I.O.S.

A COMPARISON OF SATELLITE AND SEA SURFACE MEASUREMENTS OF SIGNIFICANT WAVE HEIGHT

by

D. J. Webb

Report No. 85.

(1979)

NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE OF OCEANOGRAPHIC SCIENCES

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ABSTRACT

During the JASIN experiment in the summer of 1978, a series of sea surface wave measurements were made for comparison with wave heights deduced from the SEASAT-1 altimeter.

Comparisons were made on eight separate occasions during which the significant wave height ranged from 0.7 to 2.0 metres.

For waves above one metre, a good correlation was found between the satellite and sea surface measurements, with the satellite overestimating the wave height by about 20 centimetres. On the two occasions when the waves were below 90 centimetres, a poorer correlation was observed.

From the point of view of oceanographers interested in measuring wave fields regularly over remote areas of ocean, altimeters of the type used in SEASAT-1 appear to be accurate and extremely useful.

INTRODUCTION

In the summer of 1978, the United States of America launched a satellite, SEASAT-1*, which carried a number of instruments for monitoring the ocean surface. The main aim of the mission was to check the performance of the instruments and to check the quality and usefulness of the data they returned.

One of the instruments included was an altimeter. Physically this measures the time taken for a radar pulse to reach the sea surface and be reflected back to the satellite. If the satellite's orbit is known accurately, this information may be used to determine the earth's geoid and to observe the tides and other large scale features on the sea surface.

The radar altimeter looks at a circular region of ocean directly below the satellite, which is about 10 kms across. Within this region, that part of the radar pulse being reflected from the tops of the sea waves returns to the satellite before that reflected from the troughs of the waves. As a result the radar pulse returning to the satellite will be distorted compared to the pulse returned from an ocean with no waves. The higher the sea waves are, the greater the distortion, and so in principal the distortion can be used to measure the height of the waves.

The design of the SEASAT-1 altimeter was developed from instruments used earlier on SKYLAB and GEOS-3. The earlier instruments had provisions for measuring wave heights but their accuracy was relatively poor. In the most recent of them, GEOS-3, the r.m.s. error in estimating the significant wave height was approximately 75 cms (Rufenach and Alpers 1978, Fedor et al 1979). More importantly the data from GEOS-3 could only be obtained when it was within range of a dedicated ground station. In SEASAT-1 improvements in design meant that an r.m.s. error of 10 cms or less was to be expected and also a copy of all the altimeter data was stored on board the satellite for retrieval when it passed over a suitable ground station.

Thus, from an oceanographic point of view, the SEASAT-1 altimeter

* *Before launch SEASAT-1 had the name SEASAT-A*

was very important. It promised accurate measurements of wave height over large and remote regions of ocean, where even crude wave height data is at present rarely available. In addition, it was expected to operate for two years or more and so it would go some way towards providing the long term statistical information on wave climate which is often required.

In the summer of 1978, the Institute of Oceanographic Sciences was involved in JASIN, the Joint Air-Sea Interaction Project. This was an international oceanographic and meteorological experiment, sponsored by the Royal Society, which took place in the North Atlantic, near 59°W, 12°30'W, between July and September. Being early in SEASAT's life and as wave measuring equipment would be present, it seemed to be a good occasion for checking on the altimeter's ability to measure waveheights.

Other wave measuring instruments were also operating during JASIN but in this report we concentrate on comparing the wave height measurements made by the SEASAT-1 altimeter with those made by the Institute of Oceanographic Sciences' pitch-roll buoy.

THE PITCH-ROLL BUOY MEASUREMENTS

The pitch-roll buoy used was a development of the design described by Cartwright and Smith (1964) and Clayson and Smith (1970). The buoy is free floating, has a low moment of inertia and a large righting moment so that it closely follows the sea surface. It contains a gyro to give a vertical reference.

The buoy measures the vertical acceleration, the slope of the sea surface and the compass heading of the buoy; and records the data internally every 1/2.048 of a second. The buoy is powered by batteries which will last for four hours continuous running.

The pitch-roll buoy was carried on RRS Discovery. In operation it was necessary to fit in with the other experiments being carried out, but when possible the buoy was launched two hours before and recovered two hours after the satellite pass. This was done partly to give a long record, giving good statistics on the wave field. But also it was appreciated before the experiment, that it would rarely be practical to place the buoy directly below the satellite track and a long recording time meant that any important horizontal changes in the wave field had a chance to show up as a change with time at the measurement point as the wave field progressed past that point.

PROCESSING THE PITCH-ROLL BUOY DATA

While at sea, sections of the data were listed to ensure that the sensors were working properly. Later plots and other tests of the data were used to check for errors. For estimating wave heights, only the vertical acceleration signal was used, but the output from the other sensors was used to monitor the overall performance of the buoy. Thus the pitch and roll sensors showed when the gyro started precessing because the power supply had gone low.

The accelerometer signal was analysed by fourier transforming sections of data 125 seconds long (256 data cycles). The very lowest frequency components which contain a contribution from the long term drift of the gyro were then dropped and the other fourier components combined to give the r.m.s. water elevation during that data period. Up to forty-eight such periods were processed and combined to give a mean value for the estimated r.m.s. water elevation and an estimate of the error of the mean.

Comparisons between the SEASAT-1 altimeter and the pitch-roll buoy were made on eight occasions. The positions of the buoy on these occasions and the results obtained are given in Table 1.*

THE SEASAT ALTIMETER

The design and operation of the SEASAT-1 altimeter has been described by MacArthur (1976) and a more detailed report is due to be published in 1979. The design built upon experience gained with instruments installed in SKYLAB and GEOS-3. All of these instruments attempt to use a very short radar pulse, so that the leading edge of the returned signal from the sea surface is not

* *The significant wave height given in the tables is defined as being four times the r.m.s. water elevation.*

affected by the finite antenna beamwidth.

SKYLAB had a 13.9 GHz pulsed radar, which tracked the leading edge of the returned signal giving the satellite altitude. There were also eight sample-hold gates arranged around the tracking point which allowed samples of the leading edge to be obtained. A pulse width of 100 ns was used, and this gave an altitude precision of under one metre.

GEOS-3 was designed to operate at a higher altitude and so, in order to get more power into the radar pulse using the amplifiers available, a longer pulse was needed. The solution adopted was to use pulse expansion and compression filters. These allowed a 1 μs pulse to be used which became 12.5 ns when compressed.

SEASAT-1 orbited at a height of approximately 800 kms and covered the ground at a speed of 6.6 km sec^{-1}. The altitude used is similar to GEOS-3, but in SEASAT-1 the altimeter was designed to give a much improved resolution by using a swept frequency radar pulse. The returned signal is correlated with a replica of the transmitted signal, with the result that any time delay in the returned signal becomes mapped into a frequency offset. Thus, the range gating used in the earlier instruments is now replaced by frequency filtering.

The technique allows in SEASAT-1, a 3.2 μs chirped pulse to give the same effective resolution as a 3.125 ns pulse of fixed frequency. The returned signal from this narrower pulse can also be sampled with the same resolution of 3.125 ns allowing the distance to the sea surface to be measured, in principal, to an accuracy of better than 10 cms. The distortion of the leading edge of the returned signal should also enable the wave height to be measured to an accuracy of better than 10 cms.

