Proceedings, 9th International Symposium on River Sedimentation, Cheng Liu, ed.: Yichang, China, October 18-21, 2004, Tsinghua University Press, pp. 2549-2555; this version includes a correction in the abstract clarifying that the LISST-SL is in development as of February 2005 and cannot be deemed "reliable" until proven so through rigorous quality-control testing.

THE LISST-SL STREAMLINED ISOKINETIC SUSPENDED-SEDIMENT PROFILER

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Abstract: The new manually deployed Laser In Situ Scattering Transmissometer-StreamLined profiler (LISST-SL) represents a major technological advance for suspended-sediment measurements in rivers. The LISST-SL is being designed to provide real-time data on sediment concentrations and particle-size distributions. A pressure sensor and current meter provide real-time depth and ambient velocity data, respectively. The velocity data also are used to control pumpage across an internal laser so that the intake velocity is constantly adjusted to match the ambient stream velocity. Such isokinetic withdrawal is necessary for obtaining representative sedimentary measurements in streamflow, and ensures compliance with established practices. The velocity and sediment-concentration data are used to compute fluxes for up to 32 particle-size classes at points, verticals, or in the entire stream cross section. All data are stored internally, as well as transmitted via a 2-wire conductor to the operator using a specially developed communication protocol. The LISST-SL's performance will be measured and compared to published sedimentological accuracy criteria, and a performance summary will be placed on-line.

Keywords: Suspended sediment, Sediment measurement, Sediment Surrogate, Sediment sampling

1. INTRODUCTION

Since the 1940's, standard U.S. Government methods to measure suspended-sediment fluxes in rivers and other waterways have entailed use of manually deployed isokinetic samplers that collect and retain water samples (Federal Interagency Sedimentation Project, 2004). Results of concentration analyses on these samples are used concurrently with collected water-discharge data to compute suspended-sediment discharges. Although quite reliable, these methods are time consuming and expensive, and in some cases results are unavailable for months after sample collection. The U.S. Geological Survey (USGS) is currently investigating sediment-surrogate technologies that may offer more efficient means for measuring suspended sediments without the need for collection and subsequent analysis of a water sample. Instruments that operate on acoustic, pressure-differential, bulk-optic, digital-optic, and laser principles are being evaluated at a number of field and laboratory sites across the United States (Gray et al., 2003a; 2003b).

One mature technology that has been applied successfully in marine and estuarine systems and is now being developed for riverine systems is based on a laser multi-angle scattering method. The manually deployed Laser In Situ Scattering Transmissometer-StreamLined profiler ("LISST-SL"; Gray et al., 2002; Sequoia Scientific, Inc.[1], 2004) is designed to provide suspended-sediment particle-size distribution and concentration data isokinetically and in real time. This paper describes the principles on which the LISST-SL is based, its characteristics, design capabilities, and results of the initial velocity test on a prototype. Results of planned rigorous velocity and sedimentology tests will used to improve the design of the production version of the LISST-SL.

[1] Use of brand or firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

2. LISST-SL OVERVIEW AND FUNCTIONALITY

Developed as part of a cooperative research and development agreement between Sequoia Scientific Inc., and the USGS, the LISST-SL is an advanced instrument system that:

1. Employs laser multi-angle scattering to measure the size distribution and concentration of suspended sediments.
2. Incorporates built-in microprocessors that provide for autonomous operation and data storage, as well as remote instrument control and data transmission.
3. Is packaged in a low-drag housing that enables its use in a broad range of stream velocities.

Power is supplied from the surface via the same 2-conductor cable that is now used for deploying current meters (U.S. Geological Survey, 2004a) and samplers (Federal Interagency Sedimentation Project, 2004) used by the USGS. This feature makes the instrument usable from existing deployment platforms (U.S. Geological Survey, 2004b). With the inclusion of a propeller-type current sensor and a pressure-based depth sensor, the measured sediment-concentration data can be converted to flux values for any depth. When deployed by methods described by Edwards and Glysson (1999), these values can be summed to obtain point- or depth-integrated sediment discharge rates. This combination of capabilities provides a useful and heretofore unavailable set of measurements in real time: velocity, depth, water temperature, concentration, and particle-size distributions. The need for retention, processing and subsequent analyses of water samples is eliminated.

