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MEASURING RUN-UP ON A NATURAL BEACH

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ABSTRACT

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Field experiments have been performed to evaluate and intercompare two techniques for measuring run-up on natural beaches, resistance wires and films. Simultaneous deployment of wire sensors shows a low error (< 5%) in electronics gain, but a strong sensitivity to the elevation of the wires above the beach face. On a low slope ($\beta \sim 0.02$) beach, with incident wind waves of moderate height ($H \sim 1$ m), differences of only a few cm in the wire elevation cause variance differences as large as 25%, in otherwise identical sensors. Replicate digitizations of the same run-up film show variance differences as large as 20%, with an average deviation from the mean variance of 8%.

Use of the film and resistance wire sensors on the same run-up field showed small differences in the mean swash elevation (i.e., set-up), but an 83% difference in swash variance. Much further work is needed to determine the dependence of sensor differences on beach slope, porosity, camera elevation and other factors.

INTRODUCTION

The measurement of wave run-up, defined here as the point of "dry" beach-ocean intersection, is important from both the engineering and research standpoints. Run-up is composed of a steady superelevation (relative to sea level in the absence of gravity waves) called setup, and a fluctuating component often called swash. Both of these are of vital interest to the engineer who must design structures high enough to resist overtopping and strong enough to withstand erosion by the expected swash activity. Run-up is an important research area because swash may be diagnostic of the offshore wave motions, particularly in the surf beat frequency range.

Miche (1951) hypothesized that the swash represented the standing wave component of the incident wave field, an idea partly confirmed for steep natural beaches by Suhayda (1974). Additionally, run-up motions can also represent the shoreline expression of edge wave motions (Holman and Bowen, in press) or other types of surf beat activity.

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It is crucial that we be able to collect run-up data in the field and that we understand the differences between various sensors. To this end we have chosen for intercomparison two methods of measuring run-up on natural beaches — a dual-resistance wire sensor (Flick et al., 1979; Guza and Thornton, 1982) and time-lapse photography. Since the true run-up is not known on a natural beach, differences between instruments are not attributable to errors in a particular sensor but can only be treated as an intercalibration to allow comparison of data sets.

The first section of this paper discusses the characteristics of the analog run-up sensor, then of the time-lapse photography technique. Next, intercomparisons of the sensors are considered. Finally, some general problems of measuring swash are discussed.

CHARACTERISTICS OF THE RESISTANCE-WIRE SENSOR

The analog run-up sensor consists of two resistance wires supported at a user selected distance above the bed. Guza and Thornton (1981, 1982) used a nominal elevation of 3 cm. Seawater from the swash shorts the current path, providing a resistance which varies with swash height. The sensor is calibrated before and after each data run by shorting the wires at known distances and measuring the resulting voltages. Using data from 10 deployments, Guza and Thornton (1982) note that for the temperature-compensated instruments used here, the gains vary an average of 4.5% between pre- and post-calibration, with the maximum difference being 7.5%.

The analog sensor provides several advantages over photographic techniques. First, the data comes in a form that is readily digitized for computer analysis. Second, the location of the run-up is defined objectively, but to some degree arbitrarily because the run-up measurements reflect the selected wire elevation. Run-up films, on the other hand, must be digitized by hand, a process that requires a degree of subjective interpretation by the operator. Disadvantages of the wire sensor include seaweed fouling, sand-level change and burial, and interference by passers by. A further, more important disadvantage is the sensitivity of the sensor to changes in wire height.

The precision of the wire run-up sensor was investigated in three separate experiments, each comparing the results from two closely-spaced run-up meters. All experiments took place on Scripps Beach, a fine-sand beach having a slope of 0.02. The data were digitized 64 times per second, low-pass filtered, then sampled 2 times per second. The first experiment, May 27, 1981, featured two run-up meters, spaced 2.0 m apart, and a time-lapse run-up film shot from Scripps pier, 100 m to the south. No special attention was paid to the heights of the wires; this was considered a routine deployment with a nominal 3 cm elevation for both sensors. The time series of swash position in the plane of the beach were transformed to vertical elevation using the measured profile. The total variances of the two sensors differ by 25%, although the mean run-up elevations differ (probably fortuitously) by only 0.3 cm (Table I). The spectra (Fig. 1) are red, typical of run-up on low-slope beaches, and the two instruments compare well in spectral structure. The coherence is high at low frequencies, losing 95% significance by 0.09 Hz where the spectral energy has dropped over two orders of magnitude. The phase difference is small through the energetic part of the spectrum, but becomes distinctly non-zero at higher frequencies. The pre- and post-experiment calibration of both sensors showed very small changes, suggesting that errors in calibration are not the source of the observed variance differences.

