Advances in Monitoring Suspended Sediments with Lasers

Technology Need

Methods for measuring suspended sediments via optical turbidity are rooted in the pioneering work of Whipple and Jackson around the year 1900 that lead to a candle-based turbidity standard. The standard was

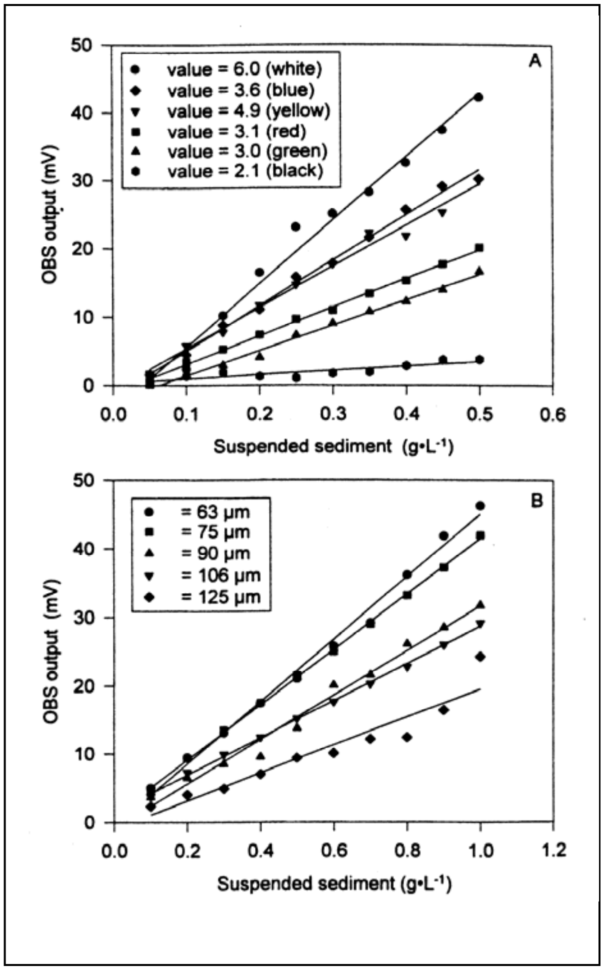

Figure 1: Change of calibration of turbidity sensors (from Sutherland et al., 2000). LISST laser sensors overcome this difficulty. [reproduced with permission].

the Jackson Turbidity Unit (JTU)[1]. The standard was known to be subjective, but measured roughly 1ppm of a specific-size silica. In time, the JTU yielded to NTU, which remains the turbidity standard to date. The suspended sediment monitoring community has treated the NTU as a measure of **total suspended load**. Indeed, *though fundamentally flawed*, NTU is the basis of nearly all monitoring today including monitoring mandated by US-EPA. The flaws in the NTU unit as a sediment monitor are two-fold: First, the conversion from turbidity to suspended load (that is the USGS's interest in TSS, SSC, EPA's requirement on TMDL) involves a calibration that changes with changes in ***grain size*** of the sediment. Second, the calibration is changed further by sediment ***color***. In a landmark paper co-authored by the inventor of one of the most widely used turbidity meters, Sutherland et al.(2000), Figure 1A, noted a *factor of 10* change in calibration based on color alone; and they reported an additional change in calibration that was linear with sediment grain size (Figure 1B). For example, the calibration would change by a *factor of 20, i.e. 2000%,* between a white 5-micron sediment and a gray 10-micron sediment. Such changes in sediment properties are not uncommon in nature. Since sediment color and grain size are generally not known during the course of a monitoring period except only at some instants, spot calibration from samples are likely to be contaminated by unknown errors when sediment properties change in space/time. The errors can reach several hundred percent, and greater. Laser sensors described here overcome both these errors and advance monitoring suspended sediments a quantum step forward.

