MICROSEISMS AND PACIFIC TYPHOONS*

By Marion H. Gilmore† and William E. Hubert‡

ABSTRACT

The Naval Aerological Service initiated a project in 1944 under the technical supervision of Father James B. Macelwane, S.J., to investigate microseisms as a possible tool in detecting and tracking severe storms at sea. The first year's work in the Caribbean demonstrated, without a doubt, that microseismic data would be of great value in the forecasting of severe hurricanes and typhoons. Additional work in the Pacific and Caribbean has proved that tropical disturbances actually cause large "microseismic storms." This paper describes the development of the Pacific Microseismic Project into a new and valuable aerological tool which will greatly aid in the saving of life and property. It is now possible to locate accurately the position of a typhoon by the Seismo method when it is more than 1,000 miles from the Tripartite Microseismic Station.

During the September 1938 hurricane, which caused much damage to shipping and coastal installations in New England, microseisms were used successfully for the first time to investigate a hurricane. In the same year they were also used to study certain deep, extratropical storms over the North Atlantic, more than 1,000 miles east and north of St. Louis University, where the experiments were made. Those first complete researches[1] into the cause and origin of certain dominant microseisms eliminated some of the confusion that surrounded the much-discussed "microseismic storms." The new data thus obtained eventually led the Naval Aerological Service to investigate microseisms as a possible tool in detecting and tracking severe storms at sea.

The necessity for accurate meteorological data became more accentuated during World War II. One of the major problems of the Armed Forces and the United States Weather Bureau in supplying this need was that of obtaining storm data from the vast expanses of the oceans where storms could form and attain dangerous proportions before their existence became known. The urgency of solving this problem prompted Captain H. T. Orville, USN, Head of the Naval Aerological Service, to initiate the present microseismic research program in one attempt at its solution. The program was started in 1943 with the primary and sole purpose of determining the possibility of using microseismic data to detect, locate, and track severe hurricanes and typhoons when they are far from land. Since major investigations during the next three years were devoted almost exclusively to practical field operations in the Gulf of Mexico, the Caribbean, and the Pacific, little or no time was given to such theoretical questions as *how* or *why* severe atmospheric disturbances could

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[1] J. E. Ramirez, S.J., "An Experimental Investigation of the Nature and Origin of Microseisms at St. Louis, Missouri," *Bull. Seism. Soc. Am.*, 30:35–84; 139–178 (1940).

cause "microseismic storms." Some of the theoretical problems discussed by Murphy[2] and Leet[3] are gradually being solved as more and more technical data are accumulated and correctly interpreted. The tendency of some writers to "jump to conclusions," based on too few data, is believed to have caused much of the recent confusion and doubt surrounding the true nature and causes of microseisms.

Recent papers by Ramirez,[1] Murphy,[2] Leet,[3] Macelwane,[4] Gutenberg,[5] Ors,[6] and Gilmore[7] have discussed many problems related to detecting and tracking severe tropical and extratropical disturbances. While it is still true that some of the papers indicate that certain definite conclusions were based on insufficient data, yet there is one conclusion which is apparently unanimous and is stressed in all the publications; that is, that it is impossible for any severe atmospheric disturbance to form near or to approach any coast or island where microseisms are regularly observed without microseismic indications a day or more in advance of the storm. Data submitted in these papers prove definitely that certain regular and dominant microseisms are produced directly by atmospheric storms over water and that it is possible to calculate accurate bearings on the storm area from the microseisms recorded at tripartite stations. These technical papers deal with special problems encountered in the microseismic work conducted in the Gulf-Caribbean area, and a few contain a detailed account of investigations carried on by the Navy.

The Navy's microseismic research project has three principal objectives: first, to obtain immediately all possible usable data on the formation and movement of hurricanes and typhoons; second, to continue experimental research in instrumental development and better operational techniques, so that each station can give more dependable and accurate information on ocean storms; and, third, to continue coöperating with the United States Coast and Geodetic Survey and other reporting seismograph agencies in the collection and distribution of valuable earthquake data recorded on the existing network of the Navy's seismograph stations. The Navy Department realizes that all these objectives are extremely difficult to meet because of the acute shortage of skilled seismograph observers, due in part to demobilization following the end of the war and in part to the rapid expansion of the microseismic project from one to ten experimental stations.

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[2] L. M. Murphy, "Winter Microseisms," *Trans. Am. Geophys. Union*, 27:19–26 (1946).

[3] L. Don Leet, "Microseisms in New England—Case History of a Storm," *Geophysics* (October 1947).

[4] J. B. Macelwane, S.J., "Storms and the Origin of Microseisms," *Annales de Géophysique*, 2:281–289 (1946).

[5] Beno Gutenberg, "Microseisms and Weather Forecasting," *Journal of Meteorology*, 4:21–28 (1947).

[6] Vincente Inglada Ors, "La exploracion de los ciclones por el movimiento microsismico," *Revista de la Real Academia de Ciencias, de Madrid*, Tomo XL (1946).

[7] Marion H. Gilmore, "Microseisms and Ocean Storms," *Bull. Seism. Soc. Am.*, 36:89–119 (1946); "Tracking Ocean Storms with the Seismograph," *Bull. Am. Meteor. Soc.*, Vol. 28, No. 2 (February 1947); "Microseisms Classified According to Type of Storm," *Trans. Am. Geophys. Union*, 27:466–473 (1946).

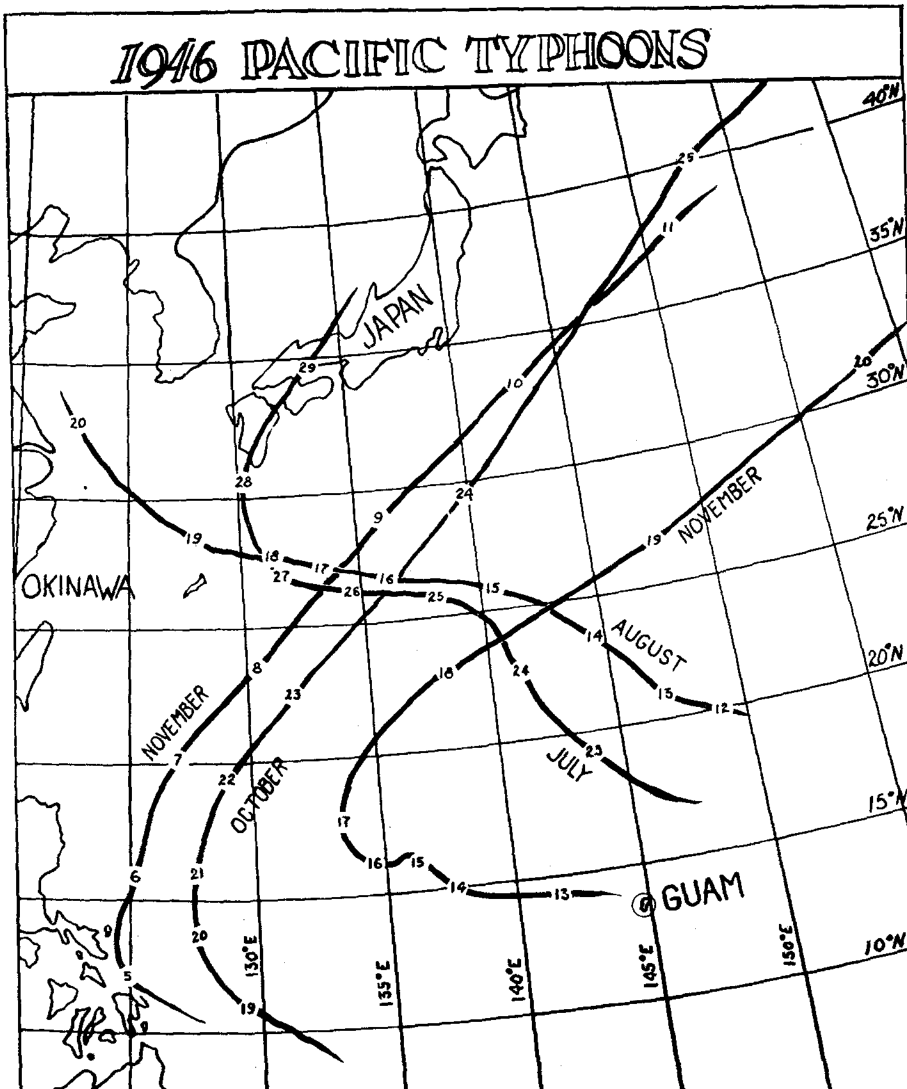


Fig. 1. Tracks of five typhoons, 1946.

The first Naval tripartite microseismic research station was established at the Naval Operating Base, Guantanamo Bay, Cuba, in the summer of 1944. This station gave such promising results in its first year's operation[5] that the Navy Department added similar stations in Florida and Puerto Rico the following year. Operational results were again considered sufficiently valuable for the establishment of four additional stations in the Gulf-Caribbean area in 1946 and one station at Guam in the Pacific. The initial installation at Guam has been in continuous operation since 18 July 1946, except for the short interval between 23 August and 19 October of that year. LTJG William E. Hubert, USN, was sent to Guam in January 1947 to supervise the microseismic work in the Pacific. He converted the station at Guam into a tripartite unit and established single units on Okinawa and at Subic Bay, near Manila. The many data used in this paper are the results of the work accomplished by Naval officers and the enlisted men working with them on this research project.

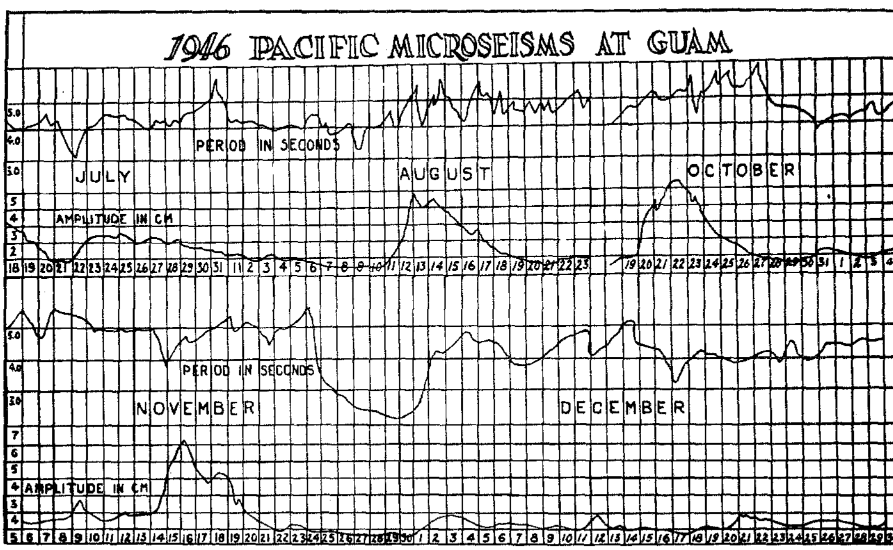


Fig. 2. Amplitudes and periods of microseisms of five typhoons, 1946.

