PROJECT SUMMARY

PROJECT TITLE Solar Sail Nano Vehicle

TECHNICAL ABSTRACT (LIMIT 200 WORDS)

Most exploratory space vehicles are propulsion limited. Extra flybys, orbit plane change maneuvers, and new targets must be planned very carefully to use the available propulsion system to it' maximum efficiency. Because of the cost of launching any spacecraft, only high value missions may be undertaken. Since a solar sail vehicle doesn't have a practical limit on the delta V it can expend, it can therefor undertake very energetic missions or several simpler ones. Current designs for high performance vehicles have considerable risk involved. A simpler micro-spacecraft derived vehicle can easily and cheaply investigate multiple near earth targets and simultaneously demonstrate the utility of small solar sails.

The Solar Sail Nano Vehicle project demonstrates a solar propelled near-Earth vehicle using conventional materials. A very small core vehicle with modern communication systems drastically reduces the size of the sails and also lends itself to hitchhiker payloads. The use of conventional simple sail and mast components coupled with our experience with very small spacecraft systems allow reasonable performance with what would otherwise be considered low performance materials.

This proposal is to continue design and construction of a small solar sail vehicle for immediate use in near earth space.

POTENTIAL COMMERCIAL APPLICATIONS

Several commercial applications of this type of vehicle are immediately obvious. The first is undoubtedly investigation and observation of other satellites. Flying in the close proximity of a aged or damaged satellite can reveal much about how to improve the design or repair damage. With the unlimited impulse available to a sail, vehicle towing may actually be possible. Towing a satellite out of GEO at the end of it’s life would allow the operator to use up the end-of-life-deorbit reserves significantly extending their revenue producing time. Similarly, illumination of solar panels with the reflected light of a sail can boost power output of satellites. Attitude and orbital placement may someday also be possible with similar systems. Another possible commercial application is providing a communication media for advertising. A maneuverable reflector can be programmed to be seen at different times in different places, consider the advertisement possibilities of a few dozen spacecraft and the appropriate commands.

NAME AND ADDRESS OF PRINCIPAL INVESTIGATOR

Gary E. Snyder, Jr. Lakewood, Colorado 80226

Part 1: Identification and Significance of the Innovation

Most exploratory space vehicles are propulsion limited. Extra flybys, orbit plane change maneuvers, and new targets must be planned very carefully to use the available propulsion system to it' maximum efficiency. Because of the cost of launching any spacecraft, only high value missions may be undertaken. Since a solar sail vehicle doesn't have a practical limit on the delta V it can expend, it can therefor undertake very energetic missions or several simpler ones. Current designs for high performance vehicles have considerable risk involved. A simpler micro-spacecraft derived vehicle can easily and cheaply investigate multiple near earth targets and simultaneously demonstrate the utility of small solar sails.

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Solar Sail Flight Vehicle

The solar sail is a space propulsion device which uses a thin reflecting foil to deflect sunlight, transferring the change in momentum of the solar light flux to the sail. The advantage of the sail is that it can produce thrust without the use of propellant. While accelerations are slow, thrust is continuous for long periods of time, allowing very high velocity changes to be developed.

The solar sail has appeared in astronautical literature since the turn of the century, first discussed by Tsilokovsky and then other early space pioneers. In the late 1970's, it was intensively studied at Jet Propulsion Laboratory as a possible propulsion option for a very high ΔV Halley's Comet mission. Because of the large mass of the spacecraft (> 2000 kg) and the large ΔV, the solar sail required for this mission was very large (> 1 sq kilometer). Largely because of the challenges associated with this and similar grandiose ideas for implementation of the solar sail concept, no solar sail has ever flown. (circ 1998 -ed.)

While most of the interest in solar sails has come from the interplanetary mission community, small solar sail spacecraft have great utility for missions in geocentric space. At altitudes above 1000 km, solar light pressure exceeds aerodynamic drag, allowing a solar sail propelled spacecraft to operate in and between many regions of interest, including high LEO, MEO, GTO, Molniya, and GEO orbits. A small solar sail spacecraft could be used to investigate other satellites, or Earth orbital regions such as the Earth/Moon Lagrange libration points or the Moon. Depending upon the duration of the mission, the solar sail vehicle could observe a target briefly or sustain the relative position for long periods of time. An additional use would be to employ solar sail spacecraft to reflect light toward other observers. Unlike other visual displays, the sail could be commanded change its appearance by rotations.

