A STUDY AND EVALUATION OF THE TRIPARTITE SEISMIC METHOD OF LOCATING HURRICANES*

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ABSTRACT

Tripartite records from the U. S. Navy stations at Bermuda, Cherry Point, and Miami were studied in detail for the 1950 hurricane season. Following a discussion of the theoretical error expected in this study, the results of single and average azimuth computation are given. Since the error between computed and observed storm azimuths exceeds the theoretical by a considerable amount, a study of the causes of the errors was undertaken. The difficulties are considered to result from instrumentations and procedure, lack of wave coherence at the three elements of the tripartite net, and refraction or multiple wave paths.

A large range in velocities was observed, with indications that the lower values are the more reliable. Selection on a velocity basis gives somewhat better success than averaging all readings over the chosen interval of time. Suggestions for improvement of the instrumentation program are given.

INTRODUCTION

THE USE of more than one seismic station in determining storm position or direction of wave approach has been described by a number of investigators, chiefly Hecker (1),† Shaw (2), Krug (3), Trommsdorf (4), Ramirez (5), Gilmore (6, 7, 8), Lynch (9), and Kammer and Dinger (10). Owing to the diversity of results obtained in the application of this procedure to the location and tracking of hurricanes, an intensive study and evaluation of the tripartite method was undertaken. Seismograms from U. S. Navy hurricane tracking stations were studied for most of the stations for the five hurricanes in the western North Atlantic Ocean for 1950. The data given here are for the stations at Bermuda, Cherry Point, and Miami (B, CP, and M respectively in figs. 1 and 2). The instruments are reported as being "always in phase," and having a galvanometer-seismometer system period of 7 seconds (with a possible error of 0.1 to 0.2 sec.). The magnification is reported as being 5,000 for all instruments. All instruments were oriented N–S, with the free end of the pendulum to the north. These stations were selected owing to their disposition in a great triangle, and the fact that one is an island station. The azimuths computed from seismic data are compared with storm azimuths determined from marine weather charts. The tracks of the hurricanes used in this study are shown in figures 1 and 2.

STORM AZIMUTH DETERMINED BY AVERAGE SEISMIC AZIMUTH COMPUTATION

Average azimuth computations.—The average azimuth of wave approach at any time was determined by selecting the sixteen most regular waves during a six-minute interval and finding the arithmetic mean for the sixteen individual directions computed for these waves. The average deviation was then computed for each set of sixteen waves. Individual directions were obtained by use of the formula developed by Gilmore (6) after Krug (3) and Ramirez (5). Table 1 compares computed average azimuth of wave approach with hurricane azimuth for the stations referred

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† Numbers in parentheses refer to works cited at the end of this paper.

to above. The observed storm azimuth given is for a line to the storm center, but the tables also give the angle subtended at each of the stations by the effective wind area of the storm. This was usually symmetrical about the line to the center. Two

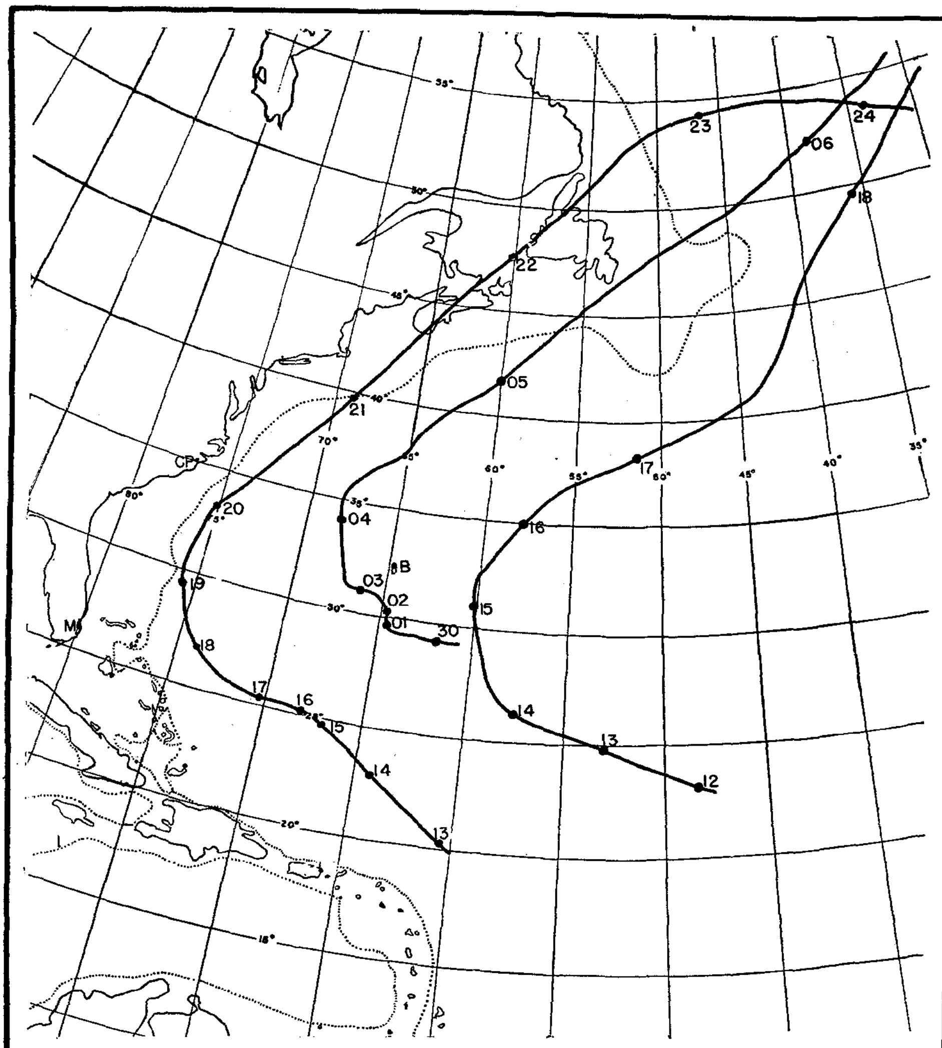

Fig. 1. Paths of hurricanes of August 13–24, September 30–October 6, and October 12–18, 1950.

observed azimuths are given where obvious ambiguity existed owing to the presence of simultaneous hurricanes.

