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New developments in measuring bed load by the magnetic tracer technique

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Abstract The parallel coil magnet tracer technique is a new method for *in situ* monitoring of bed load transport. The method requires part of the bed load to be magnetized. Many drainage basins which contain igneous or metamorphic rocks will provide enough bed load material of adequate natural magnetic field intensities such that the method can be used in many regions of the world. The novel design of the detector system, in conjunction with high sensitivity data acquisition and a fast recording system, offers features such as pebble street detection, determination of the actual pebble velocity and estimation of the size of the particles in motion.

INTRODUCTION

Measuring coarse grained bed load transport under natural conditions remains an unsolved problem. The accuracy of bed load measurements when using classical trapping systems, such as the Helley-Smith sampler, is greatly affected by the extreme temporal and lateral transport rate variations that occur naturally, even during steady flow conditions (Hubbel & Stevens, 1986).

Other alternatives, for example conveyor belt and vortex bed load traps, involve high expenses and interrupt the transport process at the measuring site.

In order to improve our understanding of bed load transport and to obtain a universal model of the transport processes it is necessary to develop measuring systems which monitor the moving material with high temporal and spatial resolution without disturbing the particle interaction or the streamflow.

PREVIOUS INVESTIGATIONS

Since 1980 our working group has been engaged in developing magnetic techniques for measuring bed load movement. Various experiments using artificially magnetic tracer particles have been undertaken on rivers in Calabria (Italy) and Bavaria (FRG). Comparable investigations have been carried out by Reid *et al.* (1984) in England and by Hassan *et al.* (1984) in Israel.

In 1981 the measuring station at Squaw Creek, Gallantin County, Montana, USA, was installed in collaboration with the Montana State University. Squaw Creek drains an area which contains about 55% andesitic volcanic and intrusive rocks with a magnetite concentration of up to 10%.

An inductive detector system was installed to record the movement of these naturally magnetized pebbles (Custer *et al.*, 1987). Although initial results have been encouraging, there are some serious inherent problems which are difficult to overcome.

The magnetic field intensity of the pebbles, which is the vector sum of remanent and induced magnetism (by the earth's magnetic field), is very small. An analysis of 441 pebbles from the river bed of Squaw Creek, carried out by Monahan & O'Rourke (1982), gives the following distribution:

Field intensity in gamma (γ) units:	< 10	10-39	40-99	100-239	> 240
Number of pebbles:	261	106	38	23	13

By comparison, the field intensity of the earth's magnetic field is about 50 000 γ (1γ = 1 ntesla = 10^{-9} V s m^{-2}).

Because the induced voltage is proportional to the temporal variation of the magnetic flux in the detector system, even weak vibrations of the detectors cause electrical pulses. Other sources of noise are line noise, car ignition and lightning.

With this first measuring system, only pebbles with a field intensity greater than 240 γ induced signals which could be clearly distinguished from the background noise.

MEASURING SCHEME OF THE NEW SYSTEM

In 1986 an improved measuring method was developed and installed at Squaw Creek, with the following objectives:

(a) improvement of sensitivity of the system to obtain signals from moving pebbles even with low field intensities;
(b) reduction of background noise;
(c) detection of moving pebbles over the total cross section of the river;
(d) detection of preferred transport paths;
(e) determination of the actual velocity of the pebbles being transported; and
(f) estimation of the size of the coarse particles that cross the detector.

To achieve these objectives a new detector system was developed. Each detector unit has a length of 1.4 m and consists of over 300 chokes (small electric coils). The axes of the chokes are perpendicular to the river bottom. The chokes of each detector are serially connected so that the total inductivity of each detector is about 21 Henry (V s A^{-1}). This design guarantees both high and equal sensitivity over the entire detector. The total detector system consists of 10 independent sensor units installed in two parallel lines in a "log" which is large enough (about 8 m) to span the whole river. The distance between the lines is 0.15 m (Figs 1 & 2).

