I.O.S.

CALIBRATION OF WAVERIDER SYSTEMS BY THE INSTITUTE OF OCEANOGRAPHIC SCIENCES TAUNTON

J D HUMPHERY

REPORT NO 133
1982

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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INTRODUCTION

Waveriders* have been used since 1973, and have been the cornerstone of our wave climate programme. The importance of the data obtained from them is such that not only is high accuracy vital but the achievement of that high accuracy must be demonstrated. There are two main facets to this problem, viz to check the calibration of the sensor/recorder system, and to check that all system components (including analysis procedures) are operating correctly during data-gathering and analysis. This report is concerned with the calibration aspect.

All buoys are calibrated before use but the method has been refined over the years. Buoys are now calibrated both before and after an ocean deployment and a check is maintained on the sensitivities of the receiving system and data logger.

Until recently all the wave measurement buoys have been Waveriders manufactured by Datawell. In early installations, Datawell Warep* telemetry receivers were used; however the system now used employs Marconi Eddystone radio receivers coupled to demodulators designed by IOS. Until recently these receivers demodulated the FM tone transmitted by the Waverider into an analogue voltage which was recorded digitally. The latest receivers miltiply the frequency of the AF sub.carrier. The frequency of the resulting tone is counted and logged each half-second; this method removes the dependence on frequency-voltage and analogue to digital conversion. (A back-up system for logging the analogue output voltage onto FM cassettes is also built into each receiver.) More details of the receiving system are given later.

From the results of the many tests and calibrations which are reported below, it is estimated that an overall accuracy of ± 2% is being achieved when measuring buoy motion. We have no means of checking that the buoys follow the water surface accurately. However, neither do we have any evidence of buoy submergence, except in one installation where the tidal currents were particularly strong.

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*Waverider and Warep are the registered trade marks of Datawell, Haarlem, Netherlands

CALIBRATIONS: General Principles

Waverider buoys measure vertical acceleration, integrate the acceleration signal twice to give displacement, and then transmit this wave height information by means of HF radio signals, usually in the 27 MHz band. The RF signals are frequency modulated by an AF tone of mean frequency 259 Hz. The nominal frequency deviation of this tone is 1.86 Hz per metre of vertical buoy displacement. The radio receiver and demodulator present the deviation from 259 Hz as a deflection on a chart recorder, as an analogue voltage varying about zero or simply present the FM sub-carrier to the output. Chart sensitivities are usually 5-0-5 m or 10-0-10 m, and the analogue voltage output varies at the rate of 1 volt per metre of vertical buoy displacement.

All the above figures are nominal; calibration is performed to determine the actual values.

Until now Waverider calibrations have been performed using a Warep receiver to demodulate the buoy signal; the analogue signal is recorded on a chart recorder. However, since any Waverider may have to be used with any receiver, it is obvious that buoy and receiver calibrations have to be performed separately. Thus the first step is to calibrate the receiving system in terms of a known frequency deviation of the input sub-carrier. This is considered below.

Receiver-Demodulator Calibration

For Warep receivers, conversion accuracy of the sub-carrier tone to chart deflection is quoted as 4%, and from tone to analogue output, it is quoted as 3.5%, both over a 0^oC-40^oC temperature range. An overall wave measurement accuracy of better than $\pm$ 2% is desirable; this obviously cannot be obtained without specific calibration information.

To test the sensitivity of the receiving system adequately, an oscillator with an accuracy in the region of 1 part in 10^4 is necessary; it should also have the facility whereby the operator can make small changes to the output frequency. Until 1980 a stable, continuously variable oscillator coupled to a precision period meter was used as the source; more recently, a synthesising generator whose output is precisely determined has been used.

No suitable oscillator was available at IOS Taunton before 1977; even when one became available there were initial difficulties in its use. For example it was necessary to use a synchronising pulse output to initiate the period meter timebase; considerable period variation was recorded if the output signal itself was used. Thus, it was not until August 1977 that a satisfactory calibration of a Warep receiver could be performed (Warep 1194). Almost from the beginning, Warep 1194 has been maintained in the laboratory for use as a buoy-calibration receiver. This is to eliminate sensitivity-variation effects between different receivers.