The radar altimeter transmits at a rate of 1000 pulses per second. After each pulse, an on board computer fourier transforms the correlated returned signal to give 63 samples describing the effective compressed returned pulse. The tracking system used to measure the distance to the ocean surface keeps the leading edge of the returned signal in the centre of the window of 63 samples.

Interference from different scatters on the sea surface means that the returned signal is very noisy. It is therefore smoothed by averaging each of the 63 samples over 50 pulses. An example of this 'smoothed' pulse is shown if Figure 1, but as can be seen a lot of random noise is still present.

Wave heights are estimated from the leading edge of the smoothed pulse. On board the satellite a very simple method of doing this was used. From the 63 samples describing the smoothed pulse, groups of samples, called gate triplets and arranged around the tracking point, were used to compute running averages giving estimates of the slope of the leading edge of the pulse. Depending on the wave height, different gate triplets gave the most sensitive result. The estimate of pulse slope was then used in a look-up table to give the significant wave height.

Ten times each second, a copy of the altimeter data, including the latest estimate of wave height and the 63 samples describing the smoothed pulse, was transmitted to the ground. For regions around the UK this data was received by RAE Oakhanger. A second copy of the data was stored on board and transmitted once each orbit to a NASA ground station.

PROCESSING THE SATELLITE ALTIMETER DATA

The satellite data received at RAE Oakhanger was combined with attitude and orbit data from NASA to produce ISDRs, the Individual Sensor Data Records. The data for the eight passes monitored by the pitch-roll buoy were made available to I.O.S.

The uncorrected wave heights estimated by the satellite as it passed between 57°N and 61°W, near the JASIN region, are plotted in figures 2 to 9. The satellite moves at 6.6 km sec^{-1}, so each pass represents over 500 km of ocean. The noise seen in the plots is believed to come predominantly from statistical fluctuations in the smoothed pulse mentioned previously, but it is possible that some comes from fluctuations in the actual surface wave field. The signal may also be affected by ships.

The data shown is raw data and two known corrections have to be made. The first, the so called $\sin^2 x/x^2$ correction, is to correct for end effects in the fourier transforms carried out on board the satellite. This correction is different for each of the gate triplets and is greatest for low amplitude waves. The second correction, the attitude correction, is to allow for the satellite not looking exactly vertically at the earth's surface.*

In order to make a comparison with the pitch-roll buoy, the time of closest approach to the buoy was determined and then the average wave height taken by eye from the plots. Listings of the altimeter derived wave height, and the gate triplet used were also available. In this manner, the average wave height could be estimated to better than 10 cm accuracy. The $\sin^2 x/x^2$ and attitude corrections were then made and the results obtained are shown in Table II. As can be seen in this table, the corrections required were large, a typical value being 60 cm. Of this about 16 cm was due to the attitude correction and the rest was due to the $\sin^2 x/x^2$ correction.

During six of the eight passes, the gate triplet used for calculating most of the wave heights was number 2. But during passes 3 and 8, when the significant wave height was below 90 cms, both triplets 1 and 2 were used. The effect of the different gate triplets can be seen in figures 4 and 9, where the raw wave height is seen to jump as the satellite altimeter changes from using one gate triplet to the other.

The switching from one gate to the other is probably a result of random fluctuations in the returned signal. The resulting jumps in the raw wave height data then probably arise from the different $\sin^2 x/x^2$ corrections that have to be made.

COMPARISON

In order to compare the altimeter and pitch-roll buoy measurements of significant wave height, they are shown plotted against

* *The corrections were made with the use of tables supplied by W. Townsend of the NASA Wallops Flight Centre.*

each other in Figure 10. The dots correspond to the corrected and the crosses to the uncorrected satellite data. The estimated standard deviation of the pitch-roll buoy measurements are shown. No similar quantity was calculated for the satellite data, but as mentioned earlier, the uncorrected values were estimated, from figures 1 to 8, to better than 10 cm accuracy.

For significant wave heights of above one metre, the agreement between the satellite and pitch roll buoy measurements is very good. The largest discrepancy occurs during run 7 when the pitch roll buoy gives 1.16m and the satellite 11 cm less. For this run the point of closest approach of the satellite to the buoy was 125 km and so the discrepancy may be due to a spatial change in the wave field.

Below one metre the agreement between the two instruments is not so good. For the gate 2 satellite measurements this is probably due to the large $\sin^2 x/x^2$ corrections needed and in fact this appears to be overcorrecting the waveheights in this region.

Gate triplet 1 was only used extensively during runs 3 and 8. In both cases the satellite measurement is within 10 cms of the pitch-roll buoy measurement. However, one disturbing feature is that in run 8, gate triplet 1 gives lower waves than in run 3, whereas gate triplet 2 and the pitch-roll buoy indicate higher waves.

CONCLUDING REMARKS

The comparisons reported here were carried out in periods of low seas and so represent a severe test of the altimeter's ability to resolve waves. However, despite this, the agreement between the satellite altimeter and pitch-roll buoy measurements is very good, the discrepancy often being less than 5 cms.

If the pitch-roll buoy measurements are assumed to be correct the results indicate that the SEASAT-A altimeter is a very accurate instrument for measuring wave heights. Its performance represents a significant advance over the performance of the GEOS-C altimeter. Also the results do not preclude the possibility that for wave heights above one metre, the satellite altimeter, with its ability to sample a large region of ocean, may be a more accurate instrument for measuring the mean sea state than the pitch-roll buoy.

Below one metre, the performance of the satellite altimeter is not so good. This poor behaviour appears to be mainly due to the fourier transform algorithms used on the satellite. If Gate triplet 2 had not been used in its insensitive region below one metre or if the fourier transform algorithm had been carried out so that a large $\sin^2 x/x^2$ correction was not necessary, better performance may have been obtained.

Unfortunately, this study did not include wave heights above two metres, and so we cannot be certain that the satellite actually continued to operate successfully when measuring higher wave fields. But it is known that the $\sin^2 x/^2$ correction actually becomes less for higher waves and no additional corrections are expected to become necessary until one reaches waves of 20 m or so when the effects of the finite beamwidth of the radar pulse start having an effect. (This finite beamwidth gives the decay of the signal near gate +30 seen in figure 1). Thus it seems very unlikely that the performance of the altimeter would be any worse for waves of up to say 15m.

In conclusion, and from the point of view of an oceanographer interested in the statistics of wave fields over large and often remote areas of ocean, I think that the SEASAT-1 altimeter was extremely successful and that its early failure in October 1978 is to be regretted.

REFERENCES

Cartwright, D.E. and N.D. Smith (1964). Buoy techniques for obtaining directional wave spectra. Buoy Technology pp 112-124, Marine Technology Society, Washington.

Clayson, C.H. and N.D. Smith (1970). Recent advances in wave-buoy technology at the National Institute of Oceanography. Conference on Electrical Engineering in Ocean Technology pp 289-306. IERE Conference Proceedings No. 19, London.

Fedor, L.S., T.W. Godbey, J.F.R. Gower, R. Guptill, G.S. Hayne, C.L. Rufenach, E.J. Walsh, (1979). Satellite altimeter measurements of sea state - an algorithm comparison. Journal of Geophysical Research (In press).

McArthur, J.L. (1976) Design of the SEASAT-A radar altimeter. OCEANS 76 Conference record. pp 10B-1 to 10B-8.

