National Aeronautics
and Space Administration

AUGUST 25, 2004
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NASA RESEARCH ANNOUNCEMENT

NEW MILLENNIUM PROGRAM
SPACE TECHNOLOGY - 9

NOTICE OF INTENT: SEPTEMBER 24, 2004
PROPOSALS DUE: NOVEMBER 24, 2004

OMB Approval Number 2700-0087

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)
HEADQUARTERS
OFFICE OF SPACE SCIENCE
300 E STREET SW
WASHINGTON, DC 20546-0001

NEW MILLENNIUM PROGRAM SPACE TECHNOLOGY-9 (ST9)

NEW
NASA RESEARCH ANNOUNCEMENT
SOLICITING TECHNOLOGY PROPOSALS

NHH04ZSS002N

CATALOG OF FEDERAL DOMESTIC ASSISTANCE (CDFA) NUMBER: 00.000

ISSUED: AUGUST 25, 2004

PROPOSALS DUE
November 24, 2004

SYNOPSIS

NASA's Office of Space Science (OSS) issues this NASA Research Announcement (NRA) for the New Millennium Program (NMP) to solicit proposals for its Space Technology-9 (ST9) system flight validation opportunity. The goal of NMP is to validate, through flight in space, breakthrough technologies that show distinct promise of being able to minimize risk of first use and reduce cost for future space science and exploration missions. This NRA solicits proposals for advanced technologies to be incorporated into a system-level flight validation experiment in the 2007-2008 time frame. NMP defines a system-level technology validation mission as one in which a single spacecraft is dedicated to the in-space validation of a system-level technology advance and incorporates those component and subsystem technology advances necessary for the success of the new system. Proposers may submit multiple proposals; however, each proposal may address technology advances in only one of the following Technology Concept Areas (TCAs):

- Solar Sail Flight System Technology,
- Precision Formation Flying System Technology,
- System Technology for Large Space Telescopes,
- Descent and Terminal Guidance System Technology for Pinpoint Landing and Hazard Avoidance, or
- Aerocapture System Technology for Planetary Missions.

Pending the submission of proposals of sufficient merit, several investigations may be selected for each of the five TCAs for a six-month study phase. The number of awards for needed technology advances and the maximum funding contemplated for the ST9 Study Phase are provided under the respective TCA descriptions in the Appendices A through E to this NRA. Successful proposals will be awarded subcontracts under NASA's contract with the Jet Propulsion Laboratory (JPL), a Federally Funded Research and Development Center (FFRDC). In order to prevent and perception of conflict of interest, JPL will not be involved in the evaluation or selection of awards under this NRA.

This ST9 opportunity is open to all types of U.S. organizations, including industry, universities, FFRDCs (including JPL), NASA Centers, the Jet Propulsion Laboratory, and other U.S. Government agencies. Participation by foreign organizations is permitted; however, NASA policy is to conduct research with foreign entities on a cooperative, no-exchange-of-funds basis.

An important objective of NASA's vision is Education and Public Outreach (E/PO). Therefore, all program participants selected for the Formulation Refinement phase are invited and encouraged to participate in the E/PO activity initiated during that phase.

Details for the solicited TCAs are given in Appendices A through E, and the due date for proposals is given in Table 2 of the *Summary of Solicitation*. Proposals submitted after this due date will be considered late and handled in accordance with the NASA FAR Supplement 1852.235-72(g).

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I. Description of Opportunity

(a) Introduction

The National Aeronautics and Space Administration's (NASA) Vision,

To improve life here, to extend life to there, and to find life beyond,

and its Mission,

To understand and protect our home planet,
To explore the Universe and search for life, and
To inspire the next generation of explorers
…as only NASA can,

allow the objectives and goals of the NASA Science Mission Office to be clearly defined as the orderly pursuit of two key strategic goals: (i) To understand the Earth system and apply Earth system science to improve prediction of climate, weather, and natural hazards, and (ii) To explore the solar system and the Universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere. Further valuable, in depth insight into these objectives may be found in the following documents:

- NASA Policy Directive (NPD) 1000.1, *"NASA 2003 Strategic Plan,"* at http://ifmp.nasa.gov/codeb/docs/2003_Strategic_Plan.pdf, and
- *Space Science Enterprise 2003 Strategy*, accessed through the links "Administration Publications" from the OSS homepage at http://spacescience.nasa.gov.

Within the directions established by NASA's Vision and Mission statements, the Space Science Enterprise pursues two, key strategic goals:

- To explore the Solar System and the Universe beyond, and
- To understand the origin and evolution of life, and search for evidence of life elsewhere.

The New Millennium Program (NMP) was created by the Space Science Enterprise in order to

- Identify by working with science-mission planners those key, breakthrough technology advances that require in-space validation to mitigate the risk of their first use, and
- Conduct the necessary in-space validation projects.

These goals also provide the data that can enhance many missions within NASA's newest Enterprise, Exploration Systems. The New Millennium Program validates technology advances that allow these Space Science goals to be achieved more readily, hastening the time when the goals of both Enterprises may be realized.

The technology objectives for which proposals are solicited under this NRA are listed in Table 1. Proposers may submit multiple proposals; however, each proposal shall address only one of the Technology Capability Areas (TCAs).

Each TCA in described in detail in Appendices A through E. Each Appendix first presents the system-level flight validation concept, which includes the advanced technology description and anticipated benefit, a description of the validation objectives, and the rationale for technology validation. Additional details are then presented for science mission applicability, representative space experience, a concept for the flight experiment, technology selection opportunities and planned funding levels, advanced technology performance requirements, and a representative project schedule. Further information on missions discussed in the science mission applicability sections can be found on the following NASA websites:

Office of Space Science (OSS)	http://spacescience.nasa.gov/
NASA OSS theme websites:	
Exploration of the Solar System (ESS)	http://sse.jpl.nasa.gov/
Structure and Evolution of the Universe (SEU)	http://universe.gsfc.nasa.gov/
Sun Earth Connection (SEC)	http://sec.gsfc.nasa.gov/
Astronomical Search for Origins (ASO)	http://origins.jpl.nasa.gov/

Each TCA is a candidate for in-space validation on the ST9 mission. In turn, each TCA requires certain technology advances at the component or subsystem level (Table 1) to be successful. The desired technological capabilities to be supplied by the specifically solicited component- and subsystem-level technology advances are described in detail in Appendices A through E of this NASA Research Announcement (NRA) (one appendix for each TCA).

Table 1. ST9 Technology Capability Area (TCA).

Technology Capability Area	Specific Solicited Technology Advances
Solar Sail Flight System Technology (Appendix A)	▪ Sail Propulsion Subsystem ▪ In-Space Inspection Subsystem ▪ Sail as Sensing Instrument
Precision Formation Flying System Technology (Appendix B)	▪ Formation Sensor ▪ Intersatellite Communication Subsystem ▪ Point-to-Point Ranging Sensor
System Technology for Large Space Telescopes (Appendix C)	▪ Sunshade ▪ Mechanical 4 K Cryocooler
Terrain-Guided Automatic Landing System Technology for Spacecraft (TGALS) (Appendix D)	▪ Terrain Sensing and Recognition Hardware and Software ▪ Propulsion Subsystem
Aerocapture System Technology for Planetary Missions (Appendix E)	▪ Aerocapture Guidance Algorithm and Software ▪ Advanced Aerocapture Instrumentation ▪ Advanced Thermal Protection Materials

As shown in Figure 1, proposers selected through this NRA will be funded to join Government members and together to form a TCA team for a six-month Concept Definition Phase to prepare the Concept Definition Study Report. Review panels selected by NASA HQ will evaluate each Concept Definition Study Report. On the basis of these evaluations, one TCA Team will be selected and funded to proceed into the Formulation Refinement Phase (the Concept Definition Phase and the Formulation Refinement Phase together comprise the Formulation Phase defined in NASA Procedures and Guidelines (NPG) 7120.5b, *NASA Program and Project Management Processes and Requirements*, November 2002).

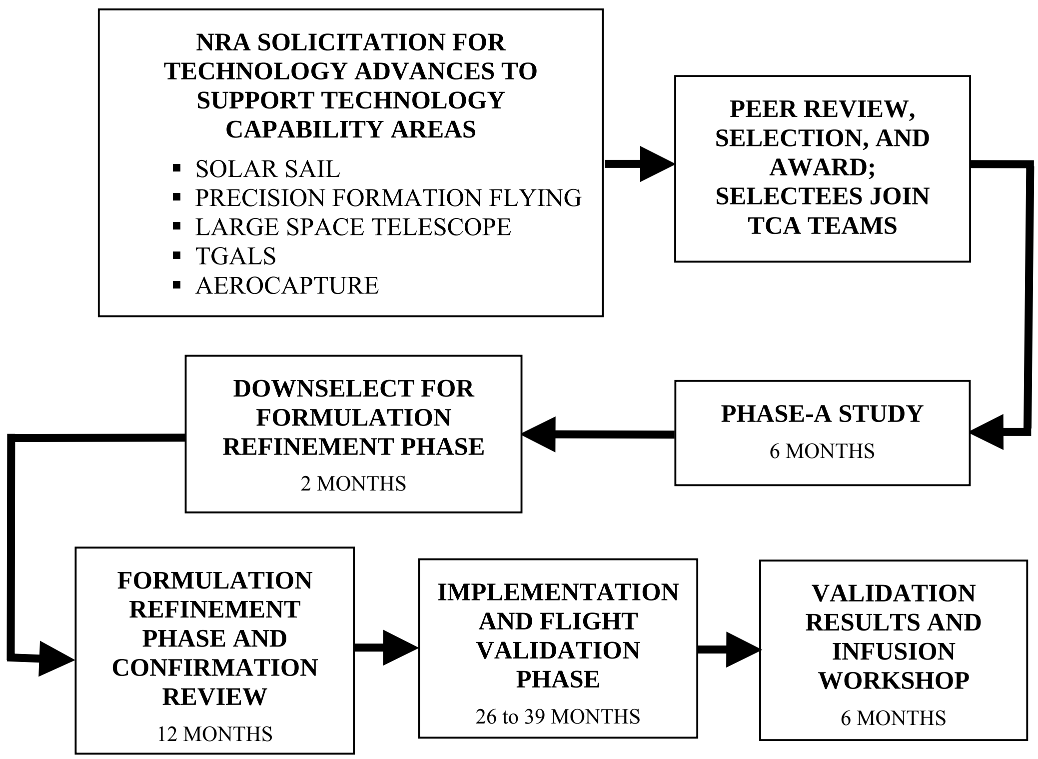


Figure 1. An overview of the ST9 Project.