Because the surface of the detector log is completely smooth, in contrast to the extreme roughness of the river bed, the risk of pebbles accumulating on the detector surface is very low. As the induced signal is a function of

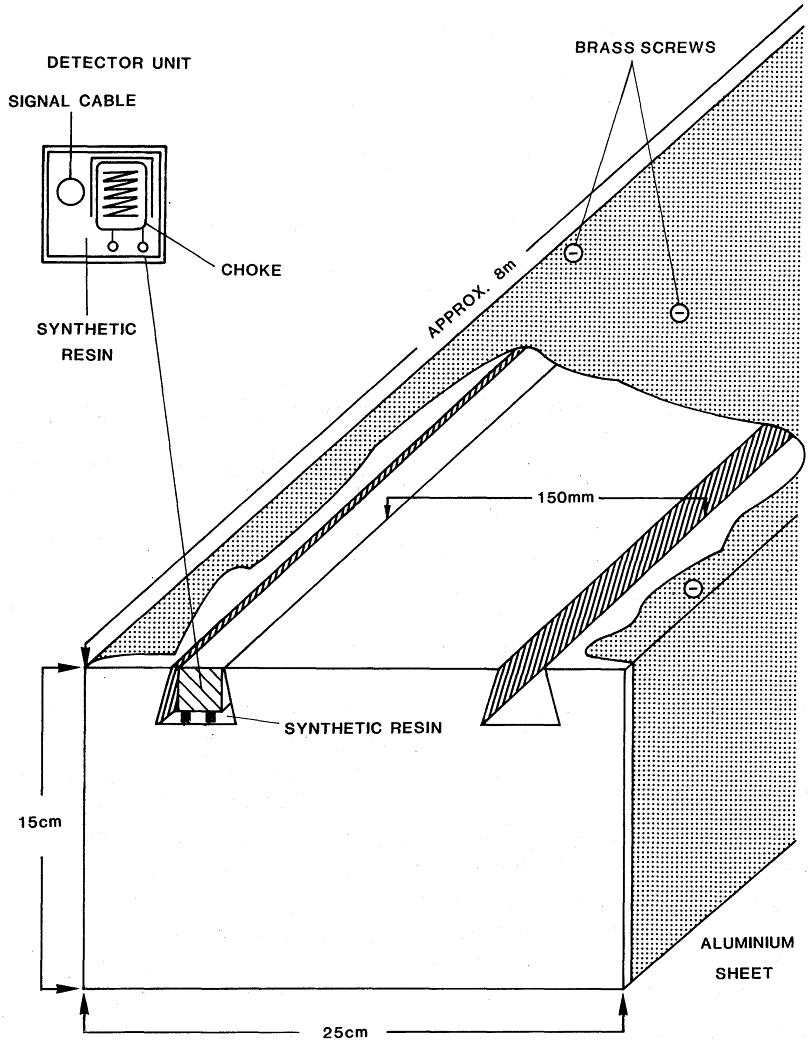

Fig. 1 Cross section of the detector log.

the velocity even the occasional settling of magnetized pebbles will not create any problems.

The arrangement of the detectors in parallel lines (parallel coil magnet tracer technique) has several advantages. External noise signals, such as log vibrations or lightning, are detected on both detector lines at the same time (coherent noise) whereas there is a distinct time different between pebble-induced signals from the upstream and downstream detector. The actual velocity of the pebble can thus be determined from the distance between the two detector lines and the time difference of the two signals.

A further problem was how to register the signals of the 10 different detector systems. In order to:

(a) obtain reliable information about the velocity of the pebbles;

(b) separate the different signals even when many pebbles cross the

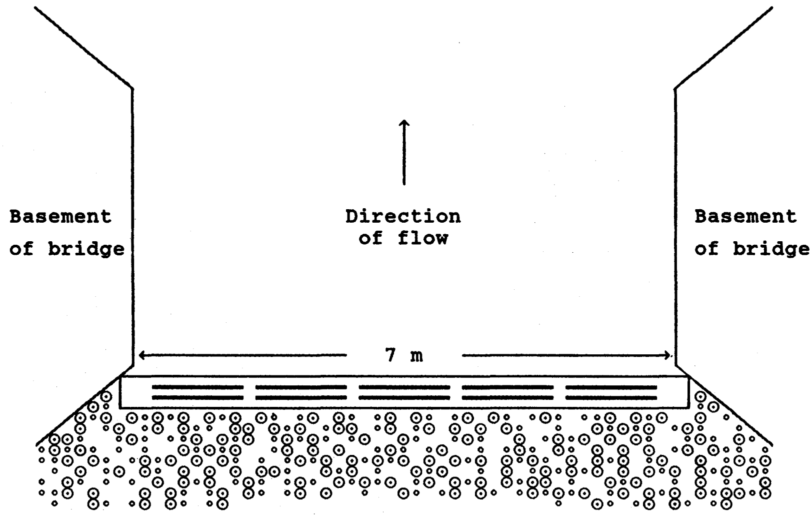

Fig. 2 View of the detector log at Squaw Creek, Montana, USA.

detector at nearly the same time; and

(c) detect coherent noise;

the signals need to be recorded on a system that permits a temporal resolution down to 1/100 of a second or less.

