COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD No. 1963/42

SOUTH-WEST PACIFIC SUBMARINE GRAVITY SURVEY OPERATIONS 1956, USING VENING MEINESZ PENDULUMS

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S. GUNSON

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SUMMARY

Details are given of a submarine gravity survey in the south-west Pacific Ocean in HM Submarine 'Telemachus'. The survey was made during June and July 1956 by personnel from Columbia University, USA and the Bureau of Mineral Resources, Geology and Geophysics, Australia.

Gravity measurements were made at regular intervals whilst at sea, and at several ports of call, during a cruise which commenced at Sydney and returned there after visiting New Zealand (Wellington and Auckland), Tonga Islands, and Fiji Islands (Suva). The survey was part of a programme of world-wide marine gravity measurements being made by Columbia University with the object of obtaining additional information on the shape and structure of the earth.

The gravity measurements were made using equipment designed by Professor F.A. Vening Meinesz and modified by Columbia University. The field data and records have been reduced by Columbia University (Dooley, 1963). This Record describes the method of calculation and the corrections applied.

1. INTRODUCTION

The submarine gravity survey described in this Record was a joint project of the Lamont Geological Observatory, Columbia University, USA and the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development, Australia. The British Admiralty and the Australian Naval Board agreed to make a submarine available for the gravity measurements. HM Submarine 'Telemachus', a unit of the Royal Navy, was stationed in Australia at the time. Naval and Bureau officers arranged the route and timetable for the proposed cruise at a meeting held in January 1956.

It was arranged that the submarine would be available in Sydney late in May, when the installations of the pendulum apparatus would begin. The cruise was arranged to start on 1st June and finish on 31st July 1956. The gravity measurements were to be taken during periods between certain tactical exercises carried out on the cruise. The route was to be from Sydney to Wellington, Auckland, Tonga Is., Fiji Is., and back to Sydney. Between Auckland and Tonga Is. a zigzag course was arranged to give as many crossings of the Tonga and Kermadec Trenches as possible. The actual survey followed this programme and is described more fully in the next ssction of this Record.

Columbia University provided all the marine gravity equipment and an experienced observer, Mr H.M. Traphagen. The Bureau of Mineral Resources provided a portable Worden gravity meter for land connexions and a geophysicist, Mr. S. Gunson, to assist Mr Traphagen and to study the technique. The Bureau also notified interested parties at the main ports of call of the survey. The Royal Navy, in addition to making the submarine available, also provided a deep echo sounder. This was supplemented, on arrival in New Zealand, by a 'bomb' sounder designed and built by the Royal New Zealand Navy.

The object of the survey was to make measurements of the force of gravity at sea in the south-west Pacific Ocean, with particular emphasis on the features known as the Tonga and Kermadec Trenches. The two main uses for this information are :

(a) in determining the figure of the Earth; at present, these determinations are based almost entirely on land gravity measurements,

(b) in the study of the Earth's crust in an area known to be unstable and of great interest to students of geodesy (Daly, 1940, p. 347).

The field records of the survey have been reduced by the Lamont Geological Observatory. Talwani, Worzel and Ewing (1960) gave results of part of the survey; further results are given by Dooley (1963).

This Record is a description by the Bureau's observer of the cruise and survey. It includes details of the installation and operation of the apparatus and the reduction of the sea records to give gravity values, as carried out at the Lamont Geological Observatory.

2. DESCRIPTION OF CRUISE

Mr H.M. Traphagen of the Lamont Geological Observatory arrived in Sydney on 20th May 1956 with the equipment required for the survey. He was joined on that date by Mr S. Gunson of the Bureau of Mineral Resources.

After preliminary organisation on 21st May, installation was begun on 22nd May and completed on 29th May. The installation would have been completed earlier but for delay in obtaining two six-volt accumulators.

During the period of installation, the submarine was berthed at the RAN Torpedo Establishment wharf at Neutral Bay, Sydney. As conditions there were suitable, the base swings for Sydney were made on the night of 30th May. An earlier attempt the previous night failed because time signals from Station WWV could not be received.

HM Submarine 'Telemachus' sailed from Sydney at 0930 hours on 1st June. The first sea observation was made at 1700 hours the same day, the submarine then being 50 miles from Sydney Heads. From then until 2100 hours on 6th June, stations were occupied at intervals of 50 miles. After this, the spacing was altered at the request of DSIR so that the sea stations would fit into the pattern of the New Zealand gravity survey. The course and the station distribution are shown on Plate 1.

The 'Telemachus' reached Wellington (NZ) at 1500 hours on 7th June. The submarine stayed in Wellington for two days, during which time the observers were fully occupied. Base records were taken and a gravity tie was established to the New Zealand pendulum station at the Dominion Observatory. Some very interesting and informative discussions were held with Dr E.I. Robertson of DSIR. The course from Wellington to Auckland was altered at Dr Robertson's suggestion, and he presented the observers with bathymetric charts embodying more recent soundings than those shown on the Admiralty charts.

Mr R. Dibble, a geophysicist of DSIR, was aboard the submarine from Wellington to Auckland. At the same time, a North American gravity meter was taken aboard. This meter was lent by DSIR to be used for gravity ties in places such as Fiji where the Worden gravity meter would be off-scale.

The 'Telemachus' left Wellington at 1400 hours on 9th June, and arrived at Auckland at noon on 15th June. On arrival, the submarine was berthed in the Calliope dry dock at the Devonport Naval Dockyard. This had been arranged by the Royal New Zealand Navy to assist the taking of base records, as the open harbour in Auckland was unsuitable because of a strong tidal stream.

A good set of base records was obtained, and the submarine moved to a normal harbour berth next morning. Until 29th June, 'Telemachus' was engaged in tactical exercises with the Royal New Zealand Navy and Air Force. During this time, the observers, who were living ashore, were able to make the gravity connexions necessary and to consider the future programme for that part of the cruise over the Tonga and Kermadec Trenches.

The submarine left Auckland at 1400 hours on Friday 29th June for Suva (Fiji) via Tonga. A zigzag course was followed to obtain the maximum number of crossings of the trenches in the time available. The station spacings ranged between 15 and 60 miles, the smaller intervals being located near the ridge and trench, where the maximum gravity variations were expected.

This section of the cruise was arduous and a break of two days in Tonga from 9th to 11th July was most welcome. The submarine arrived in Suva at 0900 hours on 14th July. As at Auckland, the 'Telemachus' engaged from here in tactical exercises and the observers lived ashore in accommodation arranged by the Mines Department of Fiji.