Records of tropical storms in the Pacific have been kept for more than 400 years, but until recently the record was very incomplete. The oldest records consisted mostly of storms that were so intense that they were chronicled in the histories of cities, towns, and areas that were partly or wholly destroyed. Other storms were unobserved and unrecorded because of their small intensity, isolated tracks, or lack of survivors. The average number of typhoons recorded in the western Pacific since 1920 is 19.6 per year.[8] During World War II, the Naval Aerological Service maintained weather stations and weather ships throughout the danger area. Reports from these units and from weather reconnaissance planes provided much better data on typhoons and hurricanes than had ever before been available. According to these records, 31 typhoons were discovered and tracked in the western Pacific in 1945 and 15 the following year. One of the 1946 Pacific typhoons was in progress when the

[8] "Typhoons and Hurricanes," Aerology Series, No. 10, NavAer 00-80U-21, pp. 8–9 (1946).

first microseismograph was installed on Guam in July. The first microseismic amplitude recorded was 31 mm., at a time when the storm was about 1,600 miles from the station and just entering the China coast. That storm soon filled while over China and the microseisms fell to a normal of 6 mm. (fig. 2).

Five other typhoons were located near Guam in 1946 during the time that the single-unit seismograph was in operation there. The tracks of these tropical storms are shown in figure 1. The dates in the circles along the tracks indicate the best estimated position of the typhoon for 0000 GCT on that day. The amplitude and period of the microseisms were measured, and their curves are shown in figure 2, which is believed to be self-explanatory. The seismographs used on Guam and Okinawa are the same type as those which are used by the Navy in the Caribbean and which have been adequately described by Sprengnether.[9]

TABLE 1

BEAUFORT SCALE FOR WIND VELOCITIES

Beaufort wind force	Description	Knots
0	Calm	Less than 1
1	Light air	1–3
2	Light breeze	4–6
3	Gentle breeze	7–10
4	Moderate breeze	11–16
5	Fresh breeze	17–21
6	Strong breeze	22–27
7	Moderate gale	28–33
8	Fresh gale	34–40
9	Strong gale	41–47
10	Whole gale	48–55
11	Storm	56–63
12	Hurricane	64–71
13		72–80
14		81–89
15		90–99
16		100–109
17		110–118

The data presented in this paper show that Pacific typhoons frequently cause large "microseismic storms" and that the amplitude depends almost entirely upon the intensity of the typhoon and its distance from the recording

[9] W. F. Sprengnether, "A Description of the Instruments Used to Record Microseisms for the Purpose of Detecting and Tracking Hurricanes," *Bull. Seism. Soc. Am.* 36:83–87 (1946).

station. Large microseisms are also associated with certain frontal systems and extratropical lows that are accompanied by winds of force 6 or higher (see table 1). Severe storms were accurately recorded by increased microseisms and tracked by microseismic bearings when they were 1,600 miles from Guam. It is therefore quite obvious that the seismograph has a much greater effective range on Pacific storms than it has for Caribbean hurricanes of the same intensity. This is apparently true because the Pacific area around Guam has fewer "microseismic barriers" than the Caribbean. Microseismic barriers are zones or boundaries that impede the free transmission of microseisms. These zones have been reported in several independent investigations of microseisms, but the actual nature of this interference barrier is not known.

A few seismologists have suggested that the microseismic barrier could be a major fault system in which the displacement of homogeneous rock strata reaches 30,000 to 50,000 feet. They contend that such zones of severe folding and faulting would be sufficient to absorb or reflect a large percentage of the energy in microseisms. A few areas of major discontinuities are known in the earth's crust and others are suspected, especially in the Caribbean. The microseismic barriers in the Caribbean do not always coincide with previously known major faults. On the other hand, the seismographs at the University of California, Berkeley, are located between two major rifts, and Dr. Perry Byerly reports no station is more troubled with large microseisms than his. Apparently, the microseisms caused by extratropical lows to the west and northwest of Berkeley have no difficulty passing over or through these faults. It is impossible to determine with present data the exact nature of the boundaries that tend to impede microseismic waves.

The L phase of recorded earthquakes and microseisms travel through the outer crust of the earth, and the velocity of these elastic waves depends greatly upon the composition of this layer. A study of the travel-time curves for the earthquake L waves reveals a very complex structure in the Caribbean, which, no doubt, has some connection with decreased microseisms in certain areas. This phase has many characteristics in common with ordinary microseisms and gradually fades into true microseisms near the end of recorded earthquakes. Gutenberg[10] and others have measured the velocity of elastic wave motion in the earth's crust and some very good travel-time curves have been drawn. The Navy's microseismic stations in the Pacific will undoubtedly aid in revising or amplifying existing travel-time curves there. The speed of the microseismic wave at Guam is about 3.16 km/sec.

The typhoon tracks (fig. 1) were determined by aircraft, ship reports, and other available meteorological data, and are considered as accurate as is possible over the vast regions of the Pacific. The second July typhoon did not attain the usual severity of most typhoons and caused the microseisms to in-

[10] Beno Gutenberg, Chapter on "Seismology" in Geol. Soc. Am., *Geology, 1888–1938. Fiftieth Anniversary Volume*, pp. 437–470 (1941).

crease in amplitude from 4 to 21 mm. The first Naval advisory was issued when the storm was about 250 miles north-northeast of Guam at 0000 GCT on 23 July (figs. 1 and 2). In the previous eighteen hours the microseisms increased to 20 mm., and they remained near that amplitude for the following six days.

TABLE 2

TYPHOON WARNINGS, OCTOBER 1946

Date; Time GCT	Lat. N	Long. E	Wind at center (knots)	Type of warning
Warnings issued by the Fleet Weather Central, Manila				
180900	10.0	132.0	30	Weak storm
190000	10.9	129.2	55	Storm
190845[a]	12.3	128.8	80	Typhoon
191200	12.6	128.3	90	Typhoon
191800	13.2	127.7	90	Typhoon
200000[a]	13.7	127.7	90	Typhoon
200600	14.0	127.5	90	Typhoon
201200	14.7	127.0	90	Typhoon
201800	15.3	126.7	90	Typhoon
210000[a]	16.0	127.6	90	Typhoon
210600[a]	16.7	128.2	110	Severe typhoon
211200	17.6	129.0	110	Severe typhoon
220000[a]	19.5	129.5	110	Severe typhoon
Warnings issued by the Fleet Weather Central, Guam				
220600	20.1	129.5	100	Typhoon
221200	21.0	130.0	90	Typhoon
230000[a]	22.5	132.0	100	Typhoon
230600	23.4	133.0	90	Typhoon
231200[a]	24.2	134.0	90	Typhoon
240000[a]	29.6	140.0	100	Typhoon
240600	32.1	142.6	80	Typhoon
241200	34.3	145.4	70	Typhoon
250000	40.0	153.0	55	Storm
250600	43.0	160.0	55	Storm

[a] Positions fixed by weather plane.

The typhoon was moving away from Guam during this time and reached a point about 1,100 miles away before the microseisms started to decrease. It has been observed that the microseismic period is usually longer when the storm is the greatest distance from the seismograph station and when the amplitude is rapidly increasing. However, in this storm, as well as in others, there could be found no definite trend of the period that could be used to foretell anything new about meteorological disturbances.

The amplitude for the first ten days of August (fig. 2) was almost constant and averaged about 5 mm. Within 36 hours the microseismic amplitude had increased to 49 mm. The first official advisory was released by the Fleet Weather Central, Guam, on 12 August, just as the microseismic amplitude

TABLE 3

TYPHOON WARNINGS, NOVEMBER 1946

Date; Time GCT	Lat. N	Long. E	Wind at center (knots)	Type of warning
Warnings issued by the Fleet Weather Central, Manila				
041500[a]	12.0	127.0	40	Storm
050000[a]	12.2	125.5	50	Storm
051200	14.3	123.9	65	Typhoon
051800	15.6	123.2	70	Typhoon
060000[a]	15.7	125.9	70	Typhoon
060600	16.3	126.2	70	Typhoon
061200	16.9	126.8	70	Typhoon
061800	17.7	127.2	70	Typhoon
070000[a]	20.0	126.8	90	Typhoon
070600	21.0	127.0	95	Typhoon
071200	22.2	127.7	95	Typhoon
Warnings issued by the Fleet Weather Central, Guam				
080000[a]	23.4	130.4	80	Typhoon
080600	24.4	132.0	65	Typhoon
081200	26.5	135.0	55	Storm
090000[a]	28.8	136.0	80	Typhoon
090600	30.5	137.5	80	Typhoon
091200	31.6	138.6	80	Typhoon
091800	32.6	140.4	80	Typhoon
100000	33.8	142.0	70	Typhoon
100600	34.5	145.0	70	Typhoon
101200	35.6	146.8	55	Storm
110000	38.0	151.0	45	Storm

[a] Positions fixed by weather plane.

reached 16 mm. There had been a very gradual increase in the microseisms during the past twenty-four hours. The largest amplitudes for this storm were recorded as the typhoon passed the nearest point about 500 miles north of the station. The microseisms remained very high for two additional days. When the storm was at least 1,000 miles away, it still caused microseisms of four times normal amplitude. The period of these microseisms was again very irregular and indicated no definite trend.

The recording vault was moved after the August typhoon and the station did not operate again until 19 October. The following day a severe and destructive storm developed about 700 miles west of Guam (fig. 1). Significant data on this typhoon, as released in official Naval advisories, are given in table 2. The microseisms increased rapidly from a low of 8 to more than 55 mm. during the next three days. During the same three-day period, the wind near

TABLE 4

TYPHOON WARNINGS ISSUED BY THE FLEET WEATHER CENTRAL, GUAM, 13–19 NOVEMBER 1946

Date; Time GCT	Lat. N	Long. E	Wind at center (knots)	Type of warning
130600[a]	14.5	141.5	60	Typhoon
140000[a]	15.0	138.0	65	Typhoon
140600	15.0	136.3	75	Typhoon
141200	15.0	135.2	80	Typhoon
150000[a]	16.0	136.5	90	Typhoon
150600	16.5	136.4	90	Typhoon
151200	17.0	136.4	90	Typhoon
151800	16.5	135.5	90	Typhoon
160000[a]	16.2	134.3	95	Typhoon
160600	16.0	133.6	95	Typhoon
161200	16.1	133.9	95	Typhoon
161800	16.0	133.5	95	Typhoon
170000	16.0	134.0	65	Typhoon
170600[a]	20.5	133.7	80	Typhoon
171200[a]	20.0	135.0	100	Typhoon
171800[a]	21.2	135.5	100	Typhoon
180000	22.3	136.4	100	Typhoon
180600[a]	23.6	139.7	100	Typhoon
181200	24.6	142.4	100	Typhoon
190000	26.6	147.7	70	Typhoon
190600	27.7	150.5	60	Typhoon
191200	29.0	153.0	50	Storm

[a] Positions fixed by weather plane.

the storm's center was estimated to have increased from 30 to 110 knots (table 2). The amplitude of the microseisms remained above 20 mm. until the typhoon had reached a point 1,200 miles north of Guam. The period again increased with the amplitude. On the other hand, after the largest amplitude was recorded, the period fluctuated over a wide range, gradually getting longer as the storm passed out of effective range of the seismograph station.

