

Fast Mie scattering image processing with graphics processing unit.

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Abstract

In order to achieve the ultimate accuracy of an interferometric particle characterisation technique, often huge data sets must be processed. Both, the inverse problem solving stage, and the data preprocessing stage for inversion, happen to be very time-consuming and resource-demanding. 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. We reported using GPU for the inverse problem solving (up to 800-fold speed-up) in our previous paper [Jakubczyk et al., Opto-Electron. Rev., 2016]. Here we report a development of two subroutines utilising GPU at data preprocessing stage: (i) A subroutine, based on ray-tracing, for retrieving information from Mie scattering images obtained with spherically aberrated lens system. (ii) An image processing subroutine, performing: pixel decoding, demosaicing, field-of-view correction, moving average versus observation azimuth angle and data points number rescaling. The image processing GPU subroutine is assisted

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with a data file-reading CPU subroutine running in parallel. All subroutines are incorporated in our PikeReader application, which we make available on GitHub repository. We obtained an overall ~ 400 -fold speed-up of calculations at data preprocessing stage in comparison to Matlab-only code running on CPU (single thread).

Keywords: Mie scattering, Compute Unified Device Architecture, image processing, graphics processing unit, optical aberration

1. Introduction

There are many well established interferometric techniques, which are used for particle characterisation. Global rainbow technique (GRT), laser imaging for droplet sizing (ILIDS), interferometric particle imaging (IPI), Mie scattering imaging (MSI), interferometric Mie imaging (IMI) are a few to mention (see eg. [1] and references therein). We also developed a variant of the method of this class, and used successfully in many experiments with both pure and composite liquids (see e.g. [2, 3, 4, 5, 6]). All these methods require solving an inverse problem in order to retrieve particle characteristics. Since we solve the inverse problem by comparing the experimentally obtained scattered light distributions with the lookup table of Mie-theory-generated patterns, we adopted the name: Mie scattering lookup table method (MSLTM). Under favourable conditions, its accuracy is as high as ± 10 nm (see e.g. [6]).

Nowadays, to achieve the ultimate accuracy of these interferometric measurement techniques, the experimental data must be processed off-line after recording. With the advent of fast, high resolution cameras, the amount of such data then becomes massively huge. In our case, data sets amount up to tens of gigabytes, in

particular for experiments on slowly evaporating droplets, running for tens of minutes. Thus, in case of MSLTM, the data processing is split into two steps, in order to facilitate it: (i) preprocessing of data for the inverse problem solving, which reduces the data set 70-fold and (ii) the inverse problem solving. For both steps of data processing, we had developed a dedicated software in Matlab. When very high accuracy is required, both Matlab applications can be very time-consuming. In order to resolve this issue, moved the essential parts of our codes to Compute Unified Device Architecture (CUDA) platform making use of graphics processing units (GPUs). We began with the code for the inverse problem solving and obtained up to 800-fold speed-up [7]. In this work we present the development of a code for fast image processing with GPU (and in parallel on CPU) at the data preprocessing stage. The whole application is called PikeReader and can be downloaded from GitHub repository [8]. GPU was used at two stages (subroutines): (a) the imaging system analysis, and (b) recorded movie processing. The overall speed-up of calculations at data preprocessing stage was ~ 400 -fold in comparison to single-thread Matlab code. In practice, the data preprocessing time was reduced to that needed for preparation of required parameters (via PikeReader's Graphical User Interface (GUI)) by the experimenter.

2. The levitated droplets - experimental setup and data acquisition procedures

In our laboratory, at the Institute of Physics, Polish Academy of Sciences, we investigate single evaporating (charged) droplets freely levitating in an electrodynamic trap. Electrodynamic levitation is nowadays a well-established technique used for non-contact trapping (and handling) of microscopic and nanoscopic ob-

jects [9]. By means of an appropriately selected configuration of AC and DC electric fields, a particle of specific range of mass to charge ratio can be indefinitely kept in a pseudo-potential minimum of (time-averaged) resultant field. A variant of the trap, realising such field configuration and suiting our demands, was designed and built in our laboratory (see e.g. [4]). A cutaway drawing of the trap is shown in the centre of figure 1.