While many have devoted attention to improving the potential performance of solar sail spacecraft by developing thinner sail materials and components, in-house demonstrations by the Principle Investigator have shown that existing technology is already adequate to create solar sail vehicles that can perform useful missions. What is needed is to get solar sail technology out of realm of the possible and into operation as a near-term, flight demonstration of a small, simple, cheap, and yet useful system. We are proposing such a flight demonstration program at a reasonable price.

Demonstration Vehicle Concept

The baseline for the Solar Sail Nano Vehicle is a small spacecraft equipped with three triangular solar sail "wings" each rotating around unique axes 120 degrees apart. The central pyramidal section is wrapped with photovoltaic cells for power production. Each solar sail wing is a right triangle with masts 15 meters on a side. The edges of the sails are held in place by deployable spring steel masts, electrothermotechnically released from their rolled up positions.

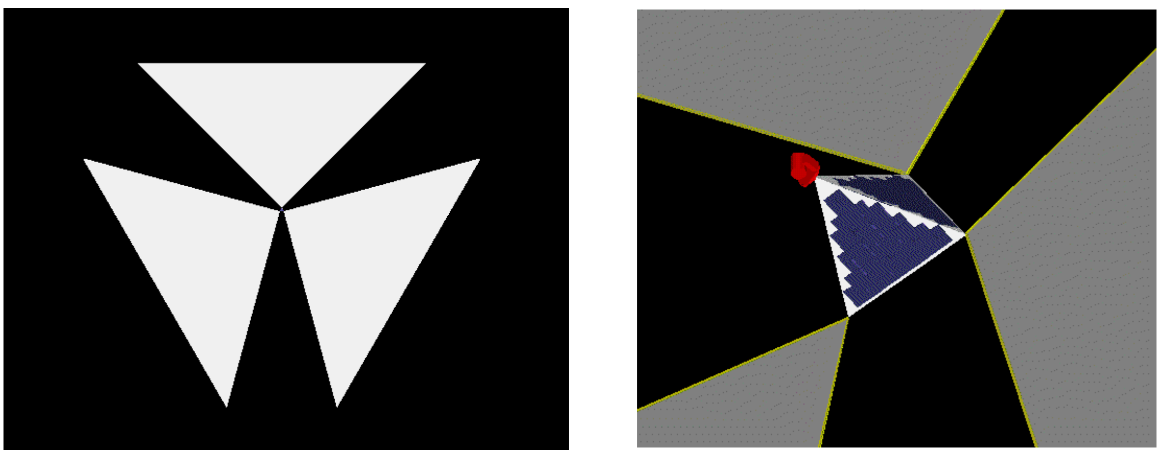

Figure 1 Solar Sail Vehicle

Our demonstration Solar Sail Nano Vehicle design concept is shown in Figure 1, while its key features are summarized in Table 1. The momentum flux of sunlight at 1 AU is 9 micronewtons per square meter. The maximum total thrust produced by the 337 m^2 of sail is thus 3 milliNewtons (mN). Conventional locally acquired materials easily produce sails with densities of 15 grams/m^2, so the total mass of the sails themselves is 5 kg or less. Again, off-the-shelf materials produce 1.05 kg masts and less than 0.95 kg for other parasitic mass such as servos, 10 kg for the spacecraft, and 3 kg for margin, for a total system mass of 20 kg. The system thus has a characteristic self-acceleration of 0.00015 m/s^2, or 13 m/s/day. If it were to continuously accelerate at this rate, a ΔV of 1 km/s could be generated in 76 days. While such continuous self-accelerations would not occur in geocentric space, the order of magnitude of this parameter shows that the spacecraft will be capable of useful maneuvers within meaningful time limits.

Mass (g)		Features	
Sail	5000	Total Sail Area	337 m^2
Masts	1050	Mast Length	15 m
Sail Servos	180	Body Edge length	30cm
Frame	2000	Side Area	390 cm^2
Computer	150	Volume	780 cm^3
PV arrays	1120	PV Power	6 watts
Batteries	400	Battery capacity	20 Watt/hours
Power Conditioning	50	Transmitter Power	5 Watts
Communications	100	Data Rate (GEO)	1200 BPS
Antennas	120	Max range	Data rate limited
Camera	100	Minimum Alt	1000 km
Camera Servos	100	Turn Rate	0.006 deg/sec^2
GPS Rcvr	150	Delta V / Day	13 m/s
Shield/Margin	15000	Mission Delta V	Unlimited
Total Mass	20000		

Table 1. Solar Sail Vehicle Information.

