UNCLASSIFIED

AD NUMBER:	AD0363623

CLASSIFICATION CHANGES

TO:

Confidential/FRD

FROM:

Secret/RD

AUTHORITY

6 Aug 1965 per AEC/DASA Document marking

THIS PAGE IS UNCLASSIFIED

UNCLASSIFIED

AD 363623

CLASSIFICATION CHANGED
TO: UNCLASSIFIED
FROM: SECRET -RESTRICTED DATA
AUTHORITY:

DNA ltr, 29 Aug 80

UNCLASSIFIED

SECURITY MARKING

The classified or limited status of this report applies to each page, unless otherwise marked. Separate page printouts MUST be marked accordingly.

"This document contains information affecting the National Defense of the United States within the meaning of the Espionage Laws, Title 18, U. S. C., Section 793 and 794. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law."

EXCLUDED FROM AUTOMATIC
REGRADING; DOD DIR 5200.10
DOES NOT APPLY

" ONE HALF ORIGINAL SIZE " **attachment A**

SECRET

WT-635

Copy No. [redacted] A

363623

TECHNICAL LIBRARY
29 JUL 1965
of the
A/1155/65
DEFENSE ATOMIC
SUPPORT AGENCY

Operation IVY

PACIFIC PROVING GROUNDS

November 1952

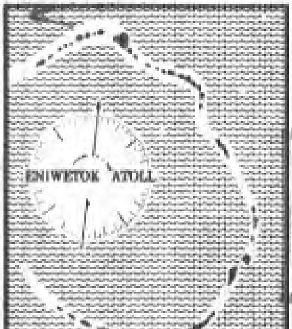
Transclassified by 3-7-58
(Signature of person authorizing
transclassification and date
thereof)

Project 6.4b

BAROMETRIC AND WATER-SURFACE WAVES PRODUCED BY MIKE SHOT

This material contains information affecting the national defense of the United States within the meaning of the espionage laws, Title 18, U.S.A., Secs. 793 and 794, the transmission or the revelation of which in any manner to an unauthorized person is prohibited by law.

CAT/



DDC
AUG 6 1965
TISIA D

RE[redacted]TA

Thi
de
co ized
person is prohibited.

FORMERLY RESTRICTED DATA
HANDLE AS RESTRICTED DATA IN FOREIGN DISSEMINATION
SECTION 144B, ATOMIC ENERGY ACT, 1954

JOINT TASK FORCE 132

DDC CONTROL
NO. 53370

SECRET

WT-635

This document consists of 40 pages

No. 213 of 220 copies, Series A

Report to the Scientific Director

BAROMETRIC AND WATER-SURFACE WAVES PRODUCED BY MIKE SHOT

By

Willard Bascom

Walter Munk

William Van Dorn

"This document conta[illegible] the National
Defense of the Uni[illegible] of the
Espiona[illegible] Laws, [illegible] and 794.
Its tra[illegible]ssion [illegible]ents in [illegible]
manner to an una[illegible] by law."

U. S. MILITARY [illegible]
FROM DDC. O[illegible]

[illegible] REPORT DIRECTLY
[illegible] THROUGH Sponsoring
Agency to:
[illegible] Agency
Washington, D. C. 20301

Scripps Institution of Oceanography
University of California
La Jolla, California
June 1953

FORMERLY RESTRICTED DATA
HANDLE AS RESTRICTED DATA IN FOREIGN DISSEMINATION
SECTION 144B, ATOMIC ENERGY ACT, 1954

~~RESTRICTED DATA~~

~~This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.~~

This material contains information affecting the national defense of the United States within the meaning of the espionage laws, [illegible] Secs. 793 and 794, the transm[illegible] of which in any manner to an unau[illegible] is prohibited by law

Excl[illegible]
downgrading and decl[illegible]

ABSTRACT

Barometric and water-surface waves generated by Mike shot were studied by means of 25 instruments in 19 locations in the Pacific Basin ranging from 12 to 4600 nautical miles from Ground Zero. Several new kinds of instruments were constructed and used, and deep-sea instrument stations were installed on the tops of two sea mounts.

The first water waves arriving at Eniwetok Island apparently traveled along paths outside the lagoon.

At several of the stations there were two distinct arrivals of water waves, the first apparently being driven by the propagated rise in atmospheric pressure caused by the explosion and thus traveling at the speed of sound and the second moving along the water surface in the usual manner at a velocity of the square root of gh.

At the distant island stations a long-continued persistence of wave activity substantially above background was observed, modulated by sporadic enhancements that suggest reflections from major land masses.

For reasons not yet completely understood, the waves were much lower than had been estimated, particularly at the nearer observation points. The highest waves recorded were less than 3 ft.

CONTENTS

Page

ABSTRACT 3

1 OBJECTIVE 7

2 BACKGROUND 7

3 INSTRUMENTATION 8

- 3.1 Absolute-pressure Recorders (BA), Mark X 8
- 3.2 Differential-pressure Recorders (BD), Mark IX 8
- 3.3 Differential-water-level Recorder (VD) 9
- 3.4 Tide Gauges (TG) 13
- 3.5 Tsunami Recorders (TR) 13
- 3.6 Microbarographs (MB) 13
- 3.7 Barographs (B) 13

4 RESULTS 14

- 4.1 Eniwetok Atoll 14
- 4.2 Marshall Islands Area (25 to 500 Miles) 15
- 4.3 Far Stations (500 to 5000 Miles) 15
- 4.4 Summary of SIO Barographic Measurements 16

5 REMARKS ON THE ANALYSIS OF DATA 17

- 5.1 Seiching 17
- 5.2 Computed Air and Water Arrivals 17

6 RECOMMENDATIONS 18

7 CONCLUSIONS 19

APPENDIX A RECORDS OF WAVE AND TIDE STATIONS 21

APPENDIX B SUGGESTION FOR A MODEL TEST AT BIKINI ATOLL 35

ILLUSTRATIONS

1 Schematic Diagram of Pressure Pickup of Mark IX Model 6 Wave Meter . . . 12

A.1 Absolute-pressure Recorder (BA), Runit 23

ILLUSTRATIONS (Continued)

Page

A.2 Absolute-pressure Recorder (BA), Eniwetok 23

A.3 Tide Gauge (TG), Eniwetok 24

A.4 Tide Gauge (TG), Kwajalein 25

A.5 Differential-water-level Recorder (VD), Wake 26

A.6 Tide Gauge (TG), Wake 27

A.7 Tide Gauge (TG), Truk 28

A.8 Differential-water-level Recorder (VD), Guam 29

A.9 Tide Gauge (TG), Yap 30

A.10 Tide Gauge (TG), Midway 31

A.11 Differential-water-level Recorder (VD), Midway 32

A.12 Differential-water-level Recorder (VD), Kawaihae, T. H. 32

A.13 Microbarograph (MB) and Tsunami Recorder (TR), La Jolla, Calif.; Tsunami Recorder (TR), Oceanside, Calif. 33

TABLES

1 Summary of Analysis of Records 10

2 Effects of High-altitude King Shot as Recorded by TG, Eniwetok 15

3 Heights of the a_1 Mode of Arrival 16

4 Barographic Measurements 17

5 Possible Arrival Times 18

BAROMETRIC AND WATER-SURFACE WAVES PRODUCED BY MIKE SHOT

1 OBJECTIVE

The object of Project 6.4b was primarily to measure the water-surface disturbances produced by Mike shot. It was believed that large waves might be raised (interesting in their own right) from which it would be possible to make some estimate of the amount of energy that went into wave making. Also, it was hoped that, even in the complex situation of the test, there would be an opportunity to check the scaling laws. As it turned out, neither was possible. In addition, it was believed that some progress could be made in determining the mechanics of the air-linked wave (a forced wave driven at high velocity by the propagated disturbance in barometric pressure). This was more successful.

The largest man-made geophysical event naturally created considerable curiosity and generated much speculation as to both immediate and ultimate effects. Chief among these was what seemed a remote but real possibility that the explosion would trigger a submarine landslide at the edge of the atoll and create a true tsunami (seismic sea wave). Fortunately this did not happen, but a secondary objective was the preparation for the measurement of such waves and the establishment of a system for warning distant populated shores if destructive waves were created.

2 BACKGROUND

When the Scripps Institution of Oceanography (SIO) was asked to participate in Operation Ivy, the first request was for predictions of the possible heights of the water-surface waves at various points. By examining the results obtained by many small TNT explosions (such as those made by Leech in the Seal experiments[1]) and using the data obtained at Operation Crossroads,[2] it was possible to make an estimate of the waves that could be expected (1) if a valid extrapolation can be made from small TNT explosions to large thermonuclear explosions in a nonhomogeneous medium and (2) if the blast were to occur at the water surface over deep water. However, because the shot was to be fired over the mid-point of a wide coral reef and because there is considerable doubt that TNT can be scaled up for interface shots, the estimate was little more than a poorly educated guess. Some of the questions that arose follow.

1. How would the reef act? The Stephenson[3] model-shot craters were examined, and it was noted that blasted reef material seemed to have reacted as sand reacts.

2. Would the crater extend beyond the reef and include water in which a wave could be generated directly?

3. Would a major piece of the outer rim of the atoll be broken away and slough off, thus causing a great wave (tsunami)—which has apparently happened on the north rim of nearby Bikini in the geologic past?

4. How much of the bomb energy would go into wave making?
5. If large waves were formed, would those sweeping around the atoll and across the islands arrive before a wave crossing the lagoon could reach the same point, thus confusing the record?

These questions could not be answered in advance and indeed have not yet been answered completely. At any rate, estimates of wave height at certain specific places were made and reported to the Scientific Director at Los Alamos, N. Mex., on June 6, 1952. For example, it was thought that the waves at Runit (inside the lagoon) might be 30 ft high; at Eniwetok (inside), 16 ft; at sea mounts 26 and 72 miles away in the open ocean to the north, 20 ft and 6 ft, respectively; and at Bikini, 2 to 6 ft. Once in the open ocean the waves would propagate with little loss of energy and radiate outward for hundreds of miles. As has already been mentioned, the possibility of tsunami generation by a submarine landslide had to be considered.

The time available from the entrance of SIO into the project until Mike shot was of the order of six months. In this time the history of near-water explosions had to be reviewed, estimates of wave height and period made, and an instrument system devised, built, and installed which would measure the waves at a number of widely separated points—each with different characteristics.

The selection of points at which instruments would be placed was based principally on the availability of favorable natural locations at a range of distances from the test site; these sites and distances are itemized in Table 1. The location of Mike shot on the north rim of the atoll facing open ocean led to the decision to utilize the crests of undersea mountains for important instrument stations, although this had never been attempted before. (These stations are called "sea mounts" in this report.)

3 INSTRUMENTATION

Because of uncertainties of prediction, there was a rather wide range of wave heights and periods over which the instruments needed to be responsive, and a number of these were required by circumstances to operate in the face of a complex high-level background composed of wind waves, swell, seiches, and tides. It was evident that only very specialized instruments would do the job and that no one instrument would be satisfactory for all the locations. Eventually it was found necessary to build three types of wave-recording instruments; these are discussed in Secs. 3.1 to 3.3.