Rufenach, C.L. and W.R. Alpers (1978). Measurements of ocean wave-heights using the GEOS-3 altimeter. Journal of Geophysical Research 83 (C10) 5011-5018.

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TABLE 1. The Pitch-Roll Buoy Results

Pass Number	Buoy Position Latitude	Longitude	Day & Time of Satellite Pass	Wave analysis period Start time	End Time	Number of 125 sec records	Significant wave height	S.D. of estimate
1	59°03'N	12°30'W	197/0424	0205	0238	16	2.26m	0.10m
2	59°24'N	12°26'W	211/0530	0505	0628	40	1.43m	0.03m
3	59°39'N	12°21'W	212/2200	2117	2236	40	0.76m	0.02m
4	58°59'N	12°51'W	214/0537	0444	0624	48	1.15m	0.02m
5	59°12'N	12°53'W	215/2206	2114	2157	21	1.70m	0.05m
6	59°09'N	13°12'W	217/0544	0450	0630	48	1.10m	0.03m
7	59°09'N	13°29'W	218/2214	2126	2249	40	1.16m	0.02m
8	59°12'N	12°35'W	221/2221	2140	2303	40	.84m	0.02m

TABLE II The Seasat-1 Altimeter results

Pass Number	Nearest approach to buoy Day and Time	Latitude	Longitude	Distance to buoy	Satellite attitude	Significant Wave Heights Uncorrected Gate 1	Uncorrected Gate 2	Corrected Gate 1	Corrected Gate 2
1	197/04:24:08	59°02'N	12°33'W	10 km	0.29°	-	2.6m	-	2.21m
2	211/05:30:25	58°52'N	13°54'W	100 km	0.28°	-	2.0m	-	1.47m
3	212/21:59:37	59°44'N	12°51'W	35 km	0.27°	1.2m	1.5m	0.85m	0.47m
4	214/05:37:30	59°02'N	12°43'W	10 km	0.26°	-	1.8m	-	1.19m
5	215/22:06:53	59°01'N	12°33'W	25 km	0.26°	-	2.15m	-	1.66m
6	217/05:44:27	58°50'N	10°57'W	100 km	0.27°	-	1.75m	-	1.11m
7	218/22:14:06	58°27'N	11°58'W	120 km	0.21°	-	1.70m	-	1.05m
8	221/22:21:06	58°29'N	10°28'W	140 km	0.09°	1.1m	1.55m	0.76m	0.69m

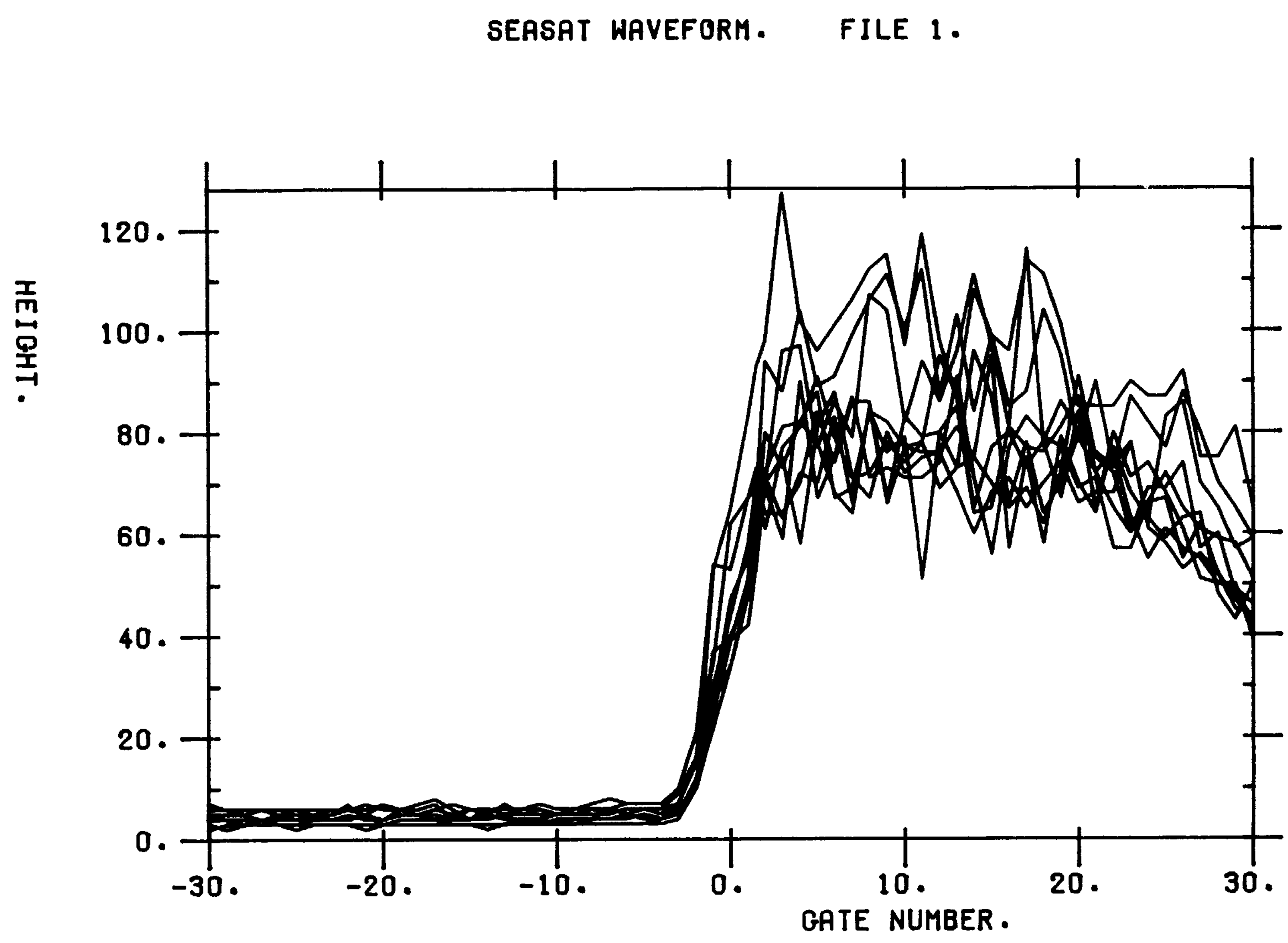

Figure 1. Ten of the 'smoothed' pulses used to estimate wave heights. These each represent an average of fifty raw pulses. Each sample gate has a width of 3.125 ns.