Base records were to be taken in Suva and arrangements were made to establish gravity ties from the Woods Hole Oceanographic Institute stations to the submarine berth. In this, as in all matters related to the survey, the Fijian Department of Mines was most helpful. Transport and labour were provided and these greatly facilitated the work of the survey. Many discussions on problems of mutual interest were held with the Director, Mr D. Lloyd, and the Inspector of Mines, Mr K. Fleischmann.

The base records at Suva were made on the night of 22nd July and the expedition left Suva for Sydney at noon the next day.

For this section of the cruise a 50-mile spacing had been intended. This spacing had to be increased to 100 miles soon after leaving Suva because of mechanical reasons concerning the operation of the submarine.

The final sea station was occupied at 2130 hours on 30th July and the submarine berthed at Neutral Bay, Sydney at 0900 hours on 31st July. The same night, an attempt to obtain base records was abandoned because it was impossible to receive a time signal. A further attempt the following night was successful and this marked the end of the survey.

The equipment was then removed from the submarine and was packed to be taken back to Columbia University by Mr Traphagen.

Mr Traphagen left Sydney by air at noon on 6th August and Mr Gunson left Sydney the same day for Melbourne.

3. EQUIPMENT

The equipment used on the survey, a Vening Meinesz pendulum apparatus, belonged to the Lamont Geological Observatory, which had modified it. The equipment is not described in detail in this Record as adequate descriptions have previously been published (Vening Meinesz, 1929; Worzel and Ewing, 1950, 1952).

The following notes describe the main components of the equipment and the special modifications and unique features of the particular set used on the survey.

Vening Meinesz pendulum apparatus and recorder

This consisted of three main pendulums swinging in the same plane :

(a) two damped pendulums, one swinging normal to, and one swinging parallel to, the main swinging plane, and

(b) one dummy pendulum which carried a thermometer

The two damped pendulums were originally assumed to hang vertically at all times, but Browne (1937) has shown that they indicate the direction of the resultant of all the acceleration fields.

The camera which was on top of the pendulum case, recorded, on a moving photographic film, the movements of light spots reflected from mirrors on tops of the pendulums. The optical arrangement was such that the movements of individual light spots were proportional to the angle between:

(a) the normal damped pendulum and the case,

(b) the centre main pendulum and the parallel damped pendulum, and

(c) each of the outer main pendulums and the centre main pendulum

There was also a temperature-sensitive element in the form of a compound bar which controlled a light spot.

Long-period horizontal pendulums

These two pendulums were mounted at right angles to each other on the pendulum case below the recorder. They measured the horizontal accelerations of the apparatus. Each pendulum controlled a light spot directed on to the photographic film. Browne (1937) has shown the need for these measurements when measuring gravity at sea with the Vening Meinesz pendulum apparatus.

Crystal chronometer

The instrument used was made by the Bell Telephone Laboratories. The chronometer drove a synchronous motor, which in turn drove two spoked wheels whose purpose was to produce the light interruptions. One wheel had one spoke only and rotated at 100 c/s. A second wheel, geared to the first, interrupted the beam for a slightly longer period at every tenth interruption of the first. Another shaft, rotating at one cycle per minute, carried a contact which closed a relay circuit once a minute to make an even longer interruption. Thus three sets of interruptions were produced on the record at intervals of 0.01 sec, 0.1 sec, and one minute.

Time-signal amplifier

The time signal from WWV was fed into this equipment and amplified to cause a neon lamp to flash once a second. This flashing lamp was used to check the chronometer rate. The wheels of the synchronous motor described above were graduated on the circumference into decimal parts. Pointers were fixed to the frame of the motor so that the graduation passed near them. The flashing lamp acted as a stroboscope when held nearby, and the numbers opposite the pointers could be read. By doing this four or five times a day, a continuous check on the chronometer rate was obtained.

Power supply

As the apparatus is designed to run from 115-V A.C. supply, it was necessary to fit transformers to the submarine's power supply of 230-V A.C. All the items run continuously on the main supply, but the crystal chronometer had a stand-by supply consisting of low and high-tension batteries floating on the main supply line. This precaution ensured that the chronometer would not stop in the event of the ship's power supply breaking down.

Recording microbarograph

This was a standard instrument with a reading accuracy of 0.1 mm.

Recording thermometer

A standard instrument used only when abnormalities appeared in the temperatures recorded in the pendulum case.

Recording hygrometer

Also a standard instrument, for emergency use.

Developing outfit

A portable three-dish arrangement similar to those commonly used on land surveys.

4. INSTALLATION

The general installation has been discussed by Vening Meinesz (1929). The following description, illustrated by Plate 2, refers to the particular arrangement used in HM Submarine 'Telemachus'.

The entire equipment, observers' luggage, and two bunks were installed in the magazine, which had been emptied of ammunition.

The free space available was 12ft x 5ft x 5ft, the greatest dimension being across the ship. Plate 2 shows how the equipment was arranged in this space.

The pendulum equipment was fixed to two wooden beams attached to the after bulkhead, and a similar arrangement was used for the shelves that held the ancillary equipment.

The bunks, which could be folded up when not in use, were attached by hinges, also to the after bulkhead, one bunk being above the other.

A minimum time of three days was required to load and install the equipment. This did not include the time taken by naval workmen to fit the shelves and bunks.

Every item in the magazine had to be small enough to go through a 22-in.-diameter hatch.

5. OBSERVATIONS

General

Two types of observations were made, namely those at sea and those at base. The first type were made when the submarine was submerged, travelling ahead, and to some extent rolling from side to side. These observations were subject to correction for such disturbances.

Base observations were made under conditions such that most of the disturbances were absent or could be ignored. Such conditions exist in a laboratory and to a lesser extent in a submarine at rest on the surface in quiet water. In the latter case, conditions were seldom perfect, but the pendulums could usually be swung with negligible disturbances caused by horizontal, vertical, or angular movements.

Reliable base records were essential to an accurate determination of the periods of the three main pendulums.

The two most important base measurements were those made before and after the survey in a laboratory at the home station (in this case Lamont Geological Observatory). These two measurements show whether the periods of the pendulums have changed during the survey.

Secondary base records were taken during the cruise. If these can be taken at places where the value of gravity is known, the survey can be divided into sections, and errors can be isolated. Therefore, it is desirable to tie the submarine survey to known values of gravity as often as possible. It is not practical to remove the equipment from the ship during a survey, and rough wind and water conditions in harbours can prevent the taking of reliable observations.