TABLE I

Comparison of means and variances from two adjacent run-up meters. Signals have been converted to vertical elevations. T is the length of the data run, var is the average variance

	$\lvert mean_1 - mean_2 \rvert$ (m)	var_1 (m^2)	var_2 (m^2)	$\frac{var_1 - var_2}{\overline{var}}$	T (min)
27 May	0.003	0.60×10^{-2}	0.83×10^{-2}	0.31	76.8
12 June A	0.001	0.75×10^{-2}	0.76×10^{-2}	0.01	55.5
12 June B	0.038	1.06×10^{-2}	1.03×10^{-2}	0.03	55.5

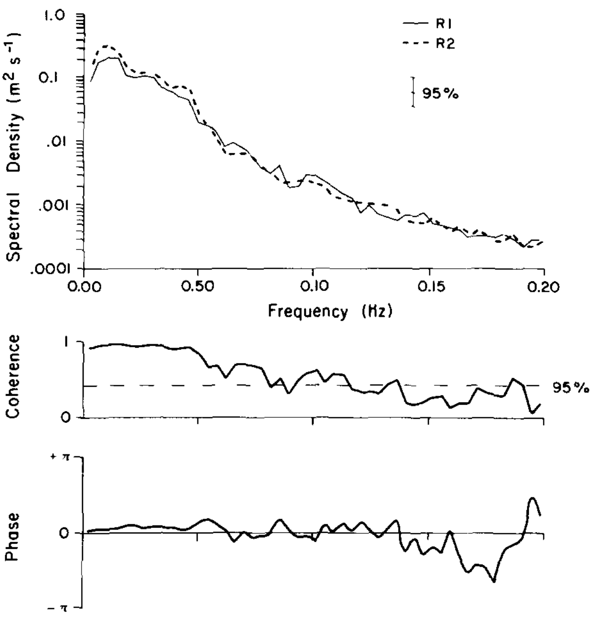

Fig. 1. Cross-spectral results between the two analog run-up sensors from the May, 1981, experiment.

Visual observation of swash suggested that dissimilarities could result from small differences in wire height. Two June experiments tested this by carefully controlling wire height during data collection. The two run-up meters were spaced 0.55 m apart. The average breaker height was about 1 m, comparable to the May experiment. For the first portion of the experiment (12 June A) the two wires were precisely leveled (3.0 cm above the bed) using a carpenters level. For the second (12 June B), sensor 2 was raised an additional 2.0 cm. Considerable care was required to keep the correct wire heights (± 0.5 cm) throughout the data runs. Figure 2 shows the results with equal wire heights. The spectra from the two meters are indistinguishable out to at least a three order-of-magnitude dropoff from the peak energy.

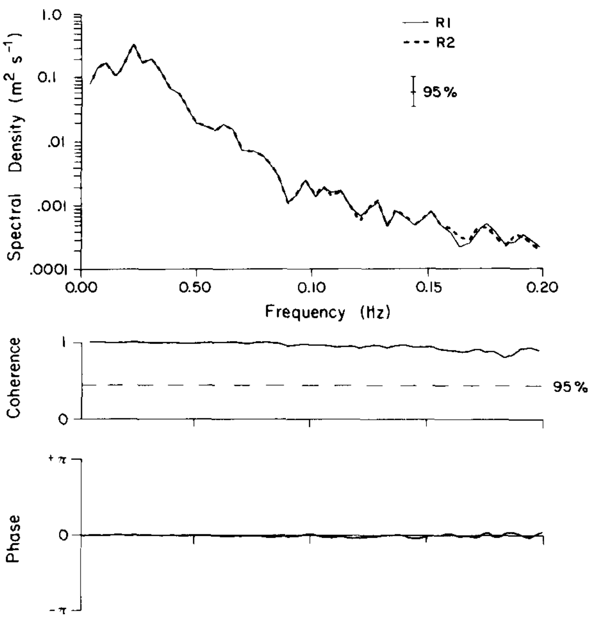

Fig. 2. Cross-spectral results between the two analog run-up sensors from the first of the June, 1981, experiments. The two wire heights were carefully levelled.

