2.15 59.50 298.85
79 . 46 2.28.21 103.32 012.23 16°38
2.26.35
fast 29 23.6.11 179.12 843.93 WSW gale 16 39 / 73.20 / 13 32.4
2.26.6 3.22.10 89.36 982.33 sq: cloudy
50°32 30′ 73.46 13734 Heavy seas 59 47.44
for ratg + 16
50.48.30

Thursday 27th April

Chron 19.2 / 26.2 12m 10s slow 59°46′ 50°48
Nly gale o'cast ~~& misty~~ squally

Friday 28th April

59° 52′ S 50° 0′ W allowing AM o'cast PM Cloud
Light NW to fresh Wly ~~o'cast~~ & misty
1m 4s more slow for rating from Wild High NW swell
Camp = 50°16′ Chron 12m 15s slow 59°52′ 50.16

Saturday 29th April

16°43
16 52 30
73 7 30 N 35°E 85 DR 24 hrs. 58 47 48 40
14 29.45 12 = 9.8 & 6.9 E = 13′ 58°38′ 50°0′
58 37.45 14°27 m W of Wallis To 27′ W Wallis
24.59.5 11°21′ AM = 54 84 39° 0′ N 53°E 458 m
+ 2.42 58.48 285.65 58.38 50.0 to Leith 90
25 1.47 104.28 013.99 274 660 = 365.8 548
21.39.41 174.37 671.74
3.22.6 87.18½ 986 83 56 = 184.5 Fresh Wly to WSW breeze
50°36½ 75 57½ 958.21 57 179.7 Cloudy & misty High
1 3 4.8 1.6 182.9 lumpy sea
365.8
0 W

Wednesday April 26th

DR N45°E 110 = 77.8 77.8 = 153 54°50″ 58°42′ 52°17
2.23.29 - 2 33 N E
26 7 2.26. 6 O 15°50 AM W 59°46′ 50°48′
30 10 + 2.15 59 50 298.85
79. 46 2 28.21 103.32 012.23 16°38′
2.26. 35 16 39 30
fast 29 23.6.11 179.12 843.93 WSW gale 73. 20.30
2.26. 6 3.22.10 89.36 982.33 sq. cloudy 13 32.46
50°32 30′ 73.46 137 34 Heavy seas 59 47 .44
for ratg + 16
50.48.30

Thursday 27th April

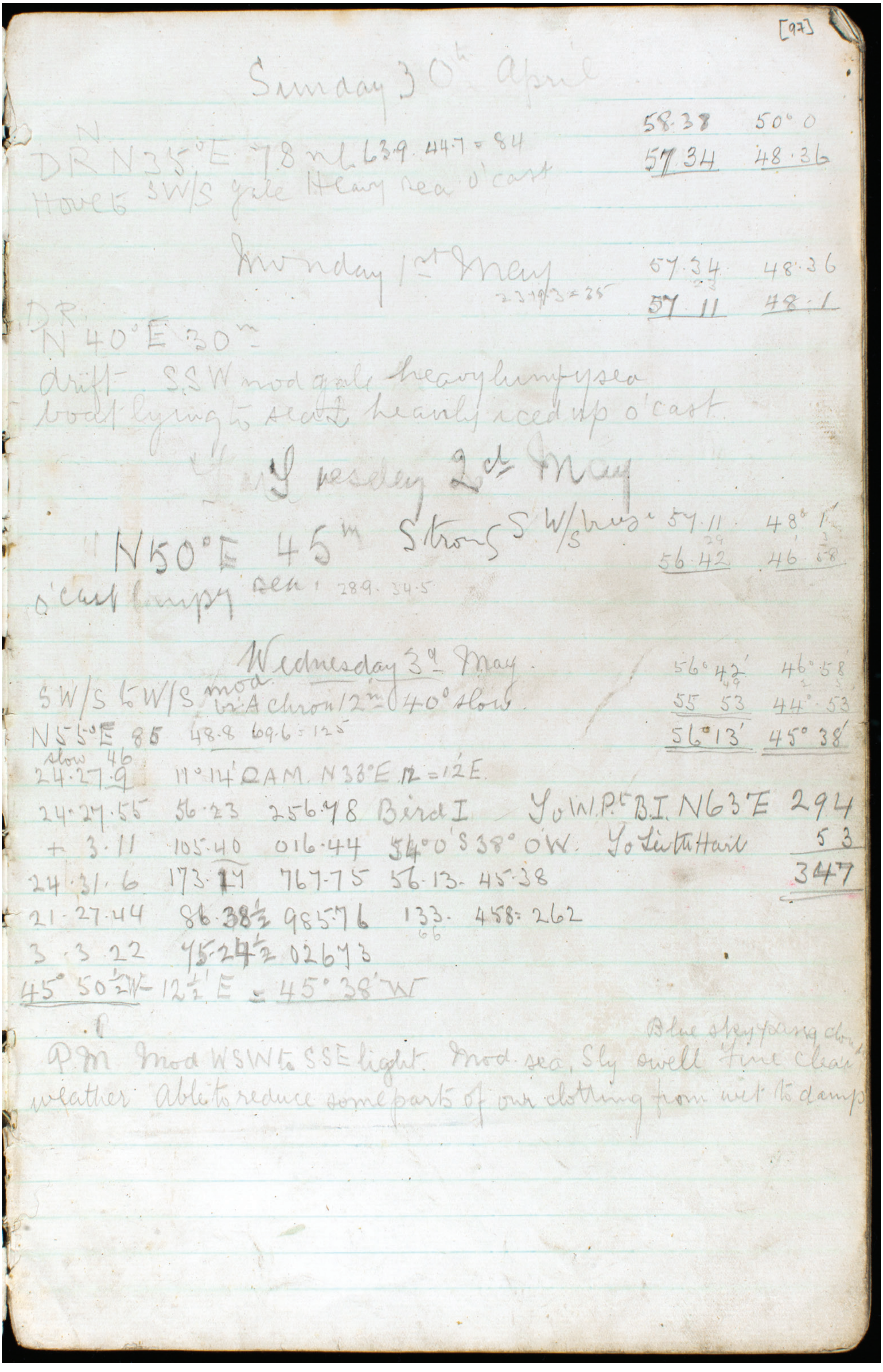
Chron 192/262 12^{m} 10^{s} slow 59°46′ 50°48′
N^{ly} gale o’cast + misty squally

Friday 28th April

59°52′S 50°0′ W allowing AM o’cast PM Cloud
Light NW to fresh W^{ly} ~~o’cast~~+mist
1^{m}4^{s} more slow for rating from Wild High NW swell
Camp = 50°16′ Chron 12^{m}15^{s} slow. 59°52′ 50°16

Saturday 29th April

16° 43′
16 . 52 30
73. 7. 30 N35°E85^{m} DR 24hrs 58.42′ 48°40
14. 29. 45 —“ — 12 =9.8N6.9E = 13′ 58°38′ 50°0′
58. 37. 45 27^{m}W. of Wallis to 27′W Wallis
24. 59. 5 11°21′AM =54°4′39°0′ N53°E 458m
\+ 2. 42 58. 48 285.65 58.38.50.0 to Leith 90
25 1 47 104.28 013.99 274 660=365.8 548
21. 39. 41 174.37` 671.74 137 330
3. 22. 6 87.18½ 986 83 56° 184.5 Fresh W^{ly} to WSW breeze
50° 31½ 75. 57½ 958.21 57° 179.7 Cloudy+misty High
13½ 4.8 lumpy sea
50 18 1.6
182.9
365.8



[97]

Sunday 30th April

58·38 50° 0
57·34 48·36

N
DR N35°E 78 m 63·9 44·7 = 84
Hove to SW/S gale Heavy sea o'cast

Monday 1st May

57·34 48·36
23
57 11 48·1

2·3 49·3 = 35

D.R.
N 40°E 30m
drift SSW mod gale heavy lumpy sea
boat lying to sea at heavily iced up o'cast

Tuesday 2d May

N50°E 45m Strong S W/S breeze 57·11 48° 1
29 3
56·42 46 58

o'cast lumpy sea 28·9. 34·5

Wednesday 3d May

56° 42' 46° 58
49 5
55 53 44° 53
56° 13' 45° 38'

SW/S to W/S mod
br A chron 12m 40° slow.
N55°E 85 48·8 69·6 = 125
slow 46
24·27·9 11° 14' AM. N38°E 12 = 12'E.
24·27·55 56·23 256·78 Bird I To W.Pt B.I. N63°E 294
+ 3·11 105·40 016·44 54° 0' S 38° 0W. To Little Hail 53
24·31·6 173·17 767·75 56·13. 45·38 347
21·27·44 86·38½ 985·76 133· 458 = 262
66
3 ·3 ·22 75·24½ 026·73
45° 50½'W − 12½'E = 45° 38'W

P.M. Mod WSW to SSE light. Mod. sea, Sly swell Fine clear Blue sky passing clouds
weather Able to reduce some parts of our clothing from wet to damp

Sunday 30h April

N 58.38 50° 0
DR N35°E 78 mls 63.9 44.7 = 84 57.34 48.36
Hove to SW/S gale Heavy sea o’cast

Monday 1st May

57.34 48.36
DR 23 19.3=35 57.11 48. 1
N40°E 30m
drift SSW mod gale heavy lumpy sea
boat lying to sea ⚓ heavily iced up o’cast

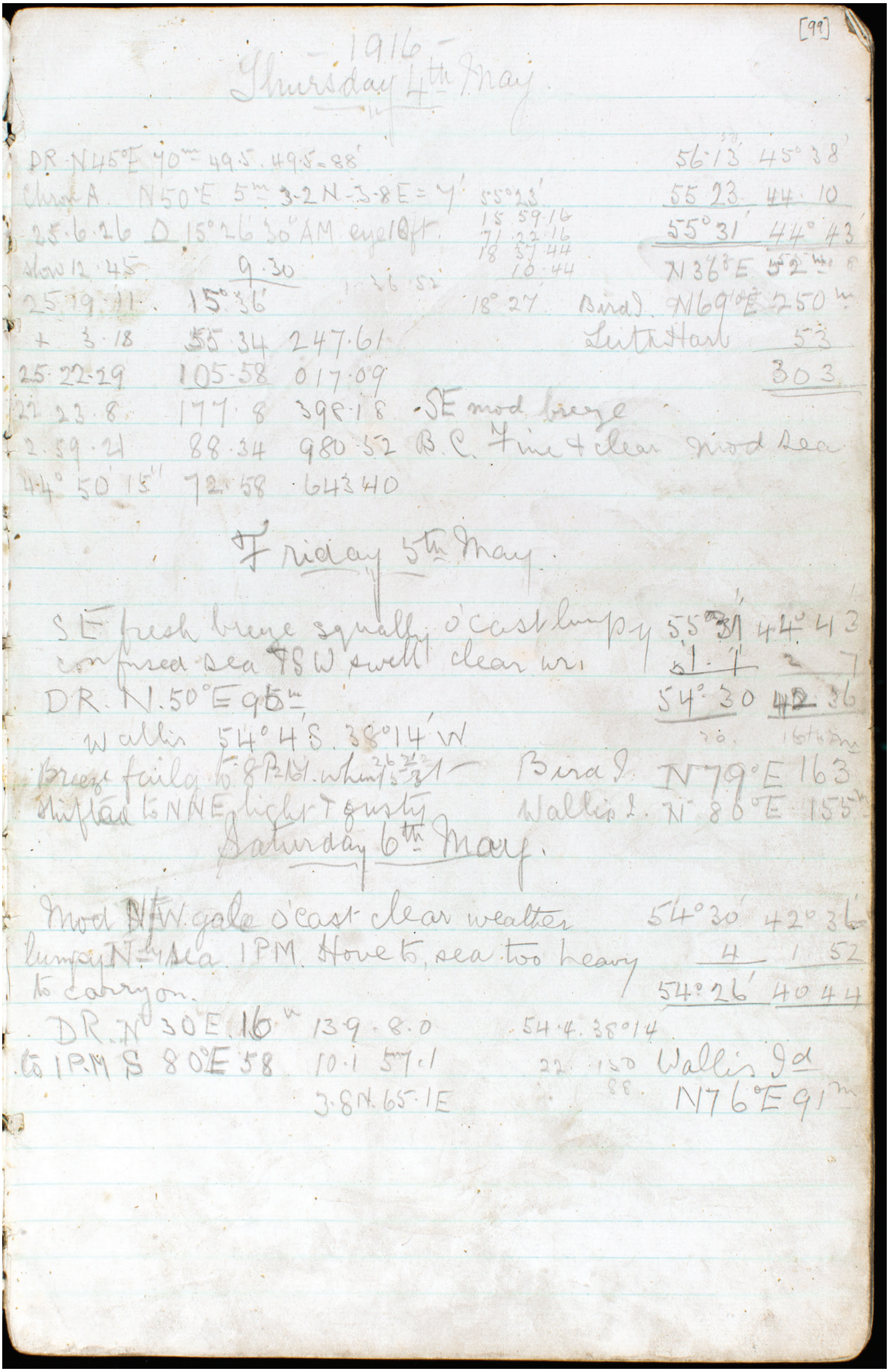
Tuesday 2d May

N50°E 45m Strong SW/S breeze 57.11 48° 1′
o’cast lumpy sea 28.9. 34.5 56.42 46 58

Wednesday 3d May

SW/S to W/S mod br A chron 12m40s slow 56°42′ 46°58′
N55°E 85 48.8 69.6 = 125 55 53 44°53′
slow 46 56°13′ 45°38′
24.27.9 11°14′ O AM N33°E 12 = 12′E
24.27.55 56.23 256.78 Bird I To W.P.t B.I. N63°E 294
\+ 3.11 105.40 016.44 54°0′S 38°0′W To Leith Harb 53
24.31. 6 173.17 767.75 56.13. 45.38 347
21.27.44 86.38 ½ 985.76 133. 458=262
3. 3.22 75.24 ½ 026 73 66
45°50½ W -12½′ E = 45°38′W

Blue sky passg cloud
PM Mod WSW to SSE light. Mod.sea, S ly swell Fine clear
weather Able to reduce some parts of our clothing from wet to damp



[99]

1916

Thursday 4th May

DR N45°E 70m 49.5. 49.5 = 88' 56°13' 45°38'
Chron A. N50°E 5m 3.2N 3.8E = 7' 55°23' 55 23 44 10
25.6.26 ☉ 15°26'30" AM eye 10ft. 15 59.16 71 22.16 18 37.44 10.44 55°31' 44°43'
Slow 12.45 9.30 N36°E 52m
25.19.41. 15°36' 1 36 52 18°27 Bird I. N69°E 250m
+ 3.18 55 34 247.61 Leith Harb 53
25.22.29 105.58 017.09 303
22.23.8 177 8 398.18 SE mod breeze
2.59.21 88.34 980.52 B.C. Fine + clear Mod sea
44°50'15" 72 58 64340

Friday 5th May

SE fresh breeze squally o'cast lumpy 55°31' 44°43'
confused sea + SW swell clear wr. 1 1 2 7
DR N.50°E 95m 54°30 42 36
Wallis 54°4'S. 38°14'W
Breeze failing to 8PM. when 26 2½ 31 — Bird I. N79°E 163
shifted to NNE light + gusty Wallis I. N 80°E 155m

Saturday 6th May

Mod NW gale o'cast clear weather 54°30' 42°36'
lumpy N'ly sea 1PM Hove to, sea too heavy 4 1 52
to carry on. 54°26' 40 44
DR N 30E 16m 13.9 8.0 54.4. 38°14
to 1PM S 80°E 58 10.1 57.1 22 1 30 88 Wallis Id
3.8N. 65.1E N76°E 91m

-1916 -

Thursday 4thMay

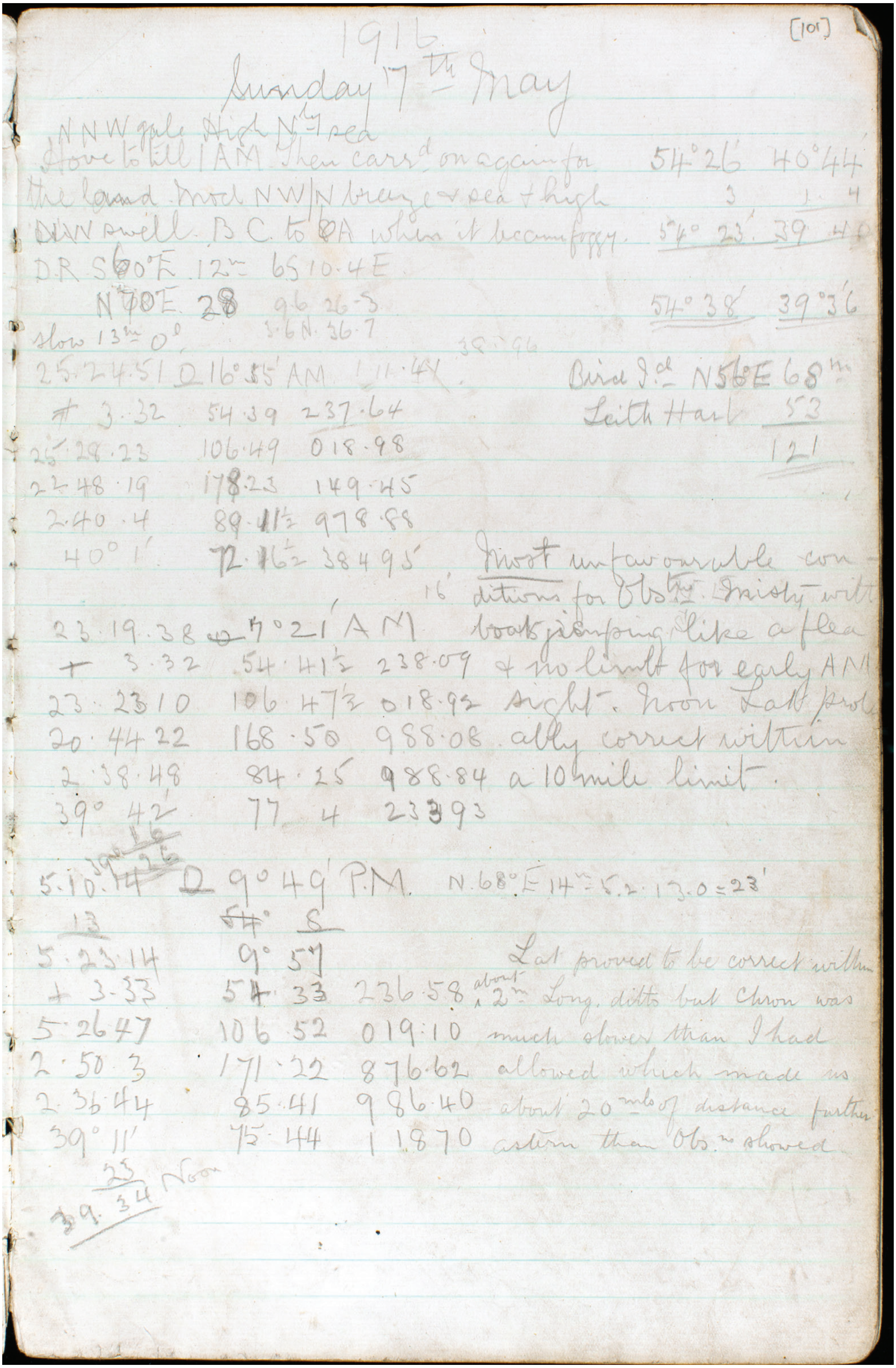
DR N45°E 70^{m} 49.5 49.5 = 88′ 56°13′ 45°38′
Chron A N50°E 5^{m} 3.2N 3.8E = 7′ 55°23′ 55.23 44.10
25.6.26 O 15°26′30″AM eye 10ft 15 59 16 55°31′44°43′
slow 12.45 9.30 71.22.16 42 55 30 8
25.19.11 15°36′ 1.36.52 18.37.44 91 403
\+ 3.18 55.34 247.61 10 44 N36°E 52^{m}
25.22.29 105.58 017.09 18° 27′
22.23. 8 177. 8 398.18 Bird I^{s} N69°E 250^{m}
2.59.21 88.34 980.52 Leith Harb. 53
44°50′15″ 72.58 643.40 SE mod breeze 303
B.C. Fine+clear mod sea

Friday 5th May

SE fresh breeze squally o’cast lumpy 55°31′44°.43′
confused sea + SW swell clear wr 1. 1′ 2. 7
DR N50°E 95^{m} 54°30 42.36
Wallis 54°4′S 38°14′W
26 262′
153
Breeze failg to 8PM when Bird I N79°E 163^{m}
shifted to NNE light and gusty Wallis I. N80°E 155^{m}