The entire spacecraft is transported to a medium or geo-transfer orbit as a hitchhiker payload. After release from the carrier spacecraft, and a suitable delay, one mast of each sail is deployed. As envisioned, and previously demonstrated, the masts will be folded and rolled to allow sufficient volume to contain the sail. After one of each mast is unrolled and deployed, the sail and remaining mast will be unrolled. Attitude stability may be assured by immediately implementing a windmill style rotation. Proper spacecraft operation may then commence.

Operation of this Solar Sail Vehicle concept can best be demonstrated by considering an example. Let's say that the vehicle is in GEO, and we wish to relocate it to another GEO position on the opposite side of the Earth. We might choose to thrust against the direction of motion for an arc segment of 120 degrees (+- 60 degrees about the location where the sail would be normal to the Sun). This is 1/3 of the orbit, and due to cosine losses (the sail would not generally be normal to the incident sunlight) of a factor of 0.707, the net ΔV per day would be (13.1)(0.707)/3 = 3.09 m/s. In 10 days of such reverse apogee kicks, a ΔV of about 31 m/s would be generated. GEO velocity and semi-major axis are 3,072 m/s and 4,2241 km, respectively. This ΔV would change the spacecraft's orbit to an ellipse with an apogee at 4,2241 km but an apogee velocity of 3,041 m/s. The perigee would drop to 40,705 km from the earth's center, and the orbital period of the spacecraft would decrease to 23.36 hours. It would thus travel around the Earth about 0.64 hours quicker than a GEO satellite, allowing it to transfer to the other side of the Earth in about 19 days. If both the time to speed up and slow down, and the orbital location change developed during thrusting are all taken into account, the entire maneuver (drop, wait, and return to GEO on the Earth's other side) would take about 30 days. This is quick enough to be useful (a high thrust chemical system expelling enough propellant to create 74 m/s of ΔV would take 14 days to perform the same maneuver).

<u>Vehicle Control</u>

Figure 2 shows the vehicle with its sail axis definitions. We term one axis the "Y" axis. The other two are the '-Y-X' and 'X-Y'.

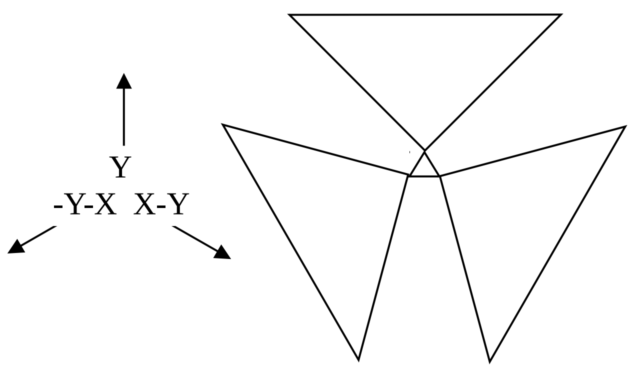

Figure 2. Solar Sail Spacecraft Vehicle Axis Definition.

Dividing the solar sail into three wings allows the spacecraft to be controlled without additional vanes or any RCS system. For example, if it is desired to turn the spacecraft about the X axis, either the Y axis sail is turned perpendicular to the incident sunlight (Z direction) or both the –X-Y and X-Y sails are turned, as displayed in Figure 2, while the other sails are kept in the sunlight normal plane. This imbalance of solar force around the vehicle center of mass results in a moment that will cause the vehicle to turn. The calculated rate of angular acceleration is 0.0001 radians/s^2, which would result in a turn of 45 degrees in 130 seconds or a turn and stop of 45 degrees in 190 seconds. This is much shorter than the natural rate of turning associated with GEO orbits (3 hours for a 45 degree turn), and indicates that for the large majority of such maneuvers, only partial tilting of the sail will be required. Turning other sets or individual sails can produce rotations about the –X-Y or X-Y axis. By rotating the vehicle about the Z axis or combining other rotation maneuvers, any rotation can be produced. If it is desired to roll the spacecraft about the Z axis, all of the sails would be turned equally a few degrees out of the their plane, thus forming a "light rotor" that will cause the vehicle to autorotate, see Figure 3.

