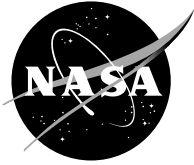


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Optical Levitation of Micro-Scale Particles in Air

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January 2004

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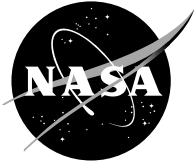
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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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Optical Levitation of Micro-Scale Particles in Air

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Summary

Success has been achieved using a radiation pressure gradient to levitate microscale particles in air for as long as four hours. This work is performed as a precursor to the development of a vacuum based optical tweezers interrogation tool for nanotechnology research. It was decided to first proceed with solving the problem of achieving optical levitation of a micro-scale particle in air before trying the same in a vacuum environment. This successful optical levitation in air confirms the work of Ashkin and Dziedzic.¹⁻⁵ Levitation of 10 and 13.8 μm diameter polystyrene spheres was achieved, as well as the levitation of 10 and 100 μm diameter glass spheres. Particles were raised and lowered. A modicum of success was achieved translating particles horizontally. Trapping of multiple particles in one laser beam has been photographed. Also, it has been observed that particles, that may be conglomerates or irregular in shape, can also be trapped by a focused laser beam. Levitated glass beads were photographed using laser light scattered from the beads. The fact that there is evidence of optical traps in air containing irregular and conglomerate particles provides hope that future tool particles need not be perfect spheres.

Introduction

Reliable interrogation and manipulation of nanoscale structures ultimately depends on the ability to probe nanoscale structures in three dimensions in any environment. While high resolution interrogation of nanoscale particles with laser light remains unlikely because nano-particles have sizes much smaller than the wavelength of light, it may be possible to probe nanoscale matter using a tool particle that is controlled by a laser beam. Many efforts are underway to develop optical tweezers for a variety of applications, but those optical tweezers generally depend on directing a laser beam through an optical microscope and using the tightly focused beam produced by the microscope's objective lens to manipulate small objects suspended in liquid on a microscope slide.⁶⁻¹⁰ For applications where the presence of air or water would not be beneficial, it is potentially useful to probe or manipulate nanoscale structures in a vacuum, without the benefit of a supporting liquid in which to suspend the material under study. Manipulating particles with laser light in air or vacuum may demand longer working distances than is possible using an optical microscope, since the object to be manipulated might of necessity be further than a few millimeters from the focusing lens. At NASA Glenn Research Center,

an investigation is underway to develop a useful means of manipulating probe-tool particles in three dimensions in a vacuum environment.

Very little has been done to produce a functional optical tweezers instrument that can function in air or in a vacuum environment. A. Ashkin and J. Dziedzic of Bell Telephone Laboratories performed some early studies of optical levitation in air and vacuum from 1970 to 1976.¹⁻⁵ However, their published reports gave little detail about many of the technical challenges involved in optical levitation. Therefore, it was necessary at NASA Glenn Research Center to establish successful techniques for optically levitating micrometer scale objects before a functional tool for nanoscale devices could be made. It was decided to first proceed with solving the problem of achieving optical levitation of a micro-scale particle in air before trying the same in a vacuum environment. The following discussion is about that effort.

Method and Experimental Apparatus

Two significant obstacles needed to be overcome in order to achieve optical levitation. The first was keeping the particles from being blown out of the laser trap by air currents in the room. The second was providing the correct amount of impulse to break the particles loose from the glass stage.

The initial configuration (figure 1) consisted of 532nm laser light, focused by a 50 mm focal-length lens. The laser light was directed beneath a glass plate, and reflected upward through the plate, to form a focus 2 or 3 mm above the plate. Initially the plate was a microscope slide. A beam block was positioned above the setup for safety, as well as to prevent reflected and scattered light from interfering with the single optical trap. Because reports of optical trapping indicate that trapping strength increases when the light incident on the focusing lens overfills the lens⁶, the beam was expanded and collimated before being focused. This proved to be a great help, and resulted in an occasional lifting of a 10 or 13.8 μm diameter polystyrene sphere into the beam after the plate was agitated slightly to break the spheres loose from the glass. Often, the particle would fall after a few seconds of levitation. Sometimes the particle would be blown horizontally out of the trap by air currents in the laboratory caused by the air conditioning, or the fan from a piece of laboratory equipment.

