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

Paul Stysley, NASA-GSFC

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Important Terms and Acronyms

AU *– American University,* ***GSFC – Goddard*** *Space Flight Center,* ***ISS*** *– International Space Station,* ***MOMA*** *- Mars Organic Molecule Analyzer****, MSL*** *– Mars Science Laboratory****, NYU*** *– New York University,* ***OSIRIS-REx*** *– Origins Spectral Interpretation Resource Identification Security Regolith Explorer,* ***SAM*** *– Sample Analysis on Mars,* ***TRL*** *– Technology Readiness Level*

1. Introduction

The study of interstellar and planetary particles is a primary goal of NASA's high profile space and Earth science programs. Planetary and interstellar missions such as Pioneer, the Viking Lander, and Cassini have relied heavily on in situ particle collection and analysis [1]. These and more recent instruments like Sample Analysis on Mars (SAM) on the Mars Science Laboratory (MSL), OSIRIS-REx, and Stardust have deployed several different in situ techniques such as Faraday traps, ablation and collection, or trapped matter in aerogel, yielding samples that are then returned to Earth [2,3]. Although these techniques have been successful, the type of particles that can be captured, how often the particles can be captured, the operational range of a lander, or the flight path of a spacecraft have severely limited available data sets. This coupled with instrument complexity and safety concerns can drive up costs and delay schedules. Innovative technologies are required to control costs and increase the viability and capabilities of critical particle collection and analysis missions. This proposal focused studying state-of-the-art laser-based tractor beams to determine their suitability for use on future Decadal Survey missions that require sample 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.

Through the Phase I study we demonstrated that, though the technology is in its infancy, tractor beams do exist but can only move a limited number of targets over micron-level distances. Available technologies are not sufficiently developed such that they would be practical for future NASA missions. In the future, we hope to apply the most promising optical trapping technology, and develop a system that could remotely optically capture a quantity of particulates and transport them back towards the direction of laser propagation over a range of millimeters, while working towards achieving meter-scale operation. The captured samples will also need to be studied to understand the effect the trapping beam has on the particulates. For flight missions these particulates would be delivered to instruments on a spacecraft or lander for continued analysis. Therefore, instead of recording data from one pass of an orbiter or being at the mercy of a solid sample inlet, scientists could choose higher quality targets over a wider range and time period while simultaneously reducing risk and complexity, bringing significantly more value to planetary missions. If properly designed and implemented, a laser-based optical trapping system can fundamentally change the way scientist's design and implement NASA missions that require spectroscopy and particle collection.

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. We also looked at whether the technique would be viable for NASA to become its primary designer and fabricator, as our particular needs are usually unique.

3. Relevance of Technology

The impact of this research is intended to combine and therefore revolutionize the remote sensing and in-situ measurement instruments fields, which fits in well with the goals of the NIAC program. By utilizing laser-based tractor beams, missions will be able to remotely target samples and study them over extended distances. Then the samples could be captured and even returned to Earth for further study. This would be accomplished by enabling and conducting fundamental research in the field of optical trapping that would push primarily the range and quality of the low TRL laser-based technologies to levels not previously considered. Once achieved, this new capability will expand NASA's long-range sample collection goals. It is also important to note that collaborations and partnerships are key to transforming the technologies that have been observed as possible instruments on NASA space flight missions during the phase 1 NIAC study.

Figure 2: A tractor beam could be well suited for the capture of Enceladus ice plume particulates

Impact for NASA

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 [4]. 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 [5]. Our tractor beam research will focus on understanding and optimizing its ability to gently capture difficult targets such as these where other technologies currently available may prove to damaging to the targets. **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**.

Commercial Impact

The capability to pull in particulates or molecular level targets remotely with laser light has a wide range of other applications. Environmental uses include aerosol and pollution monitoring, species identification, and even remote size, shape, or directional sorting and filtering. Future uses for such a technology include hazardous environment work such as remote sampling at radioactive sites or toxic spills where direct human contact could be difficult or dangerous. Precision laser-based cellular manipulation is already a well-developed technology in the biomedical field for research in antibiotics, cellular biology, and other medical research. Currently, this work has focused on only two-dimensional microscopic manipulation in a liquid medium. The implications for a 3-dimensional capability and longer range is important to advancing this medical application out of the laboratory and into public practice and pharmaceutical production.

Finally, micro-mechanical assembly at the molecular or micron-size component level can be performed to assemble micro-machines or nano-scale devices and crystals [6]. The added abilities of possible shape, charge, or dimensional sorting capability would enhance and expand the future applications of full 3-dimensional, long-range tractor beam technology.

4. Description of Studied Technology

Optical Solenoid Beams

The optical solenoid-based technology uses forces exerted with a single beam by gradients in its phase and intensity to capture and transport objects along its length. Depending on design choices, the solenoid either moves material downstream in the direction of the light's propagation, or else can act as a tractor beam, moving illuminated objects upstream. Unlike a conventional Gaussian beam of light, which is brightest along its axis, a solenoid resembles a spiral of radius R and pitch α winding around the optical axis [8]. This structure is shown schematically in Figure 3.