Saturday 6th May

Mod N/W gale o’cast clear weather 54° 30′ 42°36′
lumpy N^{ly} sea 1PM. Hove to, sea too heavy 4 1 52
to carry on. 54° 26′ 40 44
DR N 30 E 16^{m} 13.9 8.0 54.4. 38°14
to 1PM S 80°E 58 10.1 57.1 22. 150 Wallis I^{d}
3.8N.65.1E 88 . N76°E 91^{m}



[101]

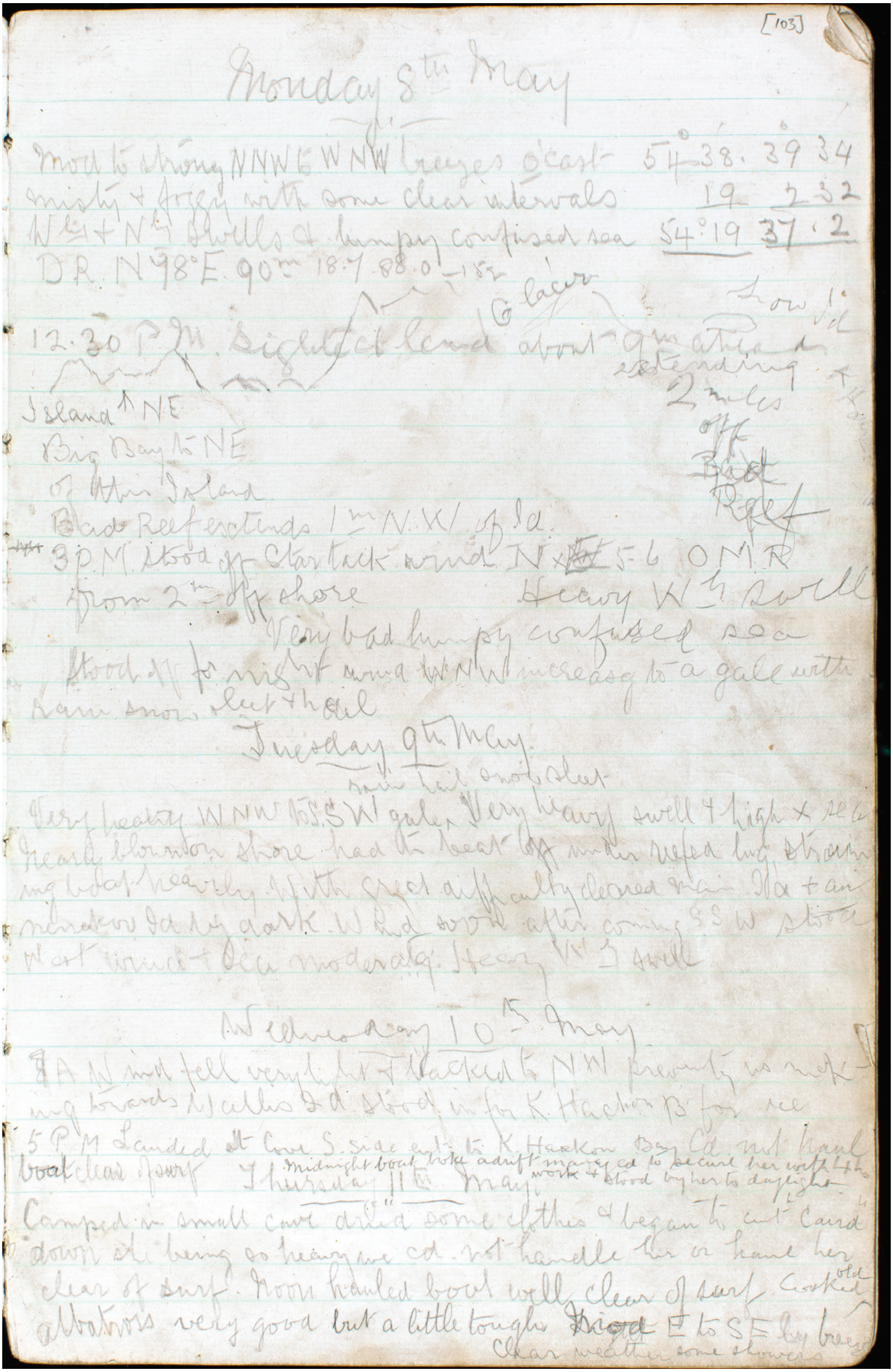
1916
Sunday 17th May

NNW gale High Nly sea
Hove to till 1 AM Then carrd on again for 54°26 40°44
the land Mod NW/N breeze & sea & high 3 1 4
NW swell. B C. to 8A when it became foggy. 54° 23' 39 40
D.R S60°E 12m 6S 10·4E
N70E 28 9·6 26·3
slow 13m 0° 3·6N. 36·7
38 96
25.24.51 ☉ 16°55' AM 1 11·44 Bird Id N56E 68m
+ 3·32 54·39 237·64 Leith Harb 53
25 28·23 106·49 018·98 121
22 48 19 178·23 149·45
2·40·4 89 11½ 978·88
40° 1' 72·16½ 38495 Most unfavourable con-
16' ditions for Obsns. Misty with
23.19.38 ☉ 7°21' AM boat jumping like a flea
+ 3·32 54·41½ 238·09 & no limit for early AM
23·23 10 106·47½ 018·93 sight. Noon Lat prob-
20·44 22 168·50 988·08 ably correct within
2·38·48 84·25 988·84 a 10 mile limit.
39° 42' 77 4 23393
16
39° 26
5·10·14 ☉ 9°49' P.M. N.68°E 14m = 5.2·13.0 = 23'
13 54° S
5·23·14 9° 57 Lat proved to be correct within
+ 3-33 54 33 236·58 about 2m Long. ditto but Chron was
5·26 47 106 52 019·10 much slower than I had
2·50·3 171·22 876·62 allowed which made us
2·36·44 85·41 986·40 about 20 mls of distance further
39° 11' 75·44 11870 astern than Obsns showed
23
39·34 Noon

1916
Sunday 7th May

NNW gale High Nly sea
Hove to till 1AM Then carrd on again for   54°26′ 40°44′
the land. Mod NW/N breeze + sea + high   3   1 4
NW swell. BC to 6 A when it became foggy.   54°23′ 39 40
DR S60° E 12m   6S 10.4E
N70° E 28   9.6 26.3   54°38′ 39°36′
Slow 13m0s   3.6N 36.7   38 96
25.24.51 O   16°55′ AM   1 11 41   Bird Id N56°E 68m
+ 3.32   54.39   237.64   Leith Harb 53
25.28.23   106.49   018.98   121
22.48.19   178.23   149.45
2.40. 4   89.11½   978.88
40° 1′   72.16½   384 95   Most unfavourable con-
16′   ditions for obstns. Misty with
23.19.38 ~~O~~   7°21′ AM   boat jumping like a flea
+ 3.32   54.41½   238.09   +no limb for early AM
23.23 10   106.47½   018.92   sight. Noon Lat prob
20.44 22   168.50   988.08   ably correct within
2.38.48   84.25   988.84   a 10 mile limit
39°42′   77 4   233 93
16
39°26′

5.10.14 O   9°49′P.M.   N68°E 14m 5.2 13.0 = 23′
13   ~~54~~° 8
5.23.14   9°57   Lat proved to be correct within
about
+ 3.33   54.33   236.58   ^2m Long. ditto but Chron was
5.26.47   106 52   019.10   much slower than I had
2.50 3   171.22   876.62   allowed which made us
2.36.44   85.41   986.40   about 20 mls of distance further
39°11′   75.44   118 70   astern than Obsns showed
23
39.34 Noon



[103]

Monday 8th May

Mod to strong NNW & WNW breezes o'cast 54°38. 39°34
misty & foggy with some clear intervals 19 2.32
Wly & Nly swells & lumpy confused sea 54°19 37.2
DR N 78°E 90m 18.7 88.0 -152

Glacier

12.30 PM Sighted land about 9m athead

Low Id extending 2 miles off ~~Bad~~ Reef

Island ↑ NE
Big Bay to NE
of this Island
Bad Reef extends 1m N.W/ of Id.
3 PM Stood off Star tack wind N x ~~E~~ 5-6 OMR
from 2m off shore Heavy Wly swell
Very bad lumpy confused sea
Stood off for night wind WNW increasg to a gale with
rain snow sleet & hail

Tuesday 9th May

rain hail snow sleet

Very heavy WNW to SSW gale, Very heavy swell & high x sea nearly blown on shore had to beat off under reefed lug straining boat heavily. With great difficulty cleared main Id & annenkov Id by dark. Wind soon after coming SSW stood West wind & sea moderatg. Heavy Wly swell

Wednesday 10th May

8 AM Wind fell very light & backed to NW presently we making towards Willis Id. Stood in for K. Haakon B for ice
5 PM Landed at Cove S. side ent. to K. Haakon Bay Cd. not haul boat clear of surf

Midnight boat broke adrift managed to secure her with 4 hrs work & stood by her to daylight

Thursday 11th May

Camped in small cave dried some clothes & began to cut Caird down she being so heavy we cd. not handle her or haul her clear of surf. Noon hauled boat well clear of surf. Cooked old albatross very good but a little tough. ~~Wind~~ E to SE by breeze
Clear weather some showers

Monday 8th May

Mod to strong NNW to WNW breezes o'cast 54° 38′ 39°34′
misty + foggy with some clear intervals 19 2 32
W$^{\underline{ly}}$ + N$^{\underline{ly}}$ swells + lumpy confused sea 54°.19 37. 2
DR N78°E 90$^{\underline{m}}$ 18.7 88.0 =152

12.30 PM sighted land about 9$^{\underline{m}}$ ahead, extending 2 miles off Bad Reef

3P.M. stood off Star tack wind NxE 5-6 OMR
from 2$^{\underline{m}}$ off shore Heavy W$^{\underline{ly}}$ swell
Very bad lumpy confused sea
Stood off for night wind WNW increasg to a gale with
rain snow sleet + hail

Tuesday 9th May

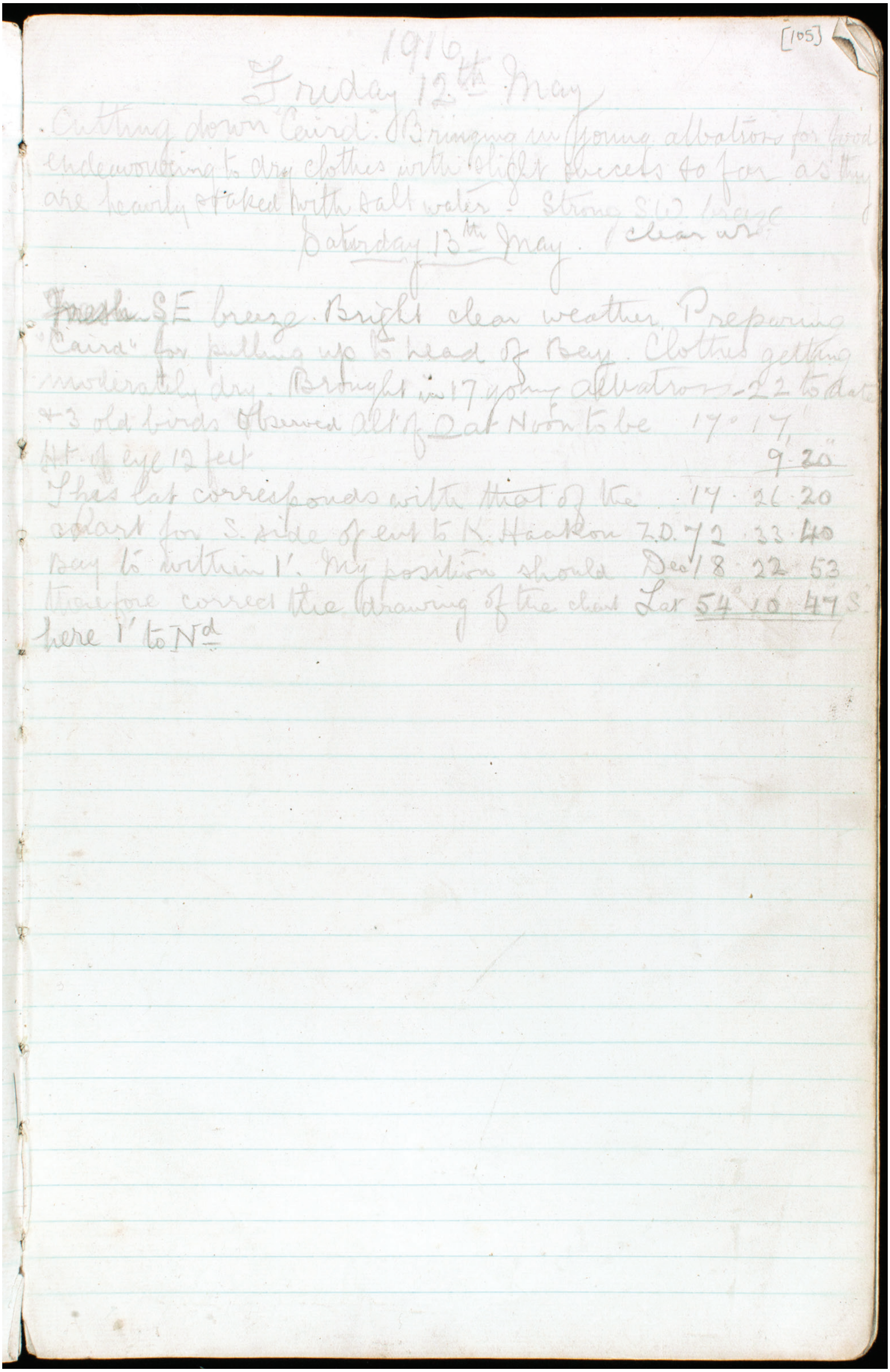
rain hail snow sleet
Very heavy WNW to S.SW gale ^ Very heavy swell + high x sea
Nearly blown on shore had to beat under reefed lug, straining boat heavily. With great difficulty cleared main Id + Annenekov Id by dark. Wind soon after S.SW stood
West wind + sea moderatg. Heavy W$^{\underline{ly}}$ swell

Wednesday 10 th May

8A Wind fell very light + backed to NW preventing us making towards Wallis Id stood in for K. Hachon B for ice
5PM Landed at Cove S. side ent. to K. Haakon Bay Cd. not haul
boat clear of surf Midnight boat broke adrift managed to secure her with 4hrs work + stood by her to daylight

Thursday 11th May

Camped in small cave dried some clothes + began to cut Caird
down she being so heavy we cd. not handle her or haul her
clear of surf. Noon hauled boat well clear of surf. Cooked old
albatross very good but a little tough. ~~Light~~Mod E to SEly breeze
Clear weather some showers



[105]

1916
Friday 12th May
Cutting down "Caird". Bringing in young albatross for food
endeavouring to dry clothes with slight success so far as they
are heavily soaked with salt water. Strong SW breeze
Saturday 13th May. clear wr.

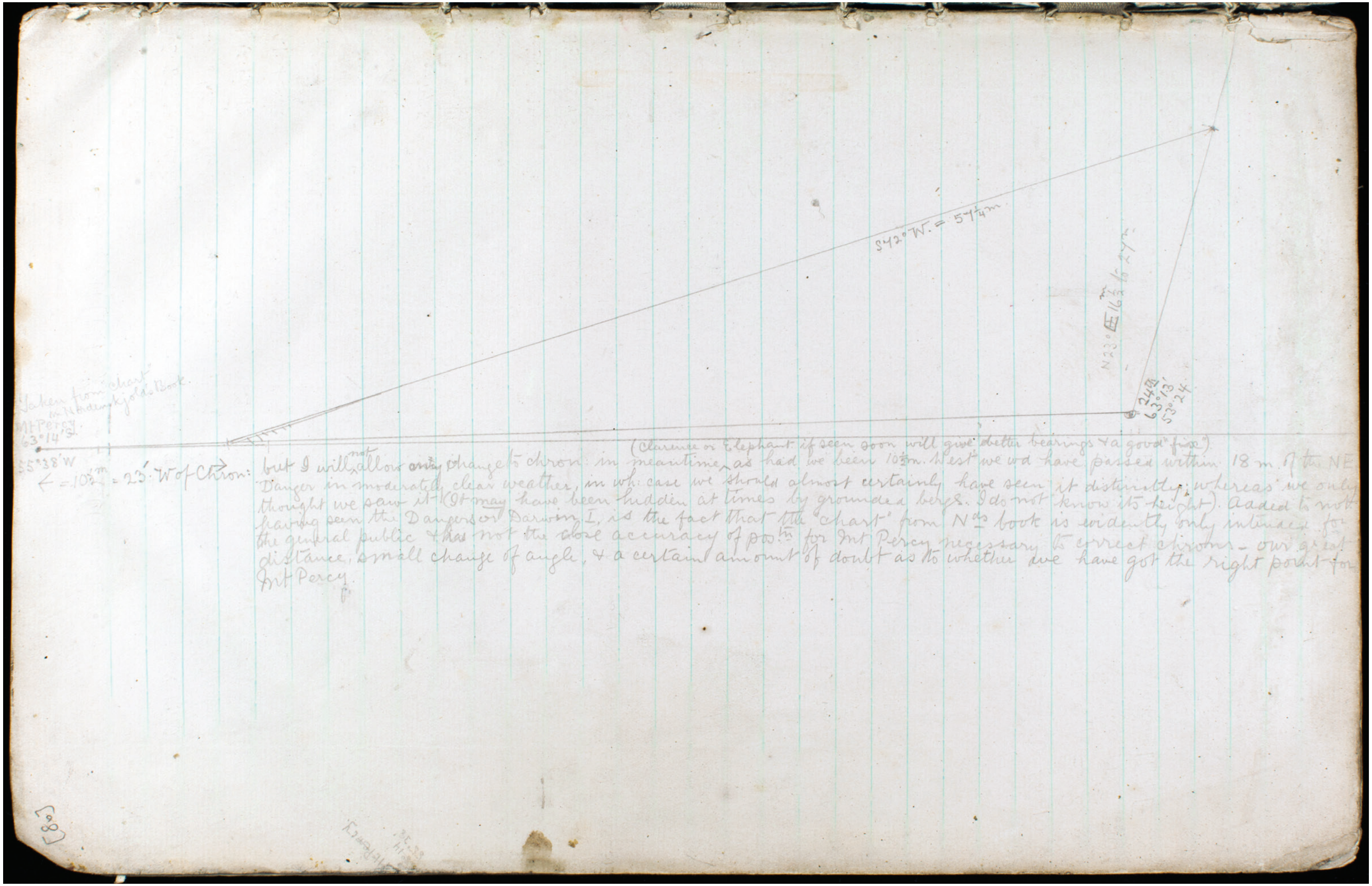
~~Fresh~~ SE breeze. Bright clear weather. Preparing
"Caird" for putting up to head of Bay. Clothes getting
moderately dry. Brought in 17 young albatross - 22 to date
& 3 old birds. Observed Alt of ☉ at Noon to be 17° 17'
Ht of eye 12 feet 9 20"
This lat corresponds with that of the 17 26 20
chart for S. side of ent to K. Haakon Z.D. 72 33 40
Bay to within 1'. My position should Dec 18 22 53
therefore correct the drawing of the chart Lat 54° 10 47 S.
here 1' to Nd

1916
Friday 12th May

Cutting down Caird. Bringing in young albatross for food
endeavouring to dry clothes with slight success so far as they
are heavily soaked with saltwater. Strong SW breeze
clear wr

Saturday 13th May

Fresh SE breeze. Bright clear weather. Preparing
Caird for pulling up to head of Bay. Clothes getting
moderately dry. Brought in 17 young albatross – 22 to date
+ 3 old birds. Observed Alt of O at Noon to be 17° 17′
Ht of eye 12 feet 9′·20″
This lat corresponds with that of the 17· 26 ·20
chart for S. side of ent to K. Haakon Z.D. 72· 33 ·40
Bay to within 1′. My position should Dec 18· 22 ·53
therefore correct the drawing of the chart Lat 54°10′ 47 S
here 1′ to Nd



Taken from "chart" in Nordenskjold's Book
Mt Percy
63°14'S.
55°38'W
← = 10½m = 23' W of Chron:

(Clarence or Elephant if seen soon will give better bearings & a good "fix")

but I will not allow ~~any~~ change to chron: in meantime, as had we been 10½m. West we wd have passed within 18 m. of the NE Danger in moderately clear weather, in wh: case we should almost certainly have seen it distinctly; whereas we only thought we saw it (It may have been hidden at times by grounded bergs. I do not know its height). Added to not having seen the Dangers or Darwin I, is the fact that the "chart" from Nds book is evidently only intended for the general public & has not the close accuracy of posn for Mt Percy necessary to correct chrons – our great distance, small change of angle, & a certain amount of doubt as to whether we have got the right point for Mt Percy.

