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Determining Wave Run-Up Using Automated Video Analysis

Donald G. Bailey and Roger D. Shand

Image Analysis Unit, and Geography Department
Massey University, Palmerston North
E-mail: D.G.Bailey@massey.ac.nz

Abstract

Wave run-up characteristics are important to a variety of coastal workers. Traditional methods of collecting the data encounter instrumentation difficulties, operator subjectivity, and high labour input and cost. By video taping the wave motion and then applying image processing techniques, these problems are overcome thereby enabling the collection of large spatial and temporal data sets.

The video record is replayed into an image analysis system which captures the intensity variation along one (or more) shore-normal transects. The resulting time-stack visually depicts the run-up motion as a function of time. An algorithm has been developed that is capable of automatically tracking the foamy water (swash) edge under most conditions.

Tracking errors may result from cloud or rain induced low contrast, foam accumulations associated with high energy conditions, or camera vibration caused by high winds. By observing the tracking characteristics in these situations and then simulating such "errors" on "ideal" output, it is found that their effect on the frequency spectrum, which is a typical end use of run-up data, is superficial in most cases.

1.0 Introduction

Determining the nature of wave run-up on a beach-face is important to coastal works: planners in defining hazard zoning and set-back criterion, engineers in designing shoreline protection and other structures, and scientists in their efforts to understand past sea levels, landscape evolution, contemporary nearshore morphodynamics with particular emphasis on low frequency water level motions, and a variety of other coastal phenomenon.

The term run-up is commonly used to describe the height or elevation to which a wave runs up the beach-face with the thin sheet of (usually broken or foamy) water being described as swash on the way up and backwash on the return [1]. Duncan [2] identified the lower limit of this swash/backwash cycle being where the sand is momentarily exposed. To convert the slope-based excursions described above into vertical and/or horizontal components the beach profile must undergo some form of survey, for example see [3-5].

In this paper the terms run-up and swash will be used interchangeably to refer to the continuous oscillations of water across the beach-face. The terms swash-front or swash- edge will refer to the actual boundary between sand and water. No consideration will be made of the vertical or horizontal components.

Previous methods of run-up sampling will be summarised and the associated limitations and difficulties outlined. The development of a video-based swash-front detection procedure using image processing is then described. This procedure overcomes many of the problems of previous methods and facilitates collection of the spatially and temporally extensive sets of run-up time series data which investigations often require. The final section evaluates the effectiveness of the new technique. As run-up measurements reflect a variety of fluid motions with differing amplitudes, periods and directions, spectral analysis is often applied to such hydrodynamic data. This, therefore, forms the basis of the evaluation criterion regarding tracking variation (error).

2.0 Previous Methods of Run-up Sampling

While run-up spectra can be derived from nearshore current records using shallow water wave theory [6], it is logistically simpler to directly measure run-up at the beach-face where a variety of sampling techniques have been used.

The use of dual resistance wires established across the beach face was described by Guza and Thornton [7] and appraised by Holman and Guza [8]. The technique was objective and the analog sensor's output easily digitized. However, it was sensitive to wire height and gain which resulted in a variance of 25%. There was also a phase error especially at higher frequencies. Field deployment was critical, and prone to fouling especially during high energy events.

Time-lapse photography using movie cameras and manual digitization by detecting the swash-front on individual frames taken one second apart has been a common procedure, for example see [9-12]. This method was found by Holman and Guza [8] to be low cost, easy to deploy even during high energy conditions, had the potential for digitizing a number of longshore ranges, and let the user "see" the phenomenon. The tedious and subjective nature of manual swash-front tracking was the major drawback with times of 30 minutes to digitise a 2048 point time series being reported. Visibility constraints, for example fog or lack of daylight was also a limitation. Using different operators, they found a standard deviation of up to 10% and that spectral coherences were losing significance for frequencies above 0.05 Hz.

Differences between measuring techniques can only be treated in terms of an intercalibration factor [8]. Their comparison using the same run-up field found systematic differences between these direct and remote sensing approaches. The film technique had a slightly higher mean (set-up) but much greater swash excursion variance - the difference being 83% This was attributable to the wires being higher than the swash thickness at its excursion extremes.

More recently, video recordings have been used and two digitization procedures developed. Quasi real time processing using an image processing package to search individual transects at regular time intervals has been used by Holman et al [13].