There were two typhoons in November near enough to Guam to be recorded on the seismograph (figs. 1 and 2). The track of the first storm closely followed that of the October storm but was about 200 miles farther from Guam. This typhoon was never reported as severe (table 3), and it was just large enough to cause microseisms at Guam. Four days after the disturbance formed off Samar, P.I., it began curving northeastward and intensified sufficiently to cause the microseisms at Guam to increase in amplitude from 5 to 25 mm. The data in table 3 show that the storm attained a wind velocity of 95 knots just after the highest amplitude was recorded, then quickly fell to 80 knots. The microseismic period did not show any significant change.

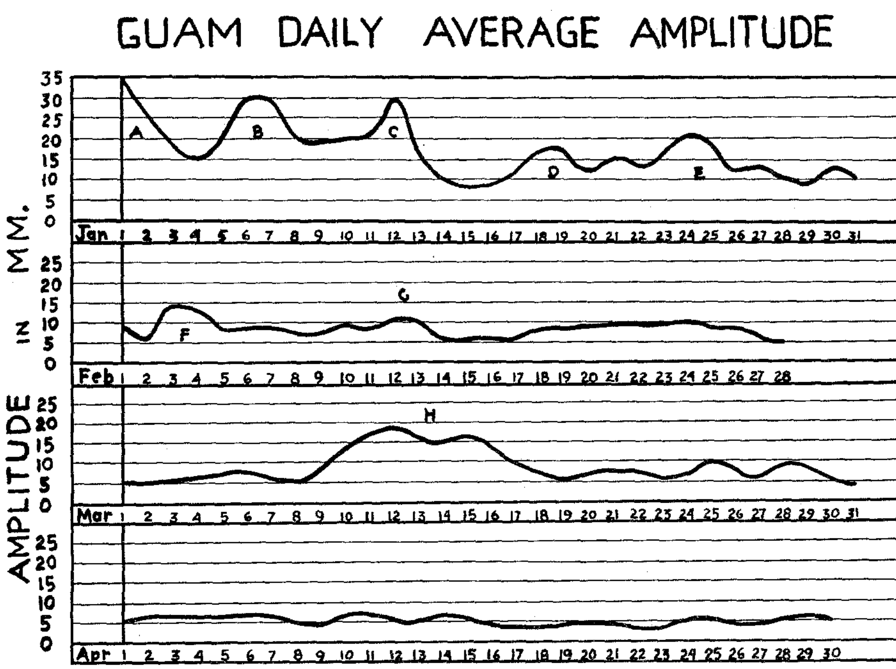


Fig. 3. Daily average amplitude of microseisms, Guam, January–April, 1947.

The last typhoon in 1946 recorded on the seismograph at Guam was discovered almost over the island on 13 November. The first official advisory on that day (table 4) was issued at 0600 GCT and estimated the intensity of the storm at 60 knots. The microseisms did not show any appreciable change until the following day. However, by 16 November they had reached a maximum of 63 mm. as the storm winds increased to 95 knots. At this time both the amplitude of the microseisms and the storm's intensity began to decrease again. The winds were soon estimated at 100 knots near the center (table 4), and during the same time the microseisms increased from 45 to 55 mm. In the following twenty-four hours both the microseisms and the storm winds began to decrease, and by noon of 19 November the storm had winds estimated at only 50 knots. Microseisms of 10 mm. were still being recorded when the storm center was some distance north and east of Japan.

Microseismic storms were not in evidence during the rest of November, and the amplitude curve (fig. 2) showed almost no deviation from a straight line until the last two days in December. Figure 3 shows a continuation of the microseismic amplitude curve for the first four months of 1947. Items marked capital "A" through "H," figure 3, were probably caused by the following meteorological changes in and near Guam:

A. 30 December to 3 January: Instrumental maladjustment and weak cold front. The weak frontal system had Beaufort force 5 winds (table 1) just south of Guam.

B. 5 to 9 January: Microseisms of nearly 30 mm., probably caused by force 6 to 7 easterly winds in area between Saipan and Marcus.

C. 11 to 13 January: Microseisms from 1 through 15 January were abnormally high and represented winter microseisms. The sharp peak registered on 12 January was probably caused by force 6 to 7 winds from Guam to Iwo Jima.

D. 18 to 19 January: Between this microseismic peak and the previous period of high winds the microseisms dropped below winter normal; i.e., less than 10 mm. A wind force 7 to 8 near Iwo Jima caused the microseisms to reach 18 mm.

E. 23 to 25 January: The microseisms remained slightly above normal and on 24 January increased to 20 mm. This was probably caused by a trailing cold front 200 miles southeast of Guam. There was also a 996-millibar low about 900 miles north of Guam, with winds of force 7. Since it was impossible to get a seismograph bearing on this and the other microseismic storms during the first four months of 1947, it is impossible to prove the source of any specific amplitude increase.

F. 2 to 4 February: By the first of February the microseisms had dropped to a summer low of 5 mm. or less. On the third they increased to 14 mm., and an area of force 5 winds was located 600 miles northeast of Guam.

G. 11 to 13 February: A small increase of winds associated with the passage of a cold front probably caused the slight increase from 7 to 21 mm.

H. 10 to 16 March: The entire microseismic curve settled down to summer normals after the peak of 12 February. The increase noted in March was likely caused by the passing of a moderate cold front at Guam with winds of 5 to 7 on the Beaufort scale.

The amplitude of the microseisms for April was very constant (fig. 3), varying between 3 and 7 mm. The whole area in and around Guam was entirely free from storms, high winds, and moderate meteorological changes during that month. On the other hand, the period of the microseisms during April was extremely erratic, fluctuating between 2.8 and 4.8 seconds (fig. 3). The sharpest change occurred at 0000 GCT on 24 April, increasing from 3.4 to 4.8 seconds in six hours. The microseisms during the same six-hour period increased only from 3.5 to 5.8 mm., which was far too little a change to have any significant meteorological connection. The sharp changes in period appear to have no specific relation to the weather in and around Guam for April.

The microseismic pattern set for April was continued through all of May except for three days around the middle of the month (fig. 4). The first thirteen days of May the microseisms ranged between 4 and 7 mm., and from the sixteenth through the rest of the month they ranged between 2.5 and 5 mm. The May typhoon (fig. 5) was very similar to the hurricane which passed through the Bahama Islands[11] in September 1946. It never covered a big area at any time and the only strong winds were found very near the center. Only four good positions were determined for the entire track of this storm. When it was still too weak to register on the Guam seismograph, a weather plane gave a good fix at 0000 GCT on 14 May; twelve hours later it passed over a ship and had winds of 65 knots near the center; on the fifteenth at 0000 GCT

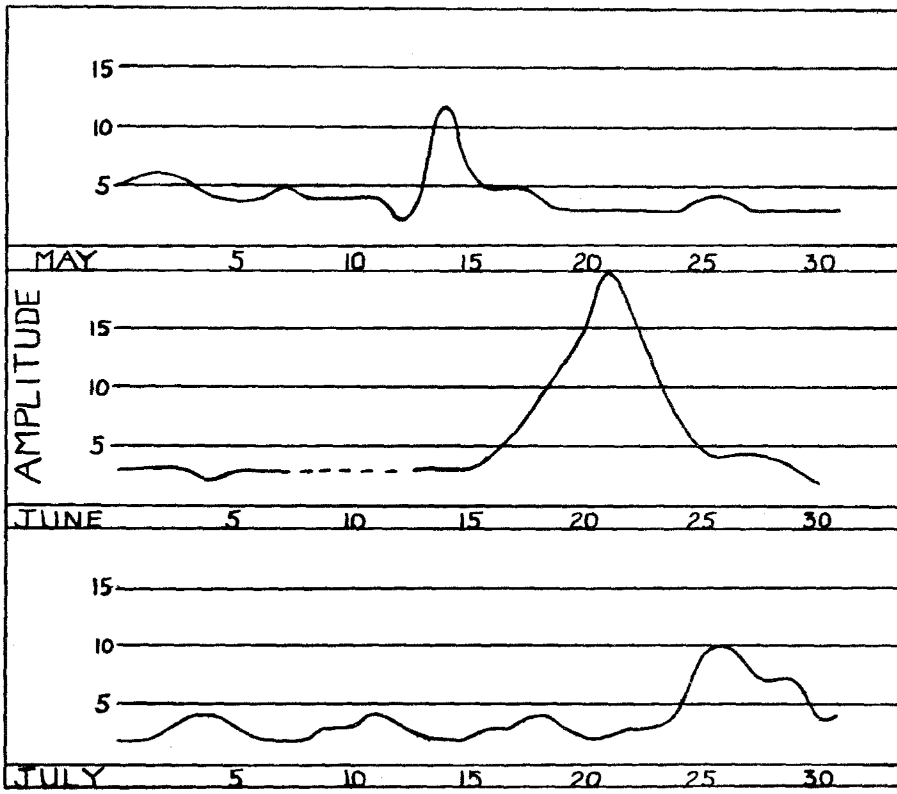


Fig. 4. Daily average amplitude of microseisms, Guam, May–July, 1947.

it passed directly over Iwo Jima; twenty-four hours later it was again located by a weather plane. In its early stages the typhoon was too weak to cause microseisms on the Guam seismograph. However, as soon as the wind increased to 65 knots the microseisms began to increase at Guam. Although the storm was traveling away from the seismograph station and attaining only an estimated 70 knots, it caused microseisms of four to five times normal. The storm filled rapidly on 16 May and the microseisms returned to normal. The microseismic amplitude curve told a true story of the intensity of this typhoon as its dis-

[11] Macelwane, *op. cit.*

tance from the station increased. The rest of May and the first half of June were very quiet, meteorologically, and during this time the microseisms never exceeded 5 mm. in amplitude at Guam. Even the period showed no erratic movements.

