ABSTRACT FOR HQ REVIEW FOR   
REIMBURSABLE SPACE ACT AGREEMENT (SAA)   
FEASIBILITY STUDY TO IDENTIFY TECHNIQUES FOR PHASING LARGE ARRAYS OF HIGH-POWER LASERS

CENTER / HQ OFFICE SUBMITTING ABSTRACT: JPL   
  
PROPOSED PARTNER:   
BREAKTHROUGH PRIZE FOUNDATION   
901 New York Avenue   
Washington, DC 20001-4432   
Type of Entity: A non-Governmental Domestic Entity   
  
Will the results of work under this Agreement be available for the direct or indirect use or benefit of any foreign entity: No   
  
Is this proposed partnership an exclusive or essentially exclusive arrangement: No

POC FOR HQ REVIEWER QUESTIONS: Doug Gilbertson/818-437-1844   
NASA TECHNICAL POINT OF CONTACT: Dr. Slava G. Turyshev/818-393-2600

DESCRIPTION OF PROPOSED ACTIVITY:   
  
The Partner has a mission to send spacecraft to nearby stars called the Breakthrough StarShot Initiative. The concept is based on gram-scale vehicles (“Starchips”) attached to meter-scale sails (“Laser/Lightsails”) (together called “Nanocraft”) propelled to approximately 20% the speed of light by means of a gigawatt-scale ground-based laser (“Photon Engine”). The Starshot project’s timeline consists of approximately 20-30 years to develop and build the system and approximately 20 years of interstellar flight, followed by approximately 4.3 years of data transmission back to Earth.   
  
The Partner released the Breakthrough StarShot Photon Engine RFP No. 2017-102 to fund study efforts to conceive and analyze one or more viable laser system architectures. The RFP was open to any potential proposers. JPL proposed a study effort based on its unique knowledge and capabilities which was selected by the Partner. Under this effort, JPL will study the feasibility of designing and building a system that would allow for coherent combination of a large number of high-power lasers capable of meeting (with a margin) the entire set of Phase 1 requirements, as specified in the Breakthrough StarShot solicitation.   
  
NASA RESPONSIBILITIES:   
  
1. Develop a model to quantify the performance of JPL’s approach for the Breakthrough Photon Engine that will rely on the pseudorandom number generation.   
2. Develop a comprehensive error budget needed to quantify the performance of the proposed system.   
3. Perform detailed simulation of using an approximate greater than 1GHz arbitrary waveform generator (AWG) to overdrive an EOM to widen the bandwidth of a seed laser which would result in over 10 GHz bandwidth signal for the laser amplifier.   
4. Perform a simulation for a cooperative beacon/wavefront/delay sensor   
5. Conduct economic/cost tradeoff study spanning laser from beacon to wavefront phase/delay sensor.   
6. Participate in Bi-monthly progress meetings   
7. Prepare a follow-on task plan, if requested.   
8. Prepare a final report.

PARTNER RESPONSIBILITIES:   
BREAKTHROUGH PRIZE FOUNDATION:   
  
1. Provide funding.   
2. Provide all schedule requirements.   
3. Monitor progress at bi-monthly meetings and provide feedback of satisfaction of results.   
  
FINANCIAL COMMITMENTS:   
TOTAL REIMBURSEMENT BY PARTNER: Less than $250,000   
TOTAL NASA COSTS WAIVED: None   
FOR RSAAs WITH NON-FEDERAL AGENCY PARTNERS, DESCRIPTION OF HOW THE NASA GOODS, SERVICES, AND FACILITIES TO BE PROVIDED ARE UNIQUE AND NOT AVAILABLE FROM THE U.S. COMMERCIAL MARKET:   
  
JPL has developed unique capabilities in the areas of long-baseline stellar interferometry, coherent laser range-Doppler imaging, and high-power laser ranging. The combination of these unique capabilities is the basis of JPL’s approach to addressing the challenges of the Breakthrough Starshot Photon Engine – a multi-kilometer scale ground-based phased array of beam-steerable lasers with a combined coherent power output of 100 GW needed to transmit this power through the Earth’s atmosphere onto a moving lightweight laser sail about 4 meters in diameter during its acceleration phase while it at a separation from the Photon Engine from 500 km to 1.5 astronomical units (AU).   
  