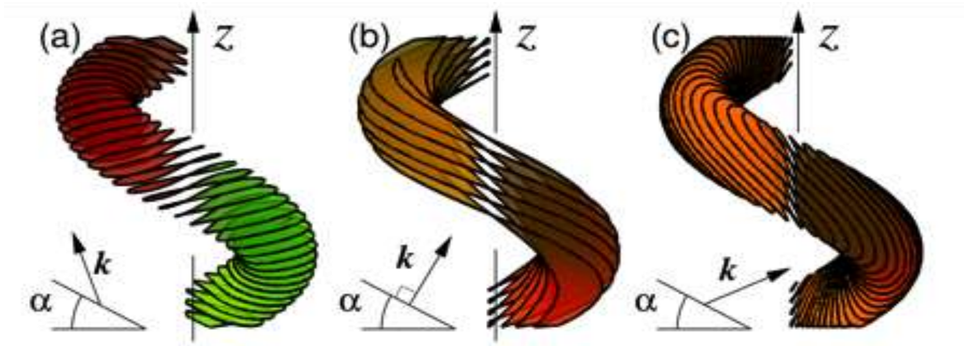


Figure 3: Controlling radiation pressure in a solenoid beam. (a) Wavefronts drawn as surfaces of constant phase direct radiation pressure downstream. (b) Radiation pressure is canceled by gradient forces when wavefronts are aligned with the spiral. (c) Retrograde tilt creates a solenoidal tractor beam.

Intensity gradients give rise to induced-dipole forces that draw objects onto the spiral. This effect is responsible for the ability of optical tweezers to trap objects at the focus of a converging beam [7]. The tilt of the beam's wavefronts, and thus the direction of the local radiation pressure [9], can be controlled independently with an integer winding number ℓ. If ℓ and α have the same sign, as indicated in Figure 3(a), radiation pressure is directed along the spiral and illuminated objects tend to spiral downstream along the solenoid. Setting $\ell = 0$ inclines the wavefronts parallel to the pitch of the intensity spiral, as in Figure 3(b). Intensity-gradient forces diametrically oppose radiation pressure in this configuration. Objects attracted to the spiral by optical forces thus experience no net force moving them either upstream or down. Choosing ℓ and α with opposite signs, by contrast, tilts the wavefronts retrograde to the spiral, as in Figure 3(c). A component of the radiation pressure consequently drives the object backwards along the spiral, thereby achieving the desired function of a tractor beam. Although radiation pressure continues to point substantially down the optical axis, the

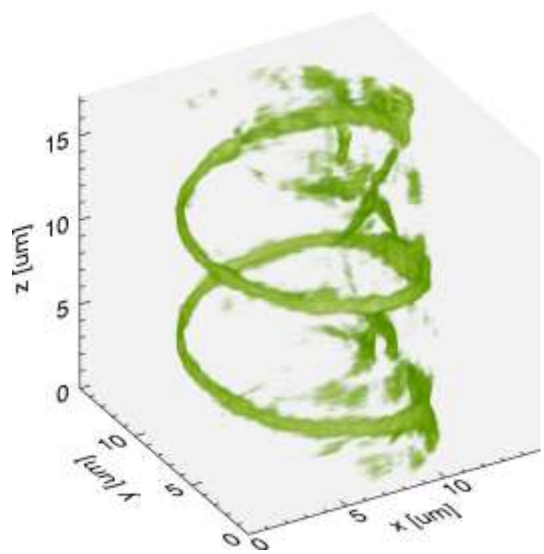


Figure 4 Volumetric reconstruction of an experimentally projected optical solenoid beam, colored by intensity. The beam is propagating upward along *z*.

superposition of radiation pressure with intensity-gradient forces has a net component in the $-\hat{z}$ direction.

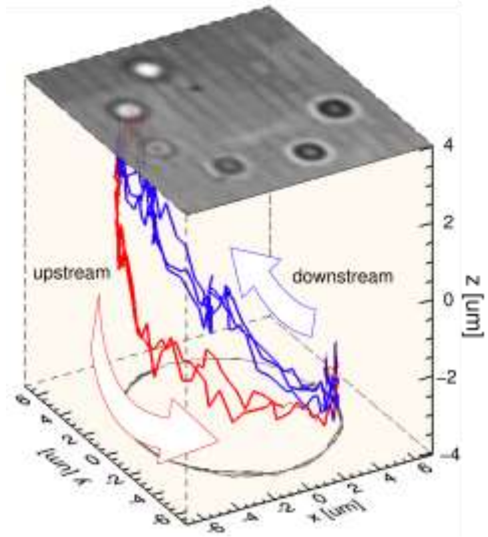


Figure 5: Experimentally measured trajectory of a colloidal silica sphere moving downstream (blue) and upstream (red) along a solenoid beam as the winding number is flipped from +30 to -30.

Solenoid beams have been implemented [7,10] using the holographic optical trapping technique [11-13]. Figure 4 shows the volumetric reconstruction [14] of two axial periods of an experimentally projected solenoid beam propagating in the $+\hat{z}$ direction with $R = 6$ μm and $\alpha = 10$ rad. The image in the upper panel of Figure 5 shows a similar beam trapping and transporting a 1.5-μm-diameter silica sphere in water. The grayscale photograph is a superposition of six microscope images obtained at different times as the particle moves around the spiral. The sphere's changing appearance as it moves in the axial direction makes possible a measurement of its three-dimensional trajectory [15], as plotted beneath the photograph in Figure 5. Setting $\ell = +30$ drives the particle downstream. Setting $\ell = -30$ reverses the particle's direction, as predicted, and moves it upstream. Alternating the sign of ℓ causes the particle reproducibly to trace out upstream and downstream trajectories, as plotted in Figure 4. These data constitute experimental verification of the tractor beam, albeit over a range of just 10 μm.