A metal box was found to shield the optical trap from air currents. Two windows were installed in the box. One window on the end of the box permitted the collimated laser light to enter the box. A second window on the side allowed camera access to the activity within. A removable lid with a handle served to allow access to change particles, as well as to clean the stage and the beam block. The box was painted flat black inside and out. The box was bolted onto an optical table, with the focusing lens, mirror, glass plate, and piezoelectric shaker inside.

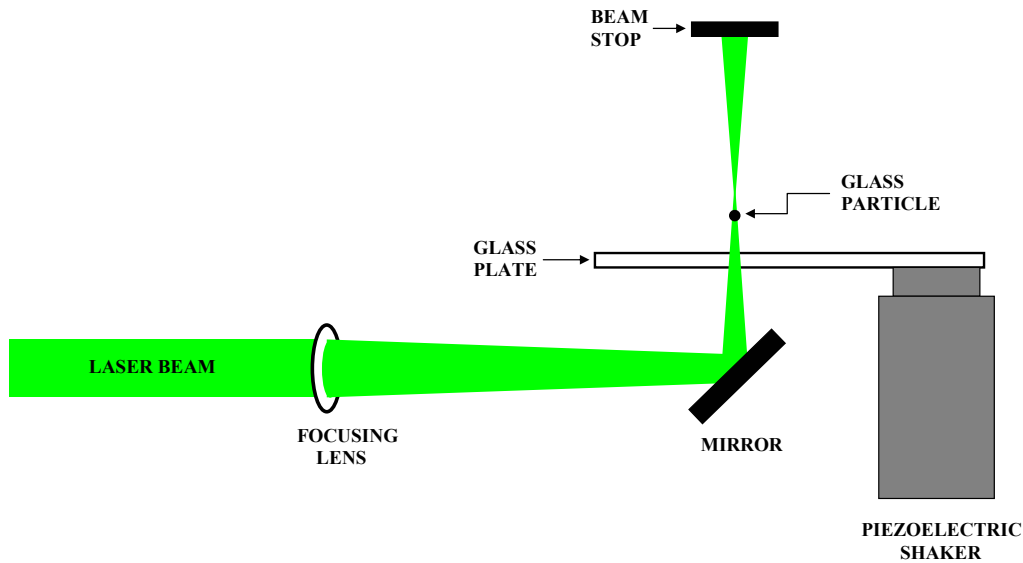


Figure 1.—Diagram showing laser beam path for optical levitation within the protective box.

The box indeed shielded the particles to the point where optical trapping was possible. We were able to begin optimization of the shaker frequency and amplitude, the beam focus height and quality, and the particle choice.

In order to lift particles from a glass plate into the focus of the laser beam, not only must the force due to gravity on the particle be overcome, but also additional forces that might cause the particles to stick to the surface must be overcome such as those due to static electricity and the Van der Waals effect. The first attempt to overcome these forces was made by gently tapping the edge of the plate with a pen hoping to jostle the particles enough that they could be lifted into the laser beam. That method proved to be ineffective. It was determined that a more suitable impulse was necessary to break the forces sticking the particles to the glass plate. Therefore, one end of the glass plate was mounted to a piezoelectric shaker. Agitating the particles by driving the shaker through some of the resonant frequency modes of the plate broke the particles loose from the glass and allowed them to drift toward the focus of the laser beam. This is similar to the method employed by Ashkin and Dziedzic^{1,5}. Adjusting the amplitude of the mechanical resonance was necessary, as it was possible to shake the particles too hard and toss them past the optical trap, or conversely, to shake the particles so lightly that they merely scooted about the glass plate. At this point in the work, it was necessary to determine for each type of particle, each glass plate, and sometimes humidity in the room the correct frequency and amplitude to drive the shaker.

Results and Discussion

Initially, microscopy calibration spheres were used as sample tool particles. Optical levitation was observed when using 13.8 μm and 10.0 μm diameter polystyrene spheres. Because these spheres come packaged in a liquid suspension, it was necessary to deposit some of the liquid onto the glass plate, and allow the liquid to dry overnight. Scraping the glass plate with a razor blade loosened the spheres from the stage leaving sufficient numbers of them undamaged. Subsequently optical levitation of polystyrene spheres was observed from times ranging from four minutes to four hours or longer. Driving the focusing lens back and forth on a translation stage allowed the height of the levitated sphere to be changed. On some occasions, trapping the polystyrene spheres was almost impossible in the ambient air environment. The spheres would clump together in large groups and stick to the glass plate. It is possible that humidity in the room contributed to the clumping.

