

Laser Diffraction Sensors measure Concentration and Size Distribution of Suspended Sediment

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Abstract: Optical turbidity sensors, transmissometers, and acoustic backscatter sensors have been well entrenched in the monitoring of suspended sediments. However, results published recently by (Sutherland, et al. 2000) note the two difficulties with turbidity sensors: the calibration changes with grain size changes, and with particle color. Similarly, (Davies-Colley & Smith, 2001) noted that transmissometers also change calibration with grain size, and have upper size cut-offs, (Voss, 1993). Acoustics usually operate at frequencies where $a/\lambda \ll 1$, (a is grain radius and λ is acoustic wavelength) where scattering varies as $\int a^6 da$, again not suitable for a mixture of grain sizes. In contrast to these 3, **laser diffraction** methods measures multi-angle scattering at small angles from which size-distribution and concentration is computed, with only a minor error due to changes in particle composition. In this paper, we describe the fundamentals of the technology, we describe a new instrument that permits measuring suspended sediment concentration in a *size-subrange*, and we provide a preview of an *isokinetic* version of the instruments, the LISST-SL.

Keywords: size distribution; suspended sediment; Sauter mean diameter; LISST; sediment monitoring.

Introduction to Laser Diffraction: Laser diffraction is a technique pioneered in the 70's (Swithenbank et al., 1976). At the time, it was widely known from light scattering physics (Mie theory) that when angular scattering from a particle is examined in small forward angles, it appears identical to the diffraction pattern from an aperture of equal diameter. There is a simple conceptual reason for it, see Figure 1. A particle blocks light waves. Some enter the particle, others are diffracted *around* the particle. The diffracted rays appear in the small-angle region. The rays that enter the particle are scattered over the full π angle range, so that their contribution to the small-angle region is minimal. As a result, diffraction dominates the small-angle scattering signal. Particle composition and color, which are represented by the refractive index as a function of light wavelength¹, became irrelevant. From the diffraction signature, which has a characteristic shape termed the Airy function (Born and Wolf, 1975), particle size and concentration can be determined by inversion of the small-angle light scattering data. In other words, if the small-angle scattering signature is observed, it leads via inversion to the size-distribution. When the size-distribution is summed, one has the total concentration. The mathematics of interpreting the multiple-small-angle scattering are briefly reviewed by us in our Marine Geology paper (Agrawal and Pottsmith, 2000).

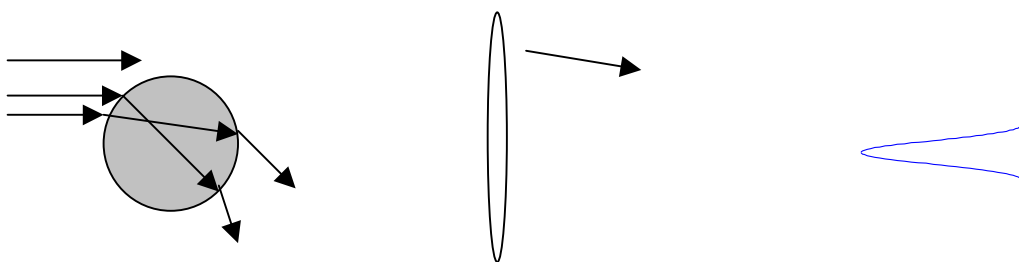


Figure 1: This sketch shows a parallel beam of light striking a spherical particle. The light that enters the particle – and that therefore feels its composition – exits at large angles to the original beam. It makes a very small contribution to the very small angle scattering. Only rays diffracted around the particle appear at the small angles, producing the Airy pattern shown on right. This is why the name: *laser diffraction*.

Thinking of particles as same-size apertures, clearly, is a great convenience. For this reason, the method was called laser diffraction. Due to its ability to size particles regardless of their composition, it is now widely

¹ e.g. a red particle has an imaginary component in its refractive index that has a minimum at red wavelength

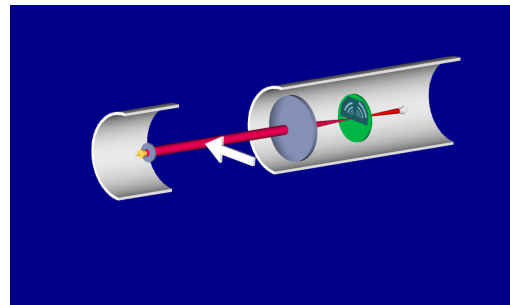
used in diverse industries – from chocolates, paints, cements, to pharmaceuticals and controlling coffee grinding. In 1994, we published the first use of this technology in the sea from an autonomous instrument, fully equipped with a computer and datalogger, running on battery (Agrawal and Pottsmith, 1994). Later, refinements to the idea of pure diffraction occurred for 2 reasons. First, there is indeed a small sensitivity in small-angle scattering to refractive index. Thus the desire for better accuracy was behind replacing the pure diffraction approximation with the full Mie theory model for scattering. The second such factor was the use of larger angles, reaching all around to 170 degrees as extensions of laser diffraction. At such large angles, it became essential to abandon the diffraction approximation, and use Mie theory.

Size Distribution measurement with LISST-100: Refer now to the optics shown in figure 2. A collimated beam illuminates particles. A receiving lens of focal length f collects scattered light. A detector is placed at the focal plane of the receiving lens. All rays originating at a particle at an angle θ , regardless of its location in the beam, arrive at the detector at a distance from center r such that $\theta = \text{atan}(r/f)$. For mathematical reasons of inverting the measured scattering to get size distribution, instead of measuring the scattered light at single points (representing single angles), ring detectors are used. These *rings* integrate all light scattered into a cone of angle centered on θ . The radii of the rings increase in fixed proportion, i.e. the radius and width of each

ring is a constant multiplier times the corresponding value for the previous ring. This *logarithmic* spacing of the rings also corresponds to a logarithmic spacing of particle sizes in the inversion. In other words, the size-distribution represents the concentration of suspended sediment in logarithmically spaced size bins.

Logarithmic size-bins are familiar to geologists as sizes that are linearly spaced in ϕ units. This is our **LISST-100** instrument. A growing list of scientific publications using the LISST-100 can be found at <http://www.sequoiasci.com/publications.asp>.

Figure 2: This is the **LISST-100**. A collimated laser beam emanates from left. Particles in the flow scatter light. A receiving lens collects the scattered light, which is detected by the *ring detector*. A hole in the center of the ring detector permits the focused laser beam to pass through, where its power is sensed. This constitutes a transmission measurement. This measurement corrects for attenuation of the scattered light that is sensed by the rings.



New Developments, LISST-25: As a precursor to the newest developments, we note first the development of the **LISST-25** sensor. The principle of the **LISST-25** is based on ideas from laser diffraction, as follows. According to diffraction, the scattered light energy falls at larger angles on the ring-detector plane for finer particles, and *vice versa*. To measure suspended sediment concentration (SSC), the sensed scattered light energy per unit sediment concentration should be identical for any size. Thus, crudely speaking, if the width of a ring at a large

angle is proportional to the scattering per unit volume for the corresponding fine particle, and so on down to all rings, then the sum of these *modulated* rings would represent the true SSC. These rings can be joined together to form a single detector. Such a detector takes the shape of a *comet* (*lower form, right*). The comet detector accomplishes an angle-weighted sum of scattering, which is directly proportional to SSC. Thus, unlike the old turbidity sensors or transmissometers, the LISST-25 responds directly to SSC, and since it too is grounded in laser diffraction

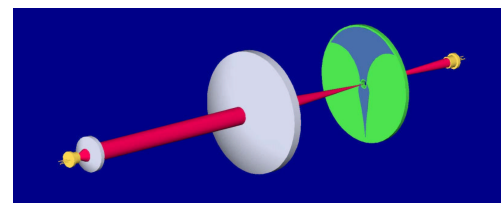


Fig.3: The use of shaped focal plane detector in LISST-25 for direct TSS measurement.

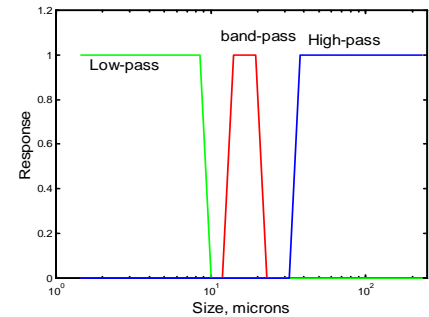
principles, its calibration is held for all sizes and colors of particles. The upper, wedge-shaped detector senses total particle area. From these two detectors, the Sauter Mean diameter (SMD) is computed as the ratio of volume/area concentrations. A change in SMD by a factor n implies a change in calibration of area-based sensors such as optical backscatter, by the same factor n .

LISST-25X: This instrument was designed in response to a need of USGS Flagstaff scientist Ted Melis, who required SSC but *excluding* fines below 63 micron in size. In response to this need, a family of new focal

plane sensor geometries was invented. This family of geometries permits measuring the concentration in any sub-range of sizes. For example, one may measure concentration of particles greater than a threshold (*high-pass*), smaller than a threshold (*low-pass*), or within a band of sizes (*band-pass*). These detectors, replacing

the comet shape of the LISST-25, take the shape of truncated comets for high-pass, or *blobs* for low-pass. The first of these instruments was tested in the Grand Canyon (see Melis, this Workshop).

Figure 4: The **LISST-25X** embodies specially shaped focal-plane detectors that can permit the user to select the size-range over which SSC is to be measured. As example, a user may choose to ignore the wash-load in a stream, or use the LISST-25X to measure the wash-load only.



LISST-SL: The newest development underway at Sequoia is a streamlined, low-drag vehicle that encloses an isokinetic withdrawal LISST-100 instrument. This device includes pressure transducers to record depth of sampling. It actively equalizes the free-stream velocity and the withdrawal speed into the nose of the vehicle using a tiny pump. The device will run on external power and will use 2-wire communication protocol. Isokineticity is assured by measuring the free-stream velocity and adjusting an in-built flow-assist pump to control withdrawal rate. The LISST-SL will have the full size-distribution measuring capabilities of the LISST-100, although the housing can enclose the LISST-25 or 25X. Field trials are scheduled for summer of 2002. The LISST-SL will also be available for towed use.

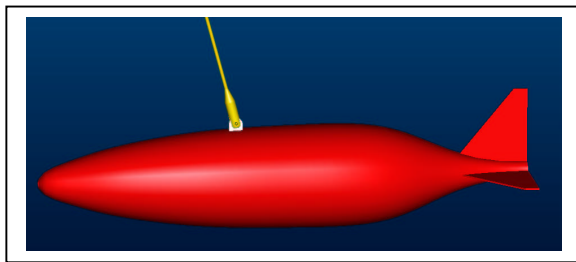
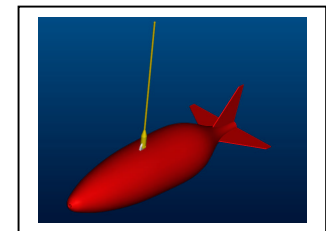


Figure 5: Two artist's views of the LISST-SL. A 2.5cm diameter opening at the nose draws water in.



Studies on Effect of Particle Shape: New research underway uses the LISST-100 to observe small-angle scattering properties of random-shape grains sorted by settling velocity. The shape effect is such that when small-angle scattering from natural grains is inverted with a model for spheres, a change in calibration is found, and fines are inverted by the inversion. Consequently, future inversion will employ a suitable model.

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