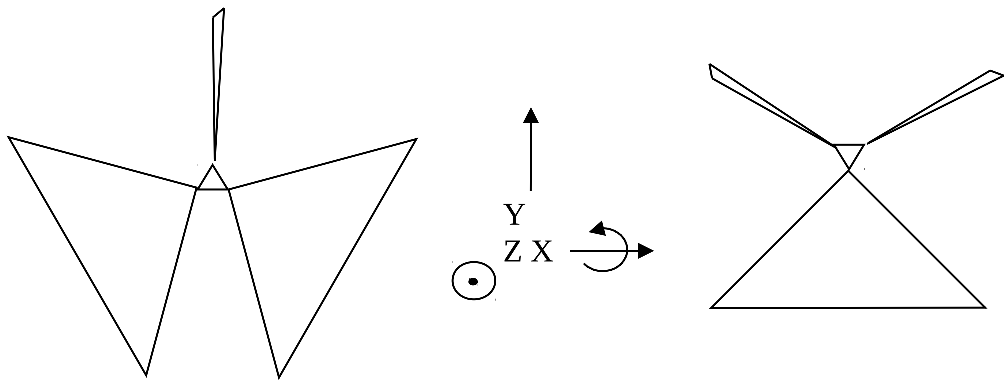

Figure 3. +X Axis Rotation.

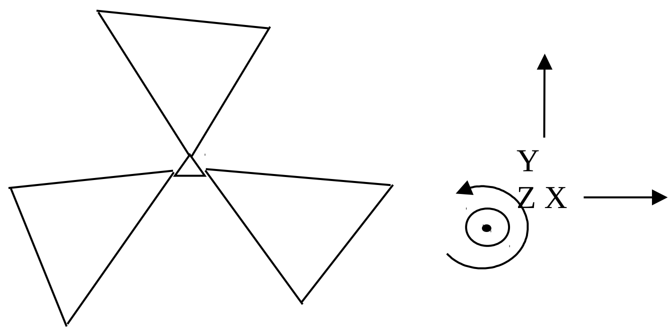

Figure 4. Z Axis Rotation.

The three triangular sail configuration has an advantage over a two sail system because there is no attitude where some control authority can not be used. The advantage over a four sail system is simply one less actuator.

It should be observed that in the past, most solar sail designs have incorporated large fixed sails with small vanes at the corners for control. While adequate for interplanetary spacecraft, such systems have insufficient control authority to rapidly turn the spacecraft in the manner required for a spacecraft operating in geocentric space. The design presented here, in which the entire wing turns, is thus uniquely appropriate to meet near Earth requirements.

Spacecraft Design

The Solar Sail Vehicle is designed as a low cost concept demonstration using existing materials and systems. In order to ride as a hitchhiker payload, it is necessarily a microspacecraft. Although it's deployed size will be quite impressive, it must mass in the tens of kilograms. Because of the low thrust environment involved in likely missions, the bare minimum lifetime of the vehicle must be at least weeks long. Conversely, the maximum lifetime of a sail vehicle is not limited by propellant usage and may be indefinite. In fact, as long as the systems continue to operate, the vehicle may be tasked with new missions as interest arises in different regions of cis-lunar space. One consideration for component failure, especially in PV arrays, is the amount of time spent in high radiation zone. Considerable shielding mass has been allocated for protection of sensitive devices.

Spacecraft Structure and Intergration.

The solar sail vehicle will consist of a central tetrahedral body with three right isosceles triangular sails extending out in one plane of the body as seen in figure 5. The sails are composed of a sheet of aluminized milar attached to 2 masts. The masts are 15 meters long and constructed from two semicircular spring steel ribbons attached back to back and to the sail as in Figure 6. The connection point between two masts forms a right angle and is attached to a rod running to the servo in the body. A right angle gives the most sail area for a given mast length. The tetrahedral body is probably composed of aluminum for simplicity. On each face is a solar array (Figure 5).