During this survey ideal conditions were experienced in Auckland, where the submarine was berthed in a closed dock. At other places it was necessary to wait for suitable weather and tidal conditions before making base records.

Another essential to the taking of reliable base records is an accurate rating of the chronometer during the period of the observations. This was a source of worry, not only for the base observations, but during the whole survey. Columbia University uses the time signals transmitted by WWV to rate the crystal chronometer. Reception of these signals during the survey was never good and was usually poor. In any future survey in these waters it would be advisable to have an alternative method of rating the chronometer.

It is usual to make records of five swings for each base observation. Of these, three are the same as for sea records, viz. the two outer pendulums are swung in opposition while the centre one hangs free. The other two records are made with one outer pendulum hanging free and the other two swinging in opposition. From these records the periods of all three pendulums can be determined.

This was done at the survey base, Lamont Geological Observatory, and served as a basis for reducing the periods determined at sea to gravity values (see section on calculations). The records at Sydney and other places where the value of g is known provided a check on whether there had been any change in the periods since the observation at Lamont.

Full details of the method of taking base records are given later.

Sea records

This description commences at the stage when the submarine has reached the depth required and is nearly trimmed (i.e. travelling at constant depth, course, and speed).

(1) Unclamp gimbal frame and wait for signal from control room that final trim has been reached. When the vessel is trimmed, watch the pendulum case to see if the ship is rolling enough for there to be danger of the case hitting the stops. If it is, re-clamp frame and advise the control room to go deeper if possible. If there is no danger, proceed as follows.

(2) Level the pendulum case. This is done by shifting a counter-weight (e.g. a spanner) on top of the case. A rough level only is necessary at this stage as it will change when the pendulums are lowered.

(3) Unlock the long-period horizontal pendulums.

(4) Lower, then raise, then lower the long-period pendulums. This is to adjust them on their seats in case they have shifted as a result of rolling, etc.

(5) Switch on the recording light.

(6) Unlock the lowering mechanism and lower the main pendulums. During this operation the observer must watch the screen and ensure that the light spots come down smoothly and remain 'still' when fully lowered. If the ship is rolling, as it will usually be, the pendulums will appear to be moving slowly. Faulty lowering can be distinguished by a higher-frequency movement.

During this and later operations the observer must operate the controls of the instrument without impeding the free movement of the case.

(7) Adjust the counter weight for final level. When first attempted, this will appear impossible because of the movement of the bubbles, but with a little practice the operation is not difficult. The following points may assist the observer:

(a) the athwartships bubble usually oscillates evenly about its position of rest. Adjust it to make equal movements left and right of the centre,

(b) adjusting the fore and aft bubble is much harder, as it reflects changes of speed of the submarine which are not as regular as the rolling. The bubble may have to be observed for up to two minutes to obtain its average position. Level requirements are within one division of centre on each bubble.

(8) Deflect each of the outer pendulums gently, watching the spots.

(9) If the centre pendulum is swinging, stop it with the deflecting lever and then free it.

(10) Release the pendulums. This should be done when there is no horizontal movement in the swinging plane. The athwartships bubble is the control for this and should be watched. This operation is largely a matter of experience.

If the release has been successful the spots on the screen will be moving with equal amplitude. If they are not, the procedure must be repeated from step No. 8.

(11) Start the film-drive motor.

(12) Switch on the power to the minute-break relay.

(13) Deflect the light spots from the screen to the paper, note the time in data book, and signal 'start of run' to the control room.

(14) Unclamp both long-period pendulums. It is good practice to always release them in the same order to ensure identification on the record.

(15) Read the temperatures, pressure, and humidity.

(16) Thirteen minutes after the start of run, signal 'middle of run' to the control room.

(17) Read the temperatures, pressure, and humidity and sketch the mean position of the bubbles. Owing to the motion of the ship some minutes are required for this.

(18) Twenty-four minutes after the start of the run commence reading the temperatures, pressure, and humidity.

(19) Twenty-six minutes after the start, deflect the spots back to the screen.

(20) Clamp long-period pendulums.

(21) Stop the main pendulums with the deflecting levers.

(22) When the pendulums are still, raise and lock them.

(23) Switch off the light and the paper drive.

(24) Raise and lock the long-period pendulums.

(25) Clamp the gimbal frame.

(26) Signal 'end of run' to the control room.

Base records

As mentioned previously, two types of base records are made. In the first type the outer pendulums are swung and the centre pendulum hangs free; in the second type the centre pendulum and one outer pendulum are swung, and the other outer pendulum hangs free.

The base records with the outer pendulums swinging are the same as the sea records and are taken in exactly the same manner except that there is no need to signal the control room. The base observation is easier because the ship is, or should be, quite still.

Some modifications to the method are necessary for the second type of record because the centre pendulum is the only one of the three main pendulums that makes its own trace on the record. Each outer pendulum forms a fictitious pendulum with the centre one to give the other pendulum traces. In the first type of record the movement of the centre pendulum is known from its trace and hence the fictitious pendulums can be corrected. For a correction to be applied to the second type of record the movement of the free outer pendulum must be known, and this can be measured only when the centre pendulum is still (Vening Meinesz, 1929). Because of this, the procedure when taking the second type of record is as follows:

> The pendulums are lowered and made to hang as still as possible. A record of about 2-min duration is made while they are in this condition. The centre pendulum and one outer pendulum (say the right) are then deflected and released. This must be done carefully so as not to disturb the left pendulum. Recording then proceeds as from step 13 of the sea observation. At the end of 26 min the centre and right pendulums are stopped without disturbing the left pendulum. A short record of about 2-min duration is made. Because the centre pendulum is now still, this record will show the amplitude picked up by the left pendulum. This completes the observation.

6. CALCULATIONS AND CORRECTIONS

General

Throughout this section the pendulums are identified by the numbers used by Columbia University. The two outer pendulums are No. 4 and 5 and the centre one is No. 6.