[98]

Taken from “Chart” in Nordenskjold’s Book.
Mt Percy
63°14′S
55°38′W
= 10 ½ $^{\underline{m}}$=23′W of Chron:
not (Clarence or Elephant if seen soon will give better bearings + a good “fix”)
but I will ^ allow any change to chron in meantime ^ as had we been 10 ½ m. West we wd have passed within 18 m. of the NE
Danger in moderately clear weather, in wh: case we should almost certainly have seen it distinctly; whereas we only
thought we saw it (It <u>may</u> have been hidden at times by grounded bergs. I do not know its height). Added to not
having seen the Dangers or Darwin I, is the fact that the “chart” from N$^{\underline{ds}}$ book is evidently only intended for
the general public thus not the close accuracy of pos$^{\underline{tn}}$ for Mt Percy necessary to correct chrons – our great
distance, small change of angle, + a certain amount of doubt as to whether we have got the right point for
Mt Percy.

Appendix B

The calculations performed in the original log book of the *James Caird* are replicated here. An attempt has been made to closely mimic the operations Worsley would have performed. When logarithms are calculated they are rounded to 5 decimal places before using them in arithmetic operations. Hour angles are rounded to the nearest second in time before being used to calculate longitude. Occasionally differences in the least significant digit remain. Some numbers given in the log come from table look ups or reverse look ups that require interpolation, which may again lead to small differences. This is particularly the case for D. Lon. used in DR where interpolation has been done. For definiteness, D. Lat. and Dep. are rounded to one decimal place and D. Lon. to the nearest integer before being used in DR calculations.

In a few places where convenient the modern practice of denoting positions in degrees and minutes to the nearest tenth of a minute is adopted.

Underlined noon DR positions and OP's remain exactly as they were recorded in the log even when the calculations undertaken here yield a slightly different result.

Initial Distance Calculation

An initial calculation of the distance and course from Cape Belsham to a point 46' West of Wallis Island is made using equations (3) evaluated by means of logarithms. It is further noted that there are an additional 27 nautical miles (50 km) to Wallis Island itself and thence 62 nautical miles (115 km) to Leith Harbour. This is the only instance in the log where there is evidence of a long hand calculation of this type being performed. Intermediate values were carefully labelled. During the voyage, course and distance to destination were obtained from traverse tables.

Cape Belsham	61° 4′ S		54° 50′ W
46′ West of Wallis	54 4		39 0
D. Lat.	420′	D. Lon.	950′
Middle Latitude, *M*	57° 34′	log cos M	9.72942
		log D. Lon.	2.97772
		log Dep.	12.70714
		log D. Lat.	2.62325
Course, *C*	50° 30′	log tan C	10.08389
	N50°30′E		
		log D. Lat.	2.62325
		log sec C	0.19649
Distance	660 miles	log Distance	2.81974
	660		
To Wallis Island	27	(46′ longitude = 27 miles at Wallis Island's latitude)	
	687 miles		
To Leith Harbour	62		
	749 miles		

Monday, 24th April (Day 1)

Time Sight

For rating chronometer 192/262 at Wild Camp

Chronometer Error	Slow	10^{m}	51^{s}						
Mean time at Greenwich	24^{h}	40^{m}	1^{s}		Sun's true altitude	8°	21.5′	AM	
Equation of Time	+	1	53		Latitude	61	4.0	sec.	0.31534
Apparent time at Greenwich	24	41	54		Polar distance	102	51.5	cosec.	0.01103
					Sum	172	17.0		
Apparent time at ship	21	4	35		Half-sum	86	8.5	cos.	8.82795
Longitude in time	3	37	19	W	Remainder	77	47.0	sin.	9.99005
Longitude	54°	19′	45″					hav.	9.14437

Tuesday, 25th April (Day 2)

Noon Position

DR 64 miles north of Cape Wild (61°4′S, 54°50′W): 60°0′S, 54°50′W

Anticipated Chronometer Errors

Chronometer	192	April	25th	12^{m}	0″	slow losing 5 seconds per day
	262		26th	12	5	
			27th	12	10	
			28th	12	15	
			29th	12	20	
			30th	12	25	

Wednesday, 26th April (Day 3)

Noon Positions

DR N45°E 110 miles from 60°0′S, 54°50′W: 58°42′S, 52°17′W

D. Lat. 77.8 Dep. 77.8 = D. Lon. 153

OP from time and noon sights: 59°46′S, 50°48′W

Time Sight

Sight times	2^{h}	23^{m}	29^{s}
		26	7
		30	10
Sum		79	46
Average	2	26	35
Chronometer Error		Fast	29^{s}

Mean time at Greenwich	2^{h}	26^{m}	6^{s}		Sun's true altitude	15 °	50.0 ′	AM	
Equation of Time	+	2	15		Latitude	59	50.0	sec.	0.29885
Apparent time at Greenwich	2	28	21		Polar distance	103	32.0	cosec.	0.01223
					Sum	179	12.0		
Apparent time at ship	23	6	11		Half-sum	89	36.0	cos.	7.84393
Longitude in time	3	22	10	W	Remainder	73	46.0	sin.	9.98233
Longitude	50 °	32 ′	30 ″					hav.	8.13734
Adjustment	+	16 ′							
Adjusted Longitude	50 °	48 ′	30 ″						

Noon Sight

Observed altitude of Sun's lower limb	16 °	28 ′		
True altitude of Sun's centre	16 °	39 ′	30 ″	
Sun's true zenith distance	73	20	30	
Sun's declination	13	32	46	
Latitude	59 °	47 ′	44 ″	S

Thursday, 27th April (Day 4)

Noon Position

DR: 59°46′S, 50°48′W

Friday, 28th April (Day 5)

Noon Position

DR: 59°52′S, 50°0′W

Alternative DR: 59°52′S, 50°16′W

Assuming the chronometer is running $1^{m}4^{s}$ (= 16′ longitude) slow from rating at Cape Wild.

Saturday, 29th April (Day 6)

Noon Positions

DR N35°E 85 miles from 59°52′S, 50°16′W:	58°42′S, 48°40′W
OP from time and noon sights:	58°38′S, 50°0′W

Position at time sight		58 °	48 ′ S				50 °	31 ′	30 ″ W
Run to noon N35°E12 miles	D. Lat.		9.8	Dep. 6.9	=	D. Lon.		13	30
Noon position		58 °	38 ′ S				50 °	18 ′	W

(Note: Noon longitude of 50°18′ not transferred to the OP)

Time Sight

Mean time at Greenwich	24^{h}	59^{m}	5^{s}	Sun's true altitude	11 °	21.0 ′	AM	
Equation of Time	+	2	42	Latitude	58	48.0	sec.	0.28565
Apparent time at Greenwich	25	1	47	Polar distance	104	28.0	cosec.	0.01399
				Sum	174	37.0		
Apparent time at ship	21	39	41	Half-sum	87	18.5	cos.	8.67174
Longitude in time	3	22	6 W	Remainder	75	57.5	sin.	9.98683
Longitude	50 °	31 ′	30 ″				hav.	8.95821

Noon Sight

Observed altitude of Sun's lower limb	16 °	43 ′	
True altitude of Sun's centre	16 °	52 ′	30 ″
Sun's true zenith distance	73	7	30
Sun's declination	14	29	45
Latitude	58 °	37 ′	45 ″ S

Distance to Destination

OP 29th April	58° 38′ S		50° 0′ W					
27 miles West of Wallis	54 4		39 0					
D. Lat.	274′	D. Lon.	660′	=	Dep.	365.7	N53°E	457 miles
					Leith Harbour			90
					Total			547 miles

Middle Latitude, M	56° 21′
½ D. Lon.	330
½ Dep., M = 56°	184.5
½ Dep., M = 57°	179.7
Difference	4.8
Interpolation for 20′	1.6
Interpolated ½ Dep.	182.9
Interpolated Dep.	365.8

Traverse **56°** Table

Dist.	D.Lat.	Dep.
.	.	.
.	.	.
.	.	.
330	184.5	-
.	.	.
.	.	.
.	.	.

Traverse **57°** Table

Dist.	D.Lat.	Dep.
.	.	.
.	.	.
.	.	.
330	179.7	-
.	.	.
.	.	.
.	.	.

Reverse look up for ½Distance and Course
½D. Lat. 137.0 ½Dep. 182.9

Traverse **53°** Table

Dist.	D.Lat.	Dep.
.	.	.
.	.	.
227	136.6	181.3
228	137.2	182.1
229	137.8	182.9
.	.	.

Sunday, 30th April (Day 7)

Noon Position

DR N35°E 78 miles from 58°38′S, 50°0′W: 57°34′S, 48°36′W

D. Lat. 63.9 Dep. 44.7 = D. Lon. 85

Monday, 1st May (Day 8)

Noon Position

DR N40°E 30 miles from 57°34′S, 48°36′W: 57°11′S, 48°1′W

D. Lat. 23 Dep. 19.3 = D. Lon. 36

Tuesday, 2nd May (Day 9)

Noon Position

DR N50°E 45 miles from 57°11′S, 48°1′W: 56°42′S, 46°58′W

D. Lat. 28.9 Dep. 34.5 = D. Lon. 63

Wednesday, 3rd May (Day 10)

Noon Position

DR N55°E 85 miles from 56°42′S, 46°58′W: 55°53′S, 44°53′W

D. Lat. 48.8 Dep. 69.6 = D. Lon. 125

OP from time sight: 56°13′S, 45°38′W

Position at time sight	56° 23′ S			45° 50′ 30″ W
Run to noon N33°E12 miles	D. Lat. 10.1	Dep. 6.5	= D. Lon.	12
Noon position	56° 13′ S			45° 38′ W

Time Sight

Chronometer Time	24^{h}	27^{m}	9^{s}						
Chronometer Error	Slow		46^{s}						
Mean time at Greenwich	24^{h}	27^{m}	55^{s}		Sun's true altitude	11°	14.0′	AM	
Equation of Time	+	3	11		Latitude	56	23.0	sec.	0.25678
Apparent time at Greenwich	24	31	6		Polar distance	105	40.0	cosec.	0.01644
					Sum	173	17.0		
Apparent time at ship	21	27	44		Half-sum	86	38.5	cos.	8.76775
Longitude in time	3	3	22	W	Remainder	75	24.5	sin.	9.98576
Longitude	45°	50′	30″					hav.	9.02673

Adjusting longitude 12.5′ E gives 45°38′W

Distance to Destination

OP 3rd May		56° 13′ S		45° 38′ W				
Bird Island		54 0		38 0				
	D. Lat.	133′	D. Lon.	458′ =	Dep.	262	N63°E	294 miles
	½ D. Lat.	66			Leith Harbour			53
					Total			347 miles

Thursday, 4th May (Day 11)

Noon Position

DR N45°E 70 miles from 56°13′S, 45°38′W: 55°23′S, 44°10′W

D. Lat. 49.5 Dep. 49.5 = D. Lon. 88

OP from time sight: 55°31′S, 44°43′W

Day’s Run from 56°13′S, 45°38′W N36°E 52 miles

D. Lat. 42 D. Lon. 55 Dep. 30.8

Position at time sight		55° 34′ S			44° 50′ 15″ W
Run to noon N50°E5 miles	D. Lat.	3.2	Dep. 3.8	= D. Lon.	7
Noon position		55° 31′ S			44° 43′ W

Time Sight

Chronometer Time	25h	6m	26s	Height of Eye	10 ft			
Chronometer Error	Slow	12m	45s	Sun's lower limb	15°	26.5′		
				Altitude correction		9.5′		
Mean time at Greenwich	25h	19m	11s	Sun's true altitude	15°	36.0′	AM	
Equation of Time	+	3	18	Latitude	55	34.0	sec.	0.24761
Apparent time at Greenwich	25	22	29	Polar distance	105	58.0	cosec.	0.01709
				Sum	177	8.0		
Apparent time at ship	22	23	8	Half-sum	88	34.0	cos.	8.39818
Longitude in time	2	59	21 W	Remainder	72	58.0	sin.	9.98052
Longitude	44°	50′	15″				hav.	8.64340

Sextant Preset for Noon Sight

DR Latitude	55°	23′	0″	S
Sun's declination	15	59	16	
Sun's true zenith distance	71	22	16	
True altitude of Sun's centre	18	37	44	
Altitude correction		10	44	
Estimated altitude of Sun's lower limb	18°	27′	0″	

Distance to Destination

OP 4th May	55° 31′ S		44° 43′ W				
Bird Island	54 0		38 0				
D. Lat.	91′	D. Lon.	403′ =	Dep.	233	N69°E	250 miles
					Leith Harbour		53
					Total		303 miles

Friday, 5th May (Day 12)

Noon Position

DR N50°E 95 miles from 55°31′S, 44°43′W: 54°30′S, 42°36′W

D. Lat. 61.1 Dep. 72.8 = D. Lon. 127

Distance to Destination

DR 5th May	54° 30′ S		42° 36′ W				
Bird Island	54 0		38 0		153	N79°E	164 miles
Wallis Island	54 4		38 14				
D. Lat.	26′	D. Lon.	262′ =	Dep.	153	N80°E	155 miles

Saturday, 6th May (Day 13)

Noon Position

DR from 54°30′S, 42°36′W to 1pm: 54°26′S, 40°44′W

N30°E 16 miles	13.9		8.0		
S 80°E 58 miles	10.1		57.1		
D. Lat.	3.8 N	Dep.	65.1 E	D. Lon.	112

Distance to Destination

DR 6th May	54° 26′ S		40° 44′ W				
Wallis Island	54 4		38 14				
D. Lat.	22′	D. Lon.	150′ =	Dep.	88	N76°E	90 miles

Sunday, 7th May (Day 14)

Noon Position

DR from 54°26′S, 40°44′W: 54°23′S, 39°40′W

S60°E 12 miles		6.0 S		10.4 E		
N70°E 28 miles		9.6		26.3		
	D. Lat.	3.6 N	Dep.	36.7 E	D. Lon.	63

OP from time and noon sights: 54°38′S, 39°36′W

Position at P.M. time sight		54° 33′ S				39° 11′ 0″ W
Run from noon N68°E14 miles	D. Lat.	5.2	Dep. 13.0	=	D. Lon.	22
Noon position		54° 38′ S				39° 33′ W

Time Sights

Mean time at Greenwich	25 h	24 m	51 s	Sun's true altitude	16°	55.0′	AM	
Equation of Time	+	3	32	Latitude	54	39.0	sec.	0.23764
Apparent time at Greenwich	25	28	23	Polar distance	106	49.0	cosec.	0.01898
				Sum	178	23.0		
Apparent time at ship	22	48	19	Half-sum	89	11.5	cos.	8.14945
Longitude in time	2	40	4 W	Remainder	72	16.5	sin.	9.97888
Longitude	40°	1′	0″				hav.	8.38495

Mean time at Greenwich	23 h	19 m	38 s	Sun's true altitude	7°	21.0′	AM	
Equation of Time	+	3	32	Latitude	54	41.5	sec.	0.23809
Apparent time at Greenwich	23	23	10	Polar distance	106	47.5	cosec.	0.01892
				Sum	168	50.0		
Apparent time at ship	20	44	22	Half-sum	84	25.0	cos.	8.98808
Longitude in time	2	38	48 W	Remainder	77	4.0	sin.	9.98884
Longitude	39°	42′	0″				hav.	9.23393

Chronometer Time	5^{h}	10^{m}	14^{s}					
Chronometer Error	Slow	13^{m}						
Mean time at Greenwich	5^{h}	23^{m}	14^{s}	Sun's true altitude	9 °	57.0 ′	PM	
Equation of Time	+	3	33	Latitude	54	33.0	sec.	0.23658
Apparent time at Greenwich	5	26	47	Polar distance	106	52.0	cosec.	0.01910
				Sum	171	22.0		
Apparent time at ship	2	50	3	Half-sum	85	41.0	cos.	8.87661
Longitude in time	2	36	44 W	Remainder	75	44.0	sin.	9.98640
Longitude	39 °	11 ′	0 ″				hav.	9.11869
Correction to Noon		22						
Longitude at Noon	39 °	33 ′						

Distance to Destination

OP 7th May	54 °	38 ′ S		39 °	36 ′ W					
Bird Island	54	0		38	0					
D. Lat.		38 ′	D. Lon.		96 ′ =	Dep.	56	N56°E	68	miles
						Leith Harbour			53	
						Total			121	miles

Monday, 8th May (Day 15)

Noon Position

DR N78°E 90 miles from 54°38′S, 39°34′W: 54°19′S, 37°2′W

D. Lat. 18.7 Dep. 88.0 = D. Lon. 151

Saturday, 13th May

Noon Sight

Observed altitude of Sun's lower limb	17 °	17 ′		
Corrections (height of eye 12ft)		9 ′	20 ″	
True altitude of Sun's centre	17 °	26 ′	20 ″	
Sun's true zenith distance	72	33	40	
Sun's declination	18	22	53	
Latitude	54 °	10 ′	47 ″	S

Navigation of the Shackleton Expedition on the Weddell Sea pack ice

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The Imperial Trans-Antarctic Expedition under the leadership of Sir Ernest Shackleton departed South Georgia bound for the Antarctic on 5 December 1914. On 19 January 1915, their ship, *Endurance*, became caught in the pack ice of the Weddell Sea and drifted with it until being crushed, sinking on 21 November. While the Expedition remained in the grip of the ice, observations continued to be made for navigational purposes. Being out of sight of land for a long period meant that there was no easy way to rate the chronometers and their drift caused the estimated longitude to become increasingly uncertain. On 24 June a series of observations of lunar occultations of fixed stars was begun as an absolute way of determining Greenwich Mean Time. These, along with other observations, are recorded in the Expedition's original logbooks that are housed at Canterbury Museum in Christchurch, New Zealand. The logs have been examined and the navigational methods used while on the sea ice are described in detail here. The calculations of a few key pages have been replicated and annotated to act as a glossary to facilitate reading the other entries.

Keywords: celestial navigation, chronometer, dead reckoning, Ernest Shackleton, ex-meridian sight, Frank Worsley, Imperial Trans-Antarctic Expedition, lunar occultation, Reginald James, time sight, Weddell Sea.

Introduction

On 8 August 1914, the Imperial Trans-Antarctic Expedition under the leadership of Sir Ernest Shackleton set sail aboard their vessel *Endurance* from Plymouth, England with the goal of traversing the Antarctic continent from the Weddell to Ross Seas. *Endurance* was under the command of New Zealand-born Captain Frank A Worsley who in subsequent events would prove to be a superlative navigator even under the most adverse of conditions. After making stops at Buenos Aires, Argentina on 26 October and Grytviken whaling station, South Georgia on 5 November, the Expedition encountered pack ice in the Weddell Sea on 7 December and became trapped on 19 January 1915. The *Endurance* began to sustain damage from the pressure of the ice and was abandoned on 27 October before being eventually crushed, sinking on 21 November. The Expedition set up camp on the sea ice, which carried them north until it began to break up within sight of Clarence and Elephant Islands. After a 7 day passage, their three small boats landed on the latter on 15 April 1916.

Navigational records from the Expedition are contained in Worsley's logbooks and loose leaf pages in Canterbury Museum's collection. These have been examined and the navigational methods employed while trapped in, and camped on, the ice are described in detail here.

As the polar night descended, the standard noon sight of the Sun for latitude and time sight for longitude were replaced by meridian and ex-meridian sights for latitude and time sights of stars. The relative stability of the ice meant that observations could be performed by theodolite rather than by sextant. Reginald James, expedition physicist, wrote 'For astronomical

Figure 1. Captain Frank Worsley (left) and Reginald James taking sights from the sea ice by the stern of *Endurance*. Worsley cradles a chronometer or stopwatch and James uses the theodolite to measure the altitude of a star. Scott Polar Research Institute, University of Cambridge, with permission. Photograph by Frank Hurley, 1915. All rights reserved.

observations the sextant or a theodolite was used. The theodolite employed was a light 3" Vernier instrument by Carey Porter intended for sledging work' (Shackleton 1920 Appendix I). James and Worsley are shown making observations in Figure 1.

Accurate time keeping by the careful calibration or rating and maintenance of the ship's chronometers was crucial for finding longitude. Being out of sight of known landmarks for long periods meant that the uncertainty in the chronometer error (CE) grew over time and with it the uncertainty in longitude. In the early twentieth century, prior to the general availability of radio time signals, an uncertainty in the CE anywhere from ½ to 2 seconds per day since the last rating could be expected. From 24 June to 15 September 1915, a series of timings of lunar occultations of fixed stars were undertaken from which the chronometer errors and rates could be reliably determined. The appearance of Mount Percy on Joinville Island in late March 1916 presented new possibilities to confirm the chronometer errors.

