SSC-280

(SL-7-23)

RESULTS AND EVALUATION OF THE SL-7 CONTAINERSHIP RADAR AND TUCKER WAVEMETER DATA

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SHIP STRUCTURE COMMITTEE

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An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

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SR-1221

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This report is one of a group of Ship Structure Committee Reports which describes the SL-7 Instrumentation Program. This program, a jointly funded undertaking of Sea-Land Service, Inc., the American Bureau of Shipping and the Ship Structure Committee, represents an excellent example of cooperation between private industry, regulatory authority and government. The goal of the program is to advance understanding of the performance of ships' hull structures and the effectiveness of the analytical and experimental methods used in their design. While the experiments and analyses of the program are keyed to the SL-7 Containership and a considerable body of the data developed relates specifically to that ship, the conclusions of the program will be completely general, and thus applicable to any surface ship structure.

The program includes measurement of hull stresses, accelerations and environmental and operating data on the S.S. Sea-Land McLean, development and installation of a microwave radar wavemeter for measuring the seaway encountered by the vessel, a wave tank model study and a theoretical hydrodynamic analysis which relate to the wave induced loads, a structural model study and a finite element structural analysis which relate to the structural response, and installation of long term stress recorders on each of the eight vessels of the class. In addition, work is underway to develop the initial correlations of the results of the several program elements.

Results of each of the program elements are being made available through the National Technical Information Service, each identified by an SL-7 number and an AD- number. A list of all SL-7 reports available to date is included in the back of this report.

This report discusses the results of the wavemeter data collection portion of the SL-7 Instrumentation Program. Comparison of estimated and measured spectra is made. Recommendations as to improvements in the wave measuring systems employed in this program are offered.

Henry H. Bell
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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FINAL REPORT

on

Project SR-1221

"Correlation and Verification of

Wavemeter Data from the SL-7"

RESULTS AND EVALUATION OF THE SL-7 CONTAINERSHIP RADAR AND TUCKER WAVEMETER DATA

by

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under

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ABSTRACT

So that more precise correlations between full scale observations and analytical and model results could be carried out, one of the objectives of the instrumentation program for the SL-7 class container ships was the provision of instrumental measures of the wave environment. To this end, two wave meter systems were installed on the S.S. SEA-LAND McLEAN. Raw data was collected from both systems during the second (1973-1974) and third (1974-1975) winter data collecting seasons.

It was the purpose of the present work to reduce this raw data, to develop and implement such corrections as were found necessary and feasible, and to correlate and evaluate the final results from the two wave meters. In carrying out this work it was necessary to at least partly reduce several other channels of recorded data, so that, as a by-product, reduced results were also obtained for midship bending stresses, roll, pitch, and two components of acceleration on the ship's bridge.

As the work progressed it became evident that the volume of documentation required would grow beyond the usual dimensions of a single technical report. For this reason the analyses, the methods, the detailed results, discussions, and conclusions are contained in a series of ten related reports.

This report, contains the last phases of the work, specifically, the discussion of results, the correlation and evaluations of final results from both wave meters, the conclusions, and the recommendations.

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INTRODUCTION

In the analysis of the wave-induced ship hull strain data obtained by SSC in the 1960's it was necessary to infer the wave environment from estimated Beaufort wind speeds. An extraordinary amount of work was required to develop the inferential techniques. These techniques appear to suffice for valid prediction of long-term trends because a great deal of averaging is carried out. Unfortunately when verification of short-term statistical predictions is desired, the use of wind as a wave environment index appears to be less than satisfactory.

As a consequence it was one of the objectives of the SL-7 full-scale instrumentation program to provide a direct instrumental measure of the wave environment so that more precise correlations could be made between full-scale observations, and analytical and model results.

To this end the ship was fitted with a micro-wave radar relative wave meter and various motion sensing devices. A "Tucker Meter" pressure actuated wave height sensing system was also installed.

The purpose of the present project is to reduce and analyze the resulting wave meter data obtained on the SEA-LAND McLEAN in the second (1973-1974) and third (1974-1975) winter recording seasons.

The purpose of the present report is to document the last phase of the program; that is, to present discussion, summary material, and the conclusions from the work. Thus this report involves material which would ordinarily be expected to comprise the last two or three sections of a single physical report on the project. That this is not the case is due to the large volume of results involved. Functionally, References 1 through 9 may be considered to be the introduction, analysis, and result sections leading up to the present material.

BACKGROUND

It was the objective of the present project to analyze and reduce data obtained by others, and for practical reasons it has been necessary to assume on the part of the reader a general familiarity with the Ship Structure Committee's SL-7 measurement program. The primary background references for the present project are References 10 through 13. Reference 10 is the basic documentation of the full-scale instrumentation system. References 11 and 12 contain, for both recording seasons in question, a quite full account of instrumentation, basic recording, and the nominal circumstances surrounding the present data. These references also contain results of analyses of longitudinal vertical midship bending stress which were carried out according to the methods of Reference 13.

Only the description of the OWHS radar system is lacking from References 11 and 12. The source for this information is Reference 14, which contains in addition results of a special correlation study between shipborne radar wave measurements and those obtained from air-borne instruments. As noted in Reference 7, it was not possible to correlate results of the present study with those of Reference 14.

Broadly, the work accomplished in the present project may be considered in four phases, the last one of which is the subject of the present report:

1. Initialization and Data Acquisition
2. Analysis and Development of Data Reduction Procedures
3. Production of Results
4. Comparison of Results, Critique and Conclusions

Phase 1 involved finding the required data, working out ways of reducing it to digital form, calibrating each channel, collating the digitized data with log book and other data from References 11 and 12, and selecting a final data set for further analysis. The documentation for this phase is contained in References 1 and 7.

Phase 2 involved basic analyses and the development of data reduction procedures. All but a minor amount of the documentation of this phase is contained in Reference 2. (Consideration of some corrections to the Tucker meter results was deferred to the present report.)

The documentation of Phase 3, the production of results is contained in References 3 through 6, 8, and 9. These references contain the results from the basic data reduction procedures described in Reference 2.

DISCUSSION OF RESULTS OF THE BASIC DATA REDUCTION PROCESS

Qualitative Observations

References 3 through 6, 8 and 9 together contain reduced results from a total of 271 recording intervals (198 from the second season, and 73 from the third). On the basis of a visual inspection of the nearly 600 pages of tables and charts there are very few generalizations which can be made without at least some trepidation. It is obvious from the results that a large number of parameters of importance have influenced the results, and that the various estimates of encountered wave height (visual, radar, Tucker and mean dynamic head) disagree significantly. The magnitude and reasons for disagreement are questions which will be taken up later.

Beyond the above, there were a number of general impressions formed by the investigator in viewing the results and these may be listed as follows:

1. There are a significant number of intervals for which the results from the radar and/or the derived mean dynamic head cannot be believed at all, and an even greater number where the double integration of accelerations is suspect. Reasons vary, and the subject will be taken up in detail in succeeding sections.

2. On the whole, Eastern and Western legs of each voyage are significantly different. Most of the visual estimates of wave direction involve following or quartering seas in the Eastern voyage legs, and head or bow seas in the Western legs. The disposition of spectral density in the stress and wave spectra is usually in rough accordance with the visual wave direction estimate. When it is not, the wave height and stresses tend to be small.

3. Since at least half of the data set involves following or quartering seas, there is a rather high incidence of very long encounter periods (up to 3 minutes in at least one case), and many cases in which both the midship longitudinal bending stress and the radar wave contain a very broad range of component frequencies. As a consequence, there are many cases in which the standard relationships between process rms and statistical averages of peak-trough excursions cannot be expected to hold.

4. It would be expected that spectra of waves would more or less resemble the stress spectrum, perhaps being a bit broader banded. Similarly, time histories of the various wave estimates and those of the corresponding stresses should look alike. These expectations normally appear to be quite well satisfied by the radar wave estimates, less well by the Tucker meter estimates, and least well by the mean dynamic head estimates. The high frequency content of the latter two tends to be less than might be expected on the basis of the stress records. The Tucker and dynamic head spectra are very often narrower band than the stress spectrum -- a result which might be expected since no corrections for wave pressure attenuation or ship-wave interference have been applied.

Radar Malfunctions/Reliability

Returning to the first of the impressions just listed, the first of a number of classes of potential errors involves the behavior of the slant range signal from the radar. As noted in References 1 and 7, it appears that the signal from the radar unit is not the range in the ordinary sense of the meaning of radar range. It is the difference in range from some nominal initial range condition. The unit has automatic features which insure initial signal acquisition -- and re-acquisition in case of temporary return signal loss. The effect is that any signal loss while both radar and wave surface are in motion is apt to change the reference to some extent.

As noted in References 1 and 7, gross changes in reference level were noticed on many of the compressed time scale records. In the initial selection of the intervals under discussion an attempt was made to eliminate intervals with obvious problems of this type. There was of course no guarantee that the procedure removed all problem intervals, and accordingly, one of the first objectives of an inspection of results in References 3 through 6, 8 and 9 was to examine the radar wave time histories for evidence of radar malfunction. The time histories shown in the references do not contain the entire interval, but the portion of interval was so selected that the maximum peak to trough radar wave height was included. It was considered highly probable that radar malfunction would produce the largest apparent peak-trough excursions, and thus that the worst of any potential problems would be visible. The radar wave elevation time history does not consist solely of the slant range, Reference 2, but all the other contributions are smooth so that sudden changes or abnormally high rates of change are highly likely to be due to the behavior of the slant range itself.

In the event, a total of 24 intervals out of the set of 271 were observed to exhibit gross malfunction, or were considered highly syspect. The particular intervals are identified in Table I. There were three types of malfunctions observed. These were labeled A through C, and the problem applicable to each interval is identified by one or two of these letters in the column of Table I headed "Comments".

Problems of type "A" involved sudden shifts in the mean level of radar wave elevation which were not reflected in any way by the stress or roll time histories. This type of problem is precisely the same as that initially observed, Reference 1.

Problems of type "B" involved sudden, large, typically flat topped excursions which were not symmetrical (crest but no trough or vice versa) and not reflected in unusual behavior of stress or roll time history.

Problems of type "C" were confined to Voyage 60 West, and were usually combined with a type "A" problem. The type "C" problem involved relatively large symmetric excursions interspersed in a generally much lower level oscillatory signal, a behavior not obvious in the stress record. Upon close examination, this behavior was visible in the compressed time scale records and involved nearly all intervals in Voyage 60W, though it did not seem to be present in either Voyages 60E or 61E.

There appeared to be little point in including the intervals shown in Table I in any subsequent comparisons.

In the second season data tapes the incidence of an obviously malfunctioning radar unit tended to be concentrated in intervals involving relatively severe waves. Up to 60% of the data on a tape covering a severe weather period was found to be unusable. In the third season data tapes the incidence of malfunction seemed appreciably higher than that in the second season -- despite the fact that almost all wave conditions in the third season were milder than those of the second season. With the inclusion of the third season intervals noted in Table I, the incidence of unusable intervals was much higher (approaching 85%) during periods of time involving waves of medium severity by second season standards.

TABLE I

INTERVALS IN WHICH GROSS
RADAR MALFUNCTIONS WERE OBSERVED
OR ARE SUSPECTED

Report/Ref.	Page	Voyage	Run	Tape	Index	Interval	Comment
3	62	32W	313	143	4	13	A
3	82	32W	413	145	20	13	A
3	88	32W	429	145	24	29	B
3	90	32W	437	145	26	37	A
3	92	32W	441	145	27	41	B
3	94	32W	450	145	29	50	A,B
4	60	33W	815	153	4	15	B
4	74	33W	841	153	11	41	B
4	80	33W	853	153	14	53	B
4	82	33W	861	153	16	61	B
6	74	35W	1710	171	17	10	B
8	48	60W	2329	217	8	29	A
8	50	60W	2333	217	9	33	A,C
8	52	60W	2337	217	10	37	C
8	54	60W	2341	217	11	41	A,C
8	56	60W	2348	217	12	48	C
8	60	60W	2401	219	16	1	A,C
8	62	60W	2409	219	18	9	C
8	64	60W	2413	219	19	13	A,C
8	66	60W	2420	219	20	20	A
8	74	60W	2433	219	24	33	A,C
8	76	60W	2437	219	25	37	A,C
8	78	60W	2442	219	26	42	A
8	80	60W	2448	219	27	48	A,C

It appears that the radar unit was less reliable during the third season than the second. The apparent reliability of the unit during the second season was not nearly as good as might be desired, and in fact was nowhere near the reliability of the various transducers, or for that matter of the Tucker wave meter system.

Double Integration Problems

It has been noted that in the review of the results in References 3 through 6, 8 and 9, there were a number of intervals where the double integration could not be believed at all, and a large number where the integration may be considered suspect. The difference between the two cases is one of degree. In cases that the double integration could not be believed the results involved extraordinary large low frequency components in the mean dynamic head and the radar wave output, and much if not all of the spectral density below the low frequency cutoff described in Reference 2. In the cases where the integration is merely suspect, substantial spectral density is below the cutoff but the results otherwise appear reasonable in relation to the nominal conditions noted in the log book and in relation to the shape of the stress spectrum.

Table II identifies the 21 particular intervals which were considered completely invalid because of double integration related problems. There were three types of problems which were obvious. These are labeled A, B and C, and the type of problem applicable to each interval is noted in the column headed "comment".

It was noted in Reference 2 that there were potential problems associated with double integration of the present acceleration data. All involved the treatment of low frequency components because of the discontinuous nature of the data. Essentially, when there are only a few periods of a component in the entire sample, the double integration of even ideally resolved data cannot be very accurate. To try to avoid the situation where ultra low frequency noise could be blown up by double integration, the double integration filter was adapted to each sample by establishing a cutoff frequency above which the double integration is proper, and below which the very low frequencies are de-emphasized. The position of the cutoff was determined by the frequency at which 2% of vertical acceleration variance is attributable to lower frequencies. It was found in Reference 2 that the method used tended to fall down badly for very long period components, say over 150 sec, and that the overall accuracy of the method was related to the resolution of the acceleration signal. The rms displacement error in percent was found to be approximately equal to the acceleration resolution in percent of rms acceleration.