Alternatively, construction of an image by capturing intensity values along a profile of interest at regular time intervals and stacking them has enabled clear identification of the swash-front through the sampling period. Aagaard and Holm [3] developed this time-stack method. They then manually digitized the swash-edge. The digitization of a 2048 point (34 minute) series took approx 30 minutes and the estimated replicate standard deviation was 5%. The reduced error relative to the earlier frame by frame manual digitizing method has been attributed to the greater ability to estimate indistinct edges using the time-stack.

Holland and Holman [14] have further automated the time-stack procedure by applying standard image processing algorithms to detect the swash-edge. Manual refinements were still required as their method could not cope in situations with low contrast between the swash and beach. Such conditions, however, are characteristic of cloud and rain and as this often accompanies higher energy events it is important that the associated run-up data can be determined.

3.0 Field Measurement

Run-up sampling for this exercise was carried out using a Panasonic MS1 video camera set up on a 45 m high cliff overlooking an oceanic coast of moderate to high wind and wave energy on the southwest coast of New Zealand's North Island. The site was 100 metres behind the foredune toe and the camera was directed seaward. The same camera orientation angles were achieved for all samples by using ground control points. These were also used for locating run-up transects. Figure 1 shows the camera view with three shore-normal transects having been selected. Multi-transect measurements are useful in determining wave type by examining the longshore phase relationship [12].

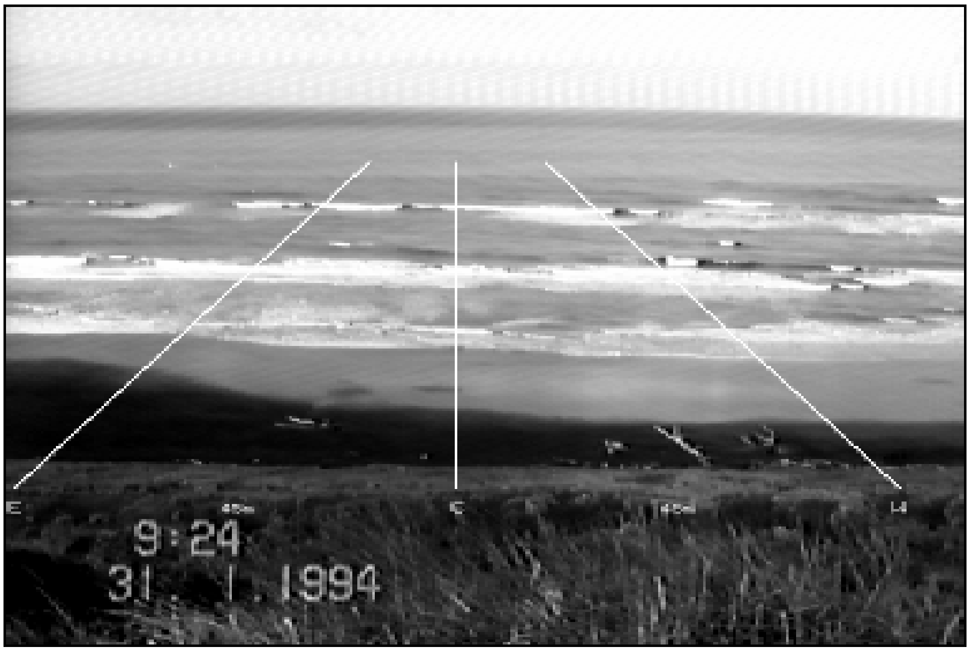

Figure 1: A video still of the field site with three shore-normal transects marked.

4.0 Image Processing Procedure

For this application, it is required that the process of extracting the swash-edge from the videotape be automated as much as practical to reduce the effects of operator subjectivity and the time associated with manual digitisation. The steps required to accomplish this will be described in turn.

4.1 Transect selection

The purpose of this step is to select the transects along which data is to be taken from the videotape. Run-up studies often require multiple shore-normal transects and replicability over time. To facilitate this, a permanent marker post has been established directly seaward of the camera and behind the foredune. When the swash is videotaped, this marker is positioned in the centre of the field of view horizontally, defining the position of the central transect. For this exercise, two additional transects 45 m on either side of the central transect are also used. In principle, these could be calculated knowing the position of the central transect and the focal length of the lens. In practise, they were determined by measuring along the beach before the study started. The transect lines are defined by the points on the beach at one end, and where the central line intersects with the horizon at the other end. (Actually the intersection point is slightly above the apparent horizon because of the curvature of the earth [15]). If the same focal length lens is used in obtaining all of the videotaped samples, the positions of the side transects may be precalculated.