Discussion of procedure.—The traces from the three elements of the tripartite station were recorded on a single drum when azimuths were to be determined, and drum speeds were increased from the normal ½ mm. per sec. to 5 mm. per sec. at Bermuda and Miami, and to 2 mm. per sec. at Cherry Point. Then the interval from an arbitrary time to the crest of the same wave on each trace was measured. From these measurements are determined arrival order (which is often obvious from visual examination) and the arrival-time differences between the waves of

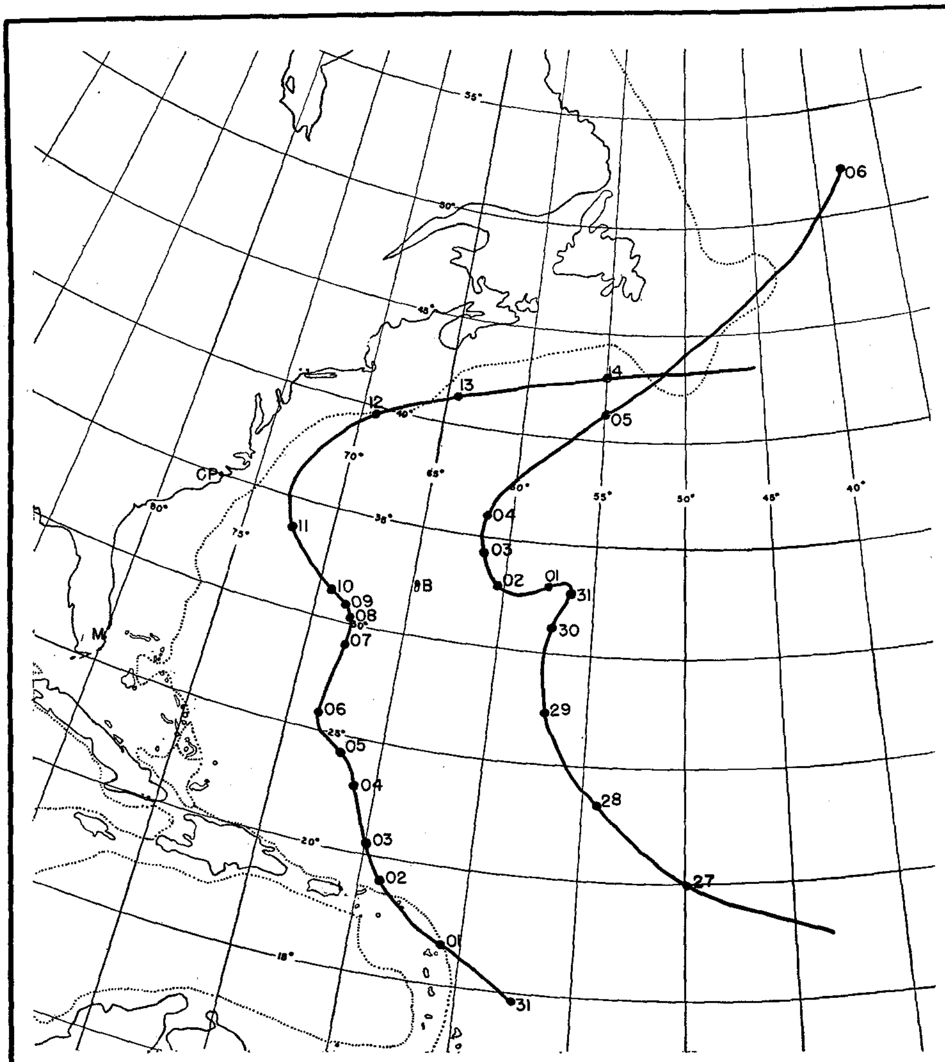

Fig. 2. Paths of hurricanes of August 27–September 6 and August 31–September 14, 1950.

first and last arrival (Δt_1), and the wave of first and second arrival (Δt_2). The maximum time difference possible occurs for a wave traveling parallel to a leg of the tripartite triangle. If a wave should arrive from a direction 180 degrees away, this maximum time difference would be the same, but the arrival order would be reversed.

Time measurements were made to one-tenth mm. (0.02 sec. for Bermuda and

Miami, and 0.05 sec. for Cherry Point) and were only converted to seconds for purposes of velocity computations. The physical nature of the records did not warrant the use of more refined measurements. This was verified by trial measurements.

Azimuths were computed from the formula:

$$\tan A = \frac{\sin B}{Rt\, Rs - \cos B}$$

where: A = direction angle between the wave front and the leg of the tripartite station connecting the elements of first and second arrivals, and thus refers to different legs for different arrival orders;

B = the vertex angle of the triangle at the element of first arrival;

$Rt = \frac{\Delta t_1}{\Delta t_2}$ or the ratio of the time difference between the first and last arrivals to that between first and second arrivals;

Rs = the ratio of the length of the leg connecting the elements of first and last arrivals to the length of the leg connecting the elements of first and second arrival.

It is important to realize the theoretical accuracy that can be obtained for the tripartite stations used. In making these determinations it is assumed that no significant velocity differences exist for the microseism periods observed. The Bermuda net will be taken as an example. This triangle is essentially equilateral with legs of 1,800 feet. The angle A, as defined, can only have values from zero to 60 degrees for any arrival order. With the further assumption that a surface wave velocity of 10,000 feet per sec. exists at Bermuda (justification for this will be given later), then the largest time differences (Δt_1) for a given arrival order will be 0.9 mm. (0.18 sec.) in view of the precision obtainable here. Again in view of the precision, Δt_2 can vary from 0.0 mm. (0.00 sec.) to 0.9 mm. (0.18 sec.) in steps of 0.1 mm. (0.02 sec.). Hence the angle A for any arrival order is determined by one of the ten possible ratios ($\Delta t_1/\Delta t_2$), and gives one of ten possible azimuth sectors whose size is 60/10 degrees. However, consideration of the significance to be attached to the ratios based on trial measurements shows that two consecutive ratios may not be truly distinct. Consequently the best theoretical accuracy would be double the sector given above (12 degrees) with half the number of possible sectors (30).