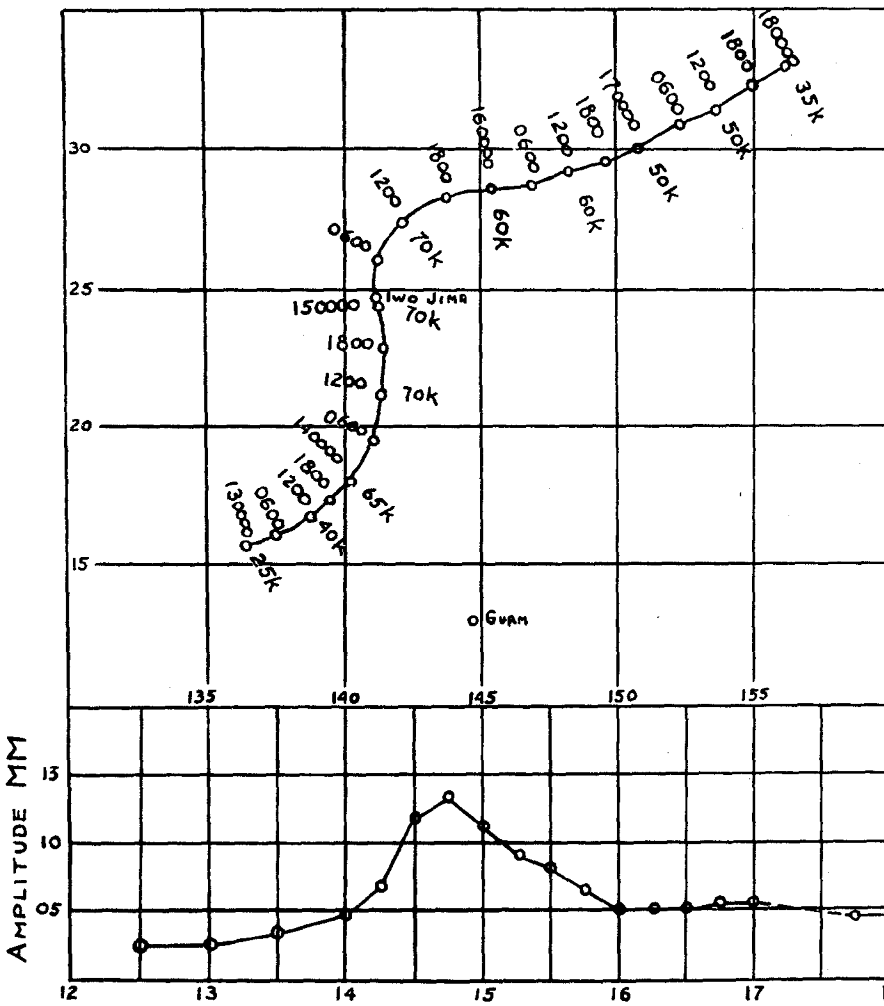


Fig. 5. Track and amplitude, typhoon of May, 1947.

The second typhoon of 1947 was located on 17 June at 1200 GCT, when it was about 770 miles west of Guam. This typhoon (fig. 6) is particularly noteworthy because it is the first storm completely tracked with bearings from the Navy's new tripartite microseismic station at Guam. The winds of this storm slowly increased in intensity from 65 to 100 knots and its distance from Guam increased from 770 to 1,600 miles as it entered the China Coast. The microseisms were below 5 mm. during the first half of June, but began to increase slightly 18 hours before the storm was discovered, and finally reached a peak

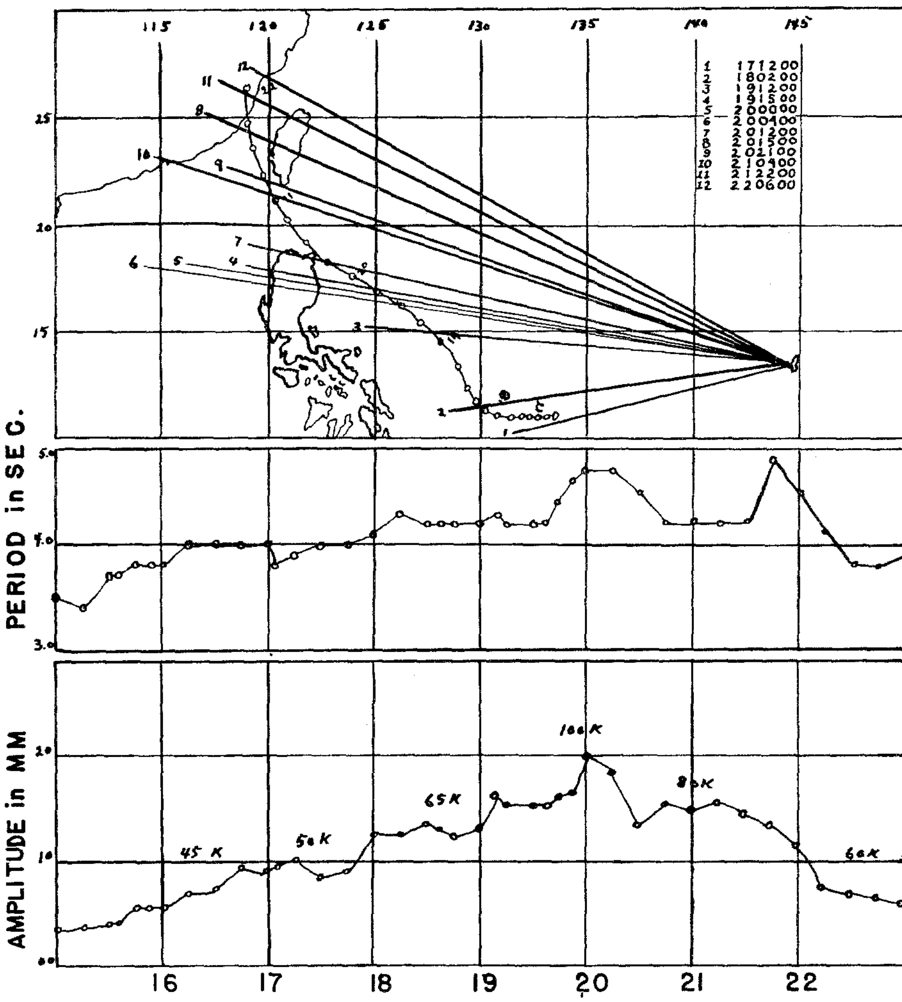


Fig. 6. Track and amplitude, typhoon of June, 1947.

of 20 mm. when the typhoon was about 1,200 miles away. All the data found in figure 6 and in table 5 merit careful study.

Before an observer reports a calculated bearing he must decide upon its accuracy from a careful study of the many data contained in the microseismic records. His judgment on its accuracy is always reported as one of the following standard forms:

1. Azimuth determined but doubtful.

2. Azimuth fairly well determined.
3. Azimuth well determined.

The seismograph bearings calculated at Guam (table 5) for the June typhoon are excellent. Only three bearings out of the twelve calculated for this storm were classed by the observer as "doubtful," and these included those with errors of 180, 70, and 40 miles from the estimated position of the storm at the time of the bearing. The bearing with error of 180 miles is far from good, but a restudy of the seismograph records will perhaps reveal some mistake that could have been avoided, such as is sometimes found in a restudy of micro-

TABLE 5

Pacific Typhoon, June 1947

Time	Bearing	Error	Direction of error	Class[a]	Distance (miles)
171200	260	40	Lagging	1	770
180200	265	0	0	2	830
191200	277	70	Lagging	1	1020
191500	282	5	0	3	1080
200000	281	70	Lagging	2	1200
200400	280	90	Lagging	2	1230
201200	285	80	Lagging	2	1380
201500	296	180	Leading	1	1410
202100	293	50	Leading	2	1420
210400	292	30	Leading	3	1460
212200	299	0	0	3	1550
220600	302	0	0	3	1600

[a] Class of bearing: 1, determined but doubtful; 2, fairly well determined; 3, well determined.

seismic data. Five bearings were listed as "fairly well determined" with estimated errors of 90, 80, 70, 50, and 0 miles, all of which will pass through some part of the typhoon where the strongest winds might be found. In this connection, it is thought probable that the bearings obtained in all microseismic calculations point toward the area of strongest winds rather than to the actual calm center. If this be true, it is obvious that some bearings will actually pass through the theoretical center while others will either lag or lead the exact center, depending *only* upon the immediate position of the strongest winds in the storm area. The four bearings classed as "well determined" missed the estimated center by 35, 5, 0, and 0 miles each, making an average error of only ten miles. The last three of these bearings given as "well determined" (table 5) were calculated for the storm when it was near the China coast about 1,500 miles from the seismograph station. A careful study of the many data in table 5 will show that only one bearing out of the twelve failed to pass through an area of strong winds surrounding the typhoon; that *all* azimuths listed as "well determined" are very accurate and highly dependable for locating the storm area; that all bearings listed as "fairly well determined" contain much valuable information for the forecaster of severe tropical storms; and that the average error of all twelve bearings was only 54 miles from the estimated center of the storm as it moved along its track. It is believed that *all bearings reported*, especially those reported as "doubtful" and "fairly well determined," can be greatly improved as more experienced and skilled observers are employed at the various microseismic stations.

Recording difficulties were encountered when the first bearings were calculated at Guam. The individual microseismic waves were not very regular at the main vault and often were not even similar to the two traces at the other units of the tripartite station. This made it difficult, if not impossible, to calculate true and accurate bearings. The similarity of the recordings from the three seismometers was improved 100 per cent when the main instrument pier was separated from the floor of the recording vault. The bearings calculated after this work was done were greatly improved and fewer doubtful azimuths were obtained, even though the distance to the typhoon was very great at all times.

The largest microseismic amplitude, of 20 mm., was recorded at 1200 GCT on 20 June and corresponds very closely with the maximum winds reported for the typhoon. The storm crossed a major Pacific fault system north of Luzon at 1500 GCT and within three hours the microseisms started a slight decline which continued for about twelve hours. A small increase was then recorded, but the microseisms never attained the maximum amplitude reported before crossing the fault. It is significant that during this time some of the best bearings were calculated. Experience has shown that in the Caribbean the microseisms were greatly decreased when a storm crossed a major fault system. If that be true in the Pacific, the increased microseismic amplitude could only mean that the storm actually gained in intensity. This is probably true, because one Navy aerological officer on a weather plane at that time reported winds near the center to be 150 knots.

The microseisms recorded on two sets of records at 1200 and 1500 GCT on 21 June were classed as very irregular. The arrival times of the various microseismic waves measured on the three records indicated that they were coming first from one direction, then from another. One wave would arrive first at station number 1, the next one at station number 2, and never followed any special order. This, of course, prevented any bearings from being calculated, even those azimuths marked "very doubtful." By this time the storm had decreased in intensity—to winds of only 80 knots. It was more than 1,500 miles from Guam when the microseisms finally dropped to normal. Decreasing winds over the China coast indicated rapid filling of the storm.

Throughout the rest of June the microseisms at Guam were normal (fig. 4).

On Okinawa they were irregular (fig. 7) although not large. The first peak reached at Okinawa on 15 June was caused by an extratropical low and frontal system near the station. The second peak was caused by the severe typhoon mentioned above and reached a maximum intensity on 21 June.