3.1 Absolute-pressure Recorders (BA), Mark X

A special set of conditions existed at Eniwetok Lagoon which made it seem logical to use an undamped pressure pickup that rested in 25 ft of water on the lagoon floor and accepted pressure from all sources. This was possible because (1) the local wind waves at the selected locations (Runit Island and Eniwetok Island) were small and of short period, (2) only low swell enters the lagoon, and (3) the tidal range (±6 ft) is small in comparison to the height of the expected waves. Moreover, it was difficult to predict the probable wave period and whether or not appreciable seiching would take place. The pressure pickup was so designed as to be able to accept a wave with a 29.5-ft crest and a 14.5-ft trough (predicted heights at Runit) with a resolution of better than 6 in. (13.1 cm of sea water per winding on the potentiometer). The signal was transmitted ashore through armored three-conductor submarine cable to automatic (untended) Esterline-Angus recorders housed in bunkers. This was believed to be the simplest possible instrument that could be built to operate untended for as long as four days. At Runit the height of the waves from the blast was about one-tenth of that expected, and as a consequence the instrument did not give a highly resolved record.

3.2 Differential-pressure Recorders (BD), Mark IX

In the Marshall Islands area outside Eniwetok Lagoon, where it was possible to predict the wave period with some confidence, a differential-pressure pickup was used which had special band-pass characteristics. By means of a system of capillaries and air volumes, these instruments were able to distinguish between the long low waves resulting from the explosion and the wind waves, the swell, and the tides. Because of the need for speed, instrument design was based on the theory that, wherever possible, tested and readily available components and techniques should be used even if these were less than the ultimate that could be desired. Accordingly, it was decided to modify the Mark IX Shore Wave Recorder (developed on the Berkeley Campus of the University of California), which was as near to being a "tried and true" instrument as wave recorders can be. In the Mark IX a flexible diaphragm responds to the pressure changes caused by passing waves and moves the slide wire of a potentiometer. A three-conductor submarine cable leads ashore, and changes in the voltage across a bridge are recorded on an Esterline-Angus recorder. The electrical system was retained almost intact, but the pressure pickup as it finally appeared (designated Model 6) had lost its resemblance to the original and was much simpler to construct.

This double-differential system consists of three chambers interconnected with capillary tubes, as shown in Fig. 1. Rapid fluctuations in pressure, created by short-period wind waves or swell, compress the compliant bellows which is open to the sea, but little or no flow of air into the signal chamber takes place. Very long period waves, such as the tides, cause air to flow from the bellows into the signal chamber and thence to the reference chamber where the long-term average outside pressure is maintained.

The particular waves that this instrument seeks are of such duration that a substantial flow of air can take place only through the outer capillary; the change in pressure in the signal chamber with respect to that in the reference chamber creates the force that drives the potentiometer. The size of the capillaries was so calculated as to "tune" the flow of air to some period T (varying from 1 to 3 min, depending on the depth of the pickup and the size of the capillaries) of optimum response. The band pass is broad and symmetrical, with the response falling off by 1/e for $T = \frac{1}{8}T_0$ and $T = 8T_0$, so that for very short and very long periods the response varies as T and T^{-1}, respectively.

Although much care and effort were spent on the Mark IX instrument system, it returned little information; this is partly because it was intended to instrument much larger waves than those which it apparently received and partly because of inexplicable inconsistencies in the field calibrations. The instrument was designed to record variations in sea level of as little as 2 in. (4.28 cm), but the least measurable signal seemed to be about 8 in. (20 cm), and this was found to change somewhat over a period of time.

The Mark IX instruments were placed in two general locations. At Bikini Atoll two shore recording installations were made in which the pressure pickups were located in 45 and 60 ft of water on the edges of the deep passes west of Chieerete and Eninman Islands. Here the instruments were placed, inspected, and calibrated by underwater swimmers, perhaps being the first time an instrument system has been tied to the SCUBA (self-contained underwater breathing apparatus).

The other Mark IX installations were made on specially developed deep-sea instrument stations moored on the crests of undersea mountains. Almost due north of Ground Zero at distances of 26 and 72 miles are two such mountains that come within about a mile of the sea surface—shallow water for the Pacific. By using the comparatively flat summits of these sea mounts as platforms, it was hoped that it would be possible to record the waves from Mike shot in the unconfused deep-water situation. The SIO research vessel, Horizon, successfully placed three of these stations on the three days before Mike shot day, and Mark IX instruments were installed thereon. No waves from Mike shot were recorded, presumably because they were too low.

3.3 Differential-water-level Recorder (VD)

The need for a simple mechanical means of measuring long-period waves at distant points (where the instruments could be tended) led to the development of a device for this purpose by William Van Dorn. This instrument was intended to be attached to a wharf or piling, and a hydraulic band-pass filter similar to that employed in the Mark IX was used. The maximum re-

Table 1 — SUMMARY OF ANALYSIS OF RECORDS

Station No.	Location and person tended by	Distance, nautical miles	Azimuth	Instrument	Mode	Signal					Background		Chart No.	Remarks
						Time of arrival, GCT		Height	Period	Number of waves or duration	Height, cm	Period		
						C[illegible]ted	Recorded							
0	Ground Zero	0				1915, 31 October								
1	Runit Island, Eniwetok Atoll (Bascom)	11.5		BA	a_1	1916	1915	106 cm	40 sec	1	Only 12 sec swell		1	Presumably air pressure; instr. at bottom in 22 ft
					w	1931	1930	60 cm	2 min	4				
2	Eniwetok Island (Bascom)	21		B	a_1	1917	1916	41 mb	1 min	1				
				BA	a_1	1917	1916	56 cm	1 min	1				Presumably air pressure; instr. at bottom in 25 ft
					w	1947	1940	84 cm	4 min	2 hr			2	
				TG	w		1925	9 cm	4 min		4 cm	3 min	3	
						1947	1938	80 cm	4 min	3.5 hr				
3	Sea mount No. 26 (Bascom)	28		BD		Instrument last sighted drifting on three floats toward China								Instr., 200 ft; depth, 5700 ft
4	Sea mount No. 72 (Bascom)	65		B	a_1	1921		5 mb	4 min	5				B aboard Horizon
				B	a_1			5 mb	4 min	5				B on float
				BD No. 7		No signal		< 50 cm	3 min					Instr., 130 ft; depth, 4500 ft
				BD No. 8		No signal								Instr., 200 ft; depth, 4500 ft
5	Chieerete Island, Bikini Atoll (Holter)	189		BD		No signal		< 30 cm	4 min					Instr. at bottom in 45 ft
6	Eninman Island, Bikini Atoll (Holter)	195		B	a_1	1934	1935	2.7 mb		2				
				BD		No signal		< 15 cm	4 min					Instr. at bottom in 60 ft
7	Kwajalein Island	371	295	TG	w	2111	2027	6 cm			3 cm	2.5 min	4	Very indefinite; poor record
8	Wake Island (Folsom)	523	208	B		2006	2006	0.7 mb	2.5 min	2				
				VD	a_1	2006	2007	16 cm	3 min	8 hr	8 cm	3 min	5	
					w	2035	2035	18 cm	3 min					
				TG	a_1	2006	2006	10 cm	2 min		5 cm	2 min		
					w	2035	2155	20 cm	2 min		5 cm	2 min	6	Good record

9	Truk Island	657	068	TG	w	2053	2104	> 4 cm	8 min	4 hr	2 cm	8 min	7	Good record
10	Guam Island (Knauss)	1033	092	B	a_1	2055	2056	0.1 mb	3 min	3 hr				
				TG		No signal		< 2 cm			2 cm	10 min		Apra Harbor
				TG		No signal		< 0.5 cm						Taragui Beach
				VD	a_1	2055	2056	22 cm	8 min		8 cm	8 min	8	Good record
					w	2150	2148	65 cm	8 min	1 day				Good record
11	Canton Island	1164	300	TG		No signal		< 1 cm						
12	Yap Island	1424	079	TG	w	2249	2322	3 cm	7 min		1 cm	7 min	9	Indefinite; bigger waves at other times
13	Midway Island (Van Dorn)	1535	230	B		No signal								
				TG	w	2305	2400	10 cm	10 min	2 hr	5 cm	10 min	10	Indefinite
				VD	a_1	2144	2200	15 cm	9 min		11 cm	9 min	11	No definite arrival but slightly increased activity
					w	2304	2324	29 cm	8 min	30 hr				Good record
14	Port Allen, Kaui	2273	259	TG		No signal		< 2 cm						
15	Oahu Island	2362	261	TG		No signal		< 2 cm						Pearl Harbor
				TG		No signal		< 4 cm						Honolulu: large waves 4 hr after computed arrival time
16	Kahului, Maui	2428	262	TG		No signal		< 12 cm			8 cm	10 min		
						1 November								
17	Kawaihae, Hawaii (Van Dorn; Kanno)	2467	263	VD	w	0125	0120	10 cm	6 min	17 hr	6 cm	6 min	12	
18	La Jolla, Calif. (Munk; Blair)	4578	275	MB	a_1	0238	0238	0.3 mb	8 to 3 min	10				
				TR	w	No signal		< 2 cm			3 cm	15 min	13	
19	Oceanside, Calif. (Munk; Blair)	4578		TR		No signal		< 2 cm			3 cm	15 min		

Summary:

7 Barograph (B)
1 Microbarograph (MB)
Total 8 air-pressure recorders

2 Bascom Absolute (BA)
4 Bascom Differential (BD)
4 Van Dorn Differential (VD)
13 Tide gauge (TG)
2 Tsunami recorder (TR)
Total 25 wave recorders

First mode air wave (a_1) = 620 knots
Second mode air wave (a_2) = 544 knots
Mean water wave (w) = 400 knots

