

Perspectives on bed load measurement

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Abstract Over the past decade there have been important developments in bed load measurement techniques for floods and debris flows in mountain areas. While suspended sediment is still the more common fraction measured, bed load remains a problem since it is not only more difficult to measure but it also causes most impact in terms of geomorphological change. Developments in field measuring techniques for bed load transport are essential and require sophistication in order to function efficiently in different environments. Optimally, bed load measuring techniques should be non-intrusive, flexible and representative for different types of transport. This contribution is the result of several decades of bed load experiments in mountain torrents focused on gravel- and cobble-bed streams and problems of developing bed load measuring approaches and devices for future application. Techniques of trapping and tracing are described and the potential of high-resolution remotely sensed images are stressed. The increasing awareness of bed dynamics and changes in gravel-bed rivers will create a growing demand for reliable field data for use in further model validation and application.

Key words acoustic detectors; bed load measurement; image analysis; radio tracing; samplers; tracers; traps; visual tracers

INTRODUCTION

Modern theoretical assessment of bed load was initiated by Du Boys in 1879 but according to Bogardi (1974) the first attempt to measure bed load volume was carried out by Schaffernak in the River Mur in Styria, Austria, 29 years later. In geology and geomorphology, the only “complete” measurement of bed load volume, including particle properties, is applied in river deltas entering lakes or reservoirs. These sinks of trapped particles provide by far the best test sites for various types of validation. The predominance of theory over field observation is typical for studies of bed load transport, even at the present time. There is a continually growing list of important publications dedicated to bed load functions, but data for validation is sparse and mostly restricted to flume experiments. This situation is further complicated by divisions between engineers and geoscientists. For example, the first bed load flume experiments were carried out by the geophysicist Gilbert (1914) in California, but these are only rarely cited or applied by European engineers. The demand for rivers to remain in geomorphological equilibrium, with neither excess erosion nor excess accretion, and the many present-day ecological problems cannot be solved merely by increasing our knowledge of hydrology and hydraulics but urgently require more field data of the corresponding sediment transport. New approaches are not only essential

for improving models, they are also essential for improving bed load measuring techniques. The aims of this contribution are to provide suggestions and perspectives for the development of bed load measurement techniques for the next decade. For this purpose, this paper will review the well known measuring techniques of sediment trapping and sampling, tracing, and surveying using both conventional techniques and remotely sensed images. The resulting contribution is based primarily on the experience of the authors and will not attempt to cover all aspects of the problem.

TRAPS AND SAMPLERS

Since the beginning of construction of hydropower schemes, the demand for improved information on bed material transport has increased. It is therefore not surprising that the first measurements were executed in alpine rivers by Austrian and Swiss engineers. Movable samplers were applied by Schaffernak (1916), Ehrenberger (1931), Mühlhofer (1933) and Nesper (1937). A bag was mounted onto a frame, or sediment was trapped in mesh-covered boxes suspended from bridges. For finer particles, such as sand and gravel, these approaches were replaced by pressure difference samplers. The entrance of these samplers was designed to allow the water velocity to remain unaltered relative to the ambient velocity. According to Bogardi (1974), the first instrument of this type was developed by Goncharov (1938) for the River Kuban. In Europe, this sampler type is known as the Arnhem sampler or VUV sampler (Karolyi, 1947) and was further developed into a standard instrument by the US Geological Survey, as the so-called Helley-Smith sampler (Hubbell, 1964). For the latter, some calibration was even carried out under field conditions as late as 1964, as reported by Hubbell (1964). Today these samplers are commonly applied by river authorities all over the globe and represent present state-of-the-art. The main restriction of this approach is the nature of unsteady bed load movement. Particles frequently move along preferred lines or bed load streets (de Jong & Ergenzinger, 1994) and appreciable amounts of data collected by lengthy measurement programmes are required to develop a reliable picture of the natural situation (de Jong & Ergenzinger, 1998). If the river carrying the sediment has a width of 100 m and the entrance to the sampler is only 0.2 m, this results in a relative factor of 500! Any slight mistake caused during the lowering of the sampler is amplified accordingly.

