

## THREE-DIMENSIONAL MEASUREMENT OF LABORATORY SUBMERGED BED FORMS USING MOVING PROBES

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### Abstract

A new technique for measurement and analysis of the development of three-dimensional bed forms is reported. Conventionally, laboratory bed forms are often assumed to be two-dimensional and described using longitudinal bed profiles measured along the centre-line of the flume. Seatek's multiple transducer arrays (MTAs) allow bed forms measurement along many profiles in spatial or temporal domain or in both, which may be transformed into a three-dimensional field of bed elevations. Measuring bed forms at a fixed position in the flume provides a comparison of the downstream migration of neighbouring bed forms, a technique termed stationary measurement herein. The ability to move the transducers along different sections of the flume results in a continuous area of bed observation, herein termed moving measurement of bed forms. The use of the MTAs is described, including specific aspects which need to be taken into account for their successful application. Verification of the accuracy of the measurements is given. Experimental runs were carried out in a 440mm-wide, glass-sided, 12m-long laboratory flume. The sediments used were a fine sand with  $d_{50} = 0.24$ -mm and a coarse sand with  $d_{50} = 0.8$ -mm. The study is part of a series of studies looking at the phenomenon of submerged sediment bed form behaviour.

*Keywords:* Submerged bed forms; Three-dimensional measurements; Sediment; Dune; Ripple; Ultrasonic depth sounder

## 1. INTRODUCTION

### 1.1. BACKGROUND

The first scientific information about submerged sand forms was obtained visually. Notably, Darwin (1883) used observations for his work on ripple-marks in sand. Eleven years earlier, Sir William Thomson (later Lord Kelvin) introduced a sounding machine using small diameter pianoforte wire. Different ways of using sonic sounding devices had been applied at deep ocean surveys with improving sound projectors and receivers (Theberge 1989). One of the first developments of a laboratory scale sonic depth probe for measuring bed configurations is that of Richardson et al (1961).

A study of the use of Seatek's multiple transducer arrays (MTAs) for measurement of submerged bed forms is presented in this paper. The particular bed forms developed in a sand bed subjected to unidirectional water flows. In the following sections, the characteristics of the MTAs are introduced. The advantages of using MTAs, relative to the conventional bed form measurement approach, are described.

### 1.2. TRADITIONAL APPROACH

The early measurements of bed form geometry were typically obtained using stationary probes, which record the shape of passing bed forms as a function of time. Additionally, depth sounding probes traveling along or across the flume have been used to record the bed profiles in spatial domains (Fig. 1). According to Crickmore (1970), the dimensions (height and length) of sand bed forms can change significantly depending on the width of the flume and the associated influence of the flume side-walls. In order to understand the influence of the side walls, it is necessary to simultaneously measure longitudinal bed form profiles at different sections across the flume and to compare these measurements. Such data further facilitate three-dimensional analysis of the bed forms.

Two methods of three-dimensional recording of migrating bed forms are possible, using stationary and moving probes respectively. The use of several stationary probes provides information about the temporal development of the shape of the bed form(s) passing a particular flume cross-section. Alternatively, a number of probes traveling along the flume at regular intervals of time can be employed. Both methods are described below.

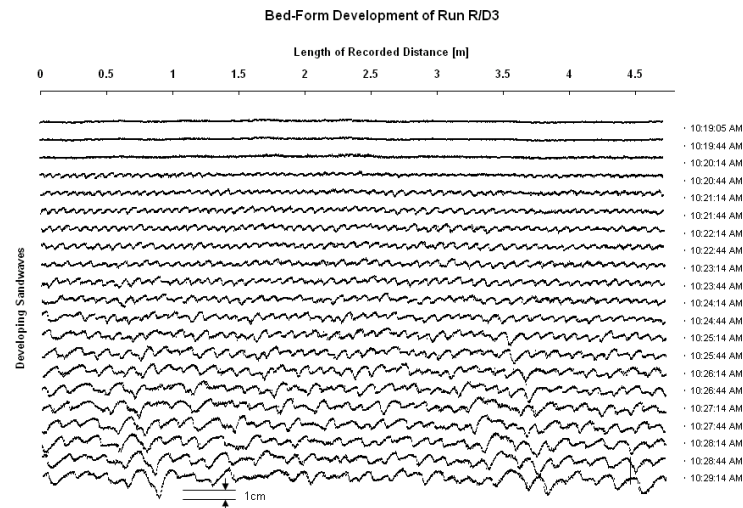


Fig. 1 Developing longitudinal sand wave profiles, measured using a single moving probe (from Friedrich et al, 2004)

