Acoustic imaging of sea-bed geometry: A High Resolution Remote Tracking Sonar (HRRTS II)

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ABSTRACT

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A High Resolution Remote Tracking Sonar (HRRTS II) is described which is capable of measuring a 2-D profile of the sea-bed over a maximum distance of 5 m under conditions of significant sediment transport. The backscattered signal from a pulsed (30 μ s) 5 MHz sonar provides acoustic range measurements of the small-scale topography generated by bedforms at any point in time as well as changes in this small-scale topography and the average elevation of sections of the sea-bed over time. Bedform height and spacing can be determined accurately although bedform shape is distorted by “smoothing” of large slope changes as a result of the finite size of the “footprint” of this narrow-beamed (0.74°) sonar. The system operates on command from a shore-based micro-computer and topographic resolution of the order of a few millimetres is possible. Resolution deteriorates as wave energy increases to levels where vibration of the transducer and large concentrations of sediment in the water column result in signal attenuation and a decrease in the signal-to-noise ratio.

Introduction

The small-scale topography ($\sim 10^{-1}$ to 10^{-2} m) of the bed of an ocean, sea or lake and its temporal variability at scales ranging from 10^0 to 10^{-1} h is of direct relevance to a range of interests in:

(1) boundary layer hydrodynamics (e.g. Grant and Madsen, 1986; Dyer and Soulsby, 1988); (2) sediment transport (e.g. Smith, 1977; Huntley and Bowen, 1989); (3) sedimentary geology (e.g. Clifton and Dingler, 1984); and (4) morphodynamics (e.g. De Vriend, 1991). At present our ability to measure the response of sea-bed topography to various boundary layer currents and sediment transport regimes is severely limited under field conditions. Even in the laboratory, continuous measurement of the elevation of an active cohesionless bed over space and time is difficult. Sensors do exist for the measurement of bed profiles under static conditions (e.g. Delft Hydraulics PV-107 Profiler), but these have only limited use during experiments with active sediment transport and cannot be

deployed in the field. The primary difficulty is one of obtaining quantitative measurements of sufficient spatial and temporal resolution without error due to interference by the sensor with either the fluid or sediment dynamics, or the evolving bed topography.

Acoustic imaging of sea-bed topography

Over the last three decades, the most common solutions adopted for imaging sea-bed topography involve either direct measurement by SCUBA divers (e.g. Ollerhead and Greenwood, 1990), optical imaging techniques (e.g. Kachel and Sternberg, 1971; Wilkinson et al., 1985; Boyd et al., 1988; Amos et al., 1988; Drake and Cacchione, 1992) or acoustical imaging techniques (e.g. Dingler, 1974; Dingler et al., 1977; McLean, 1983; Greenwood et al., 1984; 1985). Direct measurement is constrained severely both by wave conditions and the accuracy of measurement that can be achieved. Optical techniques are constrained by limits to the

optical transparency of the water column imposed both by ambient light and turbidity levels; furthermore it requires considerable image processing to obtain quantitative data and even then determination of the vertical dimension is difficult. In contrast, acoustic techniques can provide precise determination of bed elevation, although they may suffer similarly with respect to acoustic transparency of the water column.

A basic problem in the use of acoustics to produce sea-bed imagery is that reflection of sound waves may be induced by differences in mass density within the water, turbulence, air bubbles, biota, suspended in the water, etc., as well as by the sea-bed itself (Orr and Hess, 1978; Hay, 1983; Ma et al., 1983). Nevertheless, the extremely steep gradient in bulk density at the water/sea-bed interface will reflect a large proportion of any transmitted acoustic energy; indeed, low frequency acoustic transducers have been employed successfully in bathymetric surveys for many years. To obtain the resolution necessary for boundary layer studies, however, high frequency transducers must be used.