Because a large number of particles were lost while learning how to levitate them, it was decided to use industrial glass beads made for use in bead blasting as sample particles until techniques were sufficiently developed to warrant the use of more expensive sample tool particles. The glass beads used were borosilicate glass beads made by Flex-O-Lite, Inc. These glass beads were not calibrated to a specific standard, but appeared to be about 100 μm in diameter. Also, not all were spherical, and some exhibited defects when viewed through an optical microscope, as seen in figure 2. Still, the cost of obtaining them is significantly less than that for calibrated microscopy spheres. An additional advantage of using these glass beads is that they are dry when taken from the package.

Trapped particles were photographed using the light scattered from the particle. Trapping events were also videotaped with the output of a digital video camera sent to a standard video recorder. Still photographs were also taken using a digital single lens reflex (SLR) camera with a 135 mm lens. We were also able to take Polaroid and digital photographs that show the optical trap area and a trapped particle. By comparing photographs of levitated particles, beam shapes and rulers without moving or changing the camera, we are able to make an estimate of the height at which particles were trapped. Particles appeared to trap just below the focus of the beam. The highest particle trap we were able to measure was about 25 mm above the glass plate.

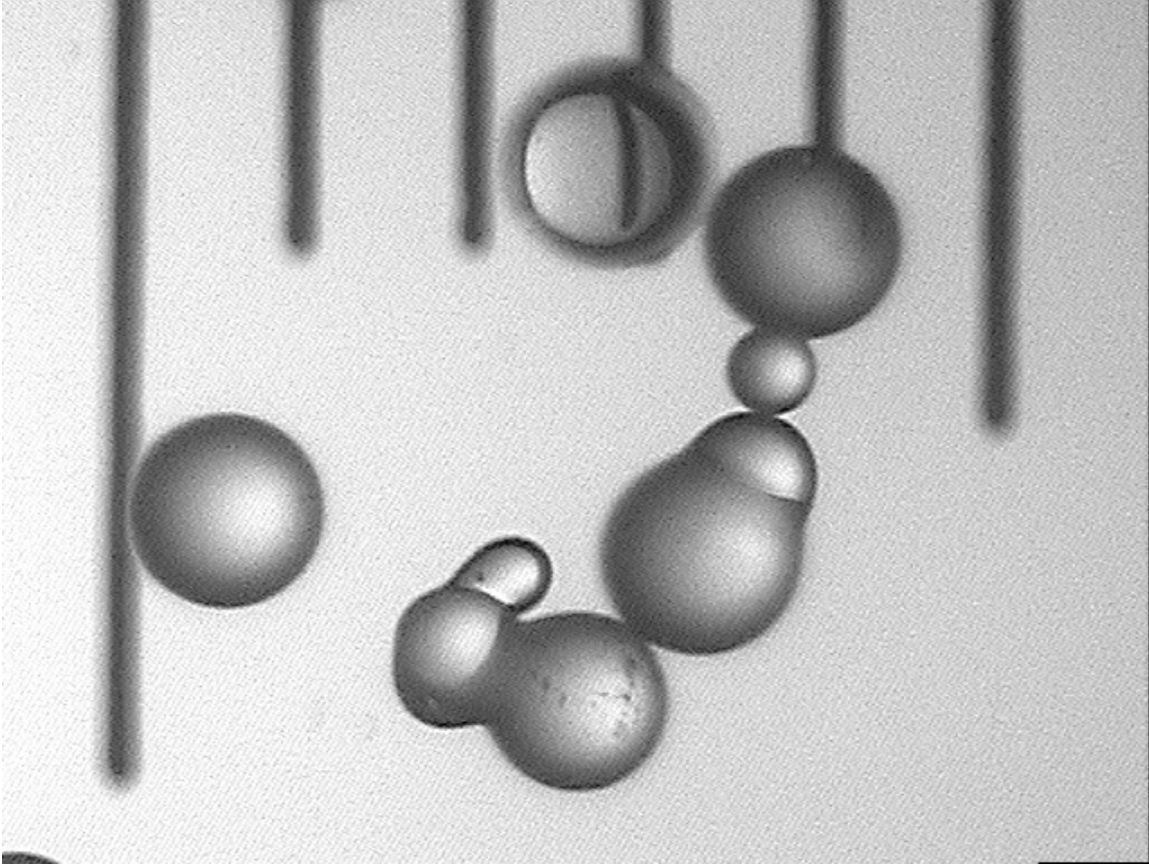


Figure 2.—Photograph showing some of the glass beads used in early optical levitation studies. The ruler beneath the beads is marked in 100 μm increments.

