Colloids and Surfaces A: Physicochem. Eng. Aspects 384 (2011) 282–288

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Comparison of interparticle force measurement techniques using optical trapping

Timothy P. Koehler, Christopher M. Brotherton, Anne M. Grillet*

Engineering Sciences Division, Sandia National Laboratories, P.O. Box 5800, MS 0834, Albuquerque, NM 87185-0834 United States

ARTICLE INFO

Article history:
Received 23 December 2010
Received in revised form 31 March 2011
Accepted 5 April 2011
Available online 12 April 2011

Keywords:
Optical trapping
Colloidal interactions
Electrostatic interactions
Blinking laser tweezers
Direct force measurement

ABSTRACT

Optical trapping has become a powerful and common tool for sensitive determination of electrostatic interactions between colloidal particles. Two optical trapping based techniques, blinking laser tweezers and direct force measurements, have become increasingly prevalent in investigations of interparticle potentials. The blinking laser tweezers method repeatedly catches and releases a pair of particles to gather physical statistics of particle trajectories. Statistical analysis is used to determine drift velocities, diffusion coefficients, and ultimately colloidal forces as a function of the center–center separation of the particles. Direct force measurements monitor the position of a particle relative to the center of an optical trap as the separation distance between two continuously trapped particles is gradually decreased. As the particles near each other, the displacement from the trap center for each particle increases proportional to the interparticle force. Although these techniques are commonly employed in the investigation of interactions of colloidal particles, there exists no direct comparison of these experimental methods in the literature. In this study, we compare measurements of interparticle forces applying both methods to a model system of polystyrene particles in an aerosol-OT (AOT) hexadecane solution where the screening lengths are very large. We found that the interaction forces measured using the two techniques compare quantitatively with each other and Derjaguin–Landau–Verwey–Overbeek (DLVO) theory. Additionally, our studies show that direct force measurements can be far more sensitive than previous studies have reported and nearly as sensitive as the blinking method.

1. Introduction

Since the discovery of optical trapping by Ashkin in 1970 [1], there have been numerous applications in the areas of soft matter, physics and biology [2]. Optical tweezers have become particularly useful in the study of colloidal systems where optical trapping enables the experimental investigation of the microrheology of suspensions [3–5], microstructural mechanics of colloidal aggregates [6,7] and interactions of colloidal particles [8–25]. A variety of optical trapping techniques have been utilized to measure particle interactions in an effort to better understand electrostatic forces between particles and the effects of polymer brushes and steric repulsions [22,23]. Additionally, models for colloidal interactions such as Derjaguin–Landau–Verwey–Overbeek (DLVO) [26,27] theory are commonly validated using various optical trapping implementations. However, there has never been a quantitative comparison between various implementations of optical trapping interaction methods.

Three optical trapping techniques are commonly employed to probe interactions between colloidal particles; direct force measurements [9–15], blinking laser tweezers [16–20], and scanning line optical tweezers [21–25]. Direct force measurements make use of linear correlation between the displacement of a particle held in an optical trap to the force exerted on that particle for small displacements. The proportionality constant, or optical trap stiffness, can be calibrated by either using a known viscous drag on the particle or measuring the diffusion of a particle held in the trap [28]. Typically, the particle position inside of the trap is determined using either a video camera or a quadrant photodiode, both of which offer similar position resolution, though the quadrant photodiode can operate at much faster speeds enabling feedback control for a "constant force" optical trap [28]. An advantage of the direct force measurement technique is the capability to measure attractive interactions [11]. The sensitivity of the resulting forces has generally been reported to be on the order of 0.1 pN and the direct force method is typically applied to measure forces of several pico-Newtons (pN) [11,14].

The second optical trapping method commonly used to measure particle interactions is blinking laser tweezers [16,19]. This technique uses a pair of particles held in separate optical traps which are repeatedly turned on and off. The two particles are free to diffuse when the optical traps are blinked off and by statistical analysis of their trajectories during this time, the force between the particles can be inferred. The optical traps in this method sim-

* Corresponding author. Tel.: +1 505 844 7453; fax: +1 505 844 6620.
E-mail address: amgrill@sandia.gov (A.M. Grillet).

0927-7757/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.colsurfa.2011.04.004

ply serve to position the particles in the field of view, away from walls and at close (potentially energetically unfavorable) separations. Crocker and Grier analyzed these data using Markovian Dynamics Extrapolation which identifies the equilibrium pair distribution from the experimentally sampled probability evolution operator [16]. More recently, Sainis et al. have proposed an alternative method which explicitly accounts for hydrodynamic coupling while calculating the forces between the particles [19,20]. Depending on the experimental operating parameters, particle interactions can be measured with a resolution of several femto-Newtons (fN). The blinking laser tweezers method is attractive to use because the force measurements occur only when the laser is inactive, thus there is no concern about optical effects. However, close range attractive interactions are difficult to measure because particles can stick together irreversibly. Disadvantages of the blinking method also include interactions between the particles and nearby surfaces, diffusion out of the focal plane, and gradients in diffusivity; all of which could cause inaccuracy in the data.