Laser Diffraction Technology

The new sensors are based on the principle of

1 http://content.honeywell.com/sensing/prodinfo/iatc95/sld003.stm

small-angle laser light scattering, originally called *laser diffraction*. At small angles, the scattered light is composed primarily of light diffracted by a particle. A simplified conceptual view of this is shown in figure 2. Diffracted light, analogous to diffracted

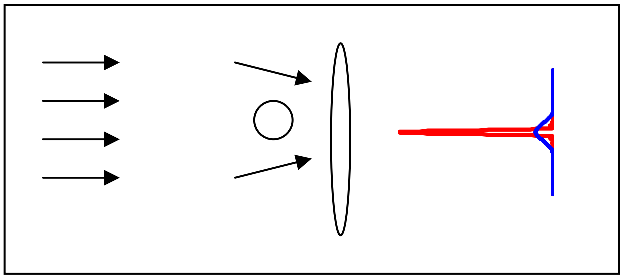

Figure 2: Laser diffraction. Rays bend around the particle to produce the scattering at small angles. The diffracted pattern is wide for fine particles, narrow for large particles; 2 examples are shown on right.

surface waves on water (with which our audience is intimately familiar), is the light that went *around* the particle, not through it. This light senses only the size of the particle and is unaffected by particle composition, i.e. color. Of the light that is transmitted *through* the particle and which therefore senses the particle composition, only a very small portion shows up at small angles, so it adds only a small amount to diffraction. Thus the sensing of a particle via its diffraction signature eliminates the old calibration error of turbidity sensors due to the first factor, i.e. color. As for grain size, the diffracted light contains information about grain size. For example, light diffracted by fine particles shows a small but broad peak (blue curve, Figure 2), and *vice versa* for large particles. Thus, measuring the angle dependence of the diffracted light incorporates the capability to measure size, and include calibration due to grain size changes. To sum, by measuring scattering at multiple angles, the laser small-angle scattering method overcomes both errors that have rendered calibration of turbidity into suspended load estimates unreliable.

Incorporating these ideas, we have developed two types of sediment sensors. The first type, **LISST-100**, measures the details of small-angle scattering at multiple angles, from which the size-distribution is obtained. Summing the size-distribution provides the total suspended load. A second, simpler sensor was later developed to provide the total suspended sediment concentration along with only a mean size. This is the **LISST-25**. This sensor offers the capability to replace the turbidity sensors since it maintains calibration despite color or grain size changes. This sensor uses a comet shaped detector to achieve constant calibration. Furthermore, with additional ingenuity, the sensor produces the Sauter Mean Diameter (SMD), which is a ratio of the volume/area concentrations. Not only is the SMD a useful measure of changes in grain size, it is *exactly* the parameter that is needed for pollutant transport studies where surface area matters. SMD changes also represent changes in calibration of turbidity type sensors since turbidity responds to area concentration of particles in suspension.

Measuring Sediment Size Distribution and Concentration with a Multi-ring Detector

Figure 3 shows the first instrument in the laser in-situ scattering and transmissometer

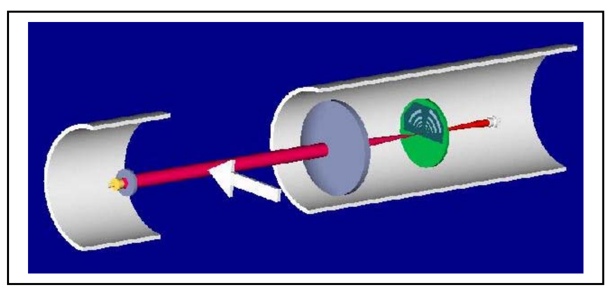

Figure 3: Optics of the LISST-100 shows a collimated beam, and a multi-ring detector behind a receive lens.

(LISST) series, the **LISST-100**. A collimated laser beam illuminates sediment particles moving with the flow (arrow). Multi-angle scattering is sensed by a set of 32 ring-shaped silicon photosensors, placed at the focal plane of a receiving lens. The multi-angle scattering is stored, and later interpreted as a size-distribution. This interpretation involves a mathematical *inversion*. A photodiode placed behind the ring detector captures the beam through a tiny hole at the center of the rings. This *optical transmission* measurement is used to compensate for attenuation of scattering by turbidity. The 32 multi-ring sensors produce a 32-bin size-distribution, i.e. the concentration of sediments in 32 size-classes. The sum of the concentrations in the 32 sizes yields the total suspended concentration, e.g. TSS, TMDL. The size classes span a wide range, from 1.25-250 microns, or in other versions, 2.5 to 500, and 7.5 to 1,500 microns, in all cases spanning a 200:1 dynamic range. It is implied that TMDL estimates made in this manner would be far superior to those made using NTU methods. The size distribution can be used for estimating other parameters, such as D_{50}.