Prior to August 1977, it was assumed that all IOS Wareps operated with nominal sensitivity. Since August 1977, Warep 1194 has been calibrated 8 times. The sensitivity figures obtained are shown in Table 1.

TABLE 1

Date	Sensitivity Hz V^{-1}	% deviation from nominal
August 1977	1.870	+ 0.54
12 April 1978	1.855	- 0.27
7 June 1978	1.858	- 0.11
18 September 1978	1.871	+ 0.59
13 February 1979	1.858	- 0.11
14 November 1979	1.850	+ 0.54
26 September 1980	1.852	- 0.43
2 June 1981	1.871	+ 0.59

The Warep is calibrated either with a 27 MHz signal which is amplitude modulated by the sub-carrier, or by injecting the sub-carrier directly into the phase-locked discriminator. The frequency of the sub-carrier is changed by accurately-known increments, producing a series of steps on the Warep chart recorder. Plotting deflection in chart divisions against frequency increment gives the Warep sensitivity in divisions per Hertz.

A more accurate method is used at IOS however. A precision chart recorder is used to measure the analogue output at each frequency step. The recorder is itself calibrated with a precision DC source, and it has a 25 cm chart which helps to reduce chart reading errors. Thus if output-voltage is plotted against frequency increments, the Warep sensitivity in V Hz^{-1} may be obtained.

Receiver calibrations are performed periodically on site to give the sensitivity of complete installations. This has been routine since 1978. IOS does not use Wareps as site receivers now however; it produces an equivalent system based on an Eddystone Radio receiver, type EC 964/7c, and these are used. An analogue signal can be fed from the receiver to a digital data logger which has a readout facility. The readout displays what is being impressed onto the magnetic tape; accordingly calibrations of the receiver and logger combination are obtained.

Both the Warep and IOS receivers use a frequency to analogue converter; the analogue signals are converted to digital values in the logger for recording. To simplify the system, frequency logging is now used at all IOS Waverider sites. The AF tone from the receiver is mixed with a 290 Hz tone, and the difference is multiplied by 128. The logger counts and records the resulting frequency each half second. At the Waverider mean frequency (259 Hz) this results in a logged value of 1984 each half second. The calibration now therefore gives a receiving and logging sensitivity in counts (N) per Hertz of input signal. Since this system of logging has been introduced on site, using IOS receivers, calibrations have been consistent to within one count, or to $\pm$ 0.05%.

During an investigation into the variability of results of Waverider buoy calibrations (see Table 3), the need for more specific information on Warep sensitivity variation was demonstrated. Any variation-tests would have to be made at different temperatures (to show up any temperature coefficient) and over an extended time (to show up any variation with time or ambient humidity).

Accordingly, a series of calibrations was carried out using Warep 1194 as the test receiver. An AF tone from a digital synthesising source was fed directly into the phase locked detector, and the analogue output was monitored on a digital voltmeter. Two series of tests were made, about a month apart and the equipment was operated continuously during each series to eliminate any "warming up" errors. Two of the first series of tests were made with the Warep (only) operating in the IOS Taunton cold store; this was to test for any temperature coefficient. (IOS Taunton does not possess an environmental chamber big enough to test the Warep. If these two low temperature tests had shown up any significant temperature effect then a more rigorous series of tests over a wider temperature range would have been made to determine the coefficient.) The ambient temperature at the time of each run was noted from a mercury-in-glass thermometer.