In the case of the type "A" problem noted for two intervals in Table II there was evidently some very low frequency noise buried in very low level acceleration. In both cases the rms acceleration was of the order of 0.02 or 0.03 g. The acceleration resolution in these cases was 0.01 g so that even if low frequency noise had not been present the rms

TABLE II

INTERVALS IN WHICH VERY LARGE
DOUBLE INTEGRATION ERRORS APPEAR

Report/Ref.	Page	Voyage	Run	Tape	Index	Interval	Comment
5	92	34W	1345	163	24	45	A
6	48	35E	1545	167	25	45	A
8	8	60E	2126	211	7	26	B
8	20	60E	2213	213	19	13	B
8	72	60W	2430	219	23	30	C
9	8	61E	2518	223	5	18	C
9	10	61E	2524	223	6	24	C
9	12	61E	2528	223	7	28	C
9	14	61E	2530	223	8	30	C
9	16	61E	2536	223	9	36	C
9	18	61E	2539	223	10	39	C
9	20	61E	2541	223	11	41	C
9	22	61E	2547	223	12	47	C
9	24	61E	2551	223	13	51	C
9	26	61E	2553	223	14	53	C
9	28	61E	2557	223	15	57	C
9	30	61E	2601	225	16	1	C
9	50	61W	2713	229	4	13	C
9	52	61W	2725	229	7	25	C
9	58	61W	2761	229	16	61	C
9	86	61W	2925	233	37	25	C

displacement error would have been 30 to 50%. These are the only intervals in the 198 reduced from the second season in which this effect was obvious.

The type "B" problem noted for two intervals in Table II is not so much a case of the double integration method failing as it is of the underlying data being bad. It appears that in both cases some sort of electrical transient (power surge ?) ran all channels into semi-saturation. The effect was to put an apparent isolated 1.7 g pulse into an otherwise low level acceleration, thus producing large spectral components near zero frequency, and from this a ridiculous result.

The last type of problem (C) noted in Table II is peculiar to third season data. The incidence of this type of gross error is rather high (17 out of 73 intervals) and is attributed to the less well resolved acceleration data. In the second season the acceleration resolution was 0.03 g (Ref.7) rather than 0.01 g (Ref.1). It thus must be expected that the double integrations of third season accelerations will contain at least three times the rms error of those of the second season since total rms acceleration levels are not different for the same apparent level of wave severity. In a few of the intervals noted in Table II there was a suggestion of apparent component accelerations having up to 10 minute periods. This, in conjunction with poor resolution and an otherwise low level acceleration signal resulted in some ludicrous results. The results shown in References 8 and 9 for the 17 intervals marked with "C" in Table II are actually the result of re-running the data reduction procedure with the proviso that the low frequency cutoff could be no lower than 0.2 rad/sec. This action converted 17 sets of ludicrous results into results which are in some cases believable, but for the most part, are still not very. Because of the arbitrariness of the selection of the low frequency cutoff, all 17 intervals are considered to contain very large errors regardless of how reasonable they may appear to be.

As in the case of the radar related problems, it was considered pointless to include the intervals noted in Table II in any subsequent comparisons or analyses.

Other Potential Sources of Error

In reviewing the results some other potential sources of error were considered. From the point of view of the radar wave the most serious of the error sources is the nature of the angle measurements. As pointed out in Reference 2 these measurements can be considered valid for the frequency range under consideration only if there is negligible true surge or sway acceleration of the ship. In the present case the alternative to making the negligible sway and surge assumptions was to do nothing. The detailed analysis of the first piece of data (Ref.2) suggested that the zero surge assumption was invalid for extreme conditions. Though no direct evidence of the invalidity of the zero sway assumption can be adduced from the data, the writer considers this assumption extremely questionable on physical grounds when roll angle is large -- and/or when the ship is in quartering seas.

There seems nothing quantitative which can be done about this problem. However it was at least possible to look at the spectra and time histories produced, with the view of correlating oddities in the various wave elevation measurements with rolling. This was done with the results in References 3 through 6, 8 and 9 -- with an essentially null result. The only obvious qualitative correlation of roll and wave measurement was in the case of the 17 intervals from the third season already discarded as having gross double integration error. In these cases the mean dynamic head looks like the roll but not much like the stress. What has evidently happened is that the small gravitational component of a relatively large roll which contributes to the body vertical acceleration has not completely been removed by the correction procedure (Ref.2), and the residual has then in turn been blown up by a partially improper double integration. The effect is consistent with (but not positively attributable to) roll measurements which are distorted by sway accelerations.

In concluding the present discussion of the results presented in References 3 through 6, 8 and 9, it should be emphasized that the analysis has been subjective. According to the writer's point of view there are a total of 45 intervals out of the 271 which are grossly wrong. It is admitted that in the analysis the benefit of doubt was given to the data. Accordingly, another analyst might well recommend more discards. As might have been expected in a data set in which the quartering/following sea condition is involved half the time, there is at least a marginal doubt about the double integrations in many of the remaining 226 intervals. An attempt to deal with these doubts in a more quantitative way will be made in succeeding sections.

COMPARISONS OF SIGNIFICANT PEAK-TROUGH WAVE HEIGHT ESTIMATES WITH THOSE DERIVED FROM THE SPECTRA

In the results of the basic data reduction process there are, for each interval, a total of six estimates of significant wave height which were derived from the measured data -- two estimates each for OWHS radar, Tucker meter and mean dynamic head. The first of the estimates shown for each of the three approaches to the encountered wave is the "significant peak to trough wave height." This estimate is the average of the 1/3 highest double amplitudes observed in 16-1/2 minutes of time history. Each double amplitude was determined by the zero crossing convention (peaks are always positive, troughs are always negative, Ref. 2). The second type of estimate is based on the spectrum and is four times the square root of spectrum area, or "4 rms." It is assumed in making this estimate that the process is sufficiently narrow banded that the Rayleigh distribution holds for the maxima of the process.

Comparisons of these two types of estimates for the same thing are of interest in two ways; first to indicate the relative importance of non-narrow bandedness, and second to aid in deciding which of the two types of estimates should be used in subsequent comparisons.

The mode of comparison chosen was to plot one estimate against the other to the same (linear) scales. Figure 1 indicates the resulting comparison between rms and peak-trough estimates from the radar for all 226 of the intervals remaining after the discards noted in the last section had been made. Because the automatic plotting system used rounds coordinates to the nearest 0.01 inches there are probably not 226 distinct points shown. However, the dashed straight line is a least square fit to all the data points.

It appears from Figure 1 that the average peak-trough estimate is about 20% lower than the 4 rms estimate. It is expected on theoretical grounds that all the peak-trough estimates should be equal or lower, and all but two are. The magnitude of the differences shown implies that the majority of the radar wave spectra are quite broad banded.

Figure 2 indicates the same sort of comparison of radar data, but for a sub-set of all available intervals. It was observed from the basic results that when there was a high proportion of radar wave spectral area below the low frequency integrator cutoff, the nominal heading was usually quartering to following seas, the spectra tended to look relatively broad banded, and the stress spectrum also contained relatively significant low frequency spectral density. It is expected that radar wave spectral densities below low frequency integrator cutoff will be in error to some extent. If the proportion of spectral area below the cutoff is 20% of total, the maximum error in the 4 rms estimate is just over 10%. A 10% error is about the magnitude which has to be accepted on statistical grounds for perfectly measured data (Ref.2). Accordingly, in producing Figure 2 consideration was given only to those intervals for which the spectrum area above the low frequency integrator cutoff is greater than 80% of total. The effect was to elininate all but about 10 of the nominal quartering/following sea conditions, and of course the vast majority of intervals where there exist significant question of double integrator error. The points remaining below the dashed line in Figure 2 are nearly all from the residual quartering/following conditions. If these were also eliminated the points remaining would all have 90% or more spectral area above low frequency cutoff. Under this additional condition the dashed trend line would shift upward and imply significant peak-trough estimates only a few precent lower than the 4 rms estimates -- and thus that the bandwidth of the encountered radar wave spectra for essentially head and bow seas is not different than expected.

Turning to the uncorrected Tucker meter data, Figure 3 indicates the comparison between significant and 4 rms estimates for all intervals. The differences are surprisingly large on the average. Evidently the visual judgment previously noted was distorted by the plotting convention in References 3 through 6, 8, and 9 where the generally much lower Tucker spectral densities are plotted to the same scale as the radar and dynamic head spectra. Inspection of the numerical data disclosed that half of the points corresponding to 4 rms Tucker estimates above 10 feet involved nominal quartering/following wave directions, and that these points produced the largest differences between 4 rms and significant peak-trough estimates. Additionally, in the case of 4 rms estimates below 4 feet there was a very high incidence of what appeared to be too many waves.

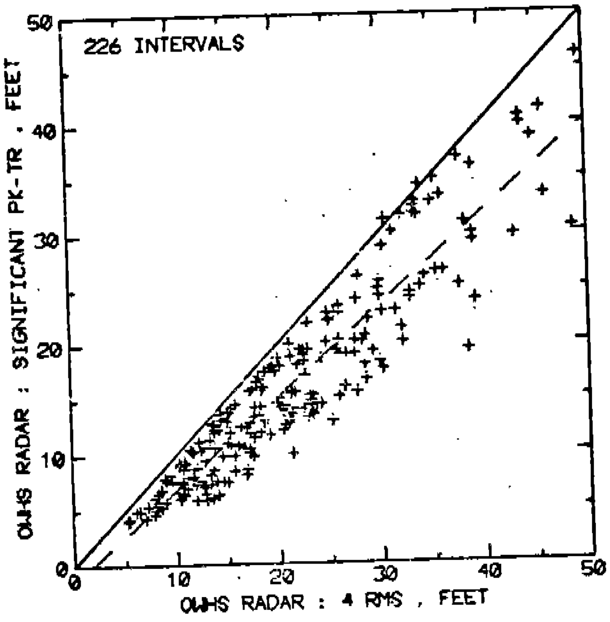

FIGURE 1 - COMPARISON OF SIGNIFICANT PEAK-TROUGH ESTIMATES WITH THE "4 RMS" ESTIMATES FROM THE OWHS RADAR SYSTEM DATA FOR ALL INTERVALS

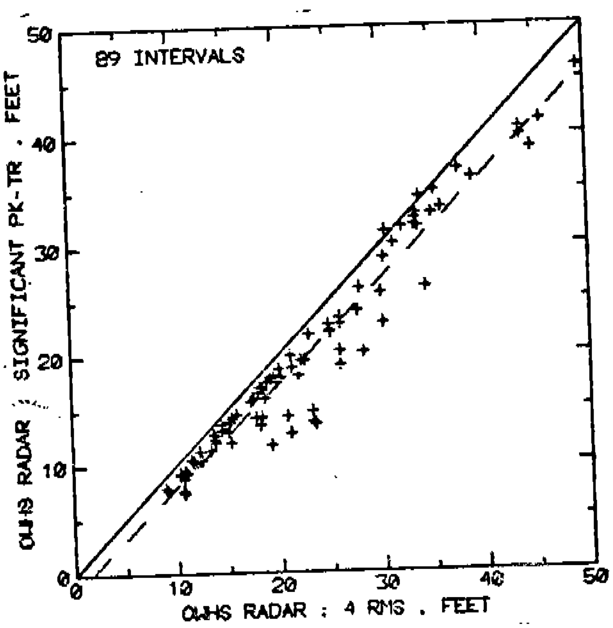

FIGURE 2 - COMPARISON OF SIGNIFICANT PEAK-TROUGH ESTIMATES WITH THE "4 RMS" ESTIMATES FROM THE OWHS RADAR SYSTEM DATA; INTERVALS PLOTTED ARE RESTRICTED TO THOSE FOR WHICH SPECTRUM AREA ABOVE THE LOW FREQUENCY INTEGRATION CUTOFF IS GREATER THAN 80% OF TOTAL

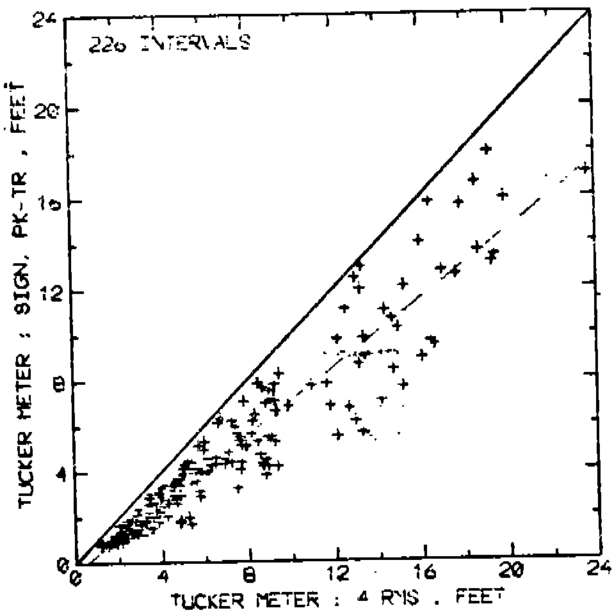

FIGURE 3 - COMPARISON OF SIGNIFICANT PEAK-TROUGH ESTIMATES WITH THE "4 RMS" ESTIMATES FROM THE UNCORRECTED TUCKER METER DATA FOR ALL INTERVALS

The Tucker channel is resolved to 0.2 feet. For 4 rms estimates under 4 feet, tape and other noise is expected to be between 20 and 80% of total rms. The peak-trough algorithm in the standard data reduction procedure is not smart enough to cope with this situation, and evidently counted a good many noise excursions as waves. An unrealistically high estimate of the number of waves means that too many of the highest waves are averaged and this will tend to drive the "significant" down.

It appears that the uncorrected Tucker signal is qualitatively similar to the radar wave with respect to bandwidth, and that some distortion has been introduced in the significant peak-trough estimates.