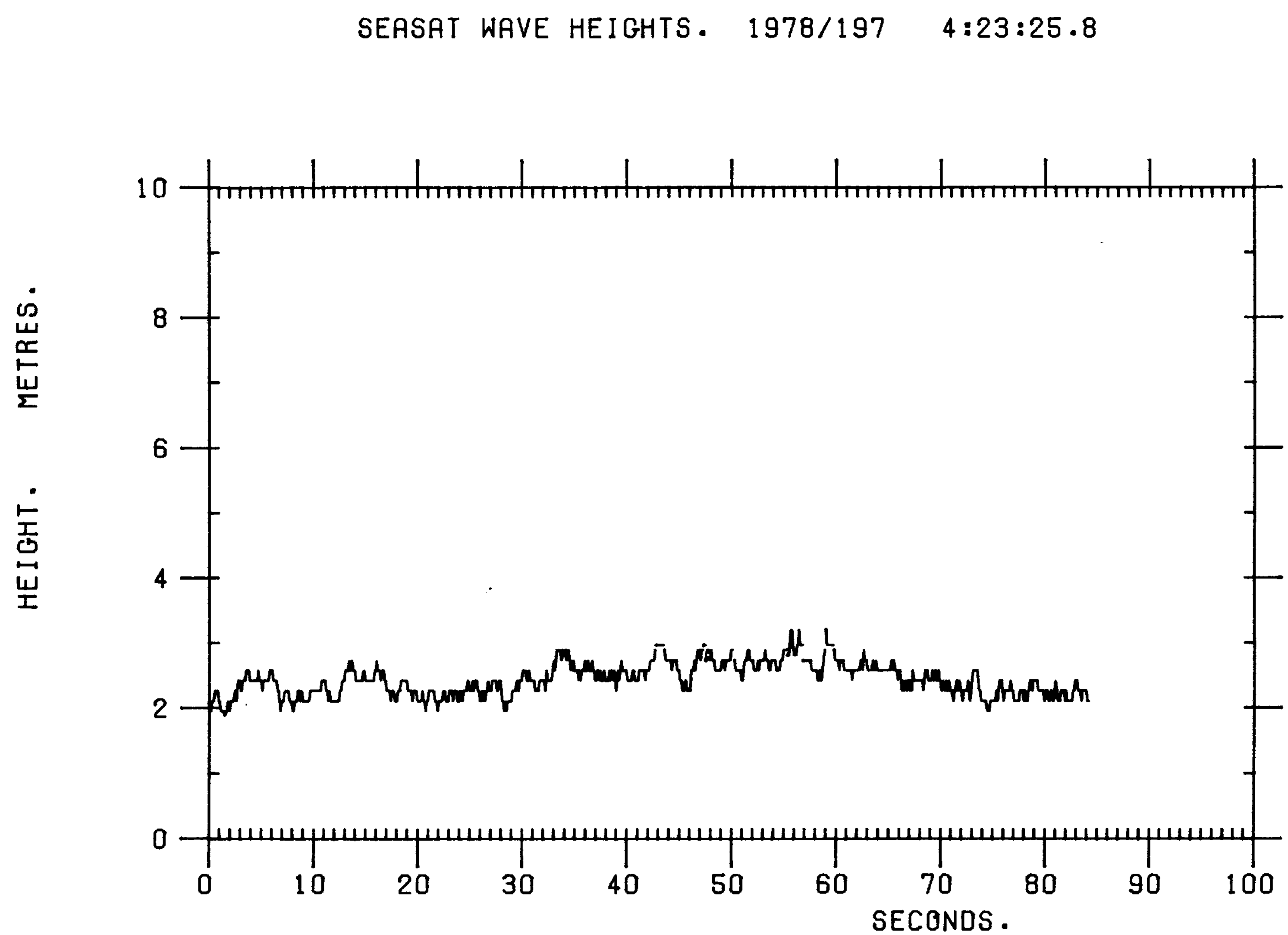

Figure 2. Values of significant wave height calculated by the altimeter on the morning of day 197 (16th July) as it passed northwestward between 57°W and 61°W. During this period the satellite travelled approximately 550 kms. Closest approach to the pitch-roll buoy occurred at 42 seconds when the sub-satellite point was within 10 kms of the buoy. Gate triplet 2 was used for most of the pass, with gate triplet 3 being used for a few higher waves. Breaks in the plot indicate a change from one gate to another.

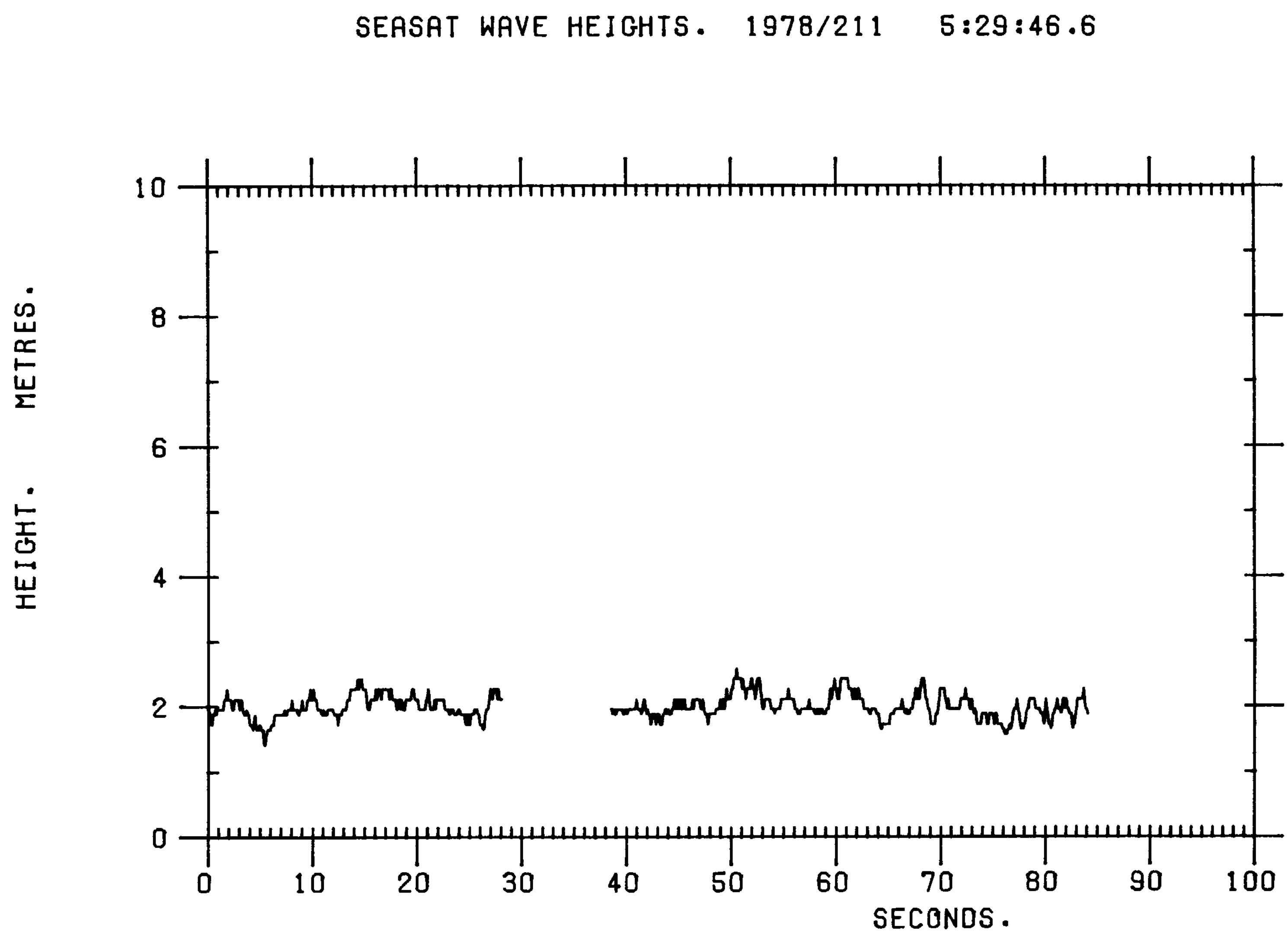

Figure 3. Uncorrected wave heights during pass 2. Closest approach occurs at 39 seconds, just after the gap in the data, when the separation was 100 kms. Gate triplet 2 was used during all of the pass. The gap in the data seen here between 28 and 38 seconds, and similar gaps in Figures 5 and 7, are due to loss of signal at the RAE Oakhanger groundstation.