2.1 Operating Principle and Limitations

At the heart of the LISST-SL system is the technique of laser multi-angle scattering, also known as laser diffraction. A collimated laser illuminates particles in its path, which scatter the light. The scattered light is measured by a set of 32 'ring' detectors, each of which measures light scattered into a specific small angle-subrange. The 32 measurements then are *inverted* to compute concentrations in 32 size classes, thus providing the particle-size distribution. The inversion represents the solution of 32 algebraic equations where there are 32 unknowns (concentration in 32 size classes) and 32 data (multi-detector output). Summing the 32 concentration values provides the total concentration. Details of the method are described by Agrawal and Pottsmith (2000).

The principle of laser multi-angle scattering is illustrated in Fig. 1. A laser beam emitted from a red diode laser enters water from a pressure-tight window. Particles in the water illuminated by the beam scatter some of the light into a receiving lens behind a second water-tight window. The lens focuses all rays originating from particles at a particular angle θ from the lens axis to a fixed point at radius $r = f\theta$ on a multi-ring detector located on the lens focal plane. Each ring detector, therefore, senses scattering at a specific small sub-range of angles. The photo-currents from the individual rings are converted to voltages and stored in a computer for subsequent processing. In contrast to the scattered light sensed by the ring detectors, the laser beam focuses to a small spot at the center of the rings, and passes through a hole there. The power of the beam transmitted through this hole is sensed by a photodiode detector (Fig. 1). This constitutes a measurement of optical transmission τ. This parameter is used for deattenuating measured scattering. It does *not* constitute a measurement of sediment concentration.

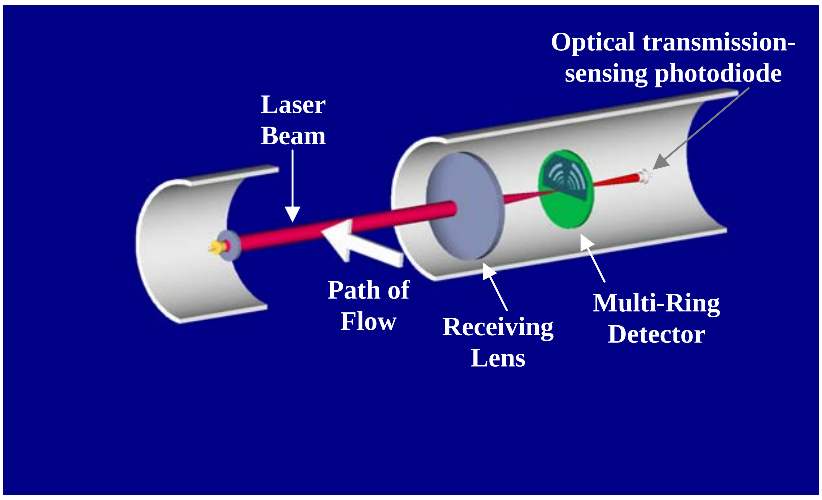

Fig. 1 A cut-away of the optics shows a laser beam traveling left to right, a receiving lens, a multi-ring detector, and an optical transmission-sensing photodiode. Particles flow with water at the arrow.

The maximum and minimum scattering angles are defined by the maximum and minimum radii of the ring detector set where:

$$\theta_{max} = atan(r_{max}/f); \text{ and}$$
$$\theta_{min} = atan(r_{min}/f). \quad (i)$$

The range of particle sizes covered by the method depends on these minimum and maximum angles as follows:

$$a_{min} = 2/k\theta_{max}; \text{ and } a_{max} = 2/k\theta_{min}, \quad (ii)$$

thus indicating an inverse relation between the size and angles. Here a is particle radius, $k=2\pi/\lambda$,with λ being the wavelength of laser light. The concentration range that can be covered is determined by the minimum strength of scattered light on the low end of concentrations, and by the occurrence of multiple-scattering at the high end. When concentrations are low, weak light scattering becomes difficult to measure, which defines the lower detection limit in clean water. This limit can be extended to even lower concentrations by increasing laser power and (or) by increasing the number of measurements that are averaged.