JPL experience in long-baseline stellar interferometry culminated with the Keck Interferometer that linked the two 10-m Keck telescopes on Mauna Kea with a baseline separation of 85 m. Phasing starlight entering two telescopes separated by 100m required equalizing the optical paths between the two telescopes which change by ~10cm/sec. JPL accomplished this with an error that is approximately 10 nanometers. This is the same type of alignment accuracy that will be required of multiple lasers forming a Photon Engine. As part of the Keck effort, JPL developed many proprietary modeling tools that precisely describe dozens of sources of disturbance from atmospheric turbulence to telescope mount vibrations, as well as the control systems to actively cancel these disturbances. The Keck Interferometer is unique in terms of size scale and accuracy. Consequently, JPL’s experience and tools are unique and not available in Industry.   
  
JPL also has unique capabilities in coherent range Doppler laser radar. JPL has developed a suite of data analysis software (i.e. "synthetic tracking toolbox") that is essential to the Breakthrough Starshot effort. Laser radar, like microwave radar is normally used to measure the range and velocity of objects using lasers (or microwaves). A variant of this technique is used for active imaging, such as in SAR (synthetic aperture radar) and its optical counterpart (SAL synthetic aperture LADAR with lasers). In the Starshot project, JPL’s unique approach is to modify this technique to wavefront sensing for the approximate million sub-aperture Starshot Photon Engine. Based on our analysis of current publications, no other researchers have used (or even thought about) using SAR/SAL techniques for wavefront sensing.   
  
During 2015-17, JPL designed, built, and now it operates a new high-power laser-ranging facility at the Optical Communication Testbed Laboratory (OCTL) situated at the JPL’s Table Mountain Observatory (TMO) that relies on a CW fiber laser at 1064 nm with a 2-kW peak power. The new high-power laser ranging facility will be used for lunar laser ranging (LLR) measurements between the OCTL and arrays of laser corner cube retro-reflectors currently on the Moon which were installed there by the Apollo astronauts. As part of this research, JPL developed instrumentation and modeling software for high power lasers. While many industrial labs, have these high-power lasers none of them are operated in a manor compatible with the wavefront sensing approach using SAR/SAL techniques. JPL has the simulation and modeling software to configure the operation of high-power fiber laser amplifiers compatible with SAL based wavefront sensing.

The capabilities for coherent beam combination available in the U.S. private sector do not meet the Partner’s needs. Although, multiple defense contractors (namely, Raytheon, Northrup Grumman, MIT/Lincoln Laboratory, and Boeing) work on phasing high-power lasers, they are not developing solutions applicable to the problem of phasing across a kilometer-sized distributed aperture. These companies are instead developing phasing techniques that can work for laser transmitters separated by a few meters. Such techniques would require optical delay lines many kilometers in length, which is infeasible in the Partner’s envisioned system.

JPL’s approach is unique: it will work for laser transmitters separated by over a kilometer from each other, it will be applicable to a fast-moving and accelerating target, it would account for the Earth’s atmosphere, and, finally, it will be feasible and scalable to millions of lasers that ultimately will be combined to form the StarShot Photon Engine.

Lastly, it should be noted that this award to JPL was the result of the Partner competitive process which was open to many organizations including large defense companies and educational organizations. As noted by the Partner, “JPL has demonstrated that they have unique experience in this field and possess certain software and modeling tools that we believe to be vital to the effort. This expertise is neither available elsewhere nor was it demonstrated in other proposals received.” Consequently, on the basis of the Partner’s selection process, JPL’s approach was also considered unique and not available from other industry or educational organizations.