The coherence is 1.0 and the phase nearly 0. The total variances differ by 1%, and the mean levels by less than 1 cm (Table I). Cross-spectra for the second phase of the experiment, with a controlled difference of wire height of 2.0 cm, are shown in Fig. 3. While the difference in total variance is only 3% (Table I), individual bands show very substantial differences at some frequencies (0.12 Hz in Fig. 3). The higher wire exhibits less variance at low frequencies but more at higher frequencies. The coherence is reduced, particularly at higher frequencies, and the phase shows a linear trend, indicating a constant 2-second lag of the lower wire with respect to the higher. This time lag is consistent with the visual observation; because of the

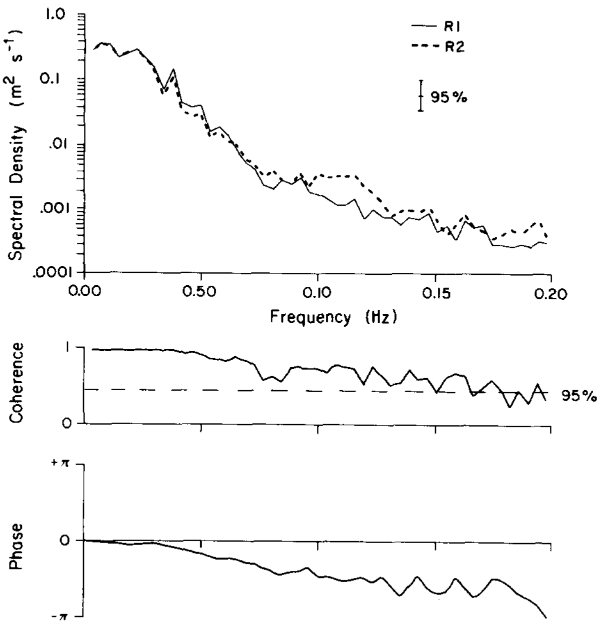

Fig. 3. Same as Fig. 2, but with wire 2 raised 2 cm above wire 1.

elongating wedge-like geometry of the uprush, a maxima on the high wire occurs a few seconds before the low wire.

Percolation and complex interaction with the following uprush make it much more difficult to visualize how phase differences occur on the downwash.

The above results indicate a sensitivity to wire height, both in variance and phase. The nature of the distortion introduced by random wire height errors resulting from deployment or beach profile variations can obviously be quite complicated (i.e., the phase variation on Fig. 1). If sufficient care is taken, however, there are very small differences between sensors which should be equivalent (Fig. 2). Judging from these experiments we would place a very rough error on the variance for an average (i.e. wire heights controlled ± 2 cm) run-up sensor deployment as 25% (15% from deployment, 10% from gain) and on phase as $5\pi f$ radians. This latter error, while small for low frequencies, is of the order of $\pi/2$ for typical incident wave frequencies. We also note that although careful wire height control leads to reproducible results, the question of what wire height is appropriate for a particular experiment may be difficult to answer.

CHARACTERISTICS OF TIME-LAPSE PHOTOGRAPHY

Time-lapse photography has been applied to a variety of nearshore problems by a number of authors (Sonu, 1972; Sasaki et al., 1976; Maresca and Seibel, 1976; Wright, 1976; Katoh, 1981; and others). This is primarily a result of the low expense and simple logistics of the technique, two of its main advantages. One of the main disadvantages has been the tedious process of manual digitization, which may explain why the above studies have not been ongoing.

