Final Report: Laser-Based Optical Trap for Remote Sampling of Interplanetary and Atmospheric Particulate Matter

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1. Applicability to Early Stage Innovation NIAC

Cutting edge and innovative technologies are needed to achieve the demanding requirements for NASA origin missions that require sample collection as laid out in the NRC Decadal Survey. This proposal focused on fully understanding the state of remote laser optical trapping techniques for capturing particles and returning them to a target site. In future missions, a laser-based optical trapping system could be deployed on a lander that would then target particles in the lower atmosphere and deliver them to the main instrument for analysis, providing remote access to otherwise inaccessible samples. Alternatively, for a planetary mission the laser could combine ablation and trapping capabilities on targets typically too far away or too hard for traditional drilling sampling systems. For an interstellar mission, a remote laser system could gather particles continuously at a safe distance; this would avoid the necessity of having a spacecraft fly through a target cloud such as a comet tail. If properly designed and implemented, a laser-based optical trapping system could fundamentally change the way scientists design and implement NASA missions that require mass spectroscopy and particle collection.

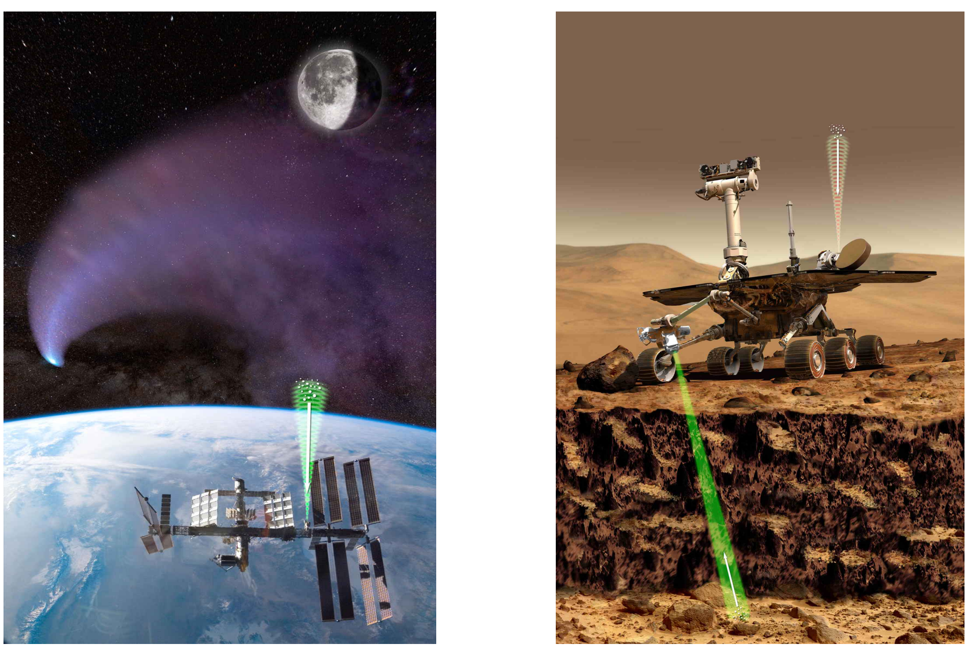

Figure 1 Possible deployment concepts of a laser-based tractor beam. On the left, a system on the ISS captures comet tail samples that pass through the Earth. On the right, a rover is able to gather far off particles despite encountering risky terrain it would otherwise avoid.

The 2013-2022 National Research Council (NRC) Planetary Decadal Survey has several high profile missions featuring orbiters that will perform interstellar and atmospheric particle sampling as well as mass spectroscopy to be carried out by landers [1]. A laser tractor beam system could add powerful remote sensing capabilities on both of these instruments and future systems by either grabbing desired molecules from the upper atmosphere on an orbiter or by trapping particles from the ground or lower atmosphere from a lander. A tractor beam could also significantly reduce the risk of rover and even eventual manned missions that involve sample collection because it could be used to study particles in currently unreachable or dangerous areas. The scientific goals of the comet, asteroid, and other interstellar particle missions currently involve capturing and returning samples to Earth. A Venture-class proposal could be developed that would put a tractor beam on the International Space Station (ISS) to capture comet particles that pass through regularly. This would be a relatively inexpensive proof-of-concept mission that would demonstrate that tractor beams could effectively capture these particles safely over a long range before graduating to a free flyer or rover mission. The tractor beam could be especially well suited for a free flyer mission for capturing delicate targets such as one to Enceladus to capture ice plume particulates [2]. Adding a tractor beam system that could continuously, carefully, and remotely capture particles over a long distance could enhance the science goals and reduce the risk (driving down costs), which would therefore increase the value of all of these missions.