To complete the comparisons, Figures 4 and 5 indicate the comparison between 4 rms and significant peak-trough estimates for the mean dynamic head at frame 119. All intervals are plotted in Figure 4. In Figure 5 the intervals plotted were restricted to those for which the dynamic head spectrum area above the low frequency cutoff is greater than 80% of total. As before, the restrictive case (Figure 5) involves mostly head/bow seas and cases of little suspicion of double integration error.

Both figures indicate relatively narrow band output as expected from visual inspection of the results. Though the Tucker meter signal is imbedded in the mean dynamic head estimates, it has relatively little influence upon the result in the higher range of wave height because the correction for the Tucker double integration is so large.

Considering all three sources of wave estimates the present comparisons confirm the high incidence of mathematically broad processes. This automatically means an interpretative problem with both the "4 rms" and "significant peak-trough" estimates for a large portion of the data. Neither estimate consistently has the conventional meaning. Of the two, the peak-trough estimates are thought to be subject to the most distortion. The 4 rms estimates are a measure of total variance, and were thus preferred for use in comparisons of one wave measuring device with another.

TUCKER METER CORRECTIONS

The "mean dynamic head" results given in References 3 through 6, 8, and 9 are essentially a corrected form of the Tucker meter data. The correction is however only for the analog double integration in the meter. No approach to correction for wave distortion is known for the "mean head." The estimation of mean dynamic head was carried along in the data reduction in hopes of indicating the overall importance of error in the double integrators installed in the Tucker meter, and no further correction was contemplated.

However in practice, some sort of correction for wave attenuation is always applied to Tucker meter data so that all results labeled "Tucker meter" in References 3 through 6, 8 and 9 involve "raw" data in this sense. It was decided in the initial analysis, Reference 2, not to

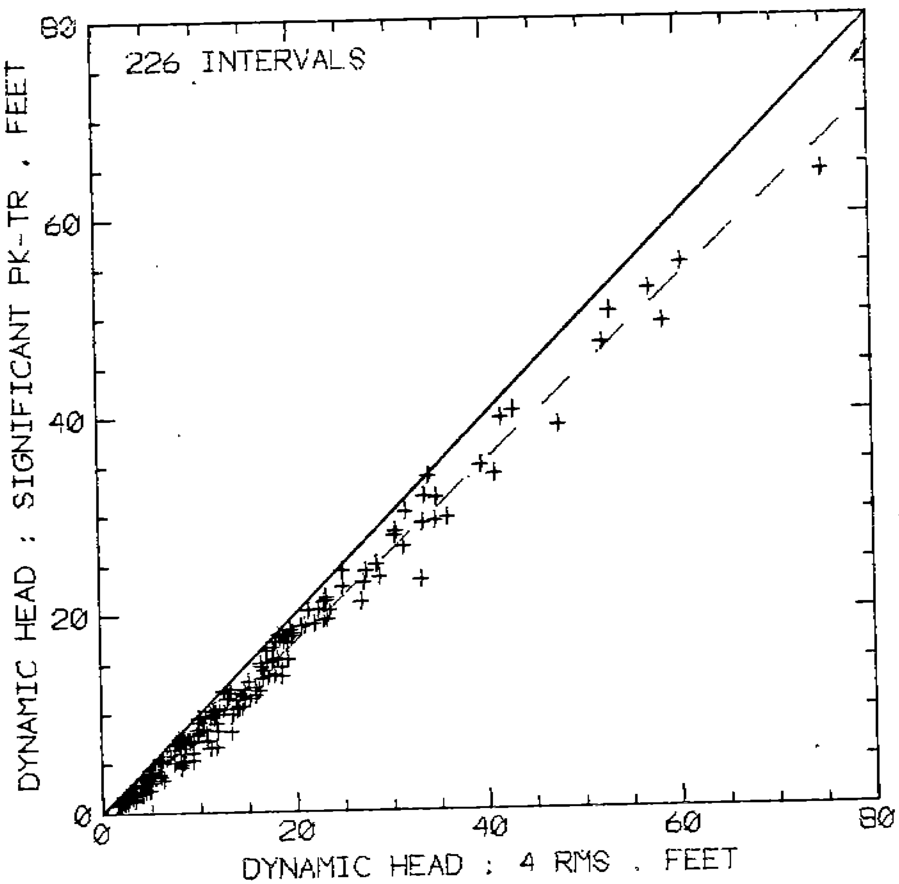

FIGURE 4 - COMPARISON OF SIGNIFICANT PEAK-TROUGH ESTIMATES WITH THE "4 RMS" ESTIMATES OF MEAN DYNAMIC HEAD: ALL INTERVALS

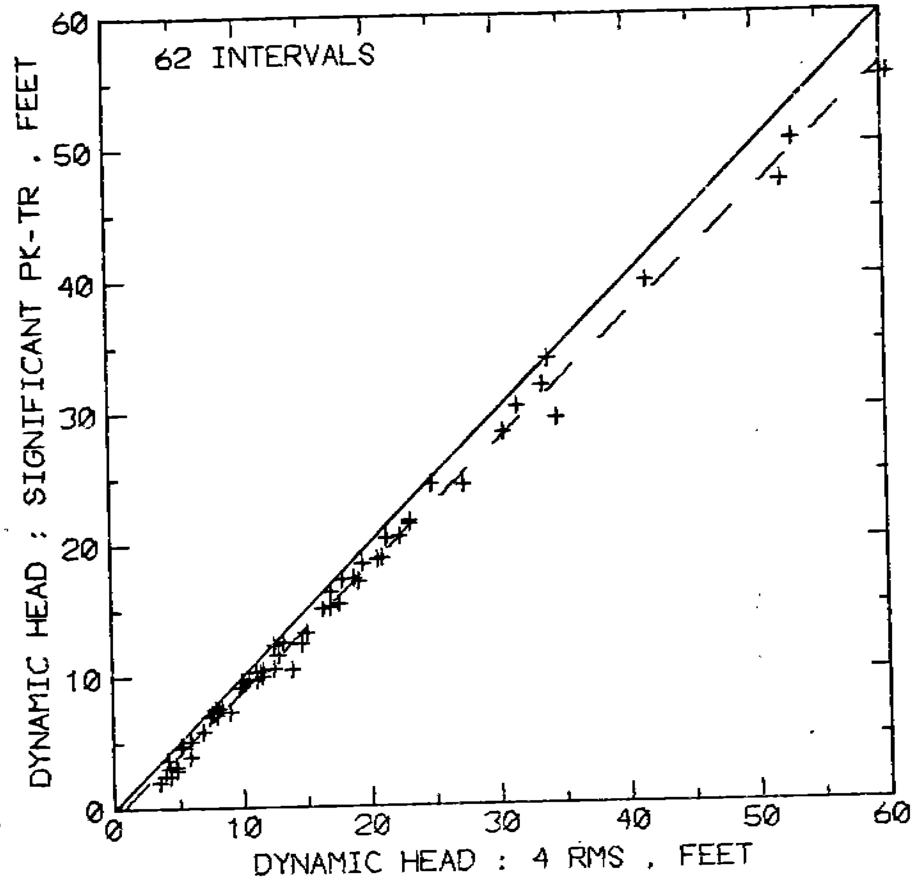

FIGURE 5 - COMPARISON OF SIGNIFICANT PEAK-TROUGH ESTIMATES WITH THE "4 RMS" ESTIMATES OF MEAN DYNAMIC HEAD: INTERVALS PLOTTED ARE RESTRICTED TO THOSE FOR WHICH SPECTRUM AREA ABOVE THE LOW FREQUENCY INTEGRATION CUTOFF IS GREATER THAN 80% OF TOTAL

include any conventional correction procedure in the basic data reduction process because it was not known what method to use and because there was doubt that existing calibration procedures were valid for the present application. In the final stages of the program this was still the case, the only material available with which to make a conventional correction to the "raw" Tucker meter data being Figure 7 of Reference 11. It was determined to apply this material to the present data.

The cited figure in Reference 11 is a series of plots of "wavemeter correction coefficient" vs. encounter frequency, for various values of mean submergence of pressure taps. The deepest submergence given is 15 feet, which seems near enough for the present case, so that this curve was used. For the 15 foot submergence the correction coefficient is defined between encounter frequencies of 0.25 and 1.65 radians/second. The corrected Tucker wave amplitude for a given frequency is the product of the correction coefficient and the raw Tucker amplitude. The correction coefficient is 1.15 at 0.25 radians/sec, decreases to unity at about 0.45 radians/sec and rises rapidly to 3.0 at 1.65 radians/sec.

For the present application it appeared that the significant range of raw Tucker meter spectral density extended beyond an encounter frequency of 1.6 in only a very few cases, and below 0.25 radians/sec in not too many more. Accordingly, the curve given in Figure 7 of Reference 11 was read off at a convenient delta frequency between 0.25 and 1.58 radians/sec, and this digital version was used in making the corrections.

There are two common methods of applying the correction. For present purposes these may be called the "characteristic period" and the "spectrum" approaches.

In the characteristic period approach the characteristic encounter period of the sample is taken to be the total sample length divided by the number of double amplitudes in the sample. This characteristic period is converted to encounter frequency and the corresponding wavemeter correction coefficient is read from the calibration curve. The final estimate is then the product of this coefficient and a measure of the raw Tucker meter amplitudes. This procedure is the one used in Reference 11. In Reference 11 the maximum raw peak-trough height for the Tucker was apparently read from oscillograph records for Voyage 32W, and the number of wave double amplitudes was assumed equal to the number of stress double amplitudes.

In the present application of the characteristic period method the number of raw Tucker double amplitudes in 16-1/2 minutes was available (Refs. 3 through 6, 8 and 9) and the correction coefficient was established in the manner just described from this data. The correction coefficient was derived for each of the 226 intervals under present consideration and it was applied to the significant peak-trough raw Tucker meter estimates. The resulting corrected and raw significant peak-trough estimates are compared in Figure 6. In the figure the raw significant height is the abscissa, the corrected height is the ordinate.

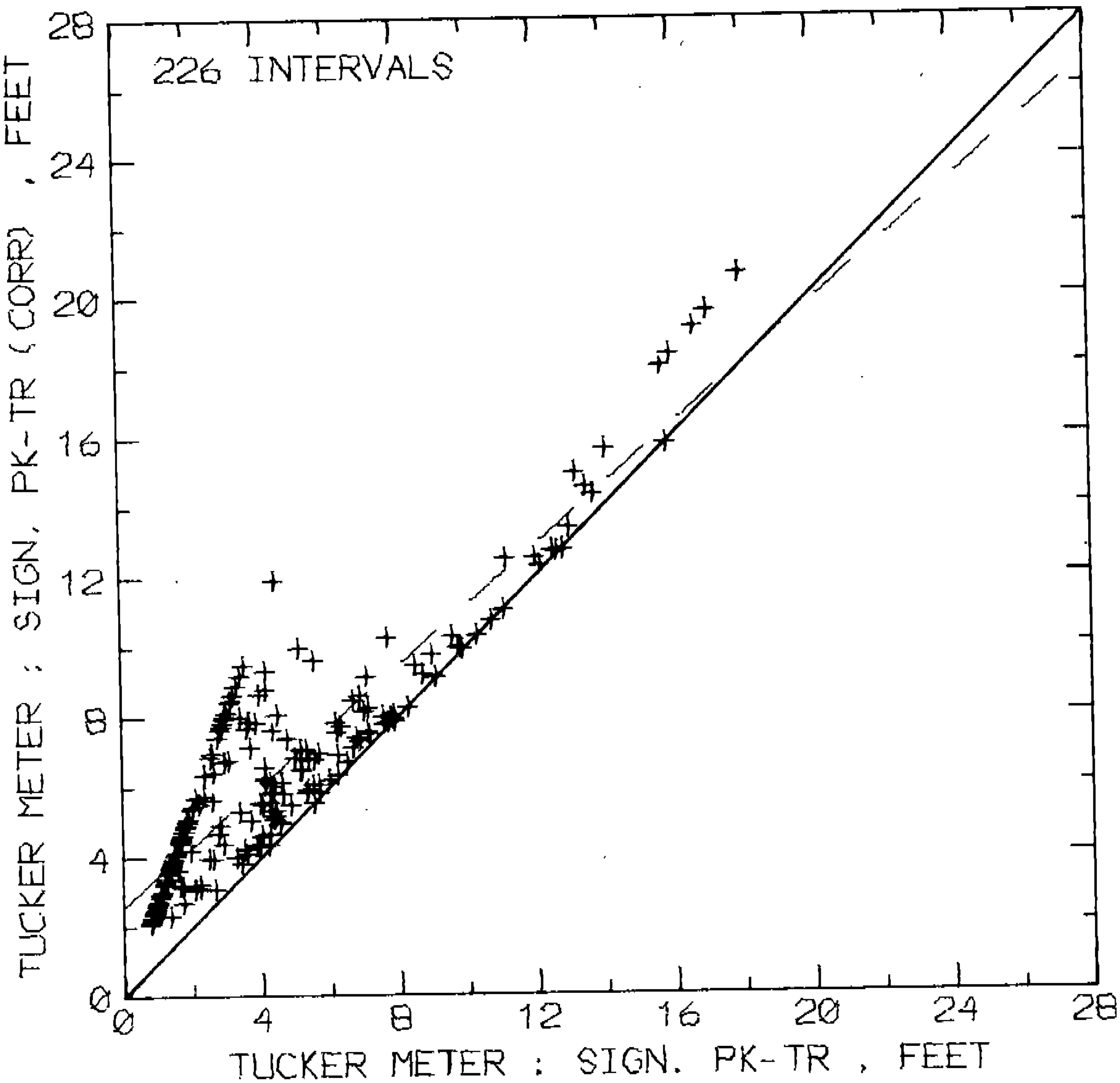

FIGURE 6 COMPARISON OF RAW AND CORRECTED SIGNIFICANT PEAK-TROUGH ESTIMATES FROM THE TUCKER METER (THE CHARACTERISTIC PERIOD APPROACH)

There is one obvious peculiarity of Figure 6. This is the compact "line" of points in the 1 to 4 foot raw wave height range. The slope of the "line" is 2.7 which is the coefficient appropriate to an encounter frequency of 1.58. What has happened is that in the computer implementation the correction coefficient was taken as 2.7 if the apparent characteristic frequency was in excess of 1.58 -- it not being considered sensible to be very serious about apparent characteristic frequencies outside the frequency range of significant raw Tucker spectral density. The result is a confirmation of remarks made in the last section that there were very often too many "waves" detected in the present Tucker data reduction process, and that the significant peak-trough heights are thus often too low.