Several improvements in instrumentation are immediately suggested in view of the foregoing discussion: (*a*) an increase in the size of the network to a limit imposed by the need for recognition of similar waves and by practical considerations; (*b*) an increase in drum speed, always accompanied by an increse in magnification to maintain sharp wave crests; (*c*) an improvement in the quality of the records, to permit greater precision of measurement; (*d*) an increase of the number of instruments used in the net, to define the wave motion better and to give additional data for computations. The combined advantage of the first three suggestions would be to permit greater precision in measurements. This would reduce the size of the theoretical sector of error for each station, and would increase the possible number of azimuths obtainable.

Discussion of results.—Table 1 shows that agreement between the computed and observed azimuths occurred only 13 times for the 148 sets of computations. Agree-

TABLE 1

COMPARISON OF COMPUTED AVERAGE AZIMUTHS WITH OBSERVED STORM AZIMUTHS

Date 1950	G.C.T.	Computed azimuth	A.D.	Observed storm azimuth	Angle subtended at station by storm (degrees)
		Bermuda			
Aug. 15	0700	030	3	021/194	N*
	1200	020	6	021/196	25/38
	2100	040	4	016/202	20/32
Aug. 16	0300	050	5	018/205	14/34
	0600	060	5	018/207	10/38
	1200	050	3	019/209	24/38
	1800	210	17	213	38
	2400	220	11	217	40
Aug. 17	0600	240	14	220	45
	1200	210	2	226	36
	1800	200	6	230	24
Aug. 18	0300	210	4	237	28
	0900	230	11	242	31
	1500	200	6	247	32
	1800	190	4	250	33
	2400	220	8	253	37
Aug. 19	0900	230	6	259	30
	1500	230	4	265	32
	1800	220	6	267	37
	2400	220	6	275	40
Aug. 20	0600	200	5	285	45
	1200	240	5	300	45
	1800	240	5	318	45
	2400	220	8	333	65
Aug. 21	0600	230	6	347	45
	1200	240	7	167/003	12/47
	1800	240	9	168/008	13/32
	2400	200	5	169/011	12/20
Aug. 22	0600	190	2	170/016	13/20
	1200	200	2	171/024	N
	2200	320	17	175/029	N
Aug. 29	2400	080	8	100	45
Aug. 30	0600	060	4	095	45
	1200	020	8	092	40
	2200	050	2	087	54
Sept. 1	1500	060	6	089	80
	2400	080	6	082	70
Sept. 2	0600	060	9	084	80
	1200	050	5	063	75
	1800	050	8	055	75
	2400	120	11	052	75

* Insufficient data.

TABLE 1—*Continued*

Date 1950	G.C.T.	Computed azimuth	A.D.	Observed storm azimuth	Angle subtended at station by storm (degrees)
Sept. 3	1200	040	5	049	80
	1800	050	5	046	60
	2400	050	6	040	50
Sept. 4	0600	020	11	034	40
	1200	030	5	038	70
	1800	040/180	10/11	039/191	40/35
	2400	190/010	7/16	194/041	50/30
Sept. 5	1200	330	11	045/199	30
	2400	010	6	054/208	13
Sept. 6	1200	340	10	213	60
	2400	250	10	220	60
Sept. 7	1200	340	5	234	90
	2400	340	3	234	120
Sept. 8	0700	330	8	236	115
	1200	290	5	239	120
	1800	280	8	239	135
Sept. 9	1200	290	6	245	130
	2400	290	8	250	100
Oct. 13	2300	320	12	134	30
Oct. 14	2300	300	12	108	60
Oct. 15	1200	240	6	081	70
	2300	230	18	068	50
			Cherry Point		
Aug. 16	1200	090	2	146	26
	1800	100	2	149	28
	2400	100	1	152	34
Aug. 17	0600	090	1	154	35
	1200	100	2	157	28
	1800	090	3	159	28
	2400	090	2	163	32
Aug. 18	0600	100	3	166	35
	0900	100	3	167	40
	1500	100	2	168	57
	2100	090	3	167	60
Aug. 19	0300	100	4	165	50
	0600	100	4	165	50
	0900	100	2	163	58
	1500	100	3	158	75
	1800	110	3	156	85
	2400	100	5	143	140
Aug. 20	0600	090	3	108	120
	1200	090	5	072	95
	1800	090	3	060	80
	2400	090	2	055	54

TABLE 1—*Continued*

Date 1950	G.C.T.	Computed azimuth	A.D.	Observed storm azimuth	Angle subtended at station by storm (degrees)
Aug. 21	0600	080	2	052	41
	1200	090	3	050/142	37/9
	1800	080	2	048/142	32/9
	2400	080	3	045/143	20/9
Aug. 31	1200	110	7	096	23
	2400	310	7	097	N*
Sept. 1	1200	100	3	100	30
Sept. 4	0020	080	7	086/140	30/15
	1200	130	3	076/141	35/25
	1800	110	4	074/142	18/23
	2400	090	3	072/143	25/30
Sept. 5	0600	090	5	143	30
	1200	110	6	143	26
	1800	080	2	143	30
	2400	100	3	140	30
Sept. 6	0600	100	2	138	30
	1200	100	3	135	40
	1800	110	4	132	37
	2400	090	5	128	30
Sept. 7	0600	100	5	124	30
	1200	090	4	122	40
	1800	080	2	121	35
	2400	090	5	120	50
Sept. 8	0600	090	5	118	35
	1200	080	3	117	40
	1800	080	2	116	35
	2400	100	5	115	40
Sept. 9	0600	100	3	116	35
	1200	100	5	118	50
Sept. 10	2400	100	2	108	80
Sept. 11	0600	100	4	090	90
	0900	080	2	079	90
	1200	080	3	071	90
	1800	080	2	059	75
	2400	100	3	054	55
Sept. 12	0600	050	1	053	50
	1200	100	4	052	45
	1800	120	2	054	40
	2400	070	3	056	35
Sept. 29	1800	090	3	116	N*
Oct. 1	1200	100	4	116	25
	1800	110	5	118	30
	2400	100	3	117	35

* Insufficient data.