To solve this, a multichannel amplifier/modulator system was developed. The signals from each detector are processed separately by a high-gain amplifier. The resulting output triggers a voltage controlled oscillator (VCO) which performs a frequency modulation of the signal. This signal is then stored on magnetic tape. To obtain synchronized recording of all detectors, the VCOs work with different centre frequencies. The signals of up to four detectors can be stored on one track of the tape. In addition, a stabilized time reference signal is provided to compensate for wow and flutter. The installed tape recorder is a four channel machine allowing 16 channels to be stored synchronously.

A schematic diagram of one channel of the recording electronics and its connection to different control systems is shown in Fig. 3. In the laboratory the information on the tape is demodulated, and can be recorded on a fast chart recorder and converted into digital signals for further processing (Fig. 4).

INITIAL RESULTS

The main task of the spring 1986 field season was to install and test the reliability of the measuring system under field conditions. During the flood event from 27 May to 6 June 1986 the system functioned satisfactorily except for the first day when electronic problems were caused by an unsteady power supply.

Figure 5 shows results obtained by counting the peaks of the output from the relatively slow control chart recorder (10 mm min^{-1}). It provides a

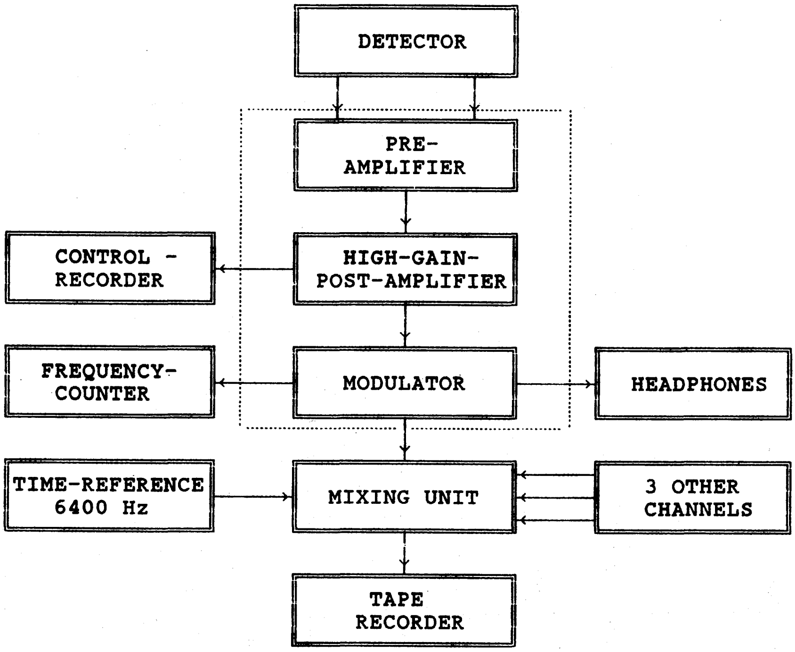

Fig. 3 Block diagram of recording electronics.