On the image processing system, a single image frame is captured from the video player. This is of the form of figure 1 (without the profile lines). The user locates and indicates the position of the permanent marker using the mouse. This determines the position of the central transect both horizontally and vertically within the image, and therefore the positions of the two side transects which are at precalculated offsets from the centre.

Since the sample length varies from 10 minutes to several hours, this needs to be specified at this stage. Because of computer memory limitations, the maximum length that may be captured at any one time is limited to 68 minutes. However, this does not pose a problem as longer samples may be captured in sections (with 2 to 4 minutes overlap) and spliced together after processing. Samples of up to 180 minutes (one full videotape) have been captured in this manner.

4.2 Time series digitisation

The next step is to capture the data from the videotape and form a time-stack. To do this, the videotape is rewound to the start of the sample, and played into the image processing system. Every quarter of a second, a single frame is captured and a 3 pixel wide strip along each of the three transect lines is loaded from the frame buffer memory into the computer. The data in each strip is then averaged horizontally to reduce noise, and the result inserted into a single column in the time-stack image. By inserting the results of successive frames captured into successive columns of the time-stack, a picture of what happens along each transect as a function of time is built up. Figure 2 shows a 6 minute segment of the time-stack for the central profile in figure 1.

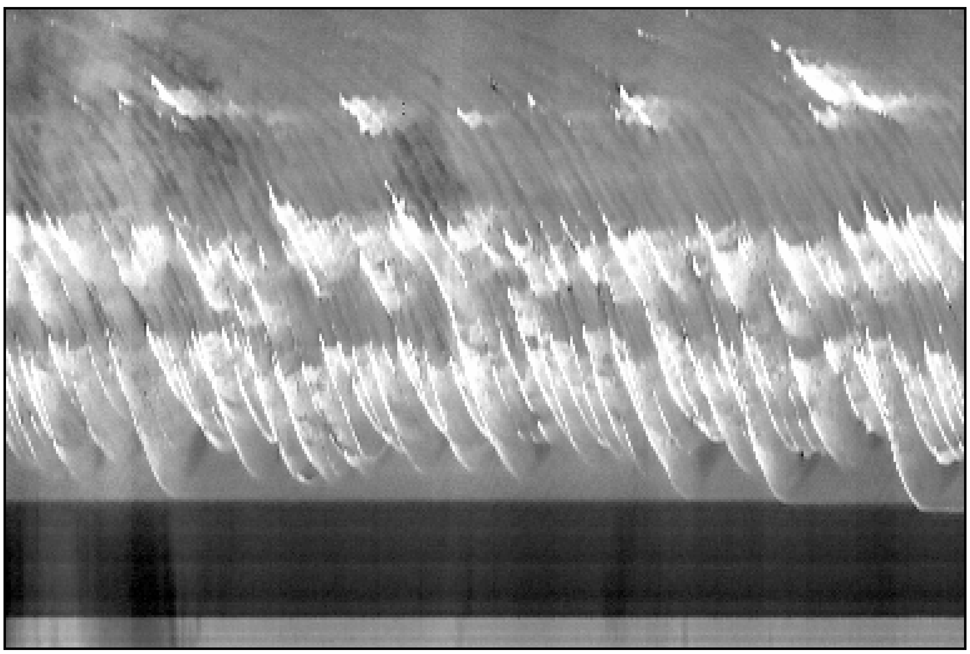

Figure 2: A 6 minute section of the time stack from the centre profile.

Although this paper is primarily concerned with measuring run-up, there are several features within figure 2 of interest. The four or five white patches along the top of the image are waves breaking on the outer bar. The periodic nature indicates the presence of low frequency (approximately 0.013 Hz) sea level changes which may be associated with wind wave grouping [16]. The band of white across the image just above half way corresponds to waves breaking on the inner bar. Further down the image is the trough (the area where almost no waves are breaking) and then the secondary breakers and swash zone. The dark area below that corresponds to the unsaturated beach surface. The average intensity of the waves breaking gives an approximate indication of the water depth along the profile [17]. Individual waves may be identified by the diagonal lines moving from upper left to lower right. As the horizontal axis corresponds to time, if the image was corrected for perspective distortion, the slope of these lines would give a measure of the wave speed.

4.3 Selection of the swash region

Each time-stack contains an enormous volume of data. For example, a 60 minute sample generates three time-stacks, each containing about 3.6 Mbytes. In wave run-up studies, only the swash zone is of immediate interest. Cropping out the unnecessary parts from the time-stack reduces the image size by about a factor of 3, speeding subsequent processing. It was also found that without cropping, the detected swash front occasionally went out to the first sand bar when there was swash activity and low contrast.