TABLE 1—*Continued*

Date 1950	G.C.T.	Computed azimuth	A.D.	Observed storm azimuth	Angle subtended at station by storm (degrees)
Oct. 2	0600	098	2	114	40
	1200	110	6	112	35
	1800	100	2	113	40
	2400	100	4	113	40
Oct. 3	1200	100	3	112	45
	1800	090	3	105	45
	2400	100	3	098	50
Oct. 4	0600	100	3	087	55
	1200	090	3	075	35
	1800	100	4	067	35
	2400	100	2	063	30
		Miami			
Aug. 18	1200	090	4	064	60
	1800	100	2	055	64
Aug. 19	0300	080	4	048	54
	1400	080	2	039	49
	2400	070	2	033	34
Aug. 20	0500	070	3	032	50
	1200	070	4	032	36
	1800	060	8	034	26
Aug. 21	0500	070	8	036	21

TABLE 2

	Bermuda	Cherry Point	Miami
Total computations	63	74	9
Success using azimuth of center	8	5	0
Success using sector of effective wind area	24	32	1

ment is here considered to occur where the computed azimuth sector (determined by the A.D.) includes the azimuth of the storm center. Poor agreement still occurs if cases are considered in which any part of the computed sector overlaps the sector to the effective wind area. Table 2 summarizes the results for both cases.

Striking negative correlation between computed and observed azimuths occurred for the Bermuda station for the hurricane of October 13–17. Table 1 indicates computed azimuths to be approximately 180 degrees in error even when the storm made its closest approach, with coincident maximum amplitudes occurring. There was clearly no meteorological ambiguity at the time. Similar results have been reported at other stations during other hurricane seasons. Careful examination of the responses and the physical characteristics of each trace gives no obvious indication that the cause is instrumental.

The foregoing data and discussion are based on average azimuths, following the standard procedure for such determinations. However, if individual wave azimuths are considered, the data can be given as in figure 3, showing angle of error against frequency of occurrence. (The data for the clearly anomalous case for Bermuda, October 13 to 17, were not used.) Smoothed frequency data are shown since each point includes values spread on both sides of the designated ordinates. The curve

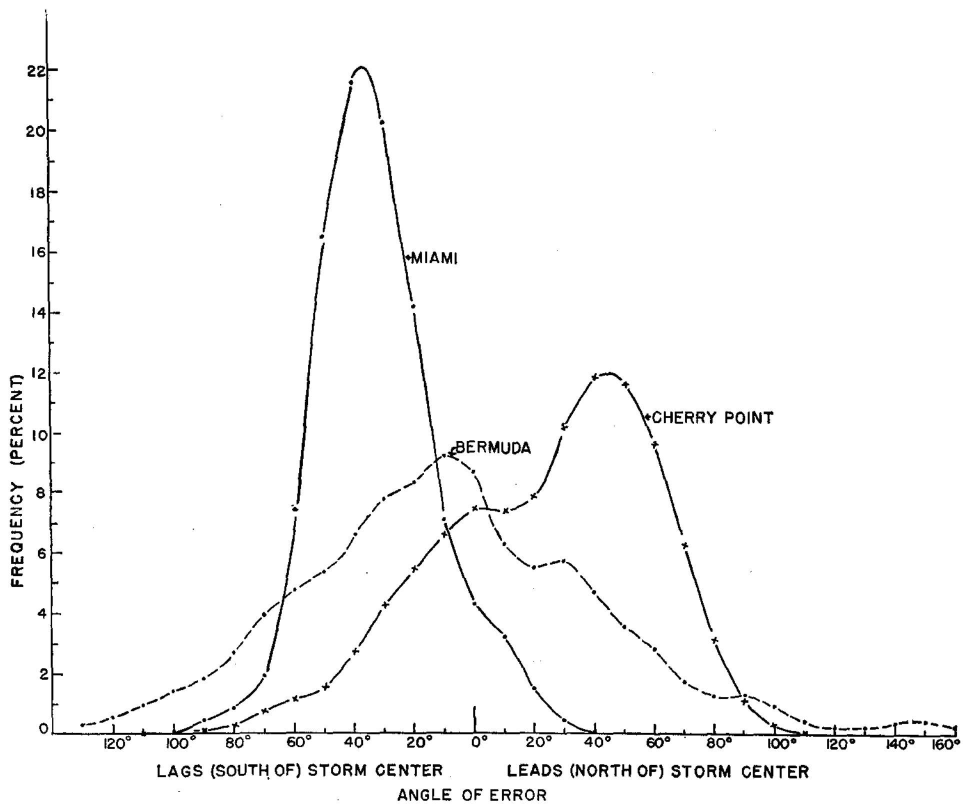

Fig. 3. Relation of angle of error to frequency of occurrence.

for Bermuda is based on 669 computed azimuths, for Cherry Point 749, and Miami 116. The distribution of the angle error is far from random, showing definite modes. The deviations of the Cherry Point and Miami curves indicate a systematic error very possibly a result of refraction. Despite the peak near zero for Bermuda, the shape of the curve indicates that poor accuracy was obtained. It appears that the method does give azimuths, although not yet accurate enough for operational purposes.

This leads to a further consideration of the causes of error and possible remedies. The sources of error resulting from procedure account for only part of the total difficulty. Other and possibly more significant causes are indicated from the study, speecially when individual waves are considered. Individual wave azimuths were based on the ratio of the time differences Δt_1 and Δt_2. The observed time differences for Δt_1 showed considerable variation, which for Bermuda ranged from 0.1 to 1.1 mm. (0.02 to 0.22 sec.). From the theoretical conditions given in the preceding section this quantity should have a very small range. Even allowing reasonable velocity variations, this tenfold range seems far too great. Careful examination and measurement of similar waves on each trace showed that they are rarely coherent, particularly with respect to period. These period differences are often adequate to account for the anomalous values of Δt_1.