In the section entitled 'The Logbook' a few of the key recorded events have been extracted. 'Navigation from *Endurance* in the Pack Ice' explains how ex-meridian and time sights of stars were used during the Antarctic winter to determine position. The section 'Longitude by Occultation of a Fixed Star' examines the timings that were made and traces the background of the methods used to reduce them. In this and the previous sections log entries on some selected dates are closely examined and replicated. 'Navigation at Ocean and Patience Camps' principally describes the efforts at position finding using Mount Percy on Joinville Island. 'The Chronometers' collects what information is available concerning the ship's chronometers and their rating process. The log entries pertaining to the passage from the icepack to Elephant Island have been transcribed and replicated in Appendix A.

A transcription and replication of the log entries that relate to the famous voyage of the *James Caird* from Elephant Island to South Georgia can be found in Bergman et al. (2018).

While the Shackleton Expedition constitutes an epic tale of Antarctic survival, the present work focuses primarily on the log book entries and technical details of the navigational methods that were used. Comprehensive accounts covering the events of the Expedition as a whole can be found elsewhere (Shackleton 1920; Worsley 1998; Alexander 2001; Lansing 2014).

The Logbook

Logbook entries follow the common standard of recording noon sights for latitude and time sights for longitude which were advanced or retarded to local noon by Dead Reckoning (DR) to give the ship's observed position at noon (Bergman et al. 2018). Weather conditions, sounding data and noteworthy events are also recorded. The log entries for 21 June, 26 July (Worsley 1915: 129, 166) and 3 October 1915 (Worsley 1916: 30) appear to show attempts to obtain lines of position using what then was known as the 'new navigation'. The graphical solutions are found on the following pages.

Entrapment in the Ice and the loss of *Endurance*

The log entry for 19 January 1915 (Worsley 1915: 64) contains the ominous words "Fast in pack", which is repeated daily until 2 February, when it becomes "F. in P." (Worsley 1915: 66) and is eventually omitted completely.

In late October 1915 (Worsley 1916: 36, 38), the following events are recorded and included an illustration of the *Endurance* trapped in ice (Fig. 2) on the entry dated 24 October 1915 and a table that recorded course and distance to possible destinations (Table 1):

> *24th [October, 1915] Strong SSE to SE breeze Cloudy & Misty*
> *6.45PM Ship sustained heavy pressure thru having got pushed into a bad angle of floes & pressure ridges which then moved in direction of arrows twisting sternpost*

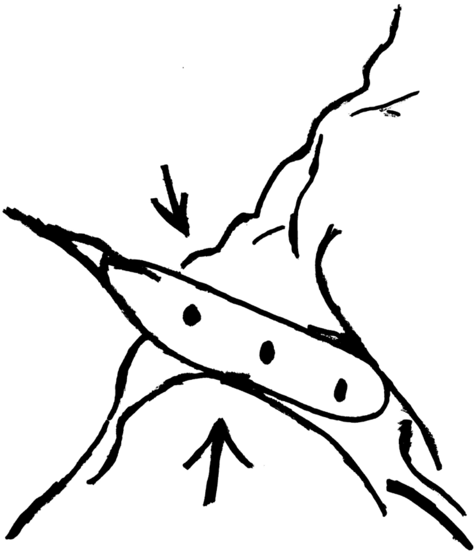


Figure 2. Copy of Worsley's sketch of *Endurance's* position in the ice pack from the log entry of 24 October, 1915.

against floe on star. quarter, starting hidden ends of planking & making ship leak badly. Rigged main pumps, got up steam & started bilge pump at 8PM. All hands watch & watch pumping ship & assistg Carp make coffer dam all night

Monday 25th
Strong SE breeze Cloudy & Misty Carp working day & night on coffer dam

Tuesday 26th Oct
7PM Very heavy pressure with twistg strain, rackg ship & openg butts of planks 3" & 4" star^{d} side 9P Lowered boats gear sledges & provisions on floe. Midnight working on floes closed leak slightly. All hands pumping all night
Mod to gentle S/W to SSW breeze Blue sky and clouds
Temper^{ture} 0 –to –15°

Wednesday 27th Oct
Gentle SSE to SSW breeze
4P Terrific pressure heaving stern up 9 feet smashing rudder, rudder post & stern post. Decks breaking up 7P. Ship too dangerous to live in we are forced to abandon her. Water overmastering pumps & coming up to fires draw fires & let down steam
Men & dogs sleep on floe.
S Lat W Long
Landed on Floe 69°5' 51° 32' 27. X.15

Later in the log book, Worsley (1916: 45) wrote:

Sunday Nov.^{r} 21st
1915 68°39'30" 52°26'30"
Endurance sank after drifting in 306 days
N38°E 605 miles
Total dist^{s} added together between Obs Pos^{ns}
= 1250 miles

Endurance				69 °	5 ′ S	51 °	32 ′ W
Paulet	N 17° W	346	miles	63 °	35 ′ S	55	52 ′ W
Snow H	N 25° W	312	"	64	22	57	6
Weather I	N 55° W	272	"	66	29	61	21
C Dundas Laurie I.S.O.	N 20° E	534	"	60	43	44	22
Estim^{d} W to Barrier	West	182	"	69	5	60	2
Thence to Snow Hill	N 14° E	292	"				

Table 1. From the log entry of 27 October, 1915: course and distance to possible destinations from the location of *Endurance* when she was abandoned. Latitudes and longitudes as known to Worsley appear to the right.

Navigation from *Endurance* in the Pack Ice

When *Endurance* became trapped "fast in pack", navigational practice continued largely as before with noon sights and time sights of the Sun being taken for position. As the polar winter approached the Sun sank lower in the sky until its true altitude could no longer be reliably determined. A last Sun sight was recorded on 11 April 1915, but from then until 28 August, except for a Jupiter sight on 19 April, celestial navigation was entirely conducted using stars. This requires the calculation of sidereal time but their use is otherwise closely analogous to noon sights for latitude and time sights of the Sun for longitude. Circumpolar stars introduce the possibility of observing lower meridian transits below the pole. Catching a star exactly at meridian passage can be challenging. Lecky (1918: Part II, Chapter VIII) advises that "to watch for the transit of a star on a dark night requires no little patience, and it has a decidedly fatiguing effect on the eye". He points out that "From the slowness of their motion in altitude, it follows that the stars near either pole are the best adapted for this observation". These are known as 'ex-meridian sights'. The altitude of a celestial body is observed near to transit and, knowing the declination, hour angle and an approximate latitude, a correction is calculated to determine its altitude at meridian passage. Since the correction is small a high degree of accuracy is not required in computing it.

A final round of sights Rigel - λ Scorpii for longitude were made on 15 October 1915, but from then on they were again made exclusively by the Sun.

As noted previously, many of the sights were taken with the theodolite that, unlike the sextant, is free from the requirement of reliably identifying the horizon. Sights made at very low temperatures, however, present special difficulties. James (Shackleton 1920: Appendix 1) wrote:

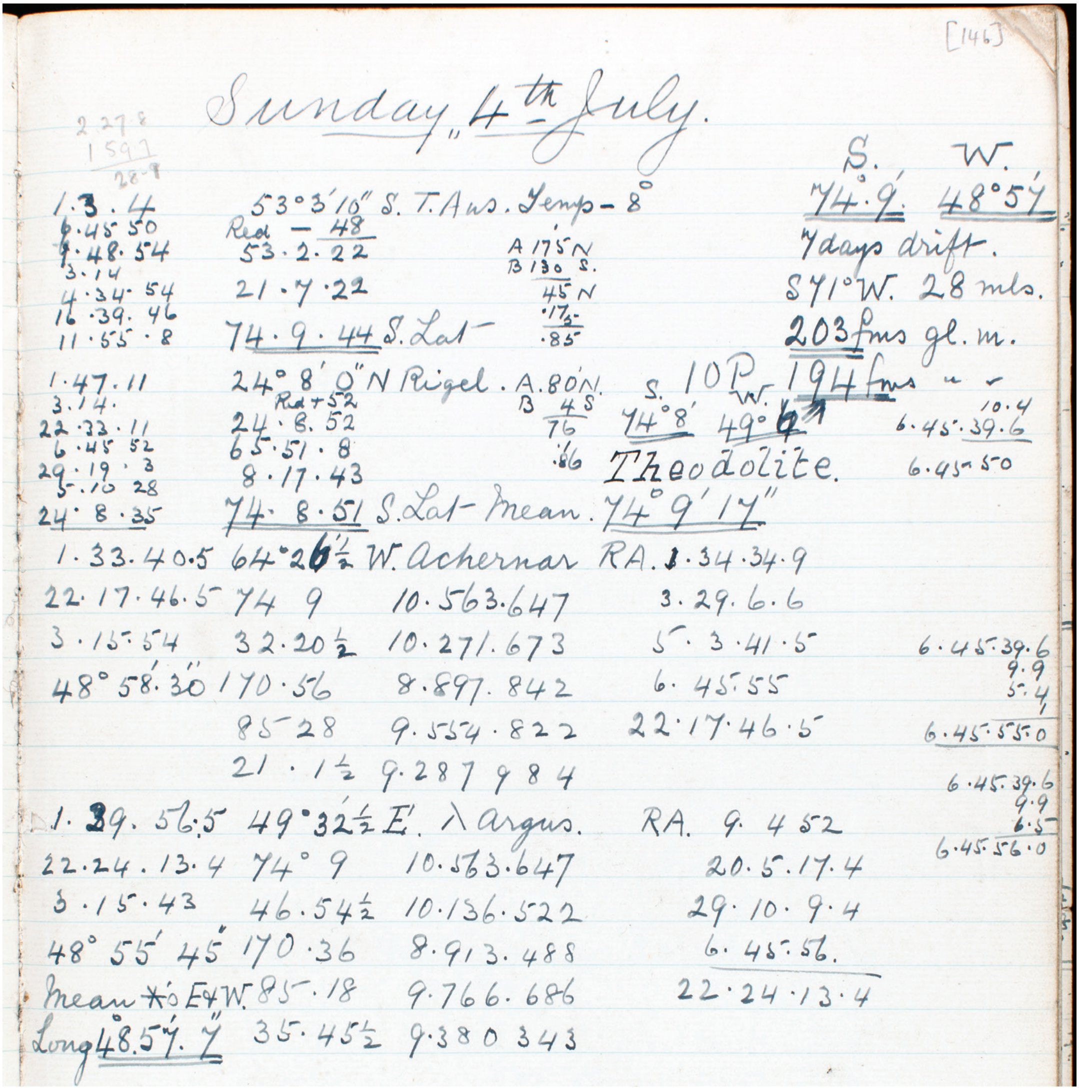
> *The chief uncertainty in this measurement is that introduced by the refraction of light by air. At very low temperatures, the correction to be applied on this account is uncertain, and, if possible, observations should always be made in pairs with a north star and a south star for latitude, and an east star and a west star for longitude. The refraction error will then usually mean out.*

On 15 September, the log (Worsley 1916: 17) contains the note:

> *all sextant & theodolite observations … refraction has been corrected by Table IV "Hints to Travellers" [Corrections of the Mean Refraction for the Height of the Thermometer]. This correction proving in [pract]ice far too small has been multiplied by 3 & inter.…*

Figure 3 shows the log entry for 4 July 1915, which is fairly typical for the period. It records the temperature as being -8° Fahrenheit (-22℃) and position obtained from the recorded observations as being "74°9'S 48°57'W". The double underline is used throughout the log to denote a final observed position and distinguishes it from intermediate calculations. A single underline denotes a position found by Dead Reckoning. The drift of S 71° W 28 nautical miles (52 km) is computed for 7 days since the last fully observed position was obtained on 27 June. On the intervening days, the position is estimated by single latitude sights on 28 June and 3 July and otherwise by Dead Reckoning. Sounding data is recorded as "203fms gl.m." indicating depth of 203 fathoms (371 m) and a bottom composed of glacial mud[1].

The direction of drift was estimated (Shackleton 1920: Appendix 1) using a device constructed by Worsley that consisted of a vane at the end of an iron rod passing through a tube in the ice into the sea below. The speed of the drift could be estimated by noting how quickly the vane returned to its original position when displaced. The speed and direction of drift could also be estimated by noting the trend of the wire when a sounding was taken. The log contains a diagram (Worsley 1915: 77) in which this is carried out.



[146]

Sunday, 4th July.

2.27.8
1591
28.9

S. W.
1.3.4 53°3′10″ S. T.Aus. Temp − 8° 74.9. 48°57
6.45 50 Red − 48 7 days drift.
9.48.54 53.2.22 A 175 N
3.14 B 130 S.
4.34.54 21.7.22 45 N S71°W. 28 mls.
16.39.46 .17½
11.55.8 74.9.44 S. Lat .85 203 fms gl. m.
1.47.11 24°8′0″N Rigel. A. 80 N. S. 10P W. 194 fms " "
3.14. Red + 52 B 4 S 10.4
22.33.11 24.8.52 76 74°8′ 49°6 6.45.39.6
6.45 52 65.51.8 .86 Theodolite. 6.45.50
29.19.3
5.10 28 8.17.43
24.8.35 74.8.51 S. Lat - Mean. 74°9′17″
1.33.40.5 64°26½ W. Achernar RA. 1.34.34.9
22.17.46.5 74 9 10.563.647 3.29.6.6
3.15.54 32.20½ 10.271.673 5.3.41.5 6.45.39.6
48°58′30″ 170.56 8.897.842 6.45.55 9.9
85 28 9.554.822 22.17.46.5 5.4
6.45.55.0
21.1½ 9.287984
6.45.39.6
1.39.56.5 49°32½′ E. λ Argus. RA. 9.4 52 9.9
6.5
6.45.56.0
22.24.13.4 74° 9 10.563.647 20.5.17.4
3.15.43 46.54½ 10.136.522 29.10.9.4
48°55′45″ 170.36 8.913.488 6.45.56.
Mean ✱'s E & W. 85.18 9.766.686 22.24.13.4
Long 48°57′7″ 35.45½ 9.380343

Figure 3. Log book entry for 4 July 1915 (Worsley 1915: 146) showing temperature, position, estimated drift and sounding data. Averaged ex-meridian sights of the stars α Trianguli Australis and Rigel determine latitude and averaged time sights of Achernar and λ Argûs (λ Velorum) provide longitude. Canterbury Museum 2001.177.1, page 146

Navigational Stars in the *Nautical Almanac*

In 1915, *The Nautical Almanac and Astronomical Ephemeris* (Nautical Almanac 1915) looked very different to the *Nautical Almanac* as it is known to practitioners of celestial navigation today. Tables were indexed with astronomical time with 0^h occurring at Greenwich Mean Noon on the day in question. The names of the brighter navigational stars are generally recognisable except for those in the defunct constellation of Argo Navis, which was officially split into Carina, Puppis and Vela by the International Astronomical Union (IAU) in 1930. In making the split, the original Greek letter designations from Argo were retained and not reallocated within the new constellations. For example, the second magnitude star λ Argûs today bears the designation λ Velorum (Suhail). Identifiers for fainter stars are selected from a hierarchy of catalogues and a large number bear the designation BAC, followed by a number of up to four digits. This refers to the British Association for the Advancement of Science Catalogue (British Association for the Advancement of Science 1845). The abbreviation B.D. refers to the Bonner Durchmusterung.

Sidereal Time

Local Sidereal Time (LST) is specified by the hour circle lying on the observer's meridian. Greenwich Sidereal Time (GST) is tabulated in the *Nautical Almanac* for Greenwich Mean Noon (0h) on each day of the year. GST advances at a rate of 9.8565 seconds per hour against Greenwich Mean Time (GMT), which is known as acceleration. At any given moment, GST − GMT = GST_0 + acceleration × GMT, where GST_0 is the tabulated value at the prior noon.

Ex-Meridian Sights for Latitude

If an object with declination, δ, is determined to have true altitude, h, at upper meridian transit, then the observer's latitude is $\phi = \mathrm{ZD} + \delta$ where $\mathrm{ZD} = 90° - h$ is the zenith distance. For a circumpolar object at lower meridian transit the observer's latitude is $\phi = h + \mathrm{p.d.}$ in which $\mathrm{p.d.} = 90° - \delta$ is the polar distance.

The Shackleton Expedition undertook ex-meridian sights of stars to determine their latitude. Dedicated tables, for example Brent et al. (1914), were available for this purpose but the Expedition instead used ABC tables, an example of which can be found in Lecky (1918: Part II Chapter IX). These were primarily designed to facilitate the computation of the azimuth of a body as might be required to determine the error in the ship's compass but they could be pressed into service to aid in the reduction of ex-meridian sights as well.

The azimuth of a body, Z_n, measured eastward from north is given by

$$\tan Z_n = \frac{-\sin t}{\cos\phi\tan\delta - \sin\phi\cos t}$$

where t and δ are the object's local hour angle and declination respectively and ϕ is the observer's latitude. Respecting the signs of the numerator and denominator of the right hand side ensures that the result for Z_n lies in the correct quadrant. ABC tables are constructed by defining

$$A = \frac{\tan\phi}{\tan t}; \quad B = \frac{\tan\delta}{\sin t}; \quad C = A + B \qquad (1)$$

and

$$\tan Z = \frac{1}{C\cos\phi}$$

Following nautical practice, rules are provided that assign names, N or S, or signs, + or −, to the quantities A, B, C and how to relate Z to Z_n. When t is near 0° or 180°

$$\frac{1}{C} = \cos\phi\tan Z \approx \cos\phi\sin Z = \left.\frac{dh}{dt}\right|_Z$$

where h is the object's true altitude with all quantities being taken to be positive. Let Δt be the difference of the local hour angle from the meridian of transit and Δh be the correction to be added to (subtracted from) h for upper (lower) transit. Assuming the ex-meridian altitude correction takes the quadratic form, $\Delta h = a \times (\Delta t)^2$, for some constant, a, then it is a simple matter to show that

$$\Delta h = \frac{1}{2}\left.\frac{dh}{dt}\right|_Z \Delta t$$

If Δt is given in units of time then Δh in arc is $\Delta h = (7.5/C) \times \Delta t$. The rules for combining A and B follow from the algebraic properties of equation (1) and imply that for circumpolar stars they should be added together for lower meridian transits and subtracted for upper transits. For all ex-meridian sights found in the log book, A is almost always assigned the name "N", B the name "S" and the two are subtracted one from the other. For most lower transits this biases the observed latitude to the north. When averaged between upper and lower transits the error in latitude is overall less than a nautical mile and generally much smaller.

Table 2 replicates the reduction of the ex-meridian sights of αTrianguli Australis and Rigel for latitude on 4 July 1915 using the altitude, Greenwich Mean Time and declination taken from the log. No great precision is required in the ex-meridian adjustment and it is clear that no great care was taken. In the log an error is made in the GST of the Rigel reduction and the *A* and *B* values are not the same as those shown here. Nevertheless the final result differs by only 20" or a third of a nautical mile.

Time Sights for Longitude

Longitude is found by comparing the observer's Local Mean Time (LMT) to GMT as read from a chronometer. A time sight measures the altitude or zenith distance of a celestial body sufficiently far off the meridian and from which its local hour angle (LHA) can be calculated. For a star at right ascension, R.A., the local sidereal time is then LST = LHA + R.A. The difference (GST − GMT) can be obtained by consulting tables in the *Nautical Almanac* as described previously and LMT = LST − (GST − GMT).

Table 3 shows the reduction of time sights of Achernar to the west and λ Argûs (λ Velorum) to the east replicated using values found in the log. The layout and labelling closely follows that described in Bergman et al. (2018) to which the reader is referred for details.

S. α Trianguli Australis (Below Pole)

Mean time at Greenwich	1^{h}	3^{m}	4^{s}	Altitude	53 °	3 ′	10 ″	A	167 N
GST - GMT	6	45	50	Reduction		−	9 ″	B	122 N
GST	7	48	54	Meridian altitude	53	3	1	C	289 N
Longitude in time	3	14		Polar Distance	21	7	22	7.5/C	0.03
LST	4	34	54	Latitude	74 °	10 ′	23 ″ S.	Δ*t*	5^{m}
Right Ascension	16	39	46					Reduction	0.15 ′
Local Hour Angle	11	55	8					=	9 ″
				GST at Noon	6^{h}	45^{m}	39.6^{s}		
				acceleration			10.4		
				GST – GMT	6	45	50		

N. Rigel

Mean time at Greenwich	1^{h}	47^{m}	11^{s}	Altitude	24 °	8 ′	0 ″	A	94 N
GST - GMT	6	45	57	Reduction		+	52 ″	B	4 S
GST	8	33	8	Meridian altitude	24	8	52	C	90 N
Longitude in time	3	14		Meridian ZD	65	51	8	7.5/C	0.1
LST	5	19	8	Declination	8	17	43	Δ*t*	8.7^{m}
Right Ascension	5	10	28	Latitude	74 °	8 ′	51 ″ S.	Reduction	0.87 ′
Local Hour Angle	24	8	40					=	52 ″
				GST at Noon	6^{h}	45^{m}	39.6^{s}		
				acceleration			17.6		
				GST – GMT	6	45	57.2		

Mean ✶'s N &S. 74 ° 9 ′ 37 ″ S.

