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Fast data preprocessing with Graphics Processing Units for inverse problem solving in light-scattering measurements

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ABSTRACT

Utilising Compute Unified Device Architecture (CUDA) platform for Graphics Processing Units (GPUs) enables significant reduction of computation time at a moderate cost, by means of parallel computing. In the paper [Jakubczyk et al., *Opto-Electron. Rev.*, 2016] we reported using GPU for Mie scattering inverse problem solving (up to 800-fold speed-up). Here we report the development of two subroutines utilising GPU at data preprocessing stages for the inversion procedure: (i) A subroutine, based on ray tracing, for finding spherical aberration correction function. (ii) A subroutine performing the conversion of an image to a 1D distribution of light intensity versus azimuth angle (i.e. scattering diagram), fed from a movie-reading CPU subroutine running in parallel. All subroutines are incorporated in PikeReader application, which we make available on GitHub repository. PikeReader returns a sequence of intensity distributions versus a common azimuth angle vector, corresponding to the recorded movie. We obtained an overall ~400-fold speed-up of calculations at data preprocessing stages using CUDA codes running on GPU in comparison to single thread MATLAB-only code running on CPU.

1. Introduction

Interferometric techniques, which are used for optical particle characterisation require solving an inverse problem ([1]). Most methodological efforts are aimed at performing the inversion procedure with high accuracy and in short time (see e.g.: [2–7]). In the work [8] we described a successful implementation of inversion algorithm (Mie Scattering Lookup Table Method) on Graphics Processing Units (GPUs; see e.g. [9,10]), making use of parallel computing (see e.g. [11,12]).

In this work we describe GPU implementation of algorithms for *data preprocessing*, a stage scarcely described in literature. Since the amount of scattering data requiring processing at this stage may easily become huge, it is a common practice to pre-reduce it either by using a linear camera or by selecting a narrow region of interest in the field of view. In case of imperfect imaging, this may slightly compromise the final inversion accuracy. Since our further investigations depend on high particle characterisation accuracy, we try to make the most of the data in the field of view, which results in extensive computations.

We perform data preprocessing in two steps: (i) finding the aberration correction function, common for all recorded images, as well as the droplet position versus the centre of the trap, and (ii) conversion of all images in a movie to a sequence of 1D distributions of light intensity versus a common 700-element azimuth angle vector (i.e. scattering diagrams). The second step includes pixel decoding, demosaicing and aberration correction, as well as pixel sorting versus azimuth angle, walking average of light intensity and reduction to 700 points. Both subroutines use GPU capabilities, while the image-conversion subroutine is fed from a movie-reading subroutine running in parallel on CPU. The overall speed-up of calculations was ~400-fold in comparison to single-thread MATLAB code. The application comprising both subroutines is called PikeReader and can be freely downloaded from GitHub repository [13].

2. Motivation and design of the optical system for observation of Mie scattering images

Our primary research interest focuses on evaporation dynamics of single, free, micrometre-sized droplets. Single droplets ranging from ~25 μm to ~500 nm in radius can be levitated in our electrodynamic trap (see e.g. [14]). In order to infer the details of the thermodynamic process (see e.g. [15–17]) the fine details of the temporal evolution of droplet radius are analysed. As a primary tool for measuring the droplet radius, we use elastic (static) light scattering with Mie Scattering Lookup Table Method [14]. For

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0022-4073/

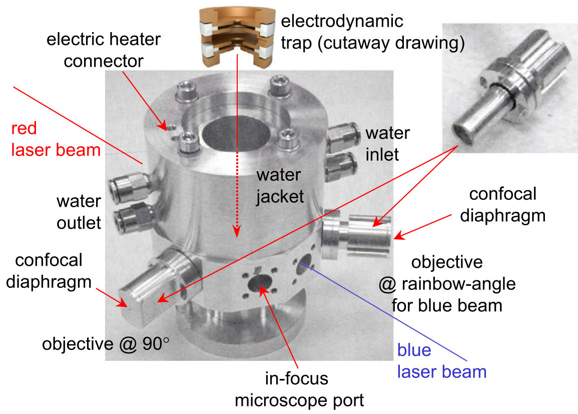

Fig. 1. Middle: partially assembled new version of climatic chamber with main optical system in place. Top: cutaway drawing of the electrodynamic trap. The location of the trap in the chamber indicated with (red) solid-and-dashed arrow. Top-right corner: an assembled optical system for Mie scattering imaging. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

droplets of pure liquids of few micrometres radius we reach an accuracy of ± 10 nm.

The observation of light scattered by a micrometre-sized droplet, confined in a centimetre sized trap (Fig. 1: top), enclosed in a decimetre sized chamber (Fig. 1: middle) requires a dedicated optical system. Since a wide-angle observation is highly preferable in view of the inversion procedure accuracy, a non-paraxial optical system is required (see Fig. 2). Usually, minimising aberrations in such a system requires a complex lens configuration or/and aspheric lenses. Available good quality objectives are comparatively large, which, in turn, scales up the whole setup and the chamber in particular. To avoid this and having in mind temperature and atmosphere composition gradient issues associated with larger vessels, we decided to use two simple lenses (Figs. 1 and 2) and to correct aberrations at the post-processing stage (see next section). The focal point of the entrance lens coincides with the droplet and there is a confocal aperture after the exit lens. The polarisers are half-way between the lenses. Since they contribute to the optical distance between the lenses, it is accounted for in the calculations.