At high sediment concentrations, light initially scattered by particles can be scattered a second time or more, thus producing more complex multiple-scattering effects. In practice, multiple-scattering can be identified from a measurement of optical transmission. This transmission is measured by the diode detector D placed behind the multi-ring detector. When the transmission reaches levels below about 75 percent of its value in particle-free clear water, multiple-scattering becomes barely noticeable. At optical transmissions as low as 30 percent, however, multiple-scattering effects do not significantly influence grain-size and concentration computations. Although errors tend to be less than 10 percent at optical transmissions as low as 10 percent, 30 percent optical transmission has been our conservative recommended lower limit for deployment of the LISST-SL.

To understand how the path length of the laser in water can be adjusted to avoid multiple scattering, consider that the optical transmission

$$\tau = e^{-cl}, \quad (iii)$$

where c is the beam attenuation coefficient, which depends on the concentration, and l is the path length in water. It follows that the optical transmission can be controlled by controlling the path length l for a desired upper limit of concentration. This suggests the use of short path optics for high-concentration environments, and vice versa. The LISST-SL uses a short path length (3 mm) to achieve a high maximum turbidity range of operation. Notably, the scattering angles, or measured size of particles are *not* affected by the selection of path length, being dependent only on ring detector radii and lens focal length, per eq. (*i*).

Numerous authors have noted, for earlier technologies, the difficulties of instrument calibrations changing with sediment color, composition, and size. For example, Sutherland et al. (2000) noted the influence of size and color on optical backscatter sensors. Thorne and Hanes (2002) noted the strong dependence of grain size on acoustic scattering. The LISST-SL technology has the advantage of holding constant calibration despite changes in sediment grain size or composition/color. The laser multi-angle scattering method depends principally on diffraction by particles, which depends only on size. Thus, the LISST-SL is insensitive to color and composition changes. Further, as the LISST-SL measures size, it compensates for size variations. In this manner, laser diffraction overcomes the aforementioned difficulties associated with optical- and acoustic-backscatter technologies.

3. LISST-SL CHARACTERISTICS

The LISST-SL prototype is shown in Fig. 2. This prototype will be rigorously tested to determine its efficacy for collecting reliable concentration and particle-size distribution data. These tests could lead to modifications of the prototype, including addition of an intake nozzle, and providing the capability to add to the instrument's submerged weight.

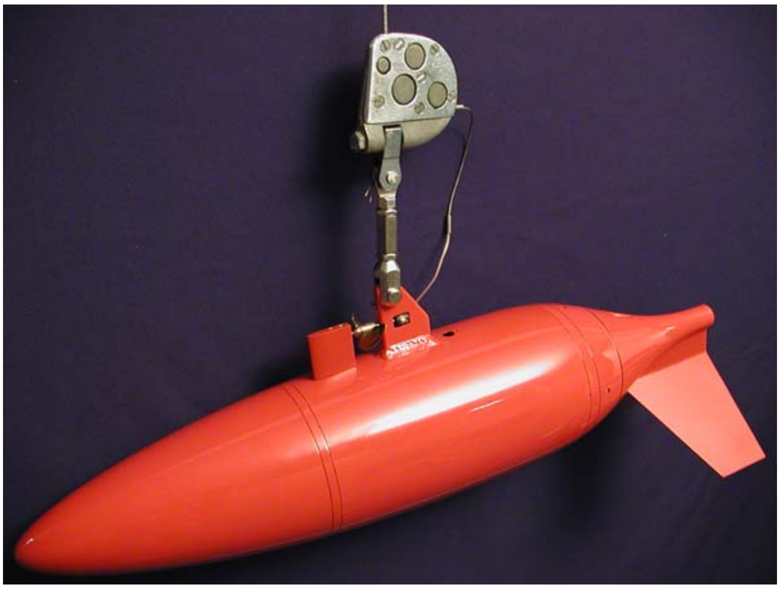

Fig. 2 The LISST-SL Profiling Instrument.

3.1 Physical Characteristics

The LISST-SL can be considered as three separate sections (Fig. 3):

1. A nose section that is solid with a straight inlet to withdraw the water-sediment mixture from the stream.
2. A middle section that contains laser and pressure sensors and associated electronics, and a single tube that conveys the water to the rear section. A propeller-type velocity sensor is affixed on the top of this section, as is an attachment point for the suspension cable.
3. A tail section containing a pump that draws the water-sediment mixture sequentially through the nose and middle sections, and discharges it back to the stream from the tail

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section. External to this section is the twin stabilizing fin (an early drawing shows the tail fin projecting upward; the LISST-SL tail fin now projects downward).