Fixed samplers are applied in some river cross sections to measure the passage of bed load. The most famous installation of this kind was set up by Leopold & Emmett (1976) at East Fork, Wyoming, USA with eight hydraulically-controlled slot intakes installed across the channel section and conveyer belts to carry sediment to the weighing station and back into the river. Milhous (1973) working in Oregon was the first to create a vortex tube intake for continuous bed load trapping. In Europe, Tacconi & Billi (1987) built a similar installation in Tuscany, Italy with a vortex tube installed diagonally across the Virginio Creek at the measuring station. There is a weir below the site, so that the bed load is easily transported back into the river. For rivers with widths of >10 m and high spatial and temporal variability of bed load discharge, such constructions are far too costly. Therefore cheaper devices, such as the Birkbeck type boxes or butts proposed by Reid *et al.* (1980), have been installed not only in Turkey

Brook in England, but also in similar-sized wadis in Israel (Reid & Laronne, 1995). The largest version currently in existence was installed in the upper River Drau in Carinthia, Austria (Habersack *et al.*, 1997). This sampler was inserted into a concrete tube with a diameter of 2 m and a depth of 1.5 m and consists of two steel boxes with a volume of 0.68 m³ covered by a wooden lid with a sliding opening 1.6 m in total length and a variable width of 0.15–0.3 m. The dimensions are defined according to the particle sizes, assuming that particles saltate in the range 16–120 mm in height and 450–1560 mm in length. The outer box is slightly larger and higher to accommodate a pressure cushion at the bottom between the boxes. To define the impact of water pressure, a second pressure stream gauge would be necessary close to the butt. Such devices measure bed load discharge with high temporal resolutions up to a filling level of about 80% of the total height of the butt box and the related grain sizes can be defined from the trapped material. However, this large bed load measuring device in the River Drau has an underwater weight of >1 t and hence is best installed under a bridge so that it can be moved with a hoist. This device is optimal for situations with no preferred “streets” of bed load transport and sediment levels below 80% of the available height. The beginning of particle discharge can be defined with confidence and high temporal resolution (Ergenzinger *et al.*, 1994a), but quite often the butt is filled to the upper confidence levels before the end of the flood.

ACOUSTIC DETECTORS

Acoustic detectors or hydro-microphones measure the noise of interparticle collisions as an indirect result of bed load transport. In 1933 Mühlhofer was the first to lower a telephone-microphone into the flooding River Inn to hear the music of the roaring bed load. Since that time, there has been a long list of successors attempting to define relations between intensity and/or frequency of noise and the causal impacts between water and particles and between the particles themselves (Bedeus & Ivicsics, 1963; Tywoniuk & Warnock, 1973). The main result of this technique is that it can be successfully applied for the definition of the onset of particle mobilization and transport. There are some hydropower schemes that control the lowering of sediment-exclusion weirs at their water intakes by using such microphones. However, there is still no simple, calibrated bed load-acoustic signal function for bed load noise detectors that can define the beginning and end of particle movement as well as the intensity of particle discharge (Johnson & Muir, 1969). Nevertheless, it is anticipated that measurements of particle to particle impact, in addition to measurements of particle vibration, will one day create distinctive signals which are easier to detect than the noise of flood waters. It is the low frequencies that are of particular interest.

TRACERS

Painted tracers and particles with exotic lithology represent the oldest approach to bed load transport measurement and according to Sear *et al.* (2000) were first applied by Richardson in 1902. He investigated the distribution of a pile of bricks on Chesil

Beach in England. This interesting experiment nevertheless suffered from the very beginning due to the neglect of the following principles, i.e. that tracer particles should have a similar grain size, shape, specific gravity and erodibility as natural particles. During the last century the use of painted or tagged particles rapidly increased, since they are cost effective and capable of solving many different problems. More modern techniques were developed and were only applied during the last 20 years. In 1998, Foster convened the annual conference of the BGRG (British Geomorphological Research Group) on "Tracers in Geomorphology" and published the results in a special volume (Foster, 2000). The chapter contributed by Sear *et al.* (2000) on "Coarse Sediment Tracing Technology in Littoral and Fluvial Environments" covers all important tracer methods and provides a good review of the literature. The new wave of tracer techniques gave rise to investigations of the following problems of coarse sediment transport:

- Boundary conditions or thresholds for initiation of motion.
- Rate and direction of bed load transport.
- Single particle transport: particle and bed properties and hydraulic conditions.
- Periods of movement and rest for single particles.
- Volumes of bed load transported and the magnitude of bed load discharge.