The principle of the solenoidal tractor beam outlined above makes few assumptions about the physical characteristics of transported objects. **The same beam should transport a wide variety of particles of different sizes, shapes and compositions.** This generality distinguishes the solenoidal tractor beam from other proposed tractor-beam implementations [16–18], all of which are finely tuned.

Optical Conveyors

Optical conveyors are created from a superposition of two coherent coaxial Bessel beams that differ in their axial wavenumbers α and β, and in their relative phase, $\varphi(t)$. This superposition has axial intensity peaks at positions $z_n(t) = [2\pi n + \varphi(t)]/(\alpha - \beta)$, each of which acts as a three-dimensional trap for bright-seeking objects. The volumetric reconstruction of the experimentally projected optical conveyor in Figure 7 shows this structure with spacing Δz

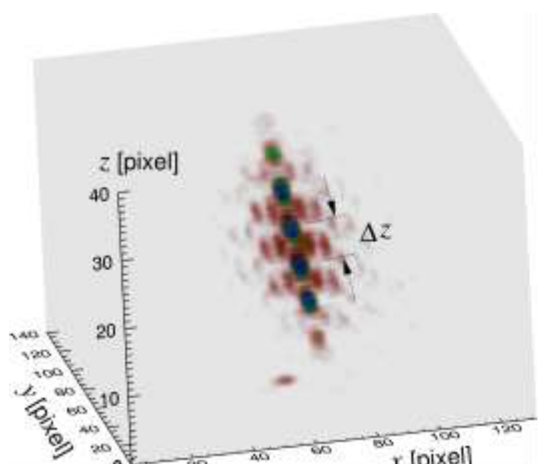


Figure 6: Volumetric reconstruction of an experimentally realized optical conveyor. This technology could trap multiple objects between each maxima.

= 2.5 μm. The self-healing nature of Bessel beams [19,20] furthermore suggests that multiple objects may be trapped along a single conveyor beam despite scattering by each of the trapped objects. Between each pair of maxima, furthermore, is an intensity minimum that is surrounded in the transverse direction by a ring-like sheath of light. This structure, which can be seen in Figure 6, constitutes an optical bottle that acts as a trap for dark-seeking objects. A single optical conveyor beam therefore can simultaneously trap light-seeking and dark-seeking particles.

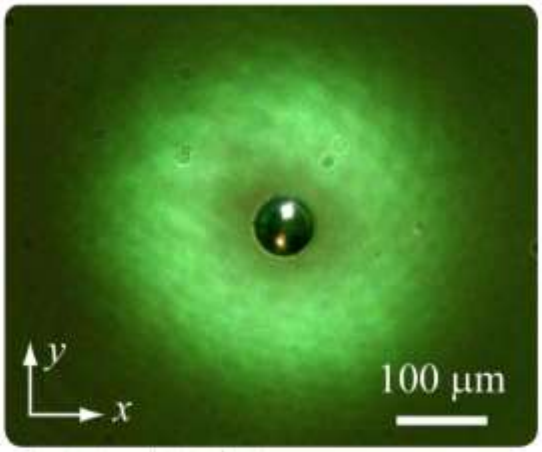
The conveyor's traps can be moved along the axial direction by changing the relative phase, $\varphi(t)$. Increasing the relative phase transports trapped objects away from the source of the beam. Decreasing the phase implements a tractor beam, with all trapped objects moving toward the source at the same rate regardless of their size, shape, or optical properties. This is a substantial advantage over proposed Bessel-based tractor beams [16,17] in which even the sign of the induced motion depends on each object's properties.

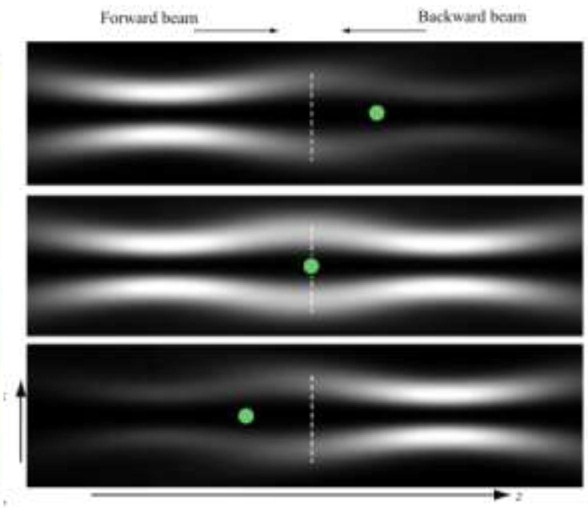
One disadvantage of an optical conveyor relative to a solenoidal tractor beam is the need to vary the relative phase with respect to time. When projected with the holographic optical trapping instrument depicted in Figure 8, this time dependence is implemented with a computer-addressable spatial light modulator. A more mechanically robust implementation might be built around a pair of discrete mode-forming optics arranged in the arms of an interferometer. The necessary phase variations then could be achieved with straightforward mechanical actuation in one of the arms using piezoelectric actuators.