Table 2. Reduction of ex-meridian sights of α Trianguli Australis and Rigel for latitude on 4 July 1915. The results are averaged to mitigate uncertainties in refraction.

W. Achernar													
Mean time at Greenwich	1^{h}	33^{m}	41^{s}	Altitude	64°	26.5′	AM		R.A.		1^{h}	34^{m}	34.9^{s}
Mean time at ship	22	17	46.5	Latitude	74	9.0	sec.	0.563647	LHA		3	29	6.6
Longitude in time	3	15	54	Polar distance	32	20.5	cosec.	0.271673	LST		5	3	41.5
Longitude	48°	58′	30″	Sum	170	56.0			GST – GMT		6	45	55.0
				Half-sum	85	28.0	cos.	8.897842	LMT		22	17	46.5
				Remainder	21	1.5	sin.	9.554822					
							hav.	9.287984					
									GST at Noon		6^{h}	45^{m}	39.6^{s}
										1 h			9.9^{s}
									acceleration	33 m			5.4^{s}
										40.5s			0.1^{s}
									GST – GMT		6^{h}	45^{m}	55.0^{s}
E. λ Argûs													
Mean time at Greenwich	1^{h}	39^{m}	57^{s}	Altitude	49°	32.5′	AM		R.A.		9^{h}	4^{m}	52.0^{s}
Mean time at ship	22	24	13.3	Latitude	74	9.0	sec.	0.563647	LHA		20	5	17.4
Longitude in time	3	15	43	Polar distance	46	54.5	cosec.	0.136522	LST		29	10	9.4
Longitude	48°	55′	45″	Sum	170	36.0			GST – GMT		6	45	56.1
				Half-sum	85	18.0	cos.	8.913488	LMT		22	24	13.3
				Remainder	35	45.5	sin.	9.766686					
							hav.	9.380343					
Mean ✶'s E &W.	48°	57′	7″						GST at Noon		6^{h}	45^{m}	39.6^{s}
										1 h			9.9^{s}
									acceleration	39 m			6.4^{s}
										56.5s			0.2^{s}
									GST – GMT		6^{h}	45^{m}	56.1^{s}

Table 3. Reduction time sights of Achernar and λ Argûs (λ Velorum) for longitude on 4 July 1915. The results are averaged to mitigate uncertainties in refraction.

Longitude by Occultation of a Fixed Star

As recounted by Reginald James (Shackleton 1920: Appendix 1):

> *During the voyage of the Endurance about fifteen months elapsed during which no check on the chronometers could be obtained by the observation of known land, and had no other check been applied, there would have been the probability of large errors in the longitudes…. In the summer, however, the [occultation] method is quite impossible since, for some months, stars are not to be seen.*
>
> *No chronometer check could be applied until June, 1915.*

In the depths of the polar night and a few days after the winter solstice, the first such occultation timing was made on 24 June of the star 42 Libræ followed by three others on the same astronomical date. These were averaged to rate the Mercer chronometer, No. 5229.

For a position of known latitude, noting the local mean time (LMT) or local sidereal time (LST) of immersion or emersion in an occultation allows the GMT or equivalently longitude to be found.

A few methods are available for this. Bessel's method projects the positions of the observer and Moon orthographically onto the so-called fundamental plane passing through the Earth's centre and with its normal in the direction of the star. This is effectively the viewpoint of an observer located on the star. The calculation is eased by the Besselian elements, T_0, q_0, p' and q' tabulated in the *Nautical Almanac* which incorporate all necessary information related to the Moon's horizontal parallax (HP) and semi-diameter. This approach results in a quadratic equation that can be solved by means of some judicious trigonometric substitutions (Chauvenet 1863: 550).

Raper's Method

The Expedition used a method detailed by Close (1905), which comes from the Royal Geographical Society's publication, *Hints to Travellers* (Godwin-Austen et al. 1883) and is attributed to Raper (1840). By accounting for the effect of parallax, the geocentric right ascension of the Moon can be determined at the moment

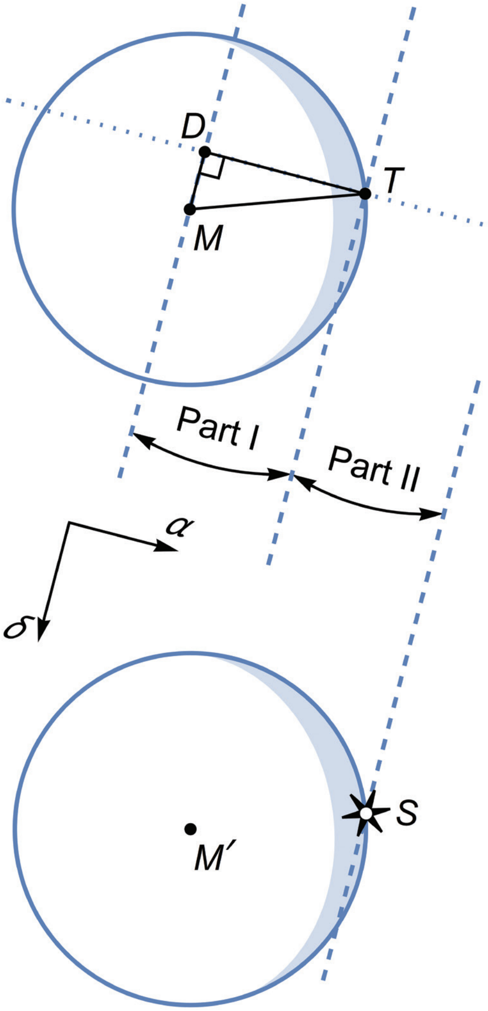


Figure 4. The occultation of 42 Libræ on 24 June 1916. The lower circle centred on M' represents the Moon as seen by the Shackleton Expedition in the Weddell Sea and the upper circle represents the view of a geocentric observer. The star disappears at the point S on the Moon's limb which corresponds to point T for the geocentric observer. Directions of increasing right ascension and declination are indicated by the axes labelled α and δ. The dashed lines are hour circles and the dotted line indicates the diurnal circle of constant declination passing through the point T.

the occultation occurs. Comparing this with tables of the Moon's position in the *Nautical Almanac* gives GMT.

Figure 4 depicts the occultation of 42 Libræ as it was observed from the Weddell Sea at $4^{h}44^{m}$ GMT in astronomical time or $16^{h}44^{m}$ civil time on 24 June 1915. At a faint magnitude of 5.1, 42 Libræ stood SE by E around 15° above the horizon before blinking out behind the dark limb of a waxing gibbous Moon two and a half days from full. The circle centred on the point M' represents the Moon's apparent position as seen by the Expedition with the point on its limb where the star disappeared labelled S. The axes labelled α and δ show the directions of increasing right ascension and (northerly) declination respectively. The upper circle centred on the point M is the Moon's disk as it would appear to a geocentric observer displaced by parallax toward the geocentric zenith. For such an observer, the position of the star is unchanged due to its great distance from Earth, and the point S on the Moon's limb now lies nearly vertically above at the point labelled T. The declination of T is the Prepared Declination. The dashed lines are hour circles of right ascension passing through S, T and M that converge to meet at the poles. The dotted line is the diurnal circle of constant declination passing through T. The angle subtended at the pole by the arc labelled Part II is the parallax in right ascension. Part I in the diagram subtends the difference in right ascension of the Moon's centre and the point T. The distance MT is the Moon's geocentric semi-diameter.

Starting from the star's R.A., Part I and Part II allow the geocentric R.A. of the Moon's centre to be computed at the time of immersion and hence GMT to be determined.

For the calculation of parallax, the relative positions of the Earth, Moon and observer need to be specified in 3-dimensional space taking account of the oblateness of the Earth. As is explained in standard texts (Smart 1948) the observer's position is specified in terms of the geocentric distance, ρ, and geocentric latitude, ϕ'. The latter differs from the astronomical latitude, ϕ, measured in celestial navigation. If a is the Earth's equatorial radius and r is the Moon's geocentric distance, then the equatorial horizontal parallax, HP, is defined as $\sin \mathrm{HP} = a/r$. Since $\rho/r = (\rho/a)\sin \mathrm{HP}$ it is intuitively plausible, and can be shown rigorously, that the impact of the observer's geocentric distance can be absorbed into a reduced or local horizontal parallax, HP$'$, satisfying the condition $\sin\mathrm{HP}' = (\rho/a)\sin \mathrm{HP}$.

Let t' and δ' denote respectively the apparent local hour angle and declination of a point S on the Moon's face as seen by an observer on the Earth's surface. It is required to compute the true hour angle, t, and declination, δ, of that point, displaced by parallax and labelled point T, as it would be seen by a geocentric observer. A derivation of the following exact formulas can be found, for example, in Loomis (1855)

$$\sin\left(t'-t\right)=\sin\mathrm{HP}'\frac{\cos\phi'\sin t'}{\cos\delta} \tag{2}$$

$$\begin{aligned}\sin\left(\delta-\delta'\right)&=\sin\mathrm{HP}'\sin\phi'\cos\delta'\\&\quad-\sin\mathrm{HP}'\cos\phi'\sin\delta'\frac{\cos\frac{1}{2}\left(t'+t\right)}{\cos\frac{1}{2}\left(t'-t\right)}\end{aligned} \tag{3}$$

Writing $\frac{1}{2}(t'+t)=t'-\frac{1}{2}(t'-t)$ leads to

$$\begin{aligned}\sin\left(\delta-\delta'\right)&=\sin\mathrm{HP}'\sin\phi'\cos\delta'\\&\quad-\sin\mathrm{HP}'\cos\phi'\sin\delta'\cos t'\\&\quad-\sin\mathrm{HP}'\cos\phi'\sin\delta'\sin t'\frac{\sin\frac{1}{2}\left(t'-t\right)}{\cos\frac{1}{2}\left(t'-t\right)}\end{aligned} \tag{4}$$

With $\cos\frac{1}{2}(t'-t)\approx 1$ and $\sin\frac{1}{2}(t'-t)\approx\frac{1}{2}\sin(t'-t)$, equation (4) can be used to obtain

$$\begin{aligned}\sin\left(\delta-\delta'\right)&=\sin\mathrm{HP}'\sin\phi'\cos\delta'\\&\quad-\sin\mathrm{HP}'\cos\phi'\sin\delta'\cos t'\\&\quad-\frac{1}{2}\left(\sin\mathrm{HP}'\cos\phi'\sin t'\right)^{2}\frac{\sin\delta'}{\cos\delta}\end{aligned} \tag{5}$$

In the approximation that $\sin\theta\approx\theta$ for small θ and $\sin\delta'/\cos\delta\approx\tan\delta'$, expressed in degrees equation (5) becomes

$$\begin{aligned}\delta = \delta' &+ \mathrm{HP}'\sin\phi'\cos\delta' \\ &- \mathrm{HP}'\cos\phi'\sin\delta'\cos t' \\ &- \frac{1}{2}\left(\mathrm{HP}'\cos\phi'\sin t'\right)^2 \tan\delta' \frac{\pi}{180}\end{aligned} \tag{6}$$

As noted earlier declination of the point *T*, δ, is called the prepared declination and is obtained by means of equation (6).

If α' is the right ascension of point *S* then, to sufficient accuracy, by equation (2) the right ascension, α, of the point *T* in degrees is

$$\alpha = \alpha' + \mathrm{HP}'\frac{\cos\phi'\sin t'}{\cos\delta} = \alpha' + \text{Part II} \tag{7}$$

where Part II is the parallax in right ascension.

Let $\alpha_{☽}$, $\delta_{☽}$ and SD denote the Moon's geocentric R.A., declination and semi-diameter respectively. In Figure 4, the right triangle *MDT* is small enough that it can be adequately treated using plane trigonometry and hence $(DT)^2 = (MT)^2 - (DM)^2 = SD^2 - (\delta - \delta_{☽})^2$. The difference in R.A. between the points *D* and *T* is then

$$\text{Part I} = \frac{\sqrt{\left(\mathrm{SD} - \delta + \delta_{☽}\right)\left(\mathrm{SD} + \delta - \delta_{☽}\right)}}{\cos\delta} \tag{8}$$

The geocentric R.A. of the Moon at the moment the occultation occurs is then

$$\alpha_{☽} = \alpha' \pm \text{Part I} + \text{Part II} \tag{9}$$

where the upper (lower) sign applies for emersion (immersion). In the 1915 *British Nautical Almanac* (Nautical Almanac 1915), the Moon's geocentric position is tabulated at hourly intervals and the time at which the GMT corresponding to $\alpha_{☽}$ is computed by simple interpolation. If α_0 is the tabulated value of the Moon's R.A. at the hour t_0 preceding the occultation and α_1 is its R.A. on the hour following then required time is

$$\mathrm{GMT} = t_0 + \frac{\left(\alpha_{☽} - \alpha_0\right)}{\left(\alpha_1 - \alpha_0\right)} = t_0 + x \tag{10}$$

The foregoing equations are algebraically fully correct but in traditional navigational practice quantities are generally considered to be positive. Rules are given as to when to add or subtract terms based on conditions, such as whether certain dependent variables have the same or contrary name, i.e. the same or opposite sign. In the case of equation (6) the three last terms on the right hand side are labelled Arc A, Arc B and Arc C respectively and are combined with δ' to obtain the geocentric declination of point *T*, δ.

Raper (1840) describes, without derivation, the procedures to be followed to obtain the geocentric declination:

> *(4.) When the lat. and decl. are of the same name, add* ***A*** *to the star's decl. ; when of contrary names, subtract it.*
>
> *When the star's hour-angle is less than* 6^h*, subtract* ***B*** *from the star's decl. ; when greater than* 6^h*, add it.*
>
> *Subtract* ***C*** *from* ***A****.*
>
> *Call the result the prepared declination.*

The rules are deduced from the algebraic properties of equation (6). In the example included by Raper, it is more or less clear that his intended meaning for the last rule would be better stated as simply 'Subtract ***C***'. *Hints to Traveller's* (Godwin-Austen et al. 1883) first gives an example of finding longitude by the occultation of a fixed star using "Raper's rule and tables" in which the difference (***A***–***C***) is computed first and then added to or subtracted from δ' according to the rule for ***A*** alone. Reeves (1904) derives equation (6) but does not correct the rule for Arc C which continues unchanged in *Hints to Traveller's* under his editorship (Reeves 1906). The value of Arc C is generally small but in principle could be as large as 17". Incorrect results are produced only for the case when declination and latitude have contrary names. The Shackleton Expedition inherited this erroneous methodology through Close (1905). Although the Moon spends half of its time in the northern hemisphere and half in the southern, the local circumstances of an occultation are more favourable for an observer in the polar regions when latitude and declination have the same name and hence the error does not manifest itself.

Proportional Logarithms

In his description of the calculation, Raper employs common logarithms for trigonometric functions and proportional logarithms or prologs for other quantities. These were originally introduced by Maskelyne (1781) as a means of simplifying the interpolation computing Greenwich time from lunar distances. The *Nautical Almanac* tabulated geocentric lunar distances at three hour intervals and for an argument in hours or degrees, the ternary proportional logarithm is defined as $\text{Prolog}(x)=\log_{10}(3/x)$. Their use here, however, offers no clear advantage over common logarithms and requires that trigonometric functions be replaced by their reciprocals.

The calculations demonstrated in *Hints to Traveller's* (Godwin-Austen et al. 1883) use four-figure logarithms, which continues up to and including the eighth edition. Both Reeves (1906) and Close (1905) give examples using five-figure logarithms but truncate the constants that enter at four digits. These truncated constants are inherited by the Expedition.

Lunar Occultations of 24 June 1915

Figures 5a and 5b show the pages where the reduction of the occultation of 42 Libræ is performed. This is the first occultation and the steps are carefully labelled.

An initial reduction of the occultation is not recorded. It changes the CE of the Mercer (5229) chronometer from $6^m\ 24^s$ fast of GMT, as entered in the log prior to the occultation, to $1^m\ 38^s$ fast. This result is used as input to the second reduction, which is seen in the log and gives a CE of $2^m\ 2.8^s$ fast. It is followed by a note "reworked with $2^m3^s = 2^m0^s.4$" indicating that a third iteration was performed.

Timings and reductions of three additional occultations were made with the CE and longitude obtained from that of 42 Libræ being used as a starting point for these subsequent reductions.

The table in the bottom of Figure 5a indicates that at least on this occasion Worsley and James worked independently on reducing the occultations. The values in the column labelled "by Capt W." are the same ones found later in the log, leaving no doubt who had carried them out. The final CE of $2^m\ 1.7^s$ fast is the average over all observations and becomes the chronometer's new working error.

Due to the limited rate of change of the Moon's right ascension, the chronometer error can in this case only be determined to a precision of ¼ second, in worst cases no better than ⅓ second. Thus the use of two decimals is unnecessary.

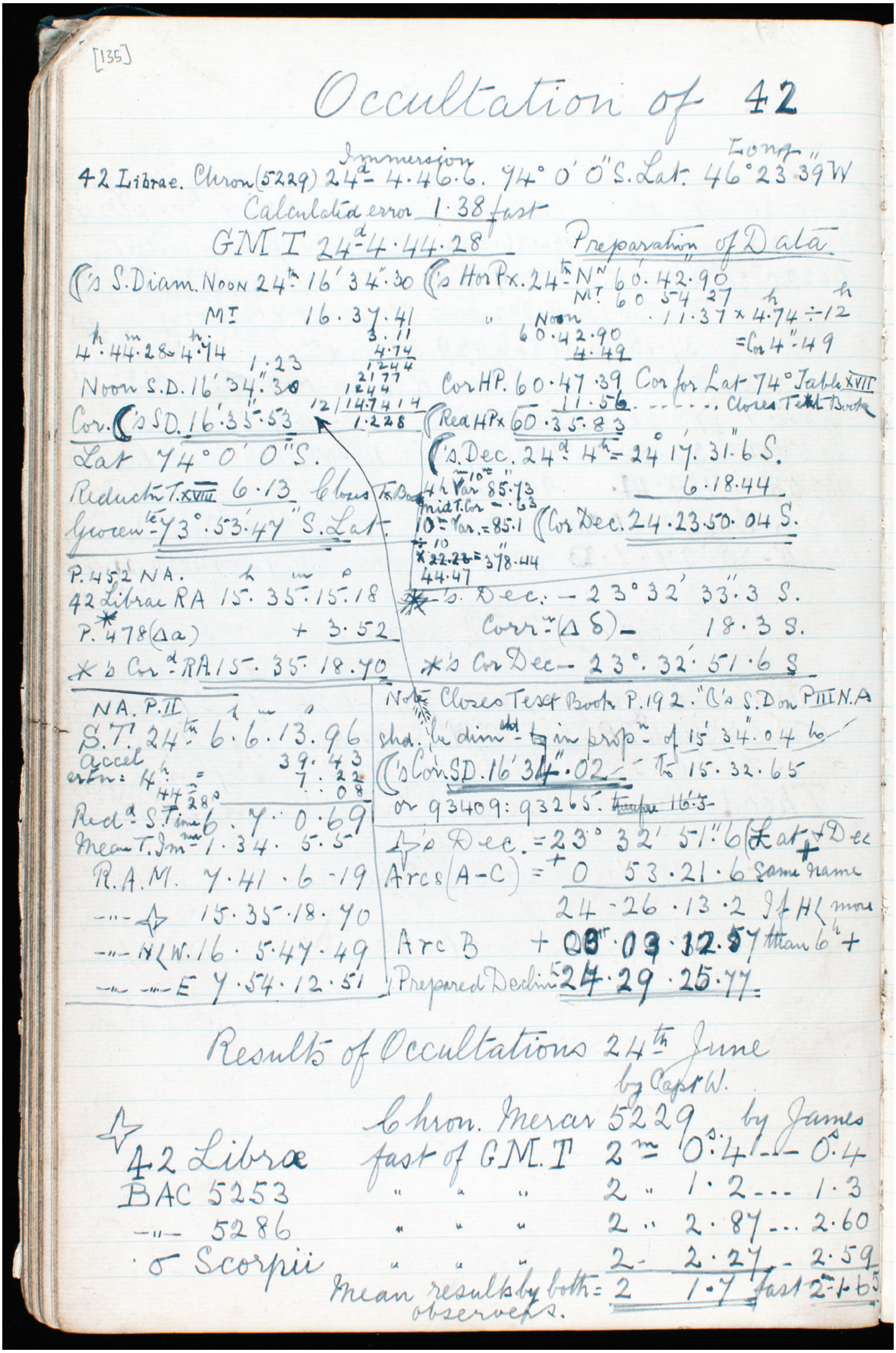
The difference between $6^m\ 24^s$ and $2^m\ 1.7^s$ is $4^m\ 22^s$, corresponding to a longitude shift of 1°5'30" to westward, or 18 nautical miles (33 km) in departure. This is the "error in longitude of a whole degree" described by James (Shackleton 1920: Appendix 1).