INPUT FREQUENCY Hz	ANALOGUE OUTPUT - VOLTS								
239	-10.542	-10.552	-10.550	-10.574	-10.553	-10.562	-10.388	-10.389	-10.543
241	-9.469	-9.479	-9.477	-9.501	-9.480	-9.489	-9.318	-9.318	-9.470
243	-8.396	-8.406	-8.403	-8.427	-8.407	-8.416	-8.246	-8.247	-8.379
245	-7.322	-7.332	-7.329	-7.353	-7.333	-7.342	-7.174	-7.175	-7.326
247	-6.248	-6.257	-6.256	-6.279	-6.259	-6.268	-6.103	-6.103	-6.250
249	-5.174	-5.183	-5.181	-5.204	-5.184	-5.193	-5.030	-5.031	-5.175
251	-4.100	-4.108	-4.107	-4.128	-4.109	-4.118	-3.958	-3.958	-4.101
253	-3.024	-3.034	-3.031	-3.054	-3.035	-3.042	-2.885	-2.886	-3.025
255	-1.949	-1.958	-1.956	-1.978	-1.959	-1.967	-1.812	-1.813	-1.950
257	-0.873	-0.882	-0.881	-0.903	-0.883	-0.891	-0.738	-0.740	-0.875
259	0.201	0.192	0.193	0.173	0.191	0.182	0.333	0.332	0.198
261	1.277	1.267	1.269	1.250	1.268	1.259	1.407	1.406	1.275
263	2.353	2.345	2.346	2.327	2.344	2.336	2.483	2.481	2.352
265	3.431	3.422	3.423	3.404	3.421	3.413	3.558	3.556	3.429
267	4.506	4.498	4.501	4.482	4.499	4.491	4.633	4.631	4.506
269	5.585	5.576	5.579	5.560	5.576	5.568	5.708	5.707	5.584
271	6.663	6.654	6.656	6.638	6.654	6.647	6.784	6.782	6.662
273	7.741	7.732	7.734	7.717	7.732	7.724	7.860	7.857	7.739
275	8.819	8.810	8.812	8.796	8.810	8.802	8.936	8.934	8.818
277	9.897	9.888	9.891	9.873	9.889	9.880	10.013	10.010	9.896
279	10.976	10.967	10.970	10.952	10.967	10.960	11.089	11.087	10.974
$\bar{a}$	0.2072	0.1981	0.2001	0.1796	0.1976	0.1892	0.3406	0.3392	0.2066
$\bar{f}$	259	259	259	259	259	259	259	259	259
Corr. Coeff.	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
Slope (Sensitivity)	0.5379	0.5380	0.5380	0.5382	0.5380	0.5381	0.5369	0.5369	0.5379
$\frac{1}{\text{Slope}}$	1.8591	1.8587	1.8587	1.8580	1.8587	1.8584	1.8625	1.8625	1.8591
Sens. dev. from nom %	-0.048	-0.070	-0.070	-0.108	-0.070	-0.086	+0.134	+0.134	-0.048
$a_{(f = 0)}$	-139.12	-139.14	-139.14	-139.21	-139.15	-139.17	-138.73	-138.71	-139.10
Temperature °C	18	20	19	22.5	19.5	21	1.5	1.2	18.5
Date	7.10.81	7.10.81	8.10.81	8.10.81	9.10.81	9.10.81	9.10.81	12.10.81	12.10.81
Time	1115	1415	0930	1445	0830	1120	1400	0900	1400