July was unusual in that no typhoons occurred in the Pacific area during that month. Okinawa recorded very irregular microseisms, but they did not get very large. The first peak reached on 9 July was caused by a small depression that formed near 17 north latitude and 130 east longitude and moved

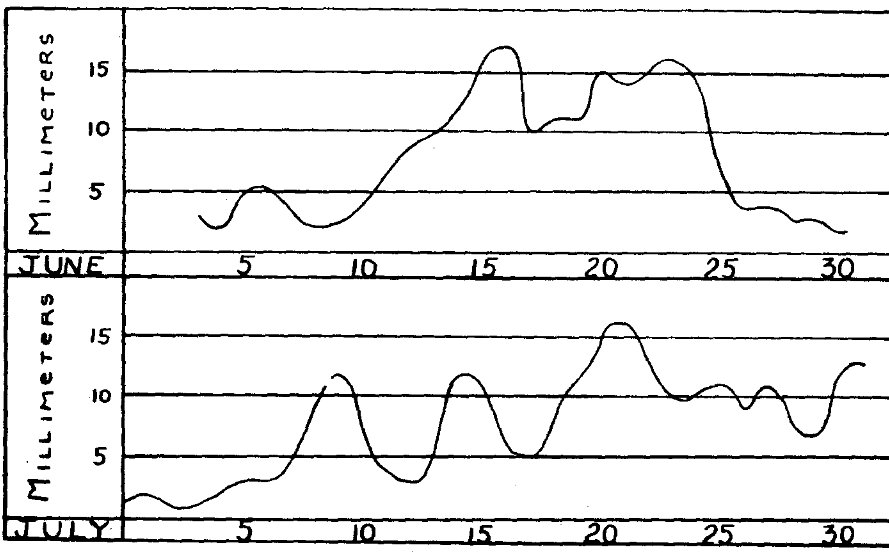


Fig. 7. Daily average amplitude of microseisms, Okinawa, June and July, 1947.

northward to pass over Okinawa and the Japanese islands of Honshu and Kyushu. The highest winds reported in this depression were of force 6. The other amplitude peaks coincided with frontal systems moving across the Yellow and East China seas.

The only appreciable rise in the microseisms at Guam was from 24 to 29 July. At that time a tropical depression formed near 16 north latitude and 137 east longitude and moved north-northwest, to pass to the south of Okinawa on 29 July, causing very large month-end amplitudes there. Force 6 winds were reported in the early stages of the depression, and several ships reported force 9 winds south of Okinawa. An attempt was made to obtain bearings from the Guam station, but it was found that the microseisms were too small and far too irregular. This was often observed in the Caribbean when microseisms were apparently being caused by a large area of high winds. The microseisms were sometimes regular, but more often they were irregular. But always the indi-

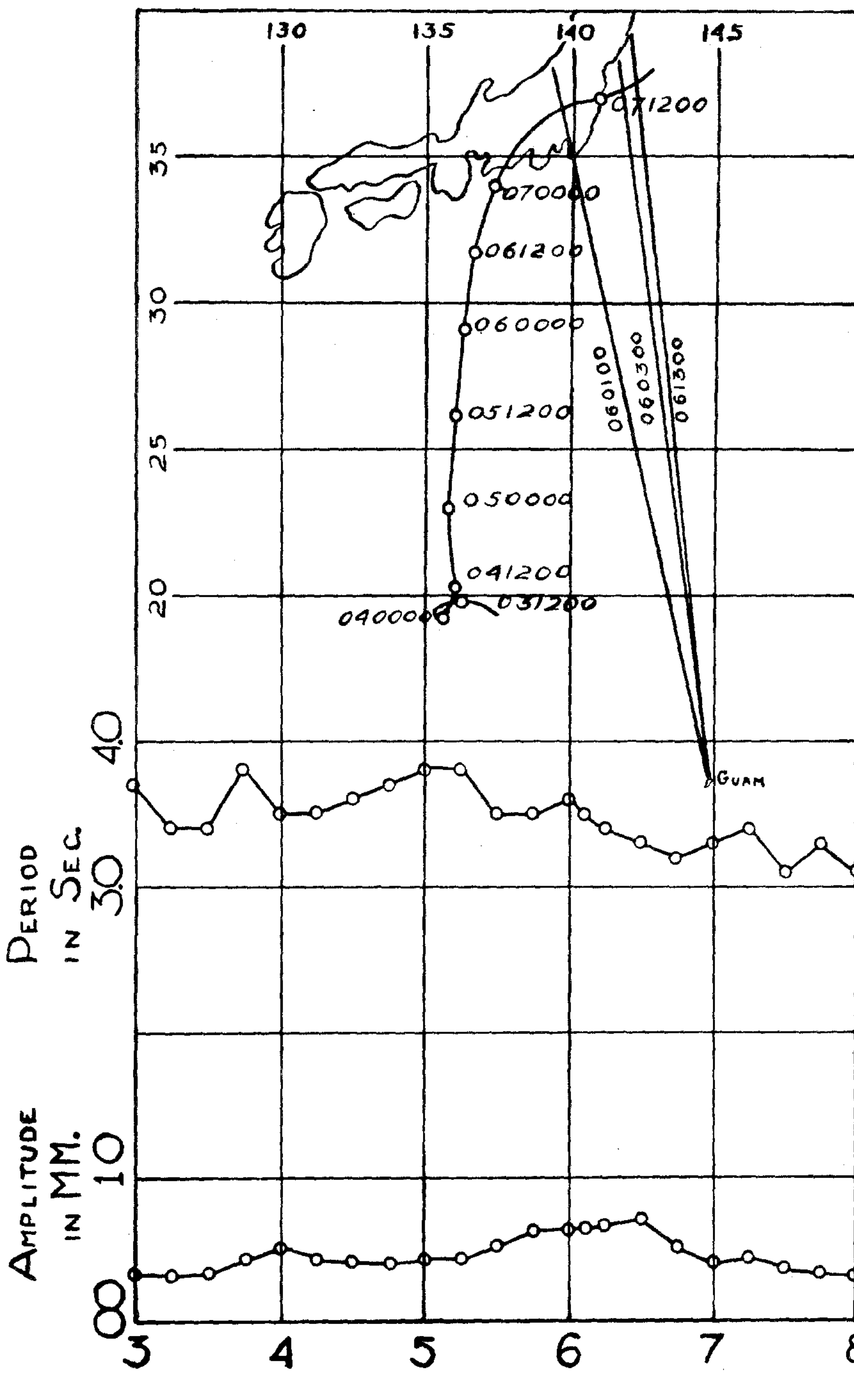


Fig. 8. Track and amplitude, first typhoon of August, 1947.

vidual microseismic waves appeared to come from widely separated points in the direction of highest winds. The more concentrated the high winds, the more accurately the bearings pointed into that area.

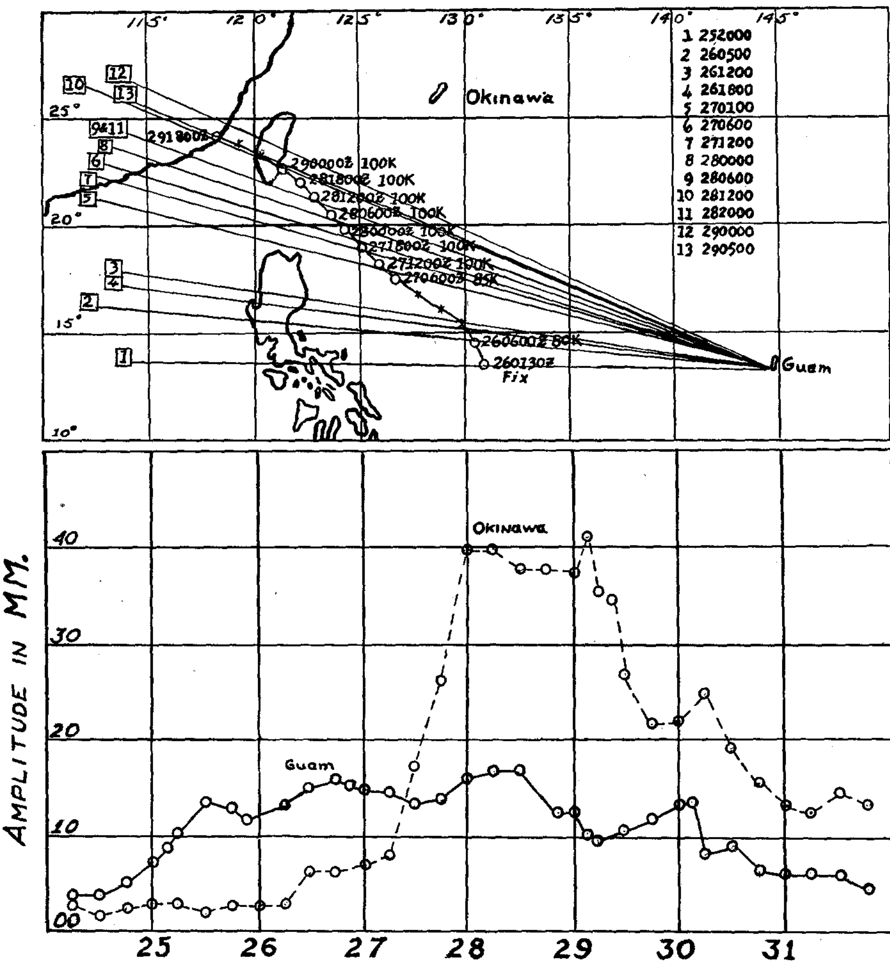


Fig. 9. Track and amplitude, second typhoon of August, 1947.

Two typhoons occurred in the Pacific during August. The first one (fig. 8) formed almost over Bird Dog Station Six, about 800 miles due west of Guam. Winds as high as 100 knots were reported for this storm over a very small area near its center. The typhoon covered so small an area that it caused microseisms of only 8 mm. at Guam, just double the August normal. The storm passed west of Okinawa and caused the microseisms to increase to 17 mm. after it had passed a point nearest the station. The amplitude was too small and too irregular to permit bearings to be taken during the early part of the storm. Three bearings were obtained about the time that both Okinawa and Guam recorded maximum amplitude as the storm was approaching Japan. The microseisms were always small and irregular and the bearings were very poor. However, it is probable that the station at Okinawa could have obtained good bearings if it had been a tripartite unit.

The second typhoon in August (fig. 9) covered a much larger area, and very good results were obtained throughout its duration even though it was a great

TABLE 6

PACIFIC TYPHOON, AUGUST 1947

Time	Bearing[a]	Error[b]	Distance (miles)
252000	272	0	820
260500	276	0	830
261200	280	0	870
261800	279	50 lag	940
270100	287	40 lead	1,010
270600	290	80 lead	1,070
271200	289	25 lead	1,130
280000	292	25 lead	1,220
280600	294	20 lead	1,270
281200	297	50 lead	1,320
282000	294	50 lag	1,380
290000	300	75 lead	1,420
290500	298	15 lead	1,460

[a] None of these bearings has been recalculated; all are the originals.
[b] Average error, 33 miles.

distance from Guam at all times. This typhoon was first definitely located when about 860 miles due west of Guam at 0130 GCT on 26 August. During the previous thirty hours the microseisms at Guam increased from 5 to 14 mm., and they remained near that amplitude for five days. The amplitude trace for Okinawa started increasing at 1200 GCT on 26 August (fig. 9) when the storm was about 800 miles due south. Eighteen hours later they increased rapidly from 8 to 40 mm. The microseisms for both Okinawa and Guam remained high until the storm moved into China and filled.

