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Design of an Integrated Shallow Water Wave Experiment

I. R. Young, M. A. Dalton, P. J. McMahon, and L. A. Verhagen

Abstract— **The experimental design and instrumentation for an integrated shallow-water surface gravity wave experiment is discussed. The experiment required the measurement of the water surface elevation, meteorological parameters, and directional spectra at a number of locations on a shallow lake. In addition, to acquire data under a wide range of conditions, an experimental period of three years was required. A system of telephone and radio modem links were installed to enable real-time monitoring of instrument performance at eight separate measurement locations on the lake. This system also enabled logging sessions to be optimized to ensure the maximum possible data return from this extended experiment.**

I. INTRODUCTION

Oceanographic experiments which employ *in situ* instruments have generally been conducted in a completely unattended mode. Instruments are deployed with preprogrammed logging sequences and recovered at a later date. As a result, there is little on-going monitoring of the experiment and consequently data return is often poor. In addition, such experimental designs preclude the flexibility of modifying logging sessions and other parameters to cater for changing environmental conditions. In contrast, laboratory experiments are based on a completely different philosophy. The experiment is highly controlled and the instrumentation is continually monitored and its performance assessed and modified.

This correspondence describes the experimental design and instrumentation associated with a large field experiment aimed at a detailed investigation of the evolution of wind-generated waves in water of finite depth. The experiment can be described as a monitored field experiment. As with all field experiments, the forcing meteorological conditions were at the whim of nature. Instrument performance was, however, continually monitored through an extensive telemetry system and performance continually optimized.

II. EXPERIMENTAL OVERVIEW AND CONCEPT

The experiment was staged at Lake George, approximately 40 km from Canberra, Australia. The lake is approximately 20 km long in the north/south direction by 10 km wide in the east/west direction, as shown in Fig. 1. The lake has an almost constant water depth of approximately 2 m. The experimental aim was to measure the evolution of the one-dimensional (1-D) spectrum, together with the wind speed and direction at a number of locations along the long north/south axis of the lake. For wind directions closely conforming to this axis, such measurements would provide a comprehensive understanding of fetch limited growth in water of finite depth. In addition, it was desired to obtain high-resolution directional spectra at one location near the center of the lake.

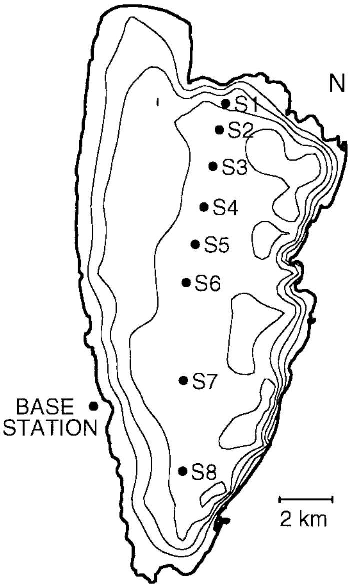

Fig. 1. Map of the Lake George experimental site. The measurement locations are labeled S1 to S8. Data were transmitted to the Base Station on the western shore of the lake where it was logged under computer control. The contour interval is 0.5 m, with a maximum contour value of 2.0 m.

Examination of historical data showed that northerly and southerly conditions occurred relatively infrequently. Hence, an experimental period of a number of years would be required to obtain a sufficiently comprehensive data set. Such an extended experiment would also have the advantage of ensuring that the water depth would vary through seasonal fluctuations, thus increasing the effective parameter range.

The protracted experimental period placed significant constraints on the experimental design. The instrumentation needed to be capable of operating for extended periods without routine intervention. As the desired north/south meteorological events occurred relatively infrequently, instrument performance needed to be continually monitored to ensure operation of all components during such events.

The final design consisted of a series of eight measurement stations as shown in Fig. 1. With the exception of station 6, each of these locations consisted of a minimum blockage space frame tower designed to present minimum interference to the wave field. A surface piercing wave staff (Zwarts pole [4]) was located at each station to measure the water surface elevation. The output of the instrument was digitized and transmitted in real time through a telemetry system to a base station (see Fig. 1) located on the shore of the lake. In addition, wind speed and direction, air and water temperature, and humidity were recorded as 10-min means and stored in on-board data loggers for down loading on maintenance visits. All instrumentation systems were powered by 12-V storage batteries. These batteries were recharged using solar cells.