If the lower range of raw wave height is disregarded the magnitude of the correction is seen to be relatively moderate -- in the range of 15 to 25%.

In the "spectrum" method of correction the wavemeter correction coefficient curve is assumed to be the inverse of the amplitude response of the Tucker meter. To correct the raw Tucker spectrum it is multiplied by the square of the correction coefficient curve. The resulting spectrum may be integrated and a corrected "4 rms" estimate formed from this result.

In implementing this method with the present data it was necessary to face the problem of what to do with raw spectral densities at frequencies where the correction curve is not defined. In those regions of frequency the raw Tucker spectrum was usually relatively low, in many cases probably consisting mostly of noise. According to the form of the corrections given in Figure 7 of Reference 11, an extrapolation of the correction curve above 1.6 radians/sec and below 0.25 radians/sec would involve considerable uncertainty, as well as (for any reasonable extrapulations) the multiplication of at least the high frequency spectral densities by factors between 10 and 1000. Increasing the influence of rounding and other noise by orders of magnitude is usually a distinctly bad idea. Thus the best course of action appeared to be to do nothing with spectral densities outside the defined range of the correction coefficient; that is, outside the range of definition the coefficient was taken as unity.

The "spectrum" method of correction as outlined was applied to all 226 intervals under discussion, the resulting spectra were integrated, and corrected 4 rms estimates were formed. A comparison of the corrected and raw estimates is given in Figure 7. The corrected 4 rms estimates are very consistently about 15% greater than the raw 4 rms estimates, scatter about the mean is very small, and there is no suggestion of the type of problems evidenced in the characteristic period correction approach, Figure 6. It thus appeared best to use only the corrected 4 rms Tucker estimates in subsequent comparisons.

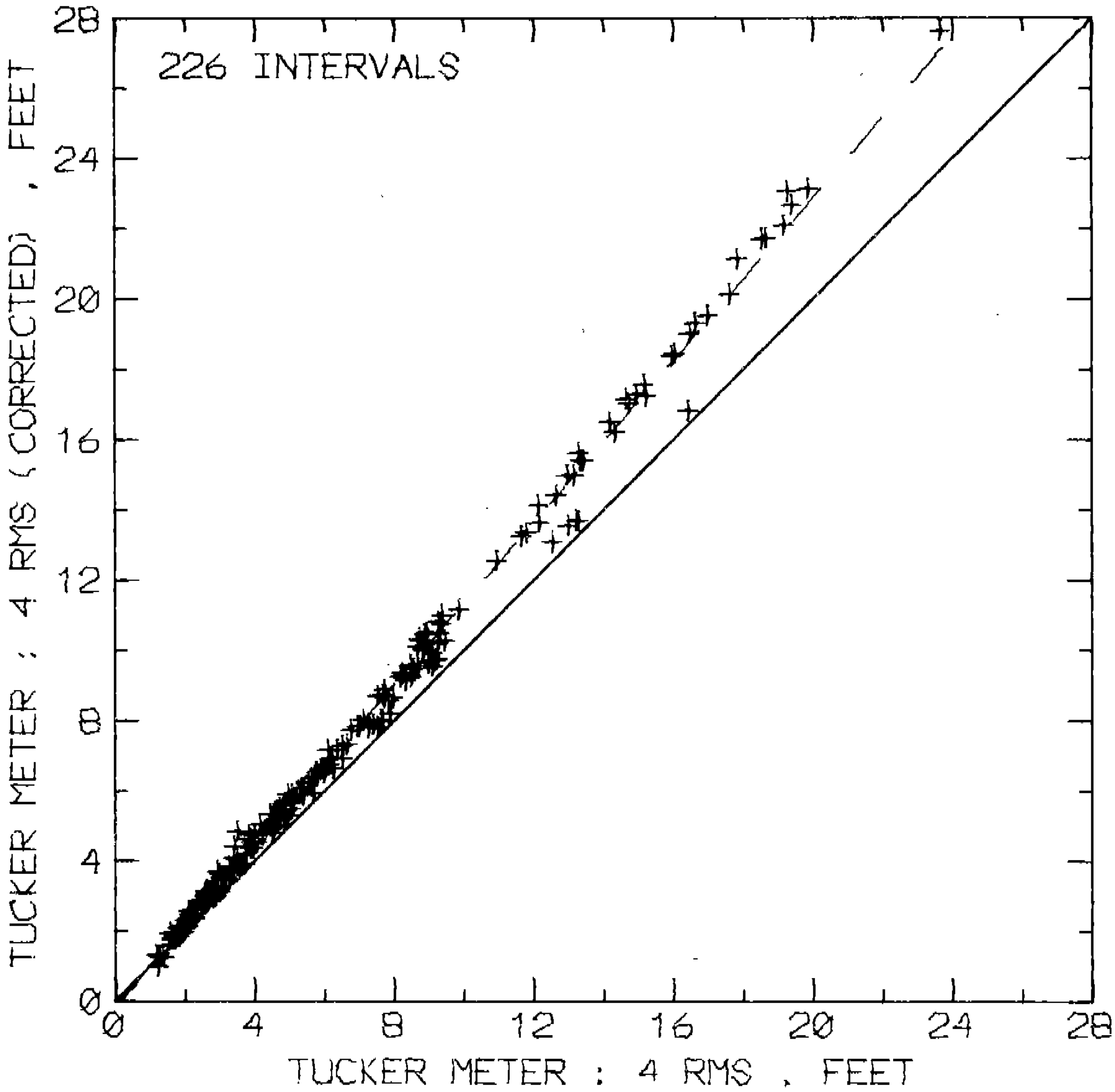

FIGURE 7 COMPARISON OF RAW AND CORRECTED 4 RMS ESTIMATES FROM THE TUCKER METER (THE SPECTRUM APPROACH)

COMPARISON OF RESULTS

OWHS Radar vs. Corrected Tucker Meter

Figure 8 indicates the comparison between the 4 rms estimates from the OWHS radar and the corrected 4 rms Tucker meter estimates. Points for all 226 intervals are shown. The scatter about the least squares line is enormous, and the line itself does not reflect the trend of the majority of points. All except 3 radar estimates are greater than the corrected Tucker meter estimates, most by very large percentage margins.

Because the correction curve for the Tucker meter does not extend to extremely low frequencies, errors for following/quartering seas would be expected. Thus it seemed fair in attempting a refinement of the correlation to exclude all intervals in which the radar spectrum area below the low frequency integrator cutoff is greater than 20% of total. As previously mentioned, this restriction has the effect of removing almost all intervals involving following/quartering seas, as well as most of those in which there is suspicion of error in the radar estimate. The result is shown in Figure 9.

Figure 9 clearly indicates that the average estimate from the radar is 3 to 4 times that from the corrected Tucker meter data. Roughly the same conclusion would result from an inspection of Figure 8, were there any reason for an arbitrary disregard of about 10% of the intervals. It appears by comparing Figures 8 and 9 that the radar and Tucker meter estimates agree only when there is reason to be suspicious about the adequacy of the radar estimate; that is, when it is somewhat doubtful that the low frequency content of the encountered wave has been correctly estimated.

In view of the large differences between the OWHS radar and the Tucker meter estimates, it was of interest to see if there is some systematic trend in the differences between the spectra. A simple approach is to form the square root of the ratio of radar and Tucker meter spectra. (The square root is just an artifice to reduce the almost certain scatter in the ratio of spectra derived from real data.) Some discretion has to be exercised in the operation because the tails of each spectrum are almost certainly strongly influenced by extraneous noise. In order to avoid the worst of the latter problem the following procedure was carried out:

1. Ten percent power bands were established for the OWHS radar, the Tucker meter, and the longitudinal stress spectra. In each case the 10% power band defines a range of encounter frequency wherein spectral densities are greater than 10% of peak. This frequency range is considered to encompass the only well resolved part of the spectrum.

2. A frequency band contained in all three 10% power bands is established from these results, excluding zero frequency if all bands include zero.

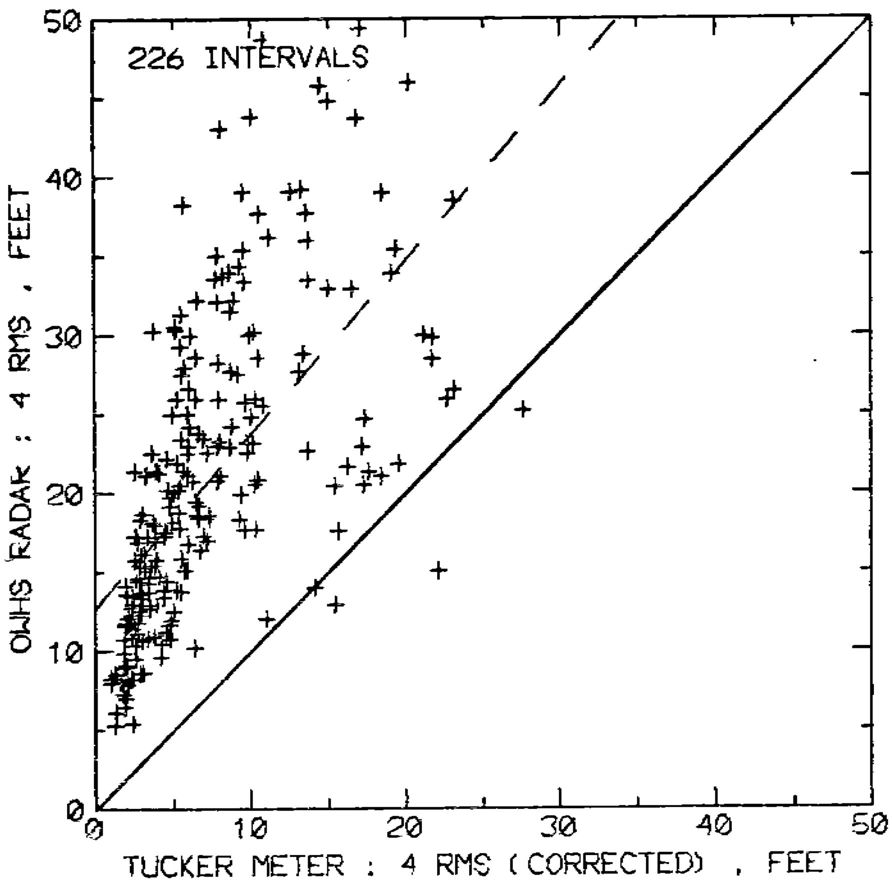

FIGURE 8 - COMPARISON OF 4 RMS ESTIMATES FROM THE OWHS RADAR WITH CORRECTED 4 RMS ESTIMATES FROM THE TUCKER METER: ALL INTERVALS

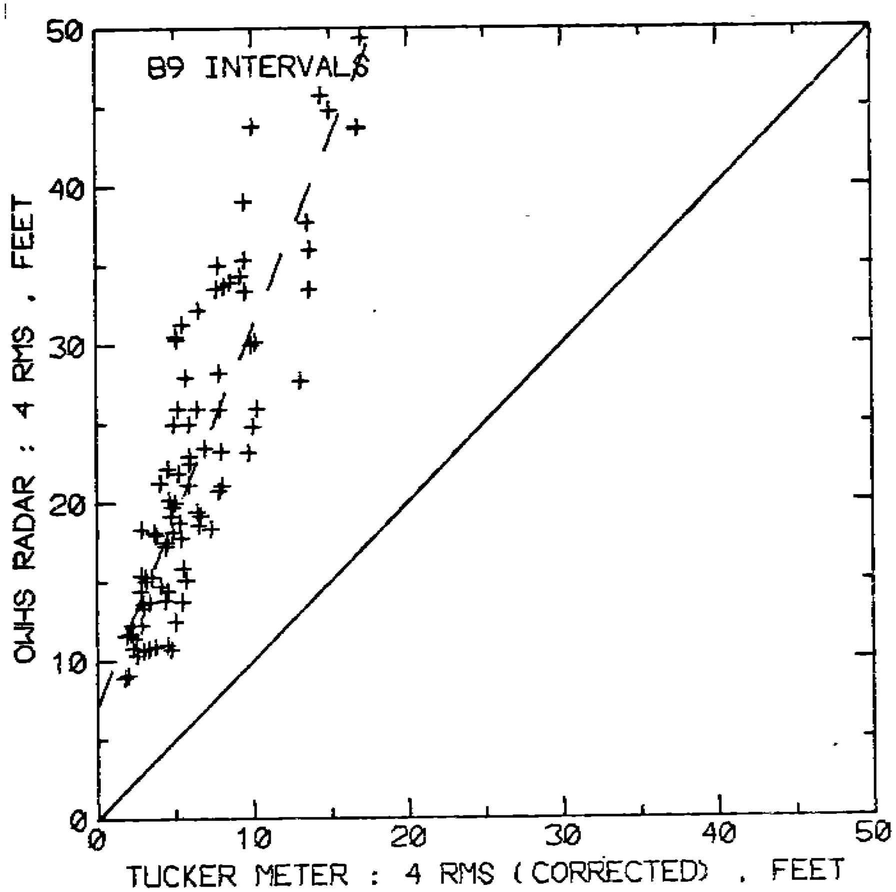

FIGURE 9 - COMPARISON OF 4 RMS ESTIMATES FROM THE OWHS RADAR WITH CORRECTED 4 RMS ESTIMATES FROM THE TUCKER METER: INTERVALS PLOTTED ARE RESTRICTED TO THOSE FOR WHICH THE RADAR SPECTRUM AREA ABOVE THE LOW FREQUENCY INTEGRATION CUTOFF IS GREATER THAN 80% OF TOTAL

3. The ratio of radar to corrected Tucker meter spectra is formed only within the band established in step 2.

In words, no spectral ratio is formed or used in comparisons unless the radar, corrected Tucker, and stress spectral densities are in excess of 10% of their respective spectral peaks. The inclusion of the stress spectrum in the procedure was for the purpose of eliminating estimates from wave spectra which were of wildly different shape than the stress spectrum in the low frequency region. Both types of wave spectra were expected to be in error at very low frequencies -- there seemed little point in forming a ratio unless there was reason to suspect that there might actually have been very low frequency wave components.