Scanning line optical tweezers is the third laser trapping based technique used to measure interaction potentials. Although it has not been as widely implemented we include it here for completeness [21,25]. For this method, the optical trap is scanned rapidly in a line at a rate faster than the diffusion time scale such that the particles will behave as if they are in a continuous line trap [29]. By modulating the speed of the laser, the center of the trap is made more energetically favorable so that the particles experience a parabolic energy well which pushes them together. The equilibrium distribution of particle separations is measured and the Helmholtz free energy of the system is calculated [22]. In this technique, the potential field introduced by the optical line trap is crucial to the interaction measurements [24].

These three methods of measuring particle interactions have been applied by various research groups on various particle systems, however, there has been no direct quantitative comparison of the different techniques. The results from these methods have all generally compared well with existing theoretical models for colloidal interactions such as DLVO theory [26,27]. In this study, particle interactions in a model experimental system of polystyrene particles suspended in hexadecane containing aerosol-OT (AOT) surfactant were measured using two of these techniques: direct force measurement and blinking laser tweezers. This model system was chosen for several reasons. First, the inherently long screening lengths allow measurements of electrostatic interactions where the particles are far apart so that errors due to overlapping particle images are not a concern [30]. Second, the high refractive index mismatch between the solvent and particles allows robust optical trapping to occur far from nearby surfaces effectively mitigating the associated hydrodynamic effects. Finally, there is published data with which to compare our results [19,20]. Also, we show that with proper implementation, the precision of direct force measurements can be significantly increased over previously published results to almost match the precision of blinking methods.

2. Materials and methods

Optical trapping was used in these experiments to manipulate microparticles in solution and was accomplished using the apparatus detailed in Fig. 1. A 1064 nm beam (A) emitted from a Ventus Doubled YAG laser is attenuated by a neutral density filter (B) and expanded before being passed to the two-dimensional acousto-optic deflector (AOD). The AOD (C), A.A. Opto-Electronics DTSXY-400-1064, is powered by an Agilent E3640A DC supply and deflects the incident beam at an angle proportional to an input frequency supplied from a control program written in LabVIEW. The beam exits the AOD and is again expanded before entering a Nikon TE2000-S inverted microscope and passing through filtered beam splitters (E) to overfill the Nikon Plan Fluor 100×/1.3 N.A. oil immersion objective (F). Multiple time-shared optical traps were created by rapidly alternating the laser beam between two or more locations at a rate faster than the particle diffusion time scale.

A Harvard Apparatus RC-30 flow chamber (G) was used to contain the particle/solvent system, which consisted of carboxyl-modified polystyrene microspheres (Invitrogen 7-2400) dispersed in hexadecane (Sigma-Aldrich) with a surfactant. The microparticles have a manufacturer-specified diameter of $2a = 2.4\,\mu m \pm 0.094\,\mu m$. The polydisperity of these particles does not affect our measurements since the standard deviation of particle sizes is much less than the particle separation. The experimental system was based on the work of Sainis et al. [19,20] for direct comparison to their blinking laser tweezers experiments. In these tests, the AOT surfactant sodium di-2-ethylhexylsulfosuccinate (Sigma-Aldrich) was used at 1 mM concentration (above the critical micellar concentration) in hexadecane to initiate long range interactions between particles [29,31]. The viscosity of the solution is assumed to be unchanged from the literature value for pure hexadecane of 6.5 mPa s.

The behavior of the optically trapped microparticles was monitored by utilizing a standard bright field white light source (H) and imaged in reflected light produced by a 120 W EXFO X-Cite Series 120 Hg-Arc lamp. An optional 1064 nm filter (J) was placed before the high-speed 12 bit Vision Research Miro 4 camera (K) to eliminate most of the reflected laser light from reaching the camera. The filter was used primarily in the direct force experiments, when the particle is imaged while inside the optical trap. The particles were imaged at 500 Hz and exposure times up to 1997.5 μs. The recorded images were then transferred to a computer for processing using a particle tracking code developed in Matlab. Errors in particle separation measurements due to optical distortions due to overlapping particle images which have been previously reported are not expected to be significant due to the large particle separations used in the these measurements [30].

Particle interactions of isolated particle pairs were observed using laser tweezers optical traps by two different methods described below. Measurements with both methods were performed with the same pair of particles to eliminate any error associated with polydisperity. The blinking laser tweezers method tracks the relative diffusion of two particles to infer an interparticle force as a function of particle separation, while the direct force method uses the Hookean spring model of an optical trap to relate the displacement of a trapped particle to the force imparted by an adjacent particle.

2.1. Blinking laser tweezers

The blinking laser tweezers method was implemented following the techniques described by Crocker and Grier [16,17] and Sainis et al. [19,20] to characterize the physical behavior of charged colloidal particles. In this method, optical traps are used to position a pair of particles at an initial surface-to-surface separation distance, s, and then the traps are turned off allowing the particles to diffuse in the liquid medium. Thus, the optical tweezers do not interfere with the particles while physical statistics are gathered to accurately capture the interaction of the two particles through their relative diffusion.