The record produced by the apparatus has seven traces, as follows:

(a) movement of the centre pendulum (No. 6),

(b) movement of the 4, 6 fictitious pendulum (No. 4 - No. 6),

(c) movement of the 5, 6 fictitious pendulum (No. 5 - No. 6),

(d) movement of the athwartships long-period horizontal pendulum,

(e) movement of the fore and aft long-period horizontal pendulum,

(f) the position and movement of the pendulum that swings normal to the main swinging plane,

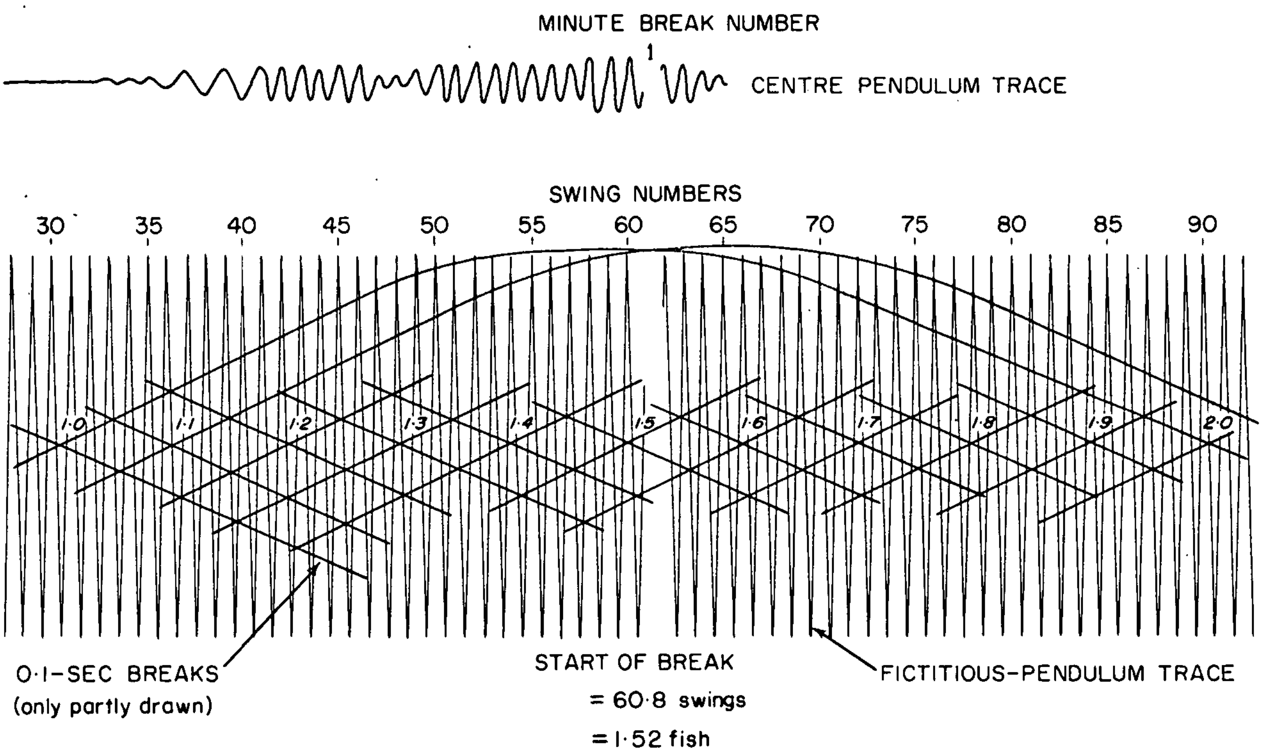
(g) a record of the variation of temperature in the pendulum case.

Data are recorded for each observation in two books:

(a) the data book - filled in by the observer,

FIGURE I

(Facing Page 10)



FISH No.	SWING No.
1·0	30·25
1·1	36·20
1·2	42·25
1·3	47·75
1·4	53·75
1·5	60·00
1·6	66·00

DETERMINATION OF RAW PERIOD

Specimen page from data book

Run No.	Date		Time	Air temp.	Bulb temp.	Humidity	Pressure	Break*	Levels∅
		Start							
		Middle							
		End							

* Break is an identifying mark placed on each record. The time of its insertion is noted in this column.

∅ Levels. If off-centre, their position is sketched.

(b) the dive record book - filled in by the officer of the watch.

Specimen page from dive record book

Run No.	Speed	Course
Time started	Time finished	
Depth and sounding at		
Start	Middle	End
Current course & speed	Wind direction & force	Sea direction & size

Determination of the raw period

(a) At the start of the record, draw in six successive crosses through the 0.1-sec breaks on the centre lines of the 4, 6 and 5, 6 traces. Number these from 1.1 to 1.6 as shown on Figure 1. The interval between 11 of these crosses forms what is known as a 'fish', and these numbers represent decimal parts of a 'fish'. The 0.1-sec breaks form sine-wave patterns, known as 'phase lag curves' on the pendulum traces. An example is shown, by Vening Meinesz (1929 , Fig. 7). In that figure the effect of vertical accelerations can be seen as a ripple on the phase lag curve.

Ensure that the lines forming the crosses are always drawn through the beginnings of the 0.1-sec breaks or through the ends. Continue to count up the crosses, marking each tenth one by 1.0, 2.0, 3.0, etc., to fit in with those already marked. Do not insert all the crosses until the end of the record is reached, when six crosses are drawn and numbered as at the beginning.

Fig. 2

GRAVITY AMPLITUDE CORRECTION

Name...No.....................Record No.............................

Instructor..Date.....................................

	#	1. $2a_6$	2. $2b$	3. $2a_{4,6}$	4. $2a_{5,6}$	5. $(2a+1.32 \times 2b)^2_{4,6}$	6. $(2a-1.32 \times 2b)^2_{5,6}$	7. $(2a_6)^2$	8. $(2b)^2$	9. $2a$	10. $(2a)^2$	11. d	12. β_c	13. β_c^2
	½×1													
	2													
	3													
	4													
	5													
	6													
	7													
	8													
	9													
	10													
	11													
	12													
	½×13													
	Average													
MEAN— 1st HALF														
MEAN— 2nd HALF														

	FIRST HALF OF RECORD	SECOND HALF OF RECORD	MEAN—ENTIRE RECORD
$0.774\,[(2a)^2 - \frac{1}{4}(2b)^2]_{4,6}$			
$_{5,6}$			

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(b) Number the last swing before the first minute-break as 60 and number sufficient swings either side of it to cover the section over which the crosses have been drawn.

(c) Note on the record the exact number of swings completed at the start of the first minute-break; in the example shown in Figure 1 this is 60.8.

(d) Count and number the minute breaks from start to finish of the record. Multiply by 60 to give seconds.

(e) Determine the number of 'fish' between the start of the first and last minute-breaks. This should be estimated to 0.01 of a 'fish'.