TABLE 2: Sensitivity changes of Warep 1194 with varying time and temperature

INPUT FREQUENCY Hz	ANALOGUE OUTPUT - VOLTS								
239	-10.524	-10.52	-10.552	-10.561	-10.564	-10.561	-10.555	-10.563	-10.560
241	-9.452	-9.45	-9.479	-9.488	-9.491	-9.488	-9.483	-9.490	-9.488
243	-8.379	-8.38	-8.406	-8.414	-8.417	-8.415	-8.409	-8.416	-8.414
245	-7.305	-7.31	-7.333	-7.340	-7.343	-7.341	-7.335	-7.343	-7.340
247	-6.231	-6.23	-6.258	-6.266	-6.269	-6.267	-6.261	-6.269	-6.266
249	-5.158	-5.16	-5.184	-5.192	-5.194	-5.192	-5.187	-5.194	-5.192
251	-4.083	-4.09	-4.110	-4.117	-4.120	-4.118	-4.112	-4.119	-4.117
253	-3.009	-3.01	-3.034	-3.042	-3.044	-3.043	-3.037	-3.044	-3.042
255	-1.933	-1.94	-1.959	-1.966	-1.969	-1.967	-1.962	-1.969	-1.967
257	-0.858	-0.86	-0.884	-0.891	-0.894	-0.892	-0.886	-0.893	-0.891
259	0.215	0.20	0.191	0.184	0.181	0.183	0.188	0.181	0.183
261	1.291	1.27	1.267	1.260	1.257	1.259	1.265	1.258	1.260
263	2.368	2.35	2.344	2.337	2.334	2.236	2.341	2.335	2.337
265	3.445	3.42	3.421	3.414	3.411	3.413	3.419	3.412	3.414
267	4.522	4.50	4.498	4.491	4.489	4.491	4.496	4.489	4.491
269	5.599	5.58	5.576	5.569	5.567	5.568	5.574	5.567	5.569
271	6.676	6.66	6.654	6.647	6.645	6.646	6.652	6.645	6.647
273	7.755	7.73	7.732	7.725	7.723	7.724	7.730	7.723	7.725
275	8.831	8.81	8.810	8.803	8.801	8.803	8.808	8.802	8.804
277	9.910	9.89	9.888	9.882	9.880	9.881	9.886	9.880	9.882
279	10.989	10.97	10.967	10.960	10.959	10.960	10.965	10.959	10.960
$\bar{a}$	0.2223	0.2110	0.1976	0.1939	0.1877	0.1895	0.1951	0.1881	0.1902
$\bar{f}$	259	259	259	259	259	259	259	259	259
Corr. Coeff.	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
Slope (Sensitivity)	0.5378	0.5371	0.5380	0.5380	0.5381	0.5380	0.5380	0.5381	0.5380
$\frac{1}{\text{Slope}}$	1.8594	1.8619	1.8588	1.8587	1.8585	1.8586	1.8587	1.8585	1.8586
Sens. dev. from nom %	-0.032	+0.102	-0.065	-0.070	-0.081	-0.075	-0.070	-0.081	-0.075
a (f = 0)	-139.07	-138.90	-139.14	-139.15	-139.17	-139.16	-139.15	-139.17	-139.16
Temperature °C	16	15.5	19.7	20.3	20.7	20.7	19.8	20.8	20.3
Date	13.10.81	14.10.81	13.11.81	16.11.81	16.11.81	18.11.81	19.11.81	20.11.81	23.11.81
Time	0830	1200	1130	0850	1445	0950	0835	0905	0930

TABLE 2 (Continued)

The results from the two series of tests are shown in Table 2. The input frequency was varied in 2 Hz increments from 239 Hz to 279 Hz, giving 21 analogue output readings between approximately $\pm$ 10 volts. For each test, the following values were calculated:

$\bar{f}$ - the average input frequency (used as a check on the calculations);

$\bar{a}$ - the average of the analogue output values;

Correlation coefficient - an indication of how close individual analogue readings were to the best straight line;

Slope - gives the sensitivity of the Warep in V Hz^{-1};

Inverse slope - nominal value is 1.86 Hz V^{-1};

% deviation - an indication of the sensitivity deviation from the nominal value of 0.5376 V Hz^{-1};

$a_{(f = 0)}$ - the analogue output value when frequency input is 0 Hz (ie the intercept).

Also recorded are:

Temperature (^oC) - the ambient temperature at the time of measurement;

Date - date on which the measurements were made;

Time - time at which the measurements were made.

From the results obtained in Table 2, it may be seen that Warep 1194 is a very stable receiver and demodulator. The sensitivity varied by less than 0.1% over all readings except those made with the Warep in the cold-store, and even these varied by less than 0.14% from nominal. The correlation coefficients all varied by less than 1 part in 10^6 from unity, and the intercept values varied by only 0.5 maximum.

A very small temperature coefficient is apparent, but this does not appear to be linear. However, its very small size did not justify a more elaborate temperature-controlled experiment to investigate it further.

It may be seen that the spread of results in Table 2 is much less than in Table 1. It is unlikely that the accuracy of Warep 1194 has improved; it is thus likely that the improvement in experimental technique used to obtain the results in Table 2 produced more consistent sensitivity figures. (Note that a good quality oscillator (a Farnell Synthesised Generator type DSG 1) and a sensitive digital voltmeter (a Keithley model 171 Digital Multimeter on the $\pm$ 10 volts range) were used.)

It should also be noted that all the calibrations performed were static, ie the input frequency was held constant while the analogue output voltage was read. At no time has IOS attempted a dynamic test of the Warep demodulator to investigate its frequency response.