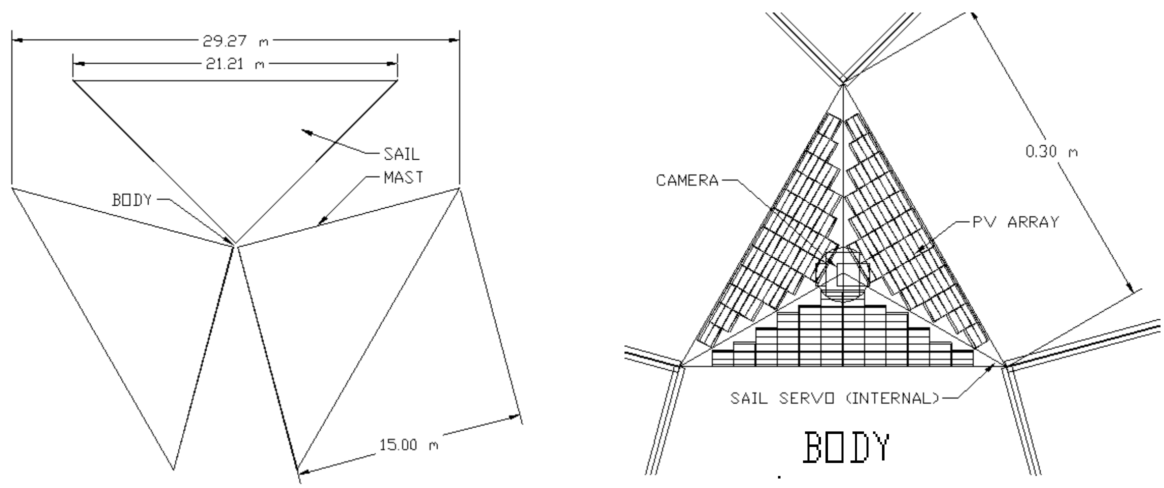

Figure 5 Solar Sail Vehicle dimensions

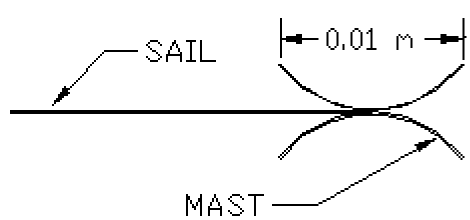

Figure 6. Mast Construction, end view

Because the 4 faces are arranged in the tetrahedral manner, there is always sunlight incident on some of the arrays. In three of the vertexes are the servos to spin the sail, and on the fourth is one of the camera's drive servos. The camera is nominally mounted on this fourth vertex although for greater view of the sail a deployable tower will be considered.

<u>Spacecraft Electronics</u>. The spacecraft is powered by photovoltaic cells and secondary batteries. The cells are sized around the spacecraft to provide enough power to run critical systems even with a temporary loss of attitude. Onboard electronics control the charging of the secondary batteries and provide variable power levels to the assorted systems. The vehicle communicates with a small UHF radio and antennas. Telemetry and commands are exchanged via a 1200 BPS packet modem. Transmitting to a 20 m receiving dish on Earth, this system has an estimated SNR of several hundred at GEO and will allow effective communication as far as lunar distances. Faster data rates are easily possible with more sophisticated equipment. A tiny CCD camera gives it a view in important directions, allowing it to image the sails to assess correct deployment. Pictures are stored, compressed, and periodically relayed to Earth. Additionally, the CCD is equipped with a normally opaque LCD filter, allowing the sun to be directly imaged. This, coupled with imaging the Earth and Moon, provides accurate attitude information.

Three electric servomotors allow each of the wings to be rotated independently. Since there are no electrically operated devices in the wings, the servos may be rotated indefinitely without the need for slip rings or cable windup. Computer control of the servos with accurate position and velocity limit structural stresses while preventing and damping oscillatory motions.

GPS and communication antennas are envisioned as mounted on the facets of the spacecraft body. Since reasonable performance with the communication system requires LNAs and T/R switches, scanning and switching between higher gain antennas pointing in all 4 directions is simple.

Ground tracking and onboard GPS provide information on the spacecraft's position. Since the orbital dynamics do not change rapidly (very low acceleration), GPS GDOP constraints are not a limiting factor. Simple, single satellite range data can easily track the orbital elements of the vehicle. A small onboard computer with large flash memory storage allows many images and command sequences to be stored. Real time control or long preprogrammed sequences allow the vehicle to be remotely operated from a single station on the ground.

It should be noted that much of the proposed spacecraft electrical system design architecture is based on a system that we were developing for prior projects. By leveraging our extensive capabilities in space exploration systems and technologies to this challenging project, a considerable amount of hardware development can be done at minimal cost to the customer.