The station in the center of the lake (S6) consisted of a large (5 m $\times$ 5 m) platform capable of housing personnel for specific experiments requiring human operation. In addition to a Zwarts pole which transmitted data in real time as at the other locations,

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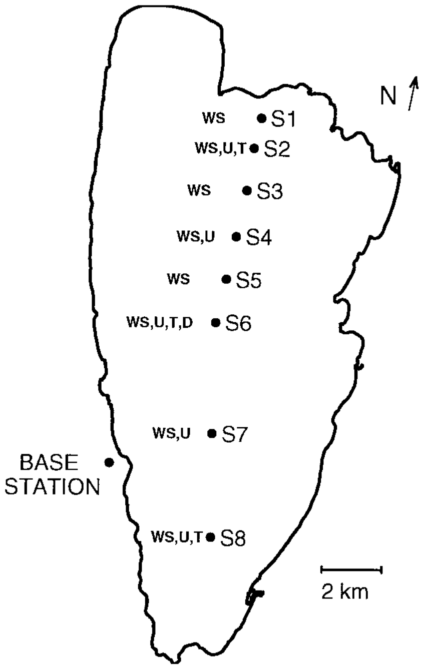

Fig. 2. Schematic diagram showing the various quantities measured at each of the stations. The stations are labeled S1 to S8. The quantities measured at each of these stations are: WS—water surface elevation; U—wind speed and direction; T—air and water temperature; D—directional spectrum.

all meteorological data were also telemetered from this location. Adjacent to the platform was a seven-element surface piercing wave array. Analysis of data from the array yielded high-resolution directional spectra. The array was connected to the platform by a series of cables laid on the lake bed. Logging of the array was controlled by a conventional personal computer located on the platform. This computer could be turned on and off with a code transmitted through the telemetry system from the base station. Once operating, the computer could be controlled remotely through a radio modem link to the base station and data acquisition commenced.

A telephone modem link was established between the base station and University College in Canberra. With the aid of this link, the performance of all instruments could be monitored. In addition, the computer on the platform could be turned on and logging of the directional array initiated. In this manner, the entire experiment could be operated remotely. Real-time data were continually available from all stations on the lake and instrument performance continually assessed.

A diagram showing the various quantities measured at each of the stations is shown in Fig. 2.

III. WAVE STAFFS

The primary sensing elements in the experimental design were Zwarts Poles [4] which were used to measure the water surface elevation. This instrument utilizes the difference in dielectric constant between the air and water to sense the water surface elevation. An electromagnetic wave, directed toward the water surface along a transmission line, will reflect from the water surface. The time it takes for the wave to travel from the source to the water surface and back is a direct measure of the water surface elevation. Rather than transmit a pulse down the transmission line and attempt to measure the time delay, the instrument sets up an electromagnetic oscillation in the line, the length of the line determining the frequency of oscillation. The transmission line was constructed in the form of two concentric aluminum tubes forming a co-axial transmission line. The final system consisted of tubes with outer diameters of 50 mm and 25 mm and an annular gap of 8 mm. Holes in the outer tube allowed water to enter and leave the annulus.

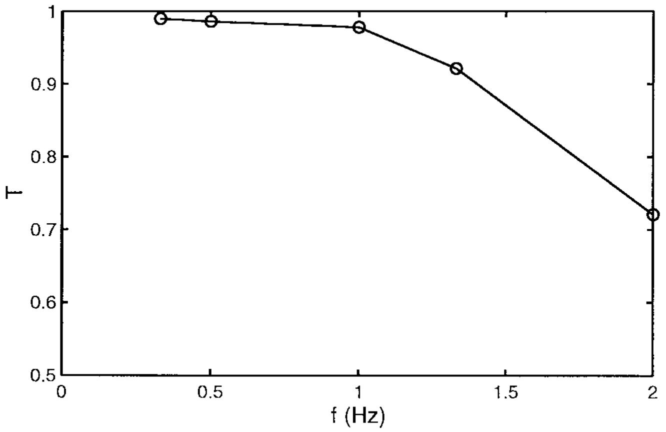

Fig. 3. Zwarts pole transfer function, T, as a function of frequency, f, obtained by oscillating the sensing element vertically in still water.

