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Time Domain Metrology with Optical Tweezers

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ABSTRACT

We describe a technique for the rapid determination of the mass of particles confined in a free-space optical dipole force trap without the need for a vacuum environment (Carlse et al., Phys. Rev. Appl. 14, 024017 (2020)). The trapping light is amplitude modulated causing the particle to be released and subsequently recaptured by the optical dipole force. The drop and restore trajectories are directly imaged using a high-speed CMOS sensor to determine the particle mass. These measurements are corroborated using the position autocorrelation function and the mean-square displacement. We also examine the prospect of extending these techniques to particles trapped in liquids.

Keywords: Optical Tweezers, Optical Dipole Force, Time Domain Video Microscopy, Mass and Damping Rate Measurements, Fluid Viscosity, Brownian Motion, Force Sensing, Metrology

1. INTRODUCTION

The optical dipole force (ODF) is a particular manifestation of the radiation pressure force exerted by light on matter. The strength of the ODF depends on the gradient of the light intensity and the index of refraction of particles scattering light. ODF traps[1-5], also known as optical tweezers, produce three-dimensional confinement of dielectric particles. The simplest experimental configuration is a single beam gradient ODF trap in which particles are trapped at the focus of a laser beam. Notable applications of the ODF include the development of far-off resonance traps (FORTs) for confining atoms[6,7], the generation of three-dimensional optical crystals using sub micrometer-sized particles[8,9], and the manipulation of biological specimens[10,11] for measurements of bond strengths[12], and protein synthesis[13,14]. Pioneering experiments in references[15-17] have also investigated the kinematics of single particles trapped in liquids or free space on timescales at which diffusive motion, first observed by the botanist Robert Brown[18] and later analytically described by Albert Einstein[19], transitions to ballistic motion.

Tweezers experiments have realized sensitive *frequency domain* measurements of physical properties such as particle mass by driving trapped particles with electrical, optical or radio frequency fields and measuring the power spectral density[20,21]. They have relied on high bandwidth *indirect imaging* methods for analyzing particle kinematics on fast time scales[22]. Such techniques employ photodiodes and fiber bundles to image the scattered light in at least two directions and generate a position sensitive differential signal. Despite impressive bandwidths (~50 MHz), their disadvantages include relatively high threshold light intensities for detection with photodiodes and the complexities of calibrating voltage readouts[23,24] that require rastering target objects and mapping of spatial intensity variations[25,26].

In contrast, this paper describes a recently demonstrated *time domain technique*[27] in which kinematics of trapped particles are directly imaged using video microscopy with a new generation of CMOS sensors. This direct-imaging technique allows for the determination of particle masses with a precision of 2% in a data collection time of only 90 s. This method also offers several advantages such as ease of visualization of targets, straightforward extraction of position, size, and shape, simplicity of spatial calibration, and the capacity to track particles scattering low levels of light. As a result, it is feasible to realize a simple benchtop tweezers setup for trapping particles in free space and liquid cultures without the need for multiple lasers, vacuum systems, and feedback loops.

2. METHODOLOGY AND RESULTS

Our experiments rely on a low-cost, high-power laser system realized by seeding a semiconductor waveguide amplifier[28]

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with light from an auto-locking external cavity diode laser[29]. This vacuum sealable system offers several advantages compared to commercially available alternatives such as portability, robustness under harsh field conditions, exceptional frequency stability (Allan Deviation (AD) floor of 2 x 10^{-12} after 300 s of averaging), desired power stability (AD floor of 2 x 10^{-6} after 10 s), rapid, high contrast amplitude modulation of ODF traps, and operation at interchangeable infrared wavelengths (e.g. 830 nm) at which damage to biological specimens can be avoided[30].

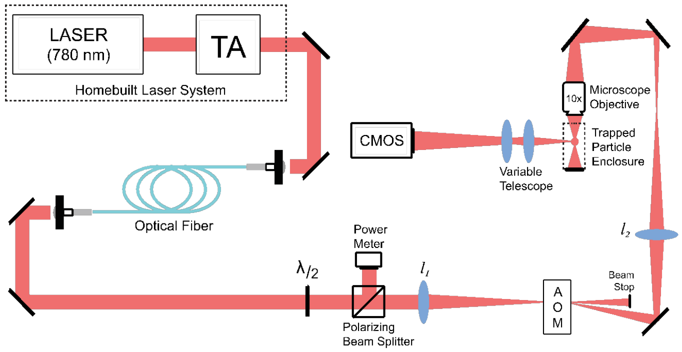

Figure 1: Benchtop Experimental Setup. Focusing lenses are indicated by l_1 and l_2 respectively.