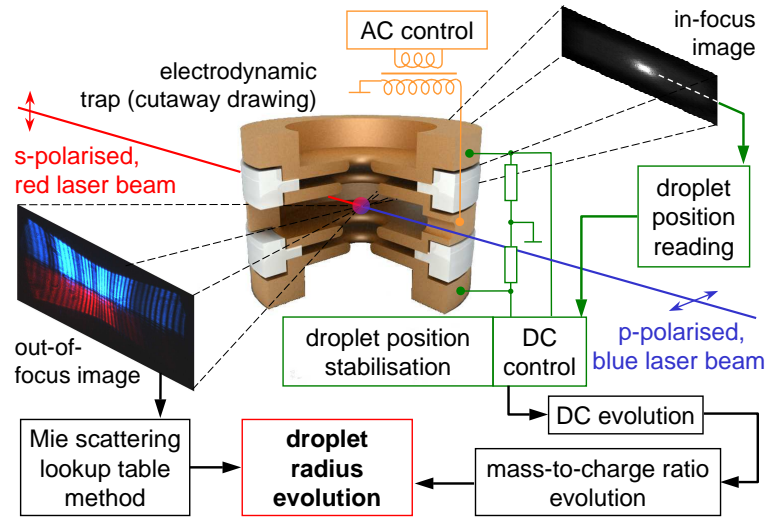


Figure 1: The basic concept of measurement. The droplet is $\sim 100\times$ enlarged for clarity.

The evaporating droplet levitating in the trap is illuminated with two coherent (laser) beams of different wavelength and mutually perpendicular polarisation (p and s in respect to the scattering plane), and a sequence of Mie scattering patterns (out-of-focus image in figure 1) is recorded as a movie. In order to avoid photophoretic instability we use laser beams with relatively low power density ~ 10 mW/mm². The analysis of the movie off-line enables us to find the temporal evolution of the droplet radius and thus to infer about the droplet evaporation process. As can be seen in figure 1, we can also use electrostatic weighting as an auxiliary

tool for the droplet radius assessment [5].

3. The motivation and design of the optical system for observation of Mie scattering images

In the process of our works (see e.g.: [4, 5]), we encountered a problem of observation of light scattered by a micrometre sized droplet (see Mie scattering out-of-focus image in figure 1), confined in a centimetre sized trap (figure 2: top), enclosed in a decimetre sized chamber (figure 2: middle). Since a wide-angle observation is highly preferable in view of the inversion procedure accuracy considerations, a non-paraxial optical system is required (see figure 3). The solutions used for the purpose of visualisation usually involve large, complex lens system or/and aspheric lenses. Large lenses, in turn, scale up the whole setup and the chamber in particular. We wanted to avoid that, having in mind various temperature and ambient atmosphere composition issues associated with larger vessels, caused, for instance by convection. Thus we decided to use simple plano-convex lenses with anti-reflection coatings (figures 2 and 3). In that case, non-paraxiality inevitably leads to spherical aberration, while chromatic aberration is intrinsic to simple spherical lenses (out-of-focus image in figure 1).

3.1. Intensity-corrected ray tracing

It should be noted here that, the information present in a recorded scattering pattern is not lost as a result of aberrations and can be fully retrieved in post data processing. However this requires the knowledge of the parameters of the lens system. Since we worked off-line, we could and were using such procedure very successfully for some time (see e.g.: [3, 4, 6, 10] and references therein). The procedure used analytical ray tracing formulas for circular entrance aperture

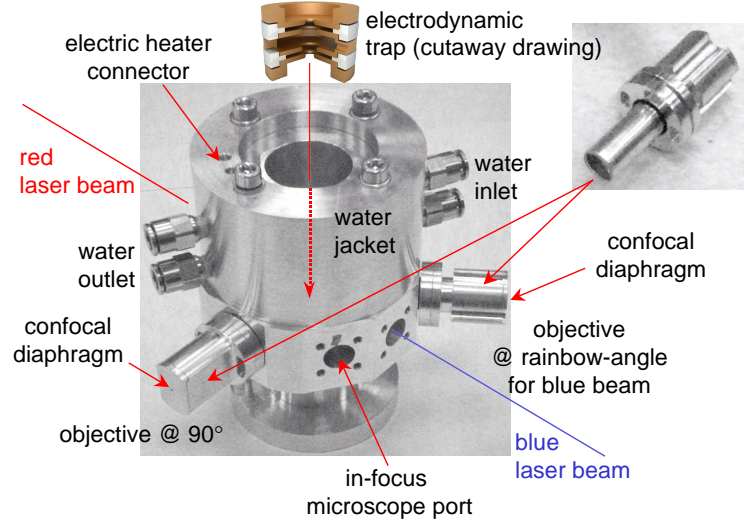


Figure 2: Middle: partially assembled climatic chamber with main optical system in place. Top: cutaway drawing of the electrodynamic trap. The location of the trap in the chamber indicated with (red) solid-and-dashed arrow. Top-right corner: an assembled optical system for Mie scattering imaging.