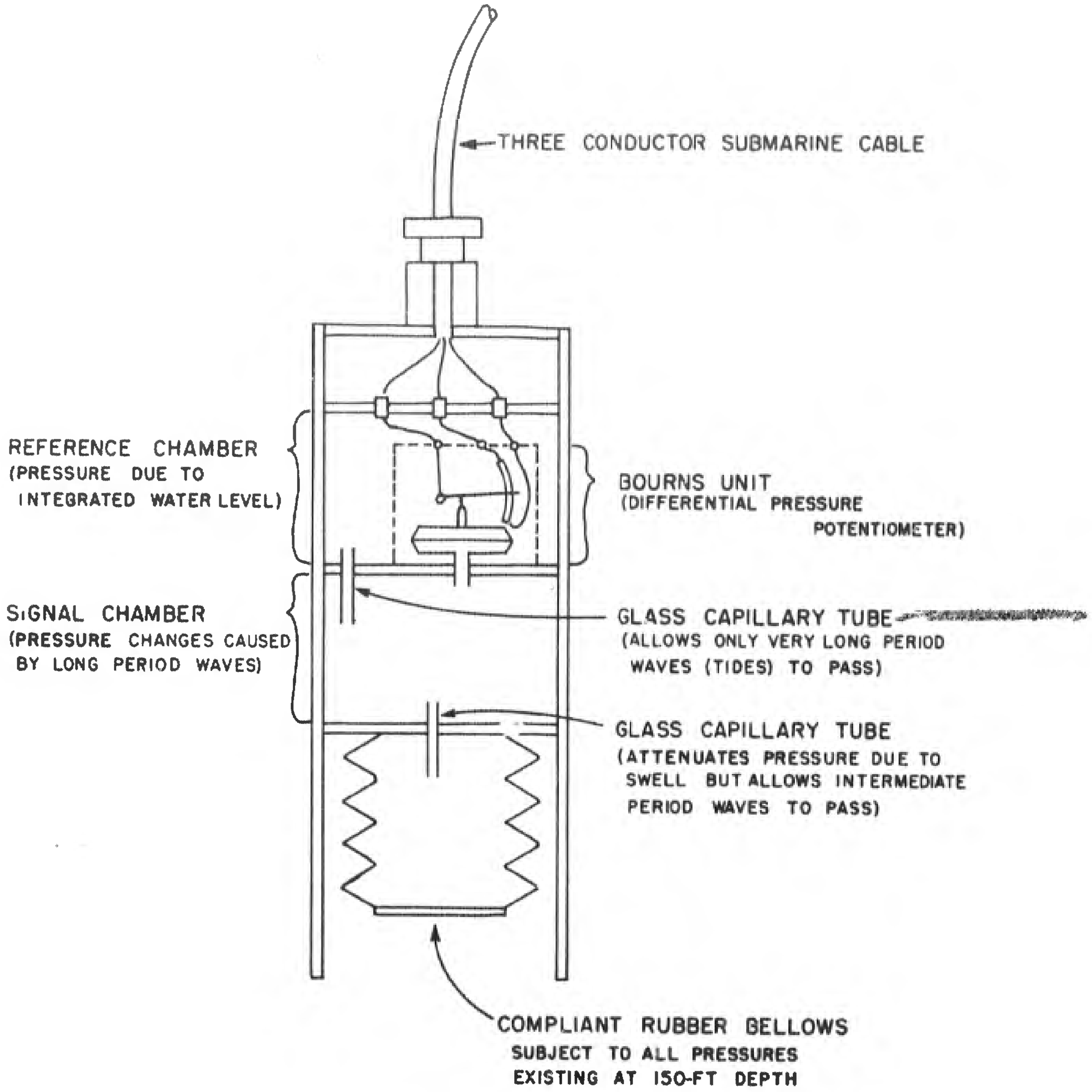


Fig. 1—Schematic diagram of pressure pickup of Mark IX Model 6 wave meter.

sponse was for a period of $T_0 = 700$ sec; 1/e of maximum response was at 130 and 3300 sec. The pen of the recorder was attached by a wire and pulley system directly to the compliant bellows so that the entire instrument was mechanical. Because such instruments need to be protected from the sea, they were set up in comparatively quiet areas (bays), which unfortunately have a natural oscillation of their own that is excited by long waves from outside; this made it impossible to determine the deep-water period of the disturbance. Moreover, these instruments were highly sensitive to waves within the band pass, and the seiching created by Mike shot caused the pen to oscillate so fast that the heights of the "folded waves" were uncertain.

From what was known of the bomb and its probable wave-generation characteristics, this was the least number of instrument types required to be constructed in order to do a satisfactory measurement job. In addition to these instruments that were especially designed and built for the instrumentation program, it was found possible to make use of certain existing instruments in the Pacific area. These are discussed in Secs. 3.4 to 3.7.

3.4 Tide Gauges (TG)

The United States Coast and Geodetic Survey operates standard tide gauges at many points in the Pacific; when apprised of the problem, they were highly cooperative and not only allowed use of the records but made an effort to ensure proper and uninterrupted functioning throughout the test. In their instrument water is admitted to the pipe through a small opening that damps out the short-period waves and swell but allows the tide to enter unimpeded. Intermediate-period waves (from 2 to 8 min) are only slightly reduced in amplitude, depending on the size of the pipe and the orifice; for a properly functioning gauge the reduction is less than 20 per cent, but fouling organisms may effectively alter the size of the orifice. Possible orifice reduction from this or other cause has been ignored in our computations, and the values in Table 1 are therefore minimum values.

3.5 Tsunami Recorders (TR)

A tsunami (seismic sea wave) recorder[4] has been in operation at La Jolla, Calif., for several years; a similar instrument, maintained at Oceanside, Calif., sends signals to La Jolla via a radio link, and the information from both is recorded side by side on a multichannel Speedomax. The tsunami recorder has three pneumatic filter stages, making it a sort of elaborate differential-water-level recorder. Maximum response is at $T_0 = 45$ min, and 1/e of maximum response is at 10 and 100 min. Waves from Mike shot were indistinguishable from background on the tsunami recorder.

3.6 Microbarographs (MB)

The microbarograph* consists of a weight suspended from a sensitive strain gauge in a carefully shielded location at the foot of Scripps Pier in La Jolla. Changes in atmospheric pressure affect the buoyancy of the suspended weight, and the output of the strain gauge is recorded on the same multichannel Speedomax as the tsunami recorders. Pressures of 0.1 mb are discernible, and time can be resolved to $\frac{1}{2}$ min.

3.7 Barographs (B)

Five ordinary Bendix-Friez barographs were placed at strategic points; from them the time of arrival of the air wave was obtainable. Similar records were also obtained from various air and weather stations. With a good deal of imagination, signals down to a fraction of a millibar can be recognized; the time scale can be read to the nearest hour or so, and with special preparations, precautions, and care it can be read to the nearest minute. At nearby stations the air waves were surprisingly sharp, and consequently the peak amplitude was probably not recorded.

---

*This Statham microbarograph would be better named "millibarograph."

4 RESULTS

Table 1 summarizes the locations and distances of the various types of instruments, the background extant at the time the signals were received, and the time of arrival, period, and height of the waves. Sections 4.1 to 4.3 serve to amplify and explain Table 1; for convenience in discussion the stations are divided into the Eniwetok, the Marshall Islands, and the far stations.

4.1 Eniwetok Atoll

At 1916Z at Eniwetok the B and the BA recorded comparable signals, whereas the TG showed no signal. At 1938 to 1940Z the BA and the TG recorded comparable signals, whereas the B showed no signal. Apparently the BA first acted as a barograph and then as a water-level recorder. This is reasonable since the BA cannot distinguish between pressure changes due to changes in air pressure above an undisturbed water surface and those due to a change in water level only.

From this it is inferred that the first arrival recorded by the BA at Runit was also the effect of air pressure. If the same ratio as that at Eniwetok is used (41 mb on B corresponds to 56 cm on BA), it is inferred that a B instrument at Runit would have recorded a double amplitude of 106 × (41/56) = 77 mb. (Note: The pressure exerted by 1 cm of sea water is 1.00 mb.)

The first water arrival at Eniwetok showed up on the TG at 1925Z but was beneath the minimum amplitude resolution of the BA (13 cm). The travel time is only 10 min, definitely too short for travel through the lagoon. Such a travel time is consistent with a longer path through the deeper water around the outside of the atoll.

As an order-of-magnitude calculation, consider a circular island of radius r_0 and bottom slope m. The depth h a distance r from shore is

$$h = mr$$

and the distance along an arc at this depth is

$$d = \theta(r + r_0)$$

where θ is the angle subtended by the arc at the island (lagoon) center. The travel time

$$\frac{d}{\sqrt{gh}} = Kr^{-1/2}(r + r_0)$$

has a minimum value $2r_0^{1/2}K$ at $r = r_0$, when

$$K = \theta(gm)^{1/2}$$

Letting $r_0 = 15$ miles, m = tan 30°, and $\theta = 120°$ gives a minimum travel time of 7 min. The time for the waves to travel from shore to this arc and then back has to be added.

The second, and higher, water arrivals as recorded on both the TG and the BA are still somewhat earlier than the computed arrival time, but not so much as to exclude the possibility that these have traveled through the lagoon. Thus the computed travel times would have to be shortened if high pressure or winds some distance from Ground Zero could have initiated the wave action.

With regard to the water arrivals at Runit, the time resolution (0.1 in./min) of the BA is too poor and the travel time is too short to give any evidence as to the travel path.

The period of the water waves was 2 min at Runit and 4 min at Eniwetok. The BA was too insensitive to record background in either location, but at Eniwetok the TG did show a background of approximately this period. The important fact here is that these periods are much shorter than the seiche period of Eniwetok Lagoon, which is about 45 min. They may, however, correspond to shelf seiches over the relatively shoal bottom on either side of the islands.

The amplitudes for the higher waves were 2 ft at Runit and nearly 3 ft at Eniwetok. It is not yet understood why they were higher at the more distant station, but this suggests a complex mechanism even at these short ranges.

It is appropriate to summarize (see Table 2) the effects of the high-altitude King shot as recorded on the Eniwetok TG, this being the only place where water waves were recorded. Here again there are two distinct arrivals, corresponding roughly to an ocean and a lagoon path, respectively. The corresponding travel times for Mike shot were 10 and 23 min for approximately twice the distance. Again, the periods are much shorter than those for the fundamental lagoon seiche.

Table 2—EFFECTS OF HIGH-ALTITUDE KING SHOT AS RECORDED BY TG, ENIWETOK

Travel time, min	Height, cm	Period, min	Number of waves
10	7	5	1
30	10	3	2

The tsunami of 4 November did, however, excite the fundamental lagoon seiche. At the beginning of the tsunami the Eniwetok TG recorded two 45-min waves of 1.4 ft height, but these then degenerated to 4 to 5 min shelf seiches of about 1 ft height, which diminished to background in one day.

If, in future tests, the waves at Eniwetok were to be four times as high, i.e., 10 ft high, they could cause some damage, especially at high tide on a stormy day. Offhand, it might be expected that, if the explosion were set off on a float in the lagoon, the resulting wave action could easily be damaging. With such an arrangement the energy might go into a long-period lagoon seiche instead of the recorded short-period shelf seiche.

It should be pointed out that the photographic records at Runit and Eniwetok qualitatively confirm the measured wave height. In addition, the record from one of the closer islands at a 4-mile range shows no discernible wave, although a long-period wave of 1 cm height could have been observed and the record was operated for an adequate length of time.

4.2 Marshall Islands Area (25 to 500 Miles)

The BD instruments on the sea mounts and at Bikini Atoll and a TG instrument at Kwajalein are included in the Marshall Islands Area.

At sea mount No. 26 the instrument broke loose and was not recovered.

At sea mount No. 72 the BD recorder indicated a change in sea level of not more than 50 cm, but no reliable calibration exists for this instrument. For the sake of comparison with the amplitudes measured at Eniwetok it will be convenient to refer the heights to a standard water depth of 20 ft. If there are no resonances, it is found from geometric optics that the height varies inversely with the fourth root of depth. Hence the wave height in 20 ft of water would have been $50 \times (4500/20)^{1/4} = 240$ cm, which is not surprising in view of the amplitudes measured in the lagoon.

At Bikini the greatest possible wave height (referred to 20 ft depth) is $15 \times (60/20)^{1/4} = 20$ cm if the Eninman instrument can be trusted or $30 \times (30/20)^{1/4} = 33$ cm otherwise.

There is a questionable indication on the Kwajalein TG of the arrival of 6-cm waves at about 2027Z, 16 min after the computed arrival.

