Experimental tradeoffs of minimalized laser tomography for large and small particle size parameters using GraVeTAS

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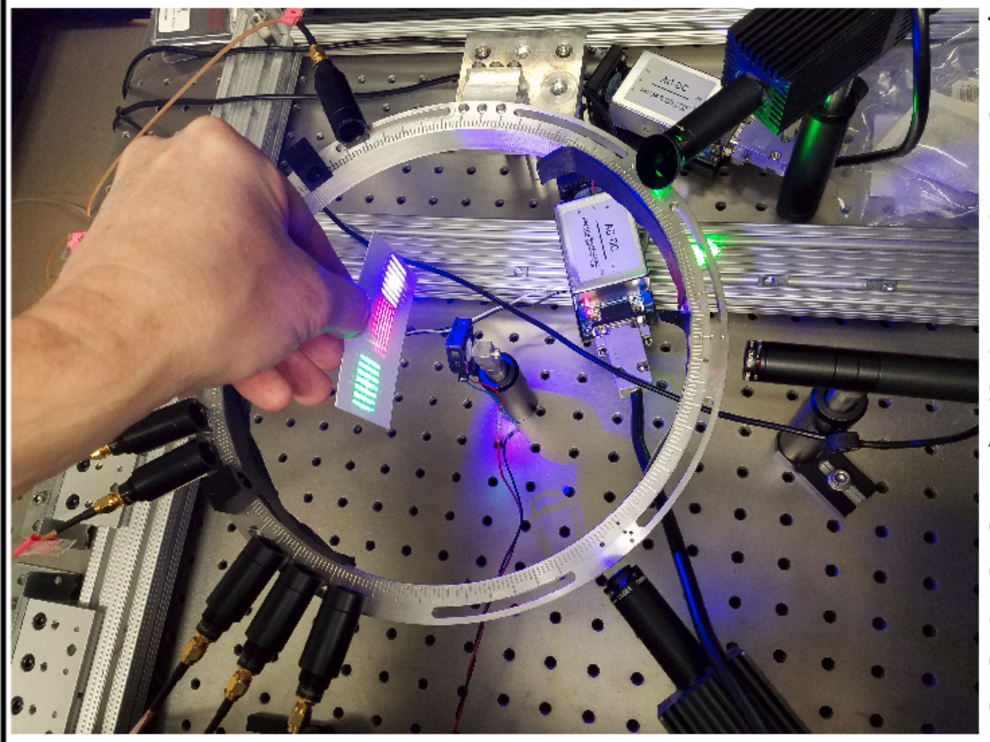
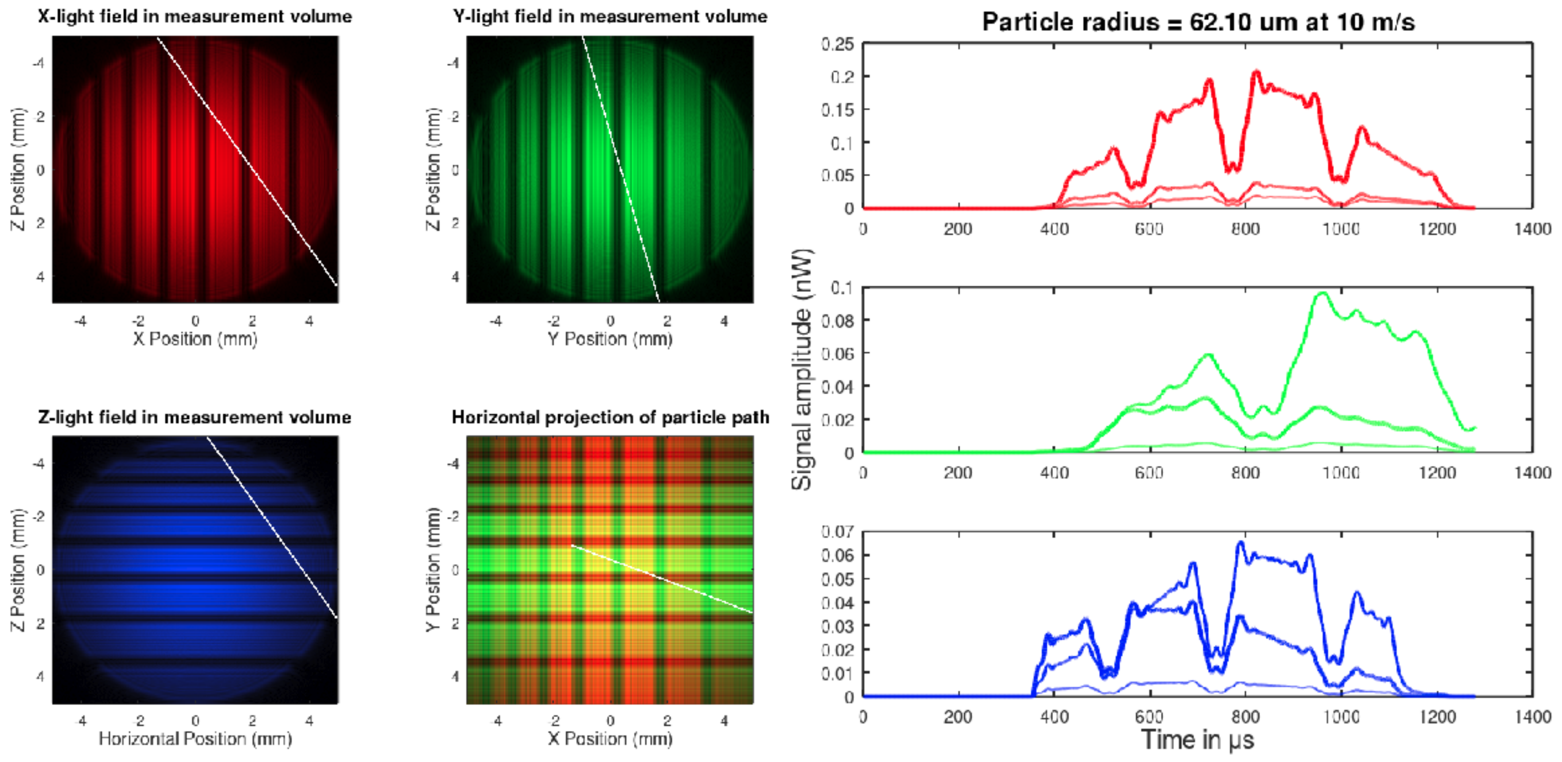
Introduction to GraVeTAS