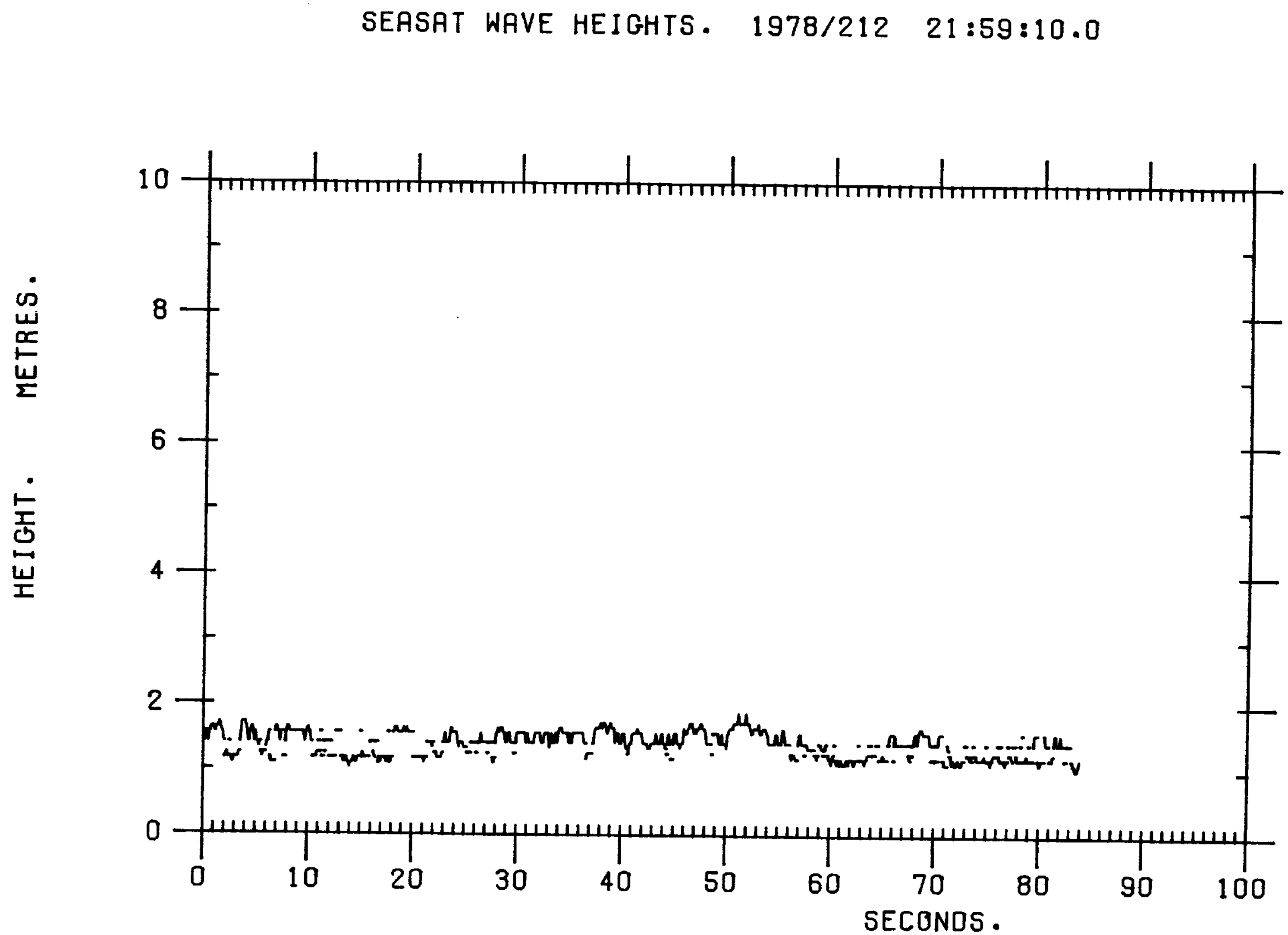

Figure 4. Uncorrected wave heights during pass 3. Closest approach occurs at 28 seconds when the separation was 35 kms. Both gate triplets 1 and 2 were used, triplet 1 giving the lower wave heights.

