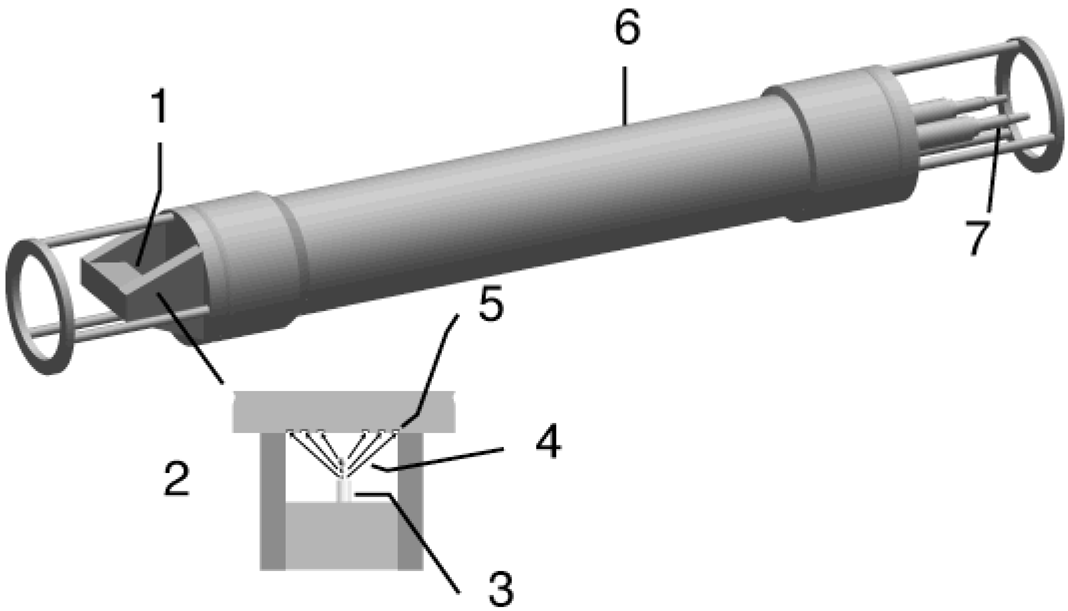
SMS-618, Particle Dynamics, Fall 2003 (E. Boss, last updated: 9/25/2003)

Laser In-Situ Scattering and Transmissometer (LISST)

From: www-ocean.tamu.edu/Quarterdeck/ QD5.1/rich7.html



1. As the LISST descends through the water it projects a laser beam toward ring-shaped detectors on the main body of the instrument.

2. This top view of LISST's laser and detectors show how the instrument uses scattering to measure particle sizes.

3. From the inside surface of the crossbar a laser beam shines on particles in the water.

4. Particles scatter the laser light at different angles depending on particle size. Small particles scatter light toward outer rings of the detector while large particles scatter light toward inner rings.

5. The amount of scattered light detected by each ring is recorded by the instrument's internal computer. These data are later converted into graphs of the abundance of particles of each size.

6. A metal cylinder houses a battery to power the instrument and a microprocessor to collect the data.

7. Waterproof connectors link LISST to other instruments and to conducting cable. Digital signals deliver data from the instrument to the surface.

Principle of operation (Based on Sequoia's application notes, downloadable from www.sequoiasci.com):

To begin with, the LISST measure transmission through a hole in the detector, with an acceptance angle of 0.1° (see last week not on transmission measurements).

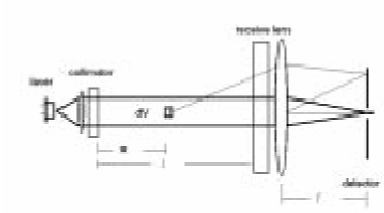


Figure 1: A collimated laser beam (left) illuminates particles between the 2 windows. A multi-ring detector placed at the focal plane of the receiving lens senses scattered light. The figure also illustrates the Fourier transform property of a lens, namely that any ray originating in water at an angle θ reaches the detector at a radius equal to $f\theta$.