Transducers operating in the megahertz frequency range which have been used to measure vertical profiles of suspended sediment concentrations also measure the distance to the sea-bed (e.g. Young et al., 1982; Hanes and Vincent, 1987; Libicki et al., 1989; Vincent and Green, 1990; Vincent et al., 1991; Hay and Bowen, 1992 etc.). Hanes et al. (1988) indicated that under ideal conditions a resolution of the bed to within ± 0.5 cm was possible using a 2.8 MHz sonar, although this accuracy depends upon both the inversion algorithm used to convert the acoustic intensity to concentration and the concentration criterion used to define the sea-bed. Furthermore, accuracy degraded rapidly with the signal attenuation caused by large concentrations of suspended solids. Wright et al. (1986) used a commercial 1 MHz digital sonar altimeter (Datasonics Model ASA-920) specifically to measure changes in sea-bed elevation over time; during energetic conditions, however, the acoustic return was extremely "noisy" preventing detection of the sea-bed (Green and Boon, 1988). None of these sensors can resolve the small-scale spatial variability in sea-bed topography, since they operate from a fixed horizontal position. Recently, Hay and Bowen (1993) have

successfully determined bedform geometry and even bedform migration rates using the coherence between several fixed sonars separated in space by a known quantity.

In the laboratory, the 2-D geometry of a cohesionless bed was measured using ultrasonic transducers over thirty years ago (Richardson et al., 1961), but to the authors' knowledge the first such profiler designed specifically for field use was the manually operated device described by Dingler (1974). Both laboratory tests and field trials under low amplitude swell demonstrated that bedform height and spacing could be resolved within 10^{-3} m (Dingler et al., 1977; Dingler and Clifton, 1984); a "smoothing" of sharp gradient changes across individual bedforms inhibited any study of ripple symmetry and, in the field, signal loss due to sediment movement occurred even under the low wave energy conditions necessary for the manually-operated drive system. McLean (1983) documented results from an acoustic profiler deployed in a tidal inlet, where large bedforms (height $\approx 10^{-1}$ m; spacing $\approx 10^0$ m) were resolved and superimposed ripples were also detected; however, no detailed description of the sensing system was presented. The first remotely operated profiler (HRRTS I) used transducers operating at two frequencies (1 and 4 Mhz) and a motor-driven tracking system (Greenwood et al., 1984). Measurements of bedform height, spacing and symmetry under energetic wave and current conditions were made (Greenwood et al., 1985); however, as with earlier sensors, a "smoothing" of bedform shape was still evident and "signal-to-noise" ratios degraded rapidly as sediment mobility increased. Despite their potential, the restricted conditions under which acoustic profilers have been successful coupled to their questionable reliability has meant that data recovery from such sensors has been limited.

In this paper a second generation High Resolution Remote Tracking Sonar (HRRTS II) is described, which is capable of monitoring both the spatial variability in sea-bed relief over distances of several meters with a resolution $\approx 10^{-3}$ m, as well as the average elevation of the bed over time. The response of the sensor under laboratory and field conditions will be used to assess the limits to sensor performance and strengths and weaknesses of the new system.

HRRTS II: A high resolution remote tracking sonar

The principle underlying the new system is simple: a high frequency sonic transducer is transported across the sea-bed on a remote track such that precise determination of the horizontal position of the transducer is known at any time; the acoustic pulse is triggered and the backscattered

signal conditioned and sampled to obtain the acoustic range to the sea-bed at a rate that allows resolution of the small-scale topography beneath the track of the moving sonar. HRRTS II is composed of four integrated subsystems (Fig. 1): (a) an Acoustic Transducer System; (b) a Remote Tracking System; (c) a Control System; and (d) a Data Acquisition System.

Fig. 1. Configuration of the subsystems constituting the High Resolution Remote Tracking Sonar (HRRTS II). Note: open arrow heads signify signal transmission, solid arrow heads signify power transmission and split arrow heads signify both.