(introduced between the trap port and the first lens), under assumption of axial symmetry of the droplet-lens system (which was fulfilled in our experiments). It required only simple planar trigonometry. The distribution (decrease) of transmitted light intensity was accounted for at the detector with the cosine law of illumination and the inverse square law, by introducing the factor of $(\cos \theta)/r^2$, where θ is the incidence angle and r is the length of the ray. The droplet eventual displacement was accounted once for the whole movie during further data processing.

In our newly developed setup, we wanted to have 8 instead of 4 horizontal ports (see figure 2), which constricted the lens system even further. In order to keep a wide field of view, we resigned from the circular entrance aperture and

put the entrance lens closer to the droplet (compare figure 3). This resulted in larger aberration. We also wanted to overcome the axial symmetry assumption because of the mechanical limitations of trap/chamber construction. Thus, finding the distortion of the field of view (figure 5, bottom-left) required an exact ray tracing in 3D (figure 3).

Since we still deal with a specific but rather simple problem, we developed a dedicated, intensity-corrected ray tracing subroutine, that suits our purposes. It is coded in a straightforward manner. Here we outline its basic steps. We consider the droplet as a point light source, which is placed at the origin of a coordinate system. Since we want to trace only those rays that pass the viewing port of our trap, we consider lines (rays) connecting the origin and a point within the viewing port. Rays falling outside of the (lenses) apertures are eliminated. For each refracting surface we find the point of intersection of the ray with the lens surface by solving a line/refracting surface (sphere or plane) set of equations. Then we find the vector normal to the refracting surface at this point and calculate the angle between the incident ray and the normal vector. Using the Snell's law in the scalar form we calculate the angle between the normal vector and the transmitted ray. In order to keep the incident and the transmitted rays in the same plane we introduce the cross product of the incident ray and the surface normal at the point of intersection. The refracted ray is also perpendicular to that cross product, which enables solving the set of equations for the refracted ray. The distribution (decrease) of transmitted light intensity is accounted for each ray at each refraction with the $(\cos\theta)/r^2$ factor again, without considering polarisation effects. Since the lenses were anti-reflection coated ($\sim 1\%$ reflection), this simple method was found quite sufficient. The steps are repeated for each refracting surface. The presence of po-

larisers between the lenses is accounted for by modifying the optical path length.