4.3 Far Stations (500 to 5000 Miles)

The most interesting feature observed at the far stations is the arrival of a water disturbance simultaneously with the a_1 air mode (for discussion of this and other modes of arrival see Sec. 5.2). This is clear at Guam and somewhat less so at Wake, and there is an indication of it at Midway. Because of the construction of the VD, the possibility that the wave recorders at these stations were simply acting as barographs as did the BA for the shock wave at Runit and Eniwetok can be immediately relinquished. At Wake the disturbance showed up on both the VD and the TG. The water disturbance was much greater than the barographic disturbance at all three localities. Thus the heights of the a_1 mode, given in Table 3, show some variation, whereas the numerical values in millibars and centimeters would have been nearly the same if the wave recorder simply measured air pressure.

The existence of such air-coupled water waves has been noted by Ewing and Press[5] in their study of the great Krakatoa explosions. The water waves owe their existence to the fact that the velocity of the free water waves ($\sqrt{gh} = 206$ m/sec) is of the same order of magnitude as that of the free air waves ($\sqrt{gh_1} = 319$ m/sec). In the final analysis this is due to the existence on the earth of just so much water and just so much air to make h and h_1 of the same order. There is, however, still the problem as to whether the two velocities are close enough to account for the measure "leakage" of energy from the air into the water. It is hoped that this problem may be further investigated at a later time.

Table 3 — HEIGHTS OF THE a_1 MODE OF ARRIVAL

Location	B value, mb	VD value, cm	TG value, cm
Wake	0.7	16	10
Guam	0.1	22	
Midway	0.2	15 (?)	

It will be noted that the ratio of the water-wave velocity to the velocity of the first air mode is 0.65, whereas for the second air mode it is 0.74. Thus the water waves should be more closely coupled to the second air mode. There is, however, no positive indication in our records of a water wave that arrived with the velocity of the second air mode. This provides evidence that the second air mode, if it does exist, is smaller compared to the first air mode.

In the cases of Guam, Midway, and Kawaihae, an enhancement in amplitude is noted many hours after the first arrival of the water waves.

These features may be the result of reflection from continents and island chains. The computed travel times are 15 hr for Kawaihae, 17 hr for Midway, and 23 hr for Guam for reflections from the American Continent, and 5 to 8 hr for Guam for a reflection from the Asiatic Continent. There is some support in the records for American reflections at Midway and Kawaihae and an Asiatic reflection at Guam, but this evidence is very poor. The problem is a complex one and needs further study. Tsunami reflections are discussed in reference 6.

Closely connected with this problem of continental reflection is the problem of island scattering. For what otherwise could be the reason for the continued disturbance between the arrival of the direct waves and the continental reflections? The duration of the direct signal should amount to a dozen or so waves, or a few hours at most. The local seiche actions also disappear within a few hours after the wind dies down. An investigation of this "afterglow" is in progress by the authors, making use of records from the tsunamis of 1 April 1946 and 5 November 1952, and possibly a South American shock, in addition to the present records.

The predominant role played by the "tuning" of the local seiches to the incoming signal in determining wave height is demonstrated by comparison of the VD records at Guam and Wake Islands. Although Guam is twice as far from Eniwetok as Wake, the wave height at Guam is over three times that at Wake. For this reason it is not considered possible to estimate quantitatively the total energy that has gone into water waves. The disturbance was equivalent to that caused by a small tsunami. The energy of the very large tsunami of 4 November 1952 was probably from a hundred to a thousand times larger.

4.4 Summary of SIO Barographic Measurements

For Runit the conversion factor from BA to B has been discussed previously. For the nearby stations the signal was remarkably sharp, and it is doubtful whether the barographs recorded more than a fraction of the peak amplitude. With increasing distance the signal softens, and the instruments can be expected to give a more faithful record. No doubt, as far as measurements of the air pressure wave are concerned, the results given in Table 4 are of little use compared to the results obtained by others using a more adequate instrumentation. The principal reason for the use of the barographs was to study the possibility of air-coupled water waves, and in this respect our expectations were fulfilled.

Table 4—BAROGRAPHIC MEASUREMENTS

Station	Distance, nautical miles	Instrument	Height, mb			Period	Number of waves
			Crest	Trough	Total		
Runit	11.5	BA	+60	−17	77	40 sec	1
Eniwetok	21	B	+31	−10	41	1 min (?)	1
Horizon	65	B	+4.7	−0.7	5.4	4 min	5
Sea mount No. 72	65	B	+4.7	−0.7	5.4	4 min	5
Eninman	195	B	+2.0	−0.7	2.7	?	2
Wake	523	B			0.7	2.5 min	2
Guam	1033	B			0.1	3 min	3
Midway	1535	B	No signal				
La Jolla	4578	MB	+0.15	−0.15	0.3	8 to 3 min	10

5 REMARKS ON THE ANALYSIS OF DATA

5.1 Seiching

Most tide gauges are located in semiprotected areas such as bays and inlets which have certain characteristic modes of oscillation depending on their dimensions. These oscillations are known as seiches. The most important is usually the fundamental mode, which is of the order of the time required for a $\sqrt{gh}$ wave to travel from one side of the area to the other and back again. Seiche action should exist also along straight, open coast lines with continental shelves and (at least theoretically) over sea mounts because outgoing waves are "refracted back" from deep water, and hence wave energy is "trapped" over the shelf or sea mount.

The problem is to reconstruct, as well as possible, the deep-water waves from the instrumental records. This involves taking into account not only the frequency-response characteristics of the instrument but also those of the local bodies of water. The latter probably have a complicated line spectrum (fundamental first overtone, etc.), and the distribution of energy along this spectrum depends also on the spectral distribution of the forcing function.

It is necessary then to study the waves caused by the explosion and their decay with distance and time by observing them through a series of response systems (instrument + local waters), each with different response characteristics and having in common only that none of them are known. Under the circumstances all one can really do is consider travel times at such stations where the waves are recorded.

In Table 1 under "Background," the period and height of the seiche (probably wind induced) before the arrival of the waves from the explosion are given. It will be noted that in each instance the period of the recorded signal is more or less the period of the seiche. This would indicate one predominant spectral line of the local waters and a rather broad spectrum of the incoming disturbance, i.e., the disturbance did not consist of a long series of fairly uniform waves.

5.2 Computed Air and Water Arrivals

With the exception of the stations at Eniwetok Atoll itself and at Guam, it is difficult to distinguish the arrival of the first waves since they hardly exceed twice the background. Thus it was necessary to follow the undesirable expedient of computing the various arrival times for each station and then searching for evidence in the records; this is unfortunate but was the best that could be done under the circumstances. However, significant records are given in Figs. A.1 to A.13. Readers will differ as to whether too much or too little imagination has been used in interpreting these records.

The records are marked with three possible arrival times; these are given in Table 5. They are also given in Table 1, together with the observed arrival times.

The velocity for the water wave represents a mean value (corresponding to a depth of 14,150 ft) which is a good enough approximation in the Central Pacific Basin. For Kawaihae this leads to a travel time of 6 hr 10 min, compared to 6 hr 5 min as obtained by numerical integration using actual depths.* For La Jolla the mean velocity gives a travel time of 10 hr 45 min, whereas numerical integration yields 11 hr 27 min.

Table 5—POSSIBLE ARRIVAL TIMES

Mode	Velocity	
	Meters/sec	Knots
a_1 (first air mode)	318.8	620
a_2 (second air mode)	280.0	544
w (water wave)	206	400

The first air mode, a_1, travels at a velocity $\sqrt{gh_1}$ for an equivalent depth of the atmosphere of $h_1 = 10.4$ km. This is the velocity with which the waves produced by the Krakatoa eruption and the great Siberian meteor were propagated. This wave motion reaches to the cold tropopause, and its velocity of 319 m/sec is less than the velocity of sound at sea level (332 m/sec).

The second air mode, a_2, corresponds to a resonance period of the atmosphere of exactly 12 hr, which has long been proposed to account for the amplification of the semidiurnal atmospheric tide. It can be shown that the tropopause is transparent to this mode and that it can be trapped only in a second temperature minimum, above the stratosphere. Pekeris detected some indications of this second mode in the Krakatoa records, but we have found no positive indication of it here. For further discussion of the air modes see reference 7.

6 RECOMMENDATIONS

It is recommended that a standard (20 kt) fission weapon be detonated at the water surface in deep water. This unconfused situation can be used to clearly establish once and for all the wave-making ability of atomic explosions and the validity of TNT scaling at an air-water interface (see Appendix B).

The object of Mike shot was to test a new weapon, and a semiquantitative go-no-go answer sufficed. The measurements of such obviously secondary effects as the waves produced had very little bearing on the immediate problem. On the other hand, the likelihood of using oceanic areas for future tests of ever-larger weapons is increasing, and almost inevitably the time will arrive when one of these will, through the mechanism of the waves produced, influence the peoples of Pacific coastal areas. The results of all atomic explosions to date are inconclusive in the sense that it cannot be determined from the study of their effects whether the TNT scaling laws hold for atomic explosions at the air-water interface (a very logical place to locate a test weapon). The energy of a much larger weapon than Mike, even though it be located on the

---

*U. S. Coast and Geodetic Survey: Seismic Sea Wave Warning System; Chart 1: Seismic Sea Wave Travel Times to Honolulu.

reef, might be released in such a manner as to generate large waves. The result, in either case, is uncertain.

7 CONCLUSIONS

The waves created by Mike shot were much smaller than anticipated and so failed to rise far above background. In spite of their low amplitude, however, it was possible to extract several useful and scientifically important pieces of information from the records.

1. The existence of an air-coupled wave at Guam and perhaps at Wake and Midway was demonstrated.
2. The records at Eniwetok Island indicated that the first wave to arrive there traveled around the atoll, in deep water, and into the lagoon, preceding the waves that directly crossed the shallow lagoon.
3. The reflection of the waves by continents is suggested by an enhancement in amplitude many hours after the first arrivals.
4. A phenomenon designated as "afterglow" was observed. Afterglow is the seiching of the various bays and lagoons long after the cessation of the original disturbance.

Certain advances were made in oceanic instrumentation and in the techniques that aid the study of reefs and waves.

1. For the first time the top of an undersea mountain was used as an instrument station, and a special light, inexpensive deep-sea mooring was devised and anchored thereon.
2. An instrument system was tied to the underwater-swimming technique, and free divers worked with instruments (adjusting air volumes, calibrating, and orienting) on the ocean bottom.
3. Coral reefs were examined in detail where divers had seldom before operated (on the outer edges of reefs, against vertical coral cliffs where line diving would be virtual suicide, and in surge channels), in spite of the fact that large sharks (previously alleged to be dangerous) abounded.
4. An absolute-pressure wave-recorder system was built for use in Eniwetok Lagoon, where it recorded both the barometric wave and the water waves.
5. A double-differential (3 chamber) shore-recording pressure pickup was built and operated both on the reefs of Bikini and on the sea-mount moorings.
6. A portable mechanical long-wave recorder was devised and built which was carried via aircraft (suitcase-sized package) to distant islands and installed by a single scientist. Four of these were operated.