The new generation of coarse grain tracers comprise:

- Luminescent tracers.
- Radioactive tracers.
- Magnetic tag tracers.
- Magnetic and aluminium tracers.
- Radiotracers.

The performance and merits of these techniques will be discussed in the following sections.

Visual tracers

This type of tracer comprises all "old" tracer techniques and technically visible tracers created using luminescent dyes. The particles are coated with dye and are detected by the naked eye during the day (normal paint) or during the night (with the help of luminescent dye radiated by UV) if deposited at the surface. Since the dispersion is three-dimensional (3-D), the recovery rate of particles in natural rivers after a flood wave is frequently only half that of the initial sample and, depending on the geomorphological setting, the recovery rates can be even worse. If only short particle transport distances are involved, as in the context of the construction and destruction of pebble clusters (Billi, 1988; de Jong, 1991, 1993), or investigation of the potential for the initiation of particle motion or local morphological dynamics (Hey & Thorne, 1984) painted pebble techniques are still useful. Frequently, only a certain width of the river bed is activated during phases of bed load transport, and this can be effectively demonstrated using lines of painted particles (Cavazza, 1981; Wilcock, 1997). Nevertheless, the dominance of painted particles in bed load studies terminated at the beginning of the 1980s since there were too many shortcomings in the application of this technique for the determination of bed load discharge.

Radioactive tracers

Radioactive tracers were mostly used in the 1960s and 1970s for the study of sand transport both in rivers and along coasts. There is a vast specialized body of literature covering not only the British (Crickmore, 1967) and French (Courtois, 1970), but also the Eastern European experiences, in particular. Gravel and coarser material was mostly labelled by inserting "pills" containing radioactive elements. The most common radioactive isotopes for bed load movement are described in a table by Richards (1982). The half-life should match the frequency of bed load transport of the river, although this principle is not always applicable. In Eastern Europe many experiments were executed with natural bed material activated in nuclear reactors. Dispersion is usually measured using a scintillation detector mounted on a sledge which is towed over the river bed. The measured spatial distribution can be interpreted using dispersion models. The most successful models are based on the Einstein (1936) approach, including assumptions of step-length distances and rest periods between periods of movement (Hubbell & Sayre, 1964). These approaches were also applied to the results obtained from radio tracers 30 years later. Since the 1970s, tracer experiments using radioactive isotopes are no longer permitted in most western countries.

Magnetic tracers

Radioactive labelling of bed load was replaced by a new technique developed by the Berlin group of physical geographers at New Year 1980, in the River Buonamico in Calabria, southern Italy. A small magnetic bar was inserted into a hole drilled into a bed load particle (Ergenzinger & Conrady, 1982). The cobbles were then placed into the bed of a small, steep creek feeding into the Lago Costantino. Bed load mobilization occurred due to snowmelt during the late afternoon of the first day of the experiment and the passage of tagged particles was successfully registered using the Faraday principle, involving a system of large coils (25 cm in diameter) mounted onto a metal beam suspended across the creek 30 cm above its bed. This first trial was so promising that it was demonstrated to the visiting Israeli scientists Schick and Hassan in summer 1980, during their excursion to southern Germany. From then on the Berlin group developed automatic magnetic measuring systems, whereas the Jerusalem group focused on the 3-D dispersion of magnetically-traced particles. The resulting publications are numerous. Those of the Schick group started with Hassan *et al.* (1984) and culminated in the review papers of Hassan & Church (1992) and Church & Hassan (1992). The Berlin group cooperated with Montana State University in Bozeman, USA and installed their device at Squaw Creek, a small river whose bed load is predominantly andesitic containing a high amount of magnetic crystals. About 66% of all pebbles have a sufficient magnetic concentration to create signals above the electronic noise level. The first results were published by Ergenzinger & Custer (1982, 1983). The technical potential of this approach, including the relation between signal volume and grain size, was highlighted by Spieker & Ergenzinger (1990). The dissertations of Bunte (1996) (published in German in 1992 and in English in 1996) and de Jong (1995) summarize the immense data set assembled by the studies undertaken by the Berlin group.