Study of Wave Coherence

The computation of wave direction is based on the assumption that the particular wave is coherent at all three elements. Measurements of the periods of supposedly identical waves almost always indicated differences in period of the order of magnitude of the arrival-time differences used in the computations. These period differences are sufficient to account for the large sector over which individual wave azimuths varied during a particular set of observations (6 minutes). This sector was often as large as 90 degrees even in cases of good agreement between computed average azimuth and observed azimuth. This effect and the usual occurrence of microseisms in beat patterns suggest that the incoherence of the individual waves over the small distance separating the elements is a result mainly of waves arriving at the same time from different directions. Similar observations and conclusions were noted by Kammer and Dinger (10), and by Leet (11), and have been developed theoretically by Bungers (12). Velocity considerations, to be given below, further support this conclusion.

The approach of microseisms from different directions at the same time may be due to a combination of factors, namely, simultaneous sources at different parts of the storm area, two or more storms at different azimuths from the station, and refraction at the continental borders, the last being admitted for earthquake Rayleigh waves. These results indicate two additional and possibly correctible sources of error. First, the instrumental frequency response at present is so broad that no single source of microseisms can be studied. It has already been shown by Donn (13) that microseism period is apparently a function of water depth conditions in the generating area. Secondly, the separation of the seismographs is not suitable to the order of magnitude of the time measurements necessary. Additional elements in the net would further correct this.

Since lack of coherence appears to be a major source of error in azimuth determinations, azimuths were computed using individual waves, and the results for each wave were compared with its coherence at the three elements. The parameters of amplitude and period were used as the measure of coherence, and only regular waves that showed no obvious incoherence were selected. Eight observation times covering 6 minutes were used and were taken from the previous data. Only 5 of 131 waves had the same period at each element for the precision used, and these show no correlation with success. Differences in period for the others varied from 0.1 mm. to 1.4 mm. None of the waves showed constant amplitude. The lack of success for the five coherent waves, assuming this small number to be significant, may be explained by (*a*) the presence of composite waves formed by waves of the same period but traveling along different paths, and (*b*) refraction. By analogy with earthquake seismology the latter may be assumed to be often of large magnitude, especially for the short-period waves studied.

Considerable variations in amplitude existed at the three elements, with a systematic but not constant difference among them. For example, element A at Cherry Point always showed much higher values than the other two elements, etc. Since the instruments have been described as being nearly identical in response and orientation, the systematic amplitude diversity is possibly the result of differences in anchoring or in local surficial geology. This effect is significant if also accompanied by phase differences which would effect azimuth computations.

Study of Velocities

Velocity data.—The method which was used by Kammer and Dinger (10) with some indications of success was applied in this study. The procedure consisted of computing azimuths and velocities for a series of waves, and attempting to reduce the

TABLE 3

	Bermuda	Cherry Point	Miami
Minimum velocity	7,500	2,100	5,100
Modal velocity	17,000	3,800	11,000
Mean velocity	17,000	6,200	13,000
Maximum velocity	80,000	20,000	60,000

angular spread of results by considering only azimuths determined from waves showing velocities below 11,000 feet per second. Encouraging but unsatisfactory results were obtained by the use of this procedure. However, an analysis of the velocity data is given below since it reveals significant information bearing on the problem.

The curves in figure 4 show the frequency distribution of velocities on a logarithmic scale for Bermuda, Cherry Point, and Miami for most of the hurricanes studied. A total of 719 individual wave velocity determinations are used for Bermuda, 731 for Cherry Point, and 116 for Miami. The points shown are plotted at the median values of the populations in nonoverlapping velocity sequences. Each curve reveals a considerable spread in velocities. Table 3 summarizes the minimum, modal, mean, and maximum velocity values for each station. The maximum values have much less reliability than the others since they depend on the smallest time differences that can be measured (0.1 mm. on the records). Hence variations are difficult to distinguish with existing drum speeds. By the same reasoning the reliability is greatest for the minimum values.

It is obvious that velocities in general are intermediate for Miami, and distinctly lowest for Cherry Point. It is further obvious, and considered of significance, that each curve shows a decided concentration of velocities even though not at the same values.

To study the significance of the velocity data given, an analysis was made of the success obtained for waves of different velocities. Cumulative frequency curves are given for Bermuda and Cherry Point in figures 5 and 6, respectively. These show angle of error (to storm center) against cumulative frequency of error for the velocities given by the curves. All velocities lie in a rather narrow band. However, to consider figure 5, for Bermuda, first, it is seen that the curves of lower velocity (8,500, 10,000, and 11,000 feet per second) lie above the others, almost overlapping, and indicate greater relative success. It is worth noting that these values are represented by relatively few observations and are at the low-velocity end of the curve. It should be noted that "success" here is quite relative since 40 to 60 per cent of the best observations still show errors of 20 to 30 degrees.

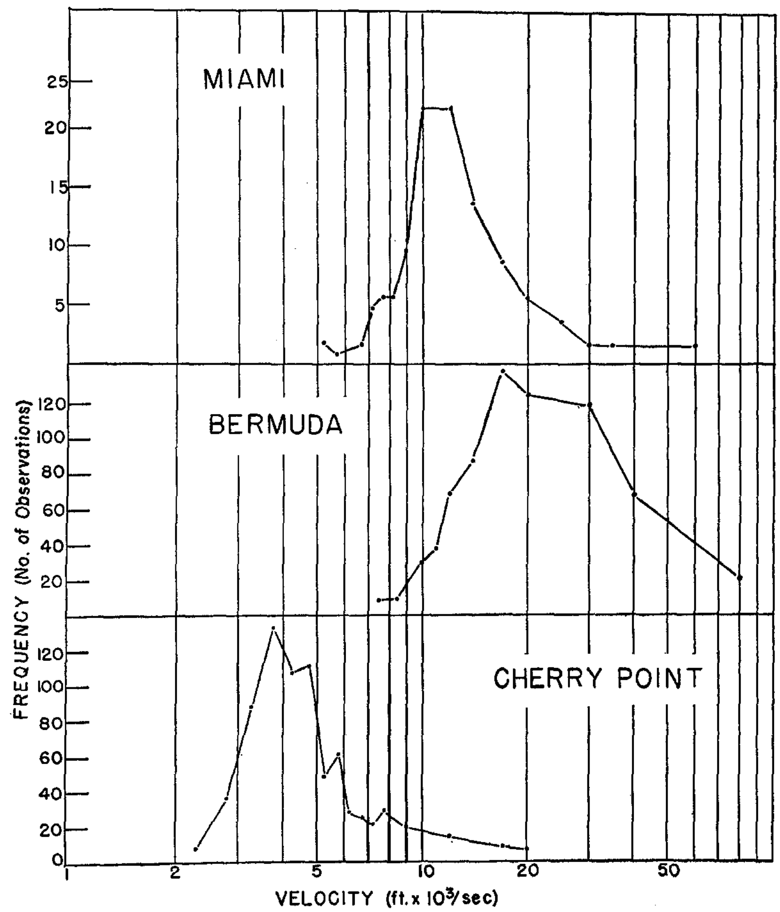

Fig. 4. Frequency distribution of velocities for most of the hurricanes studied.