The LISST measures the angular scattering:

The Sequoia LISST is currently the only commercially available technology for measuring the volume scattering function in the forward direction (Figure 2). Scattered

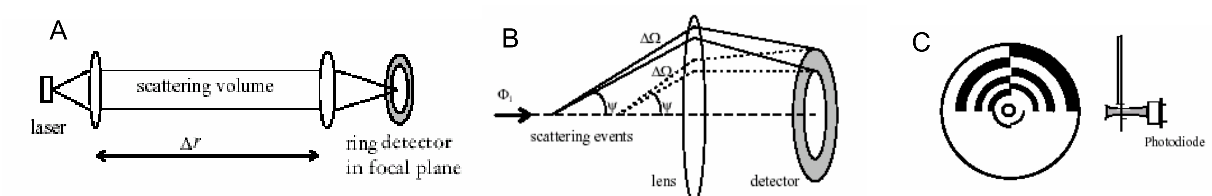


Figure 2. Conceptual diagrams of the Sequoia Laser In Situ Scattering and Transmissometer (LISST), which measure the volume scattering function in the far forward direction at 32 angular intervals. A. A laser passes through a lens into the interrogation volume. B. Scattered light within the volume passes through a lens such that all scattering events along the optical path at angle Ψ are focused onto the same radial distance from the center of the detector. C. The detector consists of 32 concentric ring detectors arrange in quarter circle arcs. From the LISST users manual.

photons are focused onto a ring detector consisting of 32 discrete concentric ring detectors such that each detector receives scattered flux from discrete scattering angles relative to the incident irradiance. The discretized detection angles range logarithmically from either 0.1^o to 20^o or 0.05^o to 10^o depending upon the configuration. The detected signal is dominated by diffraction, and the shape of the VSF is relatively insensitive to refractive index but very sensitive to particle size distribution. Using look up table generated for hundred of possible size distributions, the measured VSF is inverted to predict particle size distributions at 32 logrithmically-spaced intervals from approximately 1.25 - 250 µm or 2.5 to 500µm, respectively.

Obtaining the volume scattering function (VSF, b) with the LISST:

Consider a small length dx of the beam, located at a distance x from the transmit window. An elementary volume in the laser beam is $dV=dA\, dx$ where dA is the area of the elementary volume. Let $\beta(\theta)$ be the VSF. Let the optical path of the beam between the windows be l. For optical power Po entering from the transmit window, and with a beam attenuation coefficient c, by definition of the VSF scattered power in any direction θ will be:

$$dP = e^{-cx} P_o/A\, \beta(\theta)\, dA\, dx\, d\Omega \qquad (1)$$

where $d\Omega$ is the elementary receiver solid angle. Further attenuation of scattered light occurs by a factor $exp\{(l-x)/cos(\theta)\}$ before reaching the window. The solid angle $d\Omega$ is dS/f^2 where dS is area of an elemental ring on a detector that senses light scattered over angle θ to $\theta + d\theta$, and f is the receiving lens focal length. Substituting,

$$dP = e^{-cl} P_o/A\, \beta(\theta)\, dA\, dx\, dS/f^2 \qquad (2)$$

But, since any ring detects light scattered at the same scattering angle, $dS = 2\pi\phi f^2\, \theta d\theta$ where ϕ is the fraction of a circle covered by a detector ring. Substituting and integrating, we have the power on ring number i as

$$P_i = \iiint e^{-cl} P_o/A\, \beta(\theta)\, dA\, dx\, 2\, \pi\phi\theta\, d\theta\, . \qquad (3)$$

Now, if VSF is assumed to be independent of the location of the elementary volume in the water, and if we further assume that VSF is a slowly varying function of angle so that it remains constant over the small angle sub-range, then this is integrated over to:

$$P_i = e^{-c\, l}\, l\, P_o\, \pi\phi\, \beta(\theta)\, [\, \theta^2_{i+1} - \theta^2_i]. \qquad (4)$$

The form that is used applies to small θ. Now, the first exponential factor is recognized as optical transmission τ. Since, there are 32 detectors spanning a radius range 200:1, and detector radii increase logarithmically, if ρ represents the factor $200^{1/32}$,

$$\theta_i = \rho^{i-1}\, \theta_{min} \qquad (5)$$

so that, we have after substitution and some algebra

$$\beta_i(\theta) = [P_i /P_o]/[\, (1-\rho^{-2})\, \rho^{2i}] \,/\, [\, \pi\, l\, \phi\, \tau\, \theta^2_{min}] \qquad (6)$$

This is the essential relationship between the power sensed by each silicon ring detector and the VSF averaged over it. All quantities in the above formulation are measured with the LISST-100, though the precise magnitude of the laser power Po and scattered power P_i requires the responsivity of the detectors. Let the photo-detector response be such that the associated post-amplification voltage is:

$V_i = G_i P_i$, and
$V_o = G_o P_o$

where G is the gain, (Volts/Watt optical power). Consequently, we have:

$$\beta_i(\theta) = [G_o / G_i]/[V_i / V_o]/[(1-\rho^{-2})\rho^{2i}] / [\pi\, l\, \phi\, \tau\, \theta^2_{min}] \quad (7)$$