The selected TCA Team will use the Formulation Refinement Phase to refine the design and cost estimate for the selected validation experiment. The Formulation Refinement Phase concludes with the Preliminary Design Review, the approval of the experiment's Technology Validation Plan, and the Confirmation Review. Subject to a final authorization review, the Associate Administrator for Space Science will authorize one ST9 TCA Team to initiate the Implementation Phase. At the Confirmation Review, prior to the start of the Implementation Phase, the ST9 Project will be required to demonstrate a minimum cost reserve of 30% against the cost-to-complete estimate and a minimum of 20% funded schedule margin.

The TCA Team that proceeds to in-space validation will be required to deliver data from the flight to NASA in a Final Technology Validation Report. In addition, a Final Technology Validation Report is required from each proposer no later than six months after the flight validation of any hardware and/or software. Documentation of the technology's performance, its validation results, and the correlation of those results with models or predictions are required as part of the Final Reports. Detailed requirements for the Final Technology Validation Reports will be incorporated into the contracts (or other agreements) prior to the Implementation Phase.

The total funding allocated to the ST9 technology validation opportunity, for all phases (including the Study Phase) and all associated technologies, is $90M in Real Year dollars. Project costs will include the technology development, overall ST9 project implementation, flight operations, data processing, and technology validation reporting. The cost of access to space is not included in the $90M allocation and will be funded by the NMP office. The NASA New Start Inflation Index (available from NASA Headquarters, Office of the Chief Financial Officer, Cost Analysis Division) is to be used for determination of project costs.

Securing access to space for the ST9 concept selected for Formulation Refinement and Implementation will be the responsibility of the NMP. The ST9 opportunity for those concepts requiring orbital flight is baselined as a secondary payload launch. However, the NMP has allocated funding to acquire a "Pegasus class" launch vehicle should a dedicated launch be required.

This NRA addresses participation in the Concept Definition Phase of ST9. Accordingly, cost evaluations will be made on the proposed cost for the six-month Study Phase and for the anticipated Formulation Refinement and Implementation Phases. Questions about each of the TCAs may be directed to the Programmatic Contact identified in Table 2, Summary Information Applicable to this NRA.

All dimensions and other physical quantities used in the formulation and implementation of models, model output, or supplied in the supporting data and documentation must be in SI units, unless otherwise specified in the TCAs' performance requirements.

(b) Opportunity for Education/Public Outreach

As part of its response to the NASA mission to inspire the next generation of explorers, OSS is committed to fostering the broad involvement of the space science research community in Education and Public Outreach (E/PO) with the goal of enhancing the nation's formal education system and contributing to the broad public understanding of science, mathematics, and technology. Progress towards achieving this goal has become an important part of the broad justification for the public support of space science. In addition, an enhanced, coordinated Agency-level education program is now being undertaken through the NASA Office of Education.

OSS strongly encourages space science researchers to actively engage in education and public outreach as an important component of their NASA-supported professional activities. They key documents that establish the basic policies and guidance for all OSS E/PO activities *are Partners in Education: A Strategy for Integrating Education and Public Outreach Into NASA's Space Science Programs* (March 1995), *Implementing the Office of Space Science Education/Public Outreach Strategy* (October 1996), and the *Explanatory Guide to the NASA Office of Space Science Education and Public Outreach Evaluation Criteria* (March 2004). Additional information concerning NASA Education and Public Outreach may be found in the NASA Education Enterprise Strategy (October 2003) at http://www.education.nasa.gov/about/strategy/index.html and the Space Science Enterprise Strategy (October 2003) at http://spacescience.nasa.gov/admin/pubs/index.htm. These documents may be accessed electronically by selecting "Education" from the menu on the OSS homepage at the World Wide Web address http://spacescience.nasa.gov/ , or may be obtained in hard copy from Dr. Philip J. Sakimoto, Office of Space Science, Code S, NASA Headquarters, Washington DC 20546; (E-mail: philip.j.sakimoto@nasa.gov).

A summary of the key elements of the current OSS E/PO program that will apply to all proposers selected to participate in the Concept Definition Study Phase, is as follows:

- An E/PO plan must be included as part of the Concept Definition Study Report,
- E/PO plans will play an explicit role in the evaluation of the Study Reports and in the selection of investigations that will continue into the Formulation Refinement Phase;
- The E/PO project budget should be approximately 1% of the total proposed budget for Formulation Refinement and Implementation;
- Each NMP Project will conduct its E/PO activities in accordance with its E/PO Plan, which shall include provisions for providing technical expertise in support of the overall NMP E/PO Program; and
- Each project's E/PO activities shall emphasize technology education rather than science education, and should have a direct intellectual link to the technologies being developed by the project.

For further information regarding NMP E/PO activities, visit the NMP Website, http://nmp.jpl.nasa.gov and the "Spaceplace" http://spaceplace.jpl.nasa.gov/, or contact Ms. Nancy Leon (telephone: (818) 354-1067; E-mail: Nancy.J.Leon@jpl.nasa.gov). Questions and/or comments and suggestions about the OSS E/PO program are sincerely welcomed and may be directed to Dr. Larry Cooper (telephone (202) 358-1531; E-mail: Larry.P.Cooper@nasa.gov).

(c) NASA Safety Policy

All prospective proposers to this NRA are advised that the highest priority in all of NASA's programs is safety, which is defined to mean the freedom from those conditions that can cause death, injury, occupational illness, damage or loss of equipment or property, or damage to the environment. NASA's safety priority is to protect: (i) the public, (ii) astronauts and pilots, (iii) the NASA workforce (including employees working under NASA award instruments), and (iv) high-value equipment and property.

(d) Availability of Funds for Awards

Funds are not available for awards under this announcement at the time of its release. The Government's obligation to make awards is contingent upon the availability of appropriated funds from which payment can be made and the receipt of proposals that NASA determines are acceptable for award under this announcement.

(e) Environmental Protection Policy

Proposers are encouraged to make limited use of hazardous, toxic, ozone depleting, and nuclear materials to reduce the overall environmental risk of the mission and enable NASA to better fulfill its mission of understanding and protecting the Earth. Information about such materials will be required in order to assist in the environmental review of the mission. The contracting process will require demonstrated compliance to all known federal, state, and local environmental, health, and safety laws.

II. Award Information

(a) Funding Policies

NASA Headquarters will perform the evaluation and selection of proposals under this NRA. However, since the New Millennium Program Office is located at JPL, proposals selected for award will receive subcontracts under NASA's contract with JPL. Contract administration and Technical management of each TCA will be the responsibility of JPL. Selected offerors can expect to negotiate directly with JPL and will receive subcontracts that contain JPL's terms and conditions.

The amount of funds expected to be available for new awards for proposals submitted in response to this NRA is given in Appendices A through E. Given the submission of proposals of merit, the number of awards to be made for each TCA is also provided in this location.

In all cases, the "metric" goal of NASA is to initiate new awards within 46 days after the selection of proposals is announced, but this period may be longer based on the work load experienced by NASA's procurement personnel, the availability of funds, and any necessary post-selection negotiations with the proposing organization needed for the award in question. In this latter regard, proposers are encouraged to submit full and detailed explanations of their requested budgets (see further below) to help expedite the processing of their awards.

(b) Eligibility of Applicants

Participation in this NRA is open to all categories of U.S. and non-U.S. organizations, including educational institutions, industry and nonprofit institutions, as well as NASA Centers and other U.S. Government agencies. Historically Black Colleges and Universities (HBCUs), other minority educational institutions, small businesses, and organizations owned and controlled by socially and economically disadvantaged individuals or women, are particularly encouraged to apply. There is no restriction on the number of proposals that an organization may submit to this solicitation, or on the teaming arrangements for any one proposal, although complex teaming arrangements may increase the perceived risk of the management aspect of the proposal.

Participation by non-U.S. organizations in this program is permitted subject to NASA's policy of no-exchange-of-funds.

(c) Guidelines Applicable to Non-U.S. (Foreign) Proposals and Language Use Proposals Approved Including Non-U.S. Participation

NASA welcomes proposals having participants from non-U.S. institutions provided that they are offered on a no-exchange-of-funds basis and also comply with current U.S. restrictions concerning the export of technology. In addition to meeting the requirements discussed elsewhere in this NRA including the Appendices which apply to all proposers, foreign proposals and proposals including foreign participation must comply with the policies below.

(i) General Policies

(1) Although NASA welcomes proposals from outside the U.S., foreign entities are generally not eligible for funding from NASA. Thus such investigations and investigators must be proposed on a no-exchange-of-funds basis to NASA. In addition, proposals from foreign entities, and proposals from U.S. entities that include foreign participation must be endorsed by the respective government agency or funding/sponsoring institution in the country from which the foreign entity is proposing. Such endorsement should indicate that the proposal merits careful consideration by NASA, and, if the proposal is selected, sufficient funds will be made available to undertake the activity as proposed. These Letters of Endorsement are required from all organizations sponsoring non-U.S. participants and must be received at the address and according to the schedule given in Section III (c). Letters of endorsement must be provided from all non-Code S organizations (including foreign participants) offering goods and/or services (including the support of members of the science team) for the proposed investigation. Proposals lacking such letters, or including letters judged inadequate by NASA, may be rejected without further review. Proposals from foreign entities, and proposals from U.S. entities that include foreign participation must be on a no-exchange-of-funds basis and must be endorsed by the respective Government agency or funding/sponsoring institution in the country from which the foreign entity is proposing. Such letters of endorsement must be signed by institutional and/or Government officials authorized to commit their organizations to participation in the proposed investigation. All letters of endorsement are to be included in and submitted with the proposal. This instruction supercedes the instructions on receipt of endorsement letters provided in the *Guidebook*. Copies of faxed or E-mailed letters from non-U.S. participants may be substituted in the submitted proposals as long as original signed letters are received by the date and time specified in Section IIIc of this NRA.

(2) All foreign proposals must be typewritten in English and comply with all other submission requirements stated in this NRA. All foreign proposals will undergo the same evaluation and selection process as those originating in the U.S. All proposals must be received by the established closing date for proposals. Those received after the closing date will be treated in accordance with Section IIIc of this NRA.

(3) Successful and unsuccessful foreign entities will be contacted directly by the NASA sponsoring office. Copies of these letters will be sent to the foreign sponsor. Should a foreign proposal or a U.S. proposal with foreign participation be selected, NASA's Office of External Relations will arrange with the foreign sponsor for the proposed participation on a no-exchange-of –funds basis, in which NASA and the foreign sponsor will each bear the cost of discharging their respective responsibilities.

(4) Depending on the nature and extent of the proposed cooperation, these arrangements may entail:

- An exchange of letters between NASA and the foreign sponsor; or
- A formal Agency-to-Agency Memorandum of Understanding (MOU).