Deterministic transport in an optical conveyor can be achieved by cycling periodically through as few as three values of φ in the range $(0,2\pi)$ [21]. It has been demonstrated that even two values can induce a directed flux of fluid-borne objects through the optical thermal ratchet mechanism [22,23]. When employed for transporting under damped particles in an in viscid medium, the discrete-state optical conveyor may act as a so-called inertial ratchet whose interesting transport properties have been discussed [24], but not extensively studied experimentally.

Vortex Pipelines

A number of recent experimental efforts have shown that, under certain conditions, laser beams can also exert attractive forces on small particles. For example, a scheme using optical vortices was recently shown to effectively trap and transport micron-sized particles. In this scheme, particles are trapped between pair of counter-propagating vortex beams via the photopheretic effect. The ring-like profile of the vortices confines trapped particles to the dark core of the overlapping beams as shown in Figure 8 (a). Particles can then be transported along the center of the vortex by alternately weakening or strengthening the intensity of one of the trapping beams; an illustration of this principle is shown in Figure 8 (b).





(a) **(b)**

Figure 8: (a) Glass microsphere trapped in dark core of optical vortex, and (b) displacement of particle by variation of forward and backward beam intensities.

The optical vortex method has already demonstrated capture and transport of 50 um glass microspheres over a distance of ~1.5 m. The potential exists to extend the transport range to ~10 m, which would be highly useful for remote sample gathering [28].

Bessel Tweezers

An additional single-beam technique for optical micromanipulation and attraction was recently proposed that exploits backward scattering forces induced in particles by certain laser beams. It has been theoretically demonstrated that lasers with a Bessel beam transverse profile (Figure 5) impinging on particles at certain angles can suppress backward scattering events through interference effects between high-order multipoles. This interference effect can induce asymmetric scattering in favor of the forward direction, resulting in a net force on particles that is opposite to the direction of beam propagation. As long as this backward-directed force exceeds the net forward photon pressure, the particle will be drawn back along the beam towards the emission source. Interestingly, the magnitude of the net backward scattering force is dependent on particle size, supplying a potential means of species selective trapping and transport.

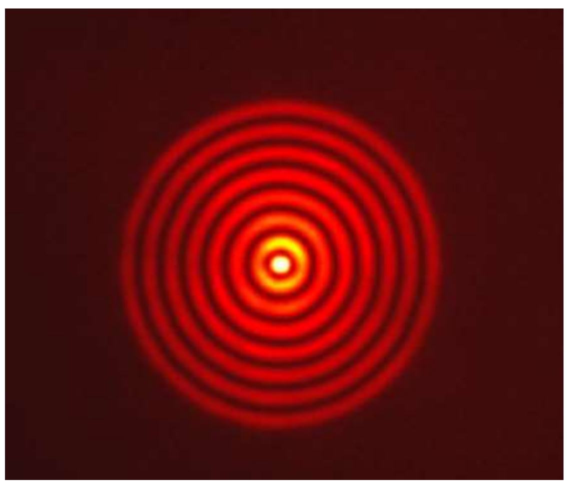


Figure 5: Transverse profile of Bessel beam.

Experimental verification of this technique has yet to be conducted, but modeling results suggest that it should be effective on um-size particles [8].

5. Phase I NIAC Results

The work plan for the Phase I NIAC centered on four key elements: a comprehensive review of state-of-the-art tractor beam technology; determination of the scalability of the potential tractor beam technologies for NASA missions; studying the possibility of laser-based active selection and sorting of trapped particle species; and finally consideration of laser system designs for possible sample collection missions. 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: List of potential tractor beam technologies under study.

Trapping Method	Demonstrated Range	Pontential Range	Environment	Required Beams
Optical Tweezers (Ashkin)	< mm	<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

Table 1 lists the trapping techniques considered in the review, showing the proven manipulation range, the environment(s) in which the technique is useful, and the number of laser beams required. In addition, an estimate of the potential operating range with continued development was made for each method. We conclude 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.

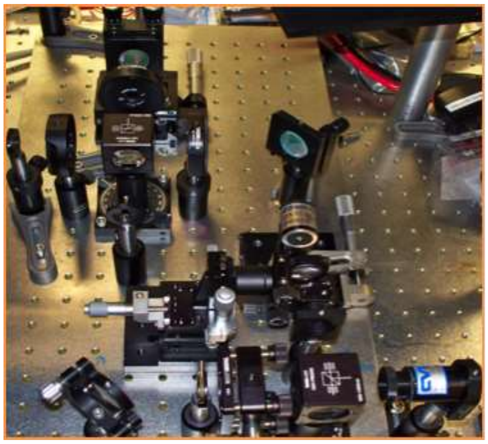


Figure 3: Experimental conveyor tractor beam system built at GSFC during Phase I NIAC.

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 3. 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 [7]. Though this part of the Phase I study is not yet completed, as a result of our work so far we are confident we will have a functioning trapping and transport system soon. The scope and scale of this effort will be widened in Phase II, with new insights and technology implemented to increase system range and robustness. It is also important to note that experimental results were not promised as a part of this Phase 1 study and all of our lab work is considered as a bonus to the promised and achieved goals.