The downward orientation of the stabilizing tail fin was selected to ensure that the tail section becomes submerged first, thereby orienting the instrument in the upstream direction before data acquisition begins. The fin also impart stability and a horizontal and upstream-facing orientation when submerged.

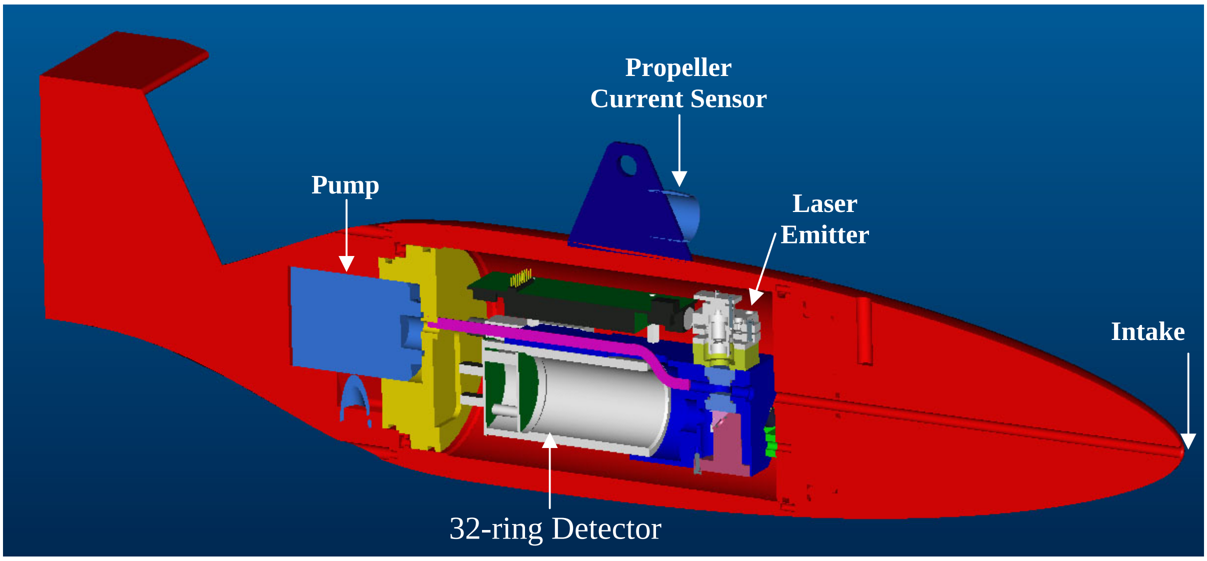

Fig. 3 A cut-away view of the LISST-SL reveals the intake tube, laser source, ring- detector placement, and pump (this early drawing shows an upward-projecting tail fin; the LISST-SL tail fin now projects downward).

The LISST-SL is designed to be light enough to be deployed by a hand-operated suspension reel, and yet be usable over a wide range of stream velocities. The shape selected for the prototype is intended to minimize drag by optimizing the axial distribution of body radius. By maintaining low drag, the weight required to maintain stability at higher velocities also is reduced. The design weight is nominally 17 kg. The instrument shape was selected for operation at Reynolds numbers $<10^7$, which corresponds to a maximum relative water velocity of about 5 m/s.

3.2 Isokinetic Characteristics

Collection of unbiased and representative concentration and particle-size data requires withdrawal of a filament of water parallel to the near-field streamline at the ambient stream velocity. Such isokinetic withdrawal is particularly important when sand-size material is in transport (Federal Interagency Sedimentation Project – FISP, 1941). The FISP considers intake velocities that are within 10 percent of the free-stream velocity to meet their definition of "isokinetic."

