THE ISOKINETIC STREAMLINED SUSPENDED-SEDIMENT PROFILING LISST-SL – STATUS AND FIELD RESULTS

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Abstract: A streamlined isokinetic sediment profiler – the LISST-SL – has been developed by this company in a Cooperative Research and Development Agreement with the U.S. Geological Survey (USGS). This device continuously measures suspended-sediment concentrations, size distributions, depths of measurements (pressure), water velocities, and water temperatures. It is cable-suspended using a standard USGS B-reel. A topside control box provides power and communication. Data are stored on a PC for subsequent windows-based processing. Due to the inclusion of a depth sensor, the wire-angle limitation of the past induced by downstream drag on the instrument is relaxed. The additional simultaneous measurement of velocity permits computation of true horizontal flux of sediment in 32 distinct size classes covering the size range 2.5 to 500 microns. Typical data at a depth are acquired in a few seconds; however, statistical stability requires averaging over several integral scales of the turbulence (this scale is z/U, where z is distance above bed, U is mean velocity). The system employs laser diffraction optics. Bluetooth may be offered.

In this paper, we present LISST-SL technical details and field data from a river in the Northwest US. Influence of shape effects on measurement accuracy is considered in a quantitative way based on new data on small-angle light scattering properties of natural dusts versus spherical particles.

INTRODUCTION

The LISST-SL instrument is a streamlined version of the standard LISST series of particle sizing systems that are now in common use; a partial list of publications appears on the company's website [http://www.sequoiasci.com/library/technical.aspx?SectionName=library]. An earlier report on this device was presented at the last such conference. Since then, field tests, an evaluation at the Federal Interagency Sedimentation Project (FISP) and further engineering development of the isokinetic controller have been performed. Furthermore, shape effects of particles are under study that, when incorporated in the algorithms for inversion of multi-angle scattering, will measurably improve measurement accuracy. These are the subjects of the present report. In the following, we summarize fundamental concepts and the instrument. We then present test results from the field as well as the laboratory. Preliminary indication of shape effects of particles is included.

The LISST series of instruments are based on the small-angle scattering principle, which is more widely recognized as laser diffraction. Briefly, light scattering at small forward angles consists of two parts: light diffracted by the obstruction that is the particle, and light that entered the particle and then emerged in the forward direction, i.e. transmitted or refracted light. Of these, at small angles, diffracted light is usually dominant, hence the name laser diffraction. This diffraction follows exactly the same form as through an aperture, which is a classical solution due to Airy, and bears his name (see e.g. Born and Wolf, 1975). For circular apertures, the Airy *function* follows the form $a^4[J_1(ka\theta)/\ (ka\theta)]^2$ where J_1 is the Bessel function of first order, k is $2\pi/\lambda$, a is particle radius and θ is scattering angle. Because diffraction does not concern particle internal properties, the measurement is insensitive to changes in particle composition or color. Thus, this method does not suffer from changed calibrations with changing sediment color – a significant shortcoming of the widely used optical backscatter sensors. Furthermore, since the size distribution is measured, the calibration of the measurement remains fixed, regardless of the sediment-size distribution. This latter advantage is central to the need for alleviating this second source of calibration change with OBS as well as acoustic sensors (Sutherland et al.2000). The full technical details of relevant light scattering theory are presented elsewhere (Agrawal and Pottsmith, 2000).

The method, unlike single particle counting methods, measures scattering of light from an ensemble of particles in a laser beam, all of which contribute to it. Of the illuminated set, each size contributes in proportion to its number and to its own characteristic diffraction form described above. The overall sum becomes the observation of multi-angle scattering. This is inverted to obtain the size distribution. Summing the size distribution produces the total suspended-sediment concentration. The other essential relevant details for this report are that the minimum and maximum scattering angles at which measurements are made determine, respectively, the maximum and minimum particle size that can be included in the inversion. For example, for optimal inversion, we set $ka_{min}\theta_{max} = ka_{max}\theta_{min} = 2$. The LISST-SL instrument is designed with θ_{min} and θ_{max} chosen to cover the size range 2.5 to 500 microns.