The Grain Velocimeter and Tomography Analysis System (GraVeTAS) is a laser-based instrument under development and in use as part of the Project for Exploration Science Pathfinder Research for Enhancing Solar System Observations (Project ESPRESSO) SSERVI node. GraVeTAS combines an optically and computationally minimized variant of the family of techniques that use scattered laser light to compute the shape and size of small suspended particles with standing wave laser velocimetry to directly measure the 3D velocity components of each particle trajectory.



Three lasers at wavelengths (445, 532, 650 nm) are encoded with a spatial quasi-chirp fringe pattern and directed to overlap at the center of a 26 cm wide rigid ring. In the volume of overlap, the linear spatial patterns are mutually orthogonal (as is shown in the image to the left.) As particles pass through this measurement volume, three sets of wavelength-selective photodiodes collect the scattered light as a time-series signal. From this data, the 3D velocity and 3D size of the particle can be computed.

The particle passes through the overlap of the beams in three dimensions, but there is no *a priori* knowledge of the vector. An example path for a particle passing through the measurement volume is shown below. The red, green and blue fringes are illustrated along their cardinal directions. The red and green measure X and Y speeds respectively and the blue measures the vertical velocity component. The fourth plot illustrates the path through the red and green lasers as seen from above.



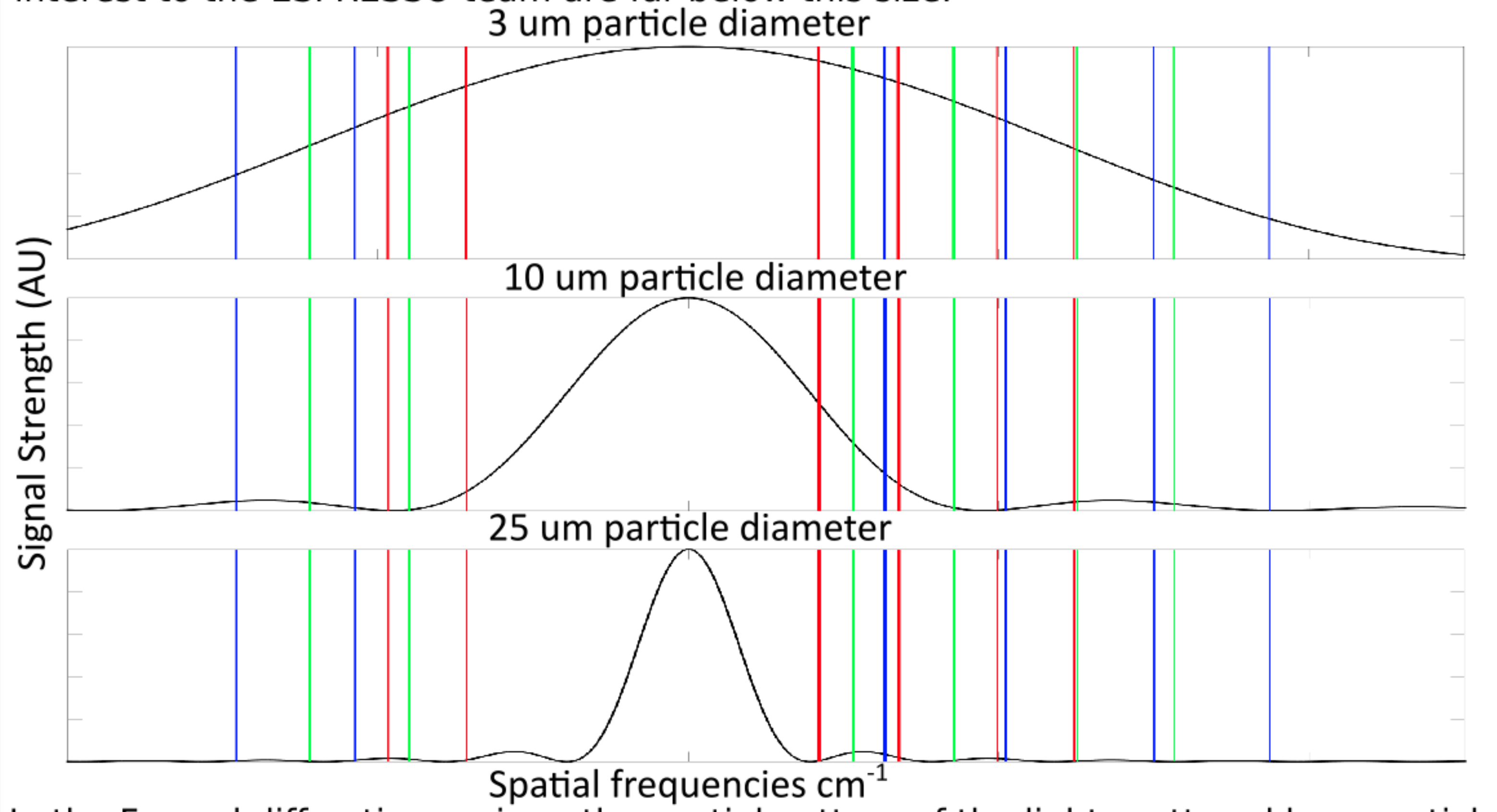
The plots on the right simulate the signals collected by each of the three detectors per laser. The darkest line represents the detector at 8.5° nominal, then -13° is lighter and 17.5° is the lightest. As a Fourier sampling system, the detectors are collecting light at set locations, but the angle at which the light is collected changes depending upon the position of the particle in the measurement volume. The beams are approximately 1cm wide, while the instrument ring has a radius of 13 cm - which means that the angle changes as the particle passes through the volume. This can be seen most obviously in the plot for the blue detectors. The 8.5° and -13° amplitude cross at around 550 us. This is due to the fact that the particle began the traverse at nearly the center of the volume and got progressively farther from the 8.5° detector.