## 2. MULTIPLE TRANSDUCER ARRAYS

### 2.1. PHYSICAL BACKGROUND

The measurement of bed deformations under water typically utilises high frequency sound wave (ultrasonic) technology. Sound waves, which are transmitted from the sensors, are reflected by a solid object. The time for the sound waves to travel from the sensor to the object and back to the sensor is recorded. The distance  $d$  from the sensor to the reflective object is given by:

$$d = \frac{c\Delta t}{2} \quad (1)$$

where  $\Delta t$  is the time of travel and  $c$  is the speed of sound in water,  $c \sim 1500\text{m/sec}$ . Karaki et al (1961) give the following equation for  $c$

$$c = 4625 + 7.68 * (T - 32) - 0.0376 * (T - 32)^2 \quad (2)$$

where  $T$  is water temperature, in degrees Fahrenheit.

An ultrasonic depth probe comprises a pulse generator (pulser), a transducer and a signal processor. A high frequency electric current is generated by the pulser and delivered to the transducer. The transducer converts the electric current into acoustic energy via a piezoelectric ceramic element, which forces the transducer to emit and transmit acoustic signals. The thickness of the piezoelectric ceramic slice is determined by the desired radiated wavelength. A thin wafer vibrates with a wavelength twice its thickness. Consequently, the thickness of the piezoelectric ceramic is half the desired radiated wavelength. The distance  $d$  is then calculated by the signal processor, which receives and amplifies returning signals.

### 2.2. EQUIPMENT

A 5-MHz ultrasonic ranging system, comprising 31 transducers, was employed for the measurements. The minimum range of the system was determined by testing to be 3.6-cm,


while the maximum range was found to be approximately 100-cm. The measuring accuracy of the system is approximately  $\pm 1.00$ -mm, as shown in Table 1 which gives statistical data relating to the performance of each sensor (standard deviation, kurtosis, skewness and mean value). The relatively uniform distribution of the skewness and kurtosis values indicates an accurate measurement with no indication of distortion either way. The low standard deviation values and generally small range differences (maximum = 1.4-mm for sensor 15) further show the reliability and accuracy of the MTAs. The transducers are linked to a pressure housing, which contains the signal processor and all required electronics. Data are recorded on a computer via the com port.

**2.3. SIGNAL CONTAMINATION**

During preliminary tests, it was observed that high suspended sediment concentrations could adversely influence the operation of the measurement system. In such situations the transmitted sound waves are reflected, at least partly, by suspended sediment particles rather than the surface of the sediment bed, i.e. the system suffers from signal contamination. The problem was especially evident for the experiments with fine sand and high velocities, where significant suspended sediment is observed at the lee side of the bed form.

When operating the transducers in regions of high suspended sediment, it was found necessary to increase the voltage threshold to minimize this effect. Background noise (i.e. suspended particles) disturbing the signal is addressed by using an electronic filter, which guarantees that the returning signal is amplified, processed and recorded only when the acoustic return exceeds the defined voltage threshold. However, there exists an upper limit for reliable operation of the instrument. The upper limit is reached when the signal is contaminated to such an extent that, at the maximal signal strength, it depicts suspended particles instead of the underlying sand bed.

Table 1. Accuracy of MTAs, based on a statistical analysis for each sensor over a measuring time of 120 seconds.