Deployment for measuring run-up films involves positioning the camera on a bluff looking in the longshore direction. Two visible markers, spaced a known distance in a cross-shore direction, define a particular range and provide scale. As with the analog sensor, the profile must be measured to allow transformation of the horizontal signal to vertical. Subsequent digitization has been partially automated. The film is replayed frame by frame, and the position of the run-up tracked with a sliding pointer attached to a potentiometer. A computer controller, sensing a frame advance in the projector, automatically digitizes the location of the pointer, converts the data to run-up using the scale provided by the markers, and stores the data in memory. This process allows the digitization of a 2048-point time series in about 30 minutes. There is no potential of bad data, equivalent to seaweed fouling in the analog sensor, so there is no need for data "deglitching". A major advantage of the photographic system is that, so long as the scale is known, the same film can be digitized at any number of longshore locations. In fact, we have used one super-8 film to provide 7 synchronous run-up time series spaced over a 1.0-km longshore distance. Photography is thwarted by darkness and fog but is surprisingly useful during storms (a recent successful deployment took place in heavy rain and winds gusting to 30 m s^{-1}). The wire sensor is extremely difficult to operate when large amounts of kelp or debris are in the swash.

The precision of the photographic technique may seem questionable since it requires subjective judgement by the operator. This is particularly true when the run-down percolates into the beach face, rather than receding in a clear downwash. Determination of the run-down location is eased by the presence of a color change marking the shoreward edge of the receding wave. Examination of the process on the beach shows the corresponding depth of water to be on the order of 0.5 cm.

To place an estimate on the precision of the technique, three replicate digitizations were done from a film from Scripps Beach (May, 1981) and five replicates from a Sept. 1980 deployment on the Oregon coast. The distances from the camera to the run-up range were 100 m and 250 m, respectively. The average breaker heights were roughly 1.0 and 3.5 m. Differences in replicate means and variances are given in Table II. The May replicates show very small differences in variance, while the September data are more scattered. For the September data, the average deviation from the mean variance was 8%, with maximum deviation of 20%. For the run-up means, the average deviation was 7 cm with a maximum of 11 cm.

Figure 4 shows five spectra obtained by multiple digitizations (by five different operators) of the September film, which was 70 minutes long. The

TABLE II

Comparison of means and variances from replicate digitizations of run-up films

	$\lvert \text{mean} - \overline{\text{mean}} \rvert$ (m)	var (m^2)	$\dfrac{\lvert \text{var} - \overline{\text{var}} \rvert}{\overline{\text{var}}}$
May 81			
A	0.002	0.0111	0.01
B	0.008	0.0116	0.04
C	0.006	0.0110	0.02
Average	0.005	0.0112	0.02
Sept. 80			
A	0.052	0.165	0.04
B	0.054	0.162	0.02
C	0.116	0.127	0.20
D	0.057	0.164	0.03
E	0.052	0.177	0.11
Average	0.066	0.159	0.08

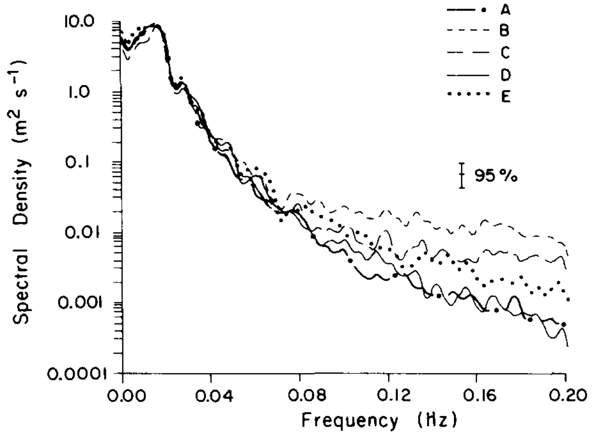

Fig. 4. Spectra from five replicate digitizations of a run-up film from the Oregon coast, September, 1980. The digitized range was 250 m from the camera, the significant horizontal swash excursion was 58 m.

spectral shapes are very similar out to a three order-of-magnitude rolloff from the peak. Coherences are typically above 0.95 through most of the energetic peak, losing significance by the time the energy is down two orders of magnitude ($f \sim 0.05$ Hz). The phases are consistently zero when the coherence is high. Note that the variances at wind wave frequencies ($f \sim 0.1$ Hz) differ by as much as an order of magnitude.

RESULTS OF INTERCALIBRATION

The May, 1980 experiment allowed the intercalibration of the analog sensor with the photographic technique. Two-run-up sensors were deployed, and the film was digitized three times. Comparisons of the same sensor type were described above (Tables I, II and Figs. 1, 4). The intercomparison run was 32 min long, so a subset of the 76.8-min-long wire record (Table I) is being used here. Table III compares average run-up wire and film statistics. The mean for the film data is 3 cm higher than for the wire sensor, equivalent to 1.3 m difference in horizontal excursion. The variance for the film data is 83% greater than that of the wires. The differences between sensor types is substantially larger than the variations within a sensor type.