Trapping the 100 μm diameter glass beads proved to be difficult at first. Often the glass beads would fall off of the glass plate when it was agitated, or would be launched with sufficient velocity to pass completely through the laser beam without being caught. To minimize the glass beads rolling off the edges of the glass stage, we changed the glass plate from a microscope slide to a 3.25 by 4 by 0.05 in. projector glass cover slide. This change provided an area about three times larger than the microscope slide. A larger plate area allowed fewer particles to roll off of the edge of the plate when it was agitated by the piezoelectric shaker. Additional improvement in trapping glass beads was gained by changing the frequency of the resonance to a higher order vibrational mode for the glass plate. The most effective frequencies for our equipment were around 18.2 kHz. Also, the amplitude of the vibration could be adjusted two ways. The voltage applied by the signal generator was controlled in discrete steps from 1 to 10 V, but the signal amplifier had a potentiometer that could more smoothly vary the amplitude of the vibration. It was determined experimentally for our purposes that setting the voltage of the signal generator to a maximum of 10 V, and varying the gain with the potentiometer on the signal amplifier, we were able to better control the launching of the glass particles, thus increasing the number of successful optical traps. This method is similar to one used by Ashkin and Dziedzic in their optical levitation experiments.^{1,5}

Most optical traps for 100 μm glass spheres as well as 10 and 13.8 μm polystyrene spheres and 10 μm glass spheres occurred when the 532 nm variable-power laser was set to an output between 2 to 2.5 W. Beam losses were presumed to be high, as light was scattered by particles that remained on the glass plate. We did not have the capability to measure laser power at the location where the particles were trapped. However, on many occasions, once a particle was trapped, it could remain in the trap while the laser power was reduced to 0.25 W. Below 0.25 W, the particle was usually lost to air currents within the box. Future experiments are planned in a vacuum environment to determine the laser power requirements for creating and maintaining optical traps for various particles.

In addition to catching spheres launched with the shaker, particles were trapped via other means. Particles were also observed to enter the optical trap by falling from above, or drifting into the beam on air currents within the box. The box was not dust free, and small air currents, presumably from warm air heated by the laser beam causes dust to blow past the laser beam. Sometimes a piece of dust was observed to slow and change direction as it encountered the area near the focused laser light. It could be easily observed by watching the camera display on a video monitor that the more closely dust passed to the area where the beam was focused, the more slowly it progressed sideways through the field of view. Some of the photographs show trapped particles that appear to be irregular, or irregularly shaped conglomerates of particles.

In order to prepare for the possibility that the focusing lens might not be able to be physically close to the tool particles, we attempted to work with longer focal length lenses. We began with a 50 mm positive lens, and later switched to a 50 mm camera lens in an effort to better accommodate the collimated light entering the box. A 135 mm camera lens was also used. Most laser tweezers apparatus use microscope objective lenses to focus the laser beam. Since we were working with much longer focal length lenses, the focusing range of our beam was very long compared to most optical traps. Also, the vertical distance over which particles could be captured was not restricted by the boundaries of a microscope slide and cover slip as in most laser tweezers apparatus.

Figure 3 shows a composite photograph of a single 100 μm glass sphere optically levitated a distance of approximately 1 mm above the glass plate. The composite picture shows the particle, the shape of the focused laser beam, and a ruler. The photograph of the particle was taken from a video tape showing the levitated particle. The beam shape was photographed by pouring liquid nitrogen into the chamber and photographing the scattered light from the plume of evaporating nitrogen, without moving the camera. The ruler was then positioned at the location of the beam and photographed also without moving the camera. The 532 nm laser light was focused with a 50 mm focal length camera lens. It can be seen that the glass sphere traps just below the waist of the beam. This is consistent with results experienced by Ashkin and Dziedzic³ for solid glass spheres.