REFERENCES

1. Final Report on Project Seal, Plate 24a, Department of Scientific and Industrial Research, Wellington, New Zealand, December 1950.
2. Report of the Coordinator of Oceanography, Operation Crossroads.
3. Kirk Stephenson, personal communication.
4. W. H. Munk, H. V. Iglesias, and T. R. Folsom, An Instrument for Recording Ultra Low Frequency Ocean Waves, Rev. Sci. Instruments, 19: 654-658 (1948).
5. M. Ewing and F. Press, Tide Gauge Disturbances from the Great Eruption of Krakatoa, Columbia University Technical Report on Seismology No. 27, April 1953; Bull. Geol. Soc. Am., 62: 1527 (1951).
6. J. D. Cochrane and R. S. Arthur, Reflection of Tsunamis, J. Marine Research, 7: 239-251 (1948).
7. M. V. Wilkes, "Oscillations of the Earth's Atmosphere," Cambridge University Press, New York, 1949.

APPENDIX A

RECORDS OF WAVE AND TIDE STATIONS

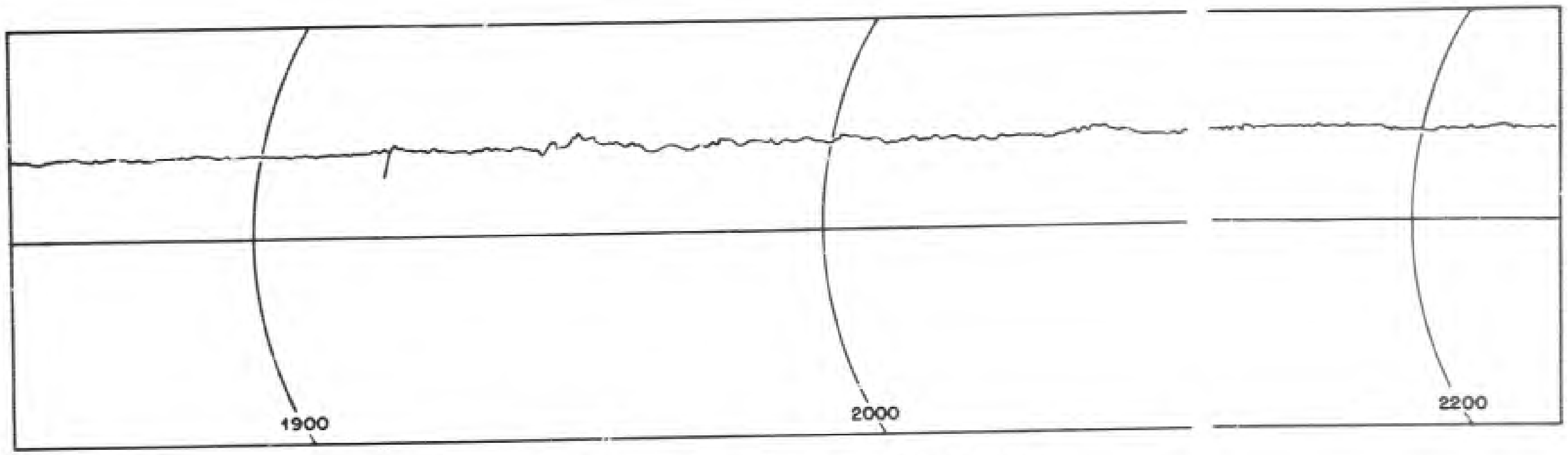


Fig. A.1—Absolute-pressure recorder (BA), Runit.

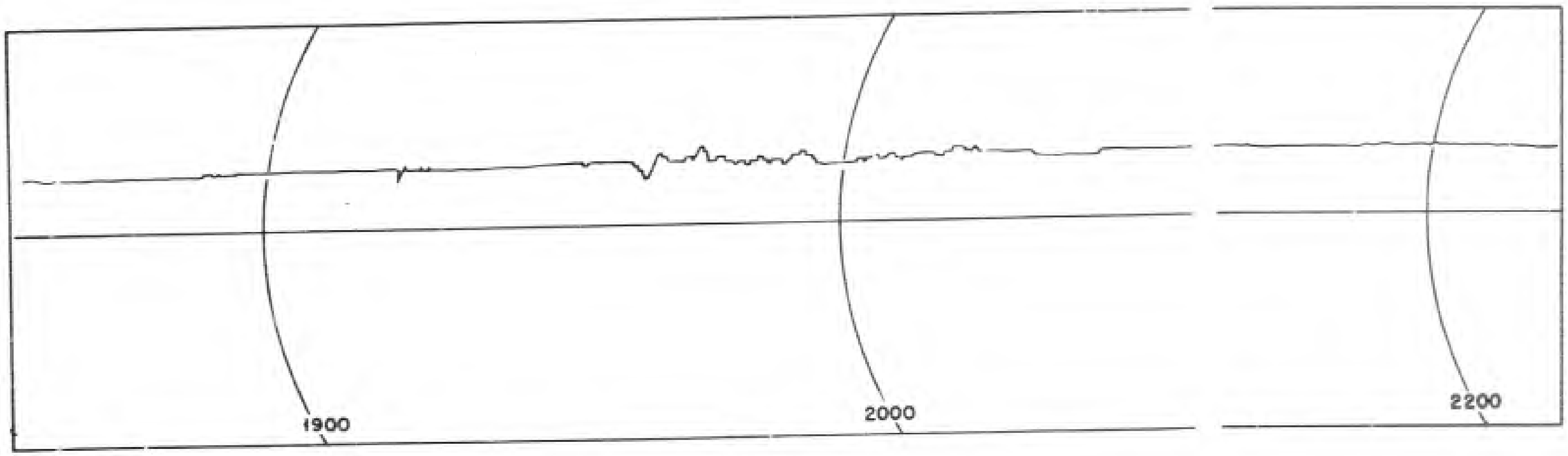


Fig. A.2—Absolute-pressure recorder (BA), Eniwetok.

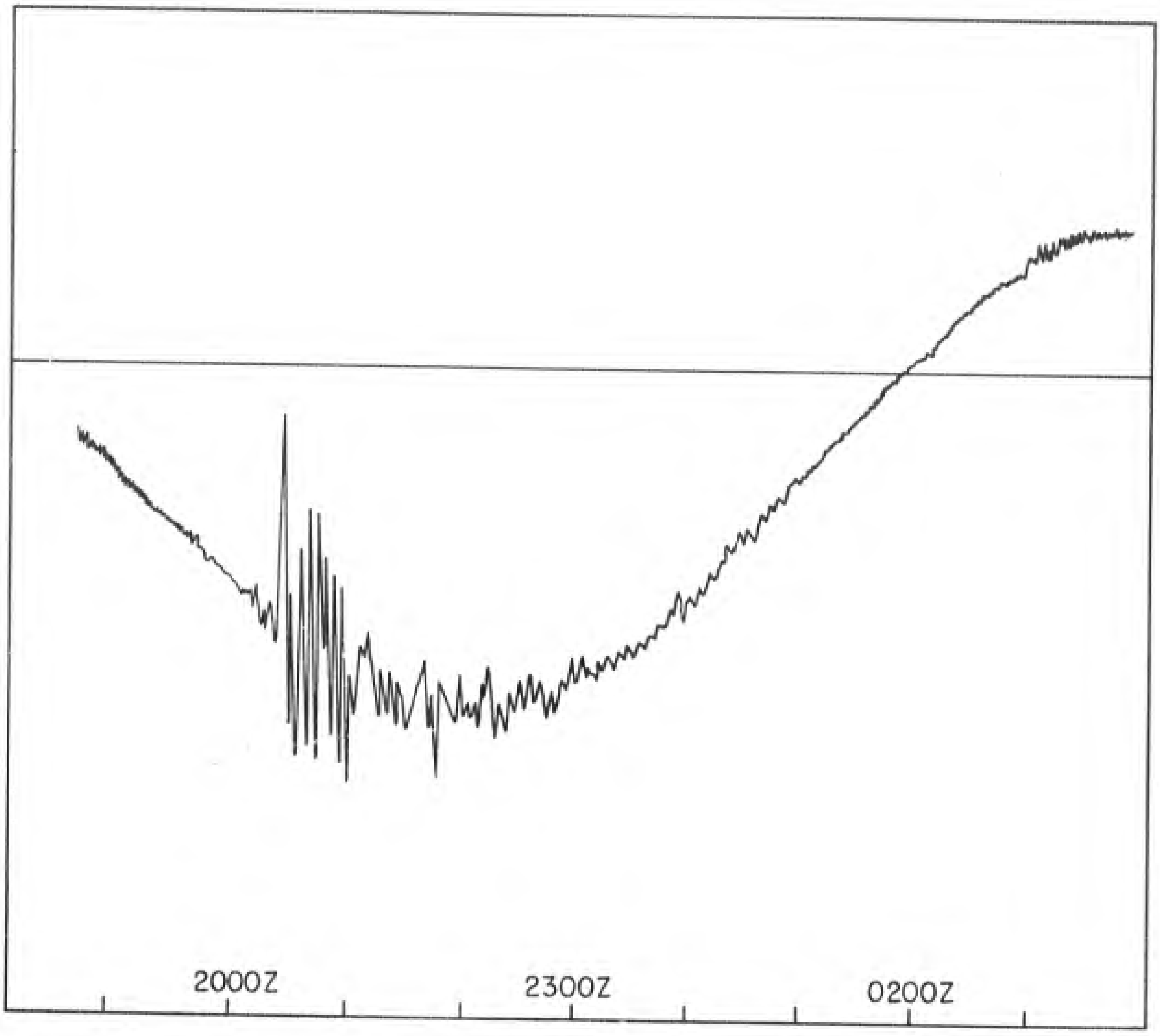


Fig. A.3—Tide gauge (TG), Eniwetok.