In the blinking laser tweezers experiments, two particles were simultaneously captured and released in adjacent optical traps at several imposed separation distances. The traps were held on for approximately 30 ms, a time sufficiently long to return the particles to their initial positions. Then the traps were turned off for another 30 ms, during which the particles move away from their initial position due to Brownian and interparticle interaction forces.

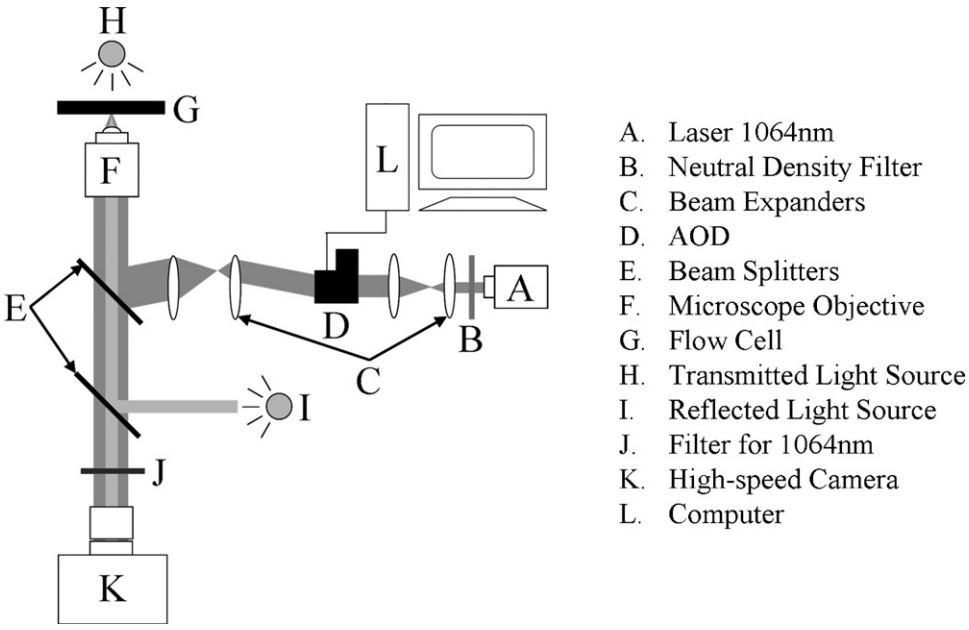

Fig. 1. Laser tweezers optical trapping experimental setup.

To mitigate hydrodynamic effects of the walls, the particles were positioned at least 30 μm (>10 particle diameters) from the nearest wall. At each separation distance, a set of 100,000 images was acquired at 500 Hz resulting in approximately 3500 independent trajectories in each set.

Following the procedures of Sainis et al. [19,20], the acquired images (*c.f.* Fig. 2) were processed to determine the relative velocity and diffusivity of the particles. A threshold filter was applied to the image set to remove any images acquired while the optical traps were activated. The remaining images were processed to determine the centers of the two particles as a function of time during each diffusion event based on the centroid finding techniques of Crocker and Grier [32]. A histogram for a particular initial separation of the particles for each time step revealed a normal distribution from which the mean, $\langle \Delta s \rangle$, and the mean squared, $\langle \Delta s^2 \rangle$, displacements were determined. The slope of these values versus time directly corresponds to the relative particle velocity (v) and diffusion coefficient (D), respectively. The velocity and diffusion coefficient are thus determined simultaneously for the entire range of interparticle separations investigated.

Following the methods of Sainis et al. [19], the interparticle potential was found to be proportional to a ratio of the velocity to diffusivity at each particle separation: $F = k_B T v/D$ where k_B and T refer to the Boltzmann constant and ambient temperature, respectively. This generalization of the Stokes–Einstein relationship assumes that the gradients in the hydrodynamic coupling are relatively weak and that the velocity and diffusivity determined in short time intervals characterize the dynamics well. Thus, the interparticle forces can be measured without knowing material properties of the particle/solvent system such as the zeta potential, ζ, and Debye screening length, κ^{-1}.

2.2. Direct force measurement technique

The magnitude of interparticle forces was also characterized by direct force measurements, in which two particles are continuously trapped at several interparticle separations [11]. The position of a particle within an optical trap is directly related to the external forces acting upon that particle (*i.e.* optical, electrostatic, and/or hydrodynamic forces). By calibrating the position of a single particle across a range of known applied forces, the electrostatic forces due to an adjacent particle can be measured.