Acoustic transducer system

The transducer is a commercially available, narrow-beam (nominal conical angle $\approx 0.72^\circ$), 5 MHz Echo Sounder (Simrad Mesotech Systems Ltd., Model 807BA) with minimum and maximum ranges of 0.097 m and 2.000 m respectively. This configuration optimizes the size of the "acoustic footprint" (≈ 0.006 m at a range of 0.75 m) and minimizes the backscatter from micro-bubbles, while still maintaining a reasonable range window. A 30 μ s (nominal) acoustic pulse is transmitted at a repetition rate of 20 Hz under the direction of an electrically programmable 8-bit micro-controller located in the transducer case. The acoustic return is subjected to a "time-varying" gain to compensate for signal loss with increasing range to the sea-bed and is mixed with an asynchronous local oscillator signal at the first detector to produce a phase and amplitude modulated signal with an intermediate frequency of 455 kHz. To avoid resolution limitations imposed by the 8-bit digital-to-analogue converter supplied by the manufacturer (used to determine the delay time of the maximum acoustic return), the intermediate frequency signal (rectified and filtered) is transmitted onshore where it can be scanned for its maximum amplitude using an alternate DC-voltage Comparator (Fig. 1). This Comparator triggers an

externally-gated Pulse Counter (Hewlett Packard HP 44715A) configured as a timer, with a 1 μ s resolution (equivalent to ± 1.5 mm). The Counter is started synchronously with the emission of the acoustic pulse and stopped by a trigger from the Comparator on detection of a pre-selected value for the magnitude of the acoustic return. The acoustic range to the sea-bed is then computed in real time by the Master Controller (Hewlett Packard, HP 330 M Micro-computer), given the speed of sound in water at that particular temperature, salinity etc. The Comparator detection level is adjustable on command from the Master Controller via a digital-to-analogue converter (Fig. 1) prior to a profiling transect. Knowledge of the background level of acoustic returns from suspended sediment can be used to adjust the detection level voltage to that appropriate for optimizing detection of sea-bed.

Remote tracking system

The Sonar is transported over the sea-bed attached to a Carrier platform ($\approx 0.25 \times 0.10$ m) bolted to an inverted aluminum U-form ($\approx 0.25 \times 0.10 \times 0.05$ m), which slides on teflon pads along a Track consisting of a matching upright U-form, ≈ 5 m in length (Fig. 2). The Sonar is suspended from a small diameter steel

Fig. 2. Side elevation schematic of the High Resolution Remote Tracking Sonar (HRRTS II—to scale). Note: the three underwater packages attached to the sonar frame house respectively the Underwater Power Supply, the Stepper Motor Micro-controller and the Analogue Interface.

pipe which is clamped vertically to the Carrier to enable in situ adjustment of the Sonar elevation to ensure the sea-bed remains within acoustic range as the bed elevation changes. To prevent the cable from the Sonar being dragged across the sea-bed or from fouling the drive train, it is suspended from a flexible steel antenna mounted on a vertical post off to the side of the Track.

The Drive Train consists of a stainless steel Lead Screw supported in the U-form Track and a Split Nut assembly attached to the underside of the Carrier. The Lead Screw is linked by universal couplings to a Stepper Motor (Superior Electric SLO-SYN Model M093-FF-402) at one end and an Optical Shaft Encoder (Dynatronics Rotopulser Model 42-600) at the other. The Motor has a maximum of 200 steps per revolution, equivalent to an angular resolution of 1.8° per step, and the Encoder has a resolution of 600 pulses per shaft revolution. The rate of advance of the Carrier depends upon: (1) the Lead Screw specifications (pitch and number of starts); and (2) the step rate of the Motor. Typically the Carrier progresses 0.00508 m per revolution of the screw at a speed of 0.005 m s^{-1} . Although this rate is adjustable, small rates are preferred for three reasons: (1) to increase the number of acoustic pulses per unit distance of horizontal travel of the Sonar to allow ensemble-averaging of the acoustic returns; (2) to reduce vibration in the Tracking System and thereby increase the stability of the elevation at which the acoustic pulse is emitted; (3) to ensure progress of the Carrier without missing steps under the extreme stresses associated with breaking waves. At a speed of travel of 0.005 m s^{-1} , the Sonar traverses 3 m of sea-bed in approximately 10 min.