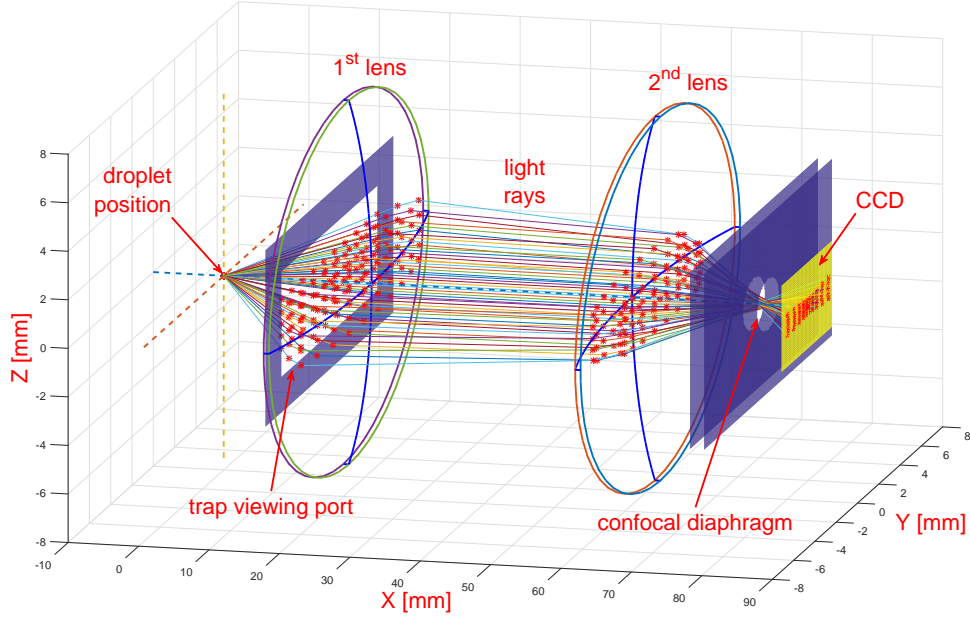


Figure 3: The concept of ray-tracing through the relevant elements of the Mie scattering imaging system.

The subroutine yielded very promising results, it was flexible in sense of the described lens system and it allowed determining the droplet position at the first stage of data processing. Unfortunately, when coded in MATLAB, it turned out to be very time consuming (~ 2 hours for 9×10^6 rays). However, it can be easily noticed that ray tracing is ideal for parallel computing, as different calculation threads do not interact. Having already had some very promising experience in this application [7], we decided to make use of GPU (as a powerful and a relatively cheap solution) and rewrote our subroutine accordingly on CUDA platform. The code was also generally optimised in the process. The project turned out very

successful, as it made the calculation of the distortion of the field of view (nearly instantaneous (< 0.3 s for 9×10^6 rays @ GTX 580 and < 0.8 s for 625×10^6 rays @ GTX Titan Black. We hope, that this will make possible accounting for (eventual) droplet movements for each movie frame. However, the so far manual parameter-preparation stage will have to be automated.

3.2. Ray-tracing CUDA algorithm

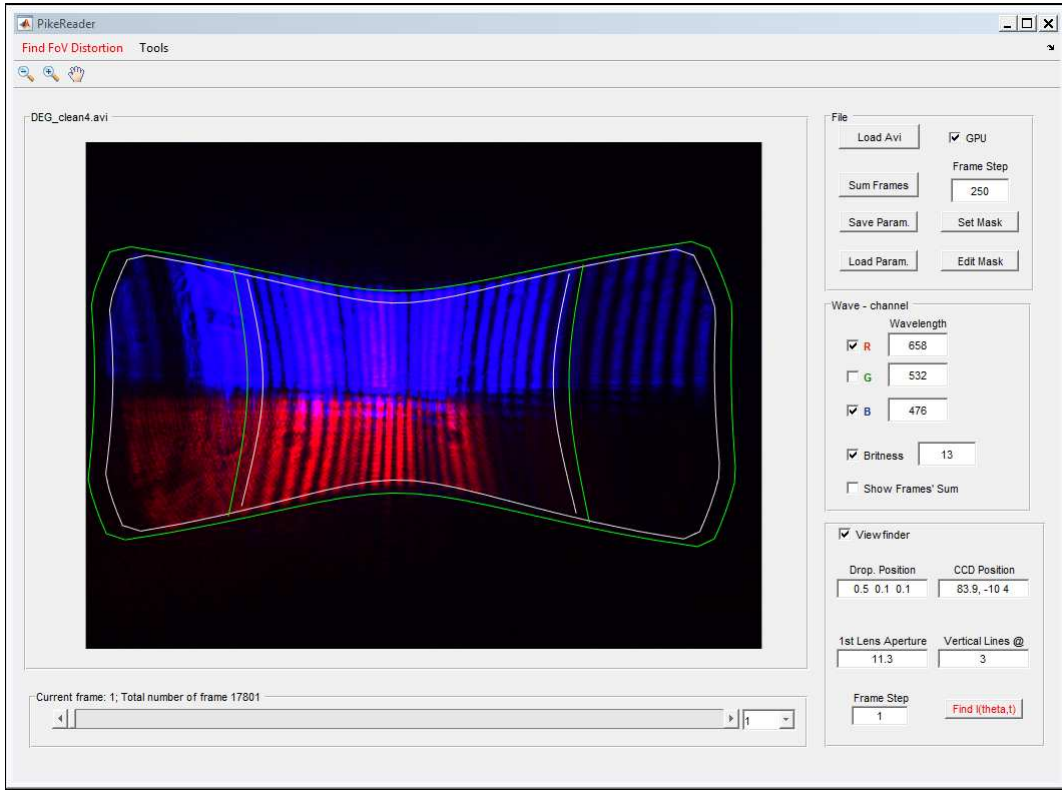


Figure 4: The Graphics User Interface of PikeReader application. $I(\theta, t)$ and Find FoV distortion marked with red lettering.