BUOY CALIBRATIONS

All IOS Taunton Waveriders are calibrated at the National Maritime Institute, Hythe. The buoys are placed in a rig which carries them in a 3 m diameter vertical circle. Rotation speed is indicated by a tachometer, but actual rotation period is measured by IOS personnel using a stopwatch. Rotation period was originally variable between 3.5 and 18 seconds (0.28-0.053 Hz); late in 1975 it was changed to 3.5-40 seconds (0.28-0.025 Hz). The slower speed was introduced at the suggestion of IOS; it gives a better test of the Waverider's response fall-off above 20 seconds period.

Prior to May 1978, recordings were only made on the chart recorder of Warep 1194, which was operated on the 5-0-5 m range. When the buoy was operated in the rig, a sinusoidal trace some 3 cm peak to peak was produced on the chart. The measured values were corrected for the nominal frequency response for the accelerometer-integrator system, and then expressed as a percentage above or below the calculated figure. An average percentage deviation was then taken over all rig rotation speeds with periods of less than 20 seconds, and this was given as the calibration figure for the buoy. No correction was made for Warep sensitivity; this was assumed to be nominal.

However, it was realised that this method did not give a sufficiently accurate result. When more precise receiver calibration information became available in 1978, the method evolved, and the procedure as used at the moment is described below.

The buoy is energised and placed in the rig, which is run for at least 20 minutes at the slowest speed to allow for settling. Records are then taken as described above, but the analogue output is monitored with the precision chart recorder. (Note: it is important that the Warep chart recorder pen arm is free to move during calibrations, otherwise the analogue output is affected by the Warep's efforts to overcome infinite friction, ie drive-voltage values are increased.)

The rig is operated at 12 or 13 different rates, with periods varying between about 40 and 3.5 seconds.

When calculating the Waverider sensitivity, runs with periods of greater than about 20 seconds, and less than about 5 seconds, are not counted. However, these runs are valuable; the long period tests show up any deficiency in the integrator system, or in the sensitivity of the accelerometer to small accelerations, while the short period tests show up any instability in the accelerometer platform (which would indicated a damaged suspension).

The records from the precision chart recorder are taken and average peak to peak deflections are measured. The frequency-response correction factor, appropriate to the rig rotation period (as determined by stopwatch) is applied, giving a corrected response in volts per metre. Ideally, this should always be unity, in practice departures from unity of more than two percent are rare, and are usually confined to either the long period or very short period tests, where the corrections are less reliable, or where mean line variation caused by accelerometer instability makes measurements of the analogue traces difficult.

The correction factor is derived from an expression for the integrator response given in the Datawell Waverider handbook, viz:

$$A = 1/(1-j\sqrt{2}\,p-p^2) \cdot 1/(1-jq)^3$$

This complex function can be simplified to give the amplitude:

$$|A| = \frac{1}{\sqrt{((1-p^2)^2 + 2p^2)\ (1+q^2)^3}}$$

where $p = \frac{T}{30.8}$ and $q = \frac{T}{460}$, T being applied wave period. No attempt has been made to measure accurately the phase angle of the response.

The expression gives the response as a proportion of the nominal value; the correction factor is the reciprocal of this value. A table of all response values between 2 and 50 seconds, by 0.1 second increments, has been prepared at IOS.

The Warep circuit has been designed to compensate for the fall-off in response of its own chart recorder at periods of less than 10 seconds. Thus the analogue output is greater than it should be at short periods, and this 'lift' is compensated by modifying the correction value obtained above. Some information on the lift is obtainable from the Datawell Warep handbook.

A recent innovation has been to calculate the Waverider calibration figures on a Hewlett Packard 9810A desk top computer. The number of runs, number of rig revolutions, the total time and the peak to peak recorded analogue output are fed in, and the computer calculates the rig revolution period, the correction factor appropriate to that period, and the corresponding corrected buoy response. When the responses of all the runs have been calculated, the average response is printed out. This is arranged to be taken over the restricted range of rig rotation periods given above, viz 5 to 20 seconds approximately.