The preliminary design analysis presented above, shows a cost-effective, near-term demonstration of Solar Spacecraft Vehicle is feasible. This concept has many challenging technical and integration issues, but does offer a "high-off" scientific pay-off in terms of low-cost planetary exploration. Therefore, we are proposing a Phase I study to address the key design issues, quantify the potential performance, and demonstrate the fundamental feasibility of the low-cost, near-term Solar Spacecraft Vehicle concept. If based on these results of this effort, the Solar Spacecraft Vehicle concept continues to look promising, a follow-on Phase II effort shall be proposed that will design and build and a demonstration Solar Spacecraft Vehicle that can be flown as a hitchhiker payload on a future launch.

Part 2: Technical Objectives

In Phase I we will examine the feasibility and potential performance of a magnetic sail propulsion system. The following questions will be addressed:

A. Technology: What are the key technologies required for the implementation of the low-cost, near-term Solar Sail Vehicle concept and what are their current readiness levels?

B. Performance: Given current technologies, what level of performance can be expected from a Solar Sail Vehicle? What are the key near-term improvements that appear feasible which could significantly improve that performance? What are the possible long-term technology improvements that appear feasible and what ultimate performance of solar sail technology would they enable?

C. Design: What is the best approach to the design of a low-cost, near-term, demonstration Solar Sail Vehicle system? What are the requirements of such a system? What is the performance of such a system? How can attitude be controlled and course adjustments be made?

D. Demonstration: What is the best option for a near-term demonstration of solar sail technology in space? How should such an experiment be designed? How can it be implemented?

As part of this proposed effort, we shall select and procure typical materials, test deployment schemes, test scaled actuators, design, build and modify existing spacecraft systems, produce a mission plan, and construct a sub-scale, breadboard-type, demonstration solar sail vehicle. In the follow-on Phase II effort, we shall design in detail, and build a demonstration Solar Spacecraft Vehicle that can be flown as a hitchhiker payload on a future launch.

Part 3: Phase I Work Plan

It is planned that the Phase I program will be a six month effort. The schedule for this shall be as follows:

Task 1. Literature, and Components Search:

Activity Schedule: Month 1 :

Manpower Support (hours):

Principle Investigator	60
Chief Scientist	6
Research Scientist	40
Design Engineer	40

A literature search will be conducted to assemble a large collection of related materials. Since the components to fabricate the sail and masts may be procured more cheaply and in superior configurations (larger or lighter pieces) from alternate suppliers, alternate sources will be investigated. Modifications to the existing spacecraft systems will be identified.

Task 2. Analysis and Simulation:

Activity Schedule: Months 1 and 2

Manpower Support (hours):

Principle Investigator	20
Chief Scientist	6
Research Scientist	40
Design Engineer	20

Analysis of servo controls, sail control authority and required computer power will be performed. Structural calculations will confirm required strength estimates for components such as the masts and sail material. Mission analysis will be started. Simulation software will be written in a IBM PC compatible language to propagate the desired vehicle trajectories using solar and atmospheric models. .

Task 3. System Design:

Activity Schedule: Months 2 and 3

Manpower Support (hours):

Principle Investigator	80
Chief Scientist	12
Research Scientist	20
Design Engineer	60

An initial design of the solar sail vehicle will be completed during this subtask effort. Vehicle performance shall be defined. Test articles such as deployment and servo control systems with scaled masses and forces will be designed. The mission simulation software will be expanded to add fidelity as needed, allowing us to simulate the solar and gravitational forces and moments on the spacecraft, modeling its behavior as it maneuvers through geocentric space. Using this software, a plan for the mission to be conducted during Phase II will be developed.

Task 4. Component Demonstration Tests:

Activity Schedule: Months 3 and 4

:Manpower Support (hours):

Principle Investigator	100
Chief Scientist	15
Research Scientist	10
Design Engineer	100

Critical solar sail vehicle components will be tested through simulation during this study task effort. Based on the preliminary design analysis discussed in Part 1, the sail servos, masts, and material will be tested at representative load, dynamic response, and duty cycle conditions of interest to the demonstration Solar Sail Vehicle system. These tests shall be performed at our test facility Lakewood, CO. This test site has fully instrumented capabilities to perform static and dynamic load, rocket engine, and high-pressure tank tests, as well as support development of complex chemical process and electrical systems. The test facility also has on-site capabilities to support manufacturing of test article, facility equipment, and electronic system hardware. We have extensive experience and capabilities to perform such a feasibility test in an efficient, timely manor.