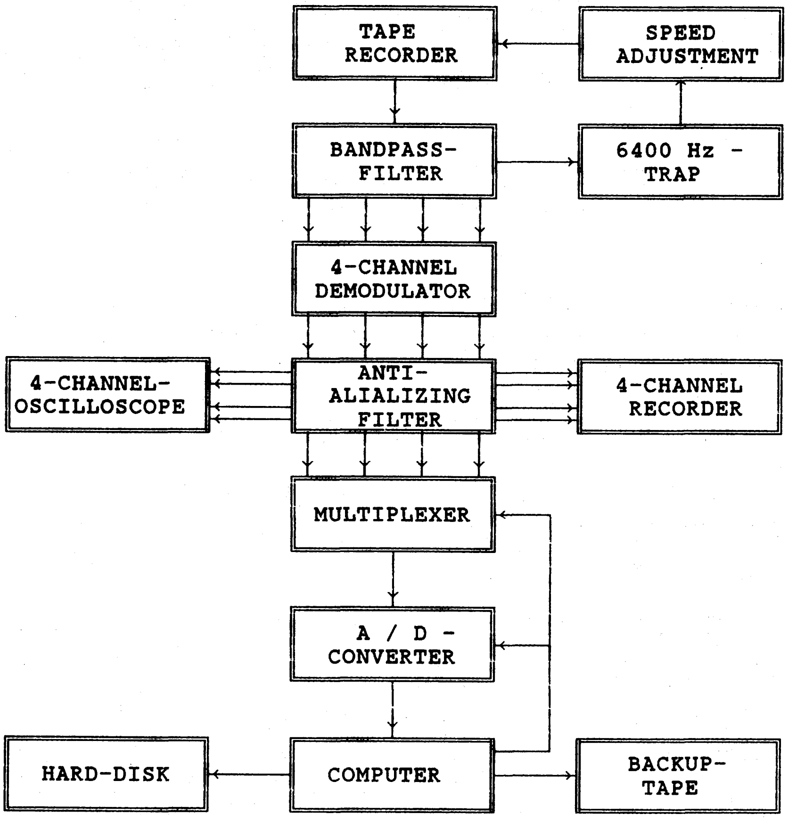

Fig. 4 Block diagram of demodulation and A/D-conversion.

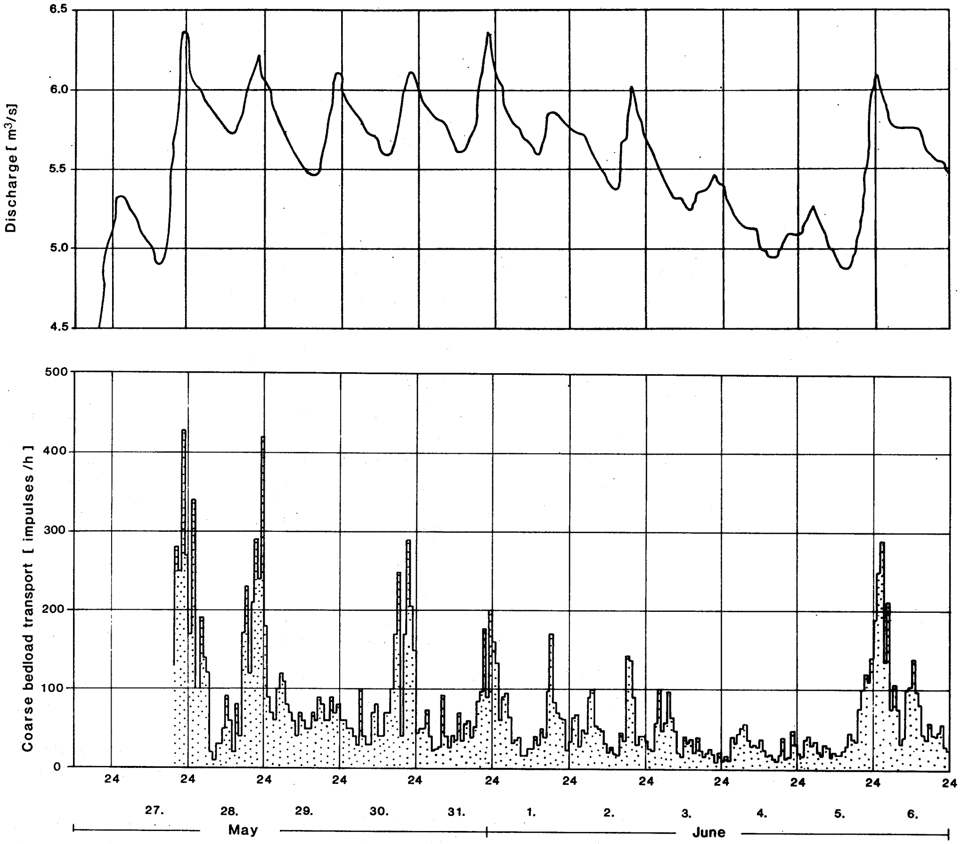

Fig. 5 Discharge hydrograph versus coarse material transport (in counts per hour) (from Bunte et al., 1987).

picture of bed load transport during several high water stages induced by snowmelt. Note that the intensity of bed load transport varies much more than that of the discharge.

Another surprising result was that almost all of the pebbles were found to have been transported over one pair of detectors, on the far right side of the river.