The many data contained in table 6 and figure 9 reveal by far the greatest single achievement of the seismograph in detecting and tracking of either typhoons in the Pacific or hurricanes in the Gulf-Caribbean. With respect to the second Pacific typhoon tracked with microseismic bearings, a vast improvement was shown in the accuracy of the six-hourly reports, especially in the accuracy of the directions to the storm area. The second August typhoon was first suspected because of an increase in the amplitude of the microseisms at

Guam one day before the first advisory was issued (fig. 9). A microseismic bearing was calculated and released at the same time as the first advisory (table 6). The first three azimuths calculated pointed directly into the center

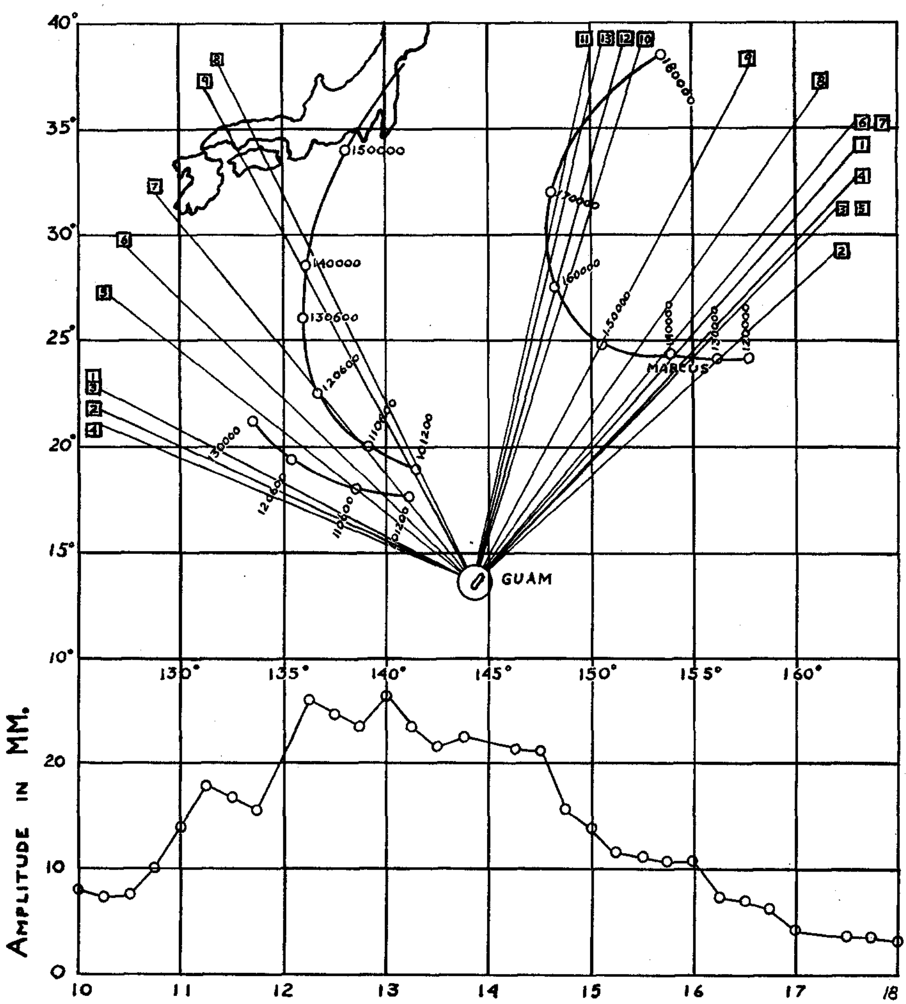


Fig. 10. Tracks and amplitudes, typhoons of September, 1947.

of the typhoon when it was more than 800 miles from the station. The two largest errors reported were sufficiently near the center to pass through an area of strong winds. The typhoon track, as plotted in figure 9, was taken from the estimated positions released by the Fleet Weather Centrals at Guam and Manila. Data for this storm have not been recalculated, but are given here exactly as released at the time of the typhoon. The thirteen bearings given in table 6 have an average error of only 33 miles from passing through the estimated position of the center, as compared with an average of 54 miles for the June typhoon. On the basis of this outstanding performance for the Guam seismograph and the large amplitude reported for Okinawa, it is reasonable to believe that excellent cross bearings could have tracked the storm accurately if Okinawa had been a tripartite station.

The tracks of the September typhoons, their microseismic bearings, and amplitude charts are shown in figure 10. The first storm was discovered at 1200 GCT on 10 September, and the last advisory was issued at noon five days

TABLE 7

PACIFIC TYPHOON DATA FOR SEPTEMBER 1947 (1)

No.	Date and time group	Bearing	Error[b]	Distance (miles)
1	111200Z	296	....	510
2	111800Z	295	....	550
3[a]	120600Z	296	....	640
4	121300Z	294	....	690
5	130000Z	303	....	790
6	130600Z	314	....	900
7	131200Z	320	....	940
8	140000Z	335	....	1060
9	141200Z	331	....	1130

[a] Bearings taken with two stations only, owing to instrumental difficulties.
[b] Errors cannot be determined because of doubtful positions of typhoon centers.

later. Before the first typhoon ended, a second storm formed and passed over Marcus Island just 800 miles northeast of Guam. It is extremely significant that acceptable bearings on both storms were calculated from different sets of microseismic waves reaching the station during the existence of the two typhoons. Two other simultaneous typhoons were recorded at Guam in October, but one set of bearings was far from good. These are the first two times on record that one tripartite microseismic station was able to track two typhoons at the same time when each storm was at a different direction from the recording station.

It is impossible to determine the accuracy of the various bearings reported for the first September typhoon found northwest of Guam (fig. 10), because the estimated positions were very uncertain during the first three or four days of its existence. Two theories attempt to explain its erratic behavior, neither of which is fully satisfactory. One suggested that the storm actually had two centers that were moving on slightly divergent tracks and that the westerly center broke away on the third day and quickly filled. The second suggested that the storm had only one greatly elongated center which varied from 60 to

150 miles from end to end. The latter theory is partly supported by a Navy aerologist's report at 0300 GCT on 13 September. He entered the southern edge of the storm in a reconnaissance plane and reported the "eye" to be more than 150 miles across, with relatively light winds on the north and west sides. Therefore, because of the doubtful location of the typhoon's track, it is impossible to evaluate the accuracy of the many microseismic bearings. On the fourth day, the storm finally settled to one track and moved on northward toward Japan.

It is significant that the first five bearings reported for the first storm gave

TABLE 8

PACIFIC TYPHOON DATA FOR SEPTEMBER 1947 (2)

No.	Date and time group	Bearing	Error	Distance (miles)
1[a]	120600Z	036	120 lead	960
2	121800Z	043	20 lead	940
3	130000Z	040	50 lead	920
4	130600Z	039	40 lead	900
5	131200Z	040	10 lead	890
6	140600Z	035	10 lead	810
7	141200Z	035	40 lag	800
8	150600Z	032	110 lag	770
9	151200Z	026	90 lag	790
10	151800Z	015	0	820
11	160000Z	009	50 lead	880
12	160600Z	013	25 lag	930
13	161200Z	010	0	990

[a] Bearings taken with two stations only, owing to instrumental difficulties.

indications that the southern path of the storm was causing larger and more regular microseisms than the other. As the southern section began to fill, the microseismic bearings gradually shifted more and more toward the north and thereafter accurately tracked that portion. These data are shown in table 7, and the data for the second storm in table 8. All the bearings are plotted in figure 10, and the various consecutive numbers in the squares at the end of the bearings are explained in tables 7 and 8. The first simultaneous bearings on the two storms were calculated for 0600 GCT on 12 September. The bearing on the first storm (item 3, table 7) was 296 degrees and came very near the estimated position of the southern path. The other calculated bearing was 036 degrees and indicated that the microseisms coming from the second storm were not yet definite enough to measure properly. Twelve hours later, excellent bearings from both typhoons were calculated, and it was possible thereafter to secure good bearings on the two storms until the first entered Japan. The last bearing obtained on the first storm was not very definite because the main microseismic waves were coming then from the second and stronger storm, which was also 300 miles nearer Guam. Altogether, over a period of more than two days, six good simultaneous bearings on the storms were calculated. A careful study of tables 7 and 8 and figure 10 will reveal that the bearings for the first storm were just a little more accurate before the second storm started causing microseisms. The same was true for the last four bearings to the second storm after the first had entered Japan.

TABLE 9

PACIFIC TYPHOON DATA FOR OCTOBER 1947 (1)

No.	Date and time group	Bearing	Error	Distance (miles)
First typhoon				
C	030600	285	30 lead	860
A	031200	288	60 lead	920
B	040000	286	30 lead	890
D	040600	284	10 lead	960
E	041200	283	10 lag	1010
C	041800	285	25 lead	1060
D	050000	284	0	1110
C	050600	285	30 lead	1160
C	051200	285	20 lead	1220
A	051800	288	70 lead	1300
F	060000[a]	279	130 lag	1380
Second typhoon				
G	020000	099	90 lag	540
H	020600	098	90 lag	560
H	021200	098	140 lag	570
I	030000	086	130 lag	600
J	030600	085	190 lag	570
K	031200	075	200 lag	570
L	040000	054	250 lag	620
M	040600	048	280 lag	740
N	041200	030	160 lag	870
O	041800	025	120 lag	1030

[a] Overland.

Before the two September storms formed, the microseismic chart (bottom of figure 10) shows that the microseisms were about 8 mm. in amplitude and that this quickly jumped to 17 mm. on 11 September. The second storm, which formed near Marcus Island, gave the amplitude another boost that sent it to about 26 mm. It remained above 20 mm. for more than two days, then gradually fell to normal by the end of 16 September. Both storms were well over 1,000 miles away by that time. No other microseismic storms were noted during September, and at the beginning of October the amplitude was only 5 mm.