It is hoped that frequency logging of Waverider buoy calibrations will be introduced soon. In addition to the recordings of the analogue output (which will still be taken as a back-up) the calibration runs will be logged on a Microdata digital data logger. The records will then be analysed fully on a computer at IOS Taunton. One problem delaying introduction of this step is that of mean line variation.

To date, 58 calibrations have been performed on IOS Taunton buoys. The results are shown in Table 3. Only one result shows a serious departure from the nominal sensitivity; that result was obtained from a test which was performed in a non-standard way and hence the accuracy is questionable.

Of the 58 results, 15 are above nominal sensitivity, 43 are below; none is exactly right. The highest reading is 2.1% above nominal, the lowest 3.4% below.

Of the 20 Waveriders in IOS possession, 5 have been calibrated 5 times. Plotting sensitivity against buoy life in days since the first calibration does not demonstrate any significant drift in the sensitivity of the 5 buoys (see Fig 1). No IOS Waverider has been calibrated more than 5 times. No tests have been performed to determine sensitivity variation with either temperature or battery supply voltage.

TABLE 3 SUMMARY OF CALIBRATION INFORMATION OF IOS(T) WAVERIDERS

	5033	5039	6242	6459	6489	6581	6850	6851	67041	67042	67043	67144	67151	67201	67213	67214	67419/7	67420/7	67406/9	67407/9
a	16.4.73	3.6.74	18.1.74	22.4.75	10.6.76	6.11.75	8.6.78	25.5.78	26.1.78	25.5.78	26.1.78	19.9.78	24.10.78	5.1.79	26.6.79	26.6.79	24.7.80	24.7.80	20.11.80	20.11.80
b	1.854	1.829	1.846	1.837	1.857	1.823	1.842	1.822	1.833	1.807	1.831	1.877	1.899	1.724 x	1.846	1.824	1.874	1.875	1.877	1.882
c	*	*	*	*	*	*	-	-	*	-	*	-	-	-	-	-	-	-	-	-
d	-	-	-	-	-			-	-	-	-	-	-	-	-	-	-	-	-	-
e	-	-	-	-	-			-	-	-	-	-	-	-	-	-	-	-	-	-
a	18.1.74	10.6.76	6.11.75	4.8.77	4.8.77			13.11.79	13.12.78	15.2.79	7.7.78	13.12.78	22.5.79	13.11.79	23.1.80	7.10.80	28.5.81			
b	1.849	1.844	1.841	1.819	1.814			1.850	1.809	1.813	1.862	1.865	1.840	1.823	1.871	1.845	1.896			
c	*	*	*	*	*			-	-	-	-	-	-	-	-	-	-			
d	278	739	658	836	421			538	322	267	163	86	211	313	212	470	309			
e	278	739	658	836	421			538	322	267	163	86	211	313	212	470	309			
a	3.6.74	11.3.77	13.4.76	24.10.78	8.6.78			18.8.81	29.8.79	4.6.80	22.5.79	15.2.79	4.6.80			27.11.80				
b	1.841	1.823	1.856	1.815	1.832			1.872	1.798	1.816	1.823	1.849	1.810			1.862				
c	*	*	*	-	-			-	-	-	-	-	-			-				
d	136	275	160	447	309			645	260	476	320	65	379			51				
e	414	1014	818	1283	730			1183	582	743	483	151	590			521				
a	13.4.76			29.8.79	19.9.78				27.11.80		7.12.80	11.3.80								
b	1.872			1.797	1.848				1.825		1.842	1.867								
c	*			-	-				-		-	-								
d	680			310	104				457		505	391								
e	1094			1593	834				1039		988	542								
a	8.12.77			23.1.80	11.3.80				18.8.81			28.5.81								
b	1.845			1.831	1.853				1.814			1.881								
c	*			-	-				-			-								
d	605			148	539				265			475								
e	1699			1741	1373				1304			1017								

x accuracy questionable

Information given:-

a Date
b Sensitivity in Hz m^{-1}
c * Indicates sensitivity figure is derived from "% deviation from nominal"
  - Indicates sensitivity figure is calculated directly from calibration information (from 25.5.78)
d Number of days since last calibration
e Number of days since first calibration

Fig. 1

Graph showing variation of Waverider Sensitivity with Age in Days from first calibration