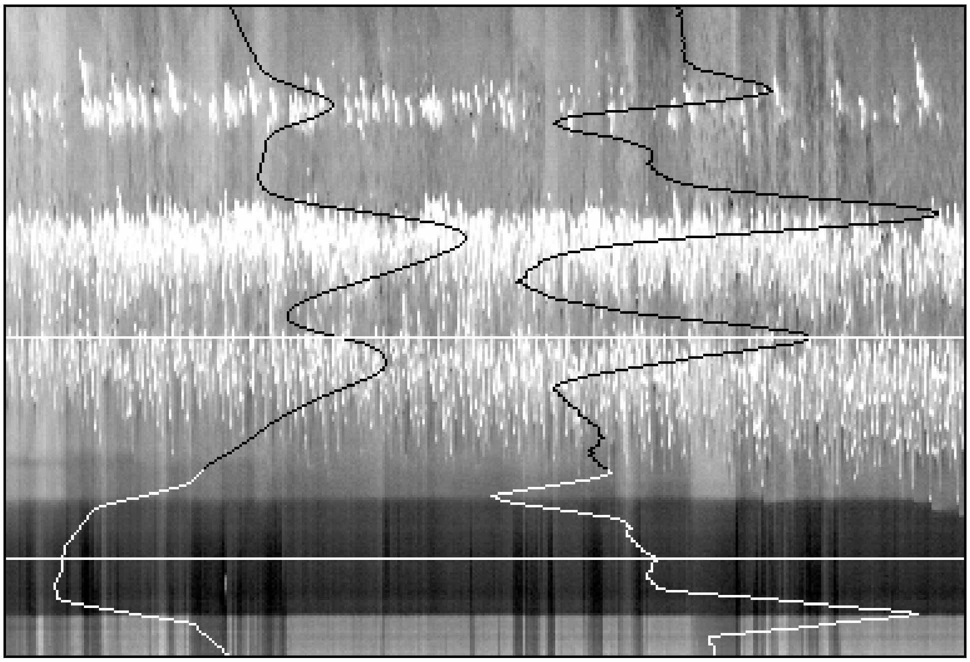

Figure 3: Compressed time stack (52 minutes) with plots of the average intensity (left) and intensity gradient (right). The region of interest crop lines are shown.

On the landward side of the swash zone, the image may be cropped anywhere on the unsaturated sand, ensuring that enough image is kept for the swash from the largest waves not to be clipped. On the seaward side, the boundary between the secondary breakers and the trough allows for maximum swash excursion when tracking while preventing errors from jumping out to the bar when there is no visible swash activity.

A procedure was developed for this step to assist the user to select appropriate cropping positions, and to remove much of the subjectivity involved. The first step is to calculate the average of the intensities of each row in the image. This average is plotted in the left half of figure 3. This is then differentiated to give the average intensity gradient (shown in the right half of figure 3). The complete time stack is compressed onto a single screen, and the intensity gradient plotted. The user is asked to select with a mouse points on the sand landward of the saturation line and on the trough seaward of the swash zone. The program then adjusts the selected points to the local maxima of the intensity gradient, and draws the limits of the swash zone, as shown in figure 3, for confirmation. The section corresponding to figure 2 is shown cropped in figure 4A.

The variation of intensity and contrast in figure 3 is caused by passing clouds.

4.4 Swash front tracking

This step takes the cropped image and detects the boundary between the sand and water. The swash is clearly defined by the heavy white lines moving downwards towards the right. The backwash is less distinct, often showing as "shadows" to the right of the swash peaks. While it would be desirable to track the backwash, this is often not possible because of its much lower and variable contrast. A more convenient approach is to track to the swash peak and then allow jumps back to the next wave. Our testing showed that the exact nature of the return track had an insignificant effect on the spectral output at the low frequencies (below 0.1 Hz). The processing sequence is as follows:

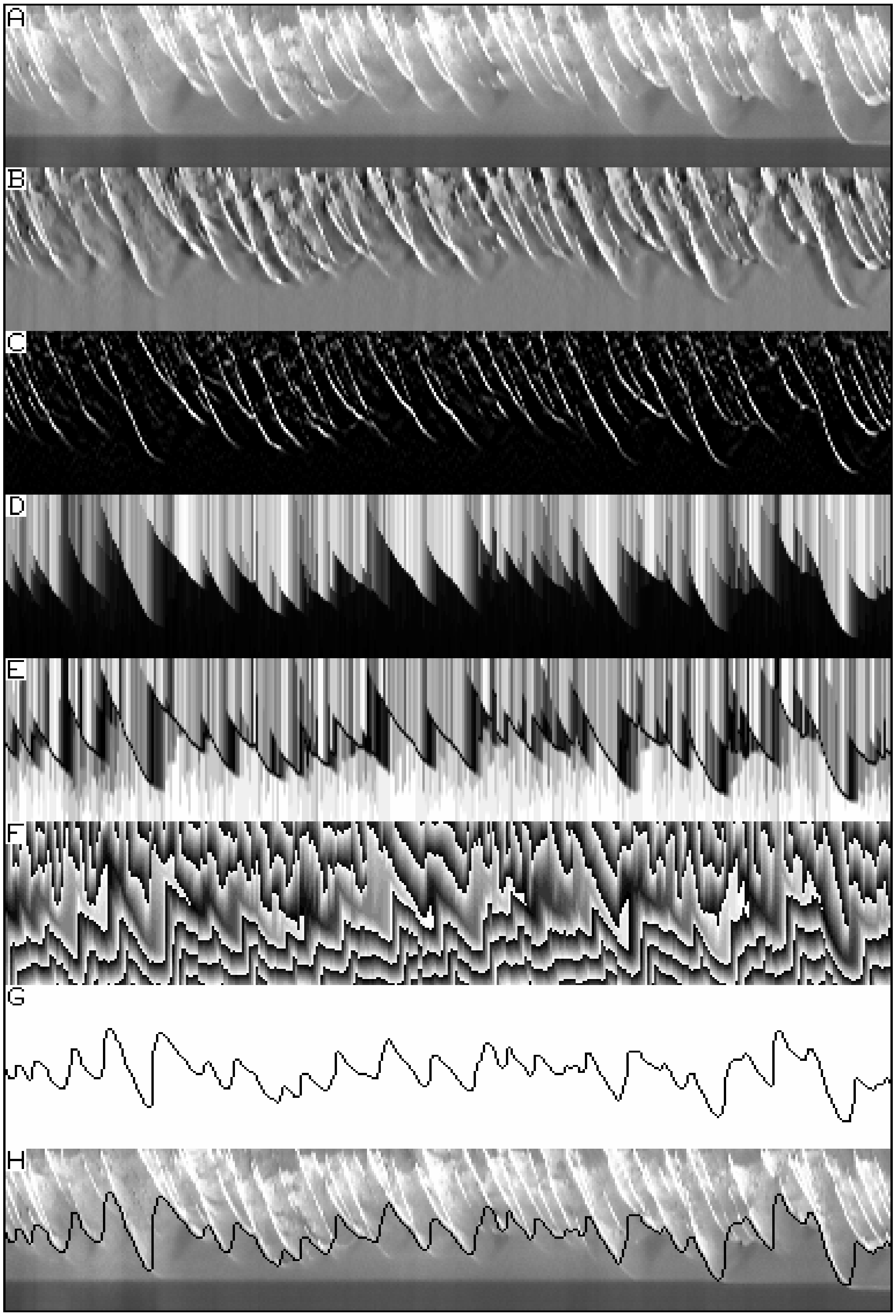

Figure 4: Swash tracking sequence: A) cropped image; B) background removed; C) vertical edges; D) smeared upwards; E) tracking penalty function; F) path cost; G) least cost path, representing tracked swash; H) path overlaid on original

1) Subtract out a horizontal average. One significant boundary in figure 4A is the line between the saturated and unsaturated sand. This boundary changes position slowly, except when the swash crosses it, as it does on the right hand edge of the figure. Other horizontal features that don't move, or only move slowly with time are debris on the beach, or, more importantly, accumulations of foam under high wind conditions. With a strong onshore wind, the foam associated with the swash comes in with the swash, but as the water recedes the foam tends to sit at the swash maximum before slowly dissipating. By averaging using a 1 x 55 pixel window (corresponds to about 14 seconds) and subtracting this average from the image, such slowly varying features are eliminated. The resultant image is then contrast stretched, giving figure 4B.