2. Goals of Awarded NIAC

The primary goal of this NIAC was to become fully informed of the current state-of-the-art in optical trapping technology. This was to be done such that models for the potential for use in remote sensing measurements could be determined and evaluated. Furthermore this NIAC would yield estimates for the scalability of the optical trapping systems in regards to range, frequency, and quantity of sample collection. When analyzing the potential of state-of-the-art optical trapping technology, special consideration was given to the range of types of particles that could be captured and if species selection was possible. The ultimate output of this NIAC was to formulate a plan to build and test a system that would demonstrate the remote sensing capability and potential of laser-based optical trapping for NASA missions.

3. Phase I NIAC Results

The field of optical trapping has matured greatly since its inception in the mid-80s, with rapid progress being made over a broad range of disciplines such as physical chemistry, biotechnology, and optical physics. So the first task of the Phase I effort was to conduct a thorough review of the expansive scientific literature available in these fields, and, at the completion of the review, to identify methods of optical trapping and transport that could serve as potential candidates for tractor beam development. Over the course of the review we were able to identify a number of promising methods of optical trapping and transport including: optical tweezers/dipole traps, optical vortex pipelines, focused Bessel beams, solenoid beams, and optical conveyer belts. The Phase I NIAC studying these techniques concentrated on determining if they can be adapted to NASA missions, with a particular focus on potential use in laser optical trapping system that could increase the range, frequency, duration, and quantity of particulate capture.

Table 1 lists the results of this study showing the selected trapping techniques considered in the review. The considered techniques were evaluated on the basis of the proven manipulation range, the environment(s) in which the technique is useful, and the number of laser beams required [3,4,5,6]. In addition, an estimate of the potential operating range with continued development was made for each method.

Table 1: List of potential tractor beam technologies under study .

Trapping Method	Demonstrated Range	Pontential Range	Environment	Required Beams
Optical Tweezers (Ashkin)	< 1mm	<1 cm	Vacuum or atmosphere	1
Vortex Pipelines (Shvedov)	1.5 m	>1 m	Atmosphere only	1 or 2
Bessel Beam (Ng)	NA	<1 cm	Vacuum or atmosphere	1
Solenoid Beam (Grier)	10 μm	>1 m	Vacuum or atmosphere	1
Conveyer Belts (Cizmar, Grier)	250 μm	>1 m	Vacuum or atmosphere	2 or more

After comparing all the different viable techniques we concluded that only solenoid beams, vortex pipelines, and optical conveyer belts are suitable for continued development efforts. These three methods were down-selected using the following criteria: successful experimental demonstration of optical trapping and transport on >0.1 μm diameter particles over a distance of at least a few microns, potential to trap and transport particles at 1 m or greater distances, and use of single or multiple co-propagating laser beams. The environmental requirements for each technique to function were also noted in the selection process. Upon completion of the down-selection process, development plans were crafted for each technique in order to determine if (1) active species filtering/selection was possible, and (2) to assist in the design of a system for future sample collection missions. To help with our assessment of the optical conveyer belt technique, a trapping system utilizing a pair of co-propagating Bessel beams was constructed as seen in Figure 2. In this system, the Bessel beams are generated by transmitting laser light through a pair of axicon optics. This setup will be used to trap and transport polystyrene spheres suspended in water over sub-mm distances, and will help our group better understand the various strengths and limitations of this technique. We are particularly interested in optical conveyer belts as this method has already experimentally demonstrated effective tractor beam action on small (<0.5 um) polystyrene spheres over a distance of 250 μm [3]. Though this part of the Phase I study was not promised in the original goals, as a result of

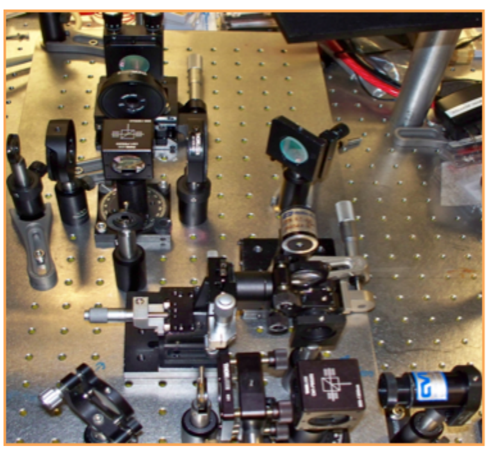

Figure 2: Experimental conveyor tractor beam system built at GSFC during Phase I NIAC.

our work so far we are confident we will have a functioning trapping and transport system soon.