For small particle displacements, optical tweezers apply a Hookean force on the particle at the imaging plane. This force, $F_{trap} = k_{trap} d$, is a function of the trap stiffness, k_{trap}, and the distance of the particle from the trap center, d. For each of the experiments discussed here, the optical trap was calibrated by determining d for several known applied forces. The trapped microsphere was dragged through the fluid medium at a known constant velocity, v_f, thereby applying a drag force, $F_D = 6\pi\eta v_f a$, on the particle (*c.f.* Fig. 3(a)), where η is the fluid viscosity. It is assumed here that the AOT surfactant affects the hexadecane viscosity negligibly. Equating the optical force to the drag force results in the calculation of the optical trap stiffness, $k_{trap} = 6\pi\eta v_f a/d$. We have compared this method of calibrating trap stiffness to tracking diffusion of a trapped particle as described by Lukic et al., and found that the two methods give the same value for trap stiffness within the measurement error [33]. However, flow-based calibration has the added advantage of ensuring that the optical trap restoring force is linear over the entire force range of interest.

Forces acting on the particle can then be calculated by measuring the displacement of the particle from the center of the trap. The calibrated particle is held stationary in the calibrated trap and a second particle is held in a second optical trap at a specified separation. Fig. 3(b) and (c) schematically represent such an experiment. At separations much greater than the Debye length (Fig. 3(b)) the two particles are not interacting and thus diffuse around the centers of their respective optical traps. As the particles are brought together (Fig. 3(c)), the particles begin to interact with each other through electrostatic repulsion and hydrodynamic coupling. Thus, the average particle location will be displaced by a distance d from the center of the optical trap allowing the calculation of $F = k_{trap} d$. A typical experiment would investigate 30 trap positions for 10 s each. Images acquired at 500 Hz were processed by first finding the centroids of the particles as a function of time. The mean displacement from trap center of the left particle and the mean distance between the two particles were then determined for each increment which led to the calculation of the interparticle force. Multiple trials were conducted during each experimental session using the same particles and averaged to reduce error in the measured force

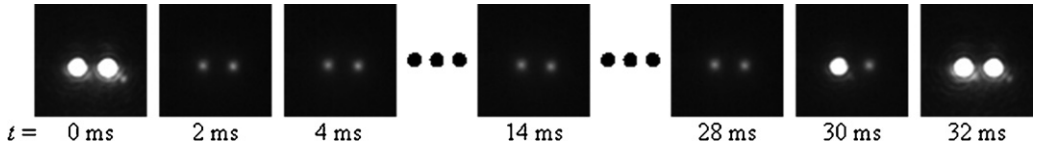

Fig. 2. Sample images recorded from a single diffusion event during a blinking laser tweezers experiment. The elapsed time, t, is relative to the last frame in which the laser trap is active. In some instances (*e.g.* at 30 ms), the time-shared traps illuminate a single particle as the traps are turned on again.

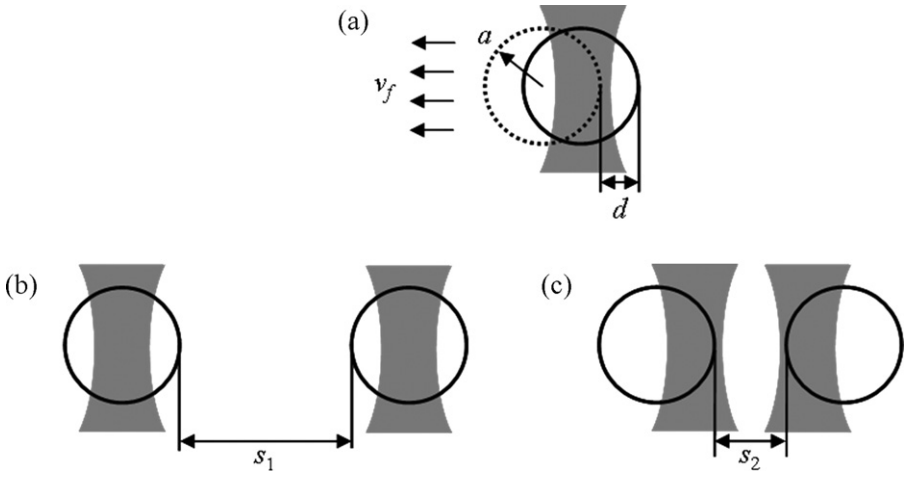

Fig. 3. Schematic of the direct force measurement technique: (a) the optical trap strength is calibrated by moving the fluid medium at a constant velocity around the trapped particle imparting a constant force, $F_D = 6\pi\eta v_f a$, on the particle and thus causing a small displacement from the trap center. The solid circle shows the equilibrium particle position without flow. The dashed circle shows the equilibrium position with flow. (b) At large interparticle separations, the particles reside in the center of the traps. (c) At close separations, the particles are displaced from the center of the optical trap due to the electrostatic repulsion.

to comparable magnitudes as those typically seen in blinking optical tweezers experiments.

3. Results and discussion

Optical tweezers based interparticle force measurements from single laboratories have typically focused on a single technique whether it be blinking laser tweezers or direct force measurements. In this section, we present measurements of particle interactions using both blinking laser tweezers and direct force measurement methods on the same particle pair. These measurements were performed on a model system to verify and replicate the measurement techniques. A quantitative comparison to theory and existing literature is discussed and used to derive an understanding of the applicability and reliability of each technique.