Considering the last reliable rating was made 242 days earlier, the error in longitude is actually remarkably small.

In principle the LMT used in the reduction of an occultation should be corrected for changes in the observer's longitude since the time sight was made. However, owing to the speed at which the Moon's shadow sweeps across the Earth's surface, the GMT determined from the occultation is relatively insensitive to the exact value of LMT that is input. For example, in the reduction of the 42 Libræ, an error of 1 nautical mile in the estimated east-west position at these latitudes corresponds to a 15 second error in LMT, but leads to only a 1 second error in the value of GMT obtained.

Table 4a replicates the data preparation recorded in the log for the second iteration using input values found in the log and following Close (1905). It consists of computing geocentric latitude and interpolating the tabulated values of the Moon's R.A., declination, HP and semi-diameter at the time of the occultation. Corrections are applied to the mean position of the star to account for precession, proper motion and annual aberration. LST is computed and from it the LHA for the star.

Worsley follows the advice of Close (1905: 192) and diminishes the Moon's calculated semi-diameter "in proportion of 15'34".09 to 15'32".65



[135]

Occultation of 42

Immersion Long
42 Librae. Chron (5229) 24d 4.46.6. 74° 0′ 0″ S. Lat. 46°23′39″W
Calculated error 1.38 fast
GMT 24d 4.44.28
Preparation of Data

☾'s S. Diam. Noon 24th 16′ 34″.30
MT 16.37.41
4h.44m.28 = 4h.74
Noon S.D. 16′ 34″.30 1.23
3.11
4.74
1244
2177
1244
12 | 14.7414
1.228
Cor. ☾'s SD. 16′.35″.53
Lat 74° 0′ 0″ S.
Reductn T. XVIII 6.13 Closes Tx Book
Geocentc 73°.53′.47″ S. Lat.

☾'s Hor Px. 24th Nn 60.42.90
Mt 60 54 27
" Noon .11.37 × 4h.74 ÷ 12h
60.42.90
4.49
= Cor 4″.49
Cor HP. 60.47.39 Cor for Lat 74° Table XVII
11.56 ……… Closes Text Book
☾ Red HPx 60.35.83
☾'s Dec. 24d 4h = 24° 17′. 31″.6 S.
4h Var 85″.73
Mid T. Cor – .63
10m Var. = 85.1
÷ 10
× 22.26 = 378″.44
44.47
6.18.44
☾ Cor Dec. 24.23.50.04 S.

P. 452 NA. h m s
42 Librae RA 15. 35. 15.18
P. 478 (Δa) * + 3.52
*'s Corrd RA 15. 35. 18.70

*'s Dec. – 23°32′ 33″.3 S.
Corrn (Δδ) – 18.3 S.
*'s Cor Dec – 23°. 32′. 51″.6 S

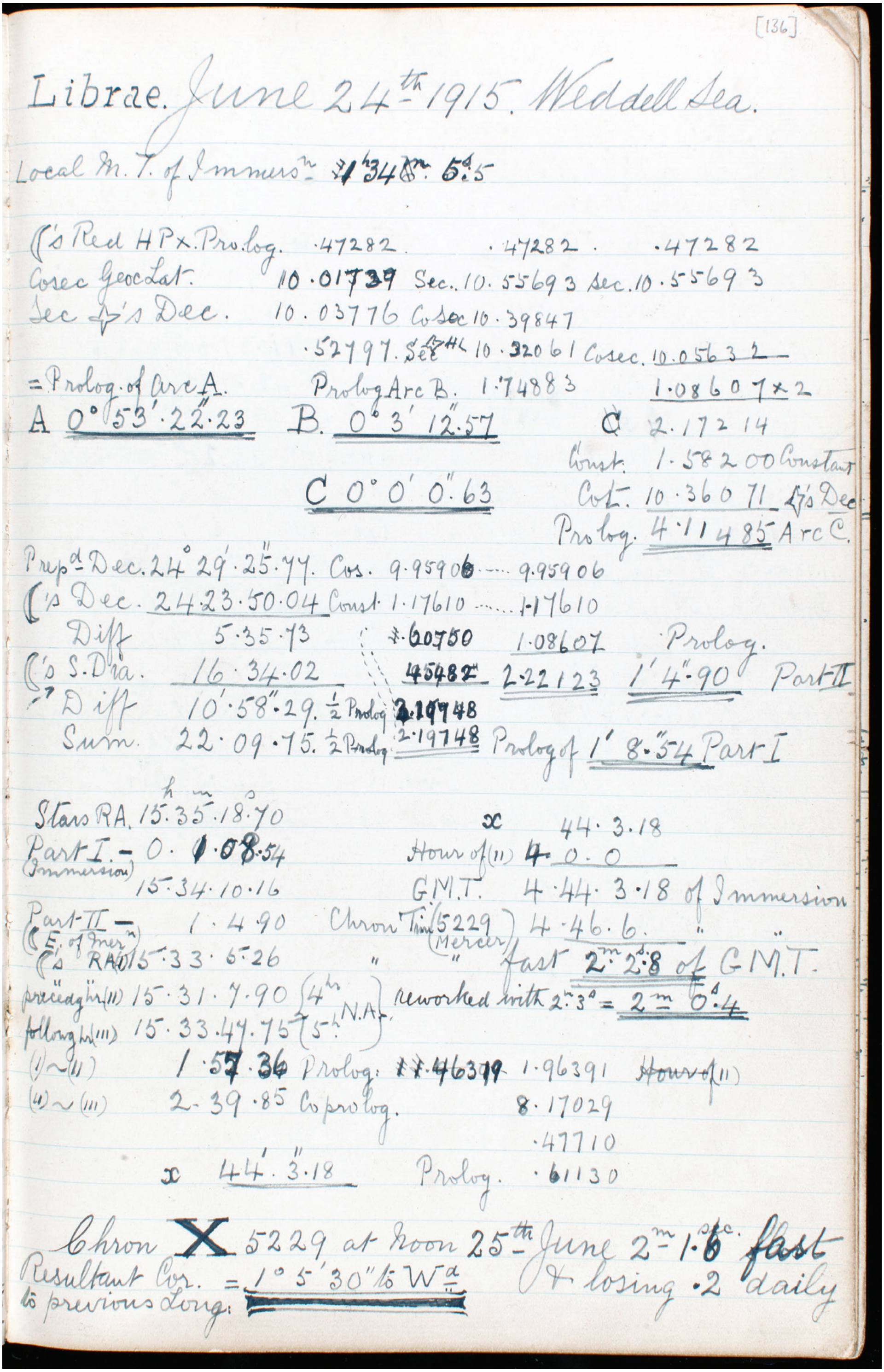
NA. P. II h m s
S.T. 24th 6.6.13.96
accel 39.43
erth: 4h = 7.22
44m = .08
28s
Redd S. Time 6.7.0.69
Mean T. Imm 1.34.5.5
R.A.M. 7.41.6.19
" ✧ 15.35.18.70
" H∠W. 16.5.47.49
" " E 7.54.12.51

Note Closes Text Book P. 192. "☾'s S.D on P III N.A
shd. be dimd ~~by~~ in propn of 15′ 34″.04 to
☾'s Cor SD. 16′ 34″.02 to 15.32.65
or 93409 : 93265. ~~[illegible] 16.5~~
✧'s Dec. = 23° 32′ 51″.6 (Lat + Dec
Arcs (A–C) = + 0 53.21.6 same name
24.26.13.2 If H∠ more
Arc B + 03′.03.12.57 than 6h +
Prepared Decln 24.29.25.77

Results of Occultations 24th June

		by Capt W.	by James
✧ 42 Libræ	Chron. Mercer 5229 fast of G.M.T	2m 0s.4	0s.4
BAC 5253	" " "	2 " 1.2	1.3
" 5286	" " "	2 " 2.87	2.60
σ Scorpii	" " "	2 2.27	2.59
	Mean results by both observers. =	2 1.7 fast	2.165

Figure 5a. First of two logbook pages (Worsley 1915: 135) showing the reduction of the occultation of 42 Libræ observed on 24 June 1915. Canterbury Museum 2001.177.1, page 135.



[136]

Librae. June 24th 1915. Weddell Sea.

Local M. T. of Immersn. 4h 34m 5s.5

☾'s Red HP × Pro.log. ·47282. ·47282. ·47282

Cosec GeocLat. 10·01739 Sec. 10·55693 Sec. 10·55693

Sec ✧'s Dec. 10·03776 CoSec 10·39847

·52797. Sec ✧HL 10·32061 Cosec. 10·05632

= Prolog. of Arc A. Prolog Arc B. 1·74883 1·08607 × 2

A 0° 53′ 22″·23 B. 0° 3′ 12″·57 C 2·17214

Const. 1·58200 Constant

C 0° 0′ 0″·63 Cot. 10·36071 ✧'s Dec

Prolog. 4·11485 Arc C.

Prepd Dec. 24° 29′ 25″·77. Cos. 9·95906 ····· 9·95906

☾'s Dec. 24 23 50·04 Const 1·17610 ······ 1·17610

Diff 5·35·73 1·60750 1·08607 Prolog.

☾'s S. Dia. 16·34·02 45482 2·22123 1′ 4″·90 Part II

Diff 10′ 58″·29. ½ Prolog 2·19748

Sum. 22·09·75. ½ Prolog 2·19748 Prolog of 1′ 8″·54 Part I

Stars RA. 15h 35m 18s·70 x 44·3·18

Part I − 0·1·08·54 Hour of (II) 4 0·0

(Immersion)

15·34·10·16 G.M.T. 4·44·3·18 of Immersion

Part II − 1·4·90 Chron Time (5229 Mercer) 4·46·6. "

(☾ E. of Merⁿ)

☾'s RA 15·33·5·26 " " fast 2m 2s·8 of G.M.T.

preceding hr (II) 15·31·7·90 {4h N.A.} reworked with 2m 3s = 2m 0s·4

following hr (III) 15·33·47·75 {5h

(I) ~ (II) 1·57·36 Prolog: 1·46319 1·96391 ~~Hour of (II)~~

(4) ~ (III) 2·39·85 Co prolog. 8·17029

·47710

x 44′·3″·18 Prolog. ·61130

Chron X 5229 at Noon 25th June 2m 1s·6 fast

& losing ·2 daily

Resultant Cor. to previous Long: = 1° 5′ 30″ to Wd

Figure 5b. Second of two logbook pages (Worsley 1915: 136) showing the reduction of the occultation of 42 Libræ observed on 24 June 1915. Canterbury Museum 2001.177.1, page 136.

Occultation of 42 Libræ **24 June 1915**

		h.	m.	s.
Chron. Time of	Immersion	4	46	6.0
Watch Error +Slow −Fast	−	0	1	38.0
Corrected Greenwich Date		4	44	28.0
Mean Time at Place		1	34	5.5
Approx. Longitude	W.	46°	23′	39″

		°	′	″	
Latitude	S.	74	0	0	
Reduction		0	6	13.2	(Table XVIII.)
Geocentric Latitude (ϕ')	S.	73	53	46.8	

	′	″	
☽'s Semi-diameter, preceding	16	34.30	(p.III., \`N.A.')
Ditto , following	16	37.41	
12-hourly difference	0	3.11	
Difference to 4h 44m 28s	0	1.23	
	16	35.53	
Irradiation adjustment		0.998	(93265/93409)
☽'s Semi-diameter at Greenwich Date (SD)	16	33.99	

	′	″	
☽'s Hor. Parall. 24th Noon	60	42.90	(p.III., \`N.A.')
Ditto Midnight	60	54.27	
12-hourly difference	0	11.37	
Difference to 4h 44m 28s	0	4.49	
☽'s Hor. Parall. at Greenwich Date	60	47.39	
Correction for Latitude	0	11.45	(Table XVII.)
☽'s Reduced Horizontal Parallax (HP′)	60	35.95	

		°	′	″	Var. in 10^{m}	
☽'s Declination, preceding	S.	24	17	31.6	85.73″	(p. X., \`N.A.')
Ditto , following	S.	24	26	0.9	84.03″	
Correction		0	6	18.41	85.10″	
☽'s Reduced Declination (δ)	S.	24	23	50.01		

Table 4a. Preparatory data for the reduction of the occultation of 42 Libræ observed on 24 June 1915. Canterbury Museum 2001.177.1, page 135.

		h.	m.	s.	
Star's R.A.		15	35	15.18	(a)
Correction	+			3.52	(b)
		15	35	18.70	

		h.	m.	s.	
Sidereal Time of G.M. Noon		6	6	13.96	(p.II., `N.A.')
	4h.	0	0	39.43	
Acceleration	44m.	0	0	7.23	
	28s.	0	0	0.08	
Reduced Sidereal Time		6	7	0.69	
Mean Time at Place		1	34	5.50	
R.A. of Meridian		7	41	6.19	
Ditto Star		15	35	18.70	
Star's Hour Angle, (t')		7	54	12.51	E.
		118°	33′	7.64″	(in arc)

		°	′	″	
Star's Declination	–	23	32	33.3	(a)
Correction	–			18.3	(b)
	–	23	32	51.6	

		°	′	″
Star's Declination, (δ')	–	23	32	51.6
Arc A	–	0	53	22.39
Arc B	–	0	3	12.58
Arc C	+	0	0	0.83
Prepared Declination, (δ)	S.	24	29	25.74

(a) "Mean Places of Occultation Stars," `N.A.'
(b) "$\Delta\alpha$, $\Delta\delta$" in "Elements of Occultation," `N.A.'

Table 4a. (continued)

Prolog(HP′)	0.47281				
$\log_{10}\csc(\phi')$	10.01738				
$\log_{10}\sec(\delta')$	10.03776				
Prolog(Arc A)	0.52795				
Arc A		0°	53′	22.39″	
Prepared Declination, δ		24	29	25.74	
$\delta_☽$		24	23	50.01	
		0	5	35.73	
SD		0	16	33.99	
Difference		0	10	58.26	
Sum		0	22	9.72	
		h.	m.	s.	
Star's R.A.		15	35	18.70	
	-	0	1	8.538	(Part I., –, Immersion)
		15	34	10.162	
	-	0	1	4.895	(Part II., –, Moon is E. of Meridian)
☽'s R.A.	(i.)	15	33	5.267	
Ditto preceding hour	(ii.)	15	31	7.90	4 h } (p. X., of `N.A.')
Ditto following hour	(iii.)	15	33	47.75	5 h
Difference between	(i.) and (ii.)	0	1	57.367	
Ditto	(ii.) and (iii.)	0	2	39.85	

Prolog(HP′)	0.47281
$\log_{10}\sec(\phi')$	10.55693
$\log_{10}\csc(\delta')$	10.39847
$\log_{10}\sec(t')$	10.32061
Prolog(Arc B)	1.74882
Arc B	0° 3′ 12.58″
$\log_{10}\cos(\delta)$	9.95906
$\log_{10}15$	1.17609
½Prolog	0.60751
½Prolog	0.45483
Prolog(Part I)	2.19749
Part I	0^h 1^m 8.538^s
Prolog	1.96388
Complement	8.17029
$\log_{10}3$	0.47712
Prolog(x)	0.61129
x	0^h 44^m 3.23^s

Prolog(HP′)	0.47281
$\log_{10}\sec(\phi')$	10.55693
$\log_{10}\csc(t')$	10.05632
	1.08606
	× 2
	2.17212
$\log_{10}(120/\pi)$	1.58203
$\log_{10}\cot(\delta)$	10.36071
Prolog(Arc C)	4.11486
Arc C	0° 0′ 0.83″
$\log_{10}\cos(\delta)$	9.95906
$\log_{10}15$	1.17609
	1.08606
Prolog(Part II)	2.22121
Part II	0^h 1^m 4.895^s

	h.	m.	s.	
Hour of (ii.)	4	0	0	
x	0	44	3.23	
GMT	4	44	3.23	
LMT	1	34	5.50	
	3	9	57.73	W.
(in arc)	47°	29′	25.90″	W.
Chron. Time	4^h	46^m	6.0^s	
Error		2^m	2.8^s	fast

Table 4b. Calculation of Greenwich Mean Time from the Local Mean Time of the occultation of 42 Libræ on 24 June 1915.

or 93409 : 93265". The semi-diameter tabulated in the *Nautical Almanac* includes adjustment for irradiation, defined as "an optical effect of contrast that makes bright objects viewed against a dark background appear to be larger than they really are" (Seidelman 1992: 729). This needs to be omitted when reducing occultations.

Unlike Close (1905) who uses linear interpolation for the Moon's declination, Worsley follows the prescription from the Explanation of the Articles section of the *Nautical Almanac* (1915: 619) and performs quadratic interpolation. For the right ascension (R.A.) and declination of the Moon, which change relatively rapidly, the *Nautical Almanac* tabulates values hourly and provides a column headed "Var. in 10^m" which permits quadratic interpolation between the values. Suppose the value of a quadratic function, $y(t)$, takes the value y_0 at $t = 0$ and its derivative takes the values y'_0 and y'_1 at $t = 0$ and $t = 1$ respectively. It is a simple matter to show that

$$\begin{aligned} y(t) &= \tfrac{1}{2}\left(y'_1 - y'_0\right)t^2 + y'_0 t + y_0 \\ &= \left\{ y'_1 \frac{t}{2} + y'_0\left(1 - \frac{t}{2}\right)\right\} t + y_0 \end{aligned}$$

The factor in curly brackets is the linearly interpolated value of y' at time $t/2$. To paraphrase the almanac (Nautical Almanac 1915: 619) the prescription to compute the Moon's declination at an intermediate time is:

> *Reduce the "Var. of Dec. in 10m" to the time midway between the time for which the Declination is required and the preceding hour in the Ephemeris, and then obtain the correction by simple proportion.*

The reduced horizontal parallax and geocentric latitude that account for the figure of the Earth is read from tables XVII and XVIII in Close (1905). These are computed based on "Clarke's first figure (1858)" geodetic reference ellipsoid (Close 1905: 209) with compression, or what is today called flattening, $f = 1/294.26$. For subsequent occultations, however, the log states "Using compress$^{\underline{n}}$ Red$^{\underline{n}}$ of Earths Polar Axis 1/293.47 Clarke 1866".

Table 4b shows the calculation of GMT from the observed LMT of immersion 42 Libræ again based on the layout given by Close (1905), but with extended annotation in some areas. Constants have been extended to full five-figure accuracy. Small differences are seen from the numbers that appear in the log mainly where interpolation has been performed. In order to avoid negative numbers, it was standard practice to add 10 to the logarithms of trigonometric functions. In many cases it is done even when strictly unnecessary, such as for secants and cosecants. In the sum of logarithms, digits in the tens column are discarded.

Excerpts of pages from the *Nautical Almanac* (1915) consulted for these inputs are given in Appendix B.

'A Very Good Series of Occultations'

Following this first round of occultations on 24 June, further sets of observations were carried out and are listed in Table 5. All observations were of immersion on the dark limb of a waxing Moon which are more reliably timed than emersion or immersion on a bright limb. With the exception of σ Scorpii all stars are relatively faint at 5th and 6th magnitude requiring that the Moon be at a reasonable altitude for them to be visible. At the latitudes concerned there are periods of several days in each synodic month when the Moon is very low or completely below the horizon. These considerations along with the constraints of weather and periods of increasing sunlight limit the availability of events suitable for timing.

The log records a longitude for each occultation but this does not enter in the reduction and does not always agree with the longitude inferred by subtracting LMT from GMT.

Intermediate calculations from the reduction of the occultation of BAC 4722 on 16 August 1915 are found on a loose leaf page (Canterbury Museum 2001.177.24, loose page).

The CE obtained from the occultations was used to correct noon longitudes from prior dates which are crossed out and adjusted accordingly.

On an unused page opposite the log entries for 1 January 1915 (Worsley 1915: 57) is written:

> *Starting from June1st 1915 the error of A. Chronometer (2235) Heath & Co. was assumed to be 29 seconds more slow than had been allowed. This was calculated back from a very good series of occultations from June 24th to Sept. 15th 1915. The changing rates were plotted on a curve by Mr Hudson Navigtg Officer & from this the corrections for longitude were deduced; as being at a maximum on June 24th & tapering down to zero at Buenos Ayres 24th Oct. 1914.*

Worsley (1915: 73) summarised the CE and rate as deduced from the occultations in an entry facing the log page of 18 March 1915. These are shown in Table 6.

Reginald James writes "After the crushing of the ship on October 27, 1915, no further occultations were observed" (Shackleton 1920: Appendix I).

Navigation at Ocean and Patience Camps

Navigation during the period camped on the ice consisted of noon sights and time sights of the Sun as well a frequent updates of the distance and bearing of potential target destinations.