(f) During each 'fish' the pendulums have lagged by one swing, so the number of swings from the first to the last minute-break equals the number of seconds minus the number of 'fish'. Add this result to the swing number at the start of the first breaks to obtain the number of the swing at the start of the last break (this could also be obtained by counting the swings but as there are about 1500 swings this is a very tedious procedure).

(g) Number sufficient swings near this to cover the section of crosses as was done at the beginning of the record.

(h) Estimate and list the swing number for each cross at the beginning and the end of a record (to 0.05 of a swing) i.e. horizontal position of cross relative to position taken as start of each swing.

(i) Step (h) gives six cross and six swing-numbers from each end of the record. Subtract the start series from the end series in order. From this, six cross differences are obtained which are the same and six swing numbers which must be averaged. This gives the ratio of 'fish' to swings.

(j) A 'fish' is the time in seconds taken for the pendulum to lose one swing relative to the second marks from the clock.

Then, number of swings per 'fish' + 1 = number of seconds per 'fish'.

$$\text{The raw period} = \frac{\text{seconds}}{\text{swings}} = \frac{\text{number of swings + number of 'fish'}}{\text{number of swings}}$$

$$= 1 + \frac{\text{'fish'}}{\text{swings}}$$

Gravity Amplitude Correction (See Figure 2)

The quantities shown on the form are read at each alternate minute mark, numbered consecutively, and entered on the form. The number of each measurement is entered in Column ~~A~~.

The measurements (made at alternate minute breaks) are:

Column (1) $2a_6$ = double amplitude of No. 6 trace (cm).

Column (2) 2b, described later.

Column (3) $2a_{4,6}$ = double amplitude of 4, 6 trace (cm).

Column (4) $2a_{5,6}$ = double amplitude of 5,6 trace (cm).

Column (5) & (6) Self-explanatory using appropriate 'a' values.

Column (7) Self-explanatory.

Column (8) " "

Column (9) 2α = Double amplitude of β trace (mm).

Column (10) Self-explanatory.

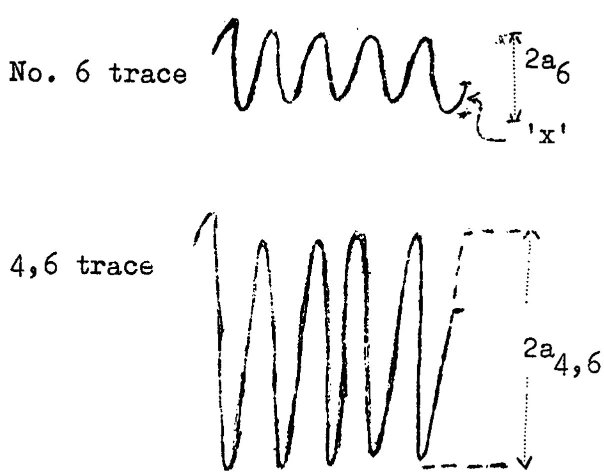
Column (11) d = distance of β trace from a reference mark (mm); this will vary if the apparatus is not accurately level.

Column (12) c = d - correct distance of β trace from the reference mark (mm). This correct distance is obtained from all records for which the apparatus was known to be levelled accurately.

Column (13) Self-explanatory.

With the exception of Columns 1, 9, 11, and 12, the average values of the quantities are obtained. In obtaining these, the first and last measurements are given half the weight of the intermediate measurements.

Determination of 2b (Column 2 of Figure 2)



(a) Find the number of degrees required to complete the swing on the 4, 6 trace. A graticule can be used to do this.

(b) Find the number of degrees from trough (or crest) to the start of the break on the No. 6 trace by finding $x/2a_6$ as a percentage and referring to a table.

(c) Add the two previous results and convert this to a percentage by using the same tables. This percentage of $2a_6$ is 2b.

2b is numerically the same but opposite in sign for the 4, 6 and 5, 6 traces. For the equipment used in the survey, 2b was positive for the 4, 6 trace if the end of the 4, 6 trace lay on the same side of its axis as the end of No 6 trace on its axis after step No. 3 had been done. When the ends lay on different sides (one below and one above) 2b was negative.

Fig 3

GRAVITY BROWNE CORRECTION

Record ____________ Date ____________

Vessel ____________ Computer ____________

	(for $2a_F$)		(for $2a_y$)		(for $2a_z$)	
	$2a_F$	T_w	$2a_y$	T_w	$2a_z$	T_{w-}
1		.00		.00		.00
½ x 1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
½ x 13						

g base gravity (980.2584)

y athwartships

z fore & aft

S slow pendulum

T_a gimbal period y direction

T_b gimbal period z direction

T_w water wave period

Mean $2a_{4,6}$ **or** $2a_{5,6}$ } use trace on which $2a_F$ is measured

$2\,\frac{\text{mean } 2a_y}{\text{mean } a_y}$ $\qquad$ $2\,\frac{\text{mean } 2a_z}{\text{mean } a_z}$

Mean T_w = 0.00

L = 0.00

H =

$1/F_y$ =

$1/F_z$ =

$$(\text{vert})\ \delta g_1 = L\left(\frac{2a_F}{2a_{(4,6)\,(5,6)}}\right)^2 \times 10^3 = \left(\frac{\qquad}{}\right)^2 \times 10^3$$

= + ____________ mgal

$$(\text{hor})\ \delta g_2 = -98\left[\left(\frac{a_y}{F_y}\right)^2 + H\left(\frac{a_z}{F_z}\right)^2\right]$$

$$= -98\left[(\quad x \quad)^2 + (\quad x \quad)^2\right]$$

$$= -98\left[\qquad + \qquad\right] = - \text{ ____________ mgal}$$

$$L = \frac{g\,\pi^2\,T^2}{18\,T_w^2} \qquad H = 1 + 2\left(\frac{T_w^2 + T_b^2}{T_w^2 - T_b^2} \cdot \frac{T^2}{T_w^2}\right)$$

$$\frac{1}{F_y} = \frac{T_{Sy} - T_a}{T_{Sy} + T_a} - \frac{\left(T_w/T_{my} - T_{my}/T_w\right)^2}{T_{Sy}/T_a - T_a/T_{Sy}} \quad ; \quad T_{my} = \sqrt{T_a T_{Sy}}$$

$$\frac{1}{F_z} = \frac{T_{Sz} - T_b}{T_{Sz} + T_b} - \frac{\left(T_w/T_{mz} - T_{mz}/T_w\right)^2}{T_{Sz}/T_b - T_b/T_{Sz}} \quad ; \quad T_{mz} = \sqrt{T_b T_{Sz}}$$

Browne Correction (See Figure 3)

This form is used to establish corrections for disturbances due to the horizontal and vertical accelerations of the pendulum apparatus.