3.1. Blinking laser tweezers

Data collected using the blinking laser tweezers method were compiled and binned by initial separation for which histograms, as shown in Fig. 4, were constructed showing relative particle displacements at time steps of 2–20 ms. Assuming Gaussian distributions for each time step, the mean ($\langle \Delta s \rangle$) and mean squared ($\langle \Delta s^2 \rangle$) displacements were determined. The slopes of $\langle \Delta s \rangle$ and $\langle \Delta s^2 \rangle$ as functions of elapsed time indicate the relative velocity and diffusivity, respectively, of the particles for a particular initial separation. Linear regression analysis of this data results in typical 95% confidence intervals on the velocity and diffusion constants of no more than 0.1 μm/s and 5×10^{-3} μm^2/s, respectively. A typical data set collected using the blinking laser tweezers method requires 4–6 h of laboratory time to acquire physical statistics at each initial separation and another 8 h to process the resulting images, of which there may be up to 2 million.

Local diffusion constants and drift velocities, as determined by the blinking laser tweezers method, are shown as a function of the surface-to-surface separation, s, in Fig. 5(a) and (b), respectively. Batchelor's prediction [34] for the diffusivity of a particle in the presence of another particle is given by:

$$D(s) = 2D_0\left(1 - \frac{3a}{2(s+2a)}\right) \quad (1)$$

where the self-diffusion coefficient, D_0, is given by:

$$D_0 = \frac{k_B T}{6\pi\eta a} \quad (2)$$

By assuming the manufacturers' specified particle diameter, there are no adjustable parameters in Batchelor's equation. The predicted hydrodynamic coupling of two particles agrees quite well with measured diffusivities, showing accurately the monotonic decrease in particle mobility due to hydrodynamic interactions at small separations as shown by the solid line in Fig. 5(a). Note that the gradients in the diffusion coefficient are small (<0.05 μm/s) rel-

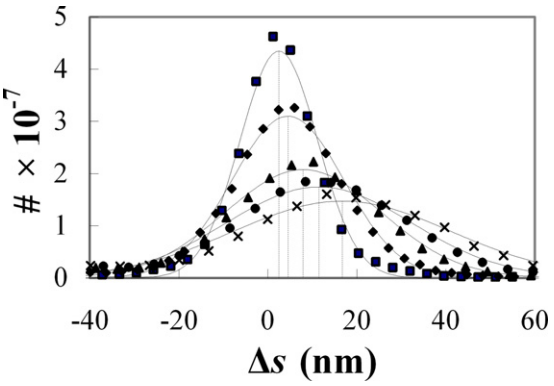

Fig. 4. Histograms of relative particle displacements at $s = 1.27$ μm for $\Delta t = 2$ (■), 4 (♦), 8 (▲), 12 (•), and 18 (×) ms. The solid lines indicate the best Gaussian curve fits for each Δt. The dotted lines represent the mean displacement for each Δt.

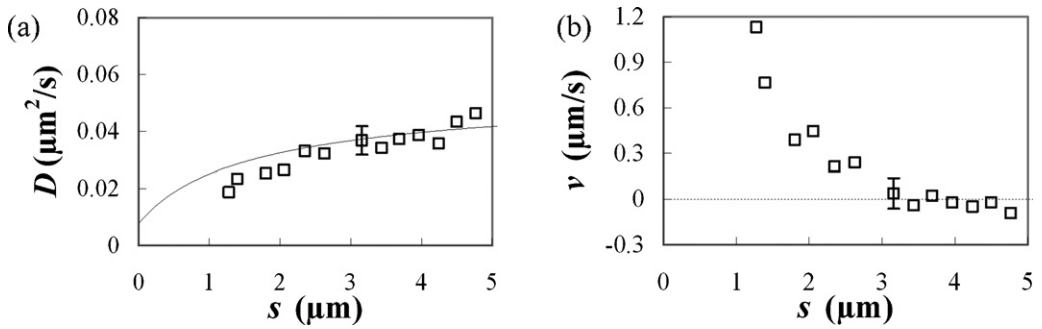

Fig. 5. (a) Typical dependence of diffusion coefficient on particle separation as measured using the blinking laser tweezers technique (□) compared to Batchelor's hindered Brownian diffusion theory (solid line) for $2a = 2.4\,\mu m$ without any adjustable parameters. The error bars at $s = 3.16\,\mu m$ indicate the typical 95% confidence interval on D of $5 \times 10^{-3}\,\mu m^2/s$. (b) Velocities determined as a function of particle separation using the blinking laser tweezers technique. Velocities greater than zero represent motion away from the other particle. The error bars at $s = 3.16\,\mu m$ indicate the typical 95% confidence interval on v of 0.1 μm/s.

ative to the error in the measured velocity. For large separations ($s > 4\,\mu m$), the relative velocity of the particles is approximately zero. The relative velocity increases as the particles are brought closer together indicating repulsive forces acting between the isolated particles.