The magnetic tracer technique was applied to determine the movement of naturally or magnetically tagged particles via detectors on the one hand and via tagged non-magnetic particles on the other hand, in order to trace their dispersion after floods with a special magnetometer. In contrast to the use of painted material, the magnetometer can sense the disturbance of the Earth's magnetic field approximately 30–50 cm below the surface of the sediment. As with radioactive tracers, it is possible to sense the dispersion of the material in three dimensions and to determine the volume of sediment moved by a single flood event from the average width of bed load streets (multiplied by the depth of the particle layer. In addition, magnetic tracers can be applied in many special fields. For example, Gintz *et al.* (1996) manufactured hundreds of artificial magnetic particles with similar weights, but a variety of different shapes (ellipsoids, spheres, rods and disks), and used them to analyse the impact of particle shape on travel length.

The detector analysis is particularly well adapted for sensing the movement of natural magnetic particles (Ergenzinger *et al.*, 1994a,b; de Jong *et al.*, 1994). Magnetic particles cross a detector log and induce a microvolt current passing through the coil system. Movement of particles is detected with very high temporal resolution (in second intervals). Comparison of bed load transport patterns between Birkbeck type boxes and automatic magnetic detection system are summarized in the joint publication by (Ergenzinger *et al.*, 1994a). The spatial resolution is defined according to the geometry of the coils and the number of coils defined over one field. The particle grain size can be derived with a high probability from the area of the induced signals. If several detector sections are mounted along the river, this makes it possible to sample the longitudinal transit of bed load. Under these conditions problems related to the movement of bed load particles in general can be solved.

Radio tracers

In the same month of the same year, the group of Emmett *et al.* (1989) and of Ergenzinger (1989) developed the use of radio tracers for application in rivers. The American group worked in Alaska while the German group worked in Upper Bavaria. Radio tracers were selected to validate the Einstein (1936) model, by measuring the step length and rest periods of coarse single particles. For this purpose a micro transmitter, with a frequency of 150 MHz and batteries 55 mm in length and 20 mm in diameter, was installed in holes drilled into natural cobbles. With an antenna type HB 9 CV the signal of 1 mW could be received over a range of up to 200 m. For the determination of step length and rest periods, a band of 12 antennae was installed along the river bank to allow simultaneous observation of up to eight radio particles with a spatial accuracy of up to 2 m. Some first results were published by Chacho *et al.* (1989) and Ergenzinger *et al.* (1989). Further details on PETSYS (Pebble Transmitter System) are provided by Ergenzinger & Schmidt (1990), Busskamp & Ergenzinger (1991) and Busskamp & Hasholt (1996).

The technique proved to be successful in shallow waters with low conductivity. However, the applied frequency is not appropriate for more saline and deeper rivers such as the River Rhine, and is absolutely inappropriate for seawater. It is,

nevertheless, surprising that the new device is not used more frequently in wadis with extreme flood peaks. There is a good chance of relocating radio-tagged cobbles, even months after insertion, and to define the dispersion of particles with different properties in families of 10–20 radio cobbles with different signals and similar or differing frequencies. The largest restriction is still the dimension of the battery. However, if the dispersion of particles is only relevant during the wet season, PETSU can be switched on after a defined time period. The signals can be located via helicopter or from vehicles. The average bed load discharge can be calculated nearly as precisely as water discharge under these conditions, from the median of the dispersal width and length and the average depth of the buried particles.

In cooperation with Christaller from the Technical College Berlin, a transmitter with different sensors, the telemetric device COSSY (Cobble Satellite System), was produced. The prototype was applied by Ergenzinger & Juepner, 1992) in a detailed study of the relationship between lift and drag forces under critical conditions. Similar investigations were undertaken by Mikos at the Technical University of Ljubljana, Croatia. Since radio tracing is very common nowadays, more devices for radio tracing are available and prices for ICs are decreasing. There is growing potential for more sophisticated devices for many special problems of bed load transport. For example, step and rest periods can be recorded and stored in individual cobbles that can be located and tapped after floods.

A further example of the application of the radio tracer technique (DUMPLING) was developed in cooperation with the Federal Agency for Geosciences in Hannover, Germany (Hanisch *et al.*, 2003).