The restriction to flow represented by the holes and the physical size of the pole (outer diameter 50 mm) obviously degrades instrument performance at high frequencies. During the instrument design phase, a series of dynamic calibrations were conducted to optimize the number and configuration of these holes. Poles were oscillated vertically in still water using a pulley and eccentric cam system whilst the position of the pole and the output from the pole were coincidently logged. The results of these calibrations for the final hole configuration are shown in the transfer function of Fig. 3. The transfer function is relatively flat for frequencies less than approximately 1.2 Hz but rapidly decays above this point.

As there was some doubt as to whether oscillating the poles in still water accurately represented the flow experienced by the poles, *in situ* comparisons were performed against twin wire resistance wave gauges. The wave gauges were sampled at the higher rate of 20 Hz to also investigate whether aliasing effects were significant at the lower 8-Hz sampling rate used for the Zwarts poles. A total of 18 intercomparisons were conducted at wind speeds ranging from 5 to 14 m/s. The results showed that the frequency response was poorer than indicated by the laboratory dynamic calibrations. In addition, the transfer function was not simply a function of frequency, f. Over the wide range of conditions tested, the transfer functions appeared to depend on the frequency of the spectral peak, f_p, and could be expressed in terms of f/f_p. This is attributed to the fact that it is the vertical velocity of the water surface that limits the instrument performance. The high-frequency waves are superimposed on the longer waves near the spectral peak. Thus the local water surface slope (and the vertical velocity) is influenced by all spectral components, not simply a single spectral component as assumed in the laboratory tests. The transfer function, averaged over all 18 tests and scaled in terms of f/f_p, is presented in Fig. 4. The transfer function was represented by a polynomial approximation as shown in Fig. 4 and used to correct all recorded data. Beyond $f/f_p \approx 5$, the transfer function becomes flat, indicating the high-frequency limit of the instrument. This is partly caused by the signal-to-noise ratio (SNR), but mostly by the diameter of the sensing pole. In response to this limitation, all spectra were truncated at $f/f_p = 5$. The transfer function exhibits erratic behavior for $f/f_p < 1$. This is caused by the fact that there is very little energy in the recorded spectra for

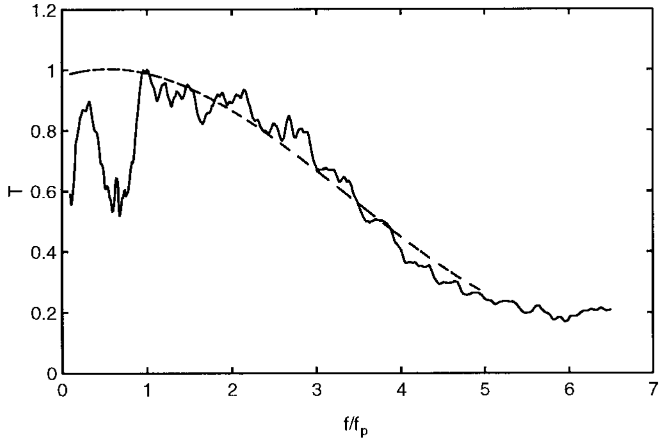

Fig. 4. Zwarts pole transfer function, T, obtained from *in situ* comparisons with a twin wire resistance gauge. Results are presented in terms of f/f_p. The dashed line represents the polynomial approximation used during the data reduction procedure.

$f/f_p < 1$. Hence, the calculated transfer function is unreliable in this region. It is believed that the Zwarts pole response continues to improve as the frequency decreases. Therefore, the polynomial approximation to the transfer function was forced to a value of one for $f/f_p < 1$.

The Zwarts pole has a number of significant advantages over comparable instruments. In contrast to resistance or capacitance gauges, Zwarts poles are physically robust, enabling long deployment periods without maintenance. Mild fouling of the instrument by aquatic growth has negligible influence on instrument performance. Naturally, however, the frequency response will degrade as the holes linking the tubes become blocked. Importantly, the instrument calibration is insensitive to changes in salinity, in contrast to alternatives.

In order to ensure that there was no long-term variation in the Zwarts pole calibration, the poles were recovered at approximately 1-year intervals and recalibrated. Over the approximately 3-year deployment period, no measurable change in the transfer function occurred.

