Laser Diffraction Method: Two New Sediment Sensors

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Abstract

Laser diffraction offers a fundamentally superior basis for measuring suspended particles as it, unlike older and simpler optical or acoustic methods, does not suffer a change in calibration with changing sediment color, composition, or size. The diffraction based LISST series instruments have, in this manner, opened new scientific vistas into particle dynamics, their settling velocities measured in-situ, and to a lesser extent, floc dynamics. The first new system, the LISST-SL, employing isokinetic sampling is now in development for the needs of the USGS. Current frontiers in research deal with particle shape effects. New data firmly point to the need for distinguishing spheres from natural, random shapes.

The second new system delivers suspended sediment concentration and a true mean size (vs. Sauter Mean Diameter provided by LISST-25's). This results from newly invented shapes of comet detectors.

Introduction

Optical Scattering: Two principal technologies dominate the monitoring of suspended sediments: optical scattering, and acoustic backscatter. The most commonly used optical method is through turbidity, as measured by sensors that measure scattering of light by particles in water. The most commonly used among these, the optical backscatter sensor and the NTU measuring instruments are both known to suffer from 2 fundamental errors: their calibration changes with sediment color, and it also changes linearly with sediment grain size. These facts were most recently elaborated by (Sutherland, 2000) figure 1.

Acoustics: In contrast to such simple turbidity sensors – which nevertheless can be used in environments where sediment grain size and color are unchanging – acoustic sensors work with the attractive possibility of range-gated sediment measurements along a line-of-sight. There is a growing body of literature on the use of acoustics for sediment monitoring, and a survey is presented by (Thorne, 2002). Acoustic systems suffer from grain size and composition changes also. This is because typical grain size, of order 10 –100 microns, is usually much smaller than acoustic wavelengths. In this situation, *single particle* scattering amplitude depends on a^3 where a is grain size. In a polydisperse environment, the acoustic pressure p is the incoherent sum weighted by the number in each size class n_i

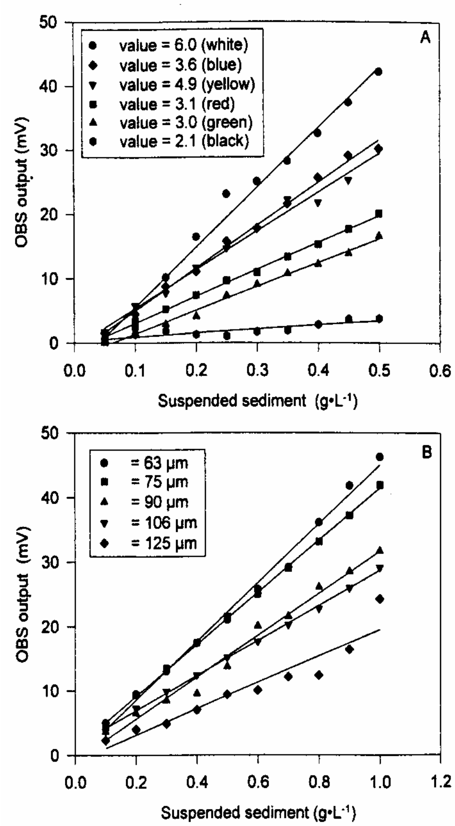

Figure 1: Change in calibration of optical backscatter sensors by factor of 10 with sediment color, or linear with size, as reported by Sutherland et al.(2000). [Reproduced with permission.]

$p \sim \sqrt{\sum n_i a_i^6}$. Whereas this is tantalizingly close to volume concentration for narrow distributions, the sum is hugely dominated by the largest particles in a dispersion. The extreme sensitivity of such systems to grain size is therefore a continuing difficulty. In any case, the measurement of p folds in the concentration and size so that only one parameter can be inferred with an assumed value for the other.

Even the multi-frequency systems that derive a 3-parameter size distribution do so only for particles of sizes such that $a \sim \lambda$. Thus, though attractive due to its remote and range-gated possibility, acoustics remain limited by fundamental physics[2]. Regardless, acoustic scattering intensity is often a cheap by-product of the Doppler velocimetry method, and has found advocates (Fugate, 2002). In particular, when flocculating particles are present, it has been noted that acoustic scattering intensity reflects the concentration of the constituent fine particles.

Laser diffraction

Although the first measurements of particle size spectra in the marine environment using laser diffraction are credited to (Bale and Morris, 1987), current practice is dominated by the LISST series instruments made by Sequoia Scientific, Inc. of Bellevue, Washington[1]. The LISST series instruments precisely measure scattering at 32 angles. This data is interpreted as a distribution of spheres by a mathematical inversion. The size range is determined by the largest and smallest scattering angles, and concentration limits are set at the low end by measurement noise, and at the high-end by multiple light scattering. The sum of the concentrations in the various size classes obtained after inversion produces the total suspended concentration. As laser diffraction does not measure particle density, the reported concentration is in volume of particles. Particle density spectrum can be measured in a separate instrument LISST-ST that combines laser diffraction with a settling column (Agrawal and Pottsmith, 2000).

Briefly, laser diffraction works as follows.

When a parallel light wave strikes a particle, part of the wave enters the particle, and part is *blocked* by it. The wave entering the particle senses particle composition (e.g. color, absorption). However, this part is scattered into a wide range of angles, very little of which appears in the original light wave direction. In contrast, light blockage produces a diffraction pattern that dominates the light intensity in the original direction. This pattern is bright, and it is identical to the diffraction through an aperture familiar to optical physicists. [It is also analogous to the diffraction of waves on water surface by a jetty]. When a lens, Figure 2, gathers the scattered plus diffracted light, diffraction shows up on lens axis. The diffraction pattern is weaker and wider for small particles, but tall and narrow for large particles. The width helps distinguish particle size while the magnitude delivers concentration.

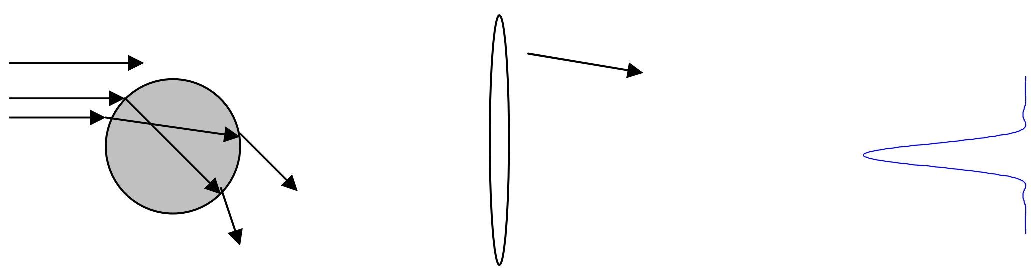

Figure 2: This sketch shows a parallel beam of light striking a spherical particle. The light that enters the particle – and that therefore feels its composition – exits at large angles to the original beam. It makes a very small contribution to the very small angle scattering. Only rays diffracted around the particle appear at the small angles, producing the Airy pattern shown on right. This is why the name: *laser diffraction*.

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[2] If acoustic frequency is increased to make $a \sim \lambda$ sound attenuation is so severe that range penetration becomes limited, thereby removing the attractiveness of line-of-sight data..

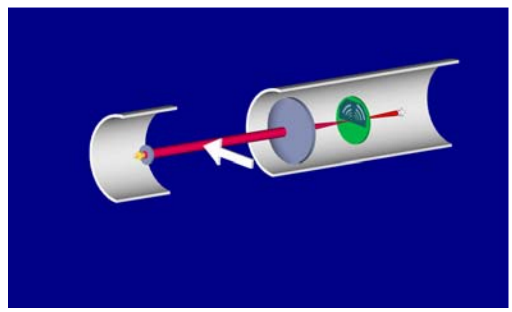
[1] A current list can be found at http://www.sequoiasci.com/library/publications.shtml

When a number of particles are present, the intensity patterns of individual particles add (this is analogous to the incoherent addition for acoustics). The resulting pattern is what the LISST instruments measure and interpret. As a small note, the diffraction pattern shown in figure 2 is intensity vs. scattering angle. For mathematical reasons, the detection of diffracted light is done with ring-shaped detectors (Figure 3). Excellent agreement between Mie's exact theory of light scattering by spheres of any size and data with our LISST-100 instrument has been published elsewhere (also see publications list at http://www.sequoiasci.com).

The LISST Instruments

LISST-100: The most widely used and the most powerful of the LISST instruments is the LISST-100. This instrument delivers the size distribution by inversion of the 32-angle scattering measurements that were described above. USGS scientists Drs. Melis, Topping and Rubin, using these instruments have recently produced valuable new insight in the transport of sediments in the Grand Canyon. This technology is now considered mature. Relatively new significant development is ongoing.

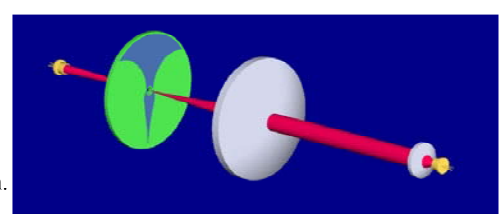
Figure 3: A cut-away view of the optics of a LISST-100. Light from a laser travels (*l to r*) through water(arrow). The receiving lens places scattered light on 32 ring detectors. Each ring measures scattering over a particular angle. A hole at center of rings passes the unscattered light to a photodiode, which measures optical transmission also.



LISST-ST: The second instrument in this series, the LISST-ST was designed to obtain settling velocity distribution of sediments of different sizes. In this case, a sample of water is trapped and particles are allowed to settle in a 30 cm tall settling column. Throughout, the size distribution is monitored near the bottom. Over time, the size distribution show zero concentration in sizes that have settled out. The time for settling is used to estimate settling velocity. From a knowledge of the size vs settling velocity, mass density can be estimated. Several authors have reported such measurements. One of the emerging conclusions is the fractal nature of marine particles, who density decreases as size increases.

LISST-25A and –25X: The first innovation based on laser diffraction directed toward a simpler, less expensive instrument was sparked by a comment of John R Gray, the co-organizer of this gathering. John wished for an instrument roughly a quarter as expensive and roughly a quarter as capable. In response, the LISST-25 was developed. Replacing the multi-ring detector of the LISST-100, a special shape for a focal plane detector was invented. This shape, which we call a comet, is the result of solving the mathematical

Figure 4: The key difference in the LISST-25 is a comet-shaped detector (lower dark element, right-most disk). The shape of this detector is mathematically derived to hold constant calibration for suspended sediments over a 200:1 size range. The upper wedge shape measures area concentration. The ratio volume/area yields the Sauter Mean Diameter.



problem: does there exist a detector shape that would measure light scattering in a manner that it holds calibration for all sizes? Indeed, the LISST-25 holds calibration for spheres over a 200:1 size range, where earlier sensors would vary in calibration by a *factor* of 200! The LISST-25 instrument is a superior sensor to the LISST-100 when only concentration measurement is required. The reason is as follows. The LISST-100 obtains sediment concentration by first inverting the 32 multi-angle scattering data to construct the size distribution, and then summing the concentrations in the 32 size classes. When small numbers of particles are present, as can happen with coarse particles, the inversion can miss them due to noise. In contrast, since the comet detector directly estimates concentration from the weighted sum of angular scattering, it misses nothing. A second attribute of the LISST-25 is that this device obtains particle area concentration from the optical transmission [earlier versions applied a wedge-shaped detector, as shown on the top part of the detector in figure 4.]. The ratio of the volume concentration and area concentration is called the Sauter Mean Diameter (SMD), first introduced in the aerodynamics- droplet combustion literature. The two types of LISST-25 refer to an analog output only version, and a second version that is fully recording and presents a coarse fraction concentration in addition to the total suspended load (see below).

Comet Shaped Detectors of the LISST-25

The original comet shape was derived, as noted above in context of the LISST-25, to measure the total suspended sediment concentration. Responding to the need of USGS scientists Drs. Melis, Topping, and Rubin, all of USGS, (also co-sponsor of this conference) we were spurred on to find ways to divide the total suspended load into two parts: a fine wash load, and a coarse load. The desired separation boundary was 63 microns. New comet shapes were invented that deliver this measurement, and this capability is now built into the LISST-25X instruments. The two distinct shapes deliver, respectively, the total concentration and SMD in the entire size range, and concentration and SMD in the coarse fraction.

It is noteworthy that the comet shapes assume nothing regarding the underlying size distribution of sediments. The only requirement is spherical shape for particles. Inaccuracies of perhaps as much as 100% may occur if the particle composition changes from mineral to biogenic. But, that is still small compared to factors of 100.

New: A Fat Comet Detector for Mean Diameter

Getting Mean Diameter D: The SMD is not part of the historical data on rivers and oceans. Geologists have recorded the diameter D_{50}. Once again, taking our cue from Dr Melis of USGS, Flagstaff two new comet shapes have been found. One of these shapes delivers the mean diameter over the entire size range, 2.5-500 microns. The other shape delivers a mean diameter in the coarse size sub-range, 63-500 microns. The precise mathematical treatment of the derivation of these shapes will be revealed in a subsequent publication.

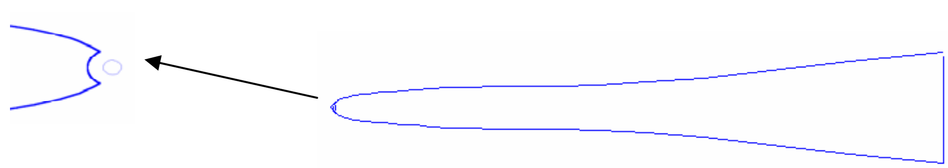


Figure 5: The *fat* comet shaped detector (right) replaces the thin comet detector of fig. 4 in a new version of the LISST-25. This *fat* comet leads to the mean diameter of the suspension, an advancement over the earlier SMD. Inset on left shows detail at nose of the comet; the circle is the hole on optical axis for passing the unscattered laser beam. Again, the comet shape is perfectly general, no restrictions are placed on the shape of the underlying size distribution.

The measurement with this fat detector is a two-step process. The output of the comet delivers a parameter, which is then used to get the mean diameter. Since the size bins are logarithmically spaced, let $p = log(d)$; then the mean diameter thus produced is

$D = exp^{<p>}$, where $<p>$ is the parameter estimated from size distribution $f(p)$ as:

$$<p> = \Sigma p\, f(p) / \Sigma f(p)$$

In this manner, e.g., a log-normal distribution produces a mean diameter D centered at the peak of the distribution. Notably, this mean diameter is *not* identical to D_{50} , though in most cases, the difference between D and D_{50} is small.

This shape is also fully general, i.e. no underlying size distribution is assumed. This fat comet has been tested to yield the correct mean diameter D in numeric simulations with single and multi-modal distributions. Laboratory testing is underway at the time of this writing.

The New Isokinetic LISST-SL

The USGS requirement to measure suspended sediments in rivers and streams with isokinetic methods lead to a Co-operative Research And Development Agreement (CRADA) between the government and this company in 2002. A streamlined body that draws a sediment-laden stream into it for laser measurements is the result. This is shown in figure 6.

The instrument incorporates a laser, optics, multi-ring detector identical to the LISST-100, and electronics for signal amplification and data scheduling and transmission. A pump is also built-in to ensure isokinetic withdrawal rates. The pump is controlled by a microprocessor, which is fed information about the river velocity by a propeller type current meter. The propeller is mounted above the body itself, and a Hall effect sensor is employed to count the number of its rotations in a short period of time. The propeller current meter is to be calibrated at the USGS's Hydraulic Instrumentation Facility (HIF) in Bay St. Louis, Mississippi.

Figure 6: The LISST-SL streamlined isokinetic-withdrawal laser suspended sediment analyzer being shown during balancing in a tub [viewed looking down]. A small propeller can be seen near the lifting point. Stabilizing fins on the back are designed to maintain orientation into the stream. An intake port at the nose is not visible.

A key feature of this design is a novel method developed by Sequoia to do power transmission as well as data exchange between a computer and the instrument using the standard 2-conductor wire familiar to USGS scientists in their sampler applications. A topside interface box is employed to enable communication between a laptop computer and the instrument.

It is expected that the development of this system will be completed by the end of 2003.

Particle Shape Effects

As we have asserted to this point, the laser diffraction method is accurate for spheres. As the multi-angle scattering is only very slightly sensitive to particle composition, the measurement of both, the size distribution and concentration for spheres is fundamentally assured by physics to be accurate. However, shape effects do reduce accuracy as the diffraction pattern of non-spheres exhibits differences. The principal difference is in the width of the main diffraction peak – the peak is broader for non-spheres. Furthermore, the minima of the diffraction from non-spheres are less deep than for spheres. Optical physicists do not understand these properties at this time, and Sequoia is a leader in such research. Until such time as these shape effects are accounted for in a fundamental way, the best possible approach appears to be to apply an empirical calibration correction.

Summary

In this paper, we have revealed a new concept comet detector that is employed for measuring the mean diameter of a suspension of particles. We have also briefly described the LISST-SL streamlined isokinetic withdrawal instrument. A fundamental area of current research is in the light scattering properties of non-spherical natural dusts.

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