Figure 10 shows the square root of the ratio between radar and corrected Tucker spectral densities for all 226 intervals. (The radar spectrum is the numerator.) In plotting each interval straight lines were used to connect the discrete estimates which could be formed within the established frequency band for that interval.

At the right of the figure a few results are shown for frequencies in excess of 1.6 rad/sec. As the sudden jump of a factor 3 at a frequency of 1.6 indicates, the data above this frequency involves uncorrected Tucker meter data. Had the Tucker correction curves been extrapolated instead of truncated the results above 1.6 rad/sec would follow the trend of those at somewhat lower frequencies.

The typical low frequency integration cutoff varied between 0.2 and 0.5 rad/sec so that there is little reason to suspect the radar result in the frequency range between 0.5 and 1.6 rad/sec. In this region there appears to be a systematic relationship between the OWHS radar and the corrected Tucker meter spectra.

At very low frequencies the ratio scatters by an order of magnitude, a result to be expected since neither wave measuring device can be expected to be perfect in this frequency region. The most surprising feature of the figure is the number of intervals for which any ratios at all were formed at the lowest admissible frequency (0.05 rad/sec). The inclusion of the stress spectra in the procedure was supposed to prevent emphasis from being put on the low frequency region. That the strategy did not work implies that there really is a great deal of low frequency stress content in the data set, and, it may reasonably be assumed, low encounter frequency wave content.

In order to eliminate the confusion injected by questionable radar estimates and quartering/following seas, the same restrictions were applied to the spectral ratio data as were applied to the 4 rms estimates in making the transition from Figure 8 to Figure 9. (Spectral ratio data was not plotted unless the radar spectrum area above low frequency integrator cutoff was greater than 80% of total.) The results are shown in Figure 11.

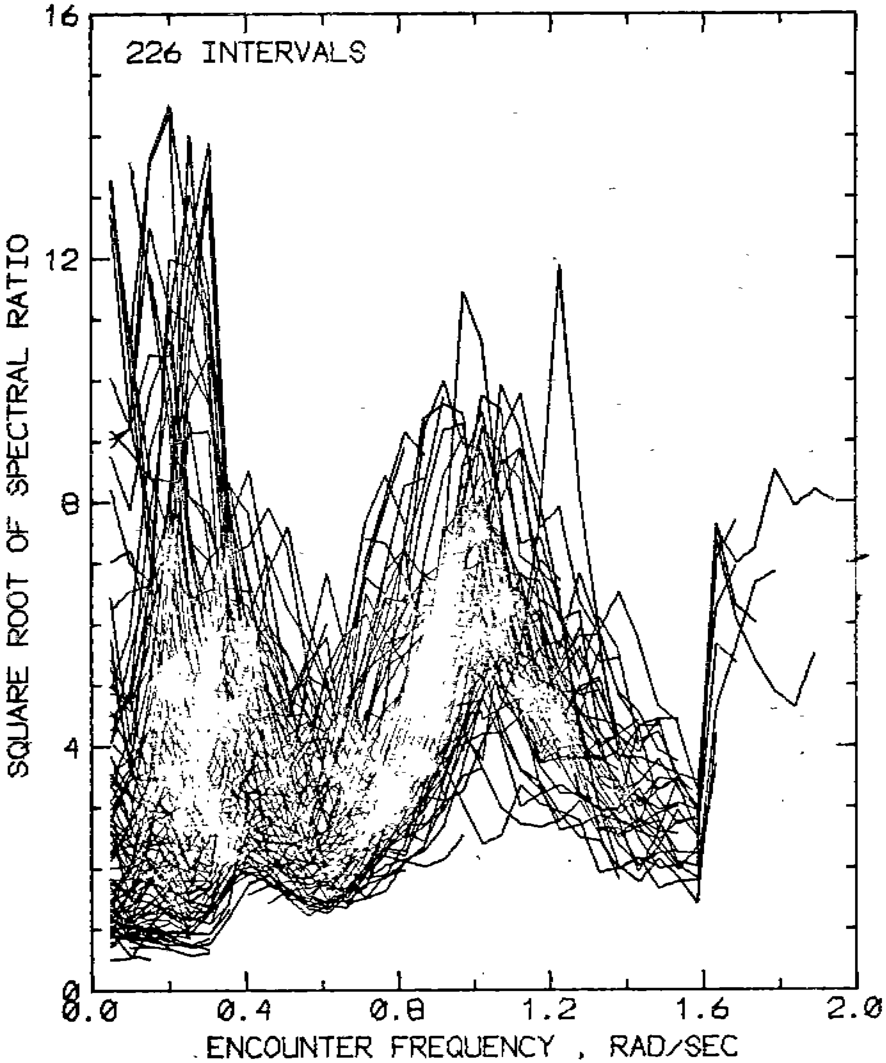

FIGURE 10 - SQUARE ROOT OF RATIO OF THE OWHS RADAR SPECTRUM AND THE CORRECTED TUCKER METER SPECTRUM (ALL INTERVALS)

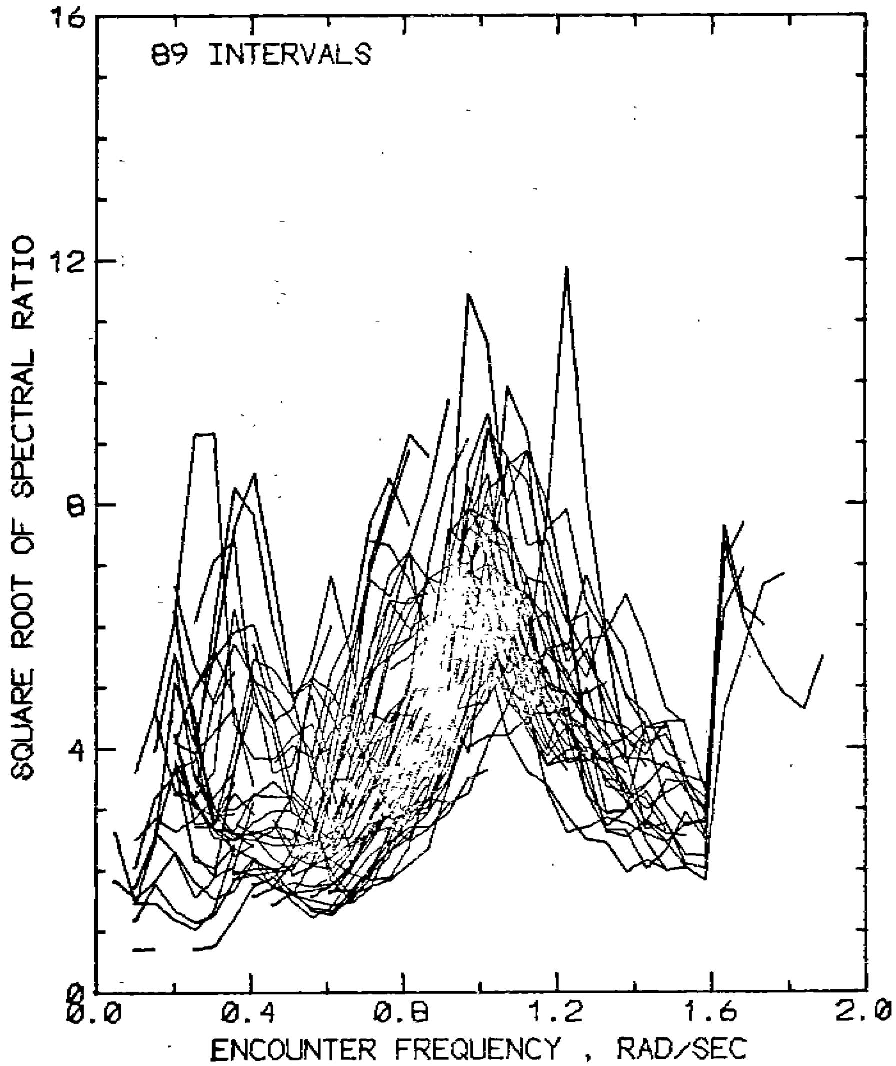

FIGURE 11 - SQUARE ROOT OF RATIO OF THE OWHS RADAR SPECTRUM AND THE CORRECTED TUCKER METER SPECTRUM (RADAR SPECTRUM AREA ABOVE LOW FREQUENCY INTEGRATOR CUTOFF GREATER THAN 80% OF TOTAL)

In the range of encounter frequency between 0.5 and 1.6 Figure 11 indicates the same trend as Figure 10. Below an encounter frequency of 0.5 there appears to be, on the average, an upward trend in the ratio as frequency decreases.

The results in Figure 11 confirm those in Figure 9. Just about any way the scatter and trend of results in Figure 11 is interpreted, regardless of frequency, there is an average factor of 3 or 4 difference between the square root of radar and corrected Tucker spectral densities, and thus between the square root of the respective spectral areas. At an encounter frequency of 1.0 rad/sec the average ratio appears to be as high as 6.

If a mean line were fitted through the data shown in Figure 11 it could be visualized as an additional wave meter correction coefficient. It is not clear at present why this fictive correction would vary with frequency as indicated in Figure 11. It is also not clear which wave measuring device it would apply to. If the radar is correct the correction would be an additional factor to the correction already applied to the Tucker meter. Alternately, if the Tucker meter is correct the radar spectrum has to be divided by the square of this fictive correction. In any event the differences between 4 rms estimates shown in Figures 8 and 9 appear to be systematic and are considered to be much too large to rationalize on the basis of random sampling errors, or upon the basis of many of the error sources previously described.

Mean Dynamic Head vs. Corrected Tucker Meter

It was noted in Reference 2 that one source of systematic error in the Tucker meter is the low frequency behavior of the double integrators installed in the system. The wave estimate called "mean dynamic head at frame 119" is the result of an attempt to correct for this behavior with the data at hand. As previously noted the estimate is quite sensitive to the adequacy of the double integration in the data reduction process. Accordingly, in comparing this estimate with the corrected Tucker meter estimates it was considered reasonable to consider only those intervals in which the dynamic head spectrum area above low frequency integrator cutoff was greater than 80% of total. The result of such a comparison is shown in Figure 12.

For corrected Tucker meter estimates above 10 feet the correction for the analog double integration inflates the 4 rms estimates by a factor between 2 and 4, for Tucker wave heights below 10 feet the mean dynamic head estimates appear to be tending toward the Tucker estimate. The result appears reasonable since very low waves probably tend to be short relative to the ship, thus the encounter frequency would be expected to be high and the ship motions small, so that errors introduced in the analog integration should also be small.

The magnitude of the differences shown in Figure 12 for high waves are very similar to those shown in Figure 9 for the radar/Tucker comparisons. Although the adequacy of the mean dynamic head estimates

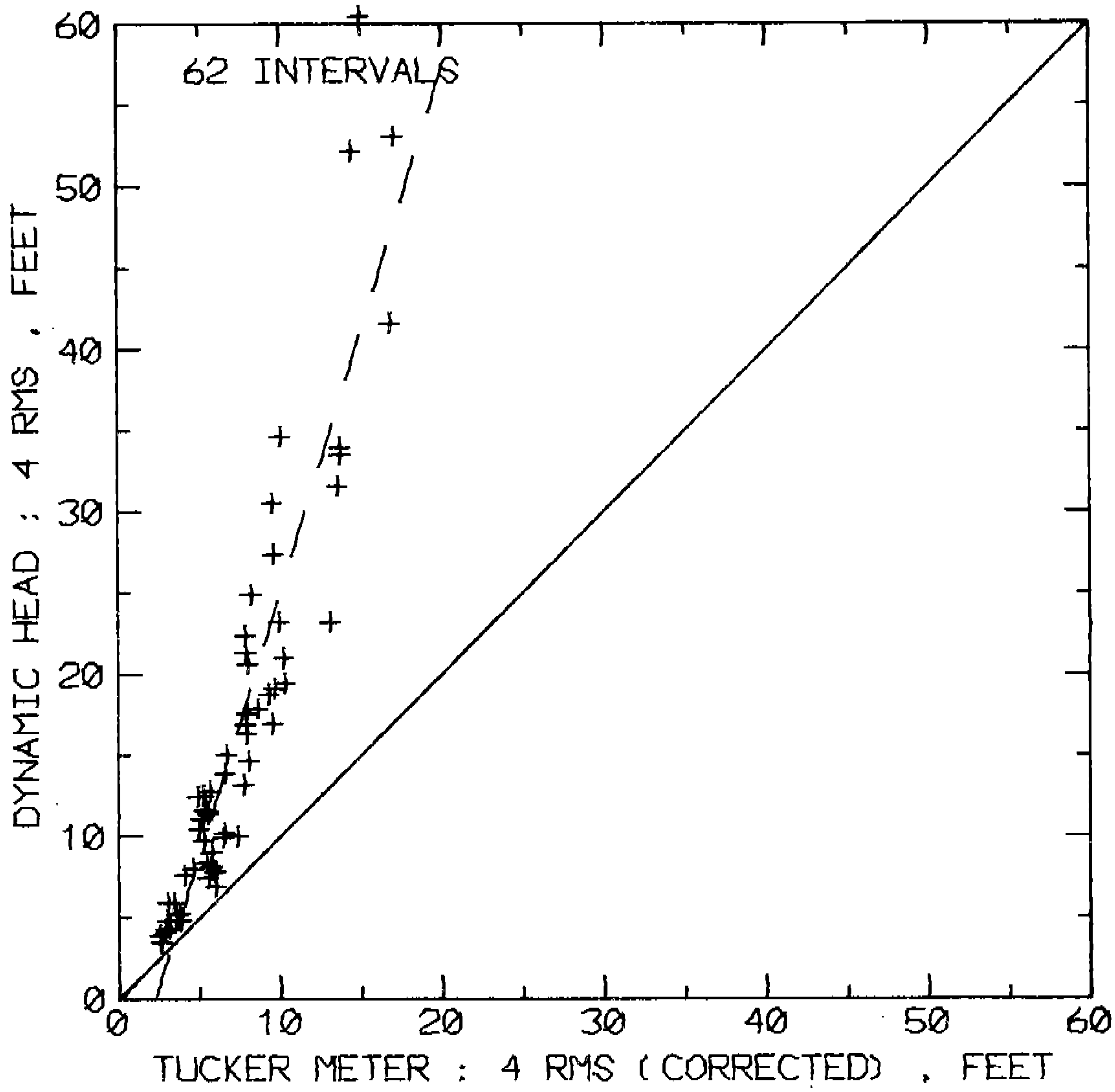

FIGURE 12 COMPARISON BETWEEN 4 RMS ESTIMATES FROM THE CORRECTED TUCKER METER DATA AND THE MEAN DYNAMIC HEAD DATA: INTERVALS PLOTTED ARE RESTRICTED TO THOSE FOR WHICH THE DYNAMIC HEAD SPECTRUM AREA ABOVE LOW FREQUENCY INTEGRATION CUTOFF IS GREATER THAN 80% OF TOTAL

as estimators of actual wave elevation is arguable, the results in Figure 12 certainly imply that quite significant errors in Tucker meter output may be attributed to the characteristics of the analog double integration.