Using the corresponding values of diffusion and velocity at each separation s, the repulsive interparticle force was calculated from the equation $F = k_B T v/D$ as described in Section 2.1. Error propagation analysis was used to determine the uncertainty in the measured force at each separation, u_F:

$$u_F = \sqrt{\left(u_v \frac{\partial F}{\partial v}\right)^2 + \left(u_D \frac{\partial F}{\partial D}\right)^2} = k_B T \sqrt{\left(\frac{u_v}{D}\right)^2 + \left(\frac{u_D v}{D^2}\right)^2} \quad (3)$$

where u_v and u_D represent the 95% confidence intervals on the drift velocity and diffusion constant respectively. Typically, the error in the force measurement is less than 10 fN at any initial separation.

The forces measured using blinking laser tweezers in a hexadecane solvent with 1 mM AOT between a pair of 2.4 μm carboxyl-modified polystyrene particles were qualitatively similar to published values for 1.2 μm polystyrene microspheres [20]. Relatively large repulsions (~250 fN) were observed for small separations and a monotonic decrease in the interparticle potential with increasing interparticle separation occurred until the particle charges were completely screened. Quantitatively, the force data is well fit by DLVO theory neglecting van der Waals forces.

$$F(s) = k_B T \left(\frac{e\zeta}{k_B T}\right)^2 \frac{a^2}{\lambda_B} \frac{e^{-\kappa s}}{s + 2a} \left(\frac{1}{s + 2a} + \kappa\right) \quad (4)$$

where Bjerrum length, $\lambda_B = 25\,nm$, characterizes the dielectric polarizability of the hexadecane solvent and is a known material parameter [20]. Fitting this function to the force data collected by the blinking laser tweezers, the Debye screening length, κ^{-1}, and the surface charge, $|e\zeta/k_B T|$ were determined assuming the manufacturer specification of the particle radius was accurate. For the data shown in Fig. 6, the curve fit parameters and 95% confidence intervals were found to be $\kappa^{-1} = 0.78 \pm 0.09\,\mu m$ and $e\zeta/k_B T = 3.1 \pm 0.3$.

3.2. Direct force measurement technique

Direct force measurements are perhaps more commonplace, but are not considered to be as accurate and have yet to be compared directly to blinking laser tweezers data for a single particle/solvent system. In performing this investigation, the direct force measurements were made directly following the blinking laser tweezers measurements using the same particles in the same solvent. In our experiments, the optical trap stiffness was calibrated as described previously at microscope stage speeds of 2–10 μm/s by incremen-

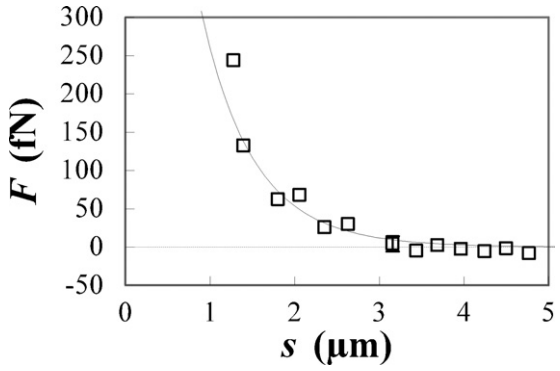

Fig. 6. Interparticle forces measured using blinking laser tweezers (□) and a curve fit to that data accounting for electrostatic repulsions (solid line). The error bars at $s = 3.16\,\mu m$ indicate the typical 95% confidence interval on F of 10 fN for blinking laser tweezers.

tally increasing the stage speed by 2 μm/s every 20 s. By oscillating the stage motion backwards and forwards in periods of 10 s, the trap was calibrated for particle displacement in both lateral directions. The resultant images were processed using the same center-finding technique as in the blinking laser tweezers method, and the particle displacement from the stationary trap position was determined at each stage speed by averaging the particle position in the image over approximately 8 s. The trap stiffness in these experiments was found to be 0.89 ± 0.02 fN/nm (*c.f.* Fig. 7).

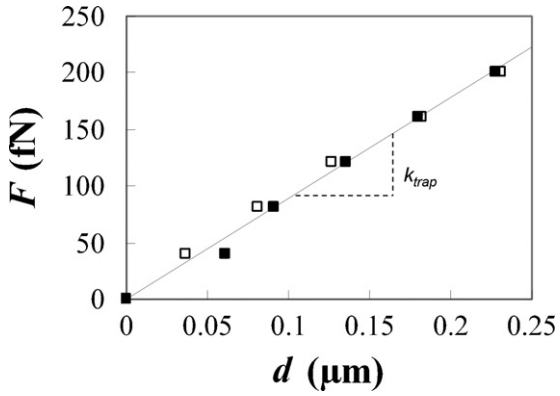

Fig. 7. A drag force applied to an optically trapped particle causes displacement from the trap center allowing for calibration of the trap stiffness over a range of forces. The open and closed symbols indicate forward and backward in-plane motion, respectively. The solid line represents the best linear fit to the data and the slope is the measured trap stiffness k_{trap}.