RESOURCE COMMITMENTS:   
PERSONNEL: CALTECH FTE: Less than 2 SUBCONTRACTOR WYE: Less than 2   
  
FACILITIES: Jet Propulsion Laboratory, 169-223 and 169-220B – the offices of Michael Shao and Slava Turyshev, correspondingly.   
  
EQUIPMENT/PROPERTY: None   
  
OTHER DIRECT COST FOR NASA INVOLVED: None

ARE THE DATA RIGHTS AND INTELLECTUAL PROPERTY PROVISIONS FOR THE PROPOSED AGREEMENT EXPECTED TO VARY FROM THE RECOMMENDED LANGUAGE IN THE SAAG? No

TERM OF AGREEMENT: 1 Years

AFFECTED NASA HEADQUARTERS MISSION DIRECTORATE(S), HEADQUARTERS MISSION SUPPORT OFFICES, OR OTHER CENTERS: Mission Directorate: Human Exploration and Operations   
  
NASA TECHNOLOGY AREAS (ROADMAPS) THIS AGREEMENT WILL LIKELY HELP ADVANCE: TA02 In-Space Propulsion Systems, TA03 Space Power and Energy Storage, TA05 Communication, Navigation and Orbital Debris Tracking and Characterization Systems

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| DESCRIPTION OF HOW AGREEMENT SUPPORTS NASA MISSION:   NASA has a special interest in supporting the Breakthrough Starshot efforts because of the several efforts relevant to optical communication and navigation in deep space, as well as direct energy transfer and propulsion. The current concept of deploying optical communications in deep space involves using a ground-based laser beacon at JPL’s Table Mountain Observatory composed of several high-power lasers, similar to those used by the Partner. Also, a part the proposed solution for the Partner’s RFP would using on-board astrometric measurements to close the feedback loop to provide precision pointing nearly in real time – a mechanism that would help NASA to implement optical laser-enabled navigation in deep space. Also, JPL has developed and collaborated on several mission concepts that rely on solar sails (notably, NEA Scout and originally Lunar Flashlight both developed in collaboration with NASA’s MSFC, etc.) – a concept similar to that but relying on laser sails and external laser propulsion is used by the Partner. Under NASA Innovative Advanced Concepts (NIAC) funding, JPL is pioneering the efforts on the developments of a breakthrough architecture that uses a kilometer-scale, multi-hundred-megawatt phased-array laser to beam power to a vehicle that converts it to electrical power for a multi-megawatt electric propulsion system. This agreement will also benefit the Deep Space Optical Communications (DSOC) mission featuring optical communication technology which is a current technology demonstration effort to be flown on the Psyche mission. These efforts are ongoing and will benefit from the results of this study.    WHAT CENTER-LEVEL DECISION-MAKING AUTHORITY (I.E., PRE-APPROVAL BOARD OR MANAGEMENT OFFICIAL) HAS AUTHORIZED THE WORK TO BE DONE UNDER THIS AGREEMENT? PLEASE CITE THE NAME AND TITLE OF THE INDIVIDUAL AND/OR BOARD AND THE DATE OF THE APPROVAL:  This effort has been approved by JPL Laboratory Deputy Director, Larry James on December 4, 2017   CONFIRM THAT THE PROPOSED PARTNERSHIP ACTIVITY WAS REVIEWED FOR ALIGNMENT WITH THE AGENCY’S CAPABILITY LEADERSHIP MODEL AND CENTER ROLES DESIGNATION AND IDENTIFY THE AGENCY CAPABILITY LEADER(S) AND/OR CENTER CAPABILITY LEADER TEAM MEMBER(S) CONSULTED OR, IF NONE WERE CONSULTED, PLEASE EXPLAIN WHY.   Capability Leadership approval is in process.    ADDITIONAL COMMENTS:   This abstract is being submitted as the Breakthough Prize Foundation is a unique space funding organization. |