Comparisons with Visual Estimates

The source of wave height estimates not thus far addressed in the present report is the visual observations reported in the log book. Several problems exist in dealing with and interpreting the visual observations. The most obvious is which of the two reported estimates (wave or swell) better describes the predominant wave system. In the data there is a high incidence of visual wave and swell estimates of the same magnitude which were noted as approaching the ship from the same direction. Other obvious problems relate to the credibility of the large percentage of visual estimates which were likely to have been recorded in darkness.

For present purposes it was assumed that the larger of the two visual estimates most closely resembles the 4 rms estimates being used in the comparisons. The main reason for this decision was that relatively few of the computed encounter spectra have the widely separated double peaks which would be expected for distinctly different swell and wave approaching from the same direction.

Figure 13 indicates the comparison with the visual estimates as just defined, of 4 rms estimates from the radar. All intervals are shown. As in a previous direct comparison with the Tucker meter, there is an enormous scatter. In this case however, the least square trend line seems a reasonable rendition of the majority of data. On the average the radar estimates appear 10 feet higher than the visual.

Figure 14 indicates the comparison between radar and visual estimates for the sub set of intervals used previously; that is, the intervals remaining after elimination of nearly all quartering/following sea conditions, and nearly all intervals where suspicion of error exists for the radar estimate. This elimination process also tends to eliminate many more cases having small visual wave estimates than cases having large ones.

Figure 15 is an additional comparison between radar and visual estimates. In this case the intervals plotted have been restricted to those for which ship speed was less than 20 knots.

It is evident from a comparison of Figures 13 through 15 that the elimination process has not made the problem clearer. Relative to the scatter which appears constant, there is little change in the trend line. Inspection of the numerical data failed to disclose any other promising combination of elimination parameters. In any event there are nearly no radar estimates which are less than the visual estimates so that the chances of a convincing one-to-one correlation are practically nil on the present basis.

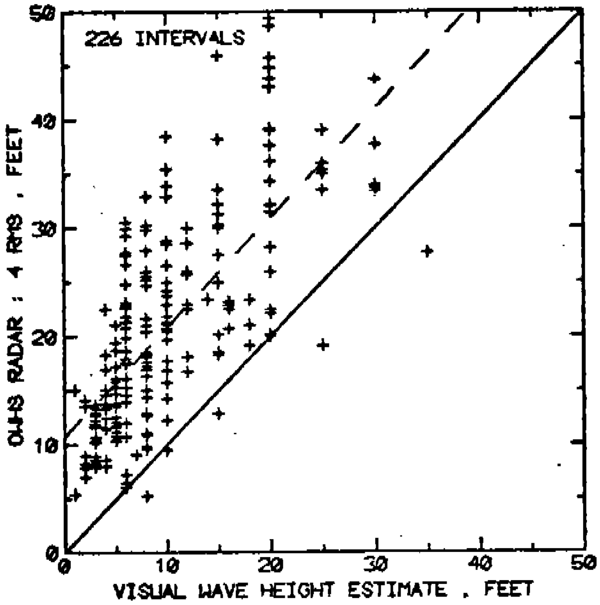

FIGURE 13 - COMPARISON OF 4 RMS ESTIMATES FROM THE OWHS RADAR WITH VISUAL OBSERVATIONS: ALL INTERVALS

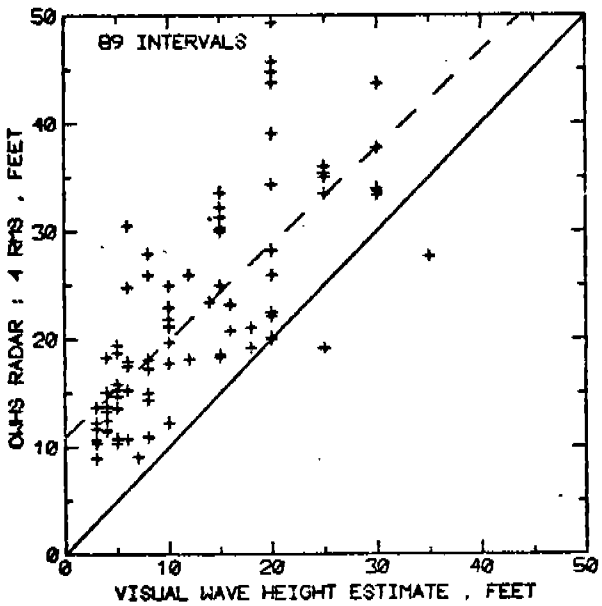

FIGURE 14 - COMPARISON OF 4 RMS ESTIMATES FROM THE OWHS RADAR WITH VISUAL OBSERVATIONS: INTERVALS PLOTTED ARE RESTRICTED TO THOSE FOR WHICH THE RADAR SPECTRUM AREA ABOVE THE LOW FREQUENCY INTEGRATION CUTOFF IS GREATER THAN 80% OF TOTAL

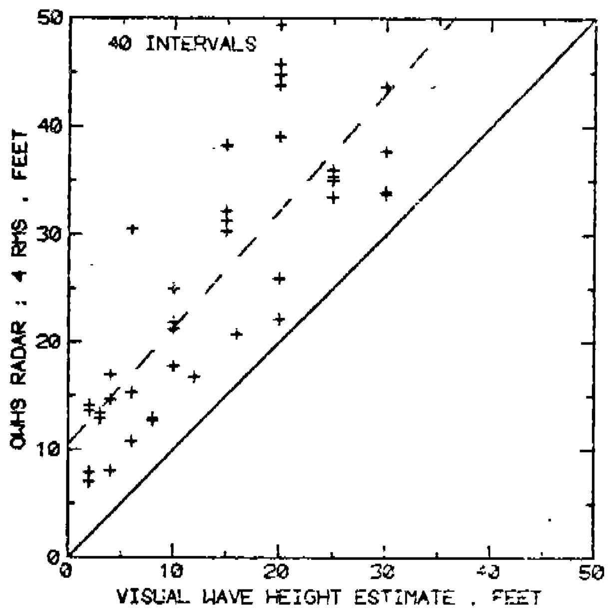

FIGURE 15 - COMPARISON OF 4 RMS ESTIMATES FROM THE OWHS RADAR WITH VISUAL OBSERVATIONS: INTERVALS PLOTTED ARE RESTRICTED TO THOSE IN WHICH SHIP SPEED WAS LESS THAN 20 KNOTS

The corrected 4 rms estimates from the Tucker meter were compared with the visual estimates for the same three data subsets as had been used for the radar data. Figure 16 indicates the comparison for all intervals. Figure 17 is the comparison after eliminating nearly all quartering/following sea cases and intervals in which the radar estimate could be questioned. Figure 18 involves all intervals where ship speed was less than 20 knots.

A comparison of Figures 16 through 18, indicates that the elimination of quartering/following seas does make a change in the correlation. For waves visually estimated as being between 5 and 12 feet a quite large scatter of results is evident in Figure 16. This scatter is much reduced in Figures 17 and 18. Inspection of the numerical data disclosed that the majority of points above the diagonal (one-to-one) line in Figure 16 were from intervals involving both high speed and quartering seas. When intervals involving either or both parameters are eliminated the average corrected Tucker estimate might be said to average about half the visual estimate, at least for visual estimates in excess of about 5 feet.

For the same reasons as described in conjunction with the comparison of mean dynamic head estimates and Tucker meter estimates, Figure 12, a comparison of 4 rms mean dynamic head estimates with visual observations, was made only for intervals in which the dynamic head spectrum area above low frequency integrator cutoff was greater than 80% of totel. This choice also tends to eliminate quartering/following sea cases, intervals in which the double integration is questionable, and many more cases of low visual wave estimates than high ones. The result is shown in Figure 19.

As may be noted in the figure, this is the only case thus far exhibited in which any of the wave height estimates correlates well on the average with any other.

There are three exceedingly wild points in the figure, all indicating a 4 rms dynamic head in excess of 50 feet. Those three points and the two directly below at a 20 foot visual wave estimate all come from Voyage 35E (Ref.6, pp 38-46), all were recorded in the same 16 hour period of time in roughly beam seas, all involve significant out-to-out rolls between 19 and 33 degrees, and in this sequence of intervals the 4 rms dynamic head increases with roll. These intervals may be candidates for disqualification on the basis of improper compensation for roll, a subject covered earlier in the report. The attribute which kept these intervals in the data set was that the stress and wave time histories looked sufficiently alike.

However, whether the wild points are eliminated or not makes little difference to the question of why half a correction to the Tucker meter (the mean dynamic head) looks any good at all relative to visual estimates. For the more severe of the conditions analyzed the mean dynamic head is not much different than the vertical displacement of the ship in way of the engine spaces.

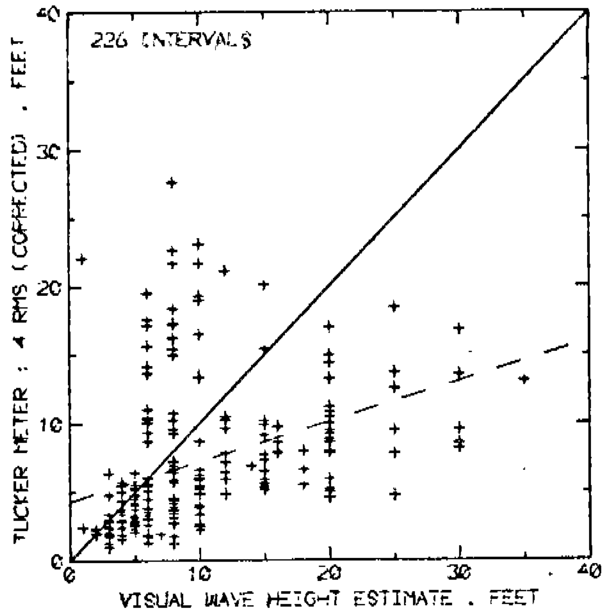

FIGURE 16 - COMPARISON OF CORRECTED 4 RMS ESTIMATES FROM THE TUCKER METER WITH VISUAL OBSERVATIONS: ALL INTERVALS

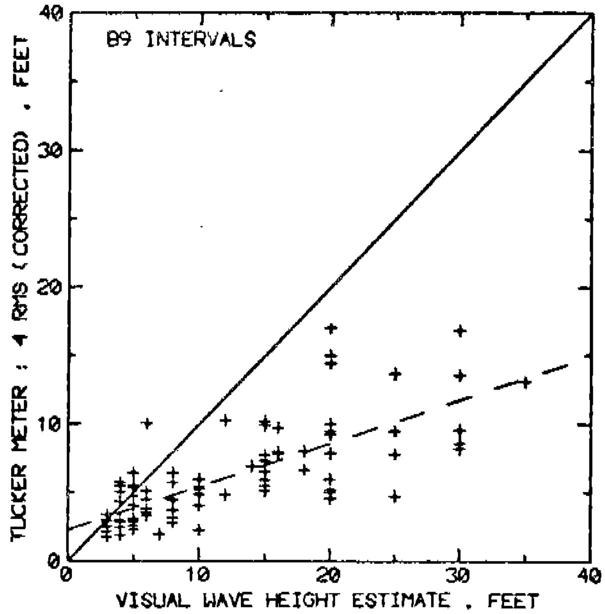

FIGURE 17 - COMPARISON OF CORRECTED 4 RMS ESTIMATES FROM THE TUCKER METER WITH VISUAL OBSERVATIONS: SAME SUBSET OF INTERVALS AS IN FIGURE 14

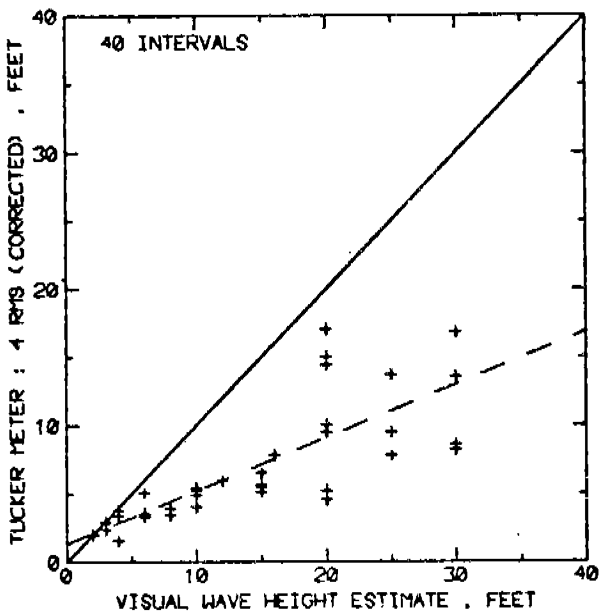

FIGURE 18 - COMPARISON OF CORRECTED 4 RMS ESTIMATES FROM THE TUCKER METER WITH VISUAL OBSERVATIONS: INTERVALS PLOTTED ARE RESTRICTED TO THOSE IN WHICH SHIP SPEED WAS LESS THAN 20 KNOTS