(ii) Export Control Guidelines Applicable to Foreign Proposals and Proposals Including Foreign Participation

(1) Foreign proposals and proposals including foreign participation must include a section discussing compliance with U.S. export laws and regulations, e.g., 22 Code of Federal Regulations (CFR) Parts 120-130; 15 CFR Parts 730-774; and 10 CFR 110 and 810, as applicable to the circumstances surrounding the particular foreign participation. The discussion must describe in detail the proposed foreign participation and is to include, but not be limited to, whether or not the foreign participation may require the prospective proposer to obtain the prior approval of the Department of State or the Department of Commerce via a technical assistance agreement or an export license, or whether a license exemption/exception may apply. If prior approvals via licenses are necessary, discuss whether the license has been applied for or if not, the projected timing of the application and any implications for the schedule. Information regarding U.S. export regulations is available at http://www.pmdtc.org and at http://www.bis.doc.gov. Proposers are advised that, under U.S. law and regulations, spacecraft and their specifically designed, modified, or configured systems, components, and parts are generally considered "Defense Articles" on the United States Munitions List and subject to the provisions of the International Traffic in Arms Regulations (ITAR), 22 CFR Parts 120-130.

Further information on foreign participation is provided in Section A Provision 1260.12(e), "Choice of award instrument" of the NASA NPG 5800.1, "*Grant and Cooperative Agreement Handbook"* (hereinafter called the *Handbook*), which can be found at http://ec.msfc.nasa.gov/hq/grcover.htm.

(d) Cost Sharing or Matching

If an institution of higher education or other nonprofit organization wants to receive a grant or cooperative agreement, cost sharing is not required. However, NASA can accept cost sharing if it is voluntarily offered. See the *Handbook*, Section B, Provision 1260.123, "Cost sharing or matching," which describes the acceptable forms of cost sharing. If a commercial organization wants to receive a grant or cooperative agreement, cost sharing is required unless the commercial organization can demonstrate that they are not likely to receive substantial compensating benefits for performance of the work. If no substantial compensating benefits are likely to be received, then cost sharing is not required, but can be accepted. See Section D, Provision 1274.204, "Costs and Payments," of the *Handbook*.

III. Proposal Application and Submission Information

(a) Source of Application Materials

All information needed to apply to this solicitation is contained in this Announcement and in the *NASA Guidebook for Proposers Responding to a NASA Research Announcement (NRA), 2004 Edition* (hereinafter called the *Guidebook*). By reference, the 2004 edition of the *Guidebook* is incorporated into this NRA, and proposers are responsible for understanding and complying with its procedures for the preparation and submission of their proposals. Proposals that do not conform to its standards may be declared noncompliant and returned without review.

Note that the introductory material and appendices of the *Guidebook* provide additional information about the entire NRA process, including NASA policies for the solicitation of proposals, guidelines for writing complete and effective proposals, and NASA's general policies and procedures for the review and selection of proposals, as well as for issuing and managing the awards to the institutions that submitted selected proposals. A group of *Frequently Asked Questions* (FAQs) provides additional miscellaneous information about a variety of the NASA proposal and award processes and procedures. Comments and suggestions of any nature about the *Guidebook* are encouraged and welcomed. They may be directed at any time to Mr. Thomas Sauret, Office of Procurement, Code H, NASA Headquarters, Washington, DC 20546-0001; E-mail: thomas.e.sauret@nasa.gov.

(b) Content and Form of the Application Submission

(i) NASA Proposal Data System

Submission of a proposal in response to this NRA requires that the proposer register with NASA's master proposal database system located at the Web site http://research.hq.nasa.gov/propsite.cfm. Potential applicants are urged to access this site well in advance of the proposal due date(s) of interest (see further below) and familiarize themselves with its structure. It is especially important to note that every individual named on the proposal's *Cover Page* (see further below) must be registered in this NASA proposal data system and that such individuals must perform this registration themselves, i.e., no one may register a second party, even the Principal Investigator of a proposal in which that person is committed to participate. Note that the data entered into this data site are strictly for NASA's use only. Requests for assistance in accessing and/or using this Web site may be directed by E-mail to proposals@hq.nasa.gov, 8:00 AM – 6:00 PM Eastern Time, or by telephone to (202) 479-9376.

(ii) Notice of Intent to Propose

A Notice of Intent (NOI) to propose is encouraged but not required for the submission of proposals to this solicitation. The information contained in an NOI is used to help expedite the proposal review activities. NOIs are submitted to NASA's master proposal database located at the Web site http://research.hq.nasa.gov/propsite.cfm (Note: interested proposers must register at this site before it can by accessed for use; see Section III (b)(i) above). This site is open for submissions for a period of ~30 days commencing ~30 days after the release of this solicitation. NOIs submitted after the due date are still useful to NASA and may be submitted as directed in Section 3.1 of the *Guidebook.*

(iii) Cover Page, Proposal Summary, and Budget Summary

All proposals submitted to this NRA must be prefaced with a required, contiguous proposal *Cover Page/Proposal Summary/Budget Summary* form that is accessed at the Web at http://research.hq.nasa.gov/propsite.cfm. This form may be accessed and submitted starting on the date of the release of this solicitation through the proposal due date. After the requested data are electronically entered and submitted, the entire form is to be printed and then signed by the designated personnel for submission with the required hard copies of the proposal. No other formal forms are required for proposal submission. See the *Guidebook*, Chapter 2, for further details.

(iv) Proposal Format and Contents

Chapter 2 of the *Guidebook* provides detailed discussions of the content and organization of proposals suitable for all responses to this NRA, as well as the default page limits of the constituent parts. For this NRA, the proposal page limit for the Scientific/Technical/ Management Section is increased to 20 pages, instead of 15 as specified in Section 2.3 of the *Guidebook.* In addition to the required topics specified in Section 2.3.5 of the *Guidebook,* Scientific/Technical/Management, proposers to this NRA are required to provide the following information:

- Justification that the proposed technology is currently at a Technology Readiness Level (TRL) 3 or higher (TRL definitions are provided in a separate document entitled *Technology Readiness Level Description for the New Millennium Program* that is accessible in the NMP ST9 document library Web site at http://nmp.jpl.nasa.gov/st9-lib);
- Description of Study Phase activities that will demonstrate how future hardware and software deliverables will be at TRL 4 or higher at the conclusion of the Study Phase;
- Description of the plan for attaining TRL 5 or higher at the end of the Formulation Refinement Phase and a description of the plan for establishing readiness for a technology validation flight in 2007-2008;
- Description of the proposed technology validation plan, including the proposed technology to be tested, the performance parameters to be measured during space flight, and a description of the relationship of the performance parameters to the specified space environment; and
- Specification of any mathematical or scaling models to be used to predict performance parameters of the technology experiment and to predict the performance of future implementations, a discussion of the extent to which these models have been verified prior to the validation flight, and a discussion of the degree to which the technology validation data will provide further verification of these models.
- The proposer must provide a statement that she/he understands NASA OSS requirements for Education and Public Outreach (E/PO) and is committed to carrying out an E/PO program that meets the goals described in Section I(b) of the AO. The proposer must also provide a brief overview of the planned E/PO activities and their relationship to the

proposed investigation. This overview should include a brief discussion of any unique characteristics of the mission that might provide unusual opportunities for E/PO. Detailed plans for implementing the E/PO activities, including identification of and formal commitment from E/PO partner institutions, will be part of the Concept Definition Study Report and will be evaluated as part of the down select process.

Proposers must provide budget data for a six-month Study Phase, the Formulation Refinement Phase, and an Implementation Phase, per Section 2.3.11, Budget Details, of the *Guidebook*, starting five months after proposal submittal.

Prospective proposers are advised that the *Cover Page* requires that all applicants must provide the Dun and Bradstreet (D&B) Data Universal Numbering System (DUNS) number for their employing organization. The DUNS number is a unique nine-character identification number provided by the commercial company Dun and Bradstreet. Applicants may call D&B at 1-866-705-5711 to register and obtain a DUN number, or access the D&B Website at http://www.dnb.com/us/. Requesting a DUNS number takes ~10 minutes by telephone or ~14 days through the Web site; both are free of charge. Organizations will use the same DUNS number with every proposal submitted for a Federal grant or cooperative agreement.

The *Cover Page* also requires a Commercial and Government Entity (CAGE) code that the applicant's organization obtains by registering in the Central Contractor Registration (CCR) database. This requirement centralizes information about grant recipients and provides a central location for grant recipients to change organizational information. Information for registering in the CCR and online documents can be found at http://www.ccr.gov. Before registering, applicants and recipients should review the Central Contractor Registration Handbook that is also located at the same site. The process for obtaining a CAGE code is incorporated into the CCR registration. (Note: Mr. Thomas Sauret, Office of Procurement at NASA Headquarters, (202) 358-1068, thomas.e.sauret@nasa.gov, can also answer questions about the DUNS number and CCR registration.)

(c) Proposal Submission Dates, Time, and Location

Regardless of the method of delivery, each proposal submitted in response to this NRA shall include a signed original plus 20 printed copies and must be physically received by 4:30 PM Eastern time on the TBD, 2004. The address for the delivery of proposals is:

Name of the Technology Concept Area.
ST9 NRA
Office of Space Science
NASA Peer Review Service
500 E Street, SW, Suite 200
Washington, DC 20024

Telephone: (202) 479-9030

Proposals that are late will be handled in accordance with NASA's policy as given in Section (g) of Appendix B of the *Guidebook* (see also Sections 3.2 and F.23 of the *Guidebook*).

(d) Proposal Funding Restrictions

- Appendices A through E provide an estimate of the funds expected to be available for competition through this NRA, as well as the approximate number of awards these funds are expected to support.
- The construction of facilities is not an allowed activity unless otherwise stated in the program description. For further information on the allowability of costs, refer to the cost principles cited in the *Handbook*, Section 1260.127.
- Travel, including foreign travel, is allowed as necessary for the meaningful completion of the proposed investigation, as well as for publicizing its results at an appropriate professional meeting.
- U.S. research award recipients may directly purchase supplies and/or services that do not constitute research from non-U.S. sources, but award funds may not be used to fund research carried out by non-U.S. organizations. However, subject to possible export control restrictions, foreign nationals may conduct research while employed by a U.S. organization.
- Profit for commercial organizations is allowed under contract awards only.
- Regardless of whether functioning as a team lead or as a team member, personnel from NASA Centers must propose budgets based on Full Cost Accounting (FCA). Non-NASA U.S. Government organizations should propose based on FCA unless no such standards are in effect; in that case, such proposers should follow the Managerial Cost Accounting Standards for the Federal Government as recommended by the Federal Accounting Standards Advisory Board (for further information, see http://www.hq.nasa.gov/fullcost/).