The instrument consists of a streamlined hull with a low drag coefficient of <0.2. A coaxial aperture at the nose is fitted with a USGS standard nozzle (Davis and the Federal Interagency Sedimentation Project, 2005) to draw water, through a long drilled conduit. Approximately midway through the passage of this water, laser optics measure multi-angle scattering. These optics consist of a laser, collimating lens, glass windows to separate river water from the optics and electronics, a receiving lens, and a custom detector (Figure 1). As for electronics, although the original prototype, which constitutes the platform for some of the test results included here used an internal micro-computer and data storage capability, the new production models only include a micro-processor. Each includes, in addition, the photo-current amplifiers and a pump controller. The micro-computer (or the micro-processor) communicates with a Topside Controller Box (TCB) where data are stored. The Controller communicates with a PC or laptop computer. For effecting isokinetic withdrawal of water from the stream, a pump assist is included. An external flow sensor is enclosed in a streamlined tube in the 'sail' of the instrument. It measures the local velocity of river flow, it is based on heated thermistor technology. The flow internal to the instrument is monitored with an identical heated thermistor sensor, so that feedback is included. The micro-computer adjusts pump drive voltage to equalize intake velocity to river flow. This also permits an operator to identify flow blockage. The TCB commands the submersible LISST-SL to deliver data according to the program parameters that an operator sets up on a laptop computer.

The system employs a pressure sensor to record the depth at which any measurement is being made. The depth data is integrated into the optical multi-angle scattering data stream that is sent to the TCB. The heated thermistor readings are also transmitted to the TCB as measures of water temperature and river velocity. By integrating the depth, water temperature and velocity data with the optical data, synchronism of data are assured. All communications and power transmission are implemented with the standard USGS B-reel.

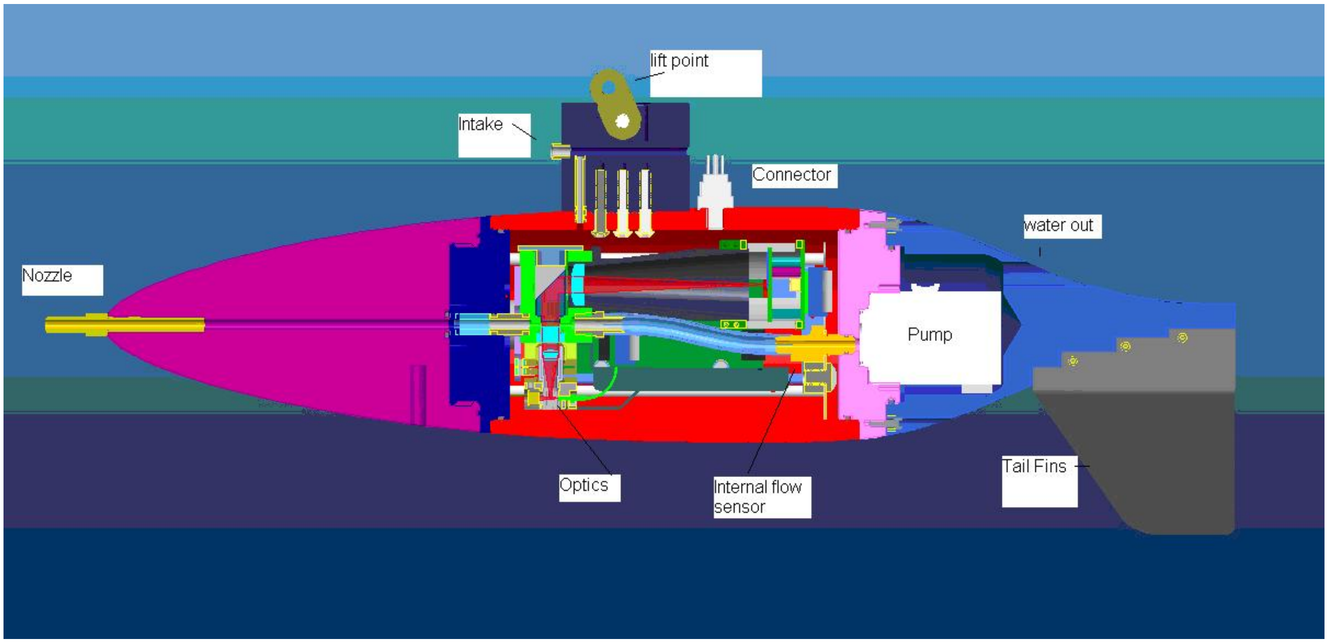

Figure 1 A cut-away of the LISST-SL instrument.