Quantities used on the form are:

(a) T_a and T_b, the periods of the apparatus swinging in the gimbal frame in the athwartships and fore-and-aft directions respectively. T_a can be obtained from the trace of the athwartships long-period pendulum and T_b from the trace of the fore-and-aft long-period pendulum. Swaying of the apparatus forms a ripple on these traces,

(b) T_{Sy} and T_{Sz}, the natural periods of the two long-period pendulums. The periods can be found on the film traces just after the pendulums are released. They oscillate for a short time at their natural frequency.

These four quantities, T_a, T_b, T_{Sy}, and T_{Sz} are normally constant throughout a cruise and mean values (derived from all the records of the cruise) would be used.

(c) $2a_F$, twice the vertical amplitude of the ripple on the phase-lag curve. This ripple is present only if the apparatus is subject to vertical accelerations,

(d) $2a_y$ and $2a_z$, the double amplitudes of the disturbances on the long-period pendulum traces.

$2a_F$, $2a_y$, and $2a_z$ are measured at every alternate minute and averaged separately. The first and last measurements are given half the weight of the others in calculating these averages. T_w is the water-wave period, and is measured on the traces of the long-period pendulum. Four measurements are made on each trace and the average is used for T_w. This period can also be derived from the phase-lag curve (associated with $2a_F$). This is not done unless some abnormality appears on the long-period pendulum traces.

T is the period of the gravity-measuring pendulums to the fourth place of decimals.

All other terms are defined on the form.

It should be noted that the correction for vertical acceleration, δg_1, is always positive, and that for horizontal acceleration, δg_2., is always negative.

Final computations (See Figure 4)

The following notes may help to explain the various columns on the form:

Column (2) This is the bulb temperature, which in most cases is nearly the same as the air temperature. If it is not, both temperatures are used.

Column (4) Humidity as read on hygrometer in pendulum case.

Column (5) Result of any correction made to the reading in (4).

Fig. 4

PENDULUM GRAVITY COMPUTATION FORM

FOR PENDULUMS 4 AND 5

LAMONT GEOLOGICAL OBSERVATORY OF COLUMBIA UNIVERSITY

* DATA FOR THESE COLUMNS FROM DATA BOOK

CRUISE ______

COMPUTATION DATE ______

COMPUTER ______

(1) RECORD	*(2) TEMP. C°	(3) 30-TEMP C°	*(4) HUMIDITY %	(5) CORR. HUMID. %	*(6) PRESS. READ mm of Hg	(7) PRESSURE mm of Hg	(8) 3/8 e′ mm of Hg	(9) (5) X (8) mm of Hg	(10) CORR. PRESS. (7)−(9)
0									
1									
2									
3									
4									
5									
6									
7									
8									
9									

(11) d .001---	(12) AIR DENS. (10) X (11)	(13) ISOCHRONOUS +0.4 X (3)	(14) -18 X (12)	(15) CORRECTION $U_{4,6}$ (13)+(14)+$\frac{T_4-T_6}{}$	(16) 4,6 $0.88 \times \frac{2b}{2a_{4,6}}$	(17) ISOCHRONOUS +1.0 X (3)	(18) 9 X (12)	(19) CORRECTION 5,6 $U_{5,6}$ (17)+(18)+$\frac{T_5-T_6}{}$	(20) $0.88 \times \frac{2b}{2a_{5,6}}$

(21)	*(22) CHRONOMETER SECS/DAY	*(23) TRUE COURSE DEGREES	(24) SIN(23)	*(25) SPEED IN KNOTS	(26) (24) X (25)	*(27) SET DEGREES TRUE	(28) SIN(27)	*(29) DRIFT IN KNOTS	(30) (28) X (29)
0									
1									
2									
3									
4									
5									
6									
7									
8									
9									

(31) (26) + (30)	(32) LATITUDE DEGREES	(33) COS (32)	(34) .0075 X (31) X (33)	*(35) KEEL DEPTH IN FEET	*(36) INSTR. DEPTH IN FEET (35) - ___	(37) -.0679 X (36)	*(38) WATER DEPTH IN FATHOMS	(39) WATER DEPTH IN METERS 1.829 X (38)	(40)

(41) PENDULUM 4	(42) TEMP. CORR. 98.4 X (3)	(43) DENS. CORR. -1319 X (12)	(44) ISOCH CORR. -(15) X (16)	(45) CHRON CORR. -116.2 X (22)	(46) -β CORR.	(47) -AMPL. CORR.	(48) Σ CORR.	(49) RAW T	(50) CORR T
0									
1									
2									
3									
4									
5									
6									
7									
8									
9									

*(51) ΔT (50) − T_4	*(52) $-\Delta g_1$ $-(51) \times 2g/T_4$	(53) Δg_2	(54) CORR. g = g + (52) + (53)	(55) BROWNE VERTICAL	(56) BROWNE HORIZONTAL	(57) EOTVOS (34)	(58) DEPTH (37)	(59) Σ CORR Σ(55)(56)(57)(58)	(60) RECORD
									0
									1
									2
									3
									4
									5
									6
									7
									8
									9

(61) PENDULUM 5	(62) 99.0 X (3)	(63) -1346 X (12)	(64) -(19) X (20)	(65) -116.2 X (22)	(66)	(67)	(68)	(69)	(70)
0									
1									
2									
3									
4									
5									
6									
7									
8									
9									

*(71) ΔT (70) − T_5	*(72) $-\Delta g_1$ $-(71) \times 2g/T_5$	(73)	(74) CORR. g + (72), (73)	(75) MEAN G MEAN (54) + (74)	(76) (59)	(77) FINAL G (75) + (76)	*(78) LATITUDE (32)	*(79) LONGITUDE	(80) RECORD
									0
									1
									2
									3
									4
									5
									6
									7
									8
									9

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Column (6) Pressure as read on baragraph.

Column (7) Reading in (6) plus instrumental correction.

Column (8) Correction for partial pressure of water vapour.

Column (11) $d = 1/760 \times 1/(1 + 0.00367t^{o}C)$. Read from graph.