		 Downstream							
Transducer No.		1	2	3	4	5	6	7	8
Standard Deviation [cm]		0.012	0.018	0.015	0.019	0.016	0.017	0.017	
Kurtosis		0.992	-0.340	-0.265	-0.085	-0.151	-0.744	-0.230	
Skewness		0.211	-0.174	0.078	0.095	-0.185	0.117	0.766	
Minimum Value [cm]		19.39	19.47	19.47	19.53	19.63	19.6	19.64	water depth
Maximum Value [cm]		19.45	19.54	19.54	19.61	19.7	19.69	19.73	
Difference Min-Max [cm]		0.06	0.07	0.07	0.08	0.07	0.09	0.09	
Mean Value [cm]		19.414	19.506	19.514	19.567	19.659	19.649	19.680	
Transducer No.		9	10	11	12	13	14	15	16
Standard Deviation [cm]		0.014	0.020	0.018	0.018	0.021	0.015	0.028	0.019
Kurtosis		-1.393	-0.249	-0.586	-0.533	-0.679	1.169	-0.534	-0.880
Skewness		-0.226	0.018	0.121	-0.372	0.680	-0.812	0.030	-0.135
Minimum Value [cm]		19.42	19.48	19.5	19.57	19.64	19.58	19.58	19.56
Maximum Value [cm]		19.48	19.58	19.6	19.66	19.72	19.69	19.72	19.64
Difference Min-Max [cm]		0.06	0.1	0.1	0.09	0.08	0.11	0.14	0.08
Mean Value [cm]		19.462	19.530	19.544	19.617	19.679	19.652	19.648	19.609
Transducer No.		17	18	19	20	21	22	23	24
Standard Deviation [cm]		0.021	0.013	0.017	0.018	0.016	0.019	0.021	0.019
Kurtosis		-0.325	-0.385	0.046	-0.584	-0.560	-0.412	-0.135	-0.672
Skewness		0.362	-0.185	0.418	0.287	0.224	0.254	0.584	-0.571
Minimum Value [cm]		19.41	19.47	19.5	19.66	19.64	19.64	19.57	19.6
Maximum Value [cm]		19.51	19.53	19.58	19.73	19.72	19.72	19.67	19.69
Difference Min-Max [cm]		0.1	0.06	0.08	0.07	0.08	0.08	0.1	0.09
Mean Value [cm]		19.455	19.499	19.540	19.690	19.682	19.676	19.616	19.643
Transducer No.		25	26	27	28	29	30	31	32
Standard Deviation [cm]		0.014	0.013	0.018	0.020	0.015	0.017	0.019	0.016
Kurtosis		-0.395	-0.524	-0.228	-0.508	-0.205	-0.286	0.011	0.500
Skewness		-0.091	-0.155	-0.114	-0.146	0.104	0.074	-0.464	0.173
Minimum Value [cm]		19.42	19.47	19.51	19.58	19.63	19.6	19.58	19.53
Maximum Value [cm]		19.47	19.53	19.6	19.69	19.7	19.69	19.67	19.61
Difference Min-Max [cm]		0.05	0.06	0.09	0.11	0.07	0.09	0.09	0.08
Mean Value [cm]		19.441	19.498	19.555	19.641	19.672	19.650	19.637	19.573

### 3. EXPERIMENTAL INVESTIGATION

Eight experiments were carried out in a 12m-long, 0.38m-deep and 0.44m-wide, glass-sided, open-channel flume. In operation of the flume, both water and sediment are continuously re-circulated. Experimental parameters are given in Table 2.

Table 2. Experimental parameters

Run Name	Pump Setting	$d_{50}$ [mm]	$S_e$	Run Duration [h:m:s]	Equilibrium	$U_{avg}$ [m/s]	$Fr$ [-]	$Re$ ( $\times 10^{-3}$ )
nsf10	10	0.24	0.001	08:00:00	yes	0.35	0.29	125
nsf15	15	0.24	0.001	05:16:00	yes	0.45	0.37	161
nsf18	18	0.24	0.001	05:26:00	yes	0.55	0.45	196
nsf20	20	0.24	0.001	05:03:00	yes	0.6	0.49	214
nsc17	17.5	0.8	0.002	06:17:00	yes	0.5	0.41	178
nsc20	20	0.8	0.003	05:45:00	yes	0.6	0.49	214
nsc24	24	0.8	0.003	04:45:00	yes	0.7	0.62	250
nsc28	28	0.8	0.004	03:08:00	yes	0.87	0.72	310

Note: Kinematic viscosity  $\nu=0.000001 \text{ m}^2/\text{s}$ ; Critical shear velocity  $u_{*c}(d_{50}=0.24\text{mm})=0.0132\text{m/s}$ ;  $u_{*c}(d_{50}=0.8\text{mm})=0.02065\text{m/s}$ ;  
 Temperature  $T=18^\circ\text{C}$ ; Specific gravity  $\rho=2.65$ ; Flow depth  $y=0.15\text{m}$ ; Hydraulic radius  $m=0.089\text{m}$   
 $d_{50}$  Median grain size,  $S_e$  Flume Slope,  $U_{avg}$  Average Flow Velocity,  $Fr$  Froude Number,  $Re$  Reynolds Number

Four runs were undertaken with each of two uniform sands. The sands used were a fine sand with median size  $d_{50} = 0.24\text{-mm}$  and a coarse sand with  $d_{50} = 0.8\text{-mm}$ . Froude number  $F$  for the 8 experiments ranged from 0.29 to 0.72. Flow depth  $y$  was kept constant at 150-mm.