IV. Proposal Review Information

(a) Evaluation Criteria

The peer evaluation of each proposal will be used to assess its intrinsic merit, its relevance to NASA's stated objectives, and its cost realism and reasonableness. See Appendix C.2 of the *Guidebook* for a detailed discussion of these criteria and their relative weights. Note the following specific points:

- Each TCA discussed in Appendices A through E will give further specific performance requirements to be considered for intrinsic merit and relevance.
- As discussed in Section I(a) above, relevance will be judged by the proposal's focus on the specific Technology Advances given in Table 1 and as further delineated in Appendices of this NRA.
- Cost sharing is not part of the evaluation criteria; however, cost sharing may affect NASA's evaluation of the intrinsic merit of the proposal.

(b) Review and Selection Processes

Proposals submitted in response to this NRA will be reviewed and selected consistent with the policies and provisions given in Appendix C.3 and C.4 of the *Guidebook*. Selection procedures will be consistent with Section C.5 of the *Guidebook*. The Selection Official is the Associate Administrator for Space Science.

(c) Selection Announcement and Award Dates

It is the stated goal for NASA that selections will be announced within 150 days of the proposal due date. However, it is OSS policy not to announce new selections until the budget for the Fiscal Year that will provide the award funds is signed into law. Therefore, a delay in the Federal budget process for NASA may result in a delay of the selection date(s).

Both the selected, as well as non-selected, proposers will be notified, consistent with the policy given in Section C.5.1 of the *Guidebook.* For selected proposers, the proposer's business office will be contacted by a NASA Awards Officer, who is the only official authorized to obligate the Government. Any cost incurred by the proposer in anticipation of an award will not be reimbursed.

V. Award Administration Information

(a) Notice of Award

Awards made through this NRA will be administered in accordance with the general policies given in the *Handbook* and Appendix D of the *Guidebook*. In the case of any conflict, the *Handbook* takes precedence. The type of award to be offered to selected proposers will generally follow the policies in Section D.1 of the *Guidebook*.

(b) Administrative and National Policy Requirements

This solicitation does not invoke any special administrative or National policy requirements. However, there are two Certifications and one formal Assurance required as part of a proposal submitted in response to this NRA (reference Appendix E of the *Handbook*).

(c) Award Reporting Requirements

The reporting requirements for awards made through this NRA will be consistent with Exhibit G of the *Handbook*. Any additional requirements will be stated in a paragraph that concludes each TCA in Appendix A.

VI. Points of Contact for Further Information

General questions and comments about the policies of this NRA may be directed to:

Dr. Paul Hertz
Office of Space Science
Code S
National Aeronautics and Space Administration
Washington, DC 20546-0001

Telephone: (202) 358-0986
E-mail: Paul.Hertz@nasa.gov

Specific questions about the TCAs in the Appendices of this NRA should be directed to:

Dr. G. S. Krishnan
New Millennium Program Executive
Office of Space Science
Code SS
Washington, DC 20546-0001

Telephone: (202) 358-0888
E-mail: G.S.Krishnan-1@nasa.gov

Inquiries about accessing or using the NASA database located at http://research.hq.nasa.gov/research.cfm should be directed by E-mail to proposals@hq.nasa.gov or by calling (202) 279-9376. This help center is staffed 8:00 AM–6:00 PM Eastern Time, Monday through Friday. If an E-mail is sent, please include a telephone number for response.

VII. Ancillary Information

(a) Announcement of Updates/Amendments to Solicitation

Additional programmatic information pertaining to this NRA may develop before its proposal due date. If so, such information will be added as an Amendment to this NRA as posted at its home Web site no later than 30 days before the proposal due date, or, if this is not possible, the proposal due date will be extended to allow 30 days for response. NASA OSS will also send an electronic notification of any such amendments to all subscribers of its electronic notification system (see item (c) below). Non-programmatic or administrative amendments will be publicized the same way, but an extension in the proposed due date, if any, may be less than 30 days.

(b) Electronic Submission of Proposal Information

The electronic submission of the combined *Cover Page/Proposal Summary/Budget Summary* is required over the World Wide Web (see also Section III(b)(iii) above). While every effort is made to ensure the reliability and accessibility of this Web site and to maintain a help center via E-mail and telephone, difficulty may arise at any point on the Internet, including the user's own equipment. Therefore, prospective proposers are urged to familiarize themselves with this site and to submit the required proposal materials well in advance of the proposal due dates given in Section III(c) and in Table 2 below.

(c) Electronic Notification of OSS Research Solicitations

OSS maintains an electronic notification system to alert interested researchers of its research program announcements. Subscription to this service is free and is accomplished through the menu item "*To subscribe to the OSS electronic notification system*" found on the OSS research page at http://research.hq.nasa.gov/code_s/code_s.cfm. Owing to the increasingly multidisciplinary nature of OSS programs, this E-mail service will notify subscribers of (i) all NASA OSS research program solicitations regardless of their type or science objectives; (ii) amendments to solicitations that have been released for which the proposal due date has not past; and (iii) special news that OSS wishes to communicate rapidly to those interested in proposing to its sponsored research programs. Altogether, a subscriber may receive 40 to 50 notifications per year. OSS maintains this subscription list in confidence, and does not attempt to discern the identity of its subscribers. Regardless of whether or not this service is used, all OSS research announcements may be accessed from the menu listing *Current (Open) Solicitations* at the Web site above as soon as they are posted (typically by ~8:30 AM Eastern Time on their release date).

(d) Archives of Past Selections

For more information about the types of research supported by previous NMP solicitations, refer to the abstracts for selected investigations available through the menu listing *Past/Archive Solicitations & Selections* at http://research.hq.nasa.gov/code_s/code_s.cfm.

(e) Restriction on Use and Disclosure of Proposal Information

Offerors should reference Appendix B, paragraph (2)(b) of the *Guidebook* for NASA policy regarding "Restrictions on Use and Disclosure of Proposal Data."

VIII. Concluding Statement

The interest and cooperation of the space science technology providers in responding to this ST9 NRA is sincerely solicited and welcome. In addition, comments about the inclusive nature and/or structure of this NRA are also welcome and may be directed to either of the points of contact identified in Section VI above.

Orlando Figueroa
Director
Solar System Exploration Division

Richard R. Fisher
Director
The Sun-Earth Connection Division

Anne L. Kinney
Director
Astronomy and Physics Division

Edward J. Weiler
Associate Administrator for Space Science

<u>Table 2</u>. Summary Information Applicable to this NRA.

Item	Summary
Program Alpha-Numeric Identifier	NHH04ZSS002N
Date of NRA Release	August 25, 2004
Access to text	Link through the menu listings for Research Solicitations, Current (Open) Solicitations, starting from the OSS home page at http://spacescience.nasa.gov/.
Guidance for preparation and submission of proposals	*NASA Guidebook for Proposers Responding to a NASA Research Announcement (NRA), 2004 Edition,* at URL http://www.hq.nasa.gov/office/procurement/nraguidebook/
Notice of Intent (NOI) to Propose (encouraged but not required):	
- Desired due date	September 24, 2004
- Web site for electronic submission	Open appropriate menu listing at http://research.hq.nasa.gov/research.cfm (available for submissions for a period of ~30 days, starting ~30 days from release of the NRA (Help Desk E-mail: proposals@nasa.gov)
- Late submission (up to 5 days prior to Proposal Deadline)	Submit information specified in Section 3.1 of *NASA Guidebook for Proposers, 2004* by E-mail to proposals@nasa.gov
Proposal Cover Page (including Proposal Summary and Budget Summary):	
- Deadline	(Same as for proposals) Print completed items from Web site http://research.hq.nasa.gov/research.cfm
- Web site for electronic submission	Same as above (Help Desk E-mail: proposals@nasa.gov)
Proposal page limits	As specified in Section III of this NRA.
Submission of proposal:	
- Required Number	Signed original proposal plus 20 copies (including printed Cover Page/Proposal Summary and Budget Summary). The Technical/Management portion and the Cost Proposal portion are to be submitted as separate documents.

Item	**Summary**
- Deadline	4:30 p.m. Eastern Time on November 24, 2004
- Address for submission by U.S. Postal Service, commercial delivery, or private courier	ST9 NRA *(insert Technology Capability Area name here)* Office of Space Science NASA Peer Review Service 500 E Street, SW, Suite 200 Washington, DC 20024 Telephone: (202) 479-9030
Selecting Official	Associate Administrator for Space Science
Announcement of selections	Goal: 150 days after Proposal Deadline
Initiation of funding for new awards	Goal: 46 days after proposal selections
Further information: - Programmatic contact	 Dr. G. S. Krishnan New Millennium Program Executive Office of Space Science Code SS Washington, DC 20546-0001 Telephone: (202) 358-0888 E-mail: G.S.Krishnan-1@nasa.gov
- For general NRA policies and procedures	Dr. Paul Hertz Office of Space Science Code S National Aeronautics and Space Administration Washington, DC 20546-0001 Telephone: (202) 358-0880 E-mail: Paul.Hertz@nasa.gov

Appendix A. Solar Sail Flight Validation

A.1 Flight Validation Concept

Solicited Advanced Technology Capabilities: The following advanced technology investigations for space validation in support of a Solar Sail Flight Validation (SSFV) experiment are solicited:

- Sail Propulsion Subsystem (SPS)
- In-Space Inspection Subsystem (ISIS), and
- Sail as Sensing Instrument (SASI).

Performance *requirements* for specific technology advances in this TCA may be found under Section A.5.

Advanced Technology Description and Benefit: The SSFV experiment will develop and operate in space a deployable solar sail that can be steered and provides measurable acceleration. The approach for this experiment will be to test and validate models and processes for solar sail design, fabrication, deployment, and flight. Such models and processes can then be used with confidence to design, fabricate, and operate the scaleable solar sails needed for future space science missions.

Solar sails are envisioned as a cost-effective means of propelling spacecraft in the inner solar system to very high velocity (delta v > 50 km/s), thereby enabling missions that seek to study the Sun and heliosphere from unique vantage points. Because they rely on the Sun's continuous supply of photons to provide propulsion, solar sails would also enable missions in non-Keplerian orbits that are currently not feasible. Additionally, the gossamer spacecraft technology validated by flight of a solar sail would benefit other future missions requiring large deployable booms and membranes, such as large-aperture telescopes that require very large sunshields.

Flight Validation Objectives: There are six validation objectives for the SSFV experiment:

1. Validate solar sail design tools and fabrication methods,
2. Validate controlled deployment,
3. Validate in-space structural characteristics,
4. Validate solar sail attitude control,
5. Validate solar sail thrust performance, and
6. Characterize the sail's electromagnetic interaction with the space environment.