2) Detect vertical edges. The swash edges may then be detected using a linear difference filter with the result shown in figure 4C. This step has been made effective by the removal of horizontal features in step 1. The backwash, having little or no contrast, is not detected unless it is accompanied by foam. As the swash reaches its maximum landward incursion, there is a often a reduction in contrast and the strength of the detected edge is correspondingly reduced. This is caused in part by the removal of the horizontal average in the previous step. Variations in contrast caused by passing clouds also tend to affect this area the most, and therefore require compensation in later steps.

3) Smear the edges upwards. By definition, anything behind the swash is in the water. Therefore, to assist the algorithm in tracking the swash edge past gaps within the edge, and making jumps from the swash maximum to the next swash, the detected edges are smeared seawards. This may be accomplished by processing the image from the bottom row upwards. If a pixel is less than the pixel below it, the value from below is copied up. The effect of this is to fill in behind the swash edge as shown in figure 4D. Gaps within the detected swash edge appear as darker vertical bands within the image. The smearing process also provides convenient links between the different waves.

4) Normalise the local contrast. Variations in contrast, formed either by a series of weak waves or by passing clouds (one small region is apparent toward the left hand end of figure 4D), are normalised at this stage. The top row of the image contains the maximum value in each column (as a result smearing operation). This is averaged horizontally using a 1 x 35 pixel window (corresponding to about 9 seconds) to obtain the trends in contrast rather than isolated variations. The image is then divided by this average to enhance the contrast where it is lower. This step enables the swash edge to be successfully tracked in all but the worst conditions. Keeping the average short allows for the compensation of even sudden changes in contrast caused by scattered cloud.

5) Define the edge region. The steps till now effectively place a boundary on the seaward extend of the swash line. Pixels with a value greater than 128 are very likely to be on the seaward side of the line, and those with values less than 128 are likely to be on the landward side. The edge region is therefore those pixels with values close to 128. However, simple thresholding is not appropriate in this instance because the contrast at the swash peak drops off gradually giving a wide indistinct region. The approach taken was to blur the image slightly (by averaging with a 3x3 window) to ensure that all edges contained pixels of intermediate values, and then calculate the absolute difference with 128. This (figure 4E) defines the edge regions, where the lower pixel values are candidate edge pixels.

6) Find the least cost path through the edge region. One approach to extract the "best" edge from figure 4E is to treat it as an optimisation problem with the pixel values in the image as a penalty function. The cost of a path from the left hand edge to the right hand edge can be defined as the sum of the values of the pixels making up that path. The path which has the smallest sum is therefore the best path, and defines the swash edge. This path is shown in figure 4G, and overlaid on the original image in figure 4H. This approach has the benefit that it is able to skip over small gaps in the defined swash boundary.

4.5 Editing

A manual editor has been included with the programme. It operates by clicking the mouse at a series of points along the desired path where serious mistracking has occurred. The selected points are simply joined with straight lines. However, it is desirable to avoid editing if possible because it is time consuming, and also introduces user subjectivity. Fortunately, our investigations found that it was rarely necessary to use it.