Comet Shape Delivers Fixed Calibration Sediment Sensor, Sauter Mean Diameter

Frequently, instead of the full size distribution, only a measure of the total suspended solids (TSS or TMDL) is of interest. A variant of the **LISST-100** has been developed for this application, called the **LISST-25**. This simpler device replaces the multi-ring detector with a patented comet shaped detector. The comet-shape of the detector is the consequence of a mathematical search for a shape, given the small-angle scattering properties of particles shown in Figure 2, that maintains constant calibration for all size particles in a size range. The size-ranges are identical to the **LISST-100**.

The concept of the comet shaped detector can be physically understood as follows. Constant calibration for any size requires that the amount of photocurrent detected be the same per unit concentration of particles, no matter the particle size. Now, as shown in Fig.1, large particles scatter most of the energy into small angles. Furthermore, because scattering is still proportional to particle area, on a per unit *volume* basis, large particles scatter less light. To equalize the photocurrent for equal concentration, we take advantage of the separation of scattering by different sizes into different angles. Because large particles scatter into small angles and they scatter less light per concentration, we use the maximum azimuth in the detector at small angles. Conversely, since fines scatter into large angles and scatter a lot more light per unit concentration, we reduce the azimuthal width of the detector at large angles. This results in a detector that tapers into a thinner tail away from the optical center - a shape we have called a comet. The precise shape is derived mathematically by solving a matrix equation relating angular scattering and size distribution.

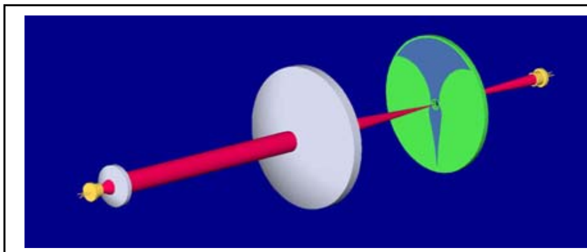

Figure 4: The *comet* and *wedge* detectors replace ring detectors. The comet produces volume concentration, wedge yields area concentration. The ratio yields SMD.

In a similar mathematical analysis, a second shape called a wedge is found that senses the total particle area, also with constant calibration regardless of size and color of particles. The ratio of the volume concentration sensed by the comet, and the area sensed by the wedge produces the Sauter Mean Diameter.

A more recent version of this device was developed at the suggestion of Dr. Ted Melis, of USGS, Flagstaff, Arizona. In this concept, two different comets are used, one to get concentration of sediments in the full size range and then in a sub-range that ignores the fines. The value of this measurement lies in separating out wash. Only coarse particles respond to local currents and waves. This device, **LISST-25**X, is currently in use in two prominent studies: the Grand Canyon in an environmental impact assessment, and by the Army Corps of Engineers in a dredging research experiment lead by Mr. Carl Miller, off the coast of North Carolina.

Yet another variant of this technology is the LISST-ST. This instrument combines the optics of the **LISST-100** with a settling column to measure settling velocities *in-situ*. The settling column is equipped with mechanisms to fill itself at pre-programmed times and trap a water sample. The evolution of size distribution in the settling column as particles settle over a day is then interpreted as settling velocities. Long seafloor deployments of this device have produced settling velocity spectra that support the idea of particle density that decreases with increasing size - a phenomenon associated with flocculation. The instrument suite is shown below. For details, please consult Agrawal & Pottsmith (2000).

References

Agrawal, Y.C. and Pottsmith, H.C., 2000. Instruments for Particle Size and Settling Velocity Observations in Sediment Transport. Marine Geology, 168(1-4): 89-114.

Sutherland, T.F, P.M. Lane, C.L. Amos, J. Downing, 2000: The calibration of optical backscatter sensors for suspended sediment of varying darkness levels, Marine Geology, 162, 587-597.

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