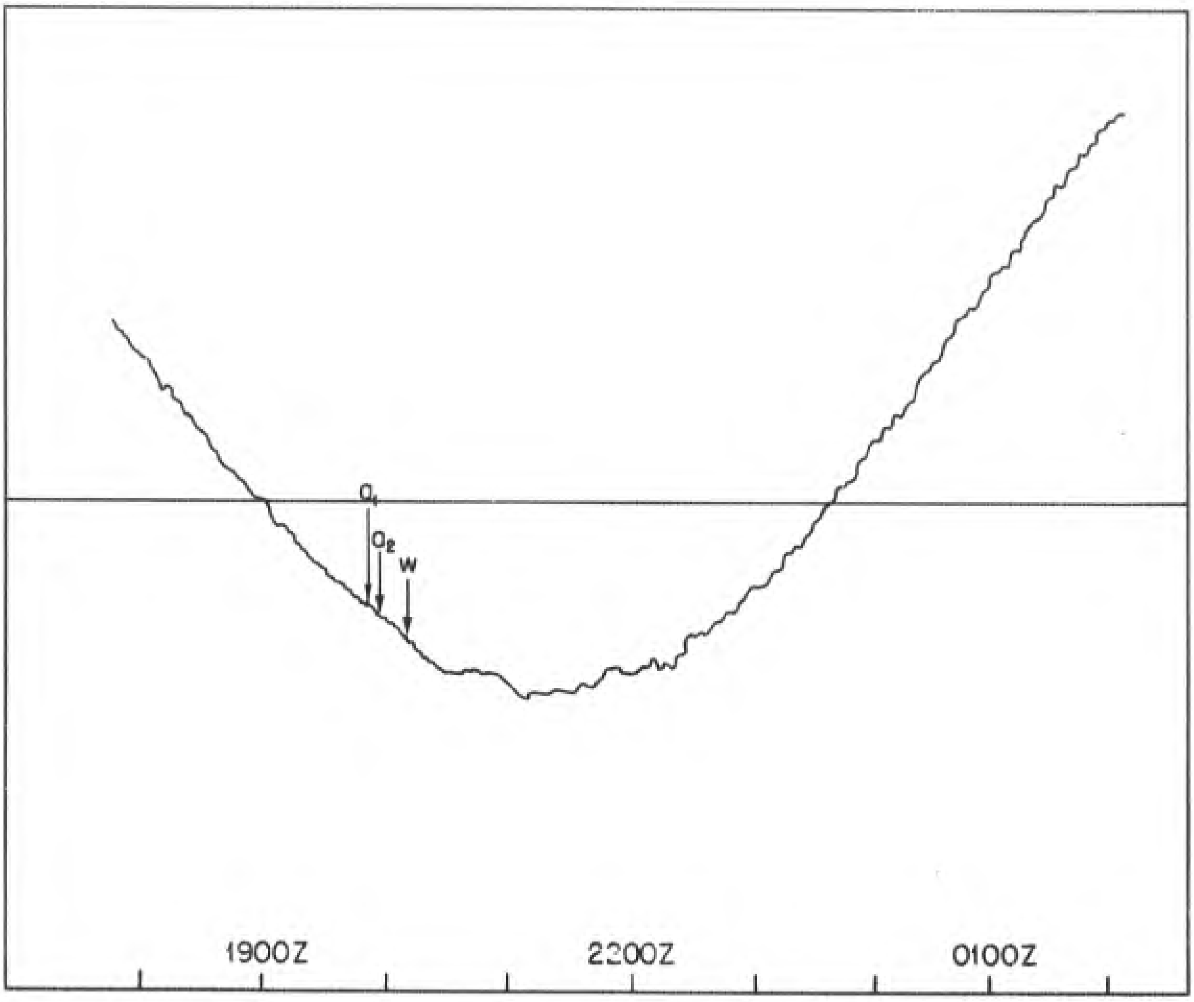


Fig. A.4—Tide gauge (TG), Kwajalein.

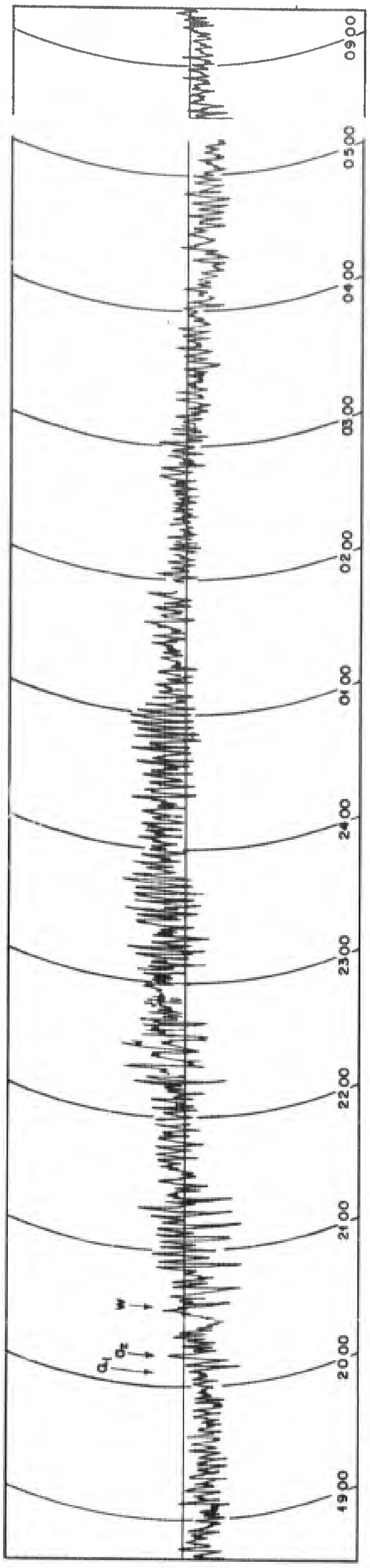


Fig. A.5—Differential-water-level recorder (VD), Wake.

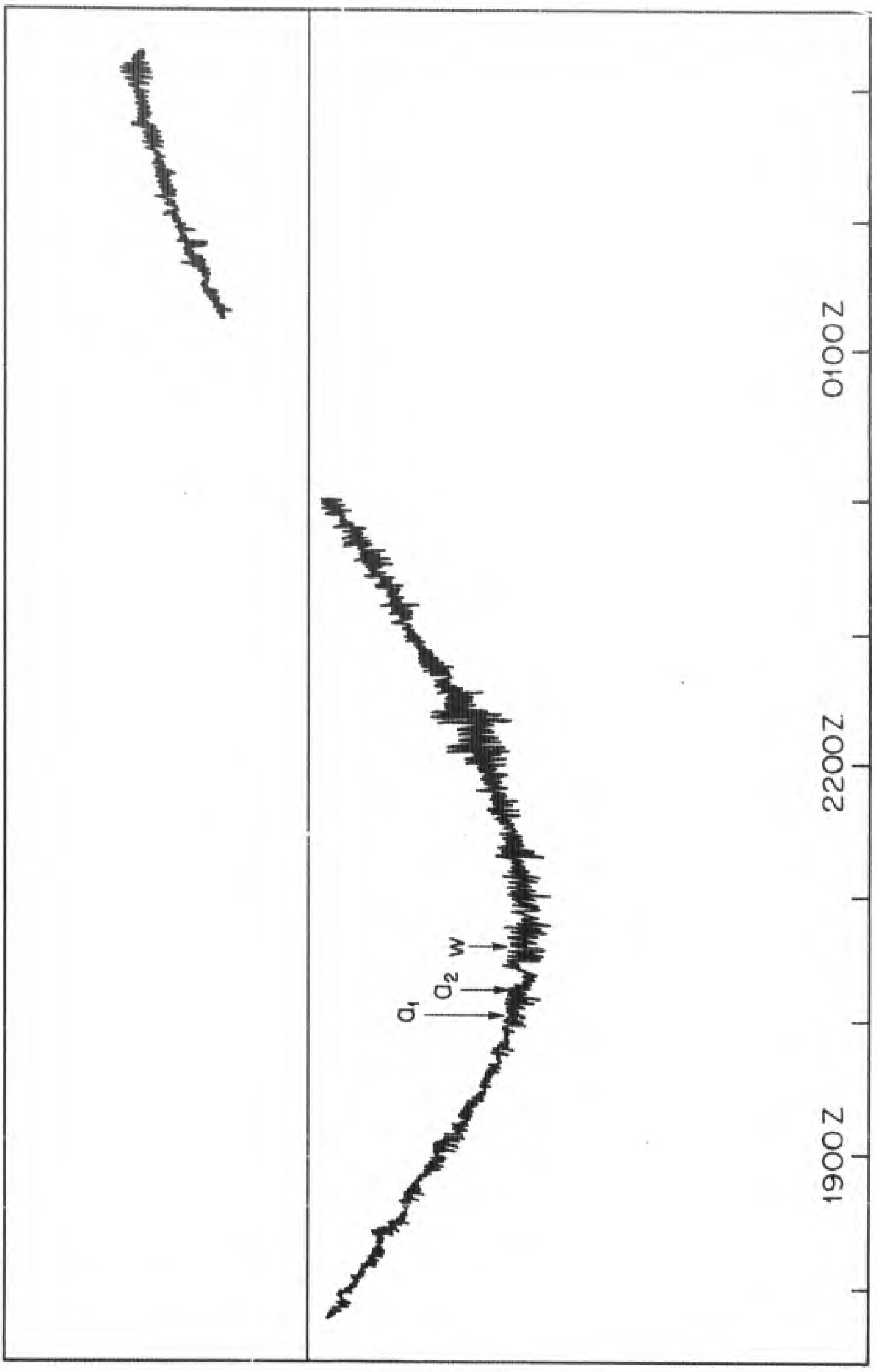


Fig. A.6 — Tide gauge (TG), Wake.

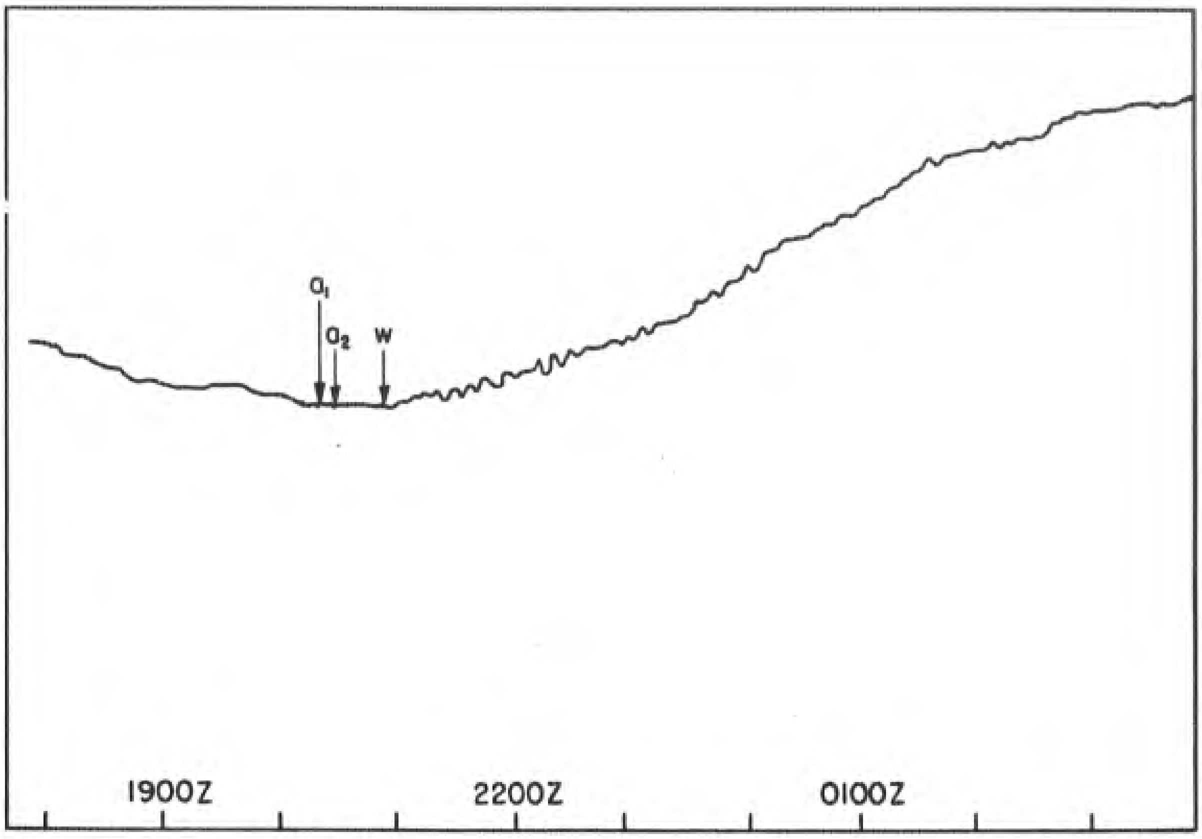


Fig. A.7—Tide gauge (TG). Truk.