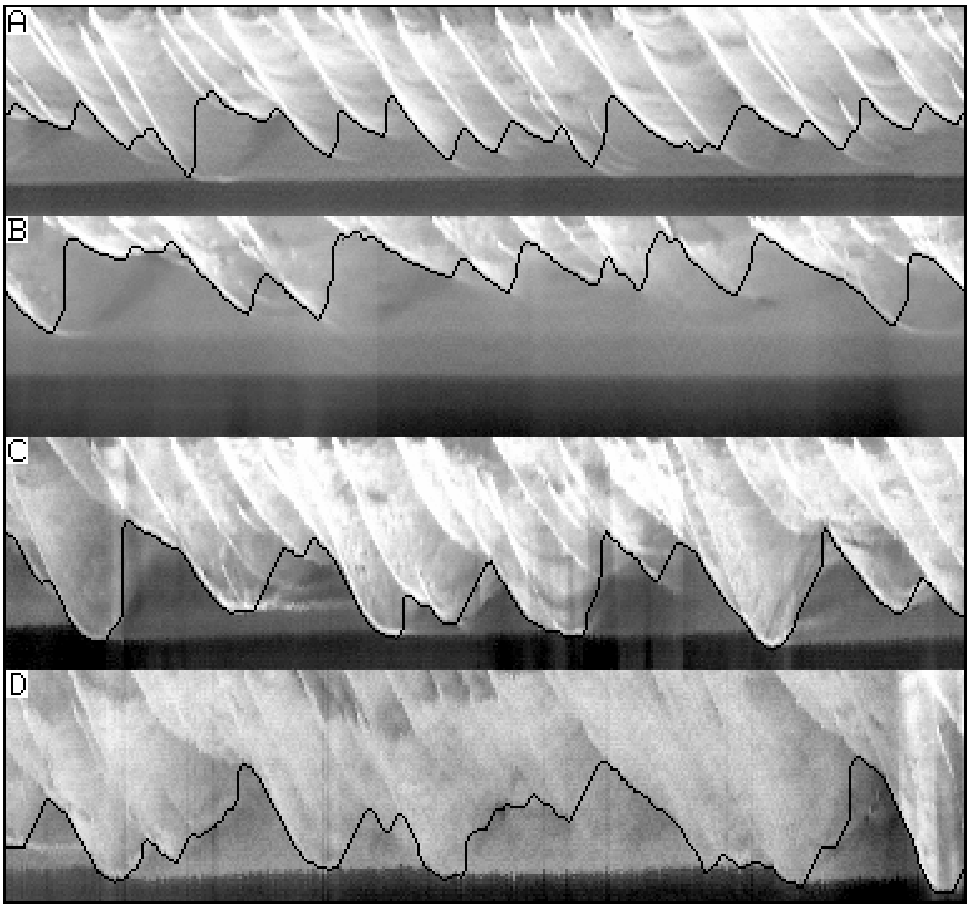

Figure 5: Tracking under different conditions: A) ideal conditions; B) low contrast; C) foam accumulation; D) very low contrast, during a rain squall.

5.0 Technique Evaluation

Since the true run-up on a natural beach is not known [8] we cannot evaluate the technique in this way. Images captured under "ideal" conditions, however, showed that the tracking algorithm yielded output consistent with that which would be manually selected.

Repeatability was generally a major weakness with the earlier techniques involving manual digitization. Repeated application of our algorithm to the same time-stack gave only slight differences between corresponding data points depending on where the cropping limits were selected. The intensity-gradient based method of determining these limits as described in section 4.3 however, achieves absolute objectivity and consistency.

The time series digitisation stage takes the same time as the sample record, however, data along three transects are acquired simultaneously. The tracking algorithm requires approximately 5 minutes to process an 8200 (35 minute) point series for each transect, compared with 30 minutes reported for the manual digitisation methods.

While the swash-edge detection algorithm was generally successful in countering serious and obvious mistracking when images suffered from a variety of contrast deviations (cloud or rain) and also from foam accumulation (high wind or wave action), they still resulted in tracking characteristics which varied from the "ideal". As editing is time consuming, it was important to determine how extensive these deviations could be before affecting the results of a spectral analysis; the typical means of analysis for such hydrodynamic data.

By observing examples of mistracking we were able to identify their characteristic signatures. Foam accumulation gave higher contrast at the swash maxima, drawing the track out past the maximum excursion before returning to the following swash front (figure 5C). Low contrast resulted in early track return to the following swash front, effectively reducing the amplitude variation (figure 5B). In very low contrast conditions, the swash was not always reliably detected. The saturation line increased in contrast as the contrast of the swash diminished (figure 5D). In extreme cases the detected swash edge tracked along the saturation line, joining successive swash maximums. This latter situation is equivalent to missing sections of the time series data.

The characteristics of early return (low contrast) and late return (residual foam) situations were simulated upon a sample with ideal conditions by manually editing the images (figure 6). The results were then subjected to spectral analysis to investigate the effects of the deviations. Visually, the important features were similar and the spectral coherence was significant for the low frequencies, up to about 0.08 Hz. In most studies, it is this low frequency region that is of interest and no editing would be required. However, if higher frequencies are required then the detected path may need to be edited manually.

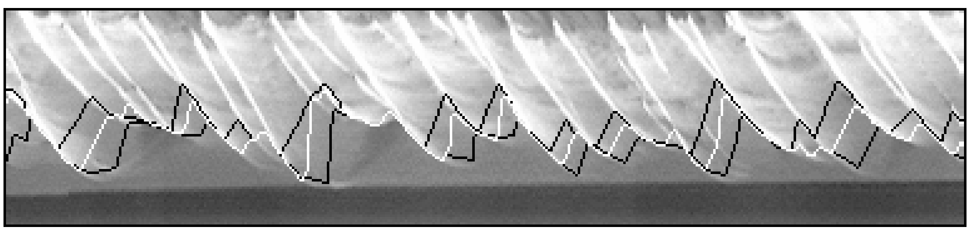

Figure 6: Automatically detected path under ideal conditions (white) and simulated early and late returns (black).