The LISST-SL achieves FISP's isokinetic-withdrawal criterion by adjusting the pump rate through the instrument to within 10 percent of the free-stream velocity sensed by the propeller velocity sensor. The propeller's spin rate is converted to a proportional voltage and recorded by a microprocessor that controls the pump rate. Because flow acceleration around the LISST-SL body could result in artificially high velocities being measured by the propeller, a direct relation between the velocity of the LISST-SL and that measured by the propeller was determined at the USGS tow-tank facility in Bay St. Louis, Mississippi, on October 28, 2003. The instrument was towed sequentially at several constant speeds, and the output of the Hall-effect sensor used to measure the propeller's spin rate was recorded (Fig. 4).

The pump rate is adjusted to match the measured free-stream velocity *U* by applying an appropriate voltage to the pump. This voltage is determined by a dedicated microprocessor. The calibration of the propeller is built-in to the microprocessor. Thus, the velocity *U* is known in a stream from this click rate (Fig. 4). The microprocessor then sets the pump drive voltage to deliver a flow rate *Q=AU*, where *A* is the inlet area of the intake. An independent,

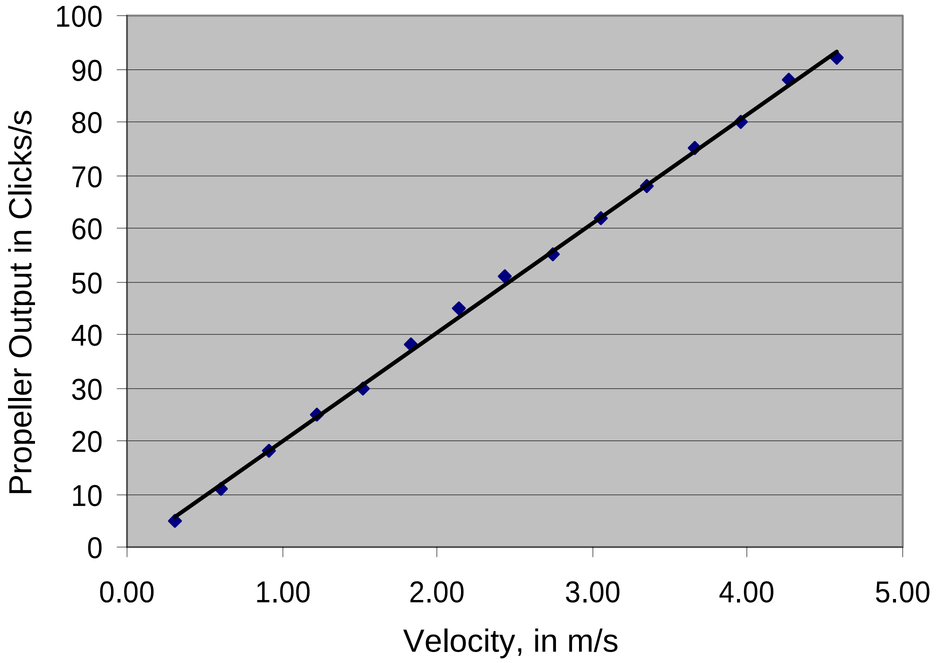

Fig. 4 LISST-SL tow-speed versus click rate of the propeller current sensor.

separate calibration of the pump was carried out to establish the relation between its voltage and flow-rate characteristics. Since the flow rate of the pump is affected by the intake head, the pump characteristics were determined as flow rate versus head for a given drive voltage. From this, and the propeller click-rate versus velocity calibration, the pump drive voltage was established for a given measured velocity *U*, and programmed into the microprocessor as determined using a look-up approach (Fig. 5). For a given *U*, a pump drive voltage is found that draws a flow rate *Q* equal to the product of the inlet area *A* of the LISST-SL and *U*, *i.e.* *Q=AU*. The intake area is 6.3 mm diameter. Feedback control has not been necessary.

3.4 Power and Control

The LISST-SL operates on 12-28 volts with a maximum current draw of approximately 2 amperes. The power is delivered using the 2-conductor cable sheathed in the cable used to suspend the device. A 'topside' controller acts as an interface between the battery, a laptop computer, and the instrument.

3.5 Data Collection, Storage, and Transmission

The LISST-SL is designed to operate either in a manual-control mode or autonomously. In either mode, the instrument must be manually raised and lowered using a cable-and-reel deployment system. The same 2-conductor cable used to deliver power also is employed for data transfer and control. A special electronic system that uses time multiplexing to achieve 2-way digital data transfer was developed. This is accomplished by briefly interrupting power transmission to exchange data between the LISST-SL and the controller.