TABLE III

Results of May, 1981 intercomparison. Run-up wires are averaged together, as are the film digitization means relative to an arbitrary datum

	$\overline{R}_V$ (m)	var (m^2)	Skewness
Films	−0.540	0.0112	4.0×10^{-4}
Wires	−0.567	0.00613	2.8×10^{-4}

Figure 5 compares the probability distribution functions for one run-up sensor and one film digitization. The data have been normalized to standard form as $(R_V - \overline{R}_V)/\sigma$, where $\overline{R}_V$ and σ are the mean and standard deviation of the vertical run-up data, R_V. Both instruments show similar distribution forms, but both forms are distinctly non-Gaussian. The high probabilities at low run-up may be associated with interaction with following bores, or with

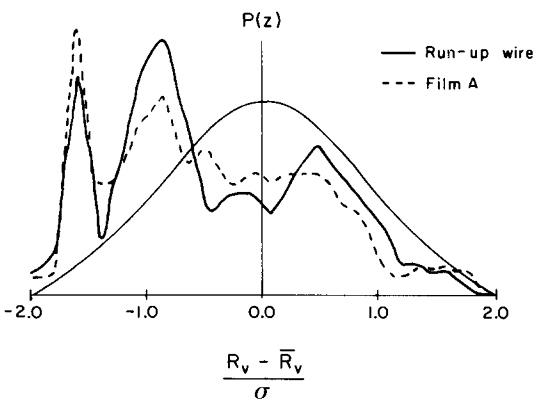

Fig. 5. Probability distributions for an analog run-up sensor and a film. The abscissa is in standard normal form. A Gaussian curve is included for comparison.

a change in beach profile such as a beach step. This peculiar type of distribution is typical for natural run-up.

Figure 6 shows spectra (50 degrees of freedom) for the three replicate digitizations of the film and for the two run-up sensors. It is apparent that the variance difference is independent of frequency, with all spectra showing similar shapes. The bottom of the figure shows coherence and phase between film digitization A and run-up sensor 1. The signals are coherent out to 0.05 Hz with phase near zero but with the analog sensor showing an increasing lead with frequency. The analog sensor leads the film for the same reason the high elevation wire leads the low elevation wire in Fig. 3.

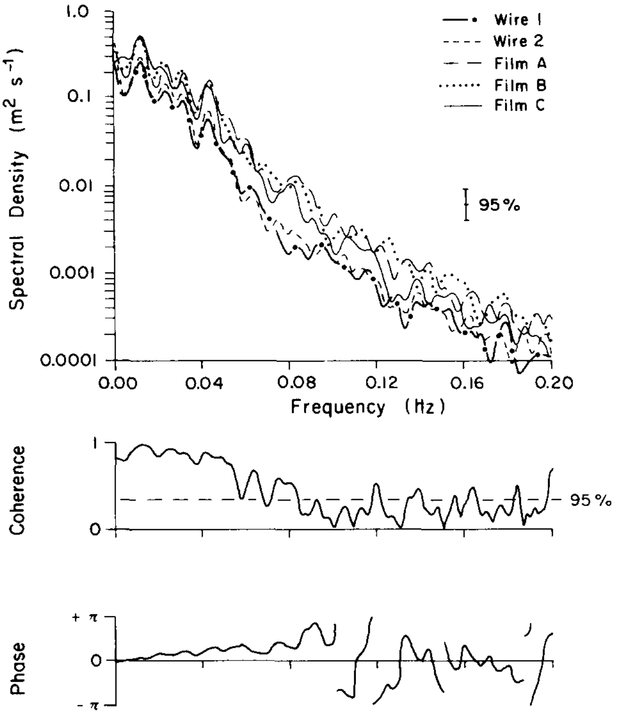

Fig. 6. Spectra from three replicate film digitizations and two analog run-up sensors in the May, 1981 experiment. The coherence and phase plots are between film A and run-up sensor 1.