The cumulative frequency curves for Cherry Point (fig. 6) are in general similar to and no better than those for Bermuda. However, in this case the higher velocities show somewhat better success, with best success given by the 7,000 ft/sec. curve. The low and high portions of all of the curves for both Bermuda and Cherry Point are of less reliability than the central portions, owing to a very irregular and very sparse distribution of velocities at low and high angles of error, respectively.

TheMiami data were too few for analysis in this manner.

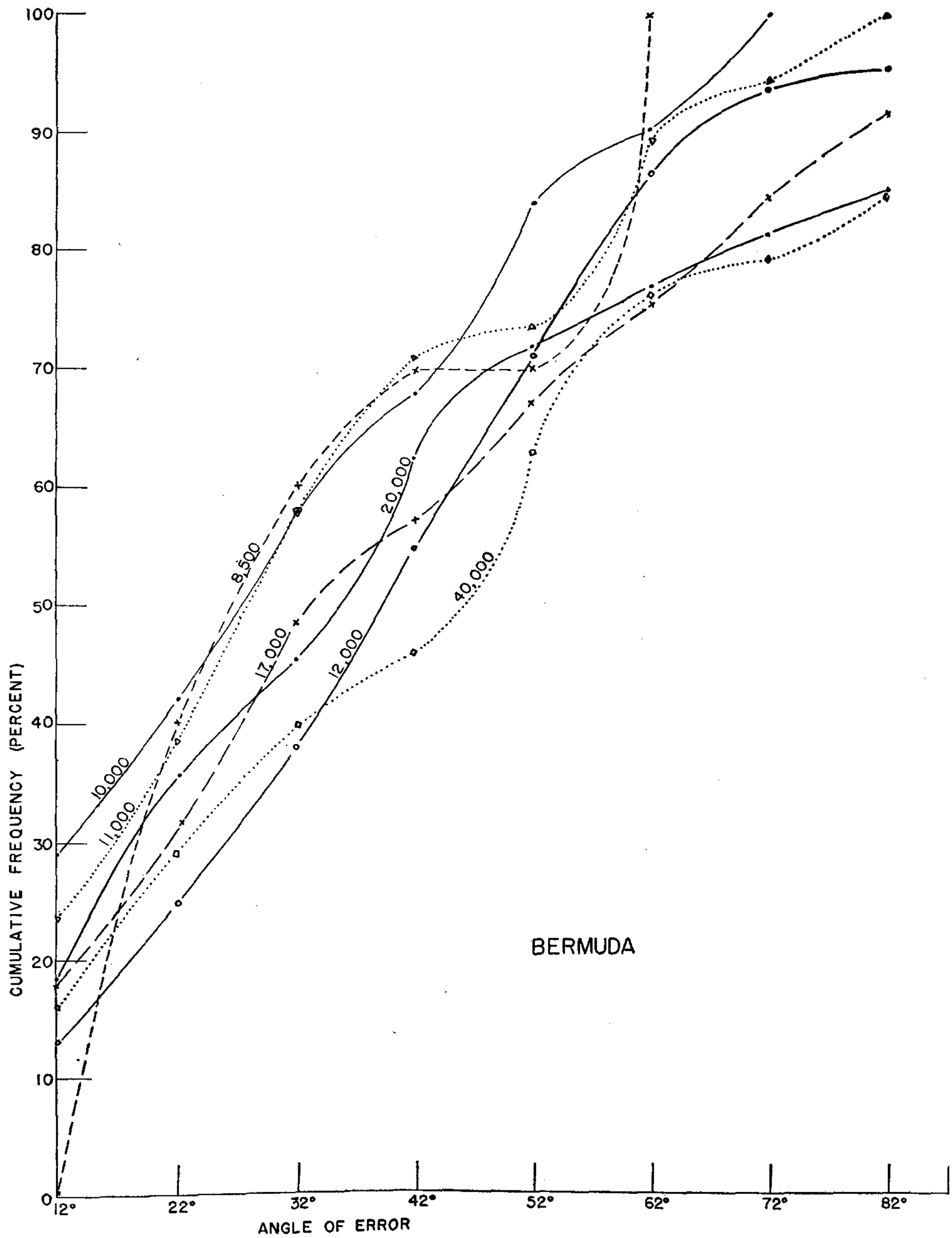

Fig. 5. Graph of cumulative frequency of angles of error associated with velocities at Bermuda. Curves show velocity in feet per second.

It is apparent that although the unique frequency curves show concentrations of velocities, these most frequent velocities do not give the best relative success. This suggests that determinations of azimuths by averaging data from the entire record should give generally poorer results than determinations based on selection. The broader distribution of Bermuda velocities may reflect the greater potential