By the end of the first day of October the microseismic amplitude increased to 20 mm., and the following day it rose to 26 mm. (fig. 11). A small circulation

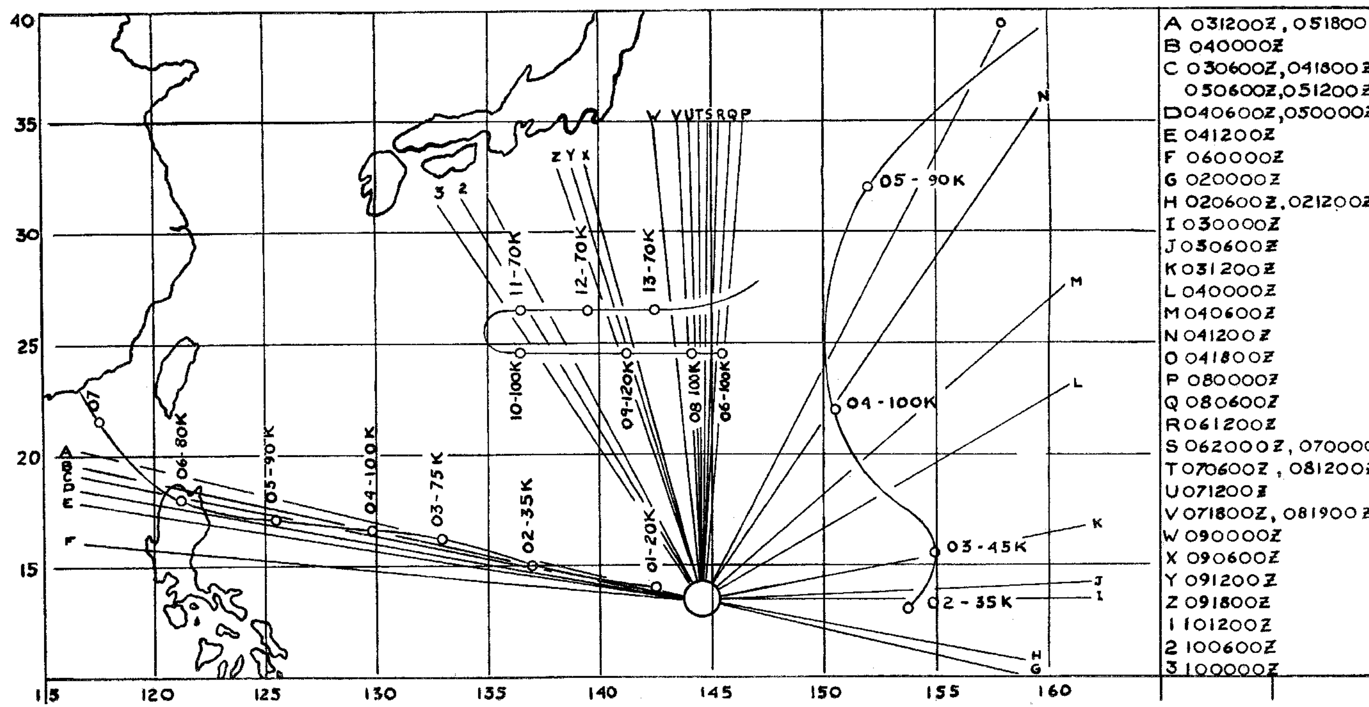
TABLE 10

PACIFIC TYPHOON DATA FOR OCTOBER 1947 (2)

No.	Date and time group	Bearing	Error	Distance (miles)
		Third typhoon		
R	061200	001	10 lead	660
S	062000	000	20 lead	660
S	070000	000	10 lead	660
T	070600	359	0	660
U	071200	358	10 lead	660
V	·071800	357	30 lead	660
P	080000	003	50 lag	670
Q	080600	002	60 lag	670
T	081200	359	60 lag	680
V	081900	357	90 lag	690
W	090000	354	100 lag	720
X	090600	346	80 lag	730
Y	091200	345	120 lag	750
Z	091800	344	180 lag	780
3	100000	328	110 lag	820
2	100600	332	140 lag	860
1	101200	336	200 lag	900

was noted just west of Guam on 1 October with winds of only 20 knots, which, on the fourth day, developed into a typhoon with winds of 100 knots. On 2 October, another storm was located due east of Guam, with winds of 35 knots, which also developed into a typhoon of 100 knots. Microseismic data for these two storms are given in table 9 and contain six simultaneous bearings on the two typhoons. Good bearings were obtained on the storm traveling west towards the Philippine Islands, except for the last one given in table 9, when the storm was almost 1,400 miles away and over land. Poor bearings were obtained on the storm that formed east of Guam and started in a northerly direction. It would therefore appear that it is only possible, under very favorable conditions, for two sets of microseismic waves to be plain enough to permit accurate bearings to be calculated on the two storms at the same time.

The amplitude of the microseisms (fig. 11) increased from 5 to 25 mm. during



A 031200Z, 051800Z
B 040000Z
C 030600Z, 041800Z
050600Z, 051200Z
D 040600Z, 050000Z
E 041200Z
F 060000Z
G 020000Z
H 020600Z, 021200Z
I 030000Z
J 030600Z
K 031200Z
L 040000Z
M 040600Z
N 041200Z
O 041800Z
P 080000Z
Q 080600Z
R 061200Z
S 062000Z, 070000Z
T 070600Z, 081200Z
U 071200Z
V 071800Z, 081900Z
W 090000Z
X 090600Z
Y 091200Z
Z 091800Z
1 101200Z
2 100600Z
3 100000Z
01-20K
02-35K
03-75K
04-100K
05-90K
06-80K
07
02-35K
03-45K
04-100K
05-90K
06-100K
08 100K
09-120K
10-100K
11-70K
12-70K
13-70K

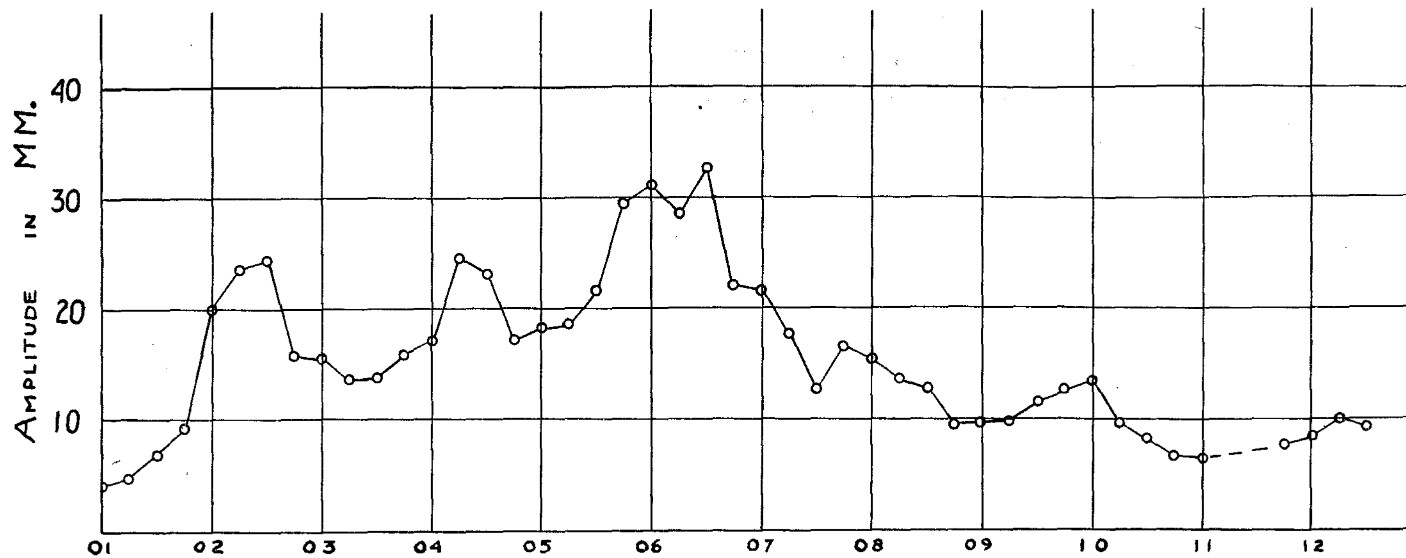


Fig. 11. Tracks and amplitudes, typhoons of September–October, 1947.

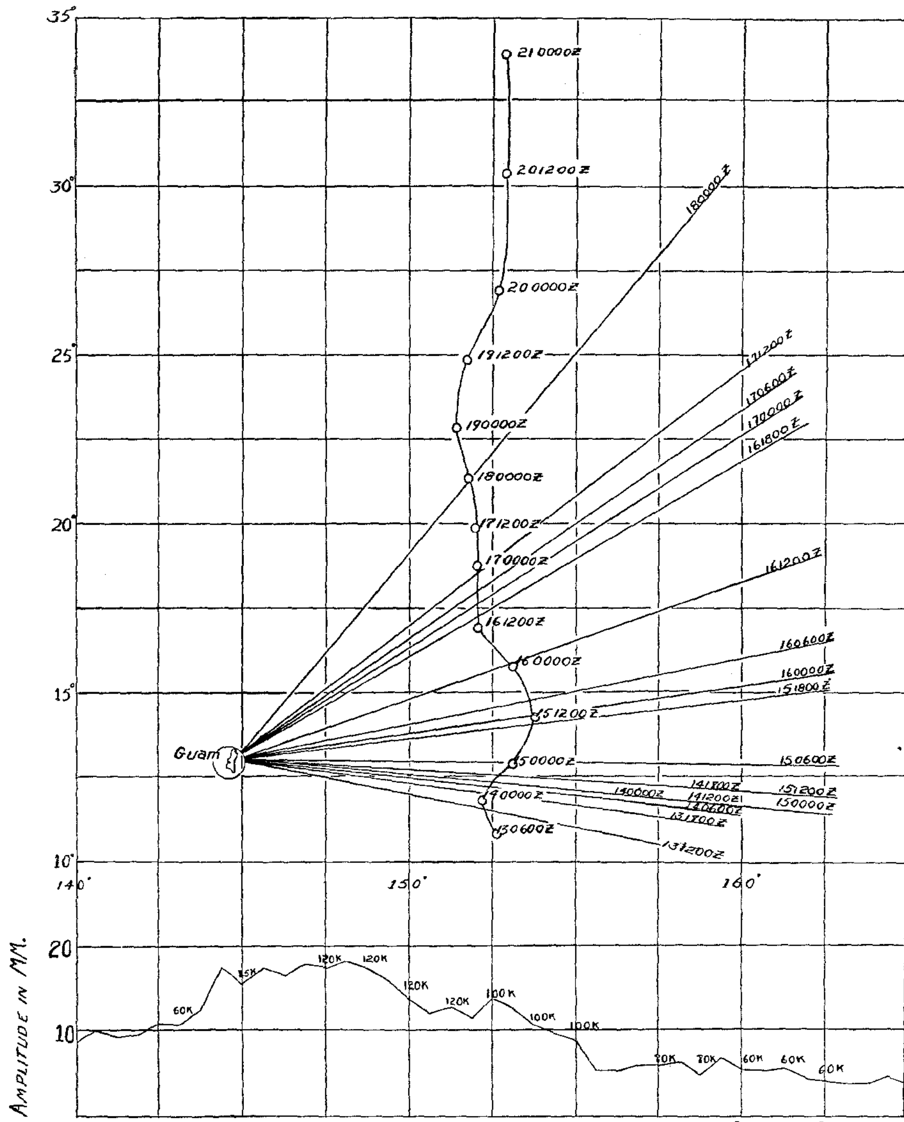


Fig. 12. Track and amplitude, fourth typhoon of October, 1947.

the early stages of the two storms, but later, as the typhoons moved away from Guam on 3 October, they fell to 14 mm. The following day, after both storms attained winds estimated at 100 knots, the amplitude curve again reached 25 mm., even though both typhoons were a much greater distance from Guam. It is apparent that the amplitude of the dominant microseisms produced by severe storms, especially in the Pacific, is directly proportional to the intensity of the storm and its distance from the recording station.