Some understanding of the differences between sensor types can be found by examining analytical models for swash motion. The simplest model would be to assume the swash consisted of only linear standing waves (Miche, 1951), and model the waves as zero-order Bessel functions (Stoker, 1957). The use of standing waves in a swash model may seem contrary to the intuitive motion that swash is the result of incident wave bores. However, Suhayda (1974), Huntley (1976) and others have presented convincing evidence that the surf beat frequencies ($f < 0.05$) which make up most of the swash variance are indeed associated with waves that are non-breaking at the shoreline. Unfortunately, the linear model cannot address details of the motion in the immediate vicinity of the shoreline without violating assumptions made in the linearization. Non-linear standing wave models do exist (Carrier and Greenspan, 1958; Spielvogel, 1976), but quantitative adaptation of these results to porous beaches with a broad range of frequencies is far beyond the scope of the present work. Qualitatively, these solutions predict that the sea surface shape near the shoreline, at maximum uprush, is concave upward resulting in a wedge shaped run-up. The measured maximum shoreward excusion of such a surface would depend strongly on the minimum depth of water defined as swash. Thus, the film would record higher uprushes than wire sensors. At the stage of maximum downwash, the sea surface is closer to perpendicular to the beach fare (Carrier and Greenspan, 1958, fig. 2) so there should be less dependence on sensor type. The net result is that non-linear standing wave models will predict that films record higher means and variances than wires, as is observed. We also note that the bore model of Hibberd and Peregrine (1979) shows even more pronounced thinning of the run-up tip during its final stages. The back-wash has features of large horizontal extent that are "extremely thin". If this model governed swash, there would be an extreme sensitivity to sensor type. Percolation presumably would have a large effect on the predictions of this theory. Our point here is that the observed sensitivity to sensor type and wire height is not unexpected theoretically. The question naturally arises as to which sensor correctly defines swash. One is tempted to answer that the correct definition of run-up is the one which gives the best agreement with theory. This is a specious argument, however, since detailed run-up theories (Hibberd and Peregrine, 1979) will clearly predict significant differences between the two methods. That is, both sensors could agree with the same theory. The "correct" definition of run-up obviously depends on what the question is. An obvious use of run-up data would be to predict surf zone infra-gravity wave motions (Suhayda, 1974). We have absolutely no idea as to the correct definition of run-up for this application, or for any other specific uses. Thus, we must treat the differences in output of the techniques in terms of an intercalibration factor only. Mostly, we must be aware of the sensitivity of the techniques and be careful, particularly with the analog sensor, to use a consistent deployment technique.

DISCUSSION

Both dual-resistance wire and time-lapse photography are good techniques for measuring wave run-up on natural beaches. Each has its advantages; for dual-resistance wire, ease of digitization, objectivity, and insensitivity to visibility; for time-lapse photography, low cost, ease of logistics, potential for digitizing a number of longshore ranges with one film, and ability to "see" the phenomenon. Both also have disadvantages; for dual wire, a variety of logistical problems, variability in gain, and sensitivity to wire height; for photography, the tedious nature and subjectivity of digitization.

There are also problems common to both systems. Due to differences and often peculiarities in natural beach profiles, it is sometimes desirable to consider not only the measured long-slope swash but the vertical component of run-up, a transformation requiring knowledge of the beach profile. An inherent limit on the accuracy of both run-up instruments is the accuracy of the available profiles. This is a particular problem when the profile changes significantly during the data run, as can commonly happen (Duncan, 1964; Waddell, 1973). In that case both instruments adjust to follow the profile variations. For the photography the adjustment is automatic, while for the analog sensor it is manual, requiring operator action to maintain constant wire elevation above the bed. However, in the absence of corresponding profile knowledge, the signal is still mapped onto the original profile, introducing error. A second problem with both systems arises from the relatively large swash excursions along the beach face. With typical vertical swash excursions the order of the incident wave height (Guza and Thornton, 1982), then the horizontal distance which must be spanned by the instrument (neglecting tides) will be of order $H_{1/3}/\tan\beta$, where β is the beach slope and $H_{1/3}$ is the significant wave height. Additional coverage is needed if the tidal level varies significantly during a run. The instrumented distance can be several hundred meters on low-slope beaches, a logistically difficult distance for the wire sensor and requiring a very wide-angle camera or high location for photographs.

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