We implemented the ray-tracing algorithm as a MEX subroutine, called RayTracingCUDA

(see RayTracingCUDA subroutine in figure 5). MEX subroutine is generally versatile and easy for using with our data processing software written in MATLAB (figure 5). In PikeReader application it is invoked with Find FoV distortion menu button. However, we would like to underline, that the subroutine is self-standing. Ray-tracing is an indispensable tool for designing optical systems and for computer generated graphics. The structure of the subroutine is as follows:

- Ray-tracing data is loaded from MATLAB memory into GPU memory.
- The ray-tracing subroutine, also called - the ray tracing kernel, is executed on GPU in massively multiple threads (512 for GTX 580). When one set of threads is executed, the next set is preloaded. Each thread has a pointer to the data and a number, unique in a single kernel call, so each thread can access different part of the data and each piece of the data has its own thread doing ray tracing. For best performance, and in order to avoid collisions, different threads shouldn't write to the same memory address.
- In order to find the values of cells of the intensity-distortion array (the distortion of a flat light intensity field in FoV), adding values from different threads is necessary. The result of unsynchronised additions from simultaneous threads into a variable at a single address may be indeterministic. To avoid indeterministic results, the so called, atomic addition is used. The atomic function is a special subroutine which guarantees indivisible access to a variable at a specific address. It requires Compute Capability 2.0 or higher. In our case, due to the nature of the problem, the synchronisation operation isn't very costly, since only few threads need to access the same cell of the image array.

- Finally, the results are copied back from GPU memory into MATLAB memory.

4. Movie processing

`I(Theta, t)` button in the PikeReader GUI (ToolTip: Find scattered light azimuthal distribution for given frames) invokes the `IntensCalc` subroutine, which is the main part of PikeReader application. For each movie frame, it returns scattered light intensity (for both polarisations), averaged over elevation angles, versus a given vector of azimuthal angles of the field of view. The results for the whole movie are stored in I_{pp} and I_{ss} arrays for p and s polarisations respectively. All compute-intensive calculations were written in CUDA C/C++ for calculation speed improvement. C++ code was compiled to Matlab mex-file (`IntensCalc.mexw64`), to interface with the rest of PikeReader Matlab application. `IntensCalc` rewritten in CUDA C++ is much faster and reduces computation times from hours to seconds. We estimated the speed-up to be ~ 400 -fold.

The `IntensCalc` subroutine structure is outlined in figure 5. The subroutine requires some pre-prepared data from PikeReader:

- movie file name, selected colour channels and other minor items passed from PikeReader GUI, all included in `handles` variable, which contains most of PikeReader environment
- number of movie frames (`NumFrames`)
- masks (corresponding to colour channels) selecting regions of interest (`ipR`, `ipG`, `ipB`)

- field-of-view distortion arrays (both angular and intensity), pre-calculated with RayTracingCUDA (Find FoV Distortion menu). Intensity arrays for each colour must be normalised and have corresponding mask applied (ICR_N, ICG_N, ICB_N).
- vectors of indices of selected pixels, sorted versus azimuth angle. The azimuth angles are assigned to pixels by RayTracingCUDA subroutine (I_S_R, I_S_G, I_S_B).

A very low execution time of IntensCalc was archived by identifying two major bottlenecks. Reading movie from a hard drive turned out to be the first major bottleneck. Storage device access times can not be directly surpassed programmatically, so it is optimal to read from the hard drive continuously. Accordingly, we decided to create a separate, hard drive-reading-only, thread, running in parallel on CPU. Secondly, we observed that, rather obviously, processing every pixel of every frame on CPU is very time consuming. We decided that these calculations should be performed in parallel on CUDA capable GPU: frame by frame, one frame at a time.