TESTS- LABORATORY

The laboratory tests were performed, both at the FISP facility in Vicksburg, MS, and subsequently again after minor optics improvement incorporated in the first commercial instrument, at the factory. These tests were intended to establish accuracy of measurement of suspended-sediment concentration. Key components of the test set up included a well-stirred reservoir into which measured amounts of sediment samples were inserted. For each sample, as it was the intention to examine accuracy at different flow-through velocities, a set of water samples were collected from the discharge end while measurements of multi-angle scattering were being made. This was meant to ensure that precisely the same water that passed through the instrument is available for physical determination of samples. The system was designed and built by Broderick Davis and Wayne O'Neil of FISP. The results of those tests were not fully within the CRADA's specifications and are not reproduced here. The identical tests were repeated at the company with the improved optics built into the first commercial Unit-001. The improved optics reduced background scattering from optical surfaces, reducing noise contamination of the results. These are displayed in Figure 2.

The true vs. estimated concentrations show a reasonable 1:1 trend, over the range of concentrations from 10-5,000 mg/l, Fig. 2 (*left*). The maximum error is 12%, at both the extremes of concentrations, i.e. at 10 and 5,000 mg/l. The error is less than 10% throughout the mid range (20-2,500 mg/l). The size distributions for the entire range of tests are displayed in Fig.2 (*right*). Clearly, the size distributions appear consistent, scaling up with increasing concentrations.

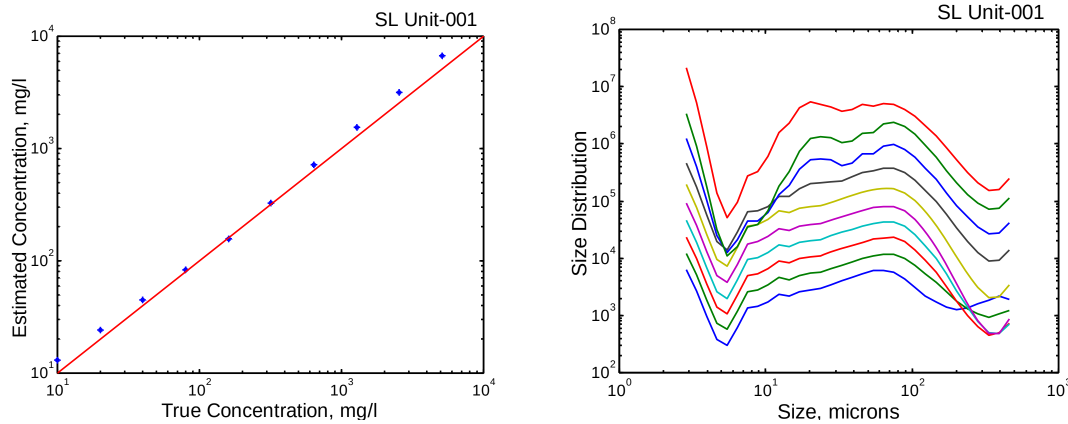

Figure 2 Test of fidelity of concentration (*left*) and size distribution over 1-5000 mg/l, and size distributions (*right*).

It is noteworthy that the rising left edge of the size distributions is attributed to shape effects. More on this is presented later in the paper. Isokinetic tests have not been carried out at the time of this writing (November 2005) but should be available in 2006.

TESTS - FIELD

On June 24, 2004, the prototype LISST-SL (i.e. previous to improved optics) was tested in Puyallup River, Washington. This river carries sediment from Mr. Rainier, a regional dormant volcano. The LISST-SL, shown in Figure 3, was lowered from a USGS standard B-reel into the river. Simultaneously, point-integrated bottle samples were collected isokinetically at the same depth and time as the LISST-SL data. These are compared in Figure 4 below. Note that the data represent less than currently achievable level of performance.

There are two segments in this data, Figure 4. In the first segment, LISST-SL sample numbers 20 to 90, a long time series was taken at a fixed depth, during which time bottle samples were also collected. The second segment shows a detailed vertical profile, between sample numbers 110 and 200 (abscissa). The yellow trace (top) shows river velocity. The dots indicate bottle data that was post processed.