Figure 3.—Composite photograph showing a single 100 μm glass sphere with the relative height above the glass plate and position within the focused beam shown.

Figure 4 is a composite photograph showing two 100 μm glass spheres trapped below the waist of the laser beam. This composite photograph was made in the same manner as was figure 3.

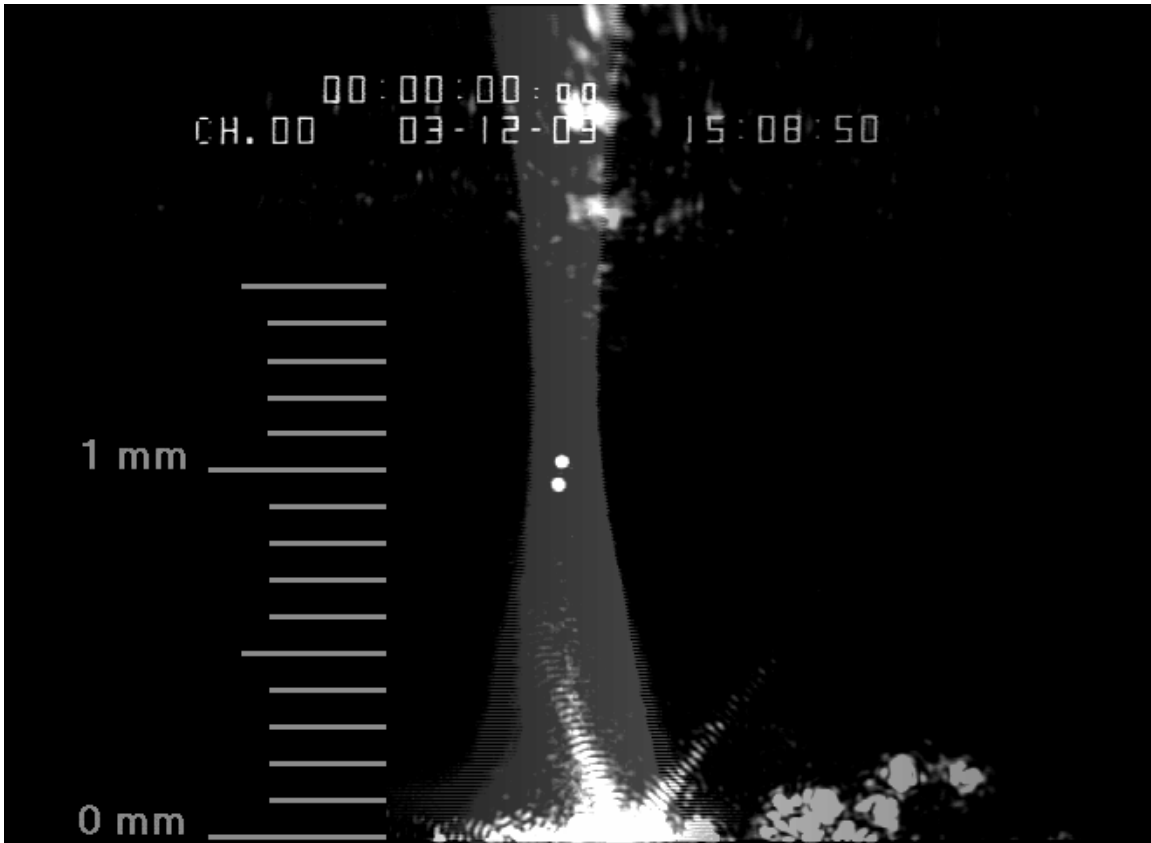


Figure 4.—Composite photograph of two glass spheres, the focused laser beam and a ruler showing their approximate heights from the glass plate.