Output from the Zwarts pole was in the form of an approximately 1200-Hz square wave (frequency changes with water surface elevation). The period of this square wave is directly proportional to the length of the air gap from the source at the top of the pole to the water surface. This period was determined using a 9.8304-MHz counter. The counter was triggered by a positive edge of the square wave and counted the period of four successive square waves. This was repeated at a frequency of 8 Hz. The four waves counted were sufficient to ensure stable results whilst maintaining the requirement that the sample be approximately instantaneous in time. These counting and timing tasks were controlled by two programmable array logic (PAL) chips. The final output was a 2-b value proportional to the water surface elevation. These two bytes were combined with an additional 2-b sequence count for transmission by the telemetry system (see Section V).

IV. DIRECTIONAL ARRAY

In addition to measuring the evolution of the 1-D spectrum with fetch, high-resolution measurements of the directional distribution of wave energy were also required. These data were obtained with a spatial array consisting of seven Zwarts poles as shown in Fig. 5. The poles were arranged in the form of a "Mercedes Star" with a central gauge and two rings of three gauges at radii of 0.20 and 0.55 m, respectively. The gauges were coincidently burst sampled at 8 Hz and the directional spectrum formed using the maximum likelihood method (MLM) [1]. Time series of duration 30 min were collected from each gauge. These time series were subdivided into 112 blocks, each of 128 points for subsequent Fourier transformation as part of the MLM analysis.

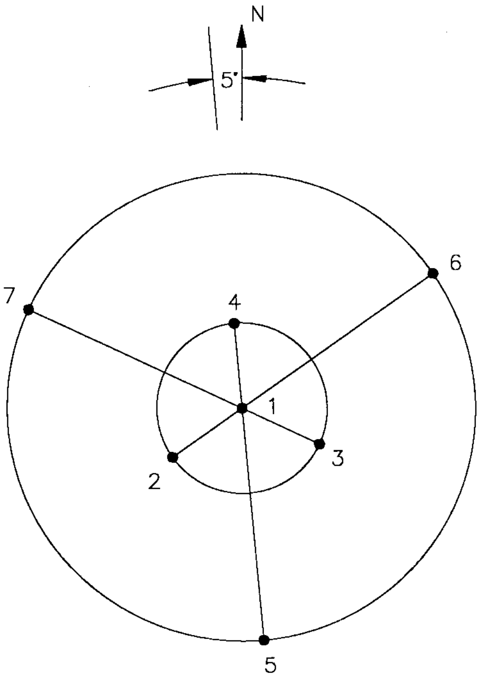

Fig. 5. Geometry of the seven-element directional array. Elements 2–4 were at a radius of 0.20 m and elements 5–7 were at a radius of 0.55 m.

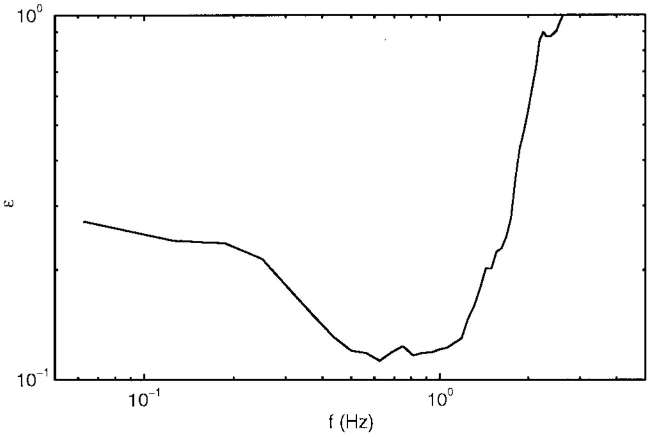

Fig. 6. The mean relative error ϵ for the directional array as a function of frequency. The frequency range of interest is 0.1 Hz $< f <$ 1 Hz for which ϵ is small and hence the array geometry is optimal.

The first step in determining the directional wave spectrum using the MLM from the coincidentally sampled water surface elevation records for each of the gauges is to form the cross spectra between all array elements. For an assumed directional spectral form, the cross spectra can be determined numerically. These cross spectra can then be processed by the MLM and the resulting directional spectrum compared with the initial input form. In order to assess the directional resolving power of the present array and analysis technique, a spreading function of the form $\cos^{2s}\theta/2$, where θ is