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 which was discussed previously in the *Optical Solenoid* section.

Also as a bonus to the Phase 1 goals, we are conducting 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.

Optical Vortex Beam Technique Detail

Optical vortex beams are generated by imposing a helical phase front on an incident laser beam. This helical phase front produces destructive interference along the beam's axis, giving rise to its distinctive ring-shaped transverse intensity profile (Figure 9). These beams can be produced externally using spiral phase plates or computer-generated holograms, or directly by using specially adapted laser cavities.

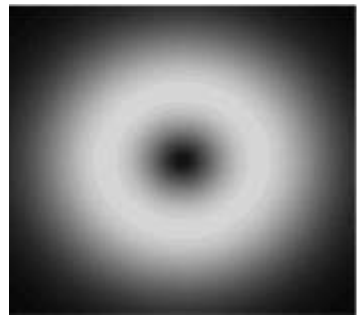


Figure 4: Intensity profile of optical vortex. The vortex technologies could apply a stronger trapping force for planetary mission.

Optical vortex beams have shown to be useful for trapping particles that are strongly light-absorbing. Trapping absorbing particles with conventional optical tweezers techniques is difficult because thermally-induced effects such as thermophoresis can easily overwhelm intensity gradient trapping forces. However, vortex beams allow for the possibility of trapping absorbing particles in the dark core of the beam via photophoretic forces. The uneven heating of the surface of an absorbing particle by the vortex beam causes molecules in the surrounding gaseous or liquid medium to rebound off the heated particle surface at higher velocities, creating a net force directed away from the outer ring; the particle is then transversely confined to the axis of the vortex beam. Photophoretic forces can easily overpower radiation pressure forces, with the former exceeding the latter by up to five orders of magnitude at normal temperatures [28].

So-called optical vortex pipelines have successfully demonstrated optical trapping and transport of particles up to 100 μm in diameter over meter-scale distances [28-31]. The primary drawback of the vortex pipelines utilized thus far is that transporting particles against the beam direction requires use of two counter-propagating beams; however, as mentioned earlier, only single-beam techniques are considered usable for potential missions.

One potential solution to this difficulty is to utilize the nonlinear effect of self-focusing observed in high intensity laser beams. Self-focusing is a nonlinear optical phenomenon arising from the Kerr Effect, where the electric field of an intense laser beam alters the refractive index of a medium according to the relation

$$n(I) = n_o + n_2 I,$$

where I is the laser beam intensity, and n_o and n_2 are the linear and nonlinear indices of refraction, respectively. The critical power required for whole-beam self-focusing to occur is given by

$$P_{cr} = \alpha \frac{\lambda^2}{4\pi n_o n_2},$$

where λ is the laser wavelength, and α is a scalar value depending on the shape of the laser pulse (usually ranging from 1.8-1.9). The peak power required for self-focusing typically falls in the MW range for solids and liquids, while gases require GW-level power. These power levels can be achieved using mode-locked lasers.

Particles trapped inside the self-focus region of an optical vortex will experience a component of the photophoretic force directed back along the direction of beam propagation, creating a tractor beam effect. The position of the self-focused region along the beam path can be moved by "chirping" the laser pulses - modifying the temporal profile of a pulse such that high optical frequencies lead low frequencies - using holographic gratings. Adjusting the self-focus point in this manner allows for the capture and transport of particles at long (>1 m) distances.

Another means of possibly adapting vortex pipelines for a tractor beam system is to use an SLM to modify the wavefronts of a collimated low-power, continuous-wave laser such that the dark core of the vortex shrinks uniformly as the beam propagates forward. Weakly diverging vortex pipelines have already been shown to propel carbon particles up to 120 μm in diameter over a distance of over a meter [28]. By proper modification of the beam wavefront, it should be possible to create a converging vortex, fully adjustable in real-time, capable of maintain sustained upstream particle motion.

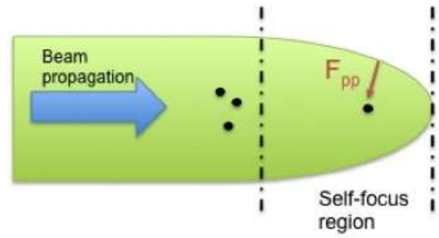


Figure 5: Particles in self-focused region of vortex beam experience force back along optic axis. Manipulation of the self-focusing effect could greatly increase the range of vortex traps.

6. Future Experiments

Vortex Experiments

Experiments with the self-focusing optical vortex traps will be to generate vortex beams from a mode-locked 532 nm laser using a lithographic phase plate. Initial testing will focus on trapping and transporting microspheres in a medium of distilled water since the critical power for self-focusing is much lower (~3-5 MW) than in air. The self-focusing properties of the vortex beam will be investigated by directing the beam into a container of distilled water and measuring the positions of the focal planes. After successful demonstration of self-focusing in water, we will seek to trap polystyrene spheres of varying diameter within the self-focused pipeline. Successful trapping will be verified using a CCD camera equipped with a microscope objective and a holographic notch filter to block scattered laser light. This same type of imaging arrangement will be used to verify trapping of particles in air using the SLM-based converging optical pipeline trap.