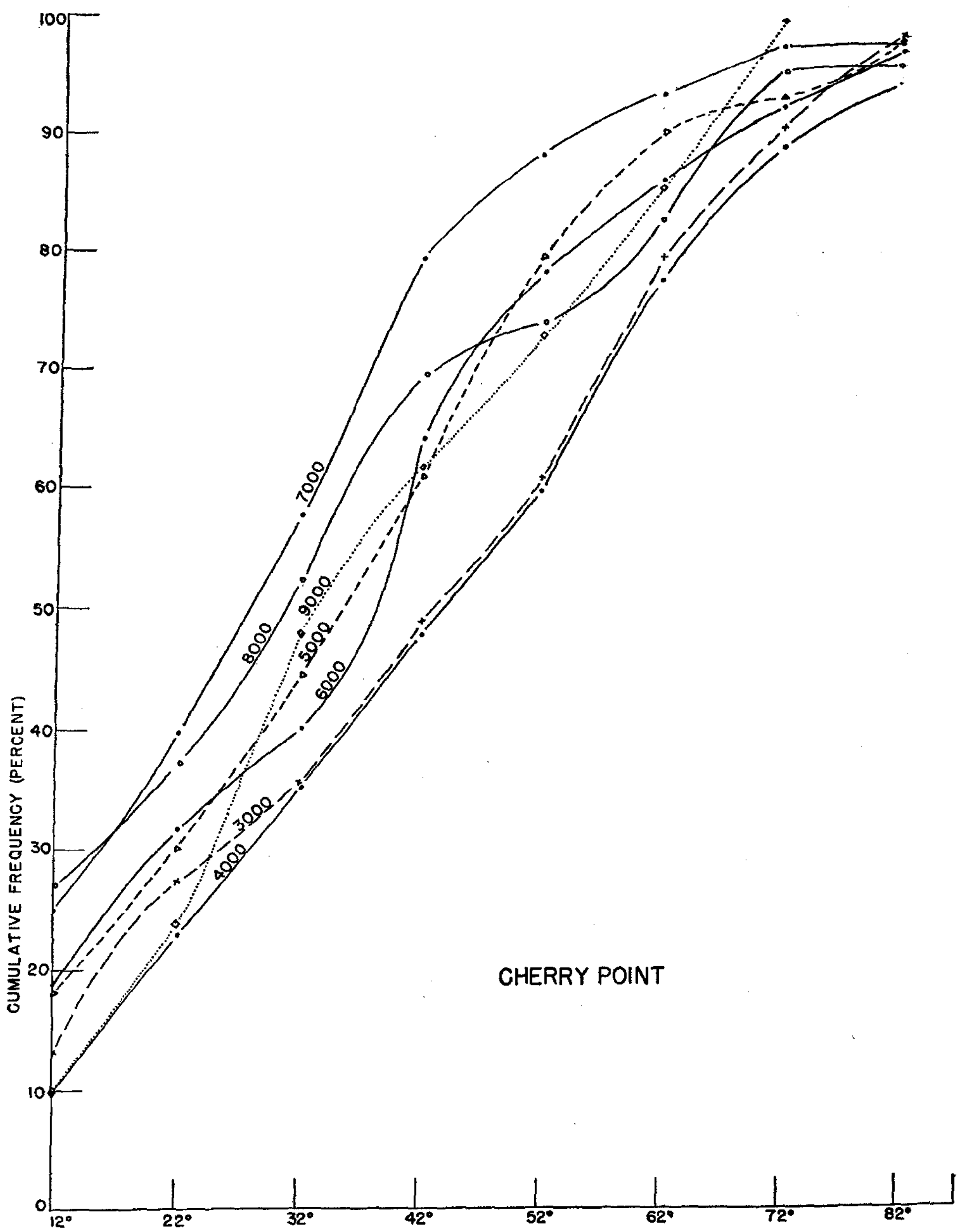

Fig. 6. Graph of cumulative frequency of angles of error associated with velocities at Cherry Point.

sources referred to earlier in connection with the A.D. differences at the stations.

A further analysis has been made in order to note any possible trends in average velocity with time. The data from Bermuda were used for this purpose. It was discovered that very short time variations occurred which could not be related to any obvious causes. However, a definite trend was apparent from September 3 through

September 8. The data for this trend, together with simultaneous average microseism amplitude and period, are shown in figure 7. Velocities, which showed about 100 per cent variation, appear to have been independent of period. The amplitude curve shows a distinct maximum at the time of maximum velocity. An amplitude minimum occurs about 1200 on September 6. During the time of maximum velocity

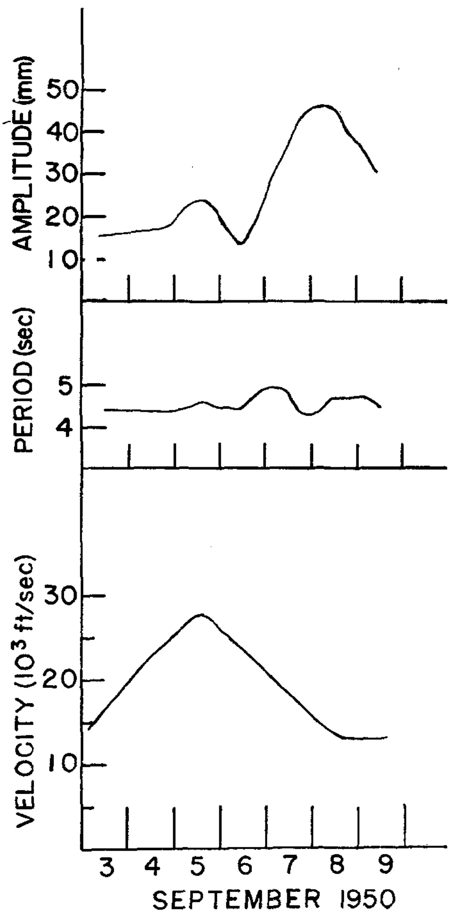

Fig. 7. Velocity, period, and amplitude data for Bermuda for September 3–9, 1950.

and amplitude, the records show that most of the waves appeared to arrive simultaneously at all three elements. In computing velocities only the waves (the minority) showing measurable time differences were used. This condition existed for a day or more and correlates with the presence of two hurricanes about 180 degrees apart and approximately equidistant from the station. The tracks of these storms are shown in figure 2. The southern storm was approaching as the northern storm receded. Hence the amplitude high on September 5 is interpreted as marking the time when the combined effect of both storms was at a maximum. During this intensity increase, time differences between "unique" waves at the Bermuda tripartite elements diminished until a standing wave effect occurred, the time of which corresponds to the time of amplitude maximum on September 5. Velocities, which vary inversely with time differences, increased to a maximum at this time. Table 1 shows that, at times during this interval, it was possible to select on the records data giving directions roughly toward both storms. Velocities decreased as time differences increased from the decreasing effect of the northern storm. A second and larger amplitude maximum occurred with the close approach of the southern storm, however velocities continued to fall to a low level. The case just discussed suggests again that velocity determinations, using tripartite stations, are often velocities of composite waves, and that storm-azimuth computations must then be erroneous. Further, in this case, the cause of the composite waves can be ascribed to the presence of wave paths from two distinct source areas.