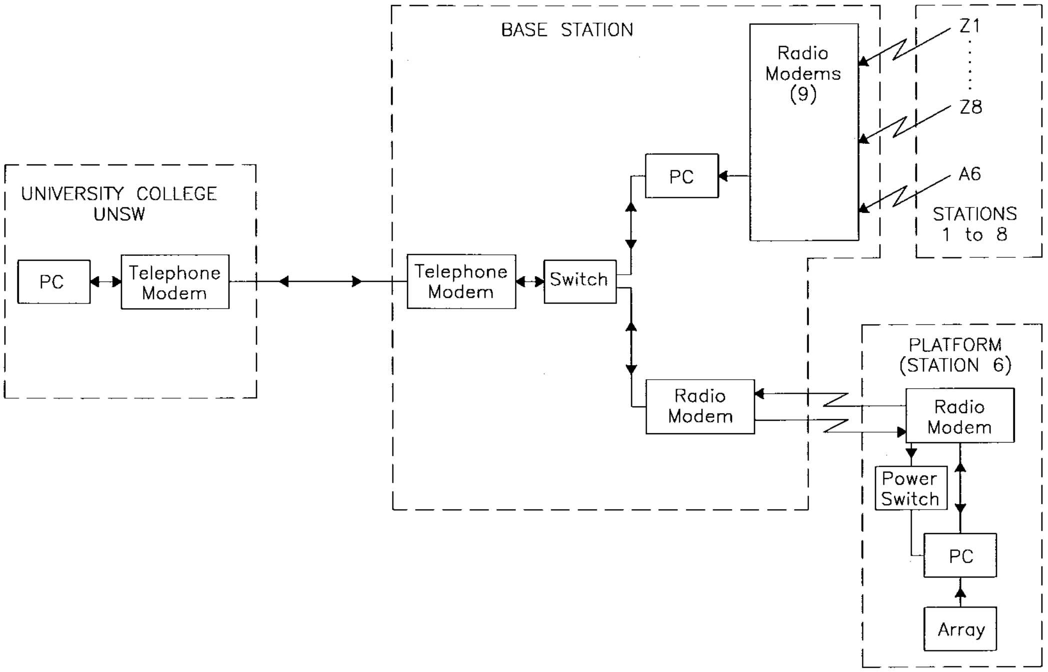

Fig. 7. Block diagram showing the data links between the various components of the experiment. The Zwarts poles are marked as Z1 to Z8 and the anemometer at Station 6 as A6. Equipment was located in four physical locations shown by the dashed boxes: University College, Canberra; Base Station; Lake Stations 1–8, and the Platform (Station 6).

direction and s is an exponent defining the spectral width [2] was assumed. A constant value of $s = 10$ was adopted at all frequencies. A small amount (1% of maximum spectral ordinate) of incoherent noise was also added to each spectral ordinate.

The directional resolving power of the instrument and analysis technique can be assessed in terms of the mean relative error, $\epsilon(f)$:

$$\epsilon(f) = \frac{\int |F(f,\theta) - \hat{F}(f,\theta)| d\theta}{\int F(f,\theta) d\theta} \tag{1}$$

where $F(f,\theta)$ is the initial analytical test spectral form and $\hat{F}(f,\theta)$ is the form recovered by the MLM analysis.

The values of $\epsilon(f)$ are shown as a function of frequency in Fig. 6. Peak spectral frequencies for the present data set are typically 0.3 Hz. It is desired to obtain reliable directional spectra within the range $0.3 < f/f_p < 3$ or $0.1 \text{ Hz} < f < 1 \text{ Hz}$. As can be seen in Fig. 6, the array geometry is optimally designed to resolve this frequency range. At low frequencies, the array performance is limited by the measurement accuracy of the array elements, whereas at high frequencies (>2 Hz), the finite spacing between array elements leads to spatial aliasing.

As demonstrated by Young [3], all array geometries and analysis techniques yield directional spectra $[\hat{F}(f,\theta)]$ broader than the input form $[F(f,\theta)]$. However, this artificial broadening can be assessed in a manner similar to that described above. The magnitude of the broadening is a function of the spectral width as defined by the parameter s. Broad spectra, $s \approx 1$, are well represented by the array whereas narrow spectra, $s \approx 15$, are significantly broadened. As the extent of artificial broadening can be determined as a function of s, the spectra obtained from the array can be corrected for the artificial broadening. As a result, spectra with very high directional resolution can be obtained.

The array was located approximately 20 m from the research platform at Station 6 (see Fig. 1). Cables laid on the lake bed connected the array to the platform, from which power was supplied and where the array output was logged. The same counter design was utilized to convert the square wave outputs of the individual elements of the instrument into digital values. In this case, however, the eight individual counter systems were constructed on a prototyping board and incorporated within a conventional PC located on the platform. This computer was operated remotely from the shore (see Section V).