Technology Validation Rationale: Because of the nature of a solar sail—a very thin and reflective membrane that must be deployed and flown in space—there are fundamental limits to ground validation and maturation. For instance, ground tests of solar sail deployment typically involve schemes that off-load the force of gravity. Though instructive, such techniques are intrusive and acknowledged to have limited ability to foretell the dynamics of zero-g deployment. Furthermore, the dimensions of existing vacuum chambers require that terrestrial testing of solar sails larger than 30 meters be done "in-air," which has a profound damping effect on a gossamer membrane. Considering that solar photon pressure at 1 AU is only 1/4000th that of the terrestrial one-g force, there is no practical method on the ground to validate fully the shape or dynamics of a low-stress membrane that is intended for operation in space. Similarly, though subsystems can be tested on the ground and associated models developed, the attitude control of a solar sail must be validated in the vacuum and zero-g environment of space. Building, deploying, and flying a hundred-meter-class solar sail for a strategic space science mission represents a significant technology advance, one that first requires a SSFV to prove out the necessary processes and analytical models.

A.2 Science Missions Applicability

Solar sails will enable several missions currently in the Sun-Earth Connection roadmap that seek to study the Sun from unique vantage points both in and outside the heliosphere. Such vantage points include: observing the Sun from high-inclination heliocentric orbit (Solar Polar Imager); leaving the heliosphere to determine the nature of interstellar space (Interstellar Probe); observing the origin of high-energy solar particles from heliosynchronous orbit (Particle Acceleration Solar Orbiter); and making sustained measurements from otherwise inaccessible, non-Keplerian, near-Earth orbits (L1 Diamond mission).

A.3 Representative Space Experience

While there have been many ground demonstrations relevant to a solar sail flight validation project, there has been little actual space flight experience. Examples include: the 1960s 33-m Echo balloon series, the 1993 20 m Znamya thin-film reflector demonstration, the 1996 14 m x 28 m Inflatable Antenna Experiment (IAE), and the 1999 34 m deployable membrane photovoltaic concentrators. Each of these resulted in the deployment of a large, thin film membrane structure in space, and several provided data on postdeployment structural performance.

A.4 Flight Experiment Concept

Experiment Concept Description: As pointed out in Section A.1, the successful SSFV experiment will develop and operate in space a deployable solar sail that can be steered and provides measurable acceleration. The advanced technologies solicited here will be integrated with three additional subsystems: a spacecraft bus, a sail imaging metrology system (SIMS), and an Electromagnetic Characterization Suite. This package will constitute a complete SSFV experiment that fulfills the identified validation objectives. These major elements and their relationships are depicted in Figure A-1.

The "reference" orbit for the purposes of this solicitation is defined as a modified Geosynchronous Transfer Orbit (GTO) at 28.5 degrees inclination, with a perigee of 1,500 km. This orbit will guide the analysis of an appropriate control system, performance, and measurement capabilities that will be required.

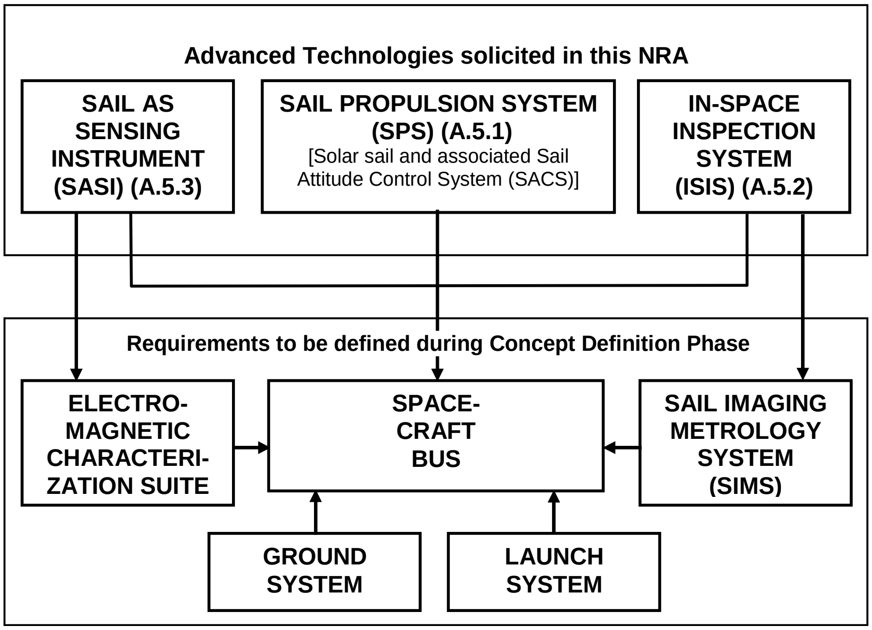


Figure A-1. Major elements of the SSFV concept.

Deployment operations will be conducted after separation from the launch system, stabilization of the spacecraft, and basic systems checkout and preparations. Upon successful deployment, a series of sail operations will complete the validation objectives. Experiment duration is expected to be on the order of two months. Extended operations and de-orbiting requirements are to be determined as part of the Study Phase.

Sail Propulsion Subsystem (SPS): The propulsive ability of a solar sail is directly related to its ability to produce and control the reaction thrust vector from the reflected sunlight. This dependence suggests that the solar sail and attitude control methods be designed as an integral system. A successful SSFV experiment will include an SPS having a sail subsystem that produces measurable thrust (capable of modifying the trajectory of the sailcraft) and a Sail Attitude Control Subsystem (SACS) capable of modifying the attitude of the sailcraft. Therefore, SPS proposals must include the capability to modify sail attitude. The SPS is the enabling technology for the first five flight-validation objectives identified in Section A.1. Specific performance requirements are given in Section A.5.1.

In-Space Inspection Subsystem (ISIS): ISIS enhances the value of the solar sail flight validation experiment by providing a capability for inspecting solar sails beyond the boom-mounted cameras of the Sail Imaging Metrology System (SIMS) described below. The ISIS is enhancing technology for the second, third, and fifth flight validation objectives identified in Section A.1, and specific performance requirements are given in Section A.5.2.

Sail-As-Sensing-Instrument (SASI) Experiment: The experiment would enable use of the large membrane and structure of the solar sail itself to sense the local environment. The SASI is enhancing technology for the sixth flight validation objectives identified in Section A.1 and specific performance requirements are given in Section A.5.3.

This NRA does not solicit the project-provided elements listed below.

Sailcraft Bus: A spacecraft will be provided by NASA to serve as the "sailcraft bus" to provide power, communications, command and control, and other resources to the ISIS, SASI, and SPS (with its associated SACS). This spacecraft will also support other flight elements such as the Electromagnetic Characterization Suite, SIMS, and other required sensors and actuators. The sailcraft bus will be the primary interface to the flight elements of the solicited technologies. The spacecraft bus and interfaces with it will be defined by the SSFV Study Team. For the purpose of responding to this NRA, you are to make conventional assumptions about your interfaces with the bus (28 V electrical bus, 1553 data, etc.) and to document your assumptions. The SSFV Study Team will develop detailed interface requirements. Proposers can assume a spacecraft wet mass of 120 kg.

Launch System: Access to space is expected via secondary payload on an appropriate launch vehicle. As this is yet to be defined, representative characteristics have been adopted for this NRA. Mass and volume targets for solicited advanced technologies can be found in the respective subsections of Section A.5. It is anticipated that the sailcraft bus will serve as the primary interface to the launch system.

Ground System: The ground segment will consist of an appropriate communication station and the facilities to command the sailcraft, and receive and analyze telemetry. Tracking facilities may also be required.

Sail Imaging Metrology System (SIMS): The SIMS, along with sensors integral to the SPS, will provide flight data that validates essential structural, dynamic, Guidance Navigation and Control (GN&C), and thermal models of the solar sail. The system is conceived to remotely monitor and record the state of the sail and its supporting structure, from deployment through operations. It will be defined during the Study Phase to incorporate the validation requirements identified by the SPS provider and NASA team members. A likely configuration consists of multiple, megapixel cameras of fixed focal length, mounted on booms that are deployed axially from the spacecraft in the sunward (and possibly the antisunward) direction.

Electromagnetic Characterization Suite: A likely configuration consists of two research-grade instruments: a magnetometer and a solar wind plasma analyzer.

A.5 Advanced Technology Performance Requirements

The solicited advanced technologies and the associated measurements, parameters, and models are described in the following subsections.

A.5.1 Sail Propulsion Subsystem (SPS)

Objectives and Requirements: The SPS constitutes an enabling subsystem for achieving SSFV Objectives 1-5, given in Section A.1. Proposals shall demonstrate (or show evidence of) an ability to meet the requirements in this section. Given resource constraints, the ability to meet estimated cost and schedule requirements is a vital consideration. Therefore, the proposer shall be capable of providing a mature engineering approach that achieves a Technology Readiness Level (TRL) of at least 5 or greater by the conclusion of the Study Phase.

The system level performance requirements for the SPS are given in Table A-1, which proposers shall meet by providing engineering analysis. In addition to describing how ST9 Requirements can be met (second column, Table A-1), proposals shall describe a pathway (through analytical models or testing) for meeting the ultimate goals (third column, Table A-1).

The SACS segment of the SPS provides the authority for controlling the flight system thrust vector, attitude, and maneuvering. While SACS concepts must demonstrate the capability to modify sail attitude and thrust vector, complete ACS implementations may employ resources on the spacecraft, such as reaction wheels, thrusters, and optical and inertial sensors. Proposals may assume that the spacecraft C&DH and software will actually perform (command) the sail attitude control based on information gathered from the SPS and spacecraft attitude control sensors, relying on SACS performance models and command interfaces provided by the SPS provider. Once the sail begins deploying, the SACS shall be responsible for the global attitude stabilization and control of the sailcraft and its thrust vector orientation, including its safing and fault recovery from any anomalous behavior.

A SACS implementation that requires little or no propellant is a requirement for future missions. While validation of such a technique is a goal, it does not preclude the flight of a propellant-aided system for attitude control for ST9, which might be useful during critical experiment phases such as deployment, perigee passes, or as backup during the validation of a zero-propellant ACS. Beyond the specifics of an ST9 implementation, proposals must address how the proposed SACS concept could evolve toward a minimal-to-zero propellant system for future missions.

Thrust vector pointing accuracy and turn rate requirements are driven by the need to maximize the efficiency of the sail as a thrusting device while minimizing navigational uncertainty over the required experiment trajectory profile. The required thrust vector control parameters are summarized in Table A-1.

Table A-1. Sail Propulsion System Technology Validation Requirements.