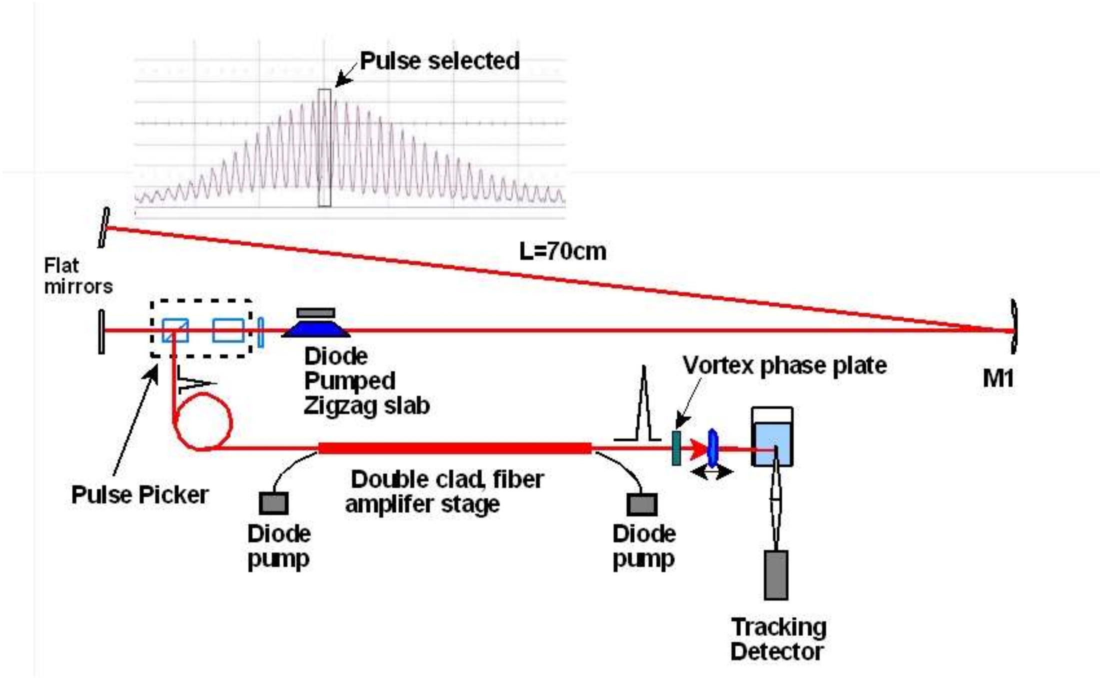


Figure 6: Layout of a self focusing

Solenoid and Conveyor Experiments

The initial round of experiments on extended-range solenoid tractor beams should focus on colloidal spheres dispersed in viscous fluids such as water. Both viscous damping and buoyant forces simplify experimental test of optical forces, in the first case by facilitating trapping and in the second case by minimizing competition with gravity. Although axial transport of micrometer-scale objects over a range of micrometers can be observed with conventional microscopy, millimeter-scale transport requires a much greater depth of focus. Optical trapping capabilities with holographic video microscopy for long-range and high-resolution three-dimensional particle tracking have to be employed to achieve these results. The holographic microscopy subsystem illuminates the sample with a collimated laser beam [32,33]. Light scattered by the sample interferes with the rest of the beam in the focal plane of the same objective lens used to project optical traps. A conventional microscope then magnifies the interference pattern, whose intensity then is recorded with a video camera. The Grier group at NYU has developed techniques for analyzing the holographic snapshots in this video stream to obtain each particle's position in three dimensions with nanometer resolution over an axial range extending to a millimeter [33–38]. Based on the exact Lorenz-Mie theory for light scattering [39], this approach also yields nanometer-resolution measurements of each sphere's radius and part-per-ten-thousand measurements of their complex refractive indexes.

Effect of Trapping on Targets

Scientist consulted at Goddard Space Flight Center who are interested in using this technology for future mission have specifically requested to know the condition of trapped particles once encountering the laser based optical forces. In order to answer their request for action, holographic tracking and characterization needs to be used to confirm the direction and rate of tractor-induced motion, while also providing the data required for assessing dependence on sample properties. Particular attention will be paid to differences in tractor efficiency arising from differences in size, composition, and shape. A combination of experimental, theoretical and computational studies will provide comprehensive assessment of the operating domain of a tractor beam, while simultaneously providing metrics with which a beam's operation may be tailored to a particular application and optimized. Holographic particle characterization also will be useful for *in situ* assessment of light-induced damage to model particles under long-term illumination by tractor beams.

The effects of the incident radiation on the captured sample particulates also need to be monitored closely. Our test plan includes analyzing both quantitatively and qualitatively the morphology and distribution of grain sizes before and after optical capture and transport; this testing will be performed microscopically using a PV100 POL polarizing microscope (equipped with four objectives and capable of both diascopic and episcopic illumination) in the Planetary Environments Lab at NASA/GSFC and an available laser surface particle counter for redundancy. In order to diagnose any changes to the chemical composition of the trapped particulates, we will examine the particulates before and after optical capture by scanning electron microscopy (SEM) methods at NASA/GSFC, including: baseline imaging; qualitative analysis via X-ray spectral mapping; and, quantitative analysis of particulate chemical composition via X-ray quantitation. We will also include the option to extend our chemical investigation to include Electron Spectroscopy for Chemical Analysis (ESCA) at NASA/GSFC and/or electron probe microanalysis (EPMA) at the University of Maryland.