Preliminary tests were undertaken using fixed bed forms in the same flume to determine the arrangement of the sensors and the velocity of the moving carriage (as described below), in order to match the desired geometry of the recording grid.

All mobile bed runs reached equilibrium stages of bed form size development, although this was only a minor criterion, because the main objective was the testing of the MTAs. Following the successful running of the 8 experiments, it is intended to use the system for further investigation of bed form mechanics.

#### 3.1. FIXED BED FORM MEASUREMENTS

Fixed bed forms featuring two different regular shapes were used. The longitudinal profile of the bed surface for the fixed bed form experiments comprised four identical bed forms with height  $H = 4\text{-cm}$  and length  $L = 25\text{-cm}$ , followed by five bed forms with  $H = 4\text{-cm}$  and  $L = 75\text{-cm}$ . The MTAs were mounted on a moving carriage, which also supported a conventional depth sounder. The fixed bed forms were fabricated from metal sheet. Sand grains were glued to the top surface of the aluminum profile, to ensure acceptable reflection of the ultrasonic signal.

The 31 sensors, operating at 5-Hz, were interrogated sequentially (starting from sensor 2 and finishing with sensor 32) and the same sequence was repeated every 0.2-s. The sensors were mounted on a skewed grid (see Figure 2) to allow for the movement of the carriage in the time interval between readings of the components of the sensor array. This ensured that measurements were obtained on an equivalent rectangular recording grid. With a carriage velocity = 0.25-m/s, the rectangular recording grid shown in Fig. 2 was generated. The

accuracy of the recorded longitudinal distance was validated by an independent position measurement. The latter, obtained using a depth sounder and potentiometer attached to the back of the carriage (Coleman 1997), gave distance-based measurements, compared to the time-dependent results of the MTAs (see Fig. 3). The comparison of both data sets showed that with a carriage velocity of 0.25-m/s, the sensor measurements have a longitudinal resolution of 12.5-mm and a transverse resolution of 25-mm (see Fig. 4).

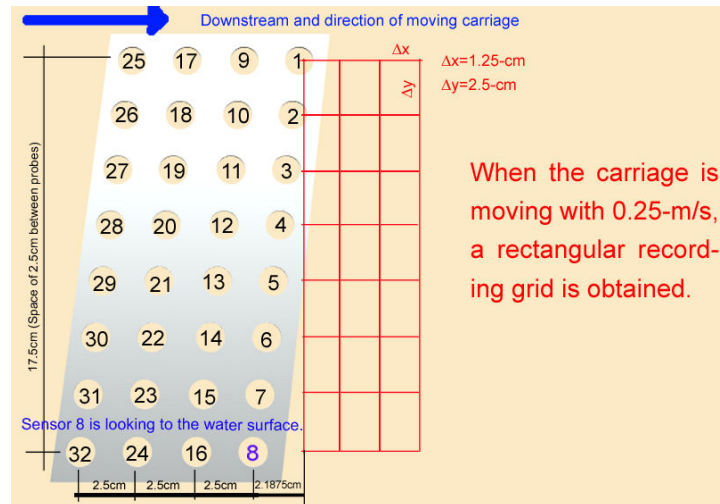


Fig. 2 Sensor arrangement on aluminum board and resulting recording grid for moving probes arrangement.

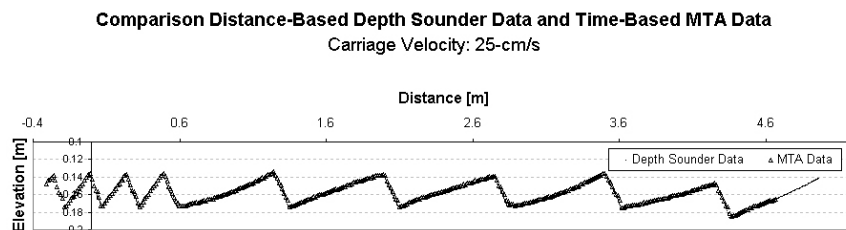


Fig. 3 Validation of longitudinal position accuracy of MTA measurements using the moving probe arrangement. Comparison of Depth Sounder and MTA data.