In addition to the lateral motion across a beam causing the angle of the detected light to change the Fourier sample collected, the motion normal to the beam propagation changes the angle subtended by the detector and thus the portion of the Fourier space being measured and the amplitude of the detected signal. All of these would seem to be insurmountable complications to the measurement, however, each of these effects are actually beneficial in determining the instantaneous position and size of the particle.

As can be seen from the plots, the quasi-chirp provides unique spacing ratios in the peaks and troughs of the detected signal without needing traveling wave architecture in the velocimetry function of the instrument. GraVeTAS uses velocimetry to aid in the determination of position which allows for certainty in the Fourier component being collected.

Performance limits: theory and simulation

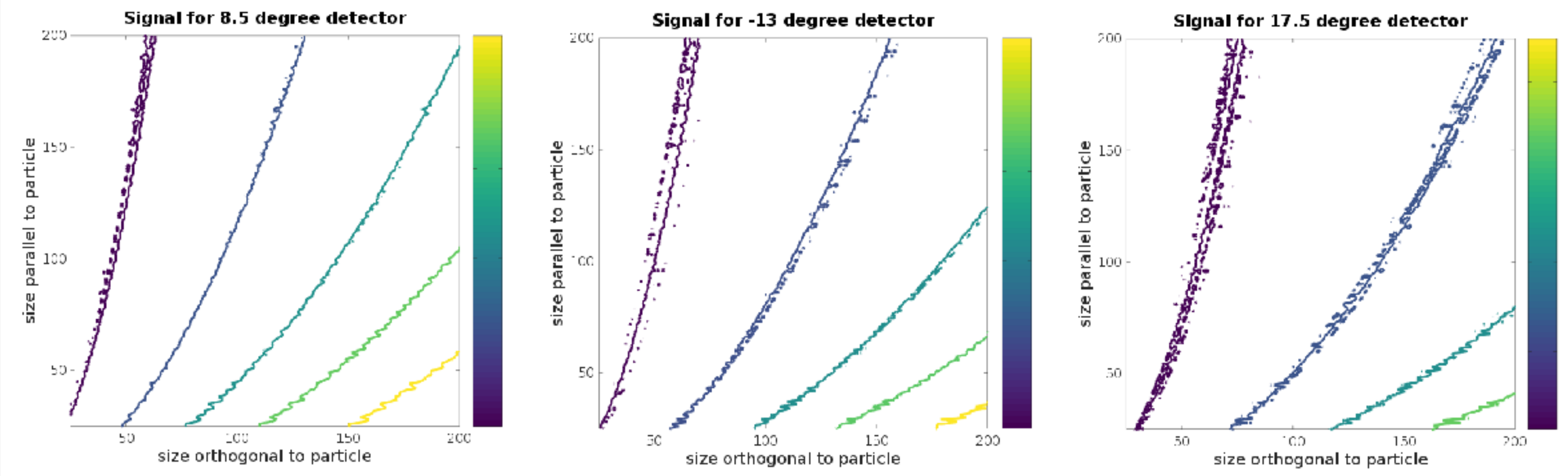
Instrument implementations using laser scattering particle sizing techniques are designed for a pre-specified range of particle size parameters (d), defined as the ratio between the particle diameter and the wavelength of light interacting with the particle. The limits of instrumental function are determined by the physics of the scattering regime, which is most commonly described by the Fresnel number $F=r^2/(L\lambda)$, where $F \ll 1$ defines the far-field regime where the assumptions of Fraunhofer diffraction hold, and $F > 1$, the near-field regime described by Fraunhofer diffraction approximation. In the case of GraVeTAS, F=0.23 for a particle of 250 um diameter. Most particles of interest to the ESPRESSO team are far below this size.