The first segment of this data is preceded by an artifact of high values which may have been contaminated by bubbles in the system, to about sample number 20. Following this, the agreement between concentrations derived from the LISST-SL and P-61 samples is within 20% with the LISST-SL results tending to be biased low. Note also the two sudden discontinuities in the P-61 sample data around sample number 45 and 52. These are unlikely to be correct, and are not supported by nearby measurement, suggesting variability in these samples. The profiled samples, points 120-200 show a distinct rise in concentration measured by the LISST–SL as it reaches maximum depth (nearest bottom), about 15 cm above bed. The increase in concentration

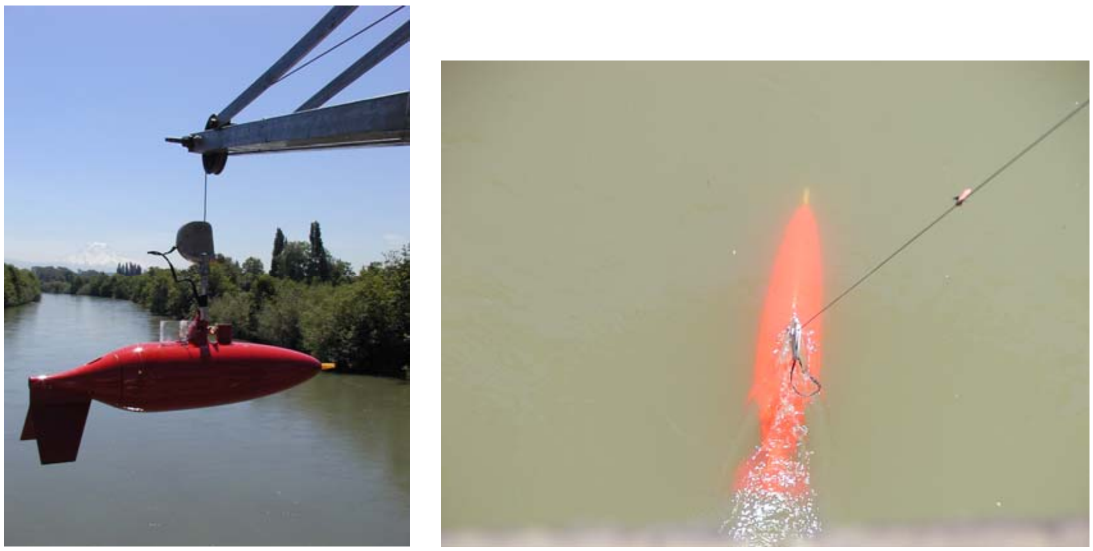

Figure 3 (*left*) The LISST-SL shown suspended from a bridge on the Puyallup river, Washington, from the B-reel frame. (*right*) View, looking down from the bridge of 'fish in water' shows the instrument aligned with flow, as indicated by the wake.