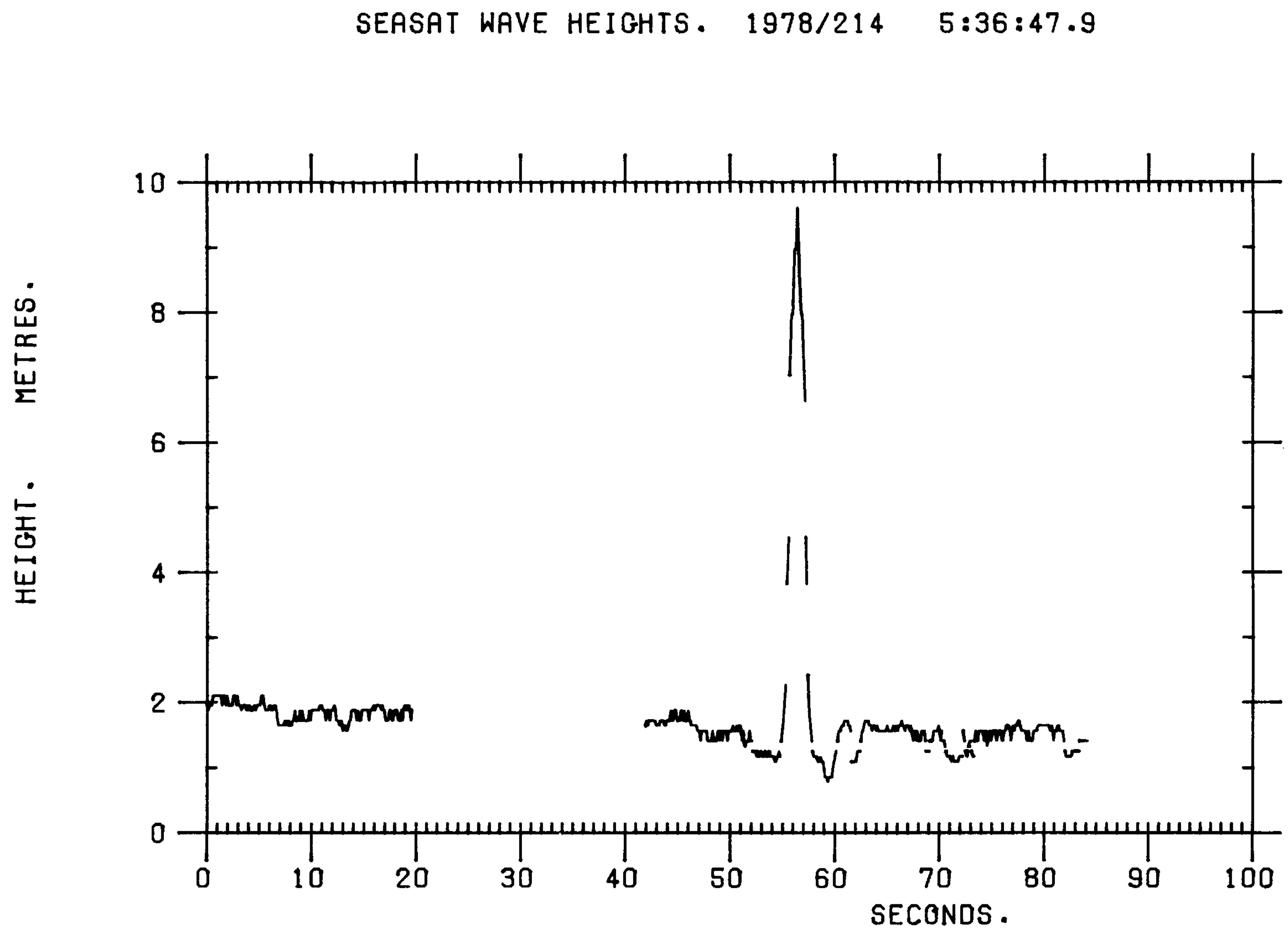

Figure 5: Uncorrected wave heights during pass 4. Closest approach was at 42 seconds when the buoy was within 10 kms of the sub-satellite point.

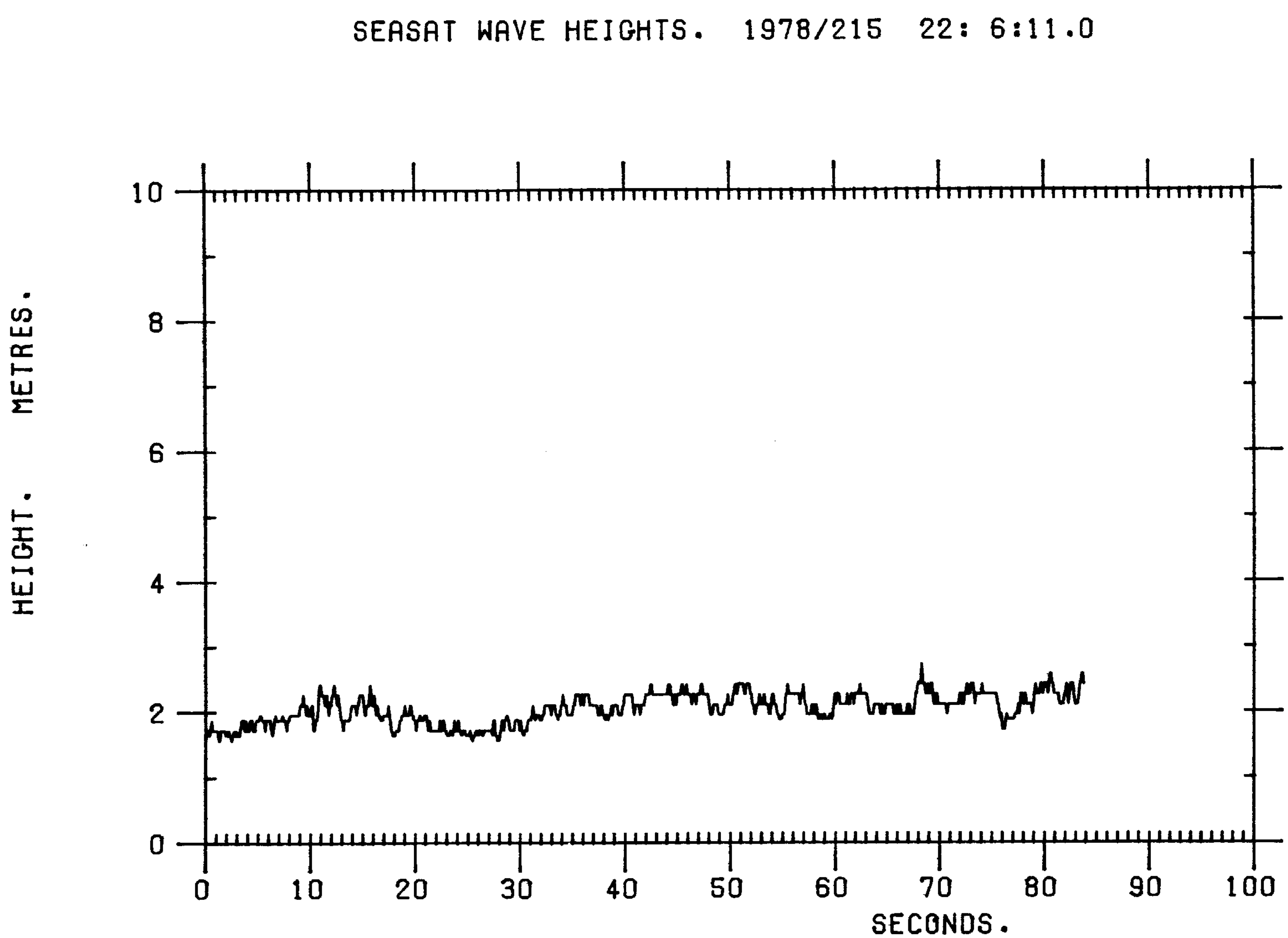

Figure 6: Uncorrected wave heights during pass 5. Closest approach was at 42 seconds when the separation was 25 kms. During these evening runs the satellite passed across the area from N.E. to S.W.