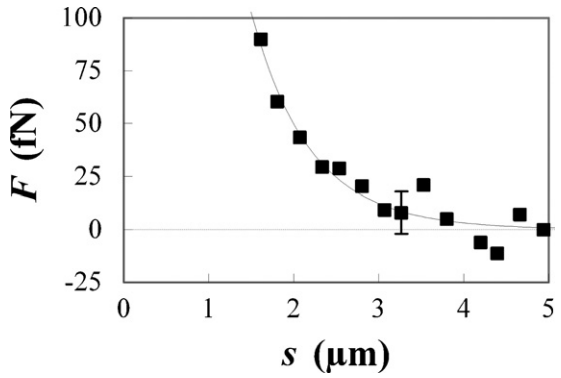

Fig. 8. Interparticle forces determined using the direct force measurement technique as a function of particle separation. The solid line represents the best curve fit to DLVO theory. The error bars at $s = 3.27$ μm indicate the typical 95% confidence interval on F of 10 fN for direct force measurements.

Fig. 8 shows direct force measurements of the interparticle force as a function of particle surface-to-surface separation, s, and a curve fit (solid line) to Eq. (3). Here, the best fits to the Debye screening length, κ^{-1}, and the surface charge, $e\zeta/k_BT$ are 0.86 ± 0.15 μm and 2.8 ± 0.3, respectively. A typical direct force measurement experiment consists of only 2–3 h of data collection and another 4 h of image processing. Error in the force measurements propagates from both the linear regression fit for k_{trap} and the resolution in the center-finding technique for d. The resulting uncertainty in the direct force measurements is thus:

$$u_F = \sqrt{\left(u_{k_{trap}} \frac{\partial F}{\partial k_{trap}}\right)^2 + \left(u_d \frac{\partial F}{\partial d}\right)^2} = \sqrt{(u_{k_{trap}} d)^2 + (u_d k_{trap})^2} \quad (5)$$

For the data shown in Fig. 8, we calculate a typical error on the order of 10 fN. The same qualitative trends of the blinking laser tweezers force data are seen again in the direct force results; a relatively large repulsive force occurs at small separations and tails off to no particle interaction at separations greater than 4 μm.

3.3. Direct comparison of two methods

Plotting the blinking laser tweezers data on the same graph as the direct force measurements along with the best curve fit to conventional DLVO theory (*c.f.* Fig. 9) shows that the force measurement techniques are in good agreement. Multiple tests not shown here indicate that both methods are repeatable and reproducible. The data acquired from both techniques was well predicted by DLVO theory and fits for the Debye screening length and surface charge agree within measurement error.

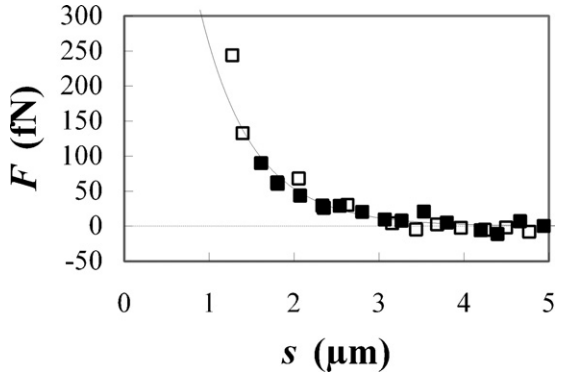

Fig. 9. Comparisons of interparticle forces acquired using the blinking laser tweezers (□) and direct force measurement (■) techniques.

4. Conclusions

Interparticle forces were measured between particle pairs using two different implementations of optical trapping. This head-to-head comparison of force measurements is the first performed on a single optical tweezers setup and verifies that these techniques, which are becoming more common investigatory tools for colloidal dispersions, provide reliable and reproducible data. The direct force and blinking laser tweezers techniques were found to produce similar results for colloidal systems with a nonpolar solvent. Our results were in good qualitative agreement with results in a similar system using smaller carboxyl-modified latex particles published by Sainis et al. [20].

Other comparisons can be drawn between the two methods. Procedural differences between the methods can also influence the choice of implementation. Blinking laser tweezers is more data intensive and time consuming to implement, while direct force measurements are quick and relatively easy to process. While an advantage of blinking laser tweezers is that the laser does not play a role in the actual measurements, it has been verified here that direct force measurements are just as trustworthy as long as the optical trap is calibrated properly before measurements are made. In past studies, a distinction between the two methods that was often drawn was that although blinking optical tweezers requires more time and effort, the results were often more precise. However, by comparing the two methods, we have shown that the errors associated with the two methods are very similar with 95% confidence intervals of approximately ±10 fN. Through quantified comparison of these two methods, it has been shown that optical trapping is a robust and reliable tool when used in the study of colloidal dispersions, especially for interparticle force measurements.