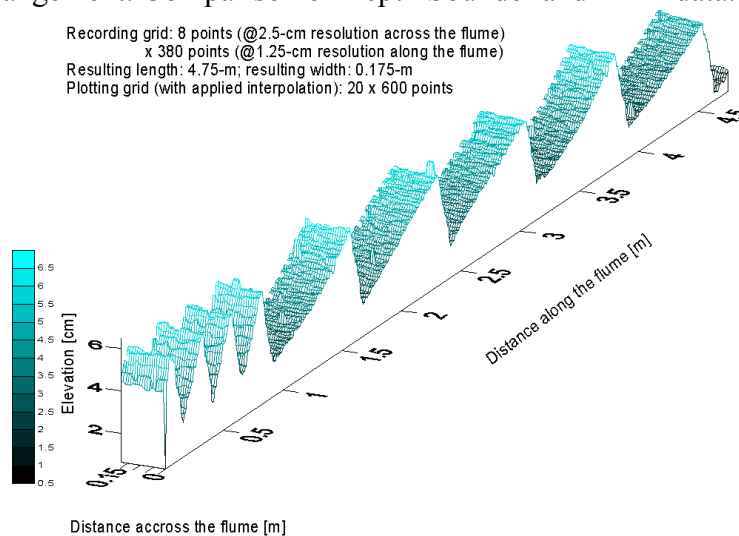


Fig. 4 Validation of three-dimensional recorded profile during preliminary testing of fixed bed forms

### 3.2. MOBILE BED STATIONARY PROBES MEASUREMENT

For stationary probe measurements, the probe arrangement employed is the same as the resulting recording grid, because no movement of the carriage occurs. The resolution of the grid was 40-mm in the longitudinal and transverse directions. An array of 8 probes along the flume and 4 probes across the flume gives a rectangular grid of dimensions 28-cm x 12-cm over which the migrating bed forms are recorded. The measurements were made using the equilibrium sand bed developed for the moving probe runs undertaken at the same flow condition (see the following section).

### 3.3. MOBILE BED MOVING PROBES MEASUREMENT

The mobile bed experiments (flat sand bed to equilibrium) utilizing moving MTA probes were carried out over several hours. Experimental parameters for these experiments are given in Table 2. The sequence of operation was as follows. Initially, the moving carriage travelled downstream for 25-s. Then the carriage was stationary for a waiting period of 5-s, after which the carriage traveled upstream for 25-s. After a further waiting period of 5-s, the carriage moved downstream again to start the second cycle. Each cycle duration was one minute. The experiment was continued with repeated cycles until appropriate bed form development had occurred. Recording of the bed profiles occurred only during the downstream-moving portion of each cycle, based on the configuration of the recording grid. Therefore, the frequency of recording of bed profiles was 1 profile per minute.

As mentioned in Section 2.2., a total of 31 sensors were used rather than the full array of 32 sensors. One of these sensors (sensor no. 8) was inverted and used to record the water surface elevation, meaning that only 30 sensors were used to record bed elevations and gaps existed in the measured bed form profiles. For the analysis of the data, interpolation procedures were used to fill the gaps in the profiles. Also, filtering methods were applied to modify faulty signals and to take into account the detection of suspended particles.

Overall, eight longitudinal profiles with a transverse resolution of 25-mm were recorded. Standard two-dimensional analysis can be applied to these profiles or new three-dimensional interpretations can be obtained.

## 4. EXAMPLES OF RESULTS

Examples of contour plots obtained using the moving probes are given in Figure 5, for dune (see Fig. 5a) and ripple development (see Fig. 5b), respectively. The two different bed form types were a function of the sediment size; only dunes developed in the coarse sand, while ripples were observed in the fine sand. Given the 0.44-m flume width, the dunes developed in the coarse sand as large two-dimensional sand forms. When fully developed, not more than 8 complete sand forms covered the measurement area. In contrast, the rippled bed exhibited the typically expected transition from two-dimensional to three-dimensional sand forms.