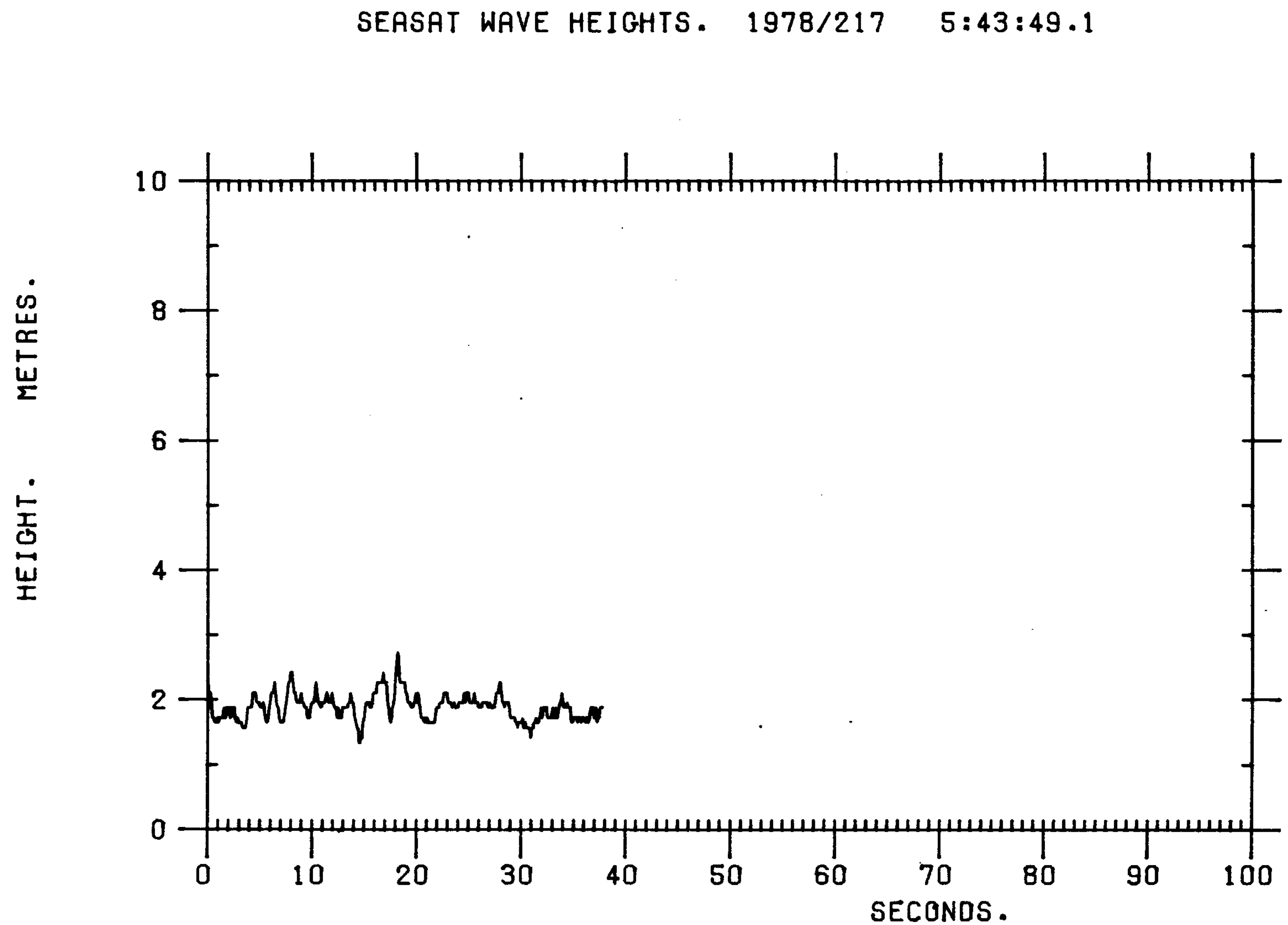

Figure 7: Uncorrected wave heights during pass 6. Closest approach would have been at 53 seconds. The nearest data received, at 37 seconds, was approximately 100 kms from the buoy.

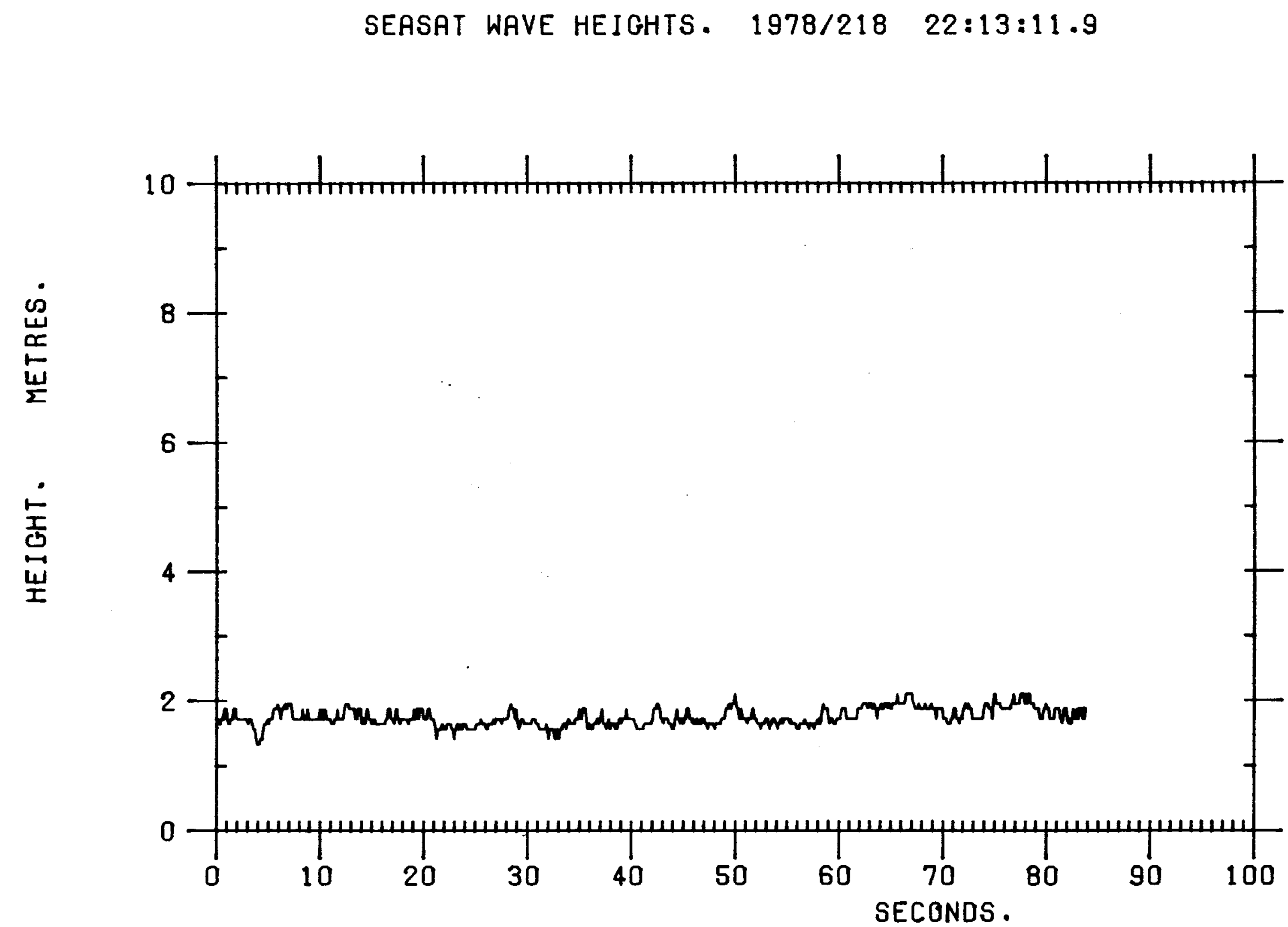

Figure 8: Uncorrected wave heights during pass 7. Closest approach is at 55 seconds when the separation is 125 kms.