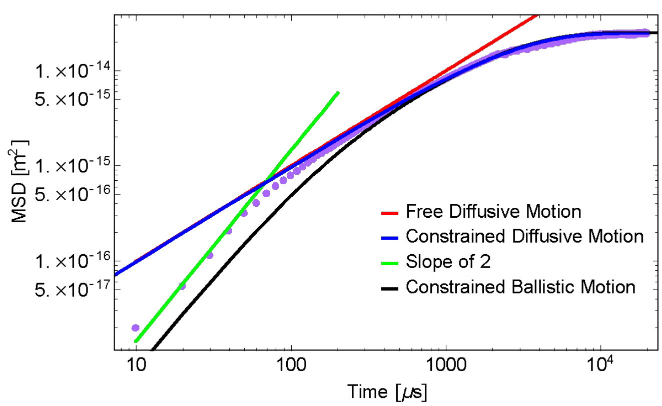

Figure 2: MSD of trapped particle (purple points) with images acquired at 10^5 fps over millisecond time scales. Green line (slope 2) indicates ballistic motion and red line (slope 1) represents diffusive Brownian motion.

The compact experimental setup is shown in Figure 1. Resins ablated from the tip of a permanent marker introduced at the focus of a laser beam are trapped by the ODF. The trapping zone is shielded from convection currents. This simple optical free space configuration can be readily modified for trapping dielectric bioparticle samples in liquids placed at the focal region of the laser beam. Figure 2 shows the mean square displacement (MSD) as function of time for a particle trajectory imaged by the CMOS sensor operating at 10^5 frames per second (fps). Here, the red line (slope of 1) represents Einstein's prediction[19] for free diffusive motion. Since the particle's random walk is confined in an overdamped harmonic potential, the MSD (purple data points) is strongly altered at long times and flattens out at the level characterized by the strength of the confinement. The blue curve models a simplified MSD in the highly overdamped approximation. At short time scales, (defined by the momentum relaxation time τ_p ~70 μs for this system), on which collisions cannot damp out the motion, the MSD deviates from the (blue curve) and transitions to the ballistic regime characterized by the green line in Figure 2 (slope of 2). This result demonstrates the use of our direct imaging technique to observe the transition from the ballistic to the diffusive regime. It is only possible to observe this transition only because of the light sensitivity of this direct imaging system and because its temporal resolution (1/frame rate) is smaller than τ_p. Preliminary estimates of the trapped particle mass can be extracted directly from the MSD. The time scale at which the change in slope occurs (~70 μs) and the measured particle size can be combined to estimate the particle mass as m = 5.7 x 10^{-14} kg[27,31]. It has also been shown that

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on these short time scales where the kinematics are relatively unaffected by both the confining potential and the surrounding fluid, the MSD can be used to infer the total kinetic energy of a trapped particle[21,31]. When combined with the equipartition theorem this provides another estimate of the mass (m = 3.5 x 10^{-14} kg[31]) which serves as a check of consistency.