As the performance and limiting factors of the measuring system needed to be investigated, different pebbles of various size and field intensities were taken from the samples that Monahan & O'Rourke (1982) used in their analysis.

The field intensities of the pebbles used for the tests varied between 300 and 10 γ; their volumes ranged from 460 to 20 cm^3. These pebbles and cobbles were passed several times over the detector log and the resulting signals were recorded on magnetic tape. After demodulating the signals in the laboratory they were transferred to mm scale graph paper at a paper speed of 100 mm s^{-1}. Figure 6 shows typical signals for two different pebbles (MC/14 and FC#18) and shows three passages of the same pebble.

The pauses between the different passages have been eliminated. The upper line represents signals from the upstream detector; the lower line the signals from the parallel downstream detector. Note the differences of signal duration and amplitude when comparing axes and field intensities of the pebbles, and the time lag of the downstream signals.

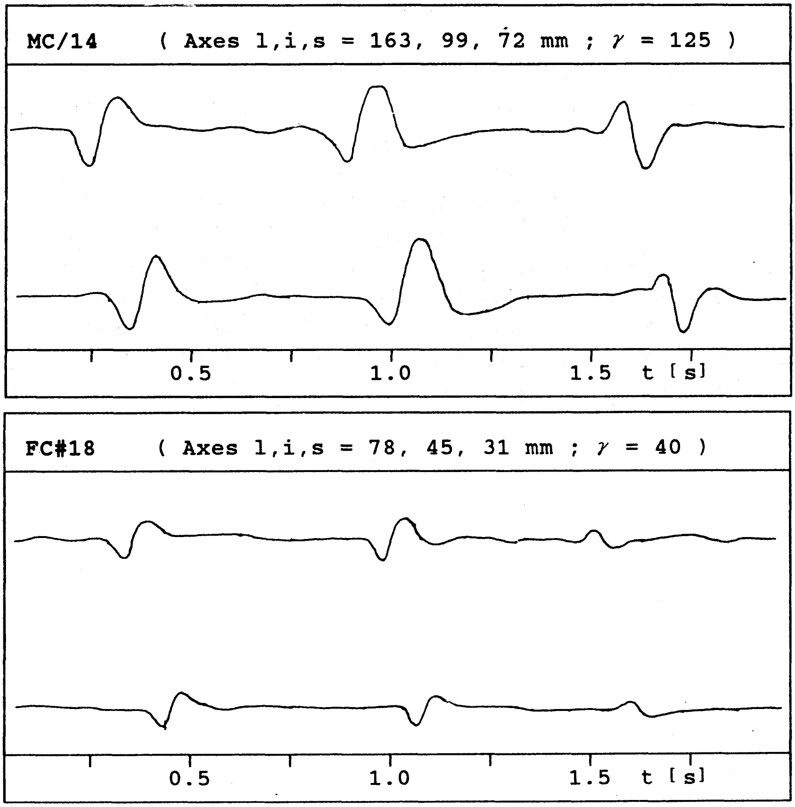

***Fig. 6** Typical signals induced by naturally magnetized pebbles.*

Estimation of pebble size

Previous experiments with artificial magnets showed that when the magnet is passed over the detector, a significant signal is produced in a range which corresponds to about five times the length of the projected axis of the magnet, assuming that the magnet is very close to the detector.

Similar results were obtained by computer simulations using formulae for simple geometric bodies (Telford *et al.*, 1978; Marek, 1984). However, the structure of the magnetic field of an irregularly shaped body such as a pebble, even when magnetically isotropic, is far more complicated than that of a magnetized sphere or a rod-like structure, for example. Nevertheless an attempt was made to estimate the size of the pebbles from the induced signals.

Figure 7 shows the estimated diameters of one pebble which crossed the detectors several times. The diameters were derived by multiplying the duration of the signals by the velocity of the pebble and then dividing the result by five. With a view to greater clarity the results have been sorted by size so that the x axis shows only the experiment number.

As expected, the estimated sizes vary within a certain range. This is not surprising because the orientation of the geometrical axes and especially of the axes of the magnetic vector was totally random during the experiments. Figure 7, however, also reveals that the diameters obtained by the very simple and rough estimation method are normally within the range between short and long axis of the particular pebble. The results of several experiments using different pebbles are shown in Table 1.