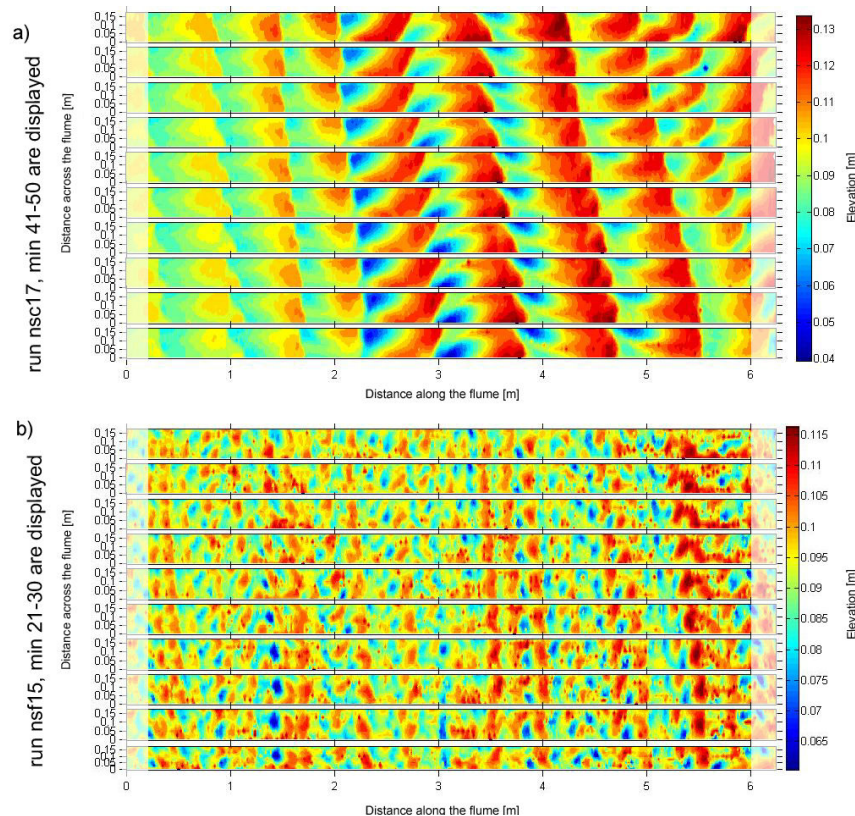


Fig. 5 Contour plots of moving probe measurements for dune development a) and ripple development b)

The acceleration and deceleration times of the carriage were observed to be 1-s each. With an operating frequency of 5-Hz, this implies that the first and last five data points of each sensor run should not be included in the recorded profile. Deletion of these points is done after the filtering has been applied to ensure as much data as possible is available for filtering (removal of faulty data) purposes. This results in a length of the three-dimensional profiles of 5.75-m.

## 5. CONCLUSIONS

MTAs are a powerful tool to record developing and migrating bed forms in laboratory environments. A methodology has been developed which uses a 30 sensor array for measurement of the three-dimensional surface shape of developing bed profiles. The MTA gives bed elevations over a substantial area of the flume (5.75-m x 0.175-m). The bed form profiles are recorded at 1 minute intervals using the technique. The MTAs work satisfactorily at high Froude numbers and the applied filtering process for missing data, especially behind the leeward side of the crests, produces good results.

It is intended to undertake similar tests in a larger (1.5-m wide) flume with a bigger area covered across the flume.



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### REFERENCES

- Coleman, S.E. (1997). "Ultrasonic Measurement of Sediment Bed Profiles." 27th Congress of the International Association for Hydraulic Research, San Francisco, California, U.S.A.: pp. B221-B226.
- Crickmore, M. J. (1970). "Effect of Flume Width on Bed-Form Characteristics." *Journal of the Hydraulics Division* 96(HY2): pp. 473-496.
- Darwin, G. H. (1883). "On the Formation of Ripple-mark in Sand." *Proceedings of the Royal Society of London* 36: pp. 18-43.
- Friedrich, H., Coleman, S. E., Melville, B.W., Clunie, T.M. (2004). "Development of Discrete Subaqueous Bedforms". *Proc. River Flow 2004, Naples, Vol.1*: pp. 761-768.
- Karaki, S.S., Gray, E.E., Collins, J. (1961). "Dual Channel Stream Monitor." *Journal Hyd. Div., Proc. ASCE, Vol.87, HY6*, pp 1-16.
- Richardson, E. V., Simons, D. B., Posakony, G.J. (1961). "Sonic depth sounder for laboratory and field use." *U.S. Geol. Survey Circ. 450*: 7 p.
- Theberge, A. E. (1989). "Sounding pole to Sea beam." *Surveying and Cartography* 5: pp. 334-346.