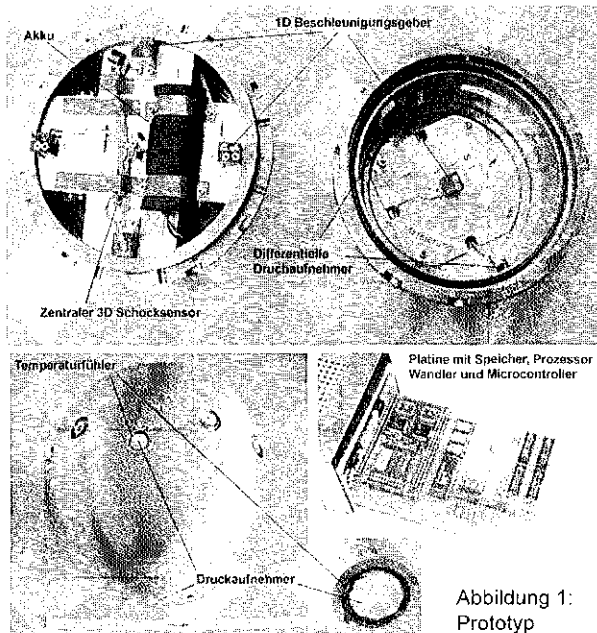


Abbildung 1:
Prototyp

Fig. 1 Prototype of the mobile measuring probe, DUMPLING, an instrumented boulder.

To monitor the internal fluid dynamics of debris flows, including particle movement, pressure, kinetic energy and the impact of other moving particles (Fig. 1) a special instrumented boulder, DUMPLING, was developed. The sensors installed inside two steel hemispheres included 3-D acceleration, differential pressure, temperature and radio signals. The data are sampled at a rate of 100 Hz and transmitted via the radio transmitter only following the end of movement. DUMPLING is 30 cm in diameter and weighs 37 kg. The advantage of instrumented boulders lies in their potential for direct measurement of internal flow, the transmission of complex information at distinct points in the flow, the mobility and flexibility of the system and the possibility for measurement under natural conditions. Figure 2 gives an indication of how DUMPLING works under natural conditions, in both the cross-section and the long profile. An ultrasonic device, together with an antenna and video camera system allows the instrumented boulder to be tracked during a debris flow. Similar smaller devices will be developed for bed load or avalanches in the near future.

VIDEO DETECTION

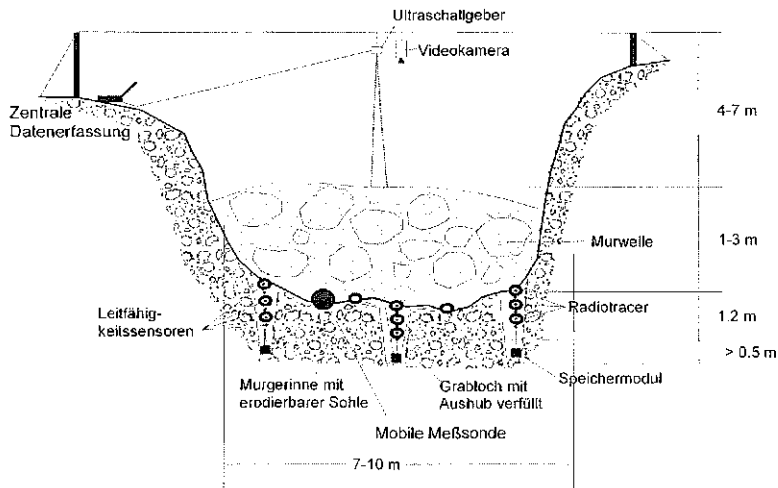
In the Schriedlaine, Upper Bavaria, Germany, natural bed load transport was measured between 1995–1997 using VICOM (Video Cobble system) (Krause, 1997). A bed load separation system was installed with an inclined steel grid separating flood water from the bed load fraction. Coarse particles in motion on the grid were filmed from above with a video camera system, and data was stored digitally. The system was not totally satisfactory, since bed load mobility was dependent on a certain threshold discharge, but, on the other hand, too much turbulence made measurements obsolete. According to the first experiments, the separation grill should have a total length of approximately 10 m and the inclination should be adapted to the dominant grain sizes. The installation should therefore include a hydraulic lever to change the inclination over the range 5–10°. Such devices can be installed at sites with specific characteristics and in combination with the construction of protection works. They should be accessible by road and near a powerline for illumination during the night.