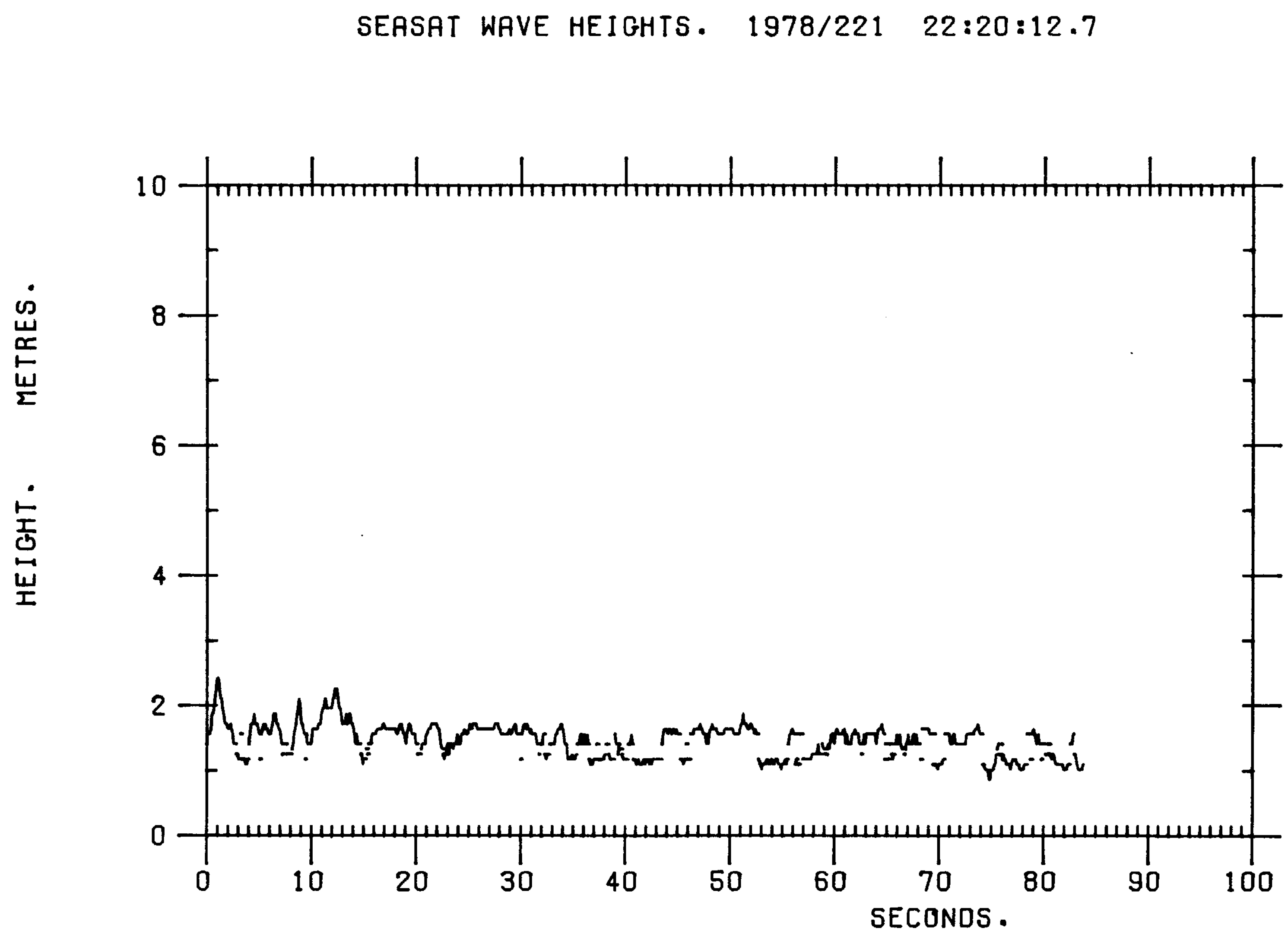

Figure 9: Uncorrected wave heights during pass 8. Closest approach is at 54 seconds when the separation is 140 kms.

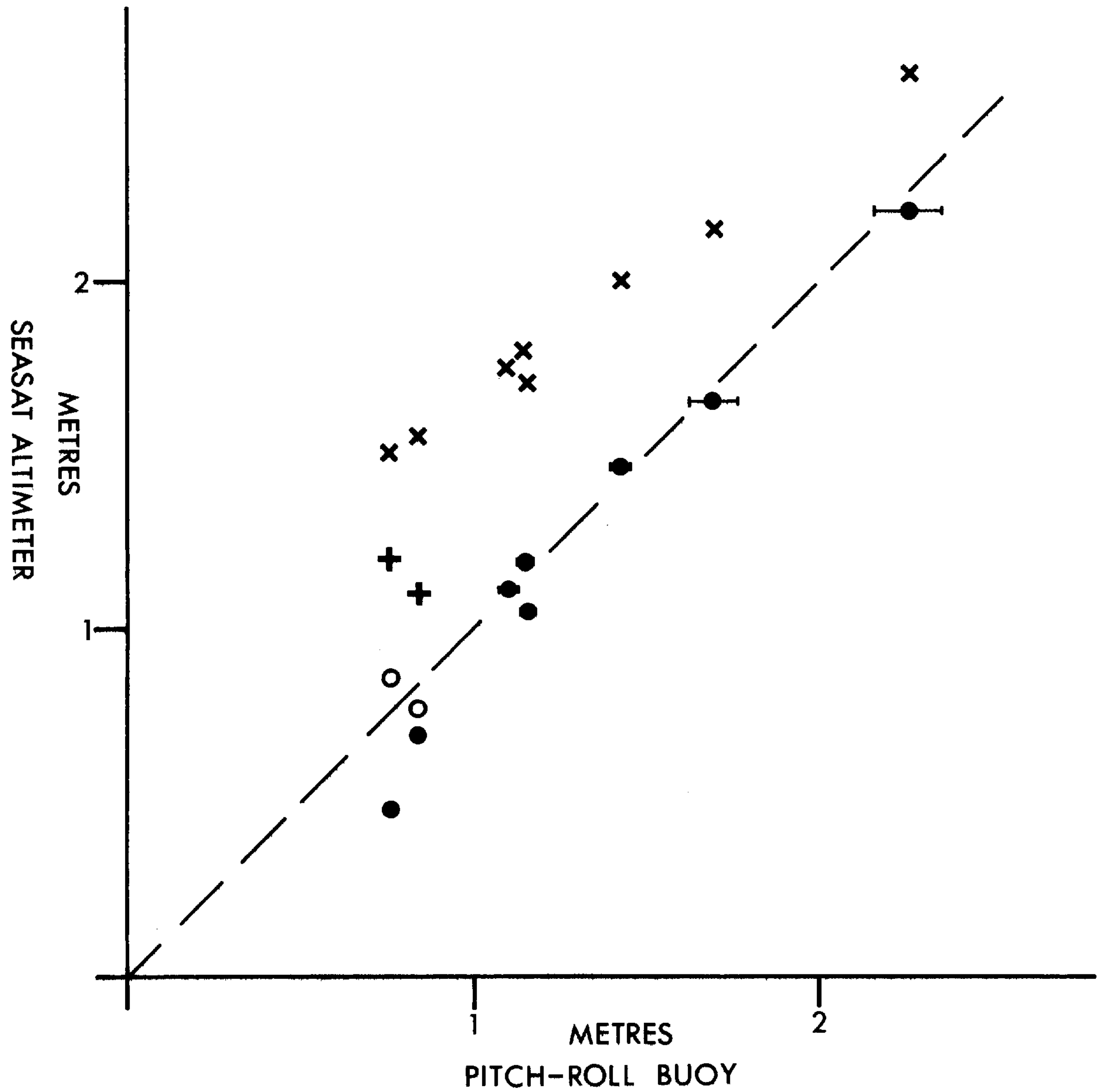

Figure 10: The altimeter and pitch-roll buoy estimates of wave height plotted against each other. ● Corrected and × uncorrected altimeter wave heights using gate 2. ○ Corrected and + uncorrected altimeter estimates using gate 1. The error bars refer to the pitch-roll buoy estimates only. The r.m.s. error on the uncorrected altimeter values is believed to be or order ± 10 cms.