The amplitude curve declined to 16 mm. as the storms slowly moved out of effective range of the Guam seismograph. On 5 October a third typhoon was forming about 600 miles north of the station, and the microseisms registered

TABLE 11

Pacific Typhoon Data for October 1947 (3)

No.	Date; Time GCT	Error	Distance	Amplitude (mm.)
		Fourth typhoon		
1	131200	10 lead	550	13
2	131800	15 lead	540	18
3	140000	25 lead	530	16
4	140600	0	540	18
5	141200	0	555	17
6	141800	0	570	18
7	150000	25 lag	590	18
8	150600	20 lag	610	18
9	151200	100 lag	630	17
10	151800	50 lag	620	16
11	160000	90 lag	610	14
12	160600	100 lag	600	12
13	161200	70 lag	590	13
14	161800	20 lag	615	12
15	170000	50 lag	640	14
16	170600	60 lag	670	13
17	171200	50 lag	690	11
18	180000	0	750	9

an abrupt increase to a maximum of 32 mm. the following day (fig. 11). The typhoon track is shown as very erratic, which makes it similar, in that respect, to the September and October hurricanes in the Caribbean. During the life of this storm, seventeen bearings were calculated and all were very good as long as the amplitude remained above 20 mm. Additional microseismic data are contained in table 10, which shows that the typhoon remained almost exactly the same distance from Guam for the first three days, or until it began to make the U turn (fig. 11). After the storm reversed its direction it lost intensity rapidly and the microseisms returned to normal. Most of the first bearings showed that they were lagging the typhoon center. This indicated that the strongest winds were in that part of the storm or that the estimated positions were being pushed forward too fast.

On 13 October the fourth typhoon of the month was located about 550 miles east-southeast of Guam at 0600 GCT (fig. 12), and six hours later the first of eighteen excellent bearings was calculated. Just before the storm formed, the microseismic curve declined to less than 10 mm. and then slowly increased to a maximum of 18 mm. It remained between 15 and 18 mm. for more than three days. In spite of the small amplitude of the microseisms very good bearings were obtained through 17 October, at which time the amplitude curve rapidly declined to a normal of 5 mm. The data in table 11 show that the average error of the first eight bearings was only 12 miles from the estimated center of the typhoon, which is an outstanding performance for any type of warning device. However, beginning at 1200 GCT on 15 October, the microseismic bearings were reported with seemingly very large errors for the next 30 hours. Because of the extreme degree of accuracy obtained in the first eight bearings it appears highly probable that at least a part of the large errors reported in the next five observations (table 11) were due to slight errors made in selecting the original positions of the typhoon and not entirely due to faults of the microseismic method. The last bearing calculated points directly into the estimated storm center when it is 700 miles from Guam. On the other hand, assuming that all estimated storm positions are 100 per cent correct, and using all the bearings calculated, the average error of each bearing is only 38 miles. This is considered excellent for a storm 500 to 700 miles away from a microseismic station.

The microseismic data presented in this paper cover two years' experimental research in the Pacific. They indicate definitely that typhoons, as well as hurricanes and extratropical lows, can and do cause microseisms. It has also been shown that the Pacific typhoons can be detected by the seismograph far in advance of their arrival and over distances as great as 1,600 miles from Guam. Extremely accurate bearings over the vast expanses of the Pacific Ocean can be calculted from the microseismic records for each severe typhoon. It has been found that microseismic bearings are more accurate when skilled and experienced technicians are available to keep the seismograph equipment at its highest operating efficiency and that the accuracy increases as the personnel gain experience in making the precise measurements necessary before bearings can be calculated.

Improvements are constantly being made in instrumental development and in operational techniques in order to improve and perfect the microseismic method of detecting and tracking of severe tropical and extratropical storms. A few of these developments have already been published in earlier reports and a few are still in the experimental stage. Perhaps the greatest single achievement in operational techniques was the development of remote recording, whereby it is now possible to have all three of the seismometers that form a single tripartite unit record on a triple-drum recorder in a central recording vault. This was easily accomplished by using Parkway cable, which is tripleshielded against any outside electric currents and is almost completely water- and moisture-proof. This cable, when the joints are properly made, allows the microseismic wave to travel in the form of an electric impulse from the seismometer to a galvanometer miles away *without any distortion.* Experimentation has been and is in progress to obtain more accurate microseismic determination of bearings on storm centers by determining the correct relationship between the base length of the units of a tripartite station and the speed of the recording drum. The results of these experiments have made it necessary, during the last four years, to reduce the distance between the units of a tripartite station from four miles to about 3,000 feet and to increase the drum speed from ½ mm. per second to more than 5 mm. per second. The 1947 operational data strongly indicate that it will be necessary to decrease further the distance between the units and to increase greatly the speed of the recording drum. It is impossible at this stage to predict what the ultimate relationship between these two variables may be in the future, because this is the type of problem that must eventually be solved by the results of operational data and not by any theoretical considerations.

It is still true that there is no theory wholly acceptable to account for the mechanism whereby microseisms are generated by meteorological disturbances such as hurricanes, typhoons, extratropical lows, monsoons, and trade winds. Neither can certain erratic changes in the microseismic period be completely explained. In trying to explain how microseisms are formed Macelwane[4] offered the "fluid columnar vortex" theory, and Gutenberg[12] said: "There is little doubt that the energy originates from the energy of the storm. . . . In hurricanes (and partly in extratropical lows) high ocean waves probably are the original source of the microseisms. However, it is not yet clear how the energy is transferred to the bottom of the ocean."

The "fluid columnar vortex" theory might explain how hurricanes, typhoons, and certain extratropical lows generate microseisms. On the other hand, it cannot explain how microseisms can be formed by strong trade winds. Observational data in the Caribbean and Pacific show that microseisms often come from an area of strong winds where there could be no vortex motion. Such microseisms are very irregular in form and the direction of approach at any one station varies over the entire area covered by the high winds. Simultaneous bearings from seismograph stations only a few hundred miles apart often show the microseisms coming from a different sector of the area of strong winds. Recent data show that the stronger the winds in such an area the larger the resulting microseisms. When the microseisms are large, they can travel through the earth's crust before they completely dissipate. Severe meteorological disturbances over water are able to cause ocean waves more than 60 feet from crest to trough. This violent turmoil going on continuously over an area larger

[12] *Op. cit.*

than 100 miles in diameter in the case of hurricanes and typhoons, much larger areas in the case of well-developed, extratropical lows, and over very elongated areas in the case of strong trade and monsoon winds, naturally expends considerable energy which, if properly transferred to the ocean bottom, would be sufficient to set up elastic waves in the earth's crust.

This problem cannot be solved until more elaborate experiments are made near the source of the microseisms. This can be accomplished in part, as Dr. Gutenberg and others have mentioned, by measuring the pressure waves at various depths in the ocean during the approach and passing of a storm. Important correlational data could be obtained by records made with various instruments aboard a submarine when it rests on the ocean floor several hundred feet below the surface during the passage of a hurricane or typhoon. The small fluctuation of pressure during a severe storm would be extremely valuable if they were recorded on a high-speed recorder. The existing records of pressure changes during a storm are from conventional barometers at very slow speed. It is impossible to study in detail the minute fluctuations of pressure unless they are recorded at a speed of 1 mm. per second on a microbarograph. Records of this type would be extremely valuable in helping solve important microseismic problems.

It is now known that elastic waves generated by severe ocean storms travel only through the earth's crust. Ramirez[13] analyzed the motion of the earth particle when it was disturbed by the passing of a microseismic storm and found certain Reyleigh wave groups to predominate. Leet[14] confirmed this discovery and also identified certain Q waves. Lee[15] attempted to use the phase relationship between the vertical and one of the horizontal components to determine the direction of approach of the microseismic wave. The same method was recently used by Leet in his study of the microseismic storm of 14–16 November 1945. The results of the work of Lee and Leet show that this method of securing a direction to a storm area is entirely unsatisfactory and untrustworthy because the microseisms used are not always true Reyleigh waves and because the directions obtained are usually very general in character and nearly always given as east, south, or southeast. The microseisms obtained during storms in the Caribbean or Pacific do not jump 45 degrees in direction between three, six, or twelve hourly reports. On the other hand, the change is very gradual. Present microseismic data show that microseisms do not always come from the center of hurricanes, typhoons, or extratropical lows. On the contrary, they appear to come from that part of the storm which has the highest winds or waves at the particular time a bearing is calculated. It is believed that because of the extreme turbulence in severe storms the center of microseismic activity shifts slightly from place to place within the area of strongest winds.

[13] *Op. cit.* [14] *Op. cit.* [15] A. W. Lee, *Proc. Roy. Soc. London*, A866: 195–199 (1935).

There is no good reason for not using microseisms in storm detection because the mechanism by which they are produced is unknown or because there are still other unsolved problems. Seismic storm detection has proven extremely accurate and is much cheaper than any other known method. It has also been demonstrated in this paper that the science of microseismic storm detection requires qualified observers who are expert in the operation and care of the equipment, and that the degree of accuracy obtained depends almost entirely upon the experience and qualifications of the person in charge of each tripartite microseismic station. Many important facts have been learned in four years of experimental research in the Caribbean and two years in the Pacific, and the results obtained lead to the following very definite conclusions:

1. Typhoons and hurricanes always cause an increase in the amplitude of microseisms when near enough to the recording station. The same is true for frontal systems and extratropical lows when accompanied by sufficient wind.

2. This increase in the amplitude of the microseisms is, in the Pacific, almost directly proportional to the intensity and size of the storm and to its distance from the recording station. The same rule applies to the Caribbean area, except that greatly reduced microseismic amplitudes are recorded when the meteorological condition causing them passes over very shallow water, over land, or over some other type of microseismic barrier. These three conditions are not often found in the typhoon belt of the Pacific.

3. Microseisms produced by the various meteorological conditions produce distinctive types of microseisms which a good observer is almost always able to identify by a careful study of the microseismic record.

4. Severe storms in the Pacific can be detected as far as 1,600 miles from Guam, except where large island groups and major fault systems exist.

5. Bearings from the disturbed meteorological area can be calculated from microseismic time differences obtained at a tripartite station. The accuracy of the bearings obtained is directly proportional to the skill and experience of the technical observer and to the operational efficiency of his instruments. Under very favorable conditions, bearings from two simultaneous storms in different directions from the station can be determined from one set of records.

6. Both the initial installation of a tripartite station and the operational cost are vastly cheaper than any other known method of ascertaining the intensity and distance of severe storms when they are several hundred miles from the station. It is believed that this is possible with an adequate number of tripartite microseismic stations and that the accuracy obtained will continue to improve.

7. The microseismic method of storm detection is especially adapted to 24-hour operation because it works as well at night as during the day.

The data presented in this paper and the conclusions reached strongly indicate the desirability of several additional tripartite stations located on the larger islands in the north quadrant from Guam and around the Philippine Island group. These stations would greatly aid in the saving of life and property during the passage of the unexpected typhoons, because with this network of tripartite stations, manned by skilled technicians, it would be impossible for a severe storm to "slip in" on an island or coastal city.

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