Column (15) As stated. T_4 & T_6 are the periods as determined at the base station, in this case Lamont Observatory.

Column (16) $2h$ and $2a_{4,6}$ are obtained from the gravity amplitude correction form.

Columns (17), (18), (19), and (20). As for columns (13), (14), (15), and (16) except that pendulums 5 and 6 are concerned.

Column (21) Not used.

Column (22) Chronometer rate as found by checking against standard time signals.

Column (27) Bearing of current } These two items are not usually known.

Column (29) Speed of current }

Column (34) This is the Eotvös term.

Column (37) Reduction to sea level.

Column (38) Should refer to same datum as (35)

Column (40) Not used.

Columns (41) and (61) Record numbers.

Columns (42) to (54) and (62) to (74) are analogous and differ only in that they deal with the 4,6 and 5,6 pendulums respectively.

Column (46) Calculated as shown on correction form.

Column (47) As above.

Column (49) Raw period derived as shown earlier.

Column (50) As stated. Equals (48) + (49).

Column (51) ΔT, as stated. T_4 is the period of No. 4 pendulum as established at the base, in this case Lamont Observatory, USA.

Column (52) As stated. g = base gravity value.

Column (53) $\Delta g_2 = 3g/T_4^{2} . (\Delta T)^2$. Terms have meanings as described above.

Column (55) Obtained from Browne correction form.

Column (56) Obtained as in (55).

Corrections

These formulae have been copied from Mr Traphagen's notes and show the number of decimal points required.

(1) Expression for use in Amplitude Correction

$0.774 \left[(2a_6)^2 - \frac{1}{4}(2b)^2\right] = 0.00$

(2) Beta Correction

$2.04 \left[(0.85)(2\alpha)^2 + \beta_c^2\right] = 0.0$

(3) Amplitude Correction

$4,6 = 4.24 \left\{(2a_{4,6} - 1.32 \times 2b)^2 + (1)\right] = 0.0$

(4) Amplitude Correction

$5,6 = 4.24 \left[(2a_{5,6} - 1.32 \times 2b)^2 + (1)\right] = 0.0$

(5) Isochronous Correction

$0.88(2b)/2a_{4,6} = 0.0000/2a_{4,6} = 0.0000$

(6) Isochronous Correction

$0.88(2b)/2a_{5,6} = 0.0000/2a_{5,6} = 0.0000$

(7) Air density

P_s, T_s } Standard pressured temperature (760 mm and 273°K)

$PV = NRT$ — T Absolute temperature of measurement

t Centigrade " " "

N = number of moles

$N_a = m_a/M_a$ = mass of dry air/mass of mole of dry air

$N_w = m_w/M_w$ = mass of water vapour/mass of mole of water vapour

ρw = density of moist air

ρa = density of dry air

e = vapour pressure of water vapour

$\rho w = (m_a + m_w)/V = (P - e)M_a/RT + eM_w/RT$

$\rho a = m_a/V = P_s M_a/RT_s$

Relative density $= \rho_w/\rho_a = (T_s/TP_s)\left[P - e(1 - M_w/M_a)\right]$

$= (P - 0.379e)/\left[760(1 + 0.00366t)\right]$

7. RESULTS

All the field data recorded on the survey have been reduced to gravity values by the staff of the Lamont Geological Observatory, Columbia University, USA. The reductions have been made by the methods explained in Section 6 of this record. Results of that part of the survey which crossed the Tonga and Kermadec Trenches have been published by Talwani et al. (1961). The results have been made available to the Bureau of Mineral Resources and have been discussed briefly by Dooley (1963).

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Mr K. Fleischmann, Inspector of Mines, Suva, Fiji,

Captain James, Harbourmaster, Suva, Fiji.

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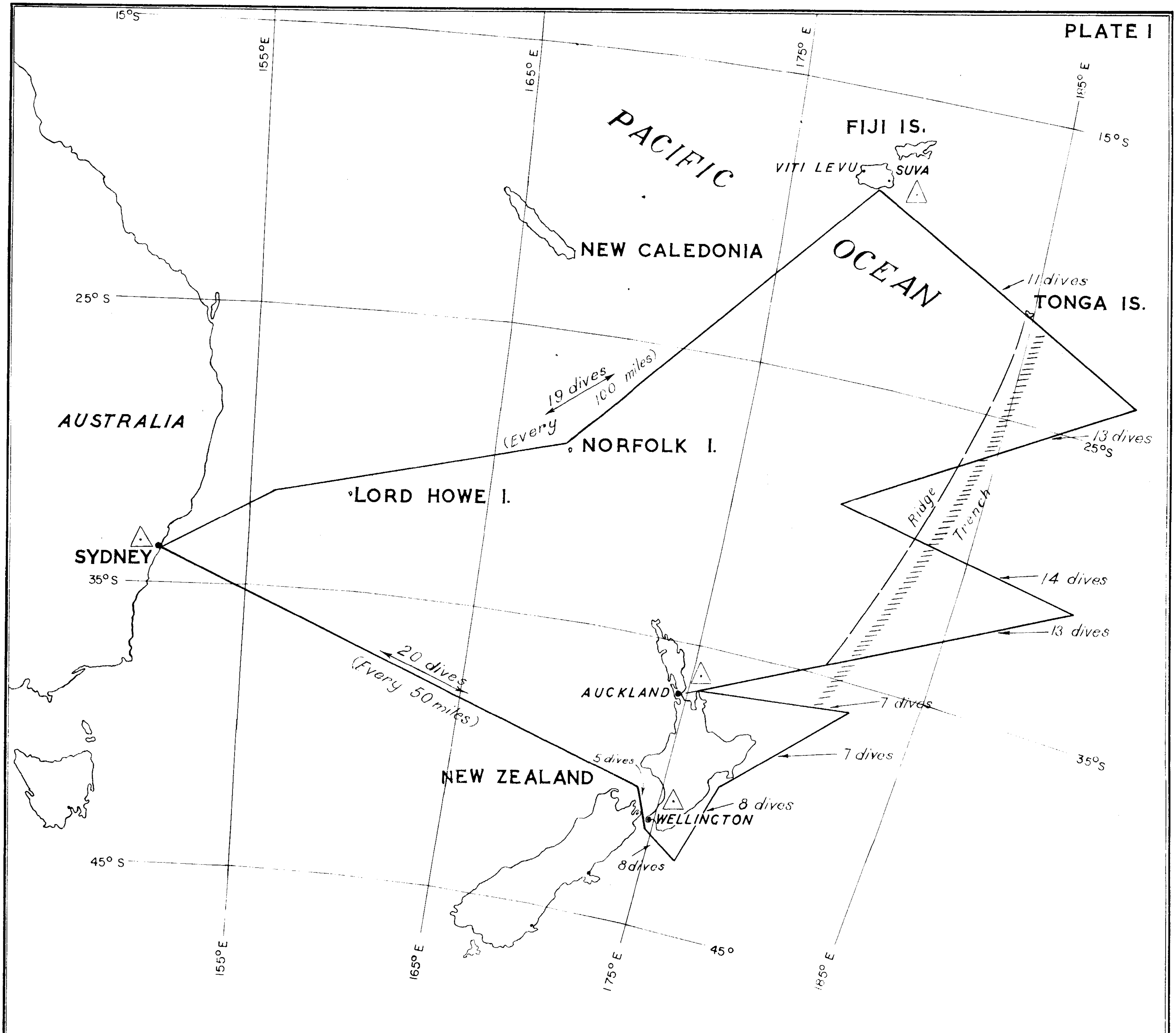
PLATE I