DERIVATION OF BED LOAD TRANSPORT FROM ANALYSIS OF SCANNED OR PHOTOGRAPHIC IMAGES

The idea of monitoring sediment size and bed change from aerial photographs led to the development of a remotely controlled, helium-filled balloon system. The river bed was analysed by means of a digital camera at 10 m height and the images were processed digitally. Similar work was carried out by Church *et al.* (1998). The advantage of the system is that at such a scale, the interpretation of the river bed is not confined to single particles, but can encompass whole entities, such as ring structures and step-pool systems (Ergenzinger, 2000). The disadvantage of such systems is their vulnerability to bursting or becoming entangled in steep, forested catchments.

Recently, high resolution image data from HRSC-A (High Resolution Stereo Camera-Airborne) flown by light aircraft by the German Aerospace Centre (DLR) has enabled new insights into bed load transport rates and size (Fig. 3). The multispectral

a) **Schematischer Meßquerschnitt**



b) **Schematisches Längsprofil**

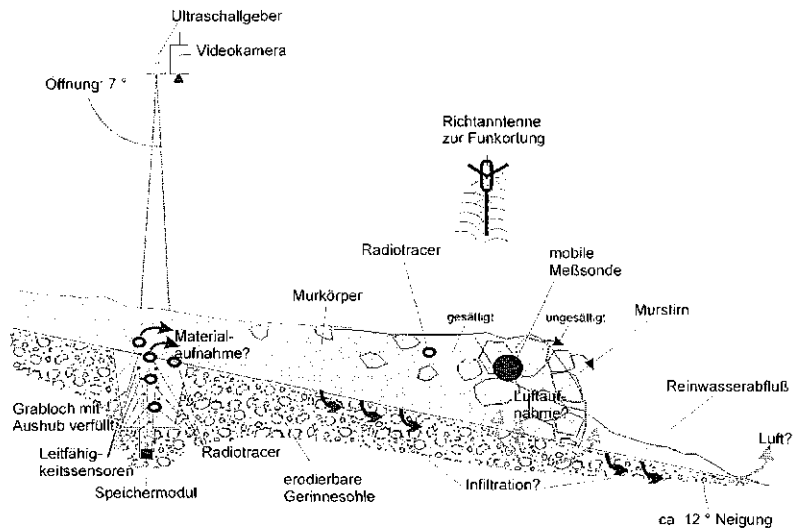


Fig. 2 Proposed measuring system with DUMPLING during debris flow.

optoelectronic digital stereo scanner has a focal length (grid size) of 17.5 cm, including five stereo CCD lines, a stereo angle of 18.9° and 12.8°, four multispectral CCD lines, a field of view of 11.9° and a data rate of 80 MBit s⁻¹ (Lehmann, 2001). The colour images can be geometrically corrected and a high-resolution DEM created with the help of GPS controlled orientation data. Such high resolution images allow detailed, non-destructive analysis of sediment sizes above 17.5 cm in diameter, arrangement and imbrication of coarse-grained alpine river beds both before and during flood events. A detailed, simultaneously constructed DEM enables the determination of changes in sediment volume.