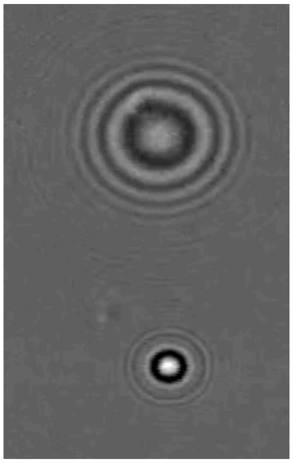

Figure 4: Experimental demonstration of two spheres trapped in optical conveyor belt

To assist with the continued development of the solenoid beam technique and to better understand its ultimate potential for NASA use, we conducted an informal collaboration with Dr. David Grier's group at NYU's Center for Soft Matter Research. Dr. Grier's group has considerable expertise in the field of holographic trapping, and developed the theory behind solenoid beams. Furthermore, Dr. Grier's group has experimentally demonstrated a solenoid tractor beam capable of moving particles by ~10 um, the only such experimental demonstration of a functional single-beam tractor beam to our knowledge. This collaboration covered a number of topics such as possible technological and theoretical advances to extend system range, particle selectivity, and design of a full tractor beam system for spacecraft or landers.

During the course of this study Dr. Grier's group experimentally demonstrated two spheres trapped simultaneously in two conveyors created from a single beam of light with a single hologram. Dr. Grier's group was able to move the spheres in both a forward and reverse motion over a total axis range of 30μm.

Also as a bonus to the original goals of the phase 1 NIAC, we also conducted introductory experiments using optical vortex tractor beams. This technique offers several advantages. First, it is possible to achieve a measure of species selectivity by varying the diameter of the vortex-trapping beam. In addition, it has been experimentally demonstrated that this technique can trap and transport particles up to 120 μm in diameter over distances of 1.5 m in air using dual-beam or single-beam methods; this experimental success makes it an intriguing option for use on planetary surfaces. The primary difficulty with optical vortex pipelines is that there is no simple means of pulling particles upstream against the direction of laser light propagation. To this end, we are currently developing a working version of an optical vortex trap using a spiral phase plate and spare laboratory laser hardware. Developing an in-house laboratory version of a vortex pipeline will give us invaluable hands-on experience with this technique, provide a testbed for implementation of new ideas, and will assist us in possibly developing a mission-type design.

4.0 Roadmap to Flight

Figure 5 shows a high level diagram of major components that will have to be developed to build a full instrument that can capture and analyze particles. These include the laser itself, the optics that manipulate the beam such that it creates an optical pull force, and the beam expander that maintain the needed beam size over a meaningful distance. It is also known that the laser tractor beam will have to be coupled with a processing/analysis component in order to be an effective systems level instrument. These technologies will involve both sample return techniques and active measurement systems such as time-of-flight and ionizing mass spectrometers. All of the instruments being considered (besides the tractor beam) currently exist at TRL-5 and above and will be largely developed outside the scope of the tractor beam efforts. Rather the main challenge in this respect is the systems engineering involved making tractor beam work with the delivery and analysis portions for space flight applications both in vacuum and in atmosphere.