SKETCH MAP OF SOUTH-WEST PACIFIC

SHOWING CRUISE OF H M SUBMARINE TELEMACHUS JUNE-JULY 1956

COURSE SHOWN THUS

BASE MEASUREMENTS SHOWN THUS △

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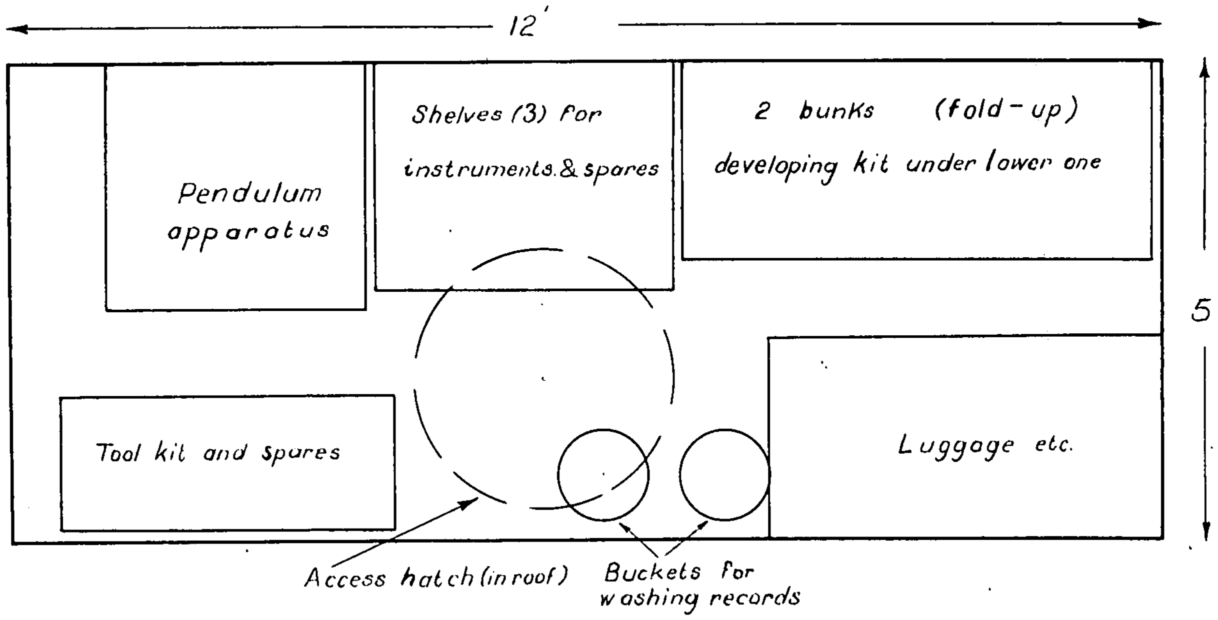
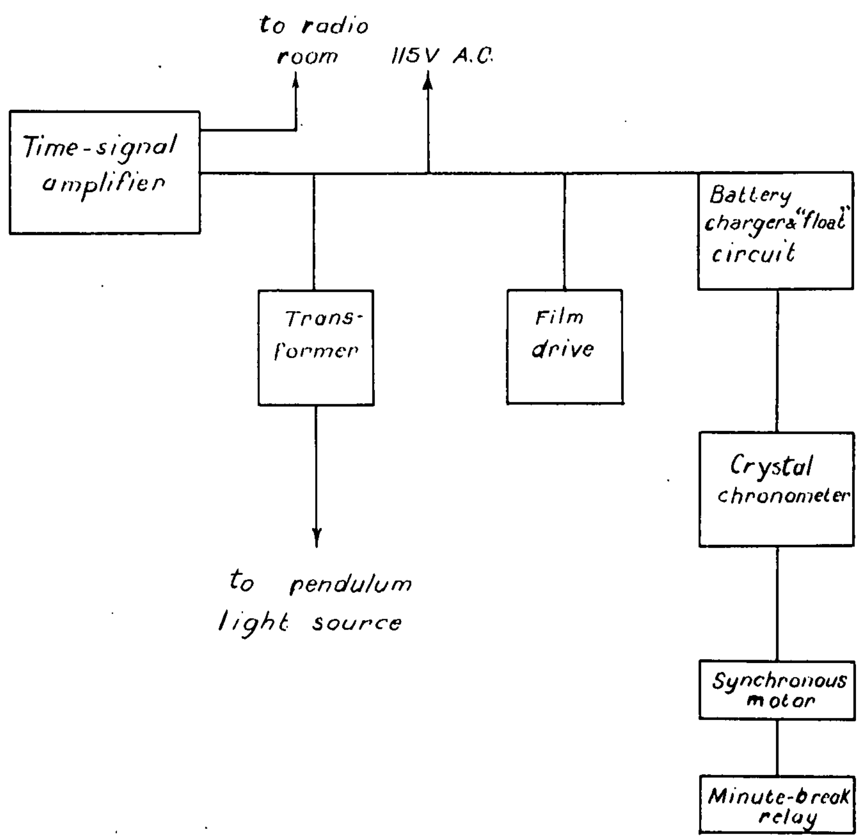
PLATE 2



FLOOR PLAN



BLOCK DIAGRAM OF POWER DISTRIBUTION

MAGAZINE OF H M SUBMARINE 'TELEMACHUS'

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