The purpose of writing the result in the above form is to show that all quantities are measured, except the responsivities G. Values of G can be obtained from standards that are traceable to the US National Institute of Standards and Technology, NIST. With a common A/D, the ratio V_i / V_o can be replaced with the ratio of the corresponding digital counts, i.e. N_i/N_o.
Thus the task of measuring the VSF reduces to recording the voltages Vi and Vo. The LISST-100 instrument records V_i from the 32 ring detectors following an *I-V* amplifier, using an overall gain of 0.5V/μW-optical. The corresponding sensitivity for the transmission sensor is ~1mV/μWoptical. As a final form, then, for the assumed value of parameters in this example:

$$\beta_i(\theta) = 2.0\ 10^{-3}\ N_i / N_0/[(1-\rho^{-2})\rho^{2i}] / [\pi\, l\, \phi\, \tau\, \theta^2_{min}] \quad (8)$$

Thus, in principle, the LISST measurement can provide the VSF.

<u>Obtaining size distribution from the LISST measurement:</u>

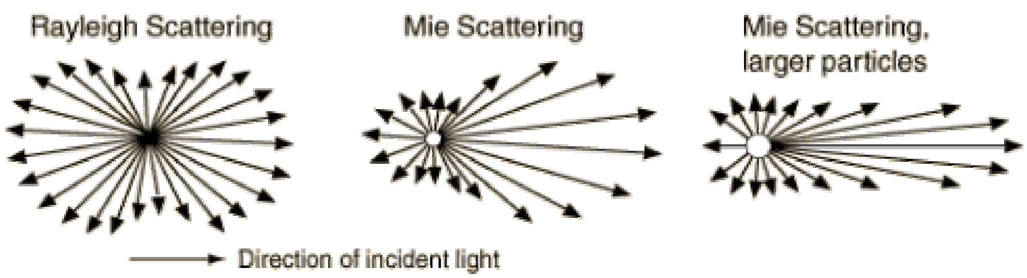


Figure 3. example of scattering patterns around spheres of different ratio to the wavelength. D<<λ (left), D~λ (center), and D>>λ (right).

The bigger the particle, the more picked its scattering around the near forward direction (Fig. 3). The LISST is supplied with an algorithm that fits the measured VSF to a sum of contributions of particle of different sizes. By requiring that all particles concentration will be positively definite and that the PSD is smoothly varying with size, the linear-least-squares best-fit solution is found.

This is how it is described in the LISST application note:

Let the energy contributed by particles of size *i* at ring *j* be called k_{ij}. Then the measured energy at any angle, E_i, is calculated by summing the contribution from all size classes:

$$E_i = \Sigma_i k_{ij} N_A(a_i), \text{ or in matrix form:}$$

$$\underline{E} = \underline{K} \bullet \underline{N}_A$$

where $\underline{K}$ is a matrix, and $\underline{N}_A$ is the area distribution written as a vector. To obtrain the size distribution, this equation is *inverted* using a least-squares best-fit algorithm, demanding the solution to also be smooth and positive. The solution thus obtained is the area distribution $\underline{N}_A$. From the area distribution it is possible to obtain the *number density* or *volume distibution* as

$$n(a_i) = N_{Ai} / a_i^2; \text{ and}$$

$$V(a_i) = N_{Ai} * a_i$$

The *total volume concentration is* $\Sigma V(a_i)$.

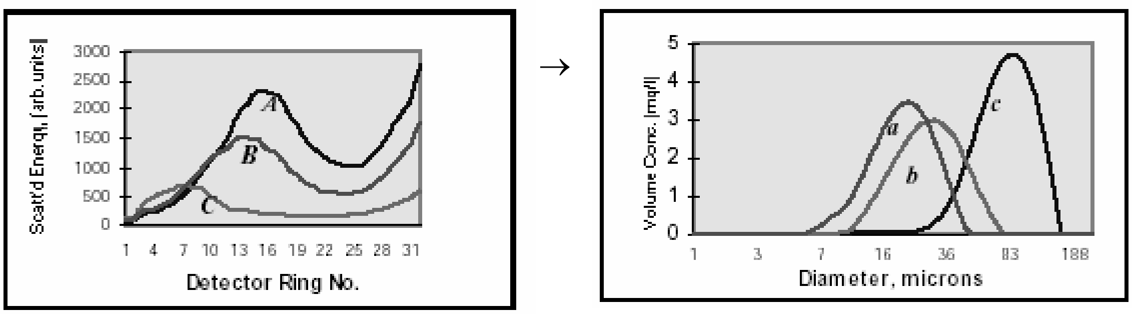


Figure 4: The distribution of intensity of the ring is mapped to a distribution of concentration as function of size.