The horizontal position of the transducer is determined by continuous sampling of the output from the Shaft Encoder using a shore-based, high-speed Pulse Counter (Hewlett-Packard HP44715A; Fig. 1); the pulse count is converted to a distance of travel by the Micro-computer using the Encoder and Lead Screw specifications. The Encoder produces 600 pulses per Screw revolution (equivalent to 0.50787 cm of horizontal travel of the Sonar Carrier) giving a theoretical positional accuracy $\approx 8.5 \mu\text{m}$. While it is unlikely (owing to deficiencies

in manufacture, lead screw flexing etc.) that such accuracy can be obtained in practice it is clear that the horizontal positioning of the Sonar is more than adequate for the resolution of form required for the study of sea-bed topography ($\pm 0.001 \text{ m}$). Furthermore, it is possible to transport the sonar to a pre-selected position along the track (e.g. for fixed-mode operation above a bedform crest or trough) by monitoring the Sonar and Encoder output in real time.

Control and data acquisition systems

The Stepper Motor is commanded underwater by a Micro-controller (Cybernetics CY512), which is serially linked through a Universal Asynchronous Receiver Transmitter (UART) circuit to the shore-based Master Controller (Fig. 1). The Micro-controller is triggered by a serial stream of configuration commands from onshore which translate into: (1) the motor step rate; (2) the drive direction; and (3) the acceleration rate. Thus the drive specifications, although controlled directly during any sampling traverse by the underwater Micro-controller, are changeable at any other time on command from onshore.

Analogue signals from the Sonar and ancillary sensors (e.g. current meters, suspended solids sensors etc.) are connected underwater through a common Interface (Fig. 1). This enables the use of multi-conductor cable for signal transmission over long distances; furthermore, line drivers can be fitted at this stage if required or signal multiplexing undertaken prior to signal transmission ashore. The only signals not connected in this way are those from the Encoder; a separate cable is used to prevent any coupling of interference from its pulsed DC-output with the continuous DC-signals from the Sonar and ancillary sensors.

A sampling sequence is initiated by a command stream from the Master Controller to the Stepper Motor Micro-controller via an RS 232 C Interface (Fig. 1). This starts the Tracking System and also initiates the acquisition of data from the Sonar, Encoder and ancillary sensors. The acoustic range to the sea-bed and the horizontal position of the Sonar are determined continuously by the Micro-computer from the respective outputs of the volt-

age Comparator and Pulse Counter (Fig. 1); the latter monitors the Encoder output as well as providing a range-to-bed timer function activated by the Voltage Comparator. Signals from the ancillary sensors are multiplexed and digitised onshore (Fig. 1) using a high speed Multiplexer (Hewlett-Packard HP44712A) and Analogue-to-Digital Converter (Hewlett-Packard HP44736A). Digital data are stored on disk with a cassette tape drive providing archiving and disk backup (Fig. 1). At a typical sampling rate of ≈ 8 Hz and a speed of travel of the sonar of ≈ 0.002 m s $^{-1}$, approximately four acoustic returns per millimetre of horizontal travel are obtained.

Power for all underwater systems (except the Encoder) is supplied by two 12-V gel cells housed underwater (Figs. 1 and 2), which can be recharged or over-ridden to allow a direct supply from shore. The 24-V supply for the Sonar is obtained through a DC-DC converter installed in the Analogue Interface housing; each ancillary sensor incorporates its own DC-DC converter and voltage regulators.

Acoustic range resolution and form definition

The range resolution of the acoustic system and the accuracy achieved in measurement of small topographic differences was evaluated in the laboratory using an acoustic calibration tank (Richards and Wilson, 1987; Richards, 1989) and an artificial bedform. The artificial bedform was constructed from a triangular ($\approx 0.04 \times 0.04 \times 0.07$ m) aluminum element, 0.03 m long, which was coated with sand to simulate the reflectance properties of the sea-bed. This element was attached to the surface of a disc at a distance of 0.0475 m from its centre and rotated about that centre at a speed of ≈ 0.053 m s $^{-1}$. The Sonar was positioned at a distance ≈ 0.50 m from the base of the element, giving a "footprint" ≈ 0.006 m. Figure 3 illustrates the 2-D profile of the artificial bedform determined acoustically by rotating it through the acoustic beam in clear water at 20°C; also superimposed is the real shape of the artificial form. The range resolution obtained in the laboratory, restricted by quantisation only, is ± 0.002 m. However, it is evident that the Sonar does not record the artificial bedform