The near horizontal (very low contrast) tracking situation was simulated by setting different length segments along both the time series mean and also along the saturation line. A loss of up to 20% of the sample data in this way had little effect on the frequency spectrum in the region calculated (up to 0.3 Hz), although those which had the swash path set along the saturation line introduced a very low frequency artefact at 0.004 Hz. This indicates that the tracked path for any sections that follow the saturation line should be edited to follow along the time series mean.

6.0 Conclusion

The main drawbacks associated with previous methods used to measure run-up consisted of the logistics of establishing and maintaining swash-zone sensors. Video techniques are affected by low light and weather conditions. Manual digitisation techniques can be used to overcome these, but are both subjective and time consuming.

In this paper, we have used the time-stack method together with image analysis to extend the usefulness of video techniques. Camera operation is still limited to daylight hours, however, atmospheric limitations such as cloud, rain, and wind have largely been overcome. While extreme storm events prohibit outside operation, housing the camera would overcome this difficulty. The only restrictions are very low contrast such as a lack of daylight or sustained heavy rain. Our results to date indicate that this technique will provide an effective yet logistically simple and inexpensive method of collecting extensive run-up information.

References:

1. **Carter R.W.C.** Coastal Environments: an Introduction to the Physical, Ecological and Cultural Systems of Coastlines. Academic Press, p 611 (1988).

2. **Duncan J.R. Jr.** The Effects of Water Table and Tide Cycle on Swash-Backwash Sediment Distribution and Beach Profile Development. *Marine Geology,* **2**:186-197 (1964)

3. **Aagaard T. and Holm J.** Digitization of Wave Run-Up Using Video Records. *Journal of Coastal Research,* **5**(3): 547-551 (1989)

4. **Holman R.A., Lippmann T.C., O'Neill P.V., and Hathaway K.** Video Estimation of Subaerial Beach Profiles. *Marine Geology,* **97**:225-231 (1991)

5. **Holman R.A., and Sallenger A.H.** Setup and Swash on a Natural Beach. *Journal of Geophysical Research,* **90**(C1): 945-953 (1985)

6. **Sallenger A.H., and Holman R.A.** Infragravity Waves Over a Natural Barred Profile. *Journal of Geophysical Research,* **92**(C9): 9531-9540 (1987)

7. **Guza R.T. and Thornton E.B.** Swash Oscillations on a Natural Beach. *Journal of Geophysical Research,* **87**(C1): 483-491 (1982)

8. **Holman R.A., and Guza R.T.** Measuring Run-up on a Natural Beach. *Coastal Engineering,* **8**:129-140 (1984)

9. **Wright P.** A Cine-Camera Technique for Process Measurement on a Ridge and Runnel Beach. *Sedimentology,* **23**:705-712 (1976)

10. **Carlson C.T.** Field Studies of Run-Up on Dissipative Beaches. *Proceedings of the 19th International Conference on Coastal Engineering, ASCE*. 708-723 (1984)

11. **Holman R.A. and Bowen A.J.** Longshore Structure of Infragravity Wave Motions. *Proceedings of the 16th International Conference on Coastal Engineering, ASCE*. 6446-6452 (1984)

12. **Holman R.A. and Sallenger A.H.** Longshore Variability of Wave Run-Up On Natural Beaches. *Proceedings of the 16th International Conference on Coastal Engineering, ASCE*. 1896-1921 (1984)

13. **Holman R.A., Howd P., Oltman-Shay J., and Komar P.** Observations of the Swash Expression of Far Infragravity Wave Motions. *Proceedings of the 22nd International Conference on Coastal Engineering, ASCE*, 1242-1253 (1990)

14. **Holland K.T. and Holman R.A.** The Statistical Distribution of Swash Maxima on Natural Beaches. *Journal of Geophysical Research,* **98**(C6):10,271-10,278 (1993)

15. **Bailey D.G. and Shand R.D.** Determining Large Scale Sandbar Evolution. *Proceedings of the First NZ Conference on Image and Vision Computing*, 109-116 (1993)

16. **Huntley D.A. and Kim C.S.** Is Surf Beat Forced Or Free? *Proceedings of the 19th International Conference on Coastal Engineering, ASCE*, 871-885 (1984)

17. **Lippmann T.C. and Holman R.A.** Quantification of Sand Bar Morphology: A Video Technique Based on Wave Dissipation, *Journal of Geophysical Research* **94**:995 - 1011 (1989)