On many occasions, more than one of the particles scattered upon the glass plate were trapped in the laser beam. Sometimes several particles would trap at different heights above and below the focus. Particles have been observed to change height within the trap area, with a particle near the bottom of the trapping area moving to the top without appearing to interfere with particles it passed as it climbed. It is known that these are separate particles trapped by the laser beam, rather than reflected and refracted images of the same particle. The particles trapped did not enter their traps at the same time, and their motion within the beam was independent of the other particles. Occasionally a particle or perhaps a conglomeration of particles would appear to break apart near the focus of the beam, sometimes trapping the pieces. Figure 5 shows a composite photograph of several glass spheres trapped in the 532 nm optical trap. This trap was made using a 135 mm camera lens to focus the beam. It can be seen that several particles have trapped below the waist of the beam. The particles appear have more than one size, and the largest particle appears irregular in the photograph. The larger bright particles may be conglomerates of smaller particles.

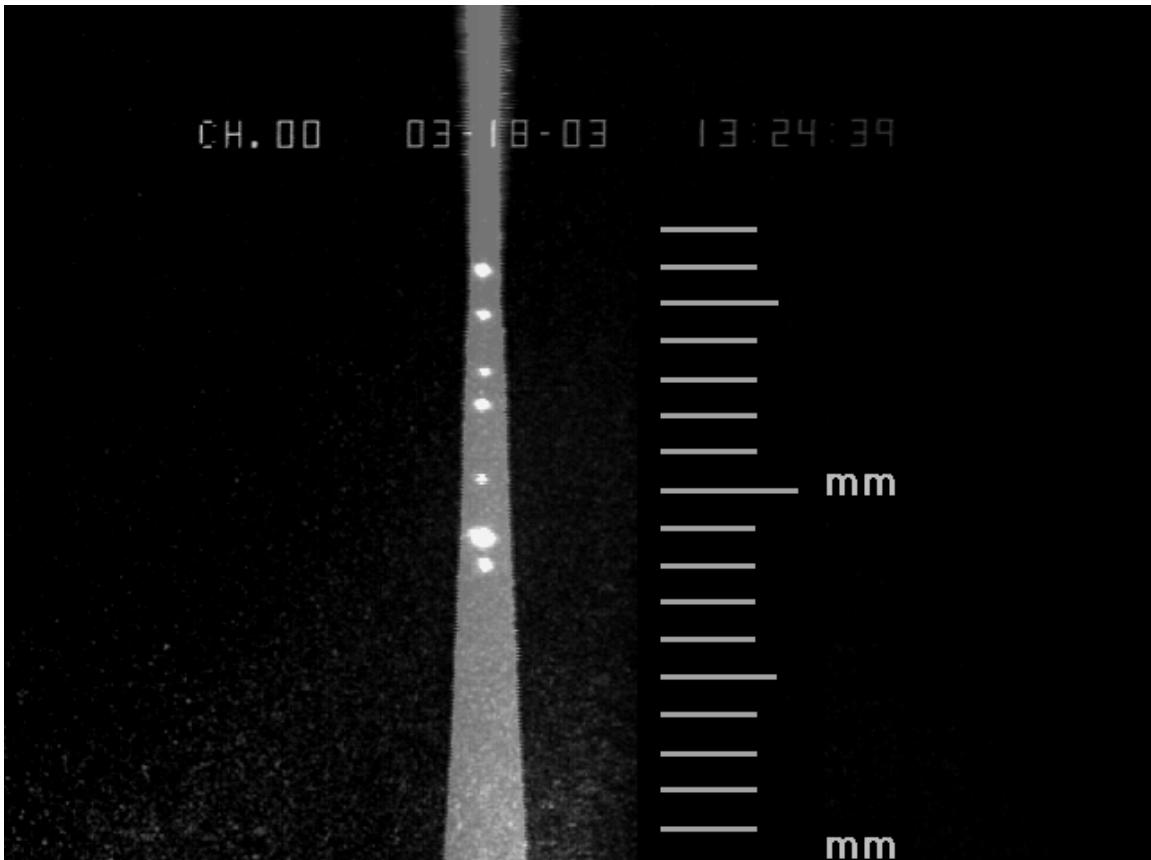


Figure 5.—Composite photograph of several trapped glass spheres, the laser beam and a ruler showing approximate height from the glass plate. Size variation among the particles is evident.

Figure 6 shows several 100 μm glass particles trapped by the laser beam. The bottom group is trapped below the focus, and the single particle near the top is above the focal range of the beam. The sphere in the upper trap only remained for a few seconds before air currents blew it out of the trap. Particles and dust that remained on the glass plate scattered some of the beam as it passed through the glass plate, but did not prevent optical trapping.