The table reveals that the probability of registering a pebble crossing the log increases with pebble size and field intensity. The lower limit is to be found at a volume of about 30 cm^3 and a field intensity of about 40 γ.

The minimum and maximum estimated diameters are normally in the range between short and long axes of the particular pebble. In many cases there is a surprising coincidence between the mean estimated diameters and average of the geometrical axes. Normally the deviation is less than 20%.

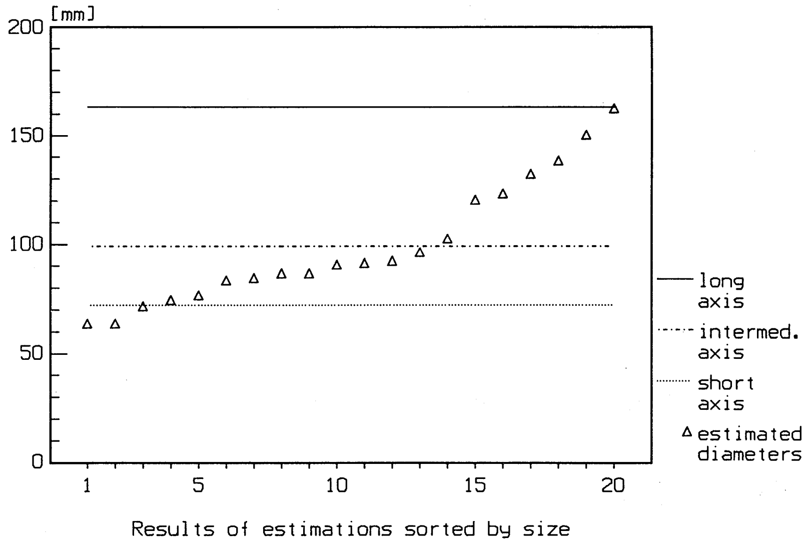

***Fig. 7** Estimation of pebble diameter: data of 20 detector passages vs real geometrical axes of pebble MC/14.*

CONCLUSION

The parallel coil magnetic tracer technique is a new method for real time recording of coarse material transport and offers new insights into bed load transport under natural conditions. It allows the detection of individual magnetized pebbles passing the measuring site. Information on pebble streets is obtained by monitoring the river cross section in several discrete steps.

Owing to the arrangement of the detectors, coherent noise signals may

Table 1 Data of analysed pebbles

Code	γ	Vol	Pass	Rec	L	I	S	E_{MAX}	E_{MIN}	$Ø_{LIS}$	$Ø_{EST}$
CC-24	300	120	20	20	91	78	39	93	55	69	71
MC/14	125	460	20	20	163	99	72	158	63	111	94
CC-30	125	70	25	20	82	54	36	83	36	57	57
CC-48	80	30	20	11	52	40	34	58	36	42	53
CC-21	50	40	20	12	77	58	31	61	35	55	48
CC-44	50	30	20	---	52	35	35	---	---	41	---
MC/33	40	160	20	18	111	106	35	72	33	84	50
FC#18	40	50	40	13	78	45	31	70	30	51	51
FC/29	40	30	30	16	53	38	20	52	31	37	43
FC/26	30	60	25	9	72	52	43	68	32	56	45
CC-97	30	20	20	---	55	37	30	---	---	41	---
CC-72	20	30	20	---	43	39	34	---	---	39	---
FC-14	10	80	20	4	87	44	43	59	36	58	50

Code, γ, Vol: data from Monaham & O'Rourke (1982)

Code : signature
γ : field intensity in gamma
Vol : volume of pebble
Pass : number of detector passages
Rec : recovery rate (number of registered passages)
L,I,S : long, intermediate, short axis (mm)
E_{max} : maximal estimated diameter (mm)
E_{min} : minimal estimated diameter (mm)
ϕ_{LIS} : arithmetic average of L, I and S (mm)
ϕ_{EST} : mean estimated diameter (mm)
--- : no signals received

be recognized and the actual velocity of individual particles determined. Furthermore, the size of the pebbles in motion can be estimated.

The simple size estimation method described above is not without its problems, especially when the signals of the pebbles interfere with noise signals. To overcome such difficulties, better signal analysing algorithms and error detection/correction schemes for further data processing need to be developed. For this reason a series of test runs using magnetized pebbles in a laboratory flume is planned in the near future. To facilitate wider usage, it is planned to develop programs for data acquisition and processing which run on personal computers.

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