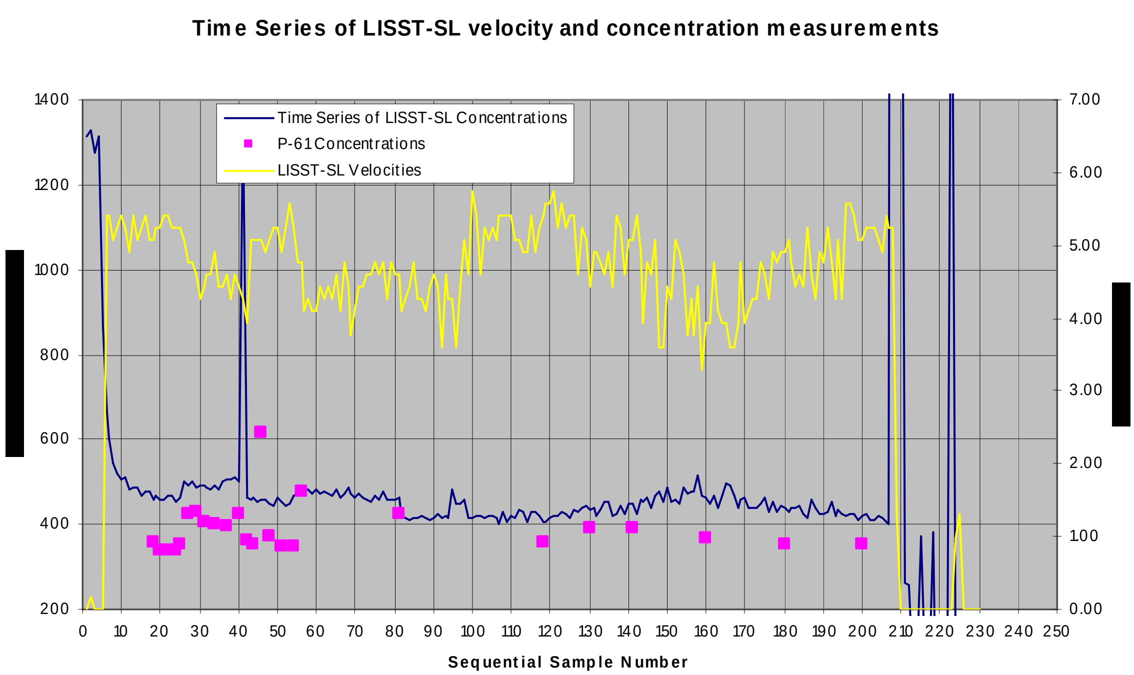

Figure 4 Time series of measurements with the LISST-SL and P-61 samples (dots).

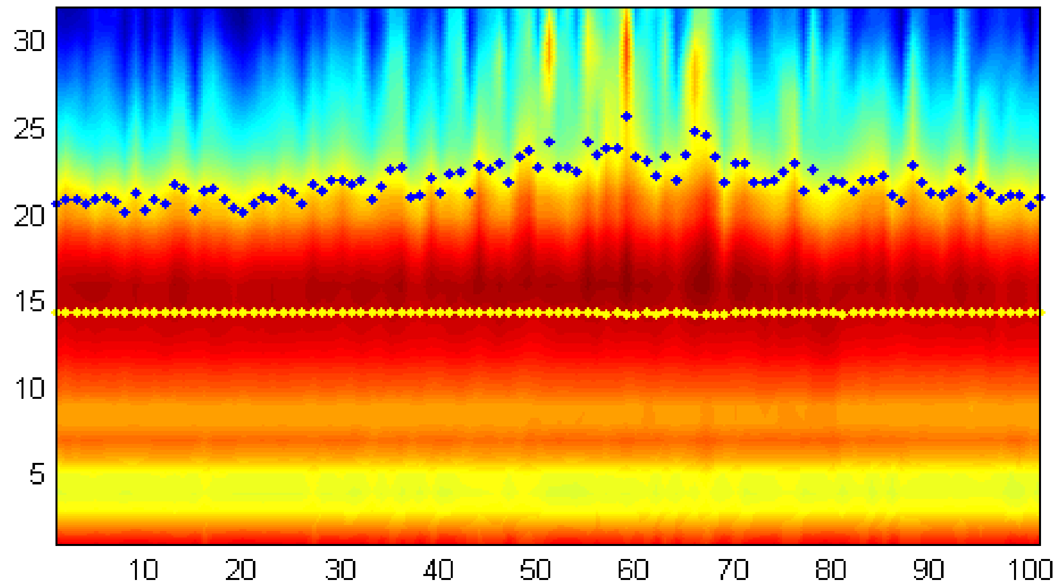

Figure 5 Detailed size distribution, concentration (blue dots) and concentration via optical transmission (yellow dots) through a vertical profile, segment 100-200 of Fig. 4.

coincides with reduced velocity – all characteristic boundary layer patterns. The profile of sediment concentration seen here is expected in any natural environment, it results from the balance of gravitational settling and turbulent diffusion. The phenomenon bears the name of Rouse (1937). The velocity series, top profile, reflects a slowing down of flow near bed. The profile properties recover on the up-cast, approximately 160-200. Strangely, bottle samples do not 'see' the increase of sediment concentration near the bed.