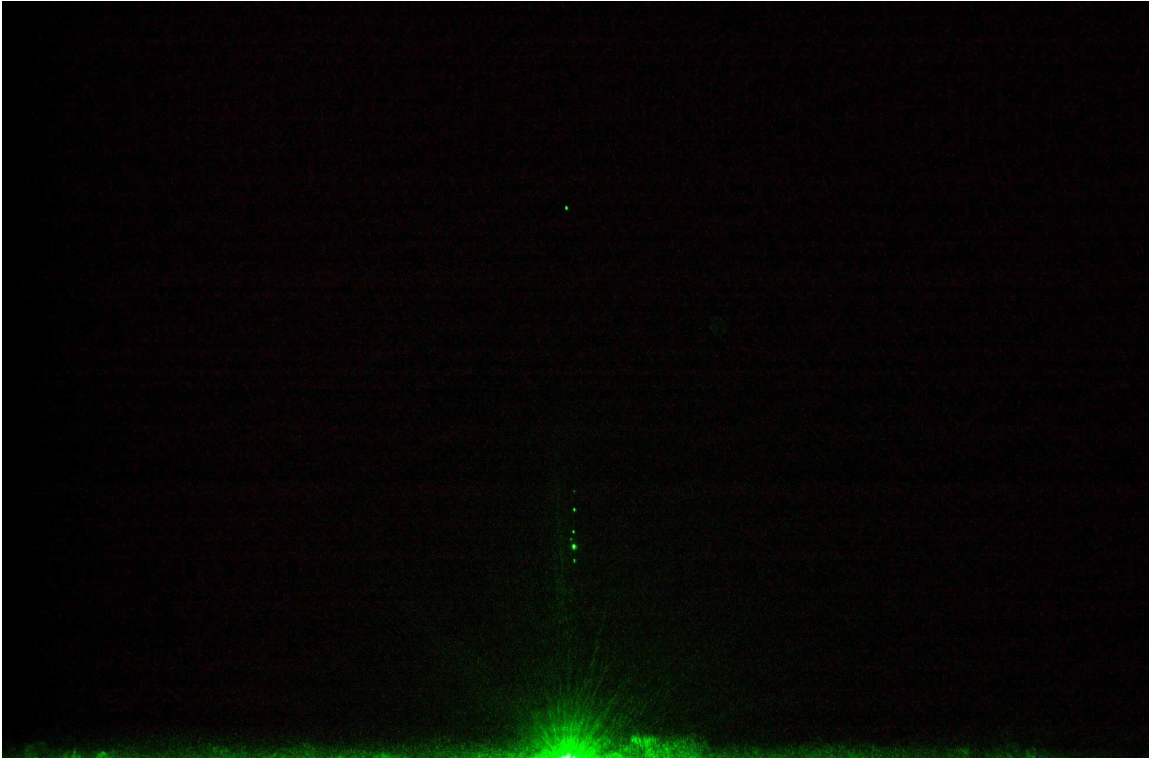


Figure 6.—Shows several particles trapped when a 135 mm camera lens was used to focus the 532 nm laser beam. The bright spot at the bottom of the photograph is light scattered by dust and particles that remain on the glass plate. The top particle was trapped above the focus for a brief time.

Particles were successfully raised and lowered by changing the distance of the focusing lens from the glass plate. By comparing photographs of levitated particles, beam shapes and rulers without moving or changing the camera, we are able to make an estimate of the height at which particles were trapped. Particles were generally trapped just below or just above the focus of the beam. This is consistent with observations made by Ashkin and Dziedzic. They found that when the diameter of the focused area of the beam is smaller than the diameter of a solid levitated sphere, stable trapping regions occurred above and below the beam focus.³ The highest particle trap we were able to measure was about 25 mm above the glass plate, before the particle was lost presumably to air currents within the box. Also, some modicum of success was established when horizontal motion of a group of particles was accomplished by slightly rotating a mirror to move the collimated beam in the horizontal direction. Figure 7 shows a group of glass spheres before horizontal motion was attempted. Figures 8 and 9 show the extremes of horizontal motion that were achieved with that group of particles. The horizontal distance traveled was estimated to be about 1.5 mm. The height is not uniform between the pictures because the mirror that was moved to redirect the beam horizontally did not exhibit strictly horizontal motion. Combined height and horizontal adjustments were not tried at this time.