Parameter	ST9 Requirement	Scalability Target	Comments
Sail Geometry	Square	N/A	Affects process & model validation. Square geometry would satisfy most OSS roadmap missions.
Sail Area	≥ 1,600 m^2	> 10^4 m^2	Area that functions as a reflective surface and generates propulsive force.
Areal Density of the Sail Propulsion System (post-deployment)	< 25 g/m^2	< 12 g/m^2	Includes sail film, structure, packaging, temperature control, cabling, retained deployment hardware, attitude control subsystem, and all flight subsystems.
Sail Reflectance (front)	> 0.70	> 0.80	Efficiency of sail. Takes into account wrinkling and nonplanarity of the sail.
Sail Emissivity (back)	> 0.30	> 0.80	Backside heat rejection capability.
Sail lifetime	> 120 days in GTO	> 5 years at 0.5 AU	Includes issues such as thermal control and durability of sail materials, structure, and system performance given thermal, UV, radiation and micrometeoroids in the specified environment.
Electrostatic charge control	Safe operation of the sailcraft in GTO	Compatible with fields & particles instruments at L1	Potential impact to sailcraft health & safety in GTO; impact on quality of science.
Sail Subsystem Mass (launch)	< 40 kg	< 120 kg	Scalability target assumes sail area of 10^4 m^2 and areal density < 12 g/m^2.
Sail Subsystem Packaged Volume	< 0.175 m^3	< 3 m^3	ST9 requirement stems from volume requirement of secondary payload opportunities.
Deployment time	< 2 hours	< 2 hours	Sail fully deployed and tensioned. Scalable goal relates to 10^4 m^2 sail.
Sail attitude control during deployment	< 35 deg half-cone angle	< 35 deg half-cone angle	Orientation of Sun line to sail plane.
Characteristic acceleration	> 0.07 mm/s^2	> 1 mm/s^2	Based upon sail area, areal densities, reflectance, and a non-sail mass (spacecraft) of 120 kg (for ST9) or 250 kg (ultimate).
Thrust Vector Turning rate	> 1.5 deg/hr	> 1.5 deg/hr	Average turn rate for any required tacking maneuver.

Parameter	ST9 Requirement	Scalability Target	Comments
Thrust Vector Pointing Range	Cone of 40 deg half angle	Cone of 60 deg half angle	For thrust control; centered upon the solar vector, thrusting away from the Sun.
Thrust Vector Proportional Magnitude Error	≤ 4% (3σ)	≤ 4% (3σ)	Control loop error for magnitude.
Thrust Vector Proportional Pointing Error	≤ 2% (3σ)	≤ 2% (3σ)	Control loop error for pointing.
Thrust Vector Pointing Error	< ± 5.0 deg (3σ)	< ± 2.0 deg (3σ)	For thrust vector magnitude error ≤ 4%, and pointing error ≤ 2%.
Pointing Stability of bus-fixed reference system	< ± 0.1 deg (3σ)	< ± 0.01 deg (3σ)	Also known as pointing jitter over observation frame time, or maximum jitter rate allowed; determined by the requirements of future payloads.

Proposers for the SPS shall be capable of specifying the required sizing and performance characteristics of sailcraft resources that are needed to support the proposed SPS with SACS design. In particular, any attitude control requirement (propulsive or reactive) that an SPS proposal levies upon the spacecraft bus must be enumerated and explained. Any proposed attitude control subsystem that employs a propellant must demonstrate that it will have no adverse effects on the sail membrane or the imaging capability of the SIMS. The SACS shall provide the orientation of the sail elements (vanes, panels, control booms, etc.) with respect to a spacecraft body reference frame to the spacecraft C&DH subsystem.

Representative Measurements, Parameters, and Model Verification: Proposals for the SPS must discuss the predictive models and measurements to be used to validate the sail propulsion system technology, the measurements to be made during ground-based testing (with an emphasis on those used to achieve TRL 5 where a component and/or breadboard has been validated in its relevant environment), and the measurements to be made during the space experiment. Also to be discussed, are how these measurements would be used to verify or calibrate the existing models and how they would be used to validate the technology, including any applicable scaling or extension of the validated model to its eventual domain of applicability.

The validation of models and processes is essential for enabling future solar sail missions. Therefore, proposals must demonstrate an understanding of the models needed to design, build, deploy, and fly 100-meter-class solar sails and discuss the data required to validate these models and assignment of specific core systems responsibility for acquiring the data using embedded SPS sensors, spacecraft sensors, or SIMS cameras.

Proposers are expected to identify their approach to model validation and experimental measurements for the following two items:

Required Models for SPS: Validation of the SPS will require the coordinated development of computational models to predict sail behavior along with ground and in-space characterization of sail performance. The SPS provider must demonstrate the capability to produce a detailed design of the SPS at the beginning of the Study Phase. This design must be able to be incorporated into a set of models that, after validation, will enable mission designers to study future, larger-sized solar sail missions. Contemplated models include structural and mechanical, thermal, attitude control, thrust performance and navigation, and environmental. Proposals must explain any significant inputs to these required models that will be developed or provided.

Data Required for SPS Model Validation: Collection of data to validate solar sail models is a high priority. Proposals must identify critical data sets required for a SSFV experiment that are needed by the models, the process validation and the requirement to scale the results to 100 meter-class solar sails. Proposals must delineate between those measurements integral with the sail structure (best implemented by the SPS provider) and those accomplished independently from the SPS by specifying requirements for the spacecraft sensors or the SIMS.

The SIMS concept likely will require photogrammetry targets on the sail membrane. Such targets are envisioned to be reflectively diffuse on sun-facing side of the sail, have sufficient contrast to be readily imaged by the SIMS cameras, and range in size from 10-200 cm^2. SPS proposals must address at least a notional method for providing or accommodating such targets. Note that the target mass is not to be included in the sail areal density as specified in Table A-1.

A.5.2 In-Space Inspection Subsystem (ISIS)

Objectives and Requirements for ISIS: This NRA solicits innovative in-space inspection concepts that enhance the value of the solar sail flight validation experiment. Proposals for an ISIS may either connect to the sailcraft via an integral boom or be free-flying; or the ISIS may operate initially connected to the sailcraft, with subsequent operation as a free-flyer. Proposals must respond to the requirements in Table A-2.

The ISIS subsystem must enhance the technology return of the experiment by validating a new technology advance for in-space inspection for solar sails performance during one or more of the following scenarios:

- **Solar Sail Deployment**: Image the SPS during its deployment;
- **Anomalous Sail Operation**: Provide data during the primary validation stage of the project, as a means of gathering additional information needed to resolve an anomaly; and
- **End of Sail Life**: Validate ISIS performance at the conclusion of the project, when sail validation experiments have been completed.

Table A-2. In-Space Inspection Subsystem Technology Validation Requirements.

Parameter	ST9 Requirement	Scalability Target	Comments
Mass	< 10 kg	N/A	
Volume	< 0.027 m^3	N/A	Nominally 30 cm on a side.
Power	< 10 W from the spacecraft bus or self-powered through integral solar array or battery.	Self-powered through integral array or battery.	
Spacecraft Interface	Body mounted; Release and free-flying from spacecraft.	N/A	
Health and Safety of Spacecraft	Minimal effect on validation of sail ACS through analysis or via actual detachment from sailcraft, or deployment at the conclusion of the critical validation phase.	N/A	
Collision avoidance (free flyers deployment only)	Safely station-keep for any applicable operational scenario (see likely characteristic acceleration in Table A-1).	N/A	
Communication	Via wired interface to spacecraft C&DH system; or direct to ground (assume GEO altitude); or wireless to ISIS-provided receiver on spacecraft.	N/A	
Image resolution	≥ 1 megapixel “global” images of deployed sail or a portion of the sail not otherwise achieved by the SIMS.	N/A	

Representative Measurements, Parameters, and Model Verification: Models needed to validate the in-space inspection system itself shall be identified and necessary validation steps described.

A.5.3 Sail as Sensing Instrument (SASI)

Objectives and Requirements: Solar sails present a unique new opportunity to make measurements of the ambient environment using the large membrane and long booms. Therefore, proposals for a SASI investigation must discuss the innovative use of solar sail structures to make novel observations and meet or exceed the range and accuracy of conventional measurement techniques.

Potential examples of novel sail instrument measurement techniques include (but are not limited to) the following:

- Detection of plasma and radio waves using the booms or sail surface as antennas;
- Detection of dust and micrometeorite impacts, either mechanically or electromagnetically; and
- Using the separation afforded by the sail booms to make gradient measurements in various plasma parameters.

Proposals may presume the availability of measurements from an Electromagnetic Characterization Suite (see Section A.4) or may propose alternative instrumentation. Resources may be constrained for those proposing their own inherent instrumentation (see Table A-3). Provision for a SASI concept must not compromise the ability to fabricate and deploy the solar sail nor interfere with its normal operations. Evidence that the measurement approach will not have such adverse effects is required. The concept must produce sufficient data for flight validation of the measurement technique by enumerating its data requirements.

Table A-3. Sail as Sensing Instrument (SASI) Technology Validation Requirements.

Parameter	Requirement	Scalability Target	Comments
Mass	≤ 1 kg	N/A	
Power	≤ 1 W	N/A	
Stowed Volume	≤ 0.0034 m^3	N/A	Nominally 15 cm on a side.

Representative Measurements, Parameters, and Model Verification: Proposals must discuss the predictive models and measurements to be used in validating the SASI technology and how they are dependent upon the specific nature of the preposed technique. Address the nature of the measurement, its potential accommodation as part of a solar sail, and a strategy for acquiring validation data.

A.6 Selection Opportunities and Planned Funding Levels

Given the submission of proposals or merit, the number of SSFV technology opportunities and funding levels planned for the Study Phase are indicated in Table A-4.

Table A-4. Award Levels for Concept Definition Study Phase.

Technology Area	Number of Selections	Maximum Funding*
Sail Propulsion System (SPS)	1	$400,000
In-Space Inspection System (ISIS)	1	$75,000
Sail as Sensing Instrument (SASI)	1	$50,000

* Proposals with budgets in excess of these amounts may be selected only if they exhibit exceptional merit and breadth of objectives.

A.7 Representative Project Schedule (for use as a reference only)

Table A-5. Solar Sail Flight System Project Schedule.