the ordinate is the size class number. Recall that the LISST-SL reports concentration in these 32 size classes. Colors indicate concentration, reds being high, blues low. It is evident that the
More detailed analysis of the multi-angle scattering data from LISST-SL supports the suspended-sediment concentration of figure 4. This is displayed in Figure 5. Here, the size distribution during the vertical profile is displayed, expanded. The abscissa is data sequential number, while
middle of this pseudo color plot displays the presence of significant concentrations in the high numbered size classes, i.e. large particles. Again, this is consistent with Rouse (1937) formulation – the faster-sinking particles stay near the bed. The blue dots (total concentration) suggest an increased concentration accompanying the large particles nearest bed. The upcast gradually shows the disappearance of large particles, and a return of the concentration to its original downcast starting value. Interestingly, a measure of sediment concentration via beam attenuation (which is similar in properties to optical backscatter), shown as yellow dots in mid-range of the plot, does not pick up this increase of concentration nearest bed. This is a consequence of the inability of such measurements (transmission, nephelometry or optical backscatter) to see large particles with sufficient sensitivity. In other words, had an OBS or beam transmissometer been in use, the concentration would be in error and no details of large grains would show up near the riverbed. To sum, the detailed profile measurement of the LISST-SL consistently finds patterns that are expected in a vertical profile, amply supported by densely populated data points, whereas sampling variability of P-16 seems to miss the detail.

PARTICLE SHAPE EFFECTS

As noted, light scattering theory is not sufficiently developed yet to easily compute the angular scattering or diffraction from arbitrarily shaped particles. In particular, the computations are possible for small sizes but become far too computationally intensive to be useful in practice. Therefore, one uses the scattering-diffraction properties of spheres. We have made strides in characterizing differences that arise from shape effects. In Figure 6, we show the measured light scattering pattern from a size fraction from Arizona dust (size 63-125 microns, obtained by careful multi-wash wet sieving), compared with the same for spheres. The difference is qualitatively evident (*left*). In particular when the scattering signature of AC Sparkplug dust particles is interpreted as a collection of spheres, it produces a size distribution shown in Figure 6 (right), which shows the apparent 'invention' of fines that were in fact absent. This is the essential consequence of shape effect. Far more exhaustive studies are underway, including the variability in scattering from particles of different sources. These data will begin the quantification of errors arising out of changes in shapes of particles from different sources. We hasted to add that these changes are still small compared to the 12% change mentioned in figure 2. These studies are important simply to place fundamental bounds on accuracy.

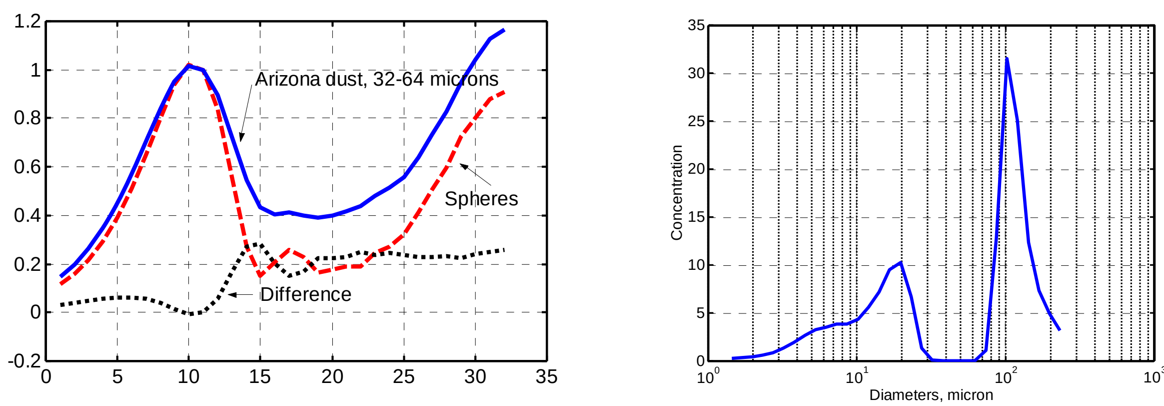

Figure 6 The difference between light scattering by Arizona dust and spheres of equivalent sizes (*left*), and the consequent invention of fines when the dust is interpreted as a set of spheres (*right,* from inversion of the 'difference' in scattering between dust and spheres).

CONCLUSIONS

Provisional results are encouraging. The LISST-SL appears capable of holding calibration within 12% over the concentration range 10-5,000 mg/l, although the accuracy is superior – better than 10% – for 20-2,500 mg/l. Field tests in a river produced an approximate 20% discrepancy with the P-61 samplers, with the original prototype, a differential that would presumably be lower with the improved commercial instrument. Interestingly, the LISST-SL clearly reveals a Rouse-like concentration behavior in concentration profile, not seen by bottle samplers, which begs explanation.

The next tasks are the completion of the isokinetic flow withdrawal system, and the incorporation of shape effects in interpreting multi-angle scattering data. These results may be available by April 2006.

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