Previously, in 4 side-port trap/chamber system we used symmetrical bi-convex lenses of 18.705 mm curvature radius and 12.6 mm diameter. The distance between apexes of the lenses was 42.57 mm. There was an additional (calibrating) circular aperture between the viewing port of the trap and the lens. The body of the objective was made of plexiglass with 16 mm entrance outer diameter.

The newly developed setup has 8 optical side-ports (see Fig. 1), which constricts the lens system even further. In order to retain a wide field of view, we got rid of the circular entrance aperture and put the entrance lens closer to the droplet (compare Fig. 2). This, however, resulted in larger optical aberrations. To minimise this, plano-convex lenses with apexes pointing inward were used. The distance between apexes was 37.4 mm. The lenses were anti-reflection coated and their curvature radius and diameter were 10.3 mm and 12.4 mm respectively. The body of the objective was made of aluminum, which allowed reduction of the entrance outer diameter to 13 mm.

3. Aberration correction in post-processing

It is well known that the information present in an image suffering aberrations is not lost. It can fully be retrieved in numerical post-processing, as long as the parameters of the lens system are known. In our experiments we record the temporal evolution of scattering patterns with aberration in the form of movies. The aberration correction procedure consists of two main steps: (i) finding the angle and intensity correction with analytical or numerical ray tracing, and (ii) applying the correction to each image in a movie. The intensity distribution generated by the transmitted rays is proportional to the spatial transmittance function of the lens system. Simultaneously, it provides a pixel-to-scattering angle mapping. Then, the raw scattering images must be divided by this distribution and each CCD pixel must be assigned the scattering angle value.

In our previous works, in order to assign the correct scattering angle value (both: azimuth and elevation) to each pixel, analytical ray tracing formulas were used. To simplify the problem, a circular

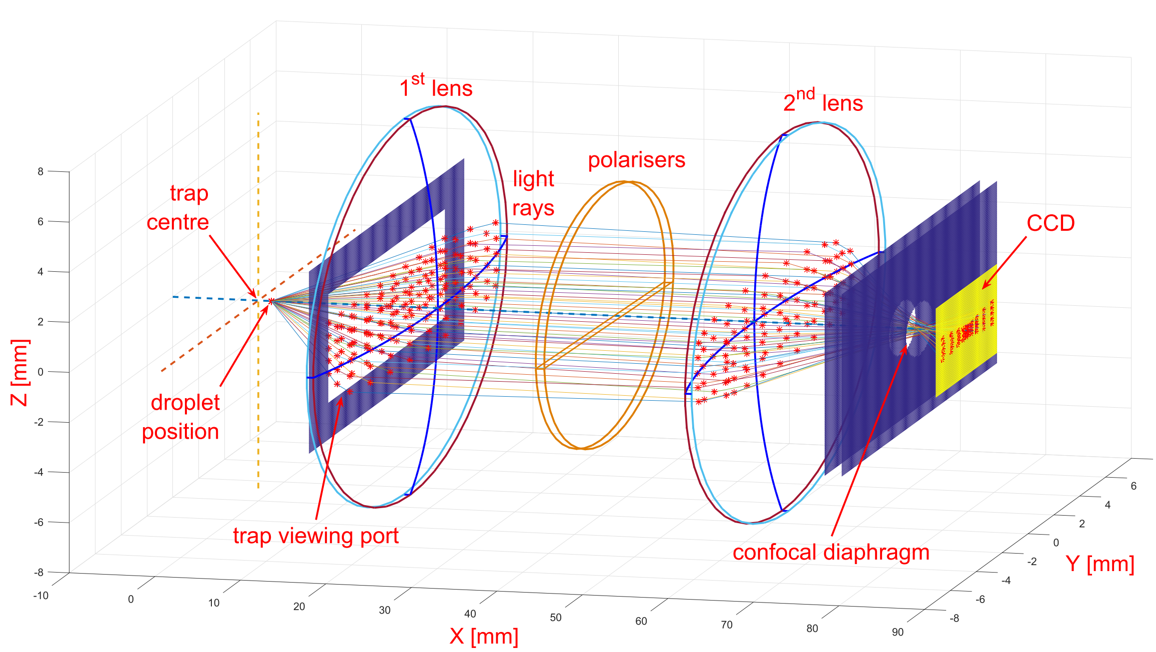

Fig. 2. Non-paraxial ray tracing through the optical elements of the Mie scattering imaging system. The x-axis scale is ~10 times compressed versus y- and z-axis. In consequence, the curvature of the viewing port is not visible. The CCD cover glass is not shown.