Milestone	Months After Release of NRA (ARN)
• Concept Definition Study Phase - Formation of Study Team - Deliver Study Report	8 months duration (5 – 13 months ARN) 5 months ARN 11 months ARN
• Formulation and Refinement Phase - Systems Requirements Review - Preliminary Design Review	12 months duration (13 – 25 months ARN) 15 months ARN 23 months ARN
• Confirmation Review	25 months ARN
• Implementation Phase - Critical Design Review - Preenvironmental Test Review - Launch - Flight Operations - Data Analysis - Final Report	27 months duration (25 – 58 months ARN) 31 months ARN 43 months ARN 49 months ARN 1 month duration (51 – 52 months ARN) 5 months duration (53 – 58 months ARN) 58 months ARN

A.8 Acronym List

AU	astronomical unit
ACS	attitude control system
C&DH	command and data handling
deg	degree
g	gram
GN&C	guidance, navigation and control
GEO	geosynchronous earth orbit
GTO	geosynchronous transfer orbit
hr	hour
IAE	inflatable antenna experiment
ISIS	in-space inspection subsystem
kg	kilogram
m	meter
mm	millimeter
s	second
SACS	sail attitude control subsystem
SASI	sail as sensing instrument
SIMS	sail imaging metrology subsystem
SPS	sail propulsion subsystem
SSFV	solar sail flight validation

TRL	technology readiness level
UV	ultraviolet
W	Watt
delta v	change in velocity of spacecraft

Appendix B. Precision Formation Flying (PFF)

B.1 Flight Validation Concept

Solicited Advanced Technology Capabilities: Appendix B describes three technology advances that support the system level Precision Formation Flying (PFF) flight validation experiment:

- Formation Sensor (FS) for measuring range and bearing between spacecraft;
- Intersatellite Communication Subsystem (ICS); and
- Point-to-point Ranging Sensor (PRS).

Advanced Technology Description and Benefit: To meet high priority science objectives, at least six missions that exploit formation flying technology are planned for the Space Science Enterprise in the next two decades. Due to limitations of launch vehicle fairing sizes and of the ability to phase optical elements over long distances on flexible structures, separated spacecraft formation flying is the only viable means to enable imaging at microarcsecond resolution. This experiment will validate the capability of multiple spacecraft flying in formation to act collaboratively to form a synthetic aperture and precisely hold the formation geometry at time scales appropriate for science imaging and interferometry.

This PFF experiment focuses on validating the ability to tightly control interspacecraft ranges, bearings, and inertial attitudes. The system level objective is to continuously and collaboratively control the interspacecraft range, bearing, and inertial attitude (relative orientation) of multiple spacecraft flying in formation over long durations of time, using intersatellite communication devices. The formation control can be either regulation, where the interspacecraft range, bearing, and inertial attitudes of the spacecraft are held fixed to a tight precision; or tracking, where the interspacecraft range, bearing, and inertial attitudes are controlled to follow a desired trajectory.

Flight Validation Objectives: The following system level PFF advanced technology validation objectives for sensing, measurement, and control are sought through this solicitation:

- The onboard, autonomous, and continuous measurement of interspacecraft range and bearing between three or more spacecraft using a FS;
- The onboard, autonomous, continuous, and precise range measurement between two or more spacecraft, using a PRS;
- The ability to perform "complementary relative sensing" (i.e., to use two sensors with different performance capabilities to cover a wider dynamic range with finer resolution than the capability of either sensor alone);
- The ability to exercise collaborative control*, through thruster controls applied to all spacecraft, of the geometry of the spacecraft formation for long durations with control loops implemented through either intersatellite radio frequency (RF) or optical cross links;

[*Collaborative control means that the interspacecraft range, bearing, and inertial attitude, of all spacecraft, are controlled to achieve the desired formation configuration while all spacecraft share relevant sensor and control information and operate based on the knowledge of each other.]

- The ability to initialize the geometry of the spacecraft formation, perform required communications, and control the spacecraft formation autonomously; and
- The ability to autonomously reconfigure or maneuver the spacecraft formation.

Technology Validation Rationale: Many relevant formation-flying technologies are sufficiently mature to meet the requirements of a NMP technology maturation and space validation project. Space validation is required because of the inability to adequately simulate the dynamics present in space, the inability to represent, on the ground or in the atmosphere, the interaction between the thrusters and the spacecraft dynamics with sensors-in-the-loop, the long distances over which the spacecraft formation must operate collaboratively, and the general inability, on the ground or in the atmosphere, to cover the full spectrum of geometric formations required by future Space Science missions.

Due to issues of RF contamination, frequency allocation and, possibly, interference with NASA policies, the use of ultra-wideband protocols (the use of short duration EMF pulses to generate broad spectrum signals) for any solicited advanced technology will not be considered.

B.2 Science Missions Applicability

NASA plans at least six PFF missions over the next two decades in which the interspacecraft range, bearing, and inertial attitude of the spacecraft are directly controlled. Examples include: the formation flying version of the Terrestrial Planet Finder, the Micro-Arcsecond X-Ray Imaging Mission, the Stellar Imager mission, and, further in the future, the Life Finder and Planet Imager missions. These missions consist of multispacecraft distributed interferometers, observing in different wavelengths, with formation sizes ranging from five to greater than 30 spacecraft.

Other mission concepts requiring precision formation flying are under consideration but have not yet been integrated into the Space Science strategic plan. All of these missions have common characteristics in that they involve multiple spacecraft whose interspacecraft range, bearing, and orientations must be controlled continuously and precisely through intersatellite communication links. Hence, these missions will also require multistage precision formation sensing, precise control actuators, robust intersatellite communication links, and distributed formation control strategies.

B.3 Representative Space Experience

Table B-1 describes the state of formation flying system capability that has been flight validated to date. In spite of such achievements, continuous collaborative control of a formation of spacecraft through intersatellite cross link has not been accomplished.

Table B-1. State of Validated Formation Flying System Capability.

Formation Flying Capability	Current TRL	Validated Performance Level	Missions or Projects on which Validated
< 2 cm S/C-to-S/C range measurement accuracy real time on-board	4	Verified to 2 cm post-flight and not in real time.	GRACE
10 cm S/C-to-S/C range control via comm. link over long range	4	< 1 m over short range.	STS, ISS
1 arc min S/C-to-S/C bearing angle measurement accuracy	4	Not validated.	
5 arc min S/C-to-S/C bearing angle control accuracy	2	Not validated.	
10 – 1,000 Kbps intersatellite comm. rate	6	300 Mbps.	TDRSS
100 m – 1 km S/C-to-S/C separation operating distance	2	> 1 km; no inter-S/C communication.	EO-1 / LS-7

B.4 Flight Experiment Concept

Experiment Concept Description: This experiment will field two to four spacecraft employing continuous closed loop control of interspacecraft range, bearing, and inertial attitude, implemented through the intersatellite communications links. Several extended experiments will be conducted with duration of four to eight hours, each of which will be characterized by a commanded formation geometry that is a small perturbation from the natural motion of the spacecraft orbital dynamics for a given formation design. The autonomously generated control commands will, in some cases, hold separations between spacecraft, and, in other cases, will track relative motion trajectories. The overall experiment can be characterized as follows:

- Two to four three-axis-stabilized spacecraft will be operated in Low Earth Orbit (LEO);
- There will be no maintenance of specific orbits;
- Separation distances during normal operations may vary between 100 m and 10 km;
- Interspacecraft range, bearing, inertial attitude, and estimation/control will be performed on-board and implemented through cross links;
- The formation orbits will be designed so as to minimize fuel consumption needed for formation keeping;

- Formation control will employ low thrust actuation devices;
- Control will be autonomous and collaborative among the spacecraft, with no ground intervention;
- Several extended PFF investigations will be conducted, each providing several hours (e.g., four to eight) of continuous collaborative formation control:
  - The investigations will take place over a six-month experiment period after initialization, and
  - Over the experiment period, formation control performance degradation will be assessed;
- Full six degree-of-freedom formation control will be performed; and
- The formation will be commanded to maintain fixed or variable distances between spacecraft.

The experiments will be designed to cover the broadest possible array of geometric formation configurations that are achievable within fuel constraints imposed in the LEO gravitational environment. The estimate is that about six different geometric formation configurations will be possible during this flight experiment. Some examples of formation geometry are:

- In-track formations, where spacecraft will maintain a set distance apart, all in the same orbit plane with different phases;
- Formations with slight variations among spacecraft in at least two of the following orbital characteristics: inclination, right ascension, and eccentricity;
- Formations, called projected elliptical formations, in which the spacecraft motions, when projected onto the Earth, form an ellipse; and
- Formations, called projected circular formations, in which the spacecraft motions, when projected on the Earth, form a circle (e.g., one trajectory to be commanded will demonstrate formation control to maintain equilateral separation between spacecraft in the projected circular formation required for space-based interferometry science missions).

B.5 Advanced Technology Performance Requirements

B.5.1 Formation Sensor (FS)

The FS is a system level sensor that provides range and bearing measurements between spacecraft, thus giving a geometric interpretation of the quality of the formation shape. A single sensor or sensor system that meets the requirements of both the Formation Sensor and the Point-to-point Ranging Sensor (described in Section B.5.3) is an allowable approach to meeting the requirements of this solicitation.

Objectives and Requirements for FS: A key technology needed for a planned formation flying missions is a FS to enable acquisition and maintenance of interspacecraft range and bearing knowledge of each spacecraft within the formation. In order to minimize the time for acquisition of interspacecraft range and bearing knowledge and, therefore, the risk of collision between spacecraft due to unknown drifts, a FS, using multiple antenna or sensor heads, with full 4π steradian (full-sky) coverage, is needed. The FS must be able to handoff to a finer resolution, limited field-of-view, fine sensing stage, which is described in Section B.5.3 below, in order to align the instruments bore sights and relay optics. The FS requires a configurable architecture to enable a wide dynamic range of operation and performance. The FS must meet the flight validation requirements listed in Table B-2 below.

Table B-2. Technology Validation Requirements for Formation Sensor.

Parameter	ST9 Requirement	Scalability Target	Comments
Range accuracy	Configurable, not to exceed 150 cm (3 σ) between 10 km to 1 km and 6 cm (3 σ) between 1 km and 100 m.	< 1 cm (3 σ) at 1 km separation.	
Bearing accuracy	Configurable, not to exceed 3 deg (3 σ) between 10 km to 1 km and 3 arcmin (3 σ) between 1 km and 100 m.	20 arcsec (3 σ) at 1 km separation.	
Bearing accuracy (all other directions)	Configurable, not to exceed 3 deg (3 σ) between 10 km and 100 m.	20 arcsec (3 σ) at 1 km separation.	
Cold start	Acquire and track multiple spacecraft range and bearing without any *a priori* information about the orientation and locations of the other spacecraft.	Acquire and track multiple spacecraft range and bearing without any *a priori* information about the orientation and locations of the other spacecraft.	
Number of active links, per S/C	N-1 where N is the number of S/C in the formation.	N-1 where N is the number of S/C in the formation.	
Mass, per S/C	< 20 kg		To be determined during Concept Definition Phase.