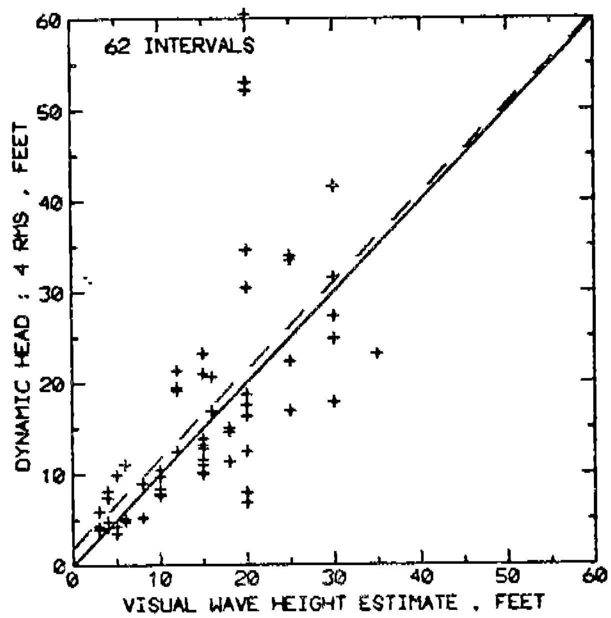

FIGURE 19 - COMPARISON OF 4 RMS MEAN DYNAMIC HEAD ESTIMATES WITH VISUAL OBSERVATIONS: INTERVALS PLOTTED ARE RESTRICTED TO THOSE FOR WHICH THE DYNAMIC HEAD SPECTRUM AREA ABOVE LOW FREQUENCY INTEGRATOR CUTOFF IS GREATER THAN 80% OF TOTAL

It is apparent from the preceding section that the two primary wave measurement systems of the present project correlate poorly with each other and with visual observation. It was thus of interest to correlate the results of each system against a different standard. One approach, (which had the advantage of convenience in the present case) is to derive apparent stress response operators and compare these results against independent data.

What is meant by apparent stress response is simply the square root of the ratio of stress to wave spectrum. If the waves are long crested and are approaching the ship from forward of the beam, the apparent stress response operator is conceptually the same as the amplitude response (stress amplitude/unit wave amplitude) which would be derived from theory or model test. In the case of the present data, the above conditions can be expected to almost never hold. In fact even if they had occurred, the data in hand is not sufficient to determine "when." The complications introduced by short crestedness and by the full range of ship-wave headings are discussed in Reference 2. In short crested seas it would be generally expected that the apparent response at a particular encounter frequency will be lower than in the long crested case due to the averaging of response over heading. Were it not for the fact that the wave spectral estimates from radar and Tucker meter are very far apart, an attempt at correlating apparent stress response operators with independent data would not be expected to shed much light on the adequacy of the wave measurements.

It was elected to use the model test data presented in Reference 15 as the "independent data" of the present exercise. The model tests described in that reference involved a small model of the SL-7 class ship which was run at two displacements, various speeds, and several headings to regular waves. The data chosen for the present work was that obtained at the "heavy" displacement, this condition corresponding to the majority of voyage legs in the present data set. The data of interest to the present work was the midship longitudinal bending moment amplitude response per unit wave amplitude.

All the moment amplitude response data from Reference 15 was converted to a form compatible with present data by use of the midship deck section modulus given in Reference 12 (1.745×10^6 in^3). The result is a computed regular wave midship deck stress response having units of (kpsi/foot). The data in Reference 15 were given as functions of wavelength to ship length ratio which, for a given ship speed and heading, determines an encounter frequency. The converted regular wave model test data are shown plotted on encounter frequency in Figure 20 for two ship speeds, 25 and 30 knots.

Figure 20 involves data for six headings -- head through following seas with the omission of beam seas. The angle convention indicated in the figure is the practical convention utilized in the log book descriptions of the present full scale data rather than the towing tank/

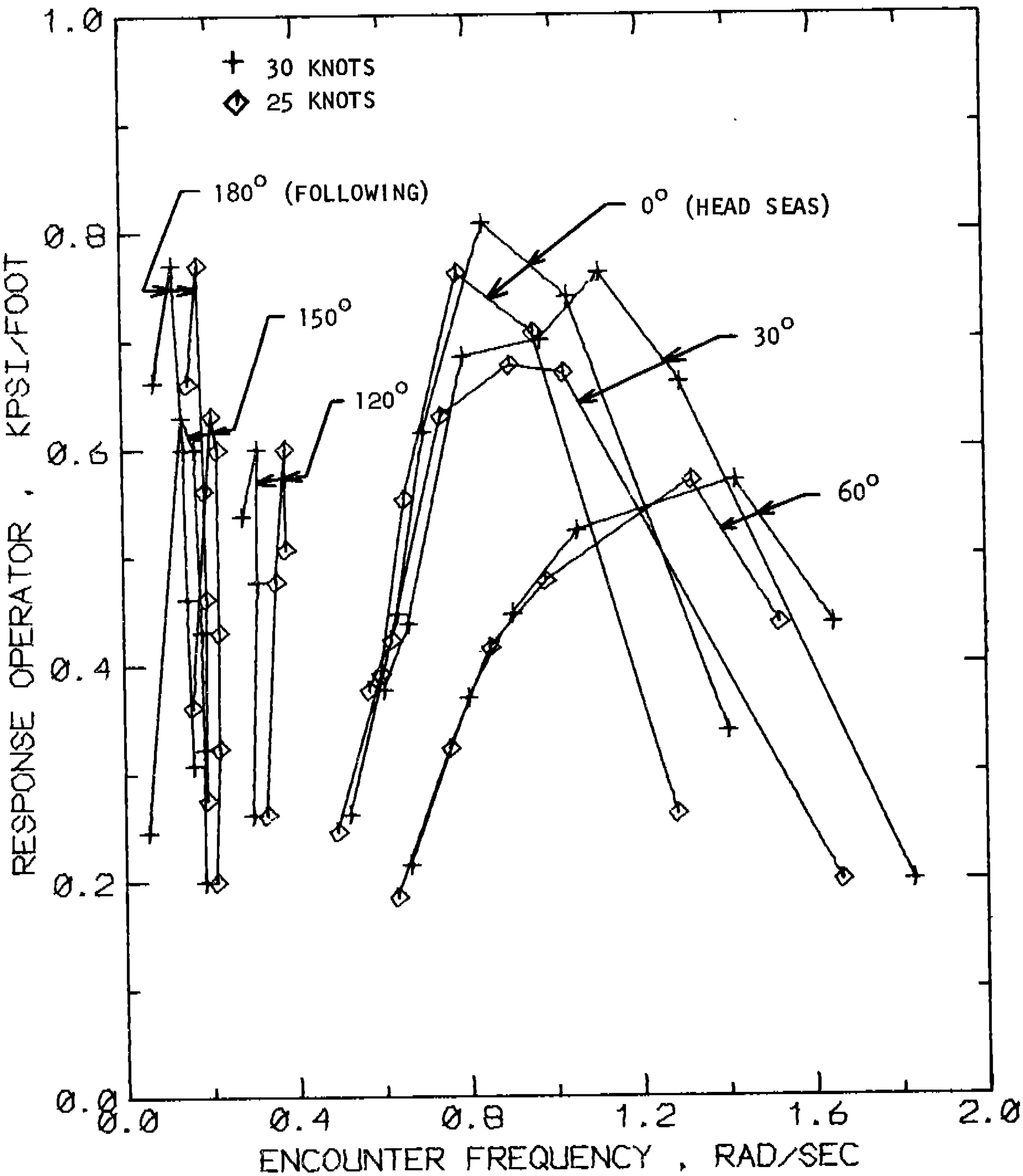

FIGURE 20 MIDSHIP LONGITUDINAL STRESS RESPONSE FROM MODEL TEST DATA; "HEAVY" DISPLACEMENT, REF. 15

theoretic convention employed in Reference 15. From previous experimental work it would be expected that beam sea stress response would fill in the "hole" around 0.4 rad/sec, peaking at about half the peak head or following sea response somewhere within the frequency range 0.35 to 0.7 radians/sec. It may be noted that much of the following/quartering sea data is multiple valued as a consequence of the frequency transformation.

In forming the apparent stress response operator from the spectra estimated in the present work, much the same approach was followed as was used in producing Figures 10 and 11. No ratio of stress spectral density to wave spectral density was formed or considered in the analysis unless both the stress and wave spectral densities were in excess of 10% of their respective peaks.

Figure 21 indicates for all intervals the apparent stress response operator derived by taking the square root of the ratio of stress to OWHS radar wave spectra. For each interval the ratios are a set of discrete points spaced at roughly 0.05 radians/sec on the frequency axis. In plotting, straight lines were drawn between these points. In the figure an approximate upper envelope to the model test data is indicated so as to make comparisons with Figure 20 more convenient. Considering the variety of operating conditions and the probable statistical variability of the spectra, the degree of collapse of all the data is considered very good.

Noting that the model test data is given only for 25 and 30 knot speeds, and, as before, that errors are expected for low frequency in many of the radar estimates, the apparent stress response operators were plotted for a restricted set of intervals. The restrictions applied were that the ship speed be in excess of 20 knots, and that radar spectrum area above low frequency integrator cutoff be greater than 80% of total. The results are shown in Figure 22. As in the restrictive comparisons previously shown, the effect of the second of these restrictions is to remove much of the following/quartering sea data and a relatively great number of nominally mild wave conditions. In contrast, the first restriction effectively removes all of the most severe sea conditions. However, a comparison of Figures 21 and 22 discloses no great contrasts in the average trends of the apparent stress response operators.

With a relatively minor exception the same procedure was applied so as to estimate and plot apparent stress response operators derived from the stress and corrected Tucker meter spectra. The results are shown in Figures 23 and 24. Figure 23 corresponds to Figure 21 in that results for all intervals are plotted. Figure 24 is the result of applying restrictions similar to those employed for Figure 22. The difference is that intervals were rejected on the basis of relative low frequency stress content, rather than the low frequency radar wave content. The consitution of the resulting sample is much the same as that utilized for Figure 22. As with the radar results in Figures 21 and 22, there is visible in Figure 24 no great change of average trend relative to the results in Figure 23. Collapse of apparent response data based on the corrected Tucker meter is at least as good as that shown for the radar

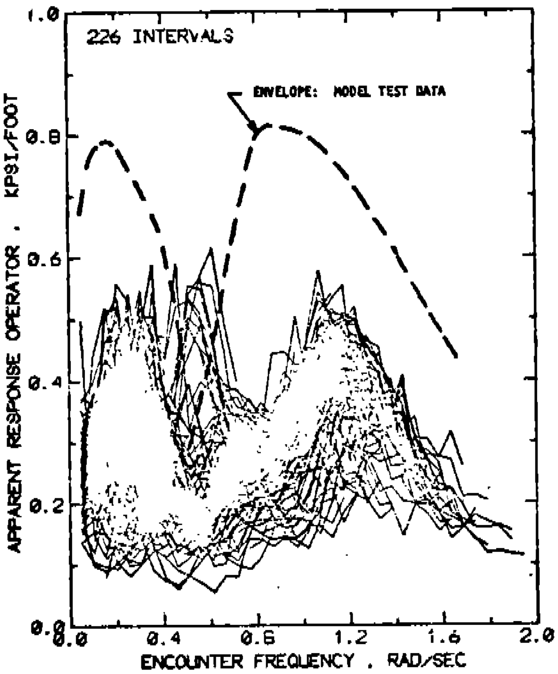

FIGURE 21 - APPARENT STRESS RESPONSE OPERATOR BASED UPON OWHS RADAR WAVE SPECTRUM: ALL INTERVALS

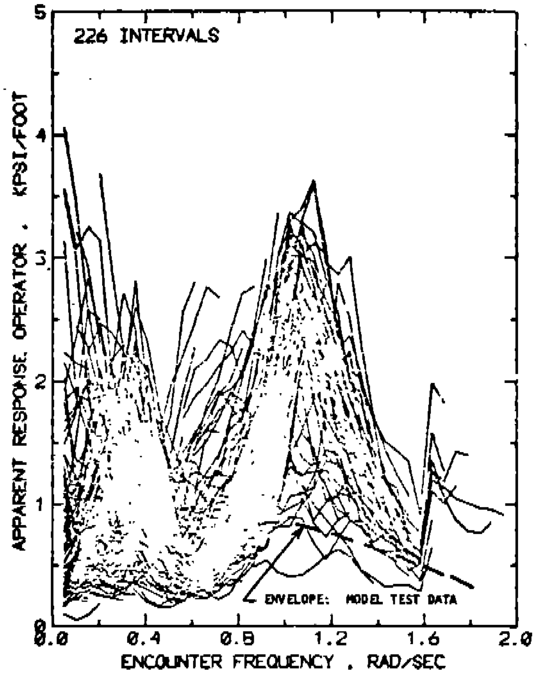

FIGURE 23 - APPARENT STRESS RESPONSE OPERATOR BASED UPON CORRECTED TUCKER METER SPECTRUM: ALL INTERVALS

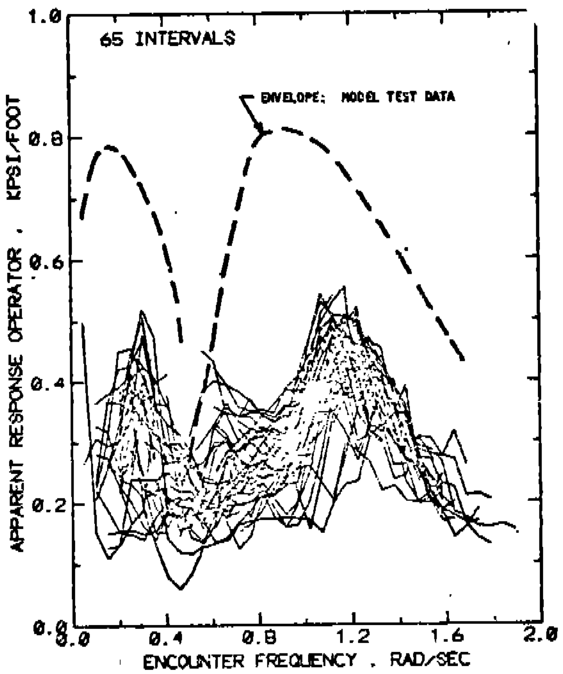

FIGURE 22 - APPARENT STRESS RESPONSE OPERATOR BASED UPON OWHS RADAR WAVE SPECTRUM: INTERVALS SHOWN ARE RESTRICTED TO THOSE IN WHICH SHIP SPEED IS GREATER THAN 20 KNOTS, AND IN WHICH RADAR SPECTRUM AREA ABOVE LOW FREQUENCY INTEGRATOR CUTOFF IS GREATER THAN 80% OF TOTAL