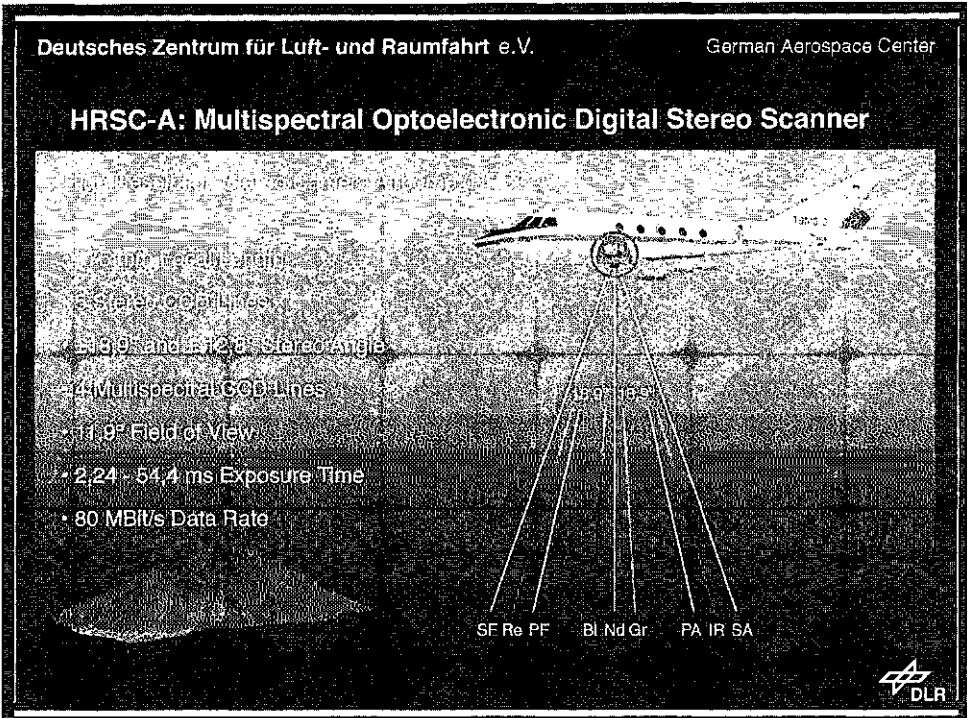


Fig. 3 HRSC-A: Multispectral optoelectronic digital stereo scanner.

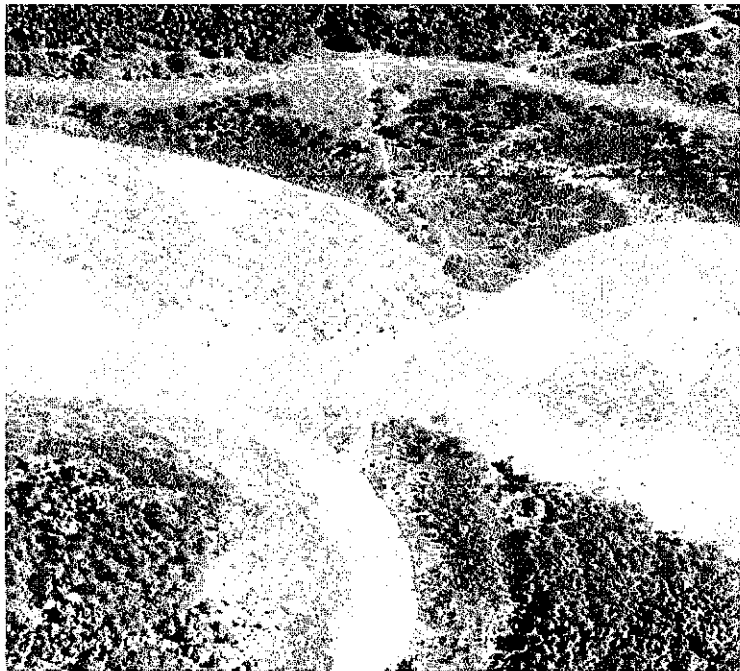


Fig. 4 Detailed analysis of sediment size, arrangement and volume changes of river beds based on HRSC image analysis with a grid size of 17.5 cm.

Such approaches are of particular interest for investigating river bed dynamics in regions with intermittent water discharge. In contrast to the previous approach of measurement of bed load and river bed changes in specific cross-sections, the new monitoring technique describes the bed changes along river sections (Ergenzinger *et al.*, 1994b). Comparison of images between floods allows bed changes to be defined from differences between river sections as well as large-scale GIS along more extensive river reaches.

CONCLUSIONS

The geomorphology and engineering toolboxes contain a number of methods for measuring bed load transport in rivers. During the last 25 years, many new techniques have been proposed and applied. Due to the effects of environmental controls at the beginning of this period, the capability of radio-active tracers was lost but replaced by aluminium and magnetic tracers, and subsequently radio tracers. The most significant limitation of all these efforts is that there has been no joint experiments for validation purposes. It is especially important to carefully determine the minimum sample size required for radio tracers to assure the validity of results. Since these types of tracers are expensive, not more than 10 radio tacked particles are commonly applied and with this limit, the probability of the results matching natural transport is uncertain. In this context the development of new approaches, moving away from single particle or cross-sectional concepts, towards approaches linking the spatial distributions of river bed changes with related transport provides new opportunities. These in turn provide new opportunities for validating the results of small-scale experiments and model output. It is arguably surprising that during a new, important era where the significance of fluvial morphology has been increased due to the freshwater guidelines of the EU and other important bodies, the number of related experts involved is decreasing and interest in investigating field-based sediment transport is gradually diminishing in relation to modelling. This stands in clear contrast to the present-day requirements. At the same time, the potential to apply the results of local as well as regional investigations is growing rapidly.

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