7. Cost and Complexity Benefit of Tractor Beams

Mechanisms destined for spaceflight and rovers have always posed a particular set of risks due to an extreme environment not conducive to lubricants, contamination, extreme temperatures, terrain, and the effects on high precision materials. Testing of all the structure, actuators, mechanical stops, encoders, and electronics for any mechanism is expensive and time consuming. Many tests at the component level, and sometimes at the system level, are performed at excessive limits to induce failure to qualify the design and learn of any design weaknesses. This is a necessary added cost to any critical robotic mechanism for flight use.

When studying materials on other planetary bodies such as asteroids or comets, a relatively simple method of sample collection for a sample return mission is to expose cells of aerogels to space. The spacecraft will then perform a high velocity "flyby" or "fly-through" such as used in comet tail missions like Stardust, or a contact method for gathering samples off an asteroid surface under development for OSIRIS-Rex. The extreme porosity of the aerogels provides a means of capturing particles that lie in its path. However, this method showed that the high impact velocities associated with a fly-by within the aerogel structure caused irreversible damage to the samples and created conditions where the silica aerogel material and cometary dust were impossible to separate for analysis. The OSIRIS-REx mission will bump into asteroid 1999 RQ36 with a robotic arm and attempt to place a dust sampling head, residing on the end of an articulated arm, gently on the surface. This head will then be placed in a protective pod and returned to Earth [40]. This technique and similar robotic arms used on rovers will be limited to a single-shot event of material collection, limited in range, and a reliance on complicated mechanism. They also rely on difficult navigation methods and even avoid attractive scientific targets due to the high risk.

The use of an optical tractor beam can allow new opportunities of long-term space analysis of planetary and interstellar samples. The ability to shadow a planetary body and study its chemical and atomic makeup over a long time period provides unique science capabilities not possible with single-shot sample returns. We intend to ultimately prove that future missions will be able to (a) grab specific particles of choice (charge, size, or shape) and (b) do so without altering the material under retrieval, and deposit them in the spacecraft's on-board spectrometers or storage devices for return. This would all be performed with minimized mechanisms, without the need for complex robotics and all the associated infrastructure and development investment. If proven, a significant leap in solar system data volume, precision, and quality will occur over the coming decades.

8. Mission Application of Technology

Provided in this section are some details of what science could be accomplished with a tractor beam on a rover mission, especially on a planetary body with an atmosphere such as Mars.

In-situ methods of chemical/structural analysis provide an ideal way to analyze precious sample specimens from surface environments and the atmospheres of planetary bodies without introducing potential contaminants or interferences via wet chemical procedures (e.g., SAM derivatization experiments). The transport of loose regolith, atmospheric particulates, and/or ablated products would advance in situ sampling techniques and complement mass spectrometer (MS) analyses, as well as the capture of potential return samples derived from of planetary/asteroidal/cometary environments. Specifically, a remote sensing instrument that could transport particulates over a finite distance, including the delivery of potential analytes to an MS ionization source or ion inlet system, would extend the sampling range of both orbiters and landers. For example, planetary rovers would benefit greatly from this technological advancement, as previously inaccessible stratigraphic sections of rock that may have been unreachable (due to topographic challenges or limitations of the rover's drilling capabilities) would now become viable samples for collection and chemical/structural analysis. Moreover, small body landers or orbiters would also benefit from the in situ sampling of specific surface features; as an example, the controlled transport of targeted cometary particulates could increase the efficiency of collection of cometary material and interstellar dust compared to the passive aerogel capture employed by the Stardust spacecraft. Furthermore, optics-based remote sampling would reduce the risk of potential cross-contamination from other sampling methods, such as aerogel and rover drilling techniques.

As another consideration, laser ablation and laser desorption MS methods, including quadrupole (Q-MS, such as that employed on SAM, LADEE and MAVEN), ion trap (IT-MS, such as that employed on MOMA) and time-of-flight mass spectrometry (TOF-MS), rely upon the delivery of planetary materials to a sample stage or plate before the sample can be ionized and accelerated into the mass spectrometer for chemical/structural analysis

[41]. For example, on the MOMA instrument samples are extracted from the Martian sub-surface via a drill that can extend two meters below the surface. This drill, which requires significant power commitments from the rover's resource allocation, is cleaned necessarily between operations to limit potential cross-contamination [42]. **An in situ optical-based remote sampler would not require such periodic cleaning procedures, which demand further time and power resources, and an optical sampler could extend theoretically well beyond two meters in reach, thus improving significantly our access to previously out-of-reach samples.** Further, as the diameter of the optical beam can be controlled on the order of µm, this technology could increase the resolution of sampling finely-layered sedimentary deposits, thereby improving our ability to characterize stratigraphic sections through geologic time.

9. Roadmap to Flight

Figure 11 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.