4.1. Movie-reading thread

The thread reading a movie from the hard drive was made fast and simple. It just reads a movie in optimal 64 kB blocks and copies it to 640 kB buffer which is slightly bigger than one frame (614400 B). 640 kB buffers are organised by a cyclic buffer of pointers. The cyclic buffer is encapsulated in a class usually referred to as a monitor, which allows easy and safe thread synchronisation. Cyclic buffer solves the problem of Random Access Memory (RAM) being usually smaller than a movie recorded in experiment (tens of GB). The reading

thread writes to the cyclic buffer, while the frame-processing thread (described in the next section) reads data from cyclic buffer, performs extensive computations and discards used data from cyclic buffer. In order to guarantee smooth data flow, each 640 kB buffer in the cyclic buffer has 4 states: *ready empty*, *ready full*, *used for writing*, *used for reading*, and the cyclic buffer has four corresponding methods: `claimForWrite`, `writeEnd`, `claimForRead`, `readEnd`. Additionally, a larger size of the cyclic buffer helps with balancing uneven reading and calculation paces, originating from operations overheads or using resources by other processes.

4.2. *Frame-control thread*

The movies are encoded in avi ARW6 (16-bit, raw) format. To our best knowledge, the Decoder for this dedicated format has not been published, so the movie format had to be analysed with a HEX editor. It was found, that due to Pike camera hardware and driver peculiarities, the positions of frames in avi container are a function of such camera parameters as shutter and exposition times. In consequence the frame data position versus the frame header can vary even within the movie. We found, that there may exist additional garbage data between a frame header and the actual frame data as well as between actual data and the JUNK section, and before the next frame header. In order to find frame data, the frame header (00db614400) must be found first. Then, after jumping by the frame size, the header of the next frame can be searched. However, the JUNK section also has to be spotted. The frame data may be found adjacent to the left of the JUNK section (if it is present) or else adjacent to the left of the next frames header.

4.3. Frame processing with GPU

The Frame-control thread retrieves frames from 640 kB buffers from the cyclic buffer, following the above procedure. It is highly probable that at least one full frame will be found in two consecutive 640 kB buffers. When a frame is successfully retrieved from the cyclic buffer, it is copied to GPU global memory, and a sequence of CUDA image-processing kernels (GPU subroutines which execute the same algorithm for every given set of data in parallel) is called.

Pixel-value kernel. First, each pixel value is calculated. The 14-bit pixel value, yielded by analog-digital converter of the camera, is stored in 2 bytes: the first is the older 8-bit part, while the second byte contains 6 younger bits in reversed order. In order to calculate the pixel value, the first byte must be right-shifted by 2 and the second byte must be 6-bit reversed (using a look-up table was found the fastest method) and added to the first one.

Demosaic kernel. Each (raw) frame is decomposed (with a demosaic kernel) into three (RGB) colours (arrays). Later operations are performed on the selected colour channels in sequence.

Distortion-correction kernel. Each selected colour channel (array) is divided by the intensity-distortion array with the corresponding mask applied. In this way, the amount of data is reduced by removing the irrelevant pixels and each frame intensity distribution is corrected.

Moving-average kernel. Next, all pixels (indices) in each colour channel are sorted versus the azimuth angle and the resulting angular intensity distributions (vectors) are smoothed with the moving average algorithm. Atomic addition doesn't really

block threads, so this step of the moving average algorithm is quite fast. However, in order to save computation time and resources, the division operations should be limited and an additional helper kernel is called just for performing divisions.

Rescaling kernel. The last kernel rescales the angular intensity distribution vectors (for each colour channel) down to a fixed length of 700. Finally, these vectors are copied from GPU memory to the corresponding addresses in Matlab memory.

5. Conclusions

Parallelization of data processing associated with particle characterisation with interferometric techniques seems very promising. In particular, harnessing of graphics processing unit (GPU), via Compute Unified Device Architecture (CUDA) platform, has enabled a very significant reduction of computation time at a moderate cost. We rewrote our Mie scattering lookup table method (MSLTM) codes from Matlab to CUDA C/C++, first for inverse problem solving [7] and now for two stages of data preprocessing for inversion code. At the second stage, we also implemented parallel data reading from hard disk. For the inverse problem solving we had obtained up to 800-fold speed-up in comparison to single-thread Matlab code, while for the data preprocessing, we obtained an overall speed-up of ~ 400 -fold. In all cases, the time used for calculations was reduced from hours to seconds. In many cases the operations have become instantaneous from the experimenter's point of view. The data preprocessing time has been practically reduced to time needed for preparation of required parameters by the experimenter. We expect that some of the parameters preparation steps can be further automated. In general, short data processing time should open way to precise on-line particle characterisation.

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