Fig. 3. Acoustic image of the transverse profile of an artificial triangular-shaped ($0.04 \times 0.04 \times 0.07$ m) bedform. Note: the solid dots represent discrete acoustic range estimates; the heavy solid line represents the correctly scaled shape of the artificial form. Note: the "Below Bed Reference" (BBR) acoustic estimates and the distortion of the crest of the bedform.

shape perfectly. Distortions occur as a result of: (1) stochastic variability in acoustic scattering; (2) the "sloping surface error" resulting from the method of detection of acoustic reflections from a sloping surface with a finite beam-width; the detection system will always select the "first" large acoustic return obtained from the "upslope" edge of the acoustic footprint; (3) the acoustic response to extreme changes in surface gradient. For example, the "smoothing" of the crest of the artificial bedform is to be expected since there will be an inherent bias in the acoustic detection system towards signals from the flanks around the crest (and at lower elevations) owing to the extremely small surface area available for acoustic reflection at the crest and the finite width of the acoustic beam. Some of the shape-distortion in Fig. 3 is undoubtedly due to the slightly "oblique passage" of the acoustic beam across the triangular form as it is rotated; this distortion is, however, extremely small and most of the distortion results from acoustic limitations. One particular anomaly is the occurrence of overestimates of the acoustic range-to-target (Fig. 3). These erroneous estimates occur even on flat surfaces and, as will be noted later, also appear in field measurements. Although shape distortion is evident, the acoustic image of this rather "extreme" ripple shape is clearly acceptable. The height of the ripple can be resolved within ± 0.001 m and the slope of the ripple flanks within $\pm 1^\circ$.

Sea-bed geometry

A trial of HRRTS II was undertaken at a depth ≈ 1.8 m on a micro-tidal shoreface (Stanhope Lane Beach, Prince Edward Island, Canada), where the average sediment size was 0.17 mm and where large concentrations of suspended sediment were induced by shoaling and breaking waves. The sonar was installed at ≈ 0.50 m elevation and the acoustic signal sampled at rates between 5 and 10 Hz; time series of “acoustic range to the sea-bed” were obtained with the sonar in motion at speeds between 0.0016 and 0.0050 m s⁻¹.

Analysis of acoustic range measurements

Figure 4 illustrates spatial series of sea-bed elevations obtained on two successive days under conditions of significant re-suspension of sediment. The horizontal distances traversed by the Sonar in these particular cases were approximately 0.33 and 0.50 m and took approximately 3.3 and 5.0 min, respectively, to complete. All the original acoustic range estimates are plotted in Fig. 4, as well as the filtered spatial series obtained using a Butterworth eight-pole cascading low-pass filter (Beauchamp, 1979). Both height and spacing of these well-developed oscillation ripples can be determined from the “raw” record of acoustic range as can the slope of the ripple flanks. However, a significant amount of “noise” hampers the measurement process. This “noise” is not simply Gaussian-distributed electronic noise, which accounts for less than ± 0.1 mm of uncertainty in range determination; rather, it arises from three other sources:

(1) “Premature detection” of an apparent sea-bed signal by the voltage comparator as a result of large amplitude acoustic returns from suspended sediment (note the large positive spikes in Fig. 4). While the mean concentration of sediment at 0.06 m above the bed was only 1.5 g l⁻¹ in this example, maximum instantaneous concentrations at the same elevation frequently exceeded this value by at least an order of magnitude; undoubtedly, instantaneous concentrations were even larger closer to the sea-bed. Fortunately, sediment re-suspension under waves is extremely intermittent, with large temporal gradients (see Greenwood

Fig. 4. Acoustic profiles of the same section of the sea-bed on successive days. Signal saturation due to bubbles and “noise” due to backscatter from suspended sediment plumes are indicated, as are the “Below Bed Reference Spikes” (BBR). Superimposed on each profile are the filtered spatial series; the number of acoustic range values plotted are 2000 (A) and 2200 (B), respectively. Note: for purposes of clarity the phase shift associated with the filter has not been removed.

et al., 1990) and thus concentrations of sufficient magnitude to produce reflections larger than that of the bed are also intermittent. With continuous, high speed sampling of the acoustic range and the relatively slow traversing speed of the sonar, a large number of “real” sea-bed returns will still be recorded.