Acknowledgements

The authors acknowledge Prof. Eric Dufresne and Prof. Eric Furst for helpful discussions. Additionally our image analysis code makes use of Matlab routines for particle center finding algorithms published by Prof. Dufresne and Prof. Daniel Blair (http://physics.georgetown.edu/matlab/).

Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

[1] A. Ashkin, Phys. Rev. Lett. 24 (1970) 156–159.
[2] A. Ashkin, IEEE J. Sel. Top. Quantum Electron. 6 (2000) 841–856.
[3] A. Meyer, A. Marshall, B.G. Bush, E.M. Furst, J. Rheol. 50 (2006) 77–92.
[4] J.C. Crocker, M.T. Valentine, E.R. Weeks, T. Gisler, P.D. Kaplan, A.G. Yodh, D.A. Weitz, Phys. Rev. Lett. 85 (2000) 888–891.
[5] R.R. Brau, J.M. Ferrer, H. Lee, C.E. Castro, B.K. Tam, P.B. Tarsa, P. Matsudaira, M.C. Boyce, R.D. Kamm, M.J. Lang, J. Opt. A: Pure Appl. Opt. 9 (2007) S103–S112.
[6] E.M. Furst, A.P. Gast, Phys. Rev. Lett. 20 (2004) 3940–3946.
[7] J.P. Pantina, E.M. Furst, Langmuir 20 (2004) 3940–3946.
[8] K. Svoboda, S.M. Block, Annu. Rev. Biophys. Biomol. Struct. 23 (1994) 247–285.
[9] E.M. Furst, Soft Mater. 1 (2003) 167–185.
[10] R.M. Simmons, J.T. Finer, S. Chu, J.A. Spudich, Biophys. J. 70 (1996) 1813–1822.
[11] T. Sugimoto, T. Takahashi, H. Itoh, S. Sato, A. Muramatsu, Langmuir 13 (1997) 5528–5530.
[12] M.T. Valentine, L.E. Dewalt, H.D. Ou-Yang, J. Phys.: Condens. Matter. 8 (1996) 9477–9482.
[13] J.-C. Meiners, S.R. Quake, Phys. Rev. Lett. 82 (1999) 2211–2214.
[14] C. Gutsche, U.F. Keyser, K. Kegler, F. Kremer, Phys. Rev. E (2007) 76.
[15] C.D. Mellor, M.A. Sharp, C.D. Bain, A.D. Ward, J. Appl. Phys. 97 (2005) 103114.

[16] J.C. Crocker, D.G. Grier, Phys. Rev. Lett. 73 (1994) 352–355.
[17] J.C. Crocker, J. Chem. Phys. 106 (1997) 2837–2840.
[18] E.R. Dufresne, T.M. Squires, M.P. Brenner, D.G. Grier, Phys. Rev. Lett. 85 (2000) 3317–3320.
[19] S.K. Sainis, V. Germain, E.R. Dufresne, Phys. Rev. Lett. 99 (2007) 018303.
[20] S.K. Sainis, V. Germain, C.O. Mejean, E.R. Dufresne, Langmuir 24 (2008) 1160–1164.
[21] R. Verma, J.C. Crocker, T.C. Lubensky, A.G. Yodh, Macromolecules 33 (2000) 177–186.
[22] R.J. Owen, J.C. Crocker, R. Verma, A.G. Yodh, Phys. Rev. E 64 (2001) 011401.
[23] J.C. Crocker, J.A. Matteo, A.D. Dinsmore, A.G. Yodh, Phys. Rev. Lett. 82 (1999) 4352–4355.
[24] R. Nambiar, J.-C. Meiners, Opt. Lett. 27 (2002) 836–838.
[25] P.L. Biancaniello, J.C. Crocker, Rev. Sci. Instrum. 77 (2006) 113702.
[26] B.V. Derjaguin, L. Landau, Acta Physicochim. URSS 14 (1941) 633.
[27] E.J.W. Verwey, J.T.G. Overbeek, Theory of the Stability of Lyophobic Colloids: The Interactions of Sol particles having and Electric Double Layer, Elsevier, New York, 1948.
[28] K.C. Neuman, S.M. Block, Rev. Sci. Instrum. 75 (2004) 2787–2809.
[29] L.P. Faucheux, G. Stolovitzky, A. Libchaber, Phys. Rev. E 51 (1995) 5239–5250.
[30] J. Baumgartl, C. Bechinger, Europhys. Lett. 71 (3) (2005) 487–493.
[31] M.F. Hsu, E.R. Dufresne, D.A. Weitz, Langmuir 21 (2005) 4881–4887.
[32] J.C. Crocker, D.G. Grier, J. Colloid Interface Sci. 179 (1996) 298–310.
[33] B. Lukic, S. Jeney, Z. Sviben, A.J. Kulik, E.-L. Florin, L. Forro, Phys. Rev. E 76 (2007) 011112.
[34] G.K. Batchelor, J. Fluid Mech. 74 (1976) 1–29.