In late March 1916, their position approached Joinville Island. Its highest peak, Mount Percy, with position taken from a chart in Nordenskjöld (1905) as 63°14'S 55°38'W (Worsley 1916: 4), could provide a means to rate chronometers and fix longitude.

On 23 March 1916 (Worsley 1916: 83) wrote the following and included an illustration of

Star	HIP	Magnitude	Altitude of Star	Age of Moon	Latitude	Greenwich Mean Time	Local Mean Time	Hour Angle
			°	days	° ′ ″	h m s	h m s	° ′ ″
24 June, 1915								
42 Libræ	76742	5.1	15	11.9	74 0 0 S.	4 44 28	1 34 5.5	118 33 8 E.
B.A.C. 5253	77858	5.4	35	12.1	73 58 0 S.	9 49 56	6 40 5	45 14 12 E.
B.A.C. 5286	78246	5.4	40	12.2	73 57 45 S.	11 44 46	8 34 55	17 36 55 E.
σ Scorpii	80112	3.1	19	12.6	73 57 0 S.	20 31 57	17 22 18	108 57 21 W.
23 July, 1915								
A Ophiuchi	84405	5.3	10	11.1	73 14 30 S.	0 36 18	21 24 8	176 20 45 E.
16 August, 1915								
B.A.C. 4722	69658	5.6	37	5.9	70 41 43 S.	8 36 0	5 15 51	10 25 32 W.
B.D. -17°4053	69792	6.4	35	5.9	70 41 43 S.	9 33 40	6 13 23.5	24 26 18 W.
B.A.C. 4739	69929	5.7	34	6.0	70 41 43 S.	10 19 11.5	6 59 2.5	35 29 19 W.
13 September, 1915								
B.D. -21°4030	73927	6.1	25	4.5	69 45 0 S.	11 57 43	8 35 51.5	75 27 20 W.
15 September, 1915								
A Ophiuchi	84405	5.3	31	6.6	69 32 0 S.	13 43 13	10 19 52	71 21 14 W.

Table 5. Lunar occultations recorded in the logbook. Astronomical dates and times are listed. The columns Star and Magnitude give the designation and magnitude listed in the *Nautical Almanac* (1915). HIP is the Hipparcos Catalogue number. Latitude, Greenwich Mean Time, Local Mean Time and Hour Angle come from values given in the logbook.

position of Mount Percy (Fig. 6): "M^t Percy West 57 miles", "Appearance of land S60°W by comp. 9/0 A.M", "in this lat. the true bearing of a place 57 miles West wd be about S86°W."

A note, "Error 14°E ?", gives the assumed compass variation or magnetic declination:

> *From these bearings it wd appear as the Mt P (if that be the highest peak we see) is further N. than 63°14'S. as on Nordenskjold's chart or else that we are further S. by some error than our Obs. shew. The latter appears very unlikely.*

24 March (Worsley 1916: 85): "M^t Percy S89°W. [true] 60½ [miles]" as calculated by traverse tables "M^{t}Percy S74°W(mag) 0°11'" measured by theodolite.

Using a height of 3,673 feet (1,120 m) (Worsley 1916: 4) the measured altitude is used to calculate the distance to Mount Percy using the formula (Worsley 1915: 1): "Height in feet × .565 ÷ angle in ' = dist in miles"

The clearly erroneous result of 173 nautical miles (320 km) is due to the use of a simple proportions, which is not applicable for objects located beyond the visible horizon. Further bearings and vertical angles are taken the same day, S75°W magnetic giving S88½°W true with error 13½°E, 0°11' altitude; by theodolite S88°24'W.

Additional observations of Mount Percy are recorded on 26 and 27 March.

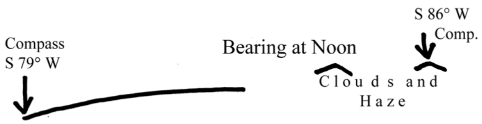


Figure 6. Copy of Worsley's sketch of the position of Mount Percy from the log entry of 23 March 1915.

On 24 March, Mount Percy had been observed bearing S88°24'W and, after drifting N23°E 16½ nautical miles (30.5 km), was measured at S73°38'W on 27 March. The distance to Mount Percy was found to be 57¼ nautical miles (106 km) on the latter date by triangulation, as shown in Figure 7. Worsley concluded (Worsley 1916: 80) that this is "10½^m = 23'W of Chron:" but that:

> *I will not allow any change to chron in meantime (Clarence or Elephant if seen soon will give better bearings & a good "fix") as had we been 10½ m West we wd have passed within 18m of the NE Danger in moderately clear weather, in wh: case we should almost certainly have seen it distinctly; whereas we only thought we saw it (It may have been hidden at times by grounded bergs. I do not know its height). Added to not having seen the Dangers or Darwin I, is the fact that the "chart" from N$^{\underline{ds}}$ book is evidently only intended for the general public & has not the close accuracy*

Chron (X) 5229 Mercer
18$^{\underline{th}}$ March Error used 3^{m}56^s.5 fast Rate used 1.5 sec gaining
The errors were subsequently by Occultations to be as follows:-

Date			(X) 5229 Chron			
			m s.		sec:	
18th March	1915	fast	1·36· 5	gaining	0.3	worked back from
24th June	–″–	–″–	2· 1·65	–″–	0.3	Occultations
23th July	–″–	–″–	2·13·25	–″–	0.4	
16th Aug	–″–	–″–	2·22·21	–″–	0.37	
13th Sept	–″–	–″–	2·25·08	–″–	0.1	

Table 6. Chronometer error and rate for the 5229 Mercer (Chron X) as obtained from the series of occultation timings, 24 June–13 September and those inferred for 18 March, 1915 (Worsley 1915: 73).

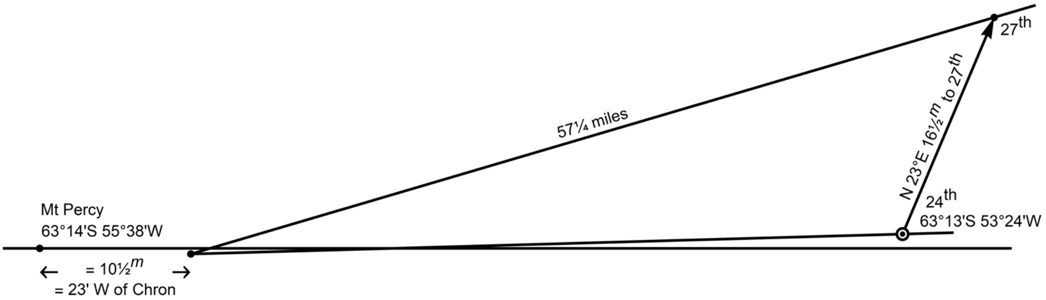


Figure 7. Triangulation of the position of Mount Percy on Joinville Island from its bearing angles on 24 and 27 March 1916 and the intervening drift.

> *of pos$^{\underline{tn}}$ for Mt Percy necessary to correct chrons – our great distance, small change of angle & a certain amount of doubt as to whether we have got the right point for Mt Percy*

James (Shackleton 1920: Appendix I) wrote that after the occultation timings ceased:

> *… calculated rates for the watches were employed, and the longitude deduced, using these rates on March 23, 1916, was only about 10' of arc in error, judging by the observations of Joinville Land made on that day.*

The logbook (Worsley 1916: 80) shows a graphical construction similar to Figure 7 (Bergman et al. 2018: Appendix A) but has the course angle from 24 to 27 March plotted incorrectly and is therefore likely to be a copy of the one actually used.

On 7 April 1916, Clarence Island was sighted and on 9 April did yield the sought after "good fix" (see Appendix A).

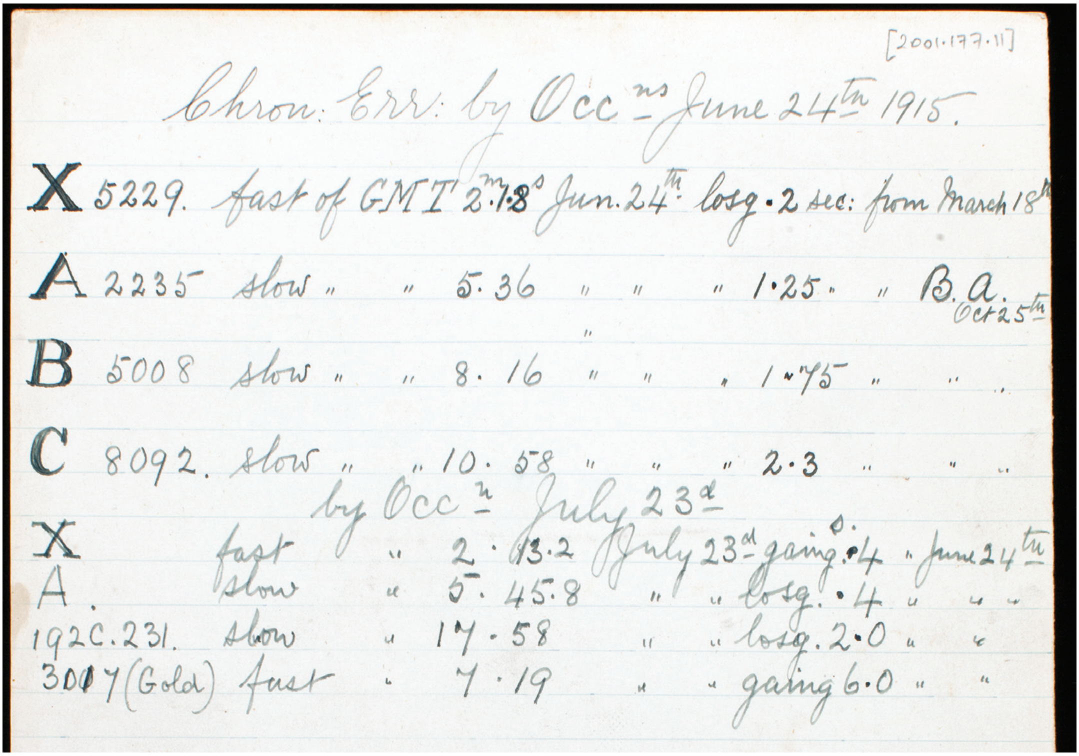
The Chronometers

Worsley (1998) states that *Endurance* set out carrying 24 chronometers. Of these, six are mentioned along with their letter designations, serial numbers, chronometer errors and rates for 24 June and 23 July 1915 (Canterbury Museum 2001.177.11, loose page front) (Fig. 8). The information is repeated for a selection of the chronometers on other dates on the reverse side. Loose leaf pages show daily comparisons with columns headed "Hudson 192/232 | Wild 192/231 | Worsley 192/262 | A" and others that are not distinguishable (Worsley 1916: 1-3).

The Mercer chronometer, No. 5229 or "Chron X" is frequently mentioned in the log suggesting that it was the primary one used. It now resides in the National Maritime Museum in Greenwich, United Kingdom (Object Id: ZAA0029)[2] and is believed to have been carried on Shackleton's famous boat journey on the *James Caird* from Elephant Island to South Georgia in 1916.

Particularly noteworthy is the Smith chronometer, serial number 192-262, that Worsley used in navigating the *James Caird* and is now in the collection of the Scott Polar Research Institute of Cambridge University, United Kingdom (Reference number: N: 999a)[3]. It makes its first appearance in the log on 2 November 1915 (Worsley 1916: 39). On this day its error is given as 40^{m} 26^{s} slow. On 7 November the error is given as 3^{m} 28.5^{s} fast apparently indicating that it had been reset. In the following weeks until 2 February 1916, entries on the daily log pages show it to be steadily losing, with a fluctuating rate of between 0 and 10 seconds per day indicating that it was being compared to another chronometer with a rate that was believed to be known.

A log page contains a list of comparisons from 3 February to 6 March 1916 (Worsley 1916: 3). Here it can be seen that Worsley's chronometer is losing 5 seconds per day, Hudson's 2 seconds



[2001·177·11]

Chron: Err: by Occns June 24th 1915.

X 5229. fast of GMT 2m 7·8s Jun. 24th losg ·2 sec: from March 18th
A 2235 slow " " 5·36 " " " 1·25 " " B.A. Oct 25th
B 5008 slow " " 8·16 " " " 1·75 " " "
C 8092. slow " " 10·58 " " " 2·3 " " "

by Occn July 23d

X fast " 2·13·2 July 23d gaing ·4 " June 24th
A. slow " 5·45·8 " " losg ·4 " " "
192C.231. slow " 17·58 " " losg. 2·0 " "
3007 (Gold) fast " 7·19 " " gaing 6·0 " "

Figure 8. Some of the chronometers carried by the Expedition giving their letter designations, serial numbers, chronometer errors and rates. Canterbury Museum 2001.177.11, loose page front.

per day and Wild's 1 second per day. From 3 February onwards, Worsley calculates with a steady rate of 5 seconds per day (losing) and uses this value during the voyage of the *James Caird*.

Acknowledgement

The authors are grateful to Canterbury Museum Human History Curator Jill Haley for her encouragement, enthusiasm, arranging access to the documents and assisting in reading the very faintest of markings in the log.

Endnotes

1 The standard nautical interpretation of gl.m. would be globigerina mud, however, it is clear from other commentary (Shackleton 1920; Wordie 1921) that the Expedition used it to indicate glacial mud or clay.

2 http://collections.rmg.co.uk/collections/objects/79134.html

3 http://www.spri.cam.ac.uk/archives/shackleton/articles/N:_999a.html

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Appendix A

The Passage to Elephant Island

This appendix describes the navigation performed during the passage from Patience Camp on the Weddell Sea to Elephant Island. Shackleton (1920) sighted Clarence Island on 7 April 1916 and later in the day Elephant Island was seen. Both were seen again the following day. The boats were launched at 1:30 pm on 9 April around 55 nautical miles from Elephant Island and the Expedition made landfall on Cape Valentine at its eastern tip on 15 April.

Time sights and the distance and bearing of Clarence and Bridgeman Islands are recorded prior to departure on 7 and 8 April. On both these days two observations were taken in the morning a few minutes apart, and when reduced with the same latitude gives nearly the same resulting longitude which provides assurance that the sights were "good". The last of these sights were timed and reduced to 0.1 seconds. In practice this is overkill in high latitudes but indicates that Worsley was striving for utmost accuracy in preparation for chronometer rating. The sight is, however, still reduced with five-figure logarithms although it might be expected that he still had six-figure tables in his possession. A bearing of Clarence Island taken around noon on 9 April was later used to rate the chronometers. No noon sights are recorded although they were taken. Most of the navigation underway is by Dead Reckoning with positions being determined by means of traverse tables. On 12 April time sights were made. On this day two morning sights were taken in rapid succession and reduced with different latitudes, again indicating that Worsley wanted to be sure of his position and gauge the magnitude of potential errors. Worsley (1998) recounts:

"....I took observation for longitude with the sextant. At noon I observed latitude....I thought we had made thirty miles towards Elephant Island. The sights proved we were thirty miles further away and had been driven nineteen miles farther south."

The entry for 13 April is labelled 13 Jan which may be an indication of the strain that Worsley was under at the time.

The navigational records of the passage are contained in just two detached log pages which, unsurprisingly considering the conditions under which they were used, are in relatively poor condition compared to much of the rest of the log (Worsley 1916: 89, 91). Numbers near the margins are often missing. In this appendix the discernible characters have been transcribed. Some of the missing values can be found in Worsley (1998) and are enclosed in curly brackets { }. Others can be calculated using the numbers that can be seen and are indicated with square brackets [ ]. Characters that cannot be read are denoted x.

Where possible, the log entries made under way replicated and were labelled using the notation and conventions established in Bergman et al. (2018). The distance and bearing calculations for 7 and 8 April are also replicated but the time sights have been omitted.

Transcript from the Log

Friday 7th April

slow 8 36

25. 5 20. O	14° 56 AM Sext		25.11 50	15 24 AM Theod		62° 8′0″ 54°22′
- 2 13	62 8½	330.42	- 2 13	62 8½	330.42	2 days N 29° E 7^{m}
25 3 7	96 49½	3.09	25 9.37	96 49½	3.09	Cl.Pk S 61°12′? N20° E 5[9^{m}]
21 25 43	173 54	725 97	21. 32 3	174 22	691.44	W53°40′
[3] 37 24	86 57	978 24	3. 37 34	87.11	977.67	Bridgeman S 88°W 5[8^{m}]
[5]4°21′	72 01	037 72	54°23′30″	71.47	002 62	

Saturday 8th April

slow 8 41

24 48 13 O	13° 27½AM Sext		25. 2 42. 5 ~~O~~	14°35½ AM Theod		62° 6′0″ 53°4[8′]
- 1 56	62 6½	329.94	- 1 55.9	62 6½	329.94	N 82° E 16^{m}
24.46.17	97 12	3.44	25. 0.46.6	97.12	3.44	Clarence N 4°E[54^{m}]
21 10 58.5	172. 46	799 90	21.25 35.5	173 54	725.97	
3 35 18.5	86 23	980 42	3.35 11.1	86.57	979.08	
53°49′37″	72 55½	113 70	53°47′50″	72 21½	038 43	

Thru mist Sunday 9th April

may have been

Elephant N 10°W true

about 12°E

Noon Clarence Pk bore ^ N 22°W(mag) abt 44^{m} = 61° 56′ 53° 5{6′}

1.0P.M. Launched boats 1.30PM. Under way to 6.15 P.M. N 21°W 11 mls

& dist

Course ^ made good approx. N 45°W 7 miles

Above DR Long & Co. being
from a bearg : of land should xxx
12′½W of prev: Obs Positions (xxx)

Monday 10th April

PM 9th			
DR N45°W 7^{m}	4.9	4.9	
to 2P.M. 10th			61° 46′ 5[4° 57′]
DR N60°W 10^{m}	5.0	8.7	N71°W[30 mls]
Est^{d} Cur^{t} W 15^{m}		15	
	9.9	28.6	

Tuesday 11th April

Est^{d} Curt W 30 ^{m} C. Melville 62° 2′ 57° 33′ 61° 46′ [56° 0′]

16′S 95

446 C. Melville S7

Wednesday 12th April

slow 9 1

24.18 19. O	9° 54 AM	S 37° W 10^{m} 8′S. 13′W	62° 15′ {53° 7′}
- 51	62 7	33.006	
24 17 28	98 40	.498	
20 45 11	170 41	90963	
3 32 7	85 20½	98583	
53° 2′	75 26½	23050	

24.17 26.	9° 50 AM	S 37° W 8^{m}	6 .35 .29 O	10° 46 PM	S 40° W 5^{m}
- 51	62.10	330.78	- 47	62.19	33.294
24 16 35	98 .40	4.99	6 34 .42	98 .46	.510
20 44 21	170 .40	910.40	3 2 2	170 .51	85.164
3 32 14	85 .20	987 83	3 .32.40	85 .55½	98.526
53° 3′ 30″	76.30	234 00	53°10′	75 . 9½	17494

Thursday 13th Jan

S 30 W 5	4.3	2.5	61° 43′	54°36′
N 33° W 10	8.4	5.4	61 11	54 50
N 45° W 40 to 8PM	28.3	28.3	32	14
	32.4	36.2		64 S

Annotated Log

Friday, 7th April

Noon Position 62°08′S, 54°22′ W

Bearing and Distance

Noon Position	62 °	8 ′ S	54 °	22 ′ W	D.Lat.	D.Lon.	Dep.	Bearing	Distance
Clarence Peak	61	12	53	40	56.0	42.0	19.9	20 °	59 miles
Bridgeman Island	62	11	56	25	-3.0	-123.0	-57.4	267 °	58 miles

Saturday, 8th April

Noon Position

DR N82°E 16 miles from 62°8′ S, 54°22′ W: 62°06′ S, 53°48′ W

D. Lat. 2.2 Dep. 15.8 = D. Lon. 33.9

Bearing and Distance

Noon Position	62 °	6 ′ S	53 °	48 ′ S	D.Lat.	D.Lon.	Dep.	Bearing	Distance
Clarence Peak	61 °	12 ′	53 °	40 ′	54.0	8.0	3.8	4 °	54 miles

Sunday, 9th April

Noon Position

DR N21°W 11 miles from 62°6′ S, 53°48′ W: 61°56′ S, 53° 56′ W

D. Lat. 10.3 Dep. 3.9 = D. Lon. 8.4

Longitude

Clarence Peak		61 ° 12 ′ S	53 ° 40 ′ W	
Latitude		61 ° 56 ′ S		
D. Lat. 44.0	Dep. 7.9 = D. Lon. 16.3			
Longitude			53 ° 56 ′ W	

Monday, 10th April

Noon Position

Wednesday, 12th April

Noon Position 62°15′ S, 53° 7′ W

Time Sight

Mean time at Greenwich	24 h	18 m	19 s	Sun's true altitude	9 °	54.0 ′	AM	
Equation of Time	-		51	Latitude	62	7.0	sec.	0.33006
Apparent time at Greenwich	24	17	28	Polar distance	98	40.0	cosec.	0.00499
				Sum	170	41.0		
Apparent time at ship	20	45	11	Half-sum	85	20.5	cos.	8.90963
Longitude in time	3	32	17 W	Remainder	75	26.5	sin.	9.98583
Longitude	53 °	4 ′	15 ″				hav.	9.23051