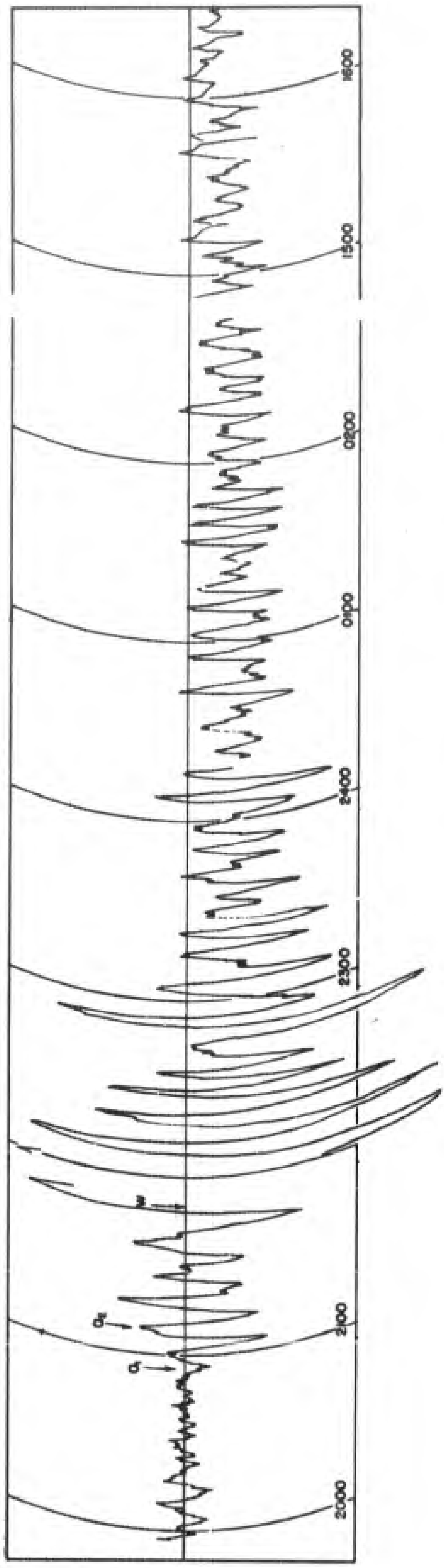


Fig. A.8—Differential-water-level recorder (VD), Guam.

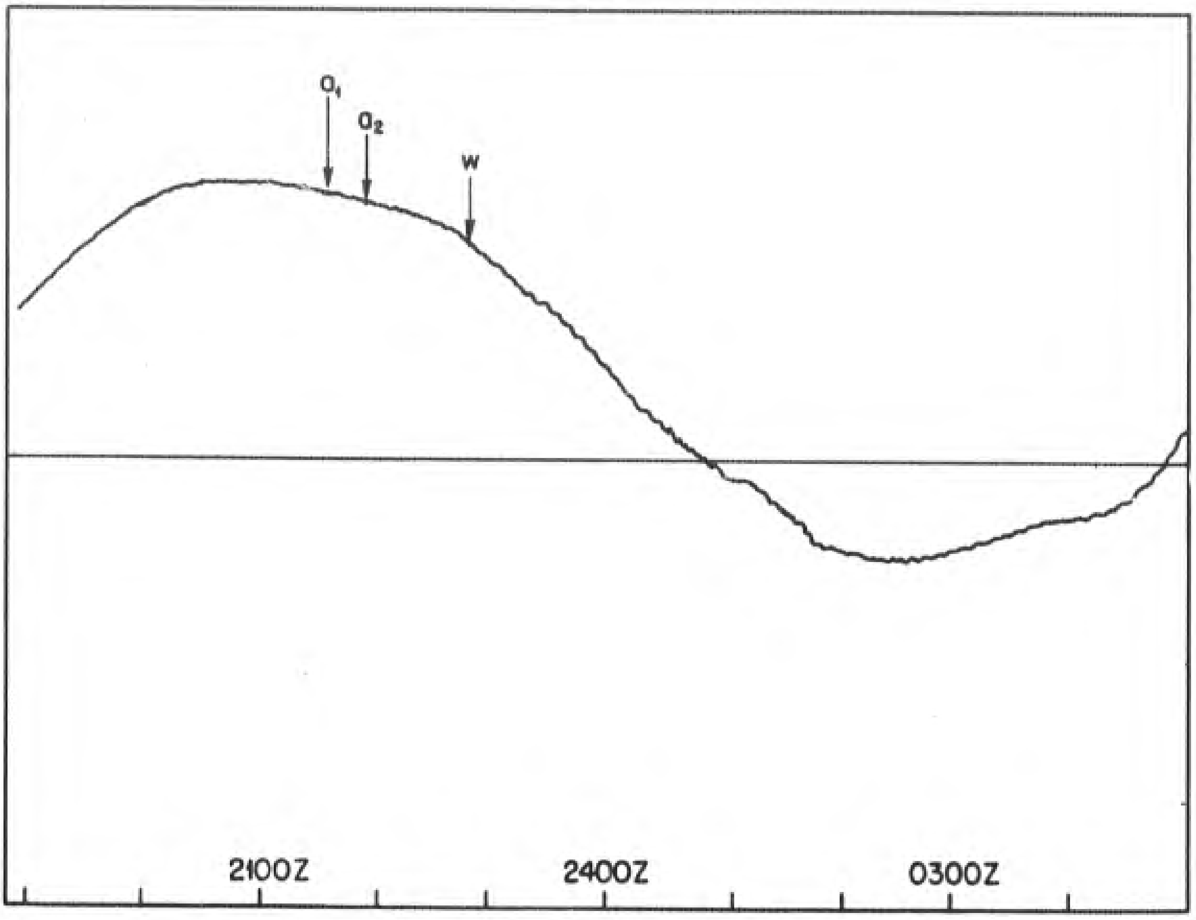


Fig. A.9—Tide gauge (TG), Yap.

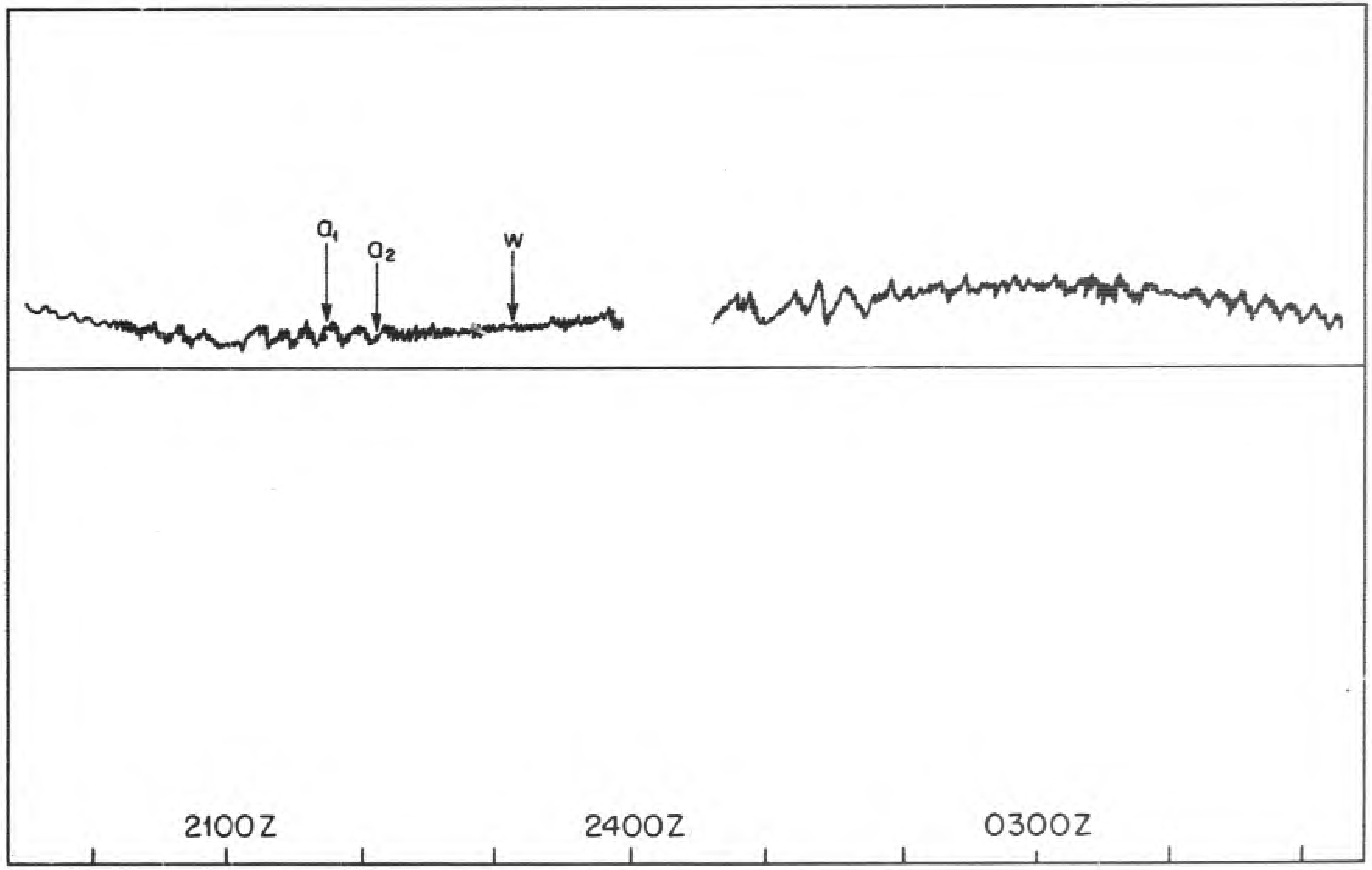


Fig. A.10—Tide gauge (TG), Midway.