Parameter	ST9 Requirement	Scalability Target	Comments
Total subsystem volume, including antennas, per S/C	< 10,000 cm^3		To be determined during Concept Definition Phase.
Orbit average DC power consumption, + 28 V, per S/C	< 30 W		To be determined during Concept Definition Phase.
Data Rate and Measurement Rate	> 1 Hz and > 1 Hz	> 1 Hz and > 1 Hz	
Min-Max Operating Range	30 m – 10 km	30 m – 10 km	
Field of View	4π steradian	4π steradian	
Operating Lifetime	At least 6 months	12 years by 2020	
Orbit Compatibility	LEO	Libration point/deep space	
Environmental Compatibility	Consistent with NASA/GSFC "General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems, and Components, Revision A".	Libration point/deep space environment.	See http://arioch.gsfc.nasa.gov/302/gevs-se/toc.htm
On-board Sensing Architecture	Applicable to 4 spacecraft in Earth orbiting and deep space PFF missions.	Up to 34 spacecraft.	
Formation Acquisition Time (range knowledge)	< 30 sec	< 30 sec	
Acquisition of new targets while tracking current targets	Simultaneous.	Simultaneous.	

Representative Measurements, Parameters, and Model Verification for Formation Sensor: Proposals for an FS must discuss the predictive models and measurements to be used in validating the formation sensor technology; existing and planned models; measurements to be made during ground-based testing, with an emphasis on those used to achieve TRL 5 where a component and/or breadboard has been validated in its relevant environment; measurements to be made during the space experiment; and how these measurements would be used to verify or calibrate the existing models and how they would validate the technology, including any applicable scaling or extension of the validated model and its domain of applicability.

At a minimum, the proposer shall be capable of providing the following telemetry measurements or their equivalent:

- Interspacecraft range and bearing in each of the spacecraft frames, between all spacecraft pairs;
- Spacecraft inertial attitude and inertial rate information for each spacecraft in its own spacecraft frame;
- Time tag associated with all data using the local spacecraft clock; and
- Time offset knowledge of each spacecraft clock with respect to a common time source (e.g., Coordinated Universal Time (UTC)).

B.5.2 Intersatellite Communications Subsystem (ICS)

Objectives and Requirements for ICS: The ICS shall meet the flight and ground validation performance requirements in Table B-3. In addition, it is desired that a relative range measurement be produced in real time.

Table B-3. Validation Requirements for Intersatellite Communications Subsystem.

Parameter	ST9 Requirement	Scalability Target	Comments
Number of active links, per S/C	N-1 where N is the number of S/C in the formation.	N-1 where N is the number of S/C in the formation.	
Communications Topology	Fully connected mesh; 2 to 4 S/C.	Fully connected mesh; up to 34 S/C.	
Duplex capability	Full	Full	
Data Bandwidth (of each link)	> 10 kbps @ maximum range, > 1 Mbps @ minimum range	1 – 3 Mbps @ maximum range	
Maximum Signal Bandwidth of all links	50 MHz	50 MHz	
Bit Error Rate	$< 10^{-6}$	$< 10^{-6}$	
Number of simultaneous range measurements	2	< 34	
Measurement accuracy, each of 3 axes	±5 cm, 3 σ	±5 cm, 3 σ	
Cold start or hand-off capability	Full cold-start (lost-in-space) capability.	Full cold-start (lost-in-space) capability.	

Parameter	ST9 Requirement	Scalability Target	Comments
Latency from Detection/Sensing to Data/Measurement Availability, including Internal Processing (does not include light time or delay imposed by serial communications)	< 10 ms	< 10 ms	
Mass, per S/C	< 8 kg		To be determined during Concept Definition Phase.
Total subsystem volume, including antennas, per S/C	< 1,000 cm^3		To be determined during Concept Definition Phase.
Orbit average DC power consumption, + 28 V, per S/C	< 20 W		To be determined during Concept Definition Phase.
Data Rate, Measurement Rate	10 kbps @ max range, 1 Mbps @ min range; > 1 Hz	10 kbps @ max range, 1 Mbps @ min range; > 1 Hz	
Min-Max Operating Range	30 m – 10 km	30 m – 10 km	
Field of View	4π steradian	4π steradian	
Operating Lifetime	At least 6 months	12 years by 2020	
Orbit Compatibility	LEO	Libration point/deep space	
Environmental Compatibility	Consistent with NASA/GSFC "General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems, and Components, Revision A".	Libration point/deep space environment.	See http://arioch.gsfc.nasa.gov/302/gevs-se/toc.htm

Parameter	ST9 Requirement	Scalability Target	Comments
On-board ICS Architecture	Applicable to 4 spacecraft in Earth orbiting or deep space.	Up to 34 spacecraft.	
Formation Acquisition Time (ICS, range and bearing knowledge)	< 30 sec	< 30 sec	
Acquisition of new targets while tracking current targets	Simultaneous.	Simultaneous.	

Representative Measurements, Parameters, and Model Verification for Intersatellite Communications Subsystem: Proposals for an ICS should discuss: predictive models and measurements to be used in validating the intersatellite communication subsystem technology; how these measurements would be used to verify or calibrate existing models; how they would be used to validate the technology; any applicable scaling or extension of the validated model and its domain of applicability; the models to be used to predict the performance of the subsystem technology; and the measurements required to validate these models.

Minimum ground validation requirements for the ICS are presented in Table B-4. The ST9 flight data will be used to validate channel simulator models with the ICS in the loop.

Table B-4. Ground Validation Requirements for Intersatellite Communications Subsystem.

Parameter	ST9 Requirement	Scalability Target	Comments
Number of active links, per spacecraft	> 5	N/A	
Data bandwidth of each link	> 10 Mbps @ maximum range	N/A	
All link acquisition times	< 10 seconds	N/A	

B.5.3 Point-to-point Ranging Sensor (PRS)

The PRS provides the finest resolution measurement of relative range. The dynamic range of the PRS drives the resolution requirement of the FS. A single sensor or sensor system that meets the requirements of both the Formation Sensor (described in Section B.5.2) and the Point-to-point Ranging Sensor is an allowable approach to meeting the requirements of this solicitation.

Objectives and Requirements for PRS: The PRS must meet the flight validation requirements listed in Table B-5 below.

Table B-5. Technology Validation Requirements for Point-to-point Ranging Sensor.

Parameter	ST9 Requirement	Scalability Target	Comments
Ranging architecture	Measure the distance between itself and one other spacecraft.	Measure distances between all spacecraft.	
Range accuracy	0.001% of the interspacecraft separation, or 3 millimeters, whichever is less stringent, 3 σ	1 nm	
Cold start or hand-off capability	Handoff from 4 cm accuracy	Handoff from 4 cm accuracy	
Latency from detection/sensing to data/measurement availability, including internal processing (does not include light time or delay imposed by serial communications)	< 10 ms	< 10 ms	
Mass, per S/C	< 5 kg		To be determined during Concept Definition Study Phase.
Total subsystem volume, including antennas, per S/C	< 6,000 cm^3		To be determined during Concept Definition Study Phase.
Orbit average DC power consumption, + 28 V, per S/C	< 10 W		To be determined during Concept Definition Study Phase.
Data rate/ Measurement rate	> 10 Hz / > 10 Hz	> 10 Hz / > 10 Hz	
Min-Max operating range	100 m –1 km	100 m – 1 km	
Field of view	At least 30 deg off sensor bore sight.	At least 30 deg off sensor bore sight.	
Operating lifetime	At least 6 months	12 years by 2020	
Orbit compatibility	LEO	Libration point/deep space	

Parameter	ST9 Requirement	Scalability Target	Comments
Environmental Compatibility	Consistent with NASA/GSFC "General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems, and Components, Revision A."	Libration point/deep space environment	See http://arioch.gsfc.nasa.gov/302/gevs-se/toc.htm
On-board relative sensing architecture	Applicable to 4 spacecraft in Earth orbit or deep space.	Up to 34 spacecraft.	
Formation Acquisition time (range and bearing knowledge)	< 30 sec	< 30 sec	
Acquisition of new targets while tracking current targets	Simultaneous	Simultaneous	

Representative Measurements, Parameters, and Model Verification for PRS: Proposals for a PRS should discuss: the predictive models and measurements to be used in validating the proposed PRS advance technology; how these measurements would be used to verify or calibrate the existing models; how they would validate the technology advance; and, any applicable scaling or extension of the validated model and its domain of applicability.

The PRS provides two significant capabilities in the proposed formation flying demonstration. It serves as the finer resolution, limited-field-of-view, fine sensing stage, and also as a benchmark for the ranging performance of the other sensors. A high-fidelity reference trajectory will be derived for performance evaluation of the integrated relative navigation performance of the suite of technologies solicited by the project. This reference trajectory will be derived by statistically combining the measurements from all three solicited advanced technologies (FS plus PRS plus ranging built-into the ICS), as well as independent combinations of measurements from any two of the three, along with knowledge of the relative dynamics. At a minimum, the following measurements will be required for validation purposes:

- Point-to-point, scalar range between one pair of spacecraft;
- Inertial attitude and inertial rate information for each spacecraft;
- Time tag associated with all data using the local spacecraft clock;
- Time offset knowledge of each spacecraft clock with respect to a common time source (e.g., UTC); and

- Comparable measurements computed from a model or directly from one of the other sensing technologies on-board.

Analytical and prototype models for the sensors (i.e., models of engineering sensors) must be validated through the use of flight data.

B.6 Technology Selection Opportunities and Planned Funding Levels

Pending the submission of proposals of merit, the number of formation-flying technology-provider opportunities and funding for the Study Phase is indicated in Table B-6.

Table B-6. Award Levels for Concept Definition Study Phase.

Technology Area	Opportunities	Maximum Funding*
Formation Sensor	1	$150,000
Intersatellite Communication Subsystem	1	$100,000
Point-to-point Ranging Sensor	1	$75,000

* Proposals with budgets in excess of these amounts may be selected only if they exhibit exceptional merit and breadth of objectives.

B.7 Representative Project Schedule (for use as a reference only)

Table B-7. Precision Formation Flying Project Schedule.

Milestone	Months After Release of NRA (ARN)
• Concept Definition Study Phase - Concept Definition Study Teams Formed - Deliver Study Report	8 months duration (5 – 13 months ARN) 5 months ARN 11 months ARN
• Formulation and Refinement Phase - Systems Requirements Review - Preliminary Design Review	12 months duration (13 – 25 months ARN) 15 months ARN 23 months ARN
• Confirmation Review	25 months ARN
• Implementation Phase - Critical Design Review - Pre Environmental Test Review - Launch - Flight Operations - Validation Data Analysis - Final Report	39 months duration (25 – 64 months ARN) 28 months ARN 53 months ARN 55 months ARN 6 month duration (55 – 