V. MONITORING AND TELEMETRY SYSTEM

An essential consideration in the experimental design was the ability to remotely control and monitor the full experiment. Fig. 7 shows a schematic diagram of the telecommunication links established to control the experiment. A 1200-baud telephone modem link was established between University College in Canberra and the base station on the shore of the lake. A switch based on PAL circuitry and located within the base station could be flipped by the transmission of a control character. Flipping the switch into one state connected the user to a PC located at the base station. Once connected to this PC, the public domain software package, PC-ELSEWHERE, was used to remotely take control of this PC. Data at a rate of 8 Hz were continuously transmitted from the Zwarts poles located at Stations 1–8 and acquired by the PC. In addition, anemometer data were transmitted from Station 6 (Platform) at a rate of 1 Hz and acquired by the PC. The telemetry system was based on FM radios in the 800-MHz band and 1200-baud modems. These telemetry links were unidirectional. As there was no microprocessor control at the measurement locations, lost data could not be retransmitted. Each data value was, however, tagged with a sequence count which was used to identify missing or corrupted data. As the maximum transmit path was approximately 16 km, data transmission errors were relatively rare and easily handled in the data postprocessing. Each station transmitted on a separate frequency and was connected to the base station PC through separate 1200-baud radio modems and a multiple serial port board. Software was written to continually poll these serial lines, store data to disk, and report errors. In this manner, real-time monitoring of wave and wind conditions, at all locations, could be conducted remotely.

Flipping the remote switch to the opposite state by the transmission of another control sequence provided access to a duplex radio modem link to the platform (Station 6) in the center of the lake. Transmission of a further control sequence closed a PAL-based power switch at the platform, thus powering the platform PC. Once booted, this PC automatically wrote a welcome message to its serial port. This message was transmitted through the telemetry and telephone links to be registered at our laboratory in Canberra. Once received, the PC-ELSEWHERE software could be initiated to take control of the PC at the platform. Logging sessions for the directional array could then be initiated remotely.

Power for the platform PC was provided by 12-V storage batteries and a 240-V inverter. The batteries were recharged by a bank of solar cells. The PC could be remotely switched off by the transmission of a control sequence to open the power switch. To prevent the PC being accidentally powered up indefinitely, the power switch was fitted with a simple timer. Once the PC was powered up, it would remain in this mode for a period of 40 min before the timer opened the power circuit. This period of operation provided sufficient time for a 30-min logging session of the directional array as well as general "house-keeping" tasks.

Initially, there was concern that noise might inadvertently trigger the platform power switch. For this reason, the PC kept a log of the time and date of each time it was powered up. During the approximately 3-year period in which the array operated, there was no evidence of a single erroneous power-up sequence.

VI. CONCLUSION

The design constraints for the proposed experiment were such that the instrumentation needed to operate for an extended period (three years) with minimal routine maintenance. In addition, as the north/south events for which the experiment was designed occurred relatively rarely, operation of the multiple sites during these events was critical. The design philosophy was to construct special-purpose surface-piercing wave staffs with frequency response optimized for the relatively high-frequency waves generated at the short fetch and shallow waters of the field site. The Zwarts poles which were designed for this purpose were extremely reliable and robust. During the three-year experiment period, not a single Zwarts pole system failure occurred. In addition, the flexibility of these instruments and physical robustness enabled the construction and deployment of a spatial array designed to give optimal resolution of the directional spectrum for the typical wave lengths expected.

A combination of low-cost telephone and radio modem links was utilized to fully monitor the experiment. In this manner, real-time data acquisition and monitoring of the vast majority of the instruments was possible. In addition, simple switches, based on PAL circuitry, which could be operated by the transmission of control characters over the telemetry system enabled operation of instrumentation which was needed only when meteorological conditions were suitable. In this manner, power supplies and data storage requirements could be most efficiently used.

The underlying design philosophy of physically robust instrumentation based on relatively simple circuitry, coupled with real-time monitoring proved a highly efficient concept. The resulting data set is the most comprehensive finite-depth, fetch-limited investigation ever conducted. A total of approximately 70 000 30-min time series of water surface elevation, together with the relevant meteorological parameters, were recorded. The careful experimental design ensured this high-quality data return.

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