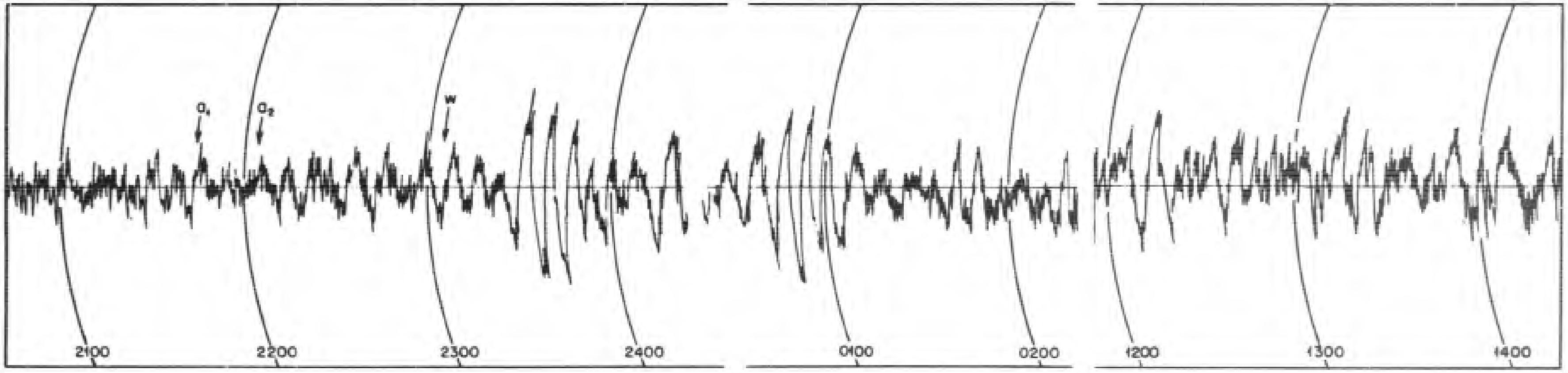


Fig. A.11—Differential-water-level recorder (VD), Midway.

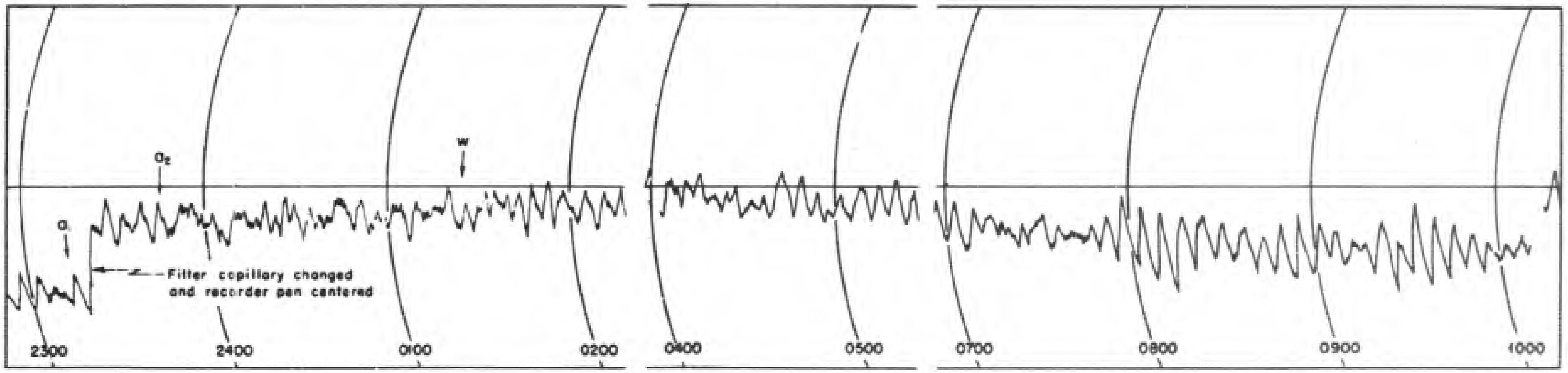


Fig. A.12—Differential-water-level recorder (VD), Kawaihae, T. H.

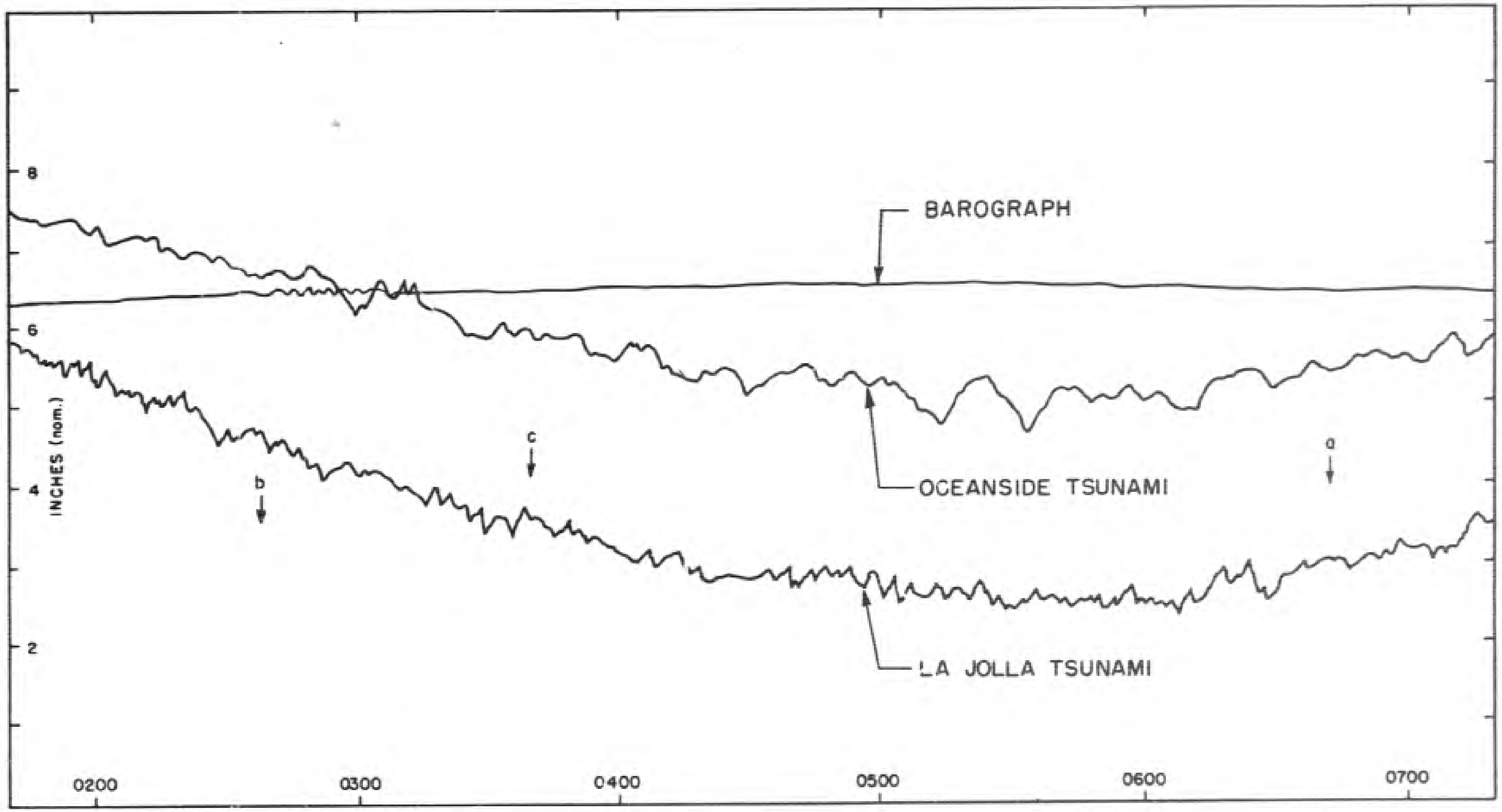


Fig. A.13—Microbarograph (MB) and tsunami recorder (TR), La Jolla, Calif.; tsunami recorder (TR), Oceanside, Calif.

APPENDIX B

SUGGESTION FOR A MODEL TEST AT BIKINI ATOLL

The change in the plan to conduct test No. 1 of the Operation Castle series at the water surface over fairly deep water (which would have been the first United States atomic weapon so detonated) and replace it with an overland shot has left in its wake a feeling of unfinished business, for there are certain important pieces of information which can only be obtained by such a test.

1. What are the subsurface pressures at various depths and distances? Aside from the theoretical value of knowing the distribution of pressures on each side of the interface of two homogeneous mediums, there is probably an immediate military use for such data. For example, how close can a submarine get to the explosion of its own torpedoes (armed with atomic warheads)?

2. What is the true nature of the base surge? How big are the drops; are they radioactive? What is the probable contaminative effect on a ship? The results of Baker shot, Operation Crossroads, were inconclusive in this respect, and more questions were presented by these results than were answered.

3. What is the nature of the water-surface waves raised by an atomic explosion at the water surface? Earlier data indicate that for TNT explosions much larger waves are raised by a surface shot than by equivalent explosions at any other depth. The British apparently regarded this piece of information as being so significant that they detonated their first atomic weapon at the water surface and have withheld the results of the test. It should be pointed out that Baker shot had the complexities that (a) the shot was not at the surface, (b) the bottom effect was great since the water was only 180 ft deep, and (c) waves propagated in shallow water.

4. Can TNT explosions be scaled up to give data on atomic explosions in nonhomogeneous mediums? There is considerable difference of opinion on this point which can hardly be resolved without a clear-cut test.

The attendant difficulties of mooring, photographing, and instrumenting a full-scale thermonuclear weapon are many, and, considering the limitations of present knowledge and the probable cost of such an event, the cancellation of the proposed water-surface test seems like a logical decision. However, it is suggested that, in order to answer the preceding questions, a substitute test be conducted which could be regarded as a model of the thermonuclear weapon. This would involve the detonation of a small fission weapon (of the order of 1 to 20 kt—equivalent weight of TNT) at or near the site originally proposed for the Operation Castle shot No. 1.

There are several logical reasons, apart from the direct value of answering the previously stated questions, for conducting such a test.

1. Such a test would be a useful "dress rehearsal" in which some of the mechanical problems of mooring, observing the oceanic currents, arranging photographic gear, etc., could be

worked out on a reduced and consequently less expensive scale. For example, some of the instruments and cameras could be hand started and operated, thus saving expensive starting mechanisms.

2. The reduced size of the test would make it possible to get much closer to Ground Zero (which considerably simplifies the wave photographic program) and make it quite certain that no widespread destructive waves will be created. (Such waves are predicted from a full-scale test if TNT scaling is used.)

3. The circumstances under which waves, pressure, and base surge would be created are greatly simplified. The proportion of heat energy to mechanical energy would be known, and the relatively small explosion would not be subject to the influence of the ocean bottom. Whereas a large explosion would "feel bottom" in the proposed 4000 ft of water, bottom sloping 22° at that, the model shot would be small enough so that these factors would become unimportant and the situation would be quite clear cut.

4. A great number of model experiments dealing with underwater explosions at the surface and at various depths have been conducted, and their results have been used to predict possible results of comparable atomic explosions. The special situation extant at the Crossroads Baker shot, the only intermediate-size explosion, does not necessarily confirm the scaling laws for other situations. In predicting pressures and surface-water waves, scientists are in the position of scaling directly from charges of the order of 8 lb of TNT to those of 8 billion lb (4 Mt), a rather large increase. There is some evidence that this is not a very accurate way to predict effects.

5. Pacific forces afloat, especially the submariners, would probably welcome an opportunity to cautiously approach a blast having a known yield and thereby accustom the personnel to direct contact with atomic weapons. This would be comparable to the experiments by the Army at Las Vegas, where ground troops were allowed to occupy positions within a few hundred yards of atomic explosions. Obviously a submarine at a nearby but safe distance would make an excellent instrument platform.