The instrument can be programmed to obtain and internally store data collected automatically. Alternately, when used in manual mode to provide the operator with real-time data, a laptop computer is interfaced with the control box.

Free-stream velocity, depth and water temperature measurements also are incorporated in the data-stream. The combination of sediment concentration, depth, and stream velocity permits accurate measurements of the sediment flux for each of 32 size ranges.

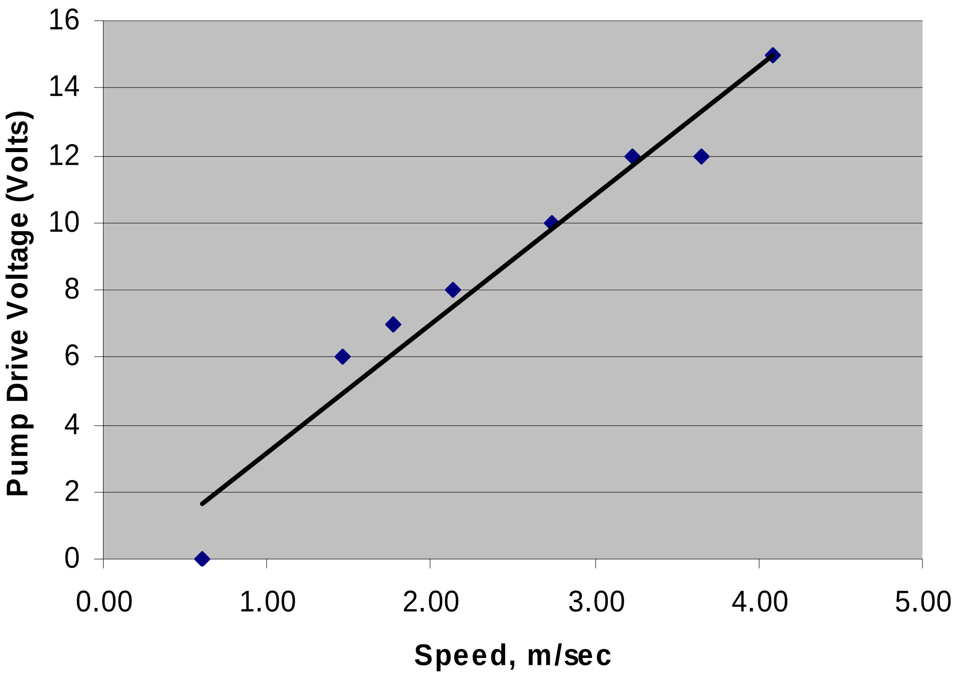

Fig. 5 The relation between free-stream velocity and pump drive voltage. The relation includes consideration of the pressure head due to the flow. A perfect linear fit is not expected due to pump discharge characteristics.

4. FUTURE SEDIMENTOLOGICAL TESTING

Continued testing of the LISST-SL for efficiency in collection of concentration and particle-size distribution data is planned, including laboratory and field tests. Laboratory tests will include use of quality-control samples of known sediment content. Field tests will include side-by-side comparisons with traditional isokinetic samplers. The results will be posted on-line (Sequoia Scientific, Inc. 2004).

5. CONCLUSIONS

The Laser In Situ Scattering Transmissometer-StreamLined (LISST-SL) is in development as part of a cooperative research and development agreement between Sequoia Scientific, Inc., and the USGS. The device is designed to measure suspended-sediment particle-size distributions, concentrations, fluxes, flow velocity, and depth in rivers. Presupposing that all testing will ultimately be successful, the LISST-SL represents a major technological advance in measurement of suspended sediment, including real-time assessment of at-a-point, vertical, or cross-sectional sediment discharges. Data quality and density will be improved over traditional means for collecting these data, and long-term costs will be reduced, as there is no longer a need for routine sample collection, processing and analysis. With completion of successful tests (a summary of which will be posted on-line), the LISST-SL will be commercially available in 2004 from Sequoia Scientific, Inc. (Sequoia Scientific, Inc., 2004).

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