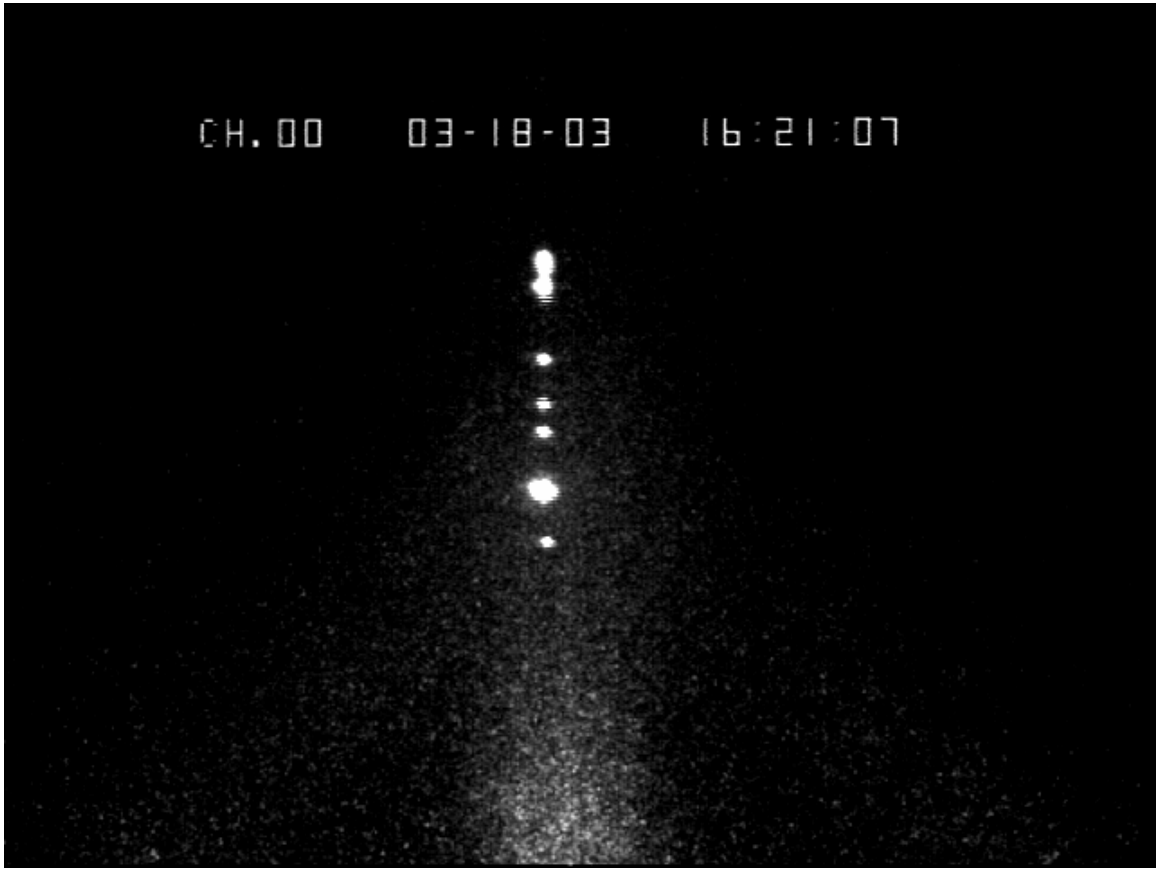


Figure 7.—Several glass beads trapped using 135 mm focal length camera lens to focus 532 nm laser light, prior to adjusting horizontal motion.



Figure 8.—The extreme right of horizontal motion that was achieved with the glass beads shown in figure 7.



Figure 9.—The extreme left horizontal motion that was achieved with the group of glass beads shown in figure 7.

Concluding Remarks

This report presents the results to date of an ongoing research effort to build an optical tweezers interrogation tool for nanotechnology research. Based on these results, we believe that it may be possible to control a probe-tool in a vacuum environment even if the tool-particle is irregularly shaped. We believe it will be possible to maintain control of a tool-particle for several hours if necessary. Further investigation into the manipulation of microscale particles in a vacuum environment is necessary in order to produce a functional probe tool.

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