(2) Saturation of the acoustic return signal as a result of backscatter induced by air bubbles in the water column (note the extremely large spikes in Fig. 4 which exceed the scale limits). However, this phenomenon is restricted to those times when individual waves break and entrain air to the depth of the sonar; such signal saturation is also intermittent and can be easily detected and eliminated by data screening.

(3) Shape-variations of the leading edge of the

amplitude-modulated envelope of the acoustic return give rise to distinct shifts in the position on the wave form identified by the comparator as the maximum amplitude location and thus the position of the apparent sea-bed. This variability in wave-form shape is the most insidious source of "noise" and has been proven to result from a phase modulation of the acoustic return produced by "ping-to-ping" changes in the position of the sonar relative to the sea-bed (Richards and Greenwood, 1993). These positional changes produce small changes in the configuration of the sea-bed scatterers, which cause "noise" in the signals returned from the sediments in the isonified area. Such positional changes are most frequently caused by vibrations induced in the supporting Track in response to wave-generated stresses. On occasions, the envelope of the return signal was observed to have several points of inflection, thereby causing the comparator to advance or delay detection of the maximum level assigned for detection of the sea-bed return by a significant time interval (on the order of several to tens of microseconds). This results in both upward and downward shifts in the acoustic range-to-bed of the order of several centimetres between "pings". Such "noise spikes" were recorded most frequently as larger than expected acoustic range values (Fig. 4) and were noted as below bed reference (BBR) spikes in the laboratory trials. They have been observed (but not explained) by other researchers (e.g. Green and Boon, 1988) and are artifacts of any temporal record obtained with a simple amplitude detection system (see Richards and Greenwood, 1993, for more information). Nevertheless, this source of "noise" is also intermittent and the relatively slow progress of the Sonar across the sea-bed coupled with a large sampling rate means that for any unit distance of travel the probability is that the majority of the maximum acoustic returns will in fact come from the solid sea-bed.

While it is impossible at this time to totally eliminate all sources of "noise", data screening (such as removal of saturation values) combined with appropriate filtering (Fig. 4) can be extremely effective in eliminating much of the "error" attributable to these sources. Certainly a high degree of confidence can be attached to the average bedform

characteristics and average bed elevation measured over a 2–3 m section of the sea-bed; furthermore, a resolution of the order of a few millimetres can be achieved. Digital filtering is not totally free of error, however, especially in cases where the "signal-to-noise" ratio is small and where the "noise" is dominantly unipolar (e.g. acoustic returns from suspended sediment). In such cases the filter will tend to integrate the noise spikes, distorting the bedform shape.

Table 1 documents bedform height (η), spacing (λ), steepness (η/λ), leading trough-to-crest distance (a), crest-to-trailing trough distance (b) and bedform symmetry (a/b) determined from the filtered series of the bedforms illustrated in Fig. 4A (Traverse F–313.7) and 4B (F–314.3). Also given are the bedform characteristics from a traverse of the same sea-bed section as that shown in Fig. 4A