We have corroborated these simple and elegant mass determinations with much higher precision by amplitude modulating the trapping light with excellent temporal control, using an acousto-optic modulator (AOM). This approach allows a trapped particle to be released and subsequently recaptured by the trapping force at varying time intervals. By imaging these different trajectories with adequate time resolution with the CMOS sensor (Figures 3 and 4) we can measure physical and surface properties of trapped particles such as mass, damping rate, and damping coefficient. When the laser confinement is turned off, the falling particle rapidly attains a terminal velocity, and its free-fall displacement as a function of time (see Figure 3) can be used to determine the in-situ damping rate Γ of the system (particle and fluid). When the confining laser force is subsequently turned on, the particle is restored to the trap center. By repeatedly averaging these trajectories at high repetition rates, we average out the stochastic motion and achieve particle tracking with excellent signal to noise ratio. If the fit to this restoration displacement-time graph (see Figure 4) is constrained by the value of Γ from the drop experiment and by accurate measurements of the spring constant of the trap (that relies on the power stability of the auto-locking laser system), it is moreover possible to infer the particle mass. In this manner, we have demonstrated the ability to infer masses of micrometer-sized resinous particles (m = 5.58 x 10^{-14} kg) with a statistical precision of 1.4% in a data acquisition time of only 90 seconds based on 13 restoration trajectories, each averaged over 100 repetitions[27]. Our results suggest that the sensitivity (~8 x 10^{-16} kg) can be significantly improved by (i) optimizing the data transfer rate and the repetition rate to enhance statistics, (ii) increasing the frame rate of the CMOS sensors (newer models can operate at up to 10^6 frames per second resulting in sufficient resolution to observe the predicted behaviour for constrained ballistic motion (black line in Figure 2)), and (iii) realizing a larger drop height-currently only ~10 μm due to the closely spaced turning points of the tightly confining optical potential, so that the field of view of the CMOS detector can be fully exploited.

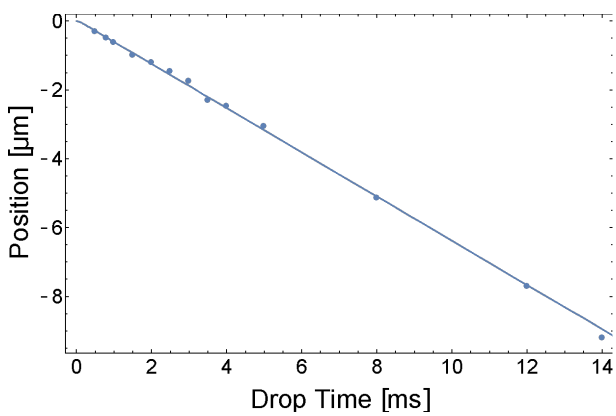

Figure 3: Displacement-time graph of particle free-fall or "drops". Data represents the average of 100 repetitions, while solid line shows a fit to the over-damped trajectory model.

Our mass determinations can be further corroborated within experimental error by measurements of damping coefficient $\gamma = m\,\Gamma$ using position autocorrelation functions (PACF) of trapped particles[27,31]. Like the MSD in Figure 2, the PACFs shown in Figure 5 are also constructed from particle kinematics imaged at rapid frame rates without laser amplitude modulation. The time constant of the PACF, known as the correlation time $\tau_0 = \gamma/\kappa$, represents the time scale on which the confining force interrupts the particle motion. As shown in Figure 6, τ_0 exhibits the predicted inverse dependence on the spring constant of the ODF trap κ, which can be controlled by the laser intensity. The value of γ from the fit can be combined with the damping rate Γ measured in the drop experiments to infer $m = 5.55\times10^{-14}$ kg with a statistical precision of 2.9% in a data acquisition time of 2 minutes. The overall accuracy of these measurement techniques is also satisfactory since the particle density inferred from the mass and volume is consistent with independent measurements[32]. Table 1 shows contemporary mass measurements based on optical tweezers[27,31] and suggests that our drop and restore time domain technique offers a competitive alternative.

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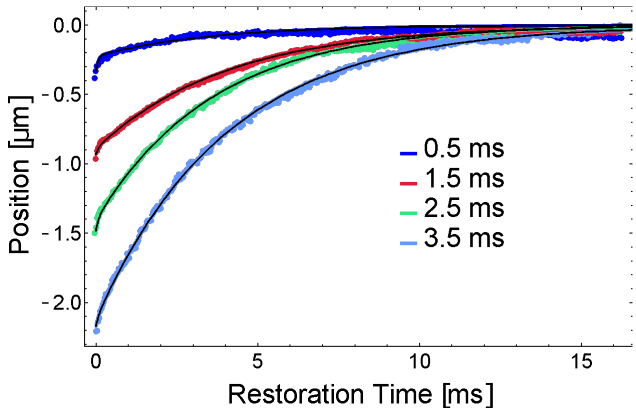

Figure 4: Trajectories of particle restorations. Each coloured data set represents the average of 100 repetitions, and the solid black lines show fits to the over-damped trajectory model; legend indicates drop times.