Time Sight

Mean time at Greenwich	24 h	17 m	26 s	Sun's true altitude	9 °	50 ′	AM	
Equation of Time	-		51	Latitude	62	10	sec.	0.33078
Apparent time at Greenwich	24	16	35	Polar distance	98	40	cosec.	0.00499
				Sum	170	40		
Apparent time at ship	20	44	48	Half-sum	85	20	cos.	8.91040
Longitude in time	3	31	47 W	Remainder	75	30	sin.	9.98594
Longitude	52 °	56 ′	45 ″				hav.	9.23211

Run to Noon S 37° W 8 miles

Time Sight

Mean time at Greenwich	6^{h}	35^{m}	29^{s}		Sun's true altitude	10 °	46.0 ′	PM	
Equation of Time	-		47		Latitude	62	19.0	sec.	0.33294
Apparent time at Greenwich	6	34	42		Polar distance	98	46.0	cosec.	0.00510
					Sum	171	51.0		
Apparent time at ship	3	2	2		Half-sum	85	55.5	cos.	8.85164
Longitude in time	3	32	40	W	Remainder	75	9.5	sin.	9.98526
Longitude	53 °	10 ′	0 ″					hav.	9.17494

Run from Noon S 40° W 5 miles

Thursday, 13th April

8PM Position

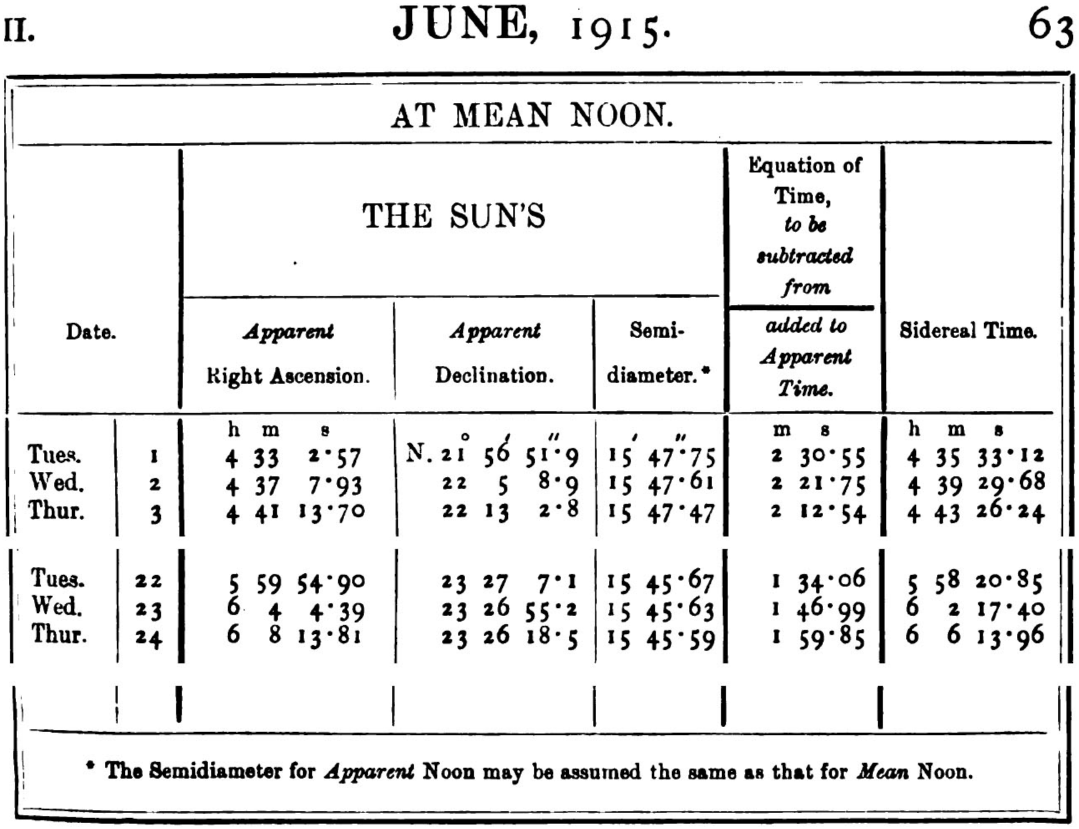
DR N48°W 49 miles from 62°15′ S, 53°19′ W: 61°43′ S, 54°36′ W

D. Lat. 32.4 Dep. 36.2 = D. Lon. 77.1

				D.Lat.	Dep.	D.Lon.
S	30°	W	5 miles	4.3	2.5	
N	33°	W	10 miles	8.4	5.4	
N	45°	W	40 miles to 8PM	28.3	28.3	
				32.4	36.2	77.1

Appendix B

Excerpts of tables from the *Nautical Almanac* (1915) consulted in the reduction of the occultation of 42 Libræ on 24 June 1915. The times listed are astronomical time with 0h occurring at noon on the date in question

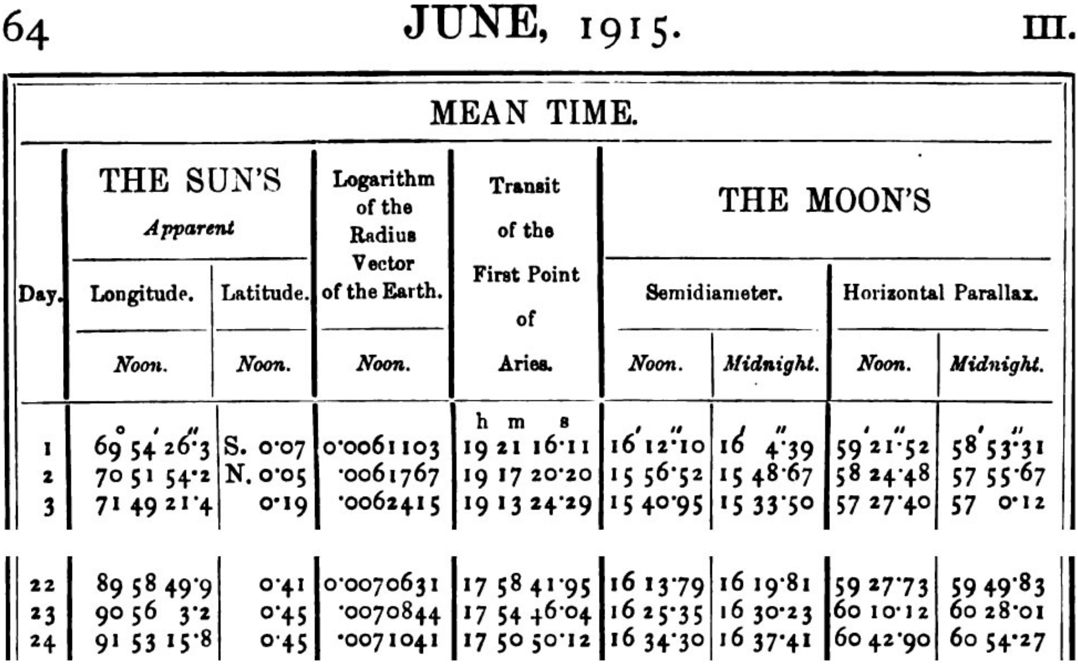


II. JUNE, 1915. 63

AT MEAN NOON.

Date.		THE SUN'S			Equation of Time, *to be subtracted from* *added to* *Apparent Time.*	Sidereal Time.
		Apparent Right Ascension.	*Apparent* Declination.	Semi-diameter.*		
		h m s	° ′ ″	′ ″	m s	h m s
Tues.	1	4 33 2·57	N. 21 56 51·9	15 47·75	2 30·55	4 35 33·12
Wed.	2	4 37 7·93	22 5 8·9	15 47·61	2 21·75	4 39 29·68
Thur.	3	4 41 13·70	22 13 2·8	15 47·47	2 12·54	4 43 26·24
Tues.	22	5 59 54·90	23 27 7·1	15 45·67	1 34·06	5 58 20·85
Wed.	23	6 4 4·39	23 26 55·2	15 45·63	1 46·99	6 2 17·40
Thur.	24	6 8 13·81	23 26 18·5	15 45·59	1 59·85	6 6 13·96

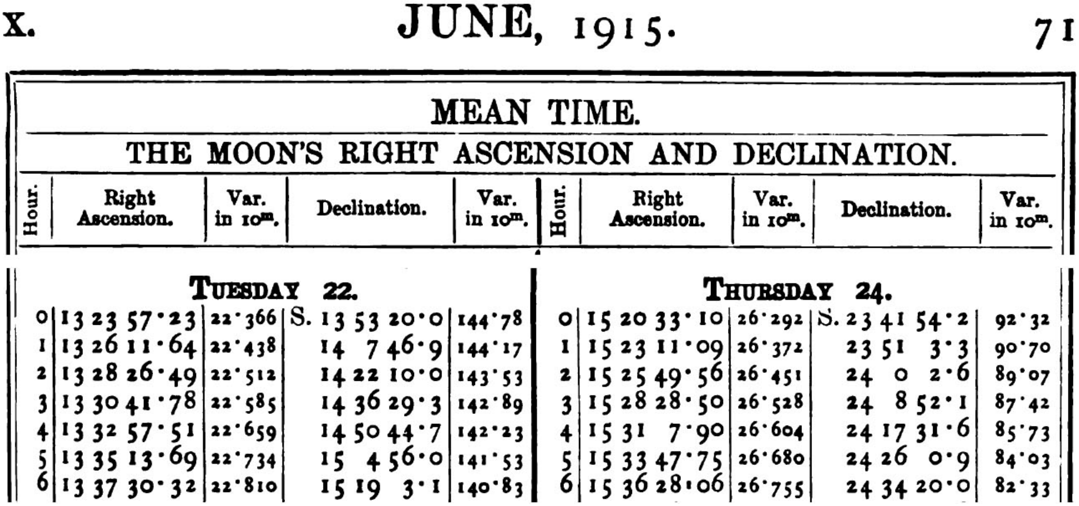
* The Semidiameter for *Apparent* Noon may be assumed the same as that for *Mean* Noon.



64 **JUNE,** 1915. **III.**

MEAN TIME.

Day.	THE SUN'S *Apparent* Longitude.	THE SUN'S *Apparent* Latitude.	Logarithm of the Radius Vector of the Earth.	Transit of the First Point of Aries.	THE MOON'S Semidiameter.		THE MOON'S Horizontal Parallax.	
	Noon.	*Noon.*	*Noon.*		*Noon.*	*Midnight.*	*Noon.*	*Midnight.*
	° ′ ″			h m s	′ ″	′ ″	′ ″	′ ″
1	69 54 26·3	S. 0·07	0·0061103	19 21 16·11	16 12·10	16 4·39	59 21·52	58 53·31
2	70 51 54·2	N. 0·05	·0061767	19 17 20·20	15 56·52	15 48·67	58 24·48	57 55·67
3	71 49 21·4	0·19	·0062415	19 13 24·29	15 40·95	15 33·50	57 27·40	57 0·12
22	89 58 49·9	0·41	0·0070631	17 58 41·95	16 13·79	16 19·81	59 27·73	59 49·83
23	90 56 3·2	0·45	·0070844	17 54 46·04	16 25·35	16 30·23	60 10·12	60 28·01
24	91 53 15·8	0·45	·0071041	17 50 50·12	16 34·30	16 37·41	60 42·90	60 54·27

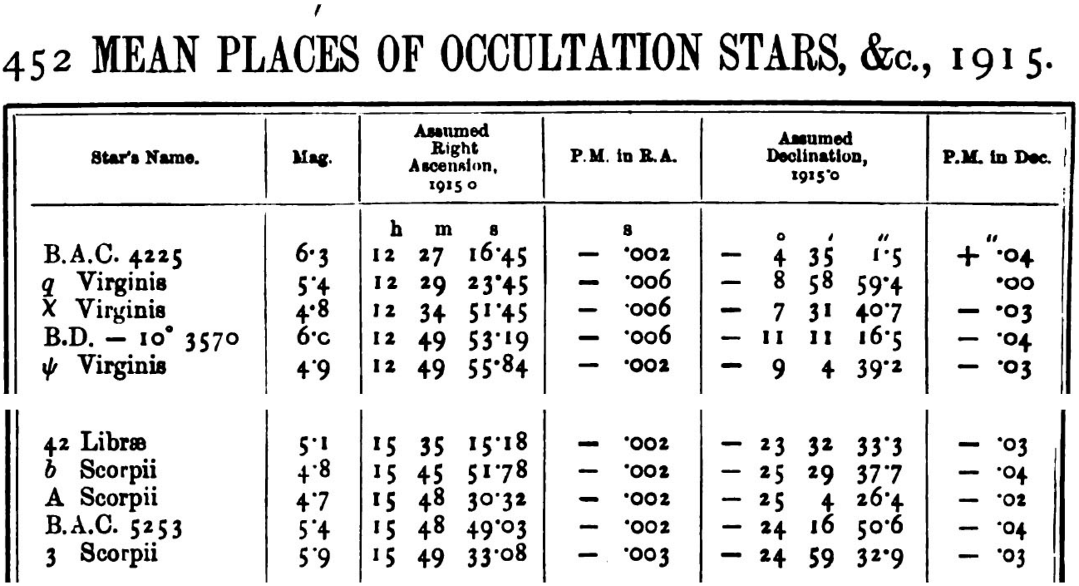


X. **JUNE,** 1915. **71**

MEAN TIME.

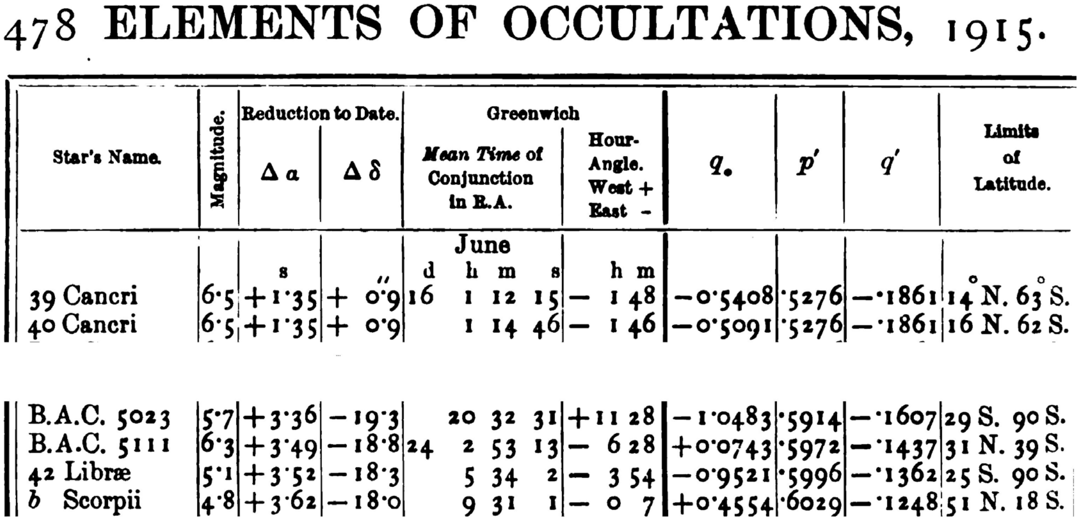
THE MOON'S RIGHT ASCENSION AND DECLINATION.

Hour.	Right Ascension.	Var. in 10ᵐ.	Declination.	Var. in 10ᵐ.	Hour.	Right Ascension.	Var. in 10ᵐ.	Declination.	Var. in 10ᵐ.
	TUESDAY 22.					**THURSDAY 24.**			
0	13 23 57·23	22·366	S. 13 53 20·0	144·78	0	15 20 33·10	26·292	S. 23 41 54·2	92·32
1	13 26 11·64	22·438	14 7 46·9	144·17	1	15 23 11·09	26·372	23 51 3·3	90·70
2	13 28 26·49	22·512	14 22 10·0	143·53	2	15 25 49·56	26·451	24 0 2·6	89·07
3	13 30 41·78	22·585	14 36 29·3	142·89	3	15 28 28·50	26·528	24 8 52·1	87·42
4	13 32 57·51	22·659	14 50 44·7	142·23	4	15 31 7·90	26·604	24 17 31·6	85·73
5	13 35 13·69	22·734	15 4 56·0	141·53	5	15 33 47·75	26·680	24 26 0·9	84·03
6	13 37 30·32	22·810	15 19 3·1	140·83	6	15 36 28·06	26·755	24 34 20·0	82·33



452 MEAN PLACES OF OCCULTATION STARS, &c., 1915.

Star's Name.	Mag.	Assumed Right Ascension, 1915·0	P.M. in R.A.	Assumed Declination, 1915·0	P.M. in Dec.
		h m s	s	° ′ ″	″
B.A.C. 4225	6·3	12 27 16·45	− ·002	− 4 35 1·5	+ ·04
q Virginis	5·4	12 29 23·45	− ·006	− 8 58 59·4	·00
χ Virginis	4·8	12 34 51·45	− ·006	− 7 31 40·7	− ·03
B.D. − 10° 3570	6·c	12 49 53·19	− ·006	− 11 11 16·5	− ·04
ψ Virginis	4·9	12 49 55·84	− ·002	− 9 4 39·2	− ·03
42 Libræ	5·1	15 35 15·18	− ·002	− 23 32 33·3	− ·03
b Scorpii	4·8	15 45 51·78	− ·002	− 25 29 37·7	− ·04
A Scorpii	4·7	15 48 30·32	− ·002	− 25 4 26·4	− ·02
B.A.C. 5253	5·4	15 48 49·03	− ·002	− 24 16 50·6	− ·04
3 Scorpii	5·9	15 49 33·08	− ·003	− 24 59 32·9	− ·03



478 ELEMENTS OF OCCULTATIONS, 1915.

Star's Name.	Magnitude.	Reduction to Date.		Greenwich		q_0	p'	q'	Limits of Latitude.
		Δ *a*	Δ δ	*Mean Time* of Conjunction in R.A.	Hour-Angle. West + East −				
		s	″	June d h m s	h m				° °
39 Cancri	6·5	+ 1·35	+ 0·9	16 1 12 15	− 1 48	−0·5408	·5276	−·1861	14 N. 63 S.
40 Cancri	6·5	+ 1·35	+ 0·9	1 14 46	− 1 46	−0·5091	·5276	−·1861	16 N. 62 S.
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Authors are encouraged to submit manuscripts no longer than 8,000 words. No absolute limit is imposed on manuscript length, but manuscripts over 8,000 words should be discussed with a member of the Editorial Board prior to submission.

Manuscripts are accepted for publication throughout the year.

Submission of Manuscripts

Manuscripts should be in MS Word 2000 or later and have 1.5 line spacing, in Arial 11 point font. These should be emailed to records@canterburymuseum.com The first page should show the author name(s) and address(es) plus email address(es), paper title and category. An abstract and keywords should also be on this page. The body of the text, references, tables and figure captions are to be on separate pages. High resolution electronic files (minimum of 600 dpi, preferably TIF files) will be required upon final submission of a revised manuscript.

Review of Manuscripts

Manuscripts will be peer-reviewed by at least two referees. The Editor will usually make and advise a decision on publication within 3 months of receiving the manuscript.

Conventions

Spelling is in accordance with the Concise Oxford English Dictionary.

Abbreviated Latin terms	Full stops should be used in abbreviations of Latin terms, such as e.g., i.e., c.f., c. 1984, et al.
Capitals	Capitals should be used sparingly. All proper names and substantives only where they refer to specific individuals, offices or organisations (e.g. Labour government; the government. Use Prime Minister, but Cabinet minister. Capitalise the first word and all the principal words in titles of publications and in chapter titles. Capitalise both words in a compound title, e.g. Governor-General.
Dates	Are written in numerals, e.g. 1800s, 8 May 1923. Spell out nineteenth century, sequential dates in full 1956–1986.
Illustrations	All illustrations, figures and/or tables must be referred to in the text with captions following the format: **Figure 1.** Description (credit [where appropriate]). Captions for composite figures should follow the following style: **Figure 1.** Brief description of the entire figure. **A,** Specific description of part A. **B,** Specific description of part B. Please indicate where in the text authors would prefer such illustrations to be placed.

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Italics	Genera, species, sub-species, names of ships, titles of published books, plays, films, pamphlets and periodicals. However, books and periodicals are not italicised in the references. In footnotes where an acronym or initialism is used for a publication title do not italicise the acronym.
Māori Language	Our practice is to use the te reo Māori word first followed by the English translation in round brackets. Macrons are standard practice where appropriate except where original texts (without macrons) are being quoted.
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