TABLE 1

Bedform characteristics determined from three traverses of HRRTS II

Traverse Number	Bedform characteristics						
	Height	Spacing	Steepness		Symmetry (cm)		
	η (cm)	λ (cm)	η/λ	(VI)	a_u	b_d	b_d/a_u
F–313.7 (Fig. 4A)	1.1	7.0	0.16	(6.25)	5	2	0.4
	1.3	12.0	0.11	(9.09)	8	4	0.5
09:0600	1.7	11.0	0.15	(6.67)	6	5	0.8
	1.3	8.0	0.16	(6.25)	5	3	0.6
Average	1.35	9.5	0.15	(7.07)	6	4.7	0.58
F–313.11 (Fig. 5)	1.0	7.0	0.14	(7.14)	4	3	0.75
	1.4	9.0	0.16	(6.25)	4	5	1.25
09:1000	1.4	9.0	0.16	(6.25)	4	5	1.25
	1.4	9.0	0.16	(6.25)	4	5	1.25
	1.1	10.0	0.11	(9.09)	5	5	1.00
	1.5	10.0	0.15	(6.67)	6	4	1.50
	1.2	9.0	0.13	(7.69)	6	3	0.50
Average	1.28	9.0	0.14	(7.05)	4.7	4.3	1.07
F–314.3 (Fig. 4B)	0.8	9.0	0.09	(11.1)	4	5	1.25
	0.9	9.0	0.10	(10.0)	5	4	0.80
10:0200	1.0	8.0	0.13	(7.69)	5	3	0.60
	0.9	10.0	0.09	(11.1)	5	5	1.00
	1.0	7.0	0.14	(7.14)	3	4	1.33
Average	0.9	8.6	0.11	(9.41)	4.5	4.2	1.00

Note: VI=vertical form index = λ/η ; a_u =distance trough-to-crest on upwave side of crest; b_d =distance crest-to-trough on downwave side of crest.

(F-313.11). The latter is illustrated in Fig. 5; direct measurements by SCUBA divers at this time revealed asymmetric oscillatory ripples with spacings of 0.09 to 0.11 m and heights of 0.005 to 0.010 m. From this comparison it is noteworthy that, while ripple spacing measurements are virtually identical, ripple height measurements by the divers are significantly biased towards lower values, reflecting the great difficulty in manually measuring ripple heights underwater.

The average statistics for the ripples from all three traverses (Table 1) would identify them all as oscillatory ripples according to the symmetry criteria of Tanner (1967; $b/a < 1.5$) and Reineck and Singh (1973; $b/a < 2.5$). The ripple indices (steepness and vertical form) recorded from the first two traverses (F-313.7 and F-313.11) indicate that these bedforms would be classified as vortex ripples ($\eta/\lambda > 0.12$; $VI = 4.5-8$; Allen, 1982); in contrast

the ripples from traverse F-314.7 appear to have been rolling grain (post-vortex) ripples ($\eta/\lambda < 0.12$; $VI > 8$; Sleath 1984; Clifton and Dingler, 1984).

Variations in form did occur over time in these examples and this variation could be determined acoustically. For example, over the 4 hours between Traverse F-313.3 and Traverse F-313.11, both ripple height and spacing were reduced (by 5%), although the steepness (vertical form) for these vortex ripples remained essentially constant. Furthermore, the ripples lost their seaward asymmetry and assumed a more symmetric form. Although these differences are difficult to prove statistically with such small samples, changes in the near-bed velocity field which could have induced such form changes did indeed occur (Table 2). A significant reduction in the period of the oscillatory currents (9%) and the associated near-bed orbital excursion (19%) would be expected to reduce the observed spacing for these vortex ripples (e.g. Miller and Komar, 1980; although, see also contrary arguments by Boyd et al., 1988). The reversal in the mean current from seaward to landward combined with the smaller orbital excursion could well have caused the elimination of the seaward asymmetric shapes which existed earlier. By the following day (Traverse

Fig. 5. An acoustic profile of the same section of sea-bed as illustrated in Fig. 4A, but acquired approximately 4 h later: (a) unfiltered acoustic record; (b) filtered spatial series using an eight-pole cascading filter with a cutoff frequency of 0.03 Hz.

TABLE 2

Near-bed oscillatory flow characteristics measured just shoreward of HRRTS II during three traverses

Traverse number	Near-bed velocity structure				
	u_m ($m\ s^{-1}$)	u_{sk}	$\bar{u}$ ($m\ s^{-1}$)	T_u (s)	d_o (m)
F-313.7	1.04 (+1.24, -0.95)	0.36	-0.02	5.3	1.75
F-313-11	0.92 (+1.08, -1.14)	0.31	0.06	4.8	1.41
F-314-3	0.84 (+1.00, -0.98)	0.08	-0.02	7.7	2.06

Note: u_m = maximum oscillatory velocity = $2.8 \times u_s$; (figures in parentheses indicate measured maxima; positive is onshore); u_s = standard deviation of oscillatory velocity; $\bar{u}$ = mean oscillatory velocity; u_{sk} = oscillatory velocity skewness; positive values indicate landward skewness. T_u = peak period of oscillatory velocity field; d_o = computed oscillatory excursion (linear theory).