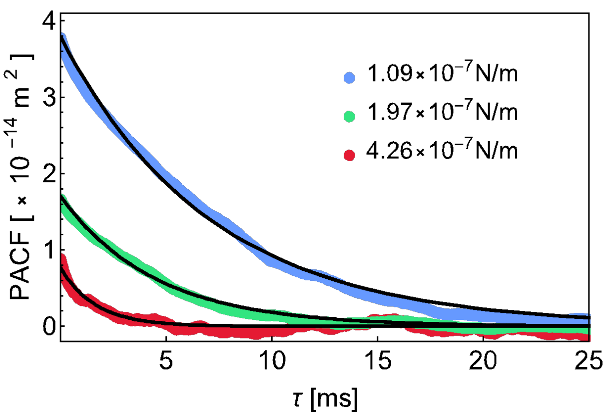

Figure 5: PACFs of particle motion at various laser powers with exponential fits based on the highly overdamped approximation.

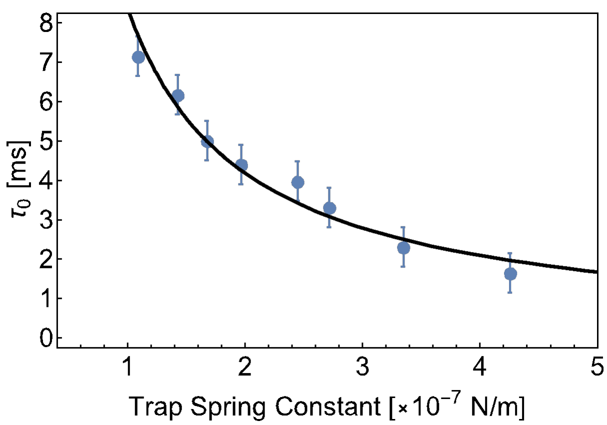

Figure 6: Time constants obtained from PACFs for a range of trap spring constants. The solid black line shows a fit to the expected $1/\kappa$ dependence.

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Table 1. Summary of contemporary tweezer-based mass measurements. The last column (divided in two) indicates the statistical (Stat.) and Systematic (syst.) uncertainties of the various measurements where given. NA indicates when a value is not reported. Experimental conditions are indicated with asterisks: *Solution-based experiment. **Photophoretic trapping experiment. ***Experiments in low-pressure vacuum environments.

Reference	Year	Technique	Mass (kg)	Uncertainty	
				Stat.	Syst.
Huang et al.* [15]	2011	Continuous VACF analysis	1.26×10^{-14}	<10%	<10%
Bera et al.** [33]	2016	Power spectrum analysis	9.68×10^{-11}	15%	NA
Lin et al.** [34]	2017	Optically forced modulation	9.00×10^{-13}	2%	6%
Chen et al.** [35]	2018	Dynamic power modulation	6.3×10^{-15}	NA	NA
Blakemore et al. [36]	2019	Electrostatic co-levitation	8.40×10^{-15}	1%	1.8%
Ricci et al.*** [20]	2019	Electrostatically driven resonance	5.58×10^{-14}	0.25%	0.5%
Hillberry et al. [21]	2020	Power spectrum calibration	2.48×10^{-14}	0.9%	3%
Carlse et al. [27]	2020	Drop-and-restore	5.58×10^{-14}	1.4%	13%

3. CONCLUSIONS

The work presented in this paper outlines simple and effective alternatives, compared to more elaborate conventional methods, for both visualizing trapped particles and measuring their masses and damping coefficients. Firstly, we have demonstrated the potential of direct imaging for observing short timescale Brownian motion in a simple apparatus and inferring masses of particles by detecting the transition to the ballistic regime. Secondly, we have presented a simple and effective technique based on drop-and-restore experiments in a gravitational field to determine the masses and damping rates of particles confined using free space optical tweezers. The mass determination, which has a statistical uncertainty of < 2%, has been corroborated by position autocorrelation measurements, and is also in agreement with preliminary mass estimates based on ballistic Brownian motion. Extensions of these techniques to liquid cultures suggest the possibilities of measuring fluid viscosity and the effects of laser heating of fluids.

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