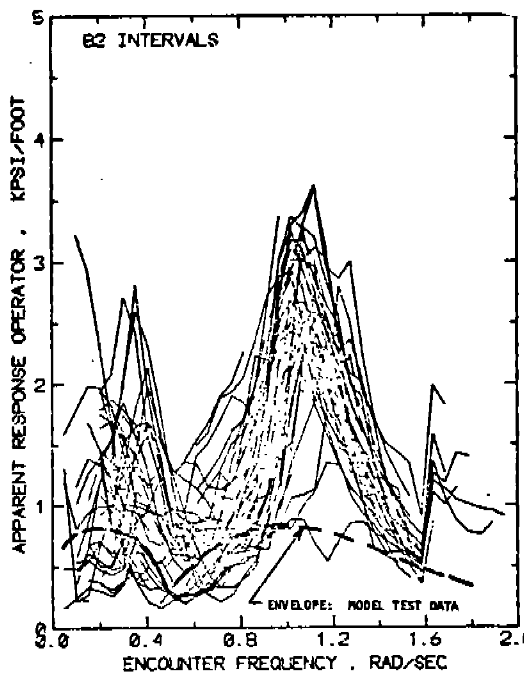

FIGURE 24 - APPARENT STRESS RESPONSE OPERATOR BASED UPON CORRECTED TUCKER METER SPECTRUM: INTERVALS SHOWN ARE RESTRICTED TO THOSE IN WHICH SHIP SPEED IS GREATER THAN 20 KNOTS, AND IN WHICH STRESS SPECTRUM AREA ABOVE LOW FREQUENCY INTEGRATOR CUTOFF IS GREATER THAN 80% OF TOTAL

based results for frequencies in excess of 0.5 rad/sec, but is less good below this frequency.

Qualitatively, the trend in the average apparent stress response operator is the same whether the basis is the OWHS radar or the corrected Tucker meter. At high frequencies there is a hump roughly corresponding to that of the head and bow sea regular wave data, Figure 20. There appears a "hole" between 0.4 and 0.6 rad/sec as would be predicted by the regular wave data, and another hump at lower frequencies which corresponds to the following/quartering regular wave data.

As must be expected from previous comparisons between radar and Tucker results, there is a very large quantitative difference in the responses derived from the two sets of wave spectrum estimates, and there was no reasonable way of plotting both sets of results to the same scale. The upper envelope to the model test data is significantly lower than most of the Tucker based results and significantly higher than the radar based results.

In further discussion of these results it should be first remarked that there is no guarantee that the model test results are correct. The magnitude of the model moment results has been confirmed experimentally by comparison with other experimental results for models of comparable proportions and speed. The model results have also been confirmed by independent theory -- to within ± 20% for the most part. In converting the model moment results to deck stress response, simple beam theory has been assumed. The model test results as a "standard" are thus not unimpeachable. On the other hand, quite a number of independent efforts have to contain large systematic errors if the model results shown are incorrect by more than ± 30% or so.

Considering the radar based results, Figures 21 and 22, the apparent response lies below the upper envelope of the model test results by 50%. Considering the probable effects of short crestedness on the apparent response and possible errors in the model tests, the radar wave spectral estimates could be anything between correct and about a factor of four too high (apparent response between correct and factor of two too low).

With respect to the Tucker based results, Figures 23 and 24, the same considerations indicate either that the corrected Tucker wave spectra are between a factor of 4 and 10 too low (apparent response between factors of two and three too high), or: that the model test results (and current theory) are low by a factor of about three.

On the whole, this evidence suggests that the OWHS radar wave spectra are closer to the mark.

CONCLUSIONS

The wave instrumentation included in the SL-7 program included a new system (the OWHS radar) and an old system (the Tucker meter). The basic minimum objective of the present project was to produce estimates of encountered wave variance or rms from the data produced by each system, and most of the work necessary in the present project was in support of this objective. Beyond this, the final objectives of the present program involved comparisons of results from the two wave measuring systems and the resolution of differences where possible. This latter objective has been addressed in the present report, and is the primary subject of the conclusions to follow.

1. The evidence strongly suggests that neither of the wave measuring systems can be regarded as a standard by which the performance of the other may be judged.

2. In the present application to a large, high speed ship, it appears that quite significant errors in the Tucker meter output may be attributed to the characteristics of the analog double integration of acceleration. Improvements to this part of the system seem feasible within present technology. If the radar estimates happen to be closer to reality than the Tucker estimates, the existing corrections to the Tucker meter output for the attenuation of dynamic pressure with depth and for interference with the waves by the ship are considerably in error. If this is true there appears no alternative to full scale calibration trials for the calibration of the system.

3. There appear to be a number of deficiencies in the installed OWHS radar system. Some of these produce errors of a magnitude which is impossible to assess because some significant pieces of information are missing. One of these deficiences had the effect of reducing the apparent reliability of the radar system to quite low levels during the periods of most interest (severe wave conditions). However it appears that all of the problems perceived in the system may be significantly reduced by less than heroic measures.

4. The source of error common to both systems has to do with the problems of double integration of low-frequency acceleration data. In the present application the speed of the ship and the prevailing weather together tend to produce encountered wave components of extremely low frequency as much as half the time. These components are lost in the Tucker analog integration and not always successfully handled by the data reduction system employed for the radar data.

5. There is a wide, systematic difference between the rms encountered waves (and the wave spectra) as measured by the radar and by the Tucker systems.

6. Estimates of significant wave height from neither system correlate particularly well with visual estimates. Relative to visual estimates the radar results are too high and the Tucker meter estimates are too low.

7. An indirect comparison of the wave spectra estimated by the two systems was made by deriving apparent midship stress response operators, and comparing these results with model test data for the SL-7 class ship. These comparisons suggest that the radar wave estimates are too high and the Tucker estimates too low. Quantitatively however, if the Tucker meter wave estimates are correct, both the model test data as well as contemporary theory for wave induced bending moments have to be in error by a factor of about three. If it can be agreed that contemporary theory and model test techniques are better than this, the evidence suggests that the radar system, despite its known deficiencies, is closer to reality.

RECOMMENDATIONS

The present recommendations involve only the question of what might be done to improve results obtained with the systems which have been discussed -- under the assumption that installation of these systems is contemplated in the same, or another, large high speed ship. Implicit in this assumption is that the overall theoretical limitation of either system is accepted. This overall limitation is that under the most ideal conditions only the encountered scalar spectrum of wave elevation can be produced.

Although the evidence is by no means conclusive, the present investigator's opinion is that the Tucker meter is not a good choice for installation in a ship of the size and speed of the SL-7 class. However should such an installation be required, it would be recommended that the double integration and computing circuits of this system be re-worked. The frequency where serious phase and amplitude distortion occurs in the double integration should be much lower than it was in the present full scale program. It may be that the most practical approach would be to record both pressure and acceleration, and carry out an after-the-fact data reduction procedure similar to that employed for the radar. With or without a re-working of the electronics, there appears no real alternative to the full scale calibration approach to the ship-wave interference effects upon the pressure head. Such trials would be recommended for any installation in large, high speed ships.

As noted in the conclusions, the radar system installed in the present program appears to have had a number of deficiencies. Despite these, the opinion of the investigator is that the radar based system should be preferred for installation in large high speed ships. A check of results against a believable standard would still be required.

In the sense used here the "radar system" includes more than just the radar unit itself. The various motion transducers and the data reduction procedure must be considered as part of the system as well. The perceived deficiencies appear to be largely curable. They may be considered under three main headings as follows:

1. The Radar Unit

Questions about the internal behavior and physics of the radar unit (how it could be bettered as a radar; if when a valid return is sensed is the indicated range correct; the nature of the physical circumstances under which return signal is lost, etc.) are all items which are beyond both the scope of the present project and the competence of the investigator. All the perceived deficiencies with the unit appear consistent with the output logic employed to deal with occasional return signal loss. Because it is necessary to know the length of the slant range vector when computing its vertical component, the output logic of the unit should be changed so that this information is not lost during a voyage -- irrespective of any return signal losses. This change would require a different approach to the return signal loss problem. The approach recommended is to hold the last valid range in the output register until the next valid range is acquired. It is suspected from the data in hand that the lapse of time between signal loss and re-acquisition is ordinarily relatively short. The effect on the data of the above recommendation would be to produce "notches" or flats in the time history. Small notches would introduce mostly high frequency noise which is far preferable in data reduction to the ultra low frequency noise injected by the logic of the present unit. Large "notches" or flats of long persistence would be relatively easy to see visually, or to detect by computer.

2. Angles

To a fair degree of approximation the angle transducers of the pendulum type used in the present program are equivalent to body fixed lateral accelerometers. They are sensitive to both rotation and acceleration. The basic recommendation is this area is to measure angles properly -- either implicitly or explicitly. In the context of the radar system this might be accomplished in two ways. One option is to mount a vertical accelerometer on the antenna and gyrostabilize both. In this case the accelerometer output would be correct with respect to true vertical and the slant range would be related to its vertical component by a constant factor. The second option would be to mount a gyrostabilized vertical accelerometer in the radar pedestal. In this case the accelerometer output would also be correct with respect to true vertical, and it would appear feasible within current state of electronic and microprocessor technology to make a continuous three dimensional vector correction to the slant range using the indicated angles from the gyro. It is felt that over and beyond the technical improvement, the resources expended in improving and automating the angle corrections could well be repaid in reduced costs of data handling and processing due to the fewer channels which would then be involved.

3. Accelerations and Double Integration

In the final analysis, the phaseless double integration scheme employed in the present data reduction was not sufficiently sophisticated. It was unable to handle ultra low frequencies as well as could be desired. However the basic problem was that the extraordinarily good acceleration resolution required in some situations was not present in the data. According to the results, it appears that if the same scheme was to be used over again, the acceleration signal out of the recording medium should have a resolution approaching ± 0.002 g. With analog magnetic tape as the recording medium this resolution might be approached in those cases where it is most needed (mild following or quartering seas) by the use of automatic gain control and the elimination of the one "g" signal bias included in the present vertical acceleration data. It should also be noted that the accelerometers used in the present application were probably not capable of this small a resolution.

While better acceleration resolution would go a long way toward improving the estimation of the vertical displacement of the radar unit, it should be emphasized that any scheme involving dis-continuous data samples has a low frequency limit below which a proper job cannot be done. Perhaps there is a practical continuous double integration scheme which does not produce phase shifts. However, the present investigator's recommendation would be to defer an extraordinary amount of effort on this problem and to accept possible errors in quartering and following seas until such time as any second generation radar system can be fully accepted in the head and bow sea situation.

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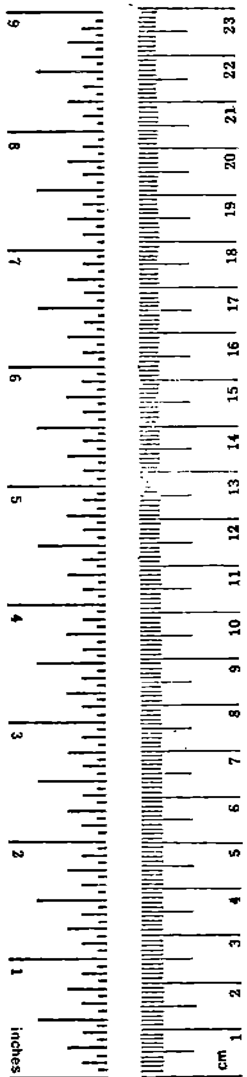
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

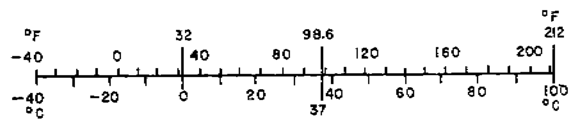
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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So that more precise correlations between full scale observations and analytical and model results could be carried out, one of the objectives of the instrumentation program for the SL-7 class container ships was the provision of instrumental measures of the wave environment. To this end, two wave meter systems were installed on the S.S. SEA-LAND McLEAN. Raw data was collected from both systems during the second (1973-1974) and third (1974-1975) winter data collecting seasons.

It was the purpose of the present work to reduce this raw data, to develop and implement such corrections as were found necessary and feasible, and to correlate and evaluate the final results from the two wave meters. In carrying out this work it was necessary to at least partly reduce several other channels of recorded data, so that, as a by-product, reduced results were also obtained for midship bending stresses, roll, pitch, and two components of acceleration on the ship's bridge.

As the work progressed it became evident that the volume of documentation required would grow beyond the usual dimensions of a single technical report. For this reason the analyses, the methods, the detailed results, discussions, and conclusions are contained in a series of ten related reports.

This report, contains the last phases of the work, specifically, the discussion of results, the correlation and evaluations of final results from both wave meters, the conclusions, and the recommendations.

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