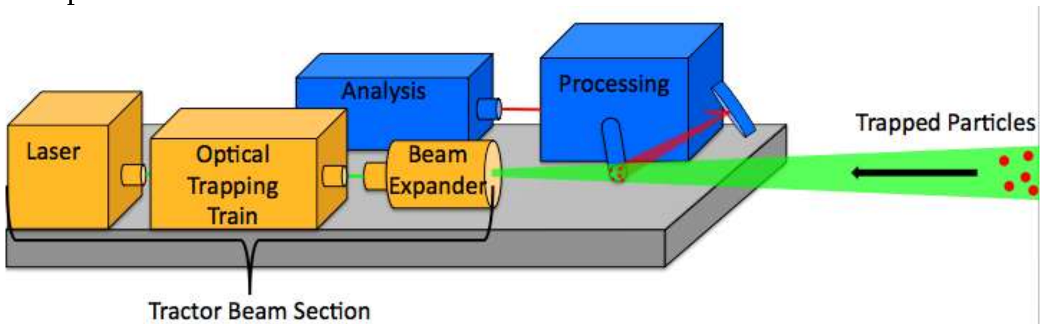


Figure 11: This is a systems view of the components that will need to be developed to make a full capture and analysis tractor beam instrument. The focus of this NIAC proposal will be to develop the yellow tractor beam system and eventually focus on coupling it to TRL 5+ processing and analysis devices.

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.

10. Personnel

PI and Co-Is of Phase 1 NIAC:

Paul Stysley (PI) (Lasers and Electro-Optics Branch NASA Goddard Space Flight Center): Mr. Stysley was hired as a NASA-GSFC civil servant in the July 2010. Before that he has been a laser engineer on a NASA grant with American University over 9 years. He has taken part in several space flight and flight-like laser projects at NASA-GSFC. These include leading the laser build and assisting with the laser management and system design on VCL, LRRP, THEO, DESDynI, and the HOMER ETU FY07 IRAD.
D. Barry Coyle (Co-I): Twenty-two years of laser research and development experience at NASA-GSFC. Began work on the PBUR cavity concepts in the late 1990's which eventually became the HOMER string of designs. Repeated records have been set in laser performance scenarios including low decay rates, measured and extrapolated

lifetimes, and unmatched optical and electrical efficiencies in Nd:YAG Q-Switched systems.

Demetrios Poulios (Co-I) (Associate Professor of Physics, The American University, Co-I on NASA Grant NNX08AJ95A): Dr. Poulios begun as a postdoctoral candidate at GSFC in 2002 and has worked on Q-switched solid-state lasers for LRRP and HOMER, Yb-doped fiber amplifiers for LVIS and LIST, and photonic crystal fiber amplifiers for ICESat-2.

Future Collaborator:

The following scientist wishes to work with us in the future to bring the state of the art tractor beam research to NASA and assist in bringing this technology to TRL 6.

David Grier (Co-I) (Professor of Physics, New York University): Dr. Grier was a postdoctoral member of the technical staff at AT&T Bell Laboratories before joining the faculty of Physics at the University of Chicago. He moved to New York University in 2003 as a founding member of the Center for Soft Matter Research, and was appointed Chair of the Department of Physics in 2005. Dr. Grier's research focuses on the interactions, dynamics and statistical physics of materials in optical force fields.
Role: David Grier will lead experiments on the optical solenoid and conveyor belt tractor beams. He will also lead research increasing the range of all technologies mentioned to 1 meter.

Science Customers:

The following scientists intend to help with the characterization of the trapped particles and wish to use the final TRL 6 tractor beam system for future space flight proposals

Ricardo Arevalo Jr. (Code 699 Planetary Science Collaborator, NASA Goddard Space Flight Center): Dr. Arevalo was hired as a NASA-GSFC civil servant scientist in August 2010. Prior, he was a postdoctoral researcher at the University of Maryland, Plasma Laboratory working in the fields of geochemical analysis and modeling. Dr. Arevalo has extensive experience in laser ablation and laser desorption mass spectrometry, particularly in the analysis of ultra-trace element abundances. He is also a member of the science team for the Mars Organic Molecule Analyzer (MOMA) instrument at NASA-GSFC.
Role: Ricardo Arevalo will lead efforts to evaluate the effects of the incident radiation on the captured/transported sample particulates, as well as facilitate future plans to integrate the tractor beam technology to a FLT-like mass spectrometer assembly. He would also assist in using this technology to propose future rover based missions.

Natasha Johnson (Code 691 Interstellar Science Collaborator, NASA Goddard Space Flight Center): Dr. Johnson's current research focuses on the formation of organics in the early solar nebula using metal-silicate grains as catalysts in a laboratory setting. Prior to arriving at Goddard as a postdoc, she received her PhD from Washington University in

St. Louis by studying the decomposition kinetics of hydrous minerals as applied to Venus. Her previous experience ranges from being a Solar Observer at Mt. Wilson Observatory, counting craters on Mars, to being a guide at a public planetarium.
Role: Natasha Johnson will assist with guiding experiments to understand the condition of the trapped particulates after capture. Her input will focus on using the tractor beam on an ISS mission to capture comet particles that pass through the Earth's orbit.

11. Conclusion

In conclusion this phase 1 NIAC is considered a 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 who are interested in using this new instrument in spaceflight proposals 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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