Task 5. Subscale Vehicle System Demonstration:

Activity Schedule: Months 4 and 5

Manpower Support (hours):

Principle Investigator	100
Chief Scientist	15
Research Scientist	10
Design Engineer	100

A sub-scale, breadboard Solar Sail Vehicle system will be design, built, and tested in this task effort. The engineering analysis, design definition, and component test results preformed during Tasks 2, 3 and 4 will be used to perform this task. Critical static load and systems integration tests, such as control response of sail system, of the whole system will performed to demonstrate the feasibility and soundness of the design.

Task 6. Vehicle Flight System Design:

Activity Schedule: Months 5 and 6

Manpower Support (hours):

Principle Investigator	80
Chief Scientist	18
Research Scientist	10
Design Engineer	100

Based on the results from the previous study subtasks, an initial design of a promising demonstration Solar Spacecraft Nano Vehicle that can be flown as a hitchhiker payload on a future launch, which will demonstrate this technology, shall be produced in this subtask effort. An engineering layout drawing and the corresponding technical description of the proposed Phase II Solar Spacecraft Nano Vehicle shall be provided, as well as supporting schedule and cost information. A final report documenting all the analytical, experimental and design results of this study will be written and delivered to the customer.

Total Project Manhours:

Principal Investigator	440
Research Scientists	130
Design Engineer	420

Part 4: Related R & D

This proposed study will draw on a gondola with required deployment, power, communications, imaging, storage, and processing systems in a sub-kilogram package. Modifying this to include attitude sensor, photovoltaic power converters, and sail motion servo systems appears to be relatively straightforward.

Most “conventional” solar sail designs have been for large, high performance systems. Our in house demonstrations have focused on smaller, simpler designs with common components. This allows for a drastic reduction in deployment complexity, cost, time, and risk. The implementation of solar sail is similar in risk to teather. We consider this project akin to the SEDS tether experiments, in contrast to the Shuttle tether flights. We wish to demonstrate the utility of the Solar Sail Vehicle while performing multiple interesting missions on a very low budget.

Part 5: Key Personnel and Bibliography of Directly Related Work

Dr. Gary E. Snyder, Jr.: Dr. Snyder has a B.S. in Electrical and Computer Engineering specializing in VLSI design and computer systems from Washington State University (1989), a M.S. (1991) and Ph.D. (1994) in Aerospace Engineering, specializing in astrodynamics, from The University of Colorado at Boulder. His Ph.D. dissertation was entitled: “Attitude Determination from a Codeless GPS Signal Processing System.” Dr. Snyder .... etc.

Part 6: Relationship with Phase II and other future R/R&D

The relationship between Phases I, II, and III of the proposed project is completely direct. The results of the Phase I study will be a feasibility demonstration and an initial design of a demonstration Solar Spacecraft Nano Vehicle that can be flown as a hitchhiker payload on a future launch. Additionally, engineering plans will also be supplied at the conclusion of the Phase I study effort to build and test demonstration Solar Spacecraft Vehicle. In Phase II, the demonstration Solar Spacecraft Vehicle designed in Phase I will be built and ground tested. In Phase III this demonstration Solar Spacecraft Vehicle will be flown as a hitchhiker payload which can be used to orbit transfer for commercial satellites or planetary exploration.

Part 7: Facilities

Part 8: Company Information

Part 9: Subcontracts and Consultants

Part 10 : Commercial Applications Potential

Several commercial applications of this type of vehicle are immediately obvious. The first is undoubtedly investigation and observation of other satellites. Flying in the close proximity of a aged or damaged satellite can reveal much about how to improve the design or repair damage. With the unlimited impulse available to a sail, vehicle towing may actually be possible. Towing a satellite out of GEO at the end of it's life would allow the operator to use up the end-of-life-deorbit reserves significantly extending their revenue producing time. Similarly, illumination of solar panels with the reflected light of a sail can boost power output of satellites. Attitude and orbital placement may someday also be possible with similar systems. Another possible commercial application is providing a communication media for advertising. A maneuverable reflector can be programmed to be seen at different times in different places, consider the advertisement possibilities of a few dozen spacecraft and the appropriate commands.