Discussion.—The large variations of velocity for waves of the same character, plus the occurrence of beats, suggest that the recorded microseisms are frequently caused by the superposition of two or more pure waves approaching from different directions. With this assumption, analysis of these interference beats revealed that, frequently, only two wave trains differing by approximately 10 per cent in period, or a continuous disturbance over this range, could have caused the microseism patterns for intervals of at least 30 seconds. This, together with observed velocity variations, leads to an interpretation of the apparently anomalous velocities and directions computed from a "unique" wave.

The assumption is made that the velocities of the component pure waves are practically independent of wave period for the periods and tripartite distances involved. Then, for the case of two such wave trains arriving at a station with the phase velocity v and the angle C between their paths the direction of the composite wave will be that of the bisector of C, and its phase velocity will be:

$$V = \frac{v}{\cos C/2} \tag{1}$$

If significant phase differences exist, appropriate modifications can be made to this simple formula.

This interpretation shows that the apparent velocity measured by a tripartite system will vary from a minimum value (the true phase velocity of the pure wave) to an infinite velocity (giving a standing wave) as C varies from 0 to 180 degrees. Thus the modal velocities shown in figure 4 would be a function of the most frequent angular separation between the paths of waves arriving simultaneously at a tripartite station. According to the formula (1), this separation must be of the order of 90 degrees or more to account for these modal values. The true surface-wave velocities should thus be close to the lowest velocities computed, or 2,100, 5,100 and 7,500 feet per second for Cherry Point, Miami, and Bermuda respectively. These are infrequent values, as is to be expected from a consideration of the factors of origin and propagation given. No satisfactory results in azimuth determinations were obtained on the basis of the lowest velocity. However, these values were very infrequent and were probably associated with serious refraction.

Summary and Conclusions

1. Theoretically, a given sequence of arrivals at the elements of a tripartite network indicates qualitatively a 60-degree sector of possible azimuths. This may be narrowed by considering the ratio $\Delta t_1/\Delta t_2$. These time differences depend upon wave velocity, direction of wave approach, and separation between seismographs, with the factor of drum speed further affecting the precision of the results. In most cases only one significant figure for time differences could be carried from the measurements, which permitted a theoretical reduction of the qualitatively determined 60-degree sector to no better than about 10 degrees.

2. Empirical studies do not support the theoretical conclusions with respect to accuracy, since a much greater error occurred for azimuths computed on both an average and a selective basis. Further, observed maximum arrival-time differences (Δt_1) show a far greater range than is expected for the tripartite station and wave velocities used.

3. Directions to storm centers based on average azimuth computations gave accuracy too poor for operational purposes. However, rough azimuths were obtainable with angles of error of from 20 to 40 degrees.

4. Several factors appear to contribute to the lack of success in locating storm areas. These are summarized as (*a*) errors resulting from procedure of measuring and computing, (*b*) errors resulting from the incoherence of waves recorded at the elements of the tripartite station, and (*c*) errors resulting from refraction and multiple wave paths.

5. To explain the discrepancies noted, attention was directed to the study of individual waves recorded at each element of the tripartite nets. Definite, often pronounced differences in period and amplitude of "unique" waves at each of the seismograph elements indicate that the waves and groups measured are incoherent, the period differences being of the same order as arrival time differences. This precludes any accuracy in computational results depending on such time differences. In some cases the presence of apparently identical waves arriving simultaneously suggests the existence of standing waves from opposite sources.

6. The foregoing led to a study of individual and average wave velocities for the three stations used. In general, wave velocities were lowest for Cherry Point and highest for Bermuda, with intermediate values for Miami. These might be a result of local geology, and are in agreement with the known geologic relations among the stations. Anomalously low and high velocities are observed at all stations, although a definite concentration is noted for each. *This study suggests that present tripartite records show the progress of a composite wave form across the net rather than a unique microseism wave traveling a unique path.* The study of average velocities for a particular case furthers this view and permits the distinction between two source areas, for the case given.

7. The cause of the ambiguity in recognizing pure waves is considered the presence of multiple paths. These in turn probably originate from a combination of refraction at coastal zones, two or more source areas, and broad source areas. Based on the assumptions made, both empirical and theoretical results suggest that the lowest velocity values observed at a station most nearly approach the velocities of the

component waves forming the recorded microseisms, which is similar to but more specific than the findings of Kammer and Dinger (10). Reliable azimuths should then be computed from the pure waves and not the composite microseisms. Such waves are difficult to distinguish with present instrumentation. Even if unique wave paths can be recognized, they may still differ from true storm azimuths, owing to refraction.

8. This study has suggested several improvements in instrumentation, listed below, which may increase the operational value of seismic storm location and reveal further significant data on the basic nature of microseisms.

a) In a net for operational purposes more than three instruments should be used, and in a research net for further study as many instruments as possible.

b) All the instruments should be vertical components, with at least one instrument having two matched horizontals associated.

c) The instruments should be sharply tuned to minimize interference of waves of different period.

d) Instruments should be spaced farther apart than they are at present for operational purposes, and at variable distances for further research. An array of numerous instruments along intersecting lines at right angles would give more information on wave propagation, and would also provide several networks of different spacing for study of azimuths.

e) Amplitudes should be increased in proportion to increasing drum speeds.

f) An improvement in the quality of records should be made, to permit greater measurement precision; for example, frequent simultaneous brief interruptions of all light beams, and finer line reproduction.

9. It is considered at present that the operational value of tripartite stations in locating and tracking storms is small, and that almost as much can be determined from a qualitative appraisal of the records as from time-consuming measurements and computations. It is further believed that attention should be concentrated in research, both experimental and theoretical, on the origin and propagation of microseisms before operational application is attempted.

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