Measuring the Size Distribution and Concentration of Particles

In this Note, we describe the principles of operation of the LISST instruments in simple terms for the non-optical specialists

SEQUOIA SCIENTIFIC, INC. ✥ **APPLICATION NOTE L001**

The measurement of particles in the marine environment has traditionally been carried out using single-parameter sensors such as the optical transmissometers, optical backscatter sensors, or acoustic scattering sensors. These are single-parameter sensors in that they obtain a single measurement as the indication of the sediment concentration. Their simplicity makes these observations attractive and easy to make. However, it is widely known that as the particle size distribution in the environment changes, so does the calibration of single-parameter based sensors. The errors can be serious if the material being sensed is significantly different in size than the material used for calibrations. A multi-parameter measurement is required. The LISST instruments obtain this multi-parameter measurement as the scattering at a set of multiple angles.

We begin with the definition of size distribution *n(a)*. If the number of particles of size *a* per unit volume of water, in a small size-range Δa is $n(a)\Delta a$, then *n(a)* is called the *size distribution*, or more clearly, number density. The *area distribution* is $N = a^2 n(a)$ and the *volume distribution* is $V = a^3 n(a)$. The total particle area per unit volume of water is the sum of all contributions, $\Sigma a_i^2 n(a_i) \Delta a_i$. Similarly, the total particle volume per unit volume of water, the *volume concentration*, V is $\Sigma a_i^3 n(a_i) \Delta a_i$. Clearly, to estimate these quantities, the function $n(a_i)$ is needed. Note that *n(a)* is a multi-parameter measurement because *n(a)* must be determined at a number sizes a_i.

We explain the operation of the instrument first. A laser beam formed by collimating the output of a diode laser illuminates the particles, Figure 1a. Scattering by particles is detected in the focal plane of a receiving lens. In this focal plane is placed a specially constructed detector consisting of 32 rings, Figure 1b.

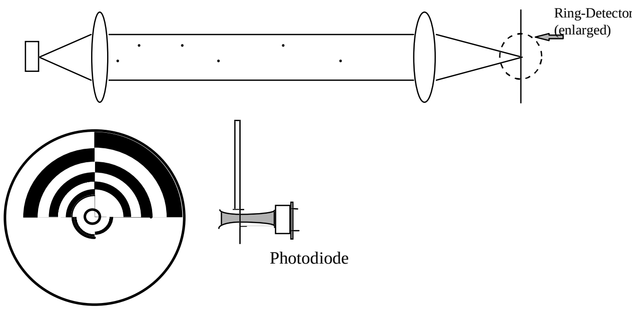

Figure 1: Operating Principle of the LISST-100

Each ring measures the scattering at a particular small range of angles. For mathematical reasons concerned with solving the equations for $n(a_i)$, the radii of the rings are arranged to increase logarithmically so that each radius is a constant times the last radius. A photodiode behind the ring detector measures optical transmission τ, Figure 1c; τ is used in correcting for background scattering from optical surfaces.

The signature of particle sizes is shown in Figure 2 for two distinct particles. These curves show the theoretically predicted scattered energy sensed by the rings for 2 different particle sizes. Again, for mathematical reasons, the curves are computed per unit area of the two particles. Small particles show a curve peaking at the larger rings, and vice versa.

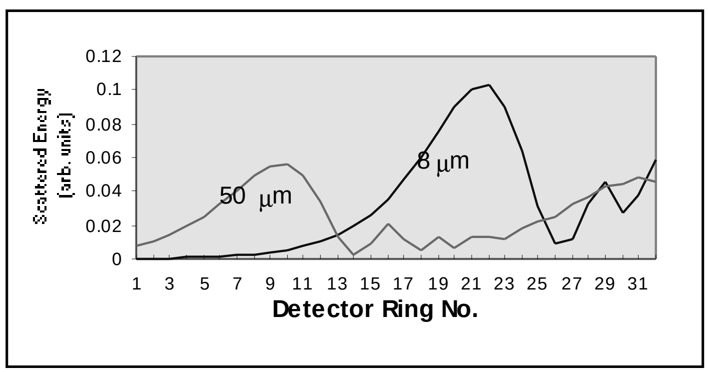

Figure 2: Signature of Particle Sizes

[These curves are computed using the full, exact solution to Maxwell's equations for light scattering by particles, the Mie theory. Homogeneous spheres are assumed.]

In an actual experiment, the measured energy distribution across the rings will be the weighted sum of all such curves for the different particle sizes. For example, if just the two particle sizes shown in figure 2 were present, then the energy distribution observed by the ring detector will be just the sum of these two curves. If twice as many particles were present in one of the sizes, then the summation will include twice the corresponding curve. In general, since many particle sizes will be present in varying amounts, the energy distribution will be a weighted sum of all the curves.

The LISST instrument records the energy distribution sensed by the ring detector. A single scan is recorded for every needed size distribution. The scans can be recorded as rapidly as 0.2 sec apart, or they may be spaced hours or days apart also. After completion of the data collection phase, the data are off-loaded and mathematically inverted to produce the size distribution. The first result of this mathematical procedure is the area distribution. By multiplying the area in each size class, by its diameter, and by dividing by a calibration constant which is typical of the instrument, the absolute volume concentration is recovered. This procedure is described in a little more detail in the box.

As an example, Figure 3 shows the measured energy distribution across the rings for 3 sample powders obtained from Duke Scientific, Inc. of Palo Alto, California. Note that the location of the peak as well as the magnitude are distinct.

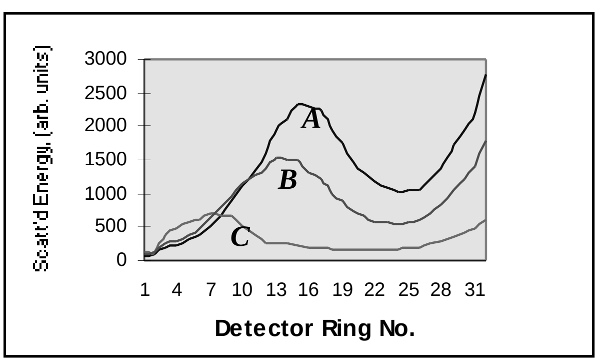

Figure 3: Energy distribution for 3 powders

The change in location of peaks in Figure 3 corresponds to change in peak in the volume distributions, as shown in Figure 4 below.

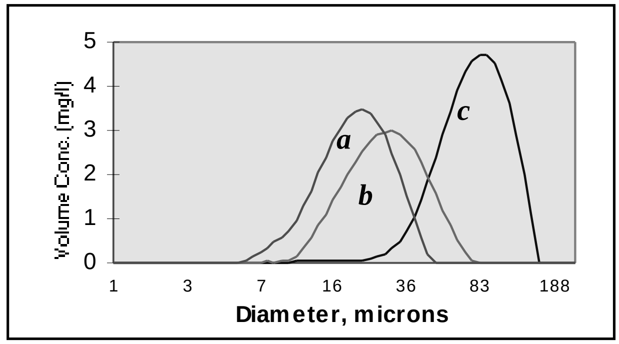

Figure 4: Volume distributions after inversion.

This constitutes the essential description of the measurement of particle size distrubiton.

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:

$$E_i = \Sigma_I k_{IJ} N_A (a_j), \text{ or in matrix form:}$$

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

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

$$n(a_i) = N_{Ai} / a_1^2; \text{ and}$$

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

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

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