F-314.3) even more significant changes had taken place; a further reduction in ripple height (30%) combined with a smaller reduction in ripple spacing (4%) had caused ripple steepness to decrease by 27% resulting in rolling grain (post-vortex) ripples. Furthermore, the symmetry index changed by about 11% as ripples became asymmetric landward. The decreased scale of the ripples is not easily explained; near-bed oscillatory velocities were significantly lower (by about 9%) but the oscillatory excursion was larger than that of the previous day (by 32%), owing to the presence of longer period swell. The latter was associated with a more regular wave field with well defined groups; it is possible that the decreased scale reflects the higher kinetic energies and bed stresses associated with the wave groups, which are not well-described by the average state of the velocity field. The change in shape would almost certainly reflect the skewness induced by the longer period swell. Further detailed analyses are clearly necessary before such relationships can be confirmed.

Discussion and conclusions

The High Resolution Remote Tracking Sonar (HRRTS II) used to determine the small-scale, 2-D geometry of the sea-bed exhibits distinct advantages over its predecessors: (1) the system can be operated upon command in a totally remote mode under even severe sea-states; (2) sea-bed profiles over distances of several metres can be obtained; (3) the vertical resolution achieved by the sonar, limited by quantisation only, is ± 0.001 m and the horizontal resolution achieved by the positioning system is of the same order; (4) the tracking system allows the sonar to be transported to any predetermined position within the limits of the 5-metre track for detailed monitoring of individual bedforms or for fixed-mode operation over a ripple crest or trough if desired.

HRRTS II suffers to some degree from the inadequacies exhibited by earlier acoustic imaging systems, namely:

(1) a degradation of the signal-to-noise ratio as wave energy and sediment mobility increases. This degradation is attributable primarily to: (a) the presence of large concentrations of acoustic scat-

terers above the sea-bed, which not only reflect large amounts of acoustic energy but also attenuate the acoustic return from the sea-bed itself; and (b) the modulation of the acoustic return signal by instability of the acoustic beam as the sonar and its supporting frame vibrate during the traverse across the sea-bed. The ability to adjust the comparator voltage levels (to optimize detection of the acoustic return from the sea-bed) on command does, however, provide a significant improvement in design; this coupled with appropriate signal processing allows valuable measurements of sea-bed geometry to be made under conditions of significant sediment transport. New approaches to the analysis of the backscattered acoustic pulse, which reduce the effects of instability of the acoustic beam and the waveform modulation resulting from it (e.g. Richards and Greenwood, 1993), will continue to improve the signal-to-noise ratio of the system.

(2) a "smoothing" of large topographic gradients. The spectral scattering of acoustic energy from a beam of finite width will always induce some distortion of this nature on a sloping surface, but the small diameter "acoustic footprint" of HRRTS II (0.006 m at a range of 0.75 m) reduces such distortion significantly for the slopes associated with natural bedforms.

Measurements of sea-bed topography can now be obtained through acoustic imaging with a spatial and temporal resolution appropriate for a range of studies concerning the inter-relationships between form roughness, boundary layer currents and sediment transport (Brander and Greenwood, 1993). Furthermore, both the evolution and migration of bedforms as well as the time-dependency of scour and accretion of small sections of the sea-bed can be effectively monitored with this sensor (Brander, 1991). It must be stressed, however, that the acoustic image obtained is 2-D, therefore, boundary roughness estimates such as bedform height, spacing, steepness etc., will be affected by the orientation of the bedforms relative to the Sonar transect and by the degree to which the bed is 3-D. It is possible to support several Sonars on the present track which, if run parallel to each other, would give some measure of the 3-D geometry. It is clear, however, that this approach is

limited and alternative acoustic techniques, such as the rotating side-scan sonar (Rubin and McCulloch, 1980; Wilson and Hay, 1993), with appropriate resolution, will be required to provide a complete description of the sea-bed topography.

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