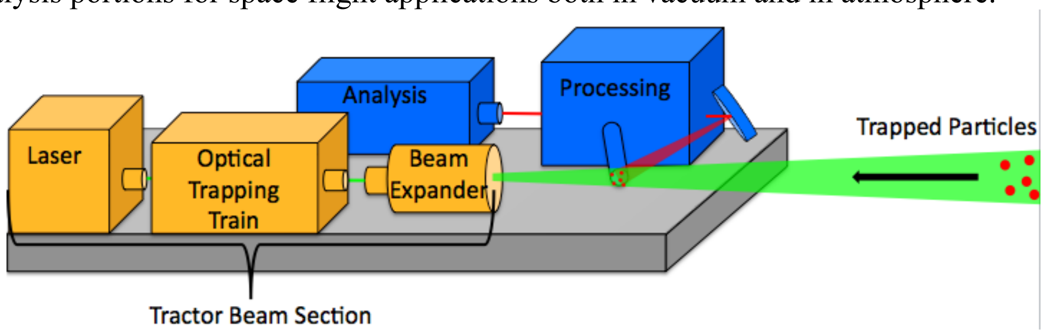

Figure 5: This is a systems view of the components that will need to be developed to make a full capture and analysis tractor beam instrument. The focus of this NIAC proposal will be to develop the yellow tractor beam system and eventually focus on coupling it to TRL 5+ processing and analysis devices.

Currently there are no known key technologies that need to be "invented" in order to start work on a full system short of the tractor beam itself. Even within the tractor beam section in Figure 5, the primary challenges exist within modifying the optical trapping train such that it is possible to capture particles over a long distance. Once the tractor beam is achieving a pull force over meters without damaging or altering particles in any way, the major remaining challenges will primarily involve engineering the different components together vs creating new technology.

Due to lack of funding the short term outlook for developing a tractor beam at NASA is grim. Long-term strategies involve encouraging fundamental research from private and academic sources, which would be monitored, verified, and eventually duplicated by NASA. NASA institutions could then enable and perform work that would significantly upgrade the engineering such that the technologies could be made to be flight ready. Once a near TRL-6 system is achieved, efforts will be made to answer calls for flight-level announcements of opportunity. The TRL development plan is presented in Table 2.

Table 2: Laser tractor beam TRL development.

TRL	Funding	Key Technology Milestones
TRL 3 (2 yrs)	NIAC, IRADs, Space Technology Research Grants	Experiments increasing the range of viable tractor beams for NASA interests from microns to millimeters. Theory behind laser tractor beam optic train will be extended to meter range. The status of captured targets will be studied.
TRL 4 (3 yrs)	Game Changing Development (GCD), STTR, SBIR, IRAD, PIDDP, ACT	Push to making a system work in vacuum over meters continues. Experiments on a full breadboard system showing a trapped particle can be delivered, processed, and analyzed in principle for either a sample return or on board analysis system. Individual components especially in the optical train will be studied for their flight robustness.

TRL 5 (1 yrs)	IIP, PIDDP, ACT STTR, SBIR IRAD	Engineering improvements moving towards space flight will be made at the component level. Simulations of a combined trapping and analysis will be made in a relevant lab environment.
TRL 6 (2 yrs)	IIP, STTR, IRAD	GEVS standard TVAC, vibration, EMI, and radiation testing will be performed on components and a full tractor beam system. Operational testing will be performed on an aircraft system or a flight relevant environment.
Flight	Venture, New Frontier	Proposals will be written focusing on a Mars rover system or putting a Venture-class tractor beam system on the ISS to trap comet particles which could leverage a future free flyer system.

5.0 Conclusion

In conclusion this phase 1 NIAC is considered a resounding success. Not only were the primary goals of determining the feasibility of tractor beams for use on NASA missions and outlining a systems level instrument met but it was found these technologies were actively being advanced in academia. It appeared the only limit to designing and testing a TRL-6 level tractor beam within the next 10 years is the desire to do so. Preliminary experiments, which were not part of the original goals, were also carried out at GSFC in order to gain better insight as to the suitability of certain technologies. This NIAC also won accolades in the press with articles in CNN, BBC, Discovery Science, and many other sources as well as winning the Best Science Story at the NASA GSFC "Science Jamboree".

Perhaps this proposals greatest achievement was in forming a collaborative between private and NASA scientist that are capable of designing a instrument that could carefully capture particles over a meaningful distance, bring that instrument to TRL 6, and that are interested in proposing this instrument to enable previously unachievable science missions. Developing this sort of collaboration, maturing ground breaking technology, and capturing the imagination of the public by making science fiction a reality is in many ways fundamental to what the NIAC program was intended to achieve. Unfortunately, short term there is no funding to continue this promising start. We are hopeful that reviewers will agree with the public in the future and see fit to continue supporting this effort soon.

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