In the Fresnel diffraction regime, the spatial pattern of the light scattered by a particle is the Fourier transform of the cross section of particle. By sufficiently sampling the light phase function, the Fourier space representation can be populated and though Fourier synthesis, the particle shape may be reconstructed. However, the sampling resolution of Fourier space determines the maximum particle size that can be reconstructed with standard Fourier synthesis. In the figure above, three Fourier slices are shown of simulated scattered light from particles of 3, 10 and 25 micron diameter. The red, green and blue line sets represent the spatial frequency sampling of the detectors. Although each set of detectors is placed at the same angular position on the ring, the spatial frequencies collected are different due to the Fourier scaling with wavelength, as described in the Fraunhofer diffraction approximation equation.

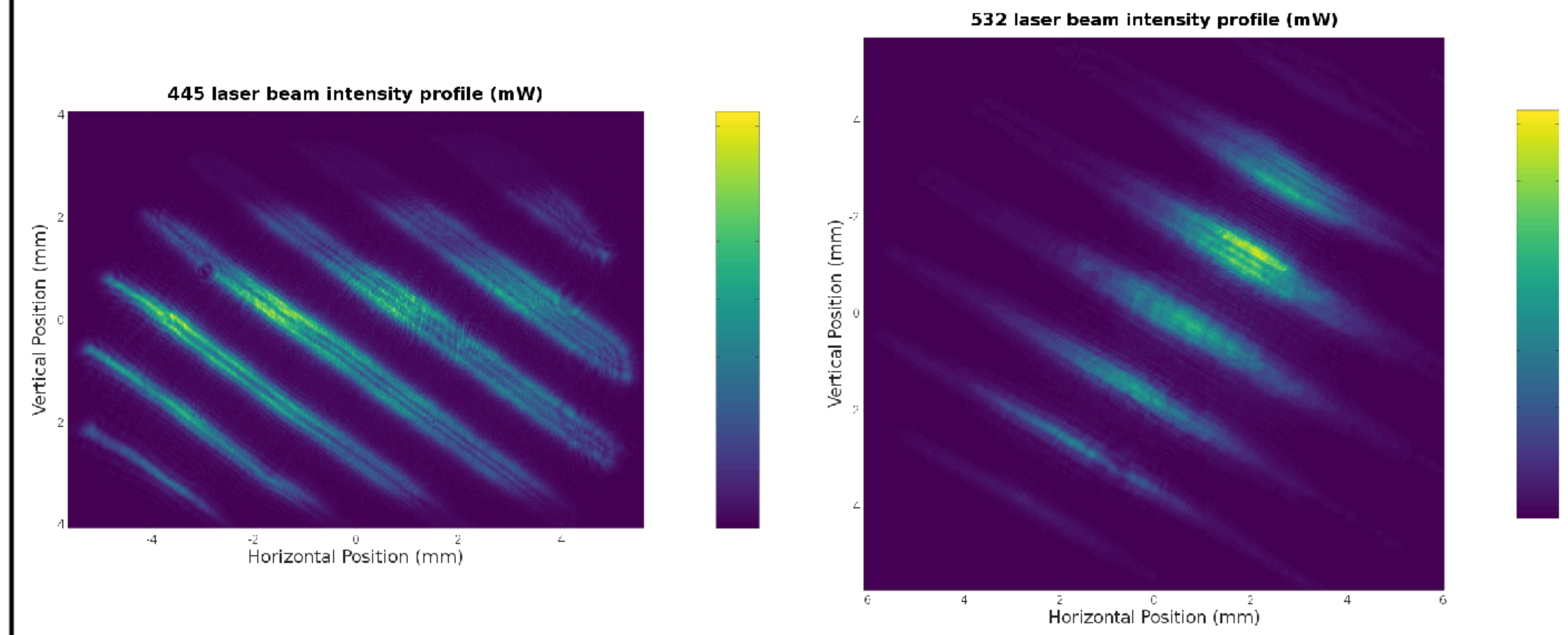
$$U(x_z, y_z) = \frac{e^{jkz} e^{\frac{jk}{2z}(x^2+y^2)}}{j\lambda z} \iint_{\infty}^{\infty} U(x_0, y_0) e^{\frac{-j2\pi}{\lambda z}(x_z x_0 + y_z y_0)} dxdy$$

So long as the lobes of the diffraction pattern are larger than twice the detector extent in spatial frequencies, the scattering function may be oversampled and direct Fourier synthesis applied. For GraVeTAS, this limit is approximately 25 um or d ≅ 50. Beyond this size, the photodiodes are effectively sampling the 2D power spectrum of the scattered light. The power spectrum can still be used to generate a particle size, but the error bars in the size determination are significantly larger. The plot below shows the signal collected for ellipsoids for on-axis and off-axis sizes from 25 to 200 um. The particles in these plots, are oriented parallel to orthogonal to the plane of the ring of detectors. Errors are larger along the contours than along the gradient.

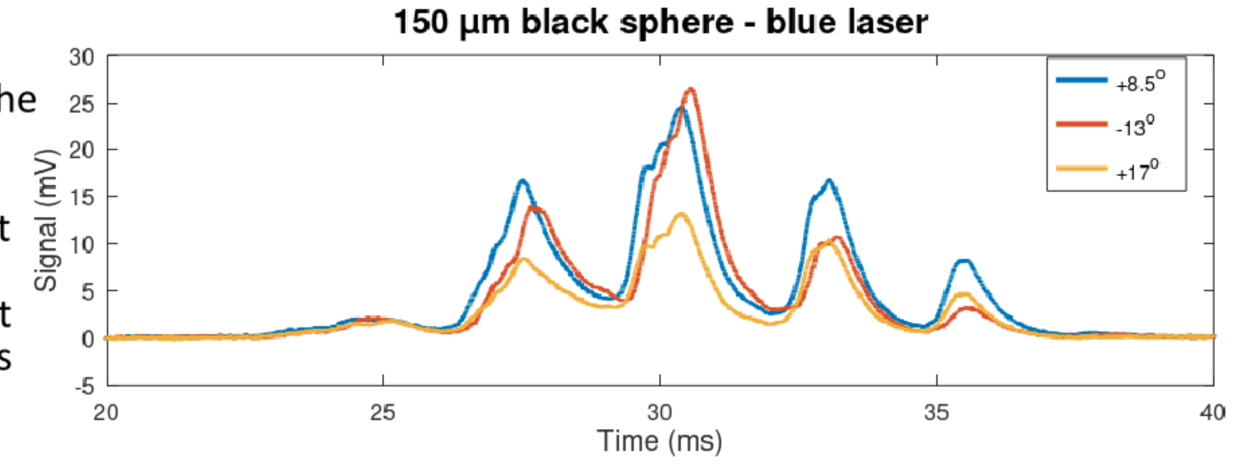


GraVeTAS experimental performance: d > 50

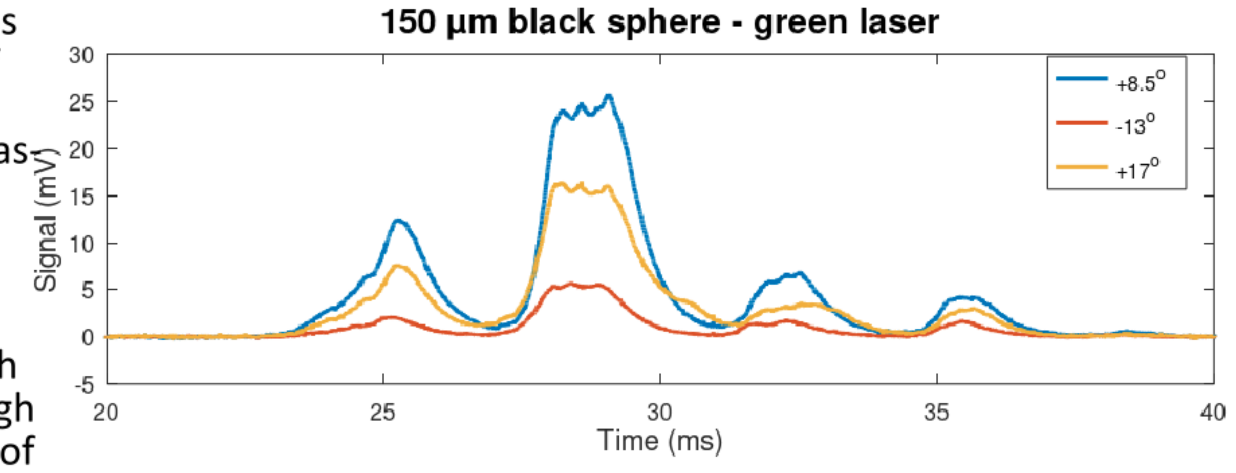
Laboratory experiments over the last year have concentrated on simplifying the data acquisition system, increasing the robustness of the instrument to optical misaligment, and calibrating the instrument response to large particle sizes and velocities. Although the instrument was designed to use three lasers for a completely orthogonal beam code geometry, we implemented a 2 beam, non-orthogonal geometry in order to simplify the search algorithms. The measured beam profiles of the 532 nm 70 mW laser and the 445 nm 167 mW laser are shown below. Each pixel is 7 microns across, and the image exposure was set just below saturation. These laser show a great deal of intensity anisotropy, but the quasi-chirp is easily recognizable by and spatially well behaved. The lasers are ~$100 COTS diodes and have low optical quality but have long term mode and power stability.



Calibrated spherical particles were dropped through the beam to test algorithms for particle location, particle velocity and 2D particle sizing error estimation. We used 150 um and 38 um polyethylene spherical particles. Each size was also tested with black polyethylene and white polyethylene to test for instrument response difference between the two. The particles were sprinkled into the instrument, but were stongly influenced by the air-handling system of the laboratory. Even at these larger particle sizes, the air currents were significant sources of experimental variability. 5 micron particles were used, but a fan was necessary to overcome eddy currents in the lab. The fan was subsequently used for velocity measurement experiments. At 1 MHz sampling and with 12 mm wide detector apertures and using photodiodes in the photovoltaic mode without preamplification, the 150 um particles generate signals in the range of 10 - 200 mV depending upon their location within the measurement volume. A representative collected time-series from six detectors for the 150 um black sphere is shown below. The quasi-chirp features are clearly visible, as is a migration of the particle across the blue laser.



Particle sizing calculations based on laser scattering is most accurate in the far-field Fraunhofer regime due to greater angular selectivity. Velocimetry is best achieved at short distances with an unimpeded path to a finite measurement volume that is sufficiently large to obtain samples of the velocity.



Conclusion:
The combination of these techniques would typically produce a conflict of function leading to reduction is performance for one or both of the measurements. GraVeTAS overcomes this by utilizing the position information from the velocimetry to determine the precise angular position and extent of the Fourier sample for each moment in time. In addition, although GraVeTAS only uses a small number of detectors, the motion of the particle across the beam provides new samples of the Fourier representation of the particle with every unique measurement.

Further work:
GraVeTAS still has only rudimentary algorithms for finding the location of the particle in the beam. More efficient algorithms are necessary to handle the volume of data that is collected in a reasonable time. Also, the instrument would benefit from cleaner, Gaussian laser profiles to maximize particle detection and minimize reconstruction errors.