Laser diffraction sediment sensors measure *in-situ* size-distribution and concentration with a fixed calibration

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Overview: Optical turbidity sensors, optical transmissometers, and acoustic backscatter sensors have been well entrenched in the monitoring of suspended sediments. However, definitive results published recently by (Sutherland, 2000) note the two difficulties with turbidity sensors: the calibration is changed whenever grain size changes, and further, calibration also changes significantly with particle color. Similarly, a survey by (Davies-Colley, 2001) notes that transmissometers also change calibration with grain size, and have upper size cut-offs, (Voss, 1993). These results confirm what is expected from Mie's classic theory of light scattering by spheres. Acoustics usually operate at frequencies where $a/l << 1$, (a is grain radius and l is acoustic wavelength) where scattering varies as *volume-squared*, 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. Measurements of concentration, TSS, are unaffected by changes in grain size or color (refractive index). The technique is widely used in industry. The present authors pioneered its use in the aquatic environment. In this paper, we describe the fundamentals of the technology, we note research currently in progress in the Grand Canyon by USGS scientists, we describe a new instrument that permits measuring TSS in a *size-subrange*, we conclude with a preview of an *isokinetic* version of the instruments, the LISST-SL and with effects of particle shape.

What is Laser Diffraction: Laser diffraction is a technique pioneered in the 70's (Swithenbank et al., 1976). At the time, it was widely known fromlight 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 the same diameter . There is a simple conceptual reason for it. 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. This property permitted the replacement of particles with apertures. Particle composition and color, which are represented by the refractive index as a function of light wavelength[1], became irrelevant. From the diffraction signature, which has a characteristic shape termed the Airy function (Born and Wolf, 1975), particle size and concentration of particles could at once 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, TSS. The mathematics of interpreting the multiple-small-angle scattering are briefly by us in our Marine Geology paper (Agrawal and Pottsmith, 2000).

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 used in diverse industries – from chocolates, paints, cements, to pharmaceuticals. In 1994, we published the first use of this technology in the sea from an autonomous instrument, equipped fully with a computer and datalogger, running on battery (Agrawal and Pottsmith, 1994). 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.

Basic Implementation, 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 thefocal plane of the receiving lens. All rays originating at a particle at an angle θ 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

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

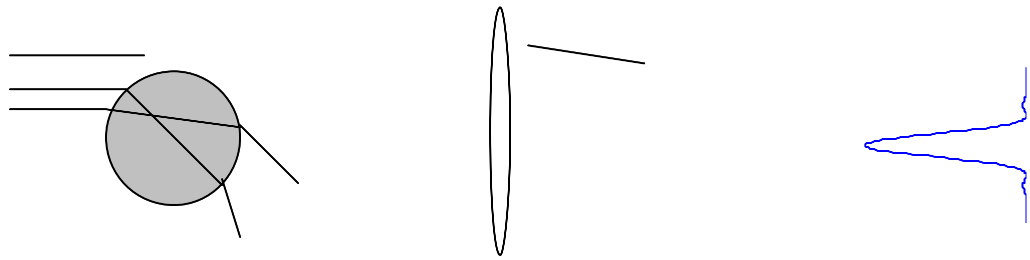
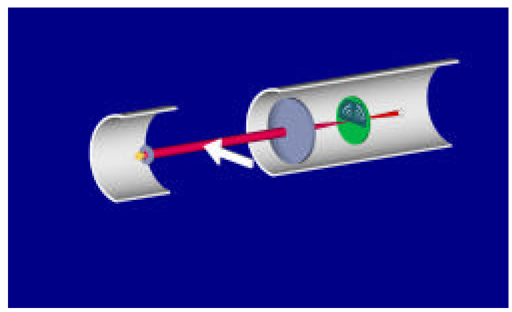


Figure 1: This sketch shows a parallel beam of light striking a spherical particle. The light that enters the particle – and that therefore feels its composition – exits at large angles to the original beam. It makes a very small contribution to the very small angle scattering. Only rays diffracted around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

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.

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.



<u>New Developments</u>: As a precursor to the newest developments, we note first the development of the LISST-25 TSS 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 true TSS, 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 TSS. 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 TSS. Thus, unlike the old turbidity sensors or transmissometers, the LISST-25 responds directly to TSS, and since it too is grounded in laser diffraction 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 is computed as the ratio of volume/area concentrations.

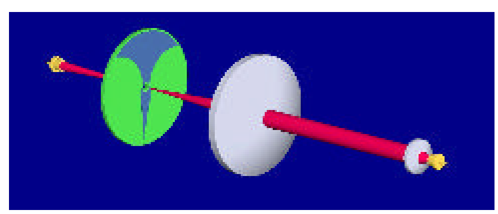


Fig.3: The use of shaped focal plane detector in LISST-25 for direct TSS measurement.

<u>LISST-25X</u>: The first new development since Reno-2001 is the LISST-25X. This instrument was designed in response to a need of the USGS Flagstaff scientists, wherein the required suspended sediment concentration was not to include 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 ring detector, take the shape of truncated comets for high-pass, or *blobs* for low-pass. The first of these instruments are being tested in the Grand Canyon at about the time of this Conference (see Melis, this conference).

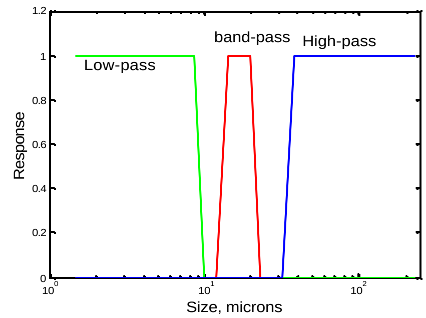


Figure 4: The LISST-25X embodies specially shaped focal-plane detectors that can permit the user to select the size-range over which TSS is to be measured. As example, a user may choose to ignore the wash-load in a stream, or use the LISST-25X to measure the wash-load only.

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.

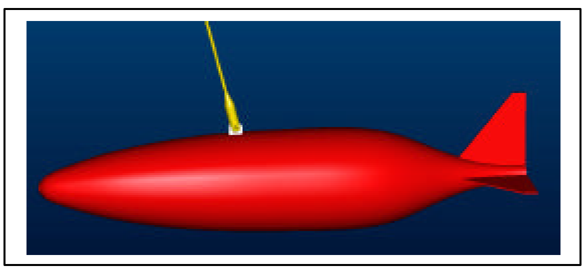
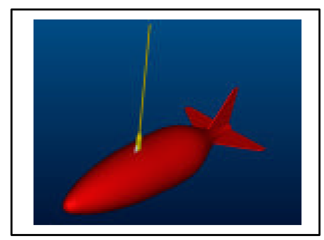


Figure 5: Two *artist's views* of the **LISST-SL**. A 2.5cm diameter opening at the nose draws water in.



Studies on Effect of Particle Shape: New research on the small-angle scattering properties of natural AC Coarse particles have been underway at Sequoia. Sorting the particles by settling velocity, scattering properties are measured using a LISST-100. Early data reveal differences from scattering by spheres. This work will be published elsewhere. The consequence of shape effects appears to that when small-angle scattering from random-shaped natural grains is inverted with a model based on apertures/spheres, fines are invented by the inversion, slightly biasing the TSS. In future, we envisage replacing the spheres model with a model for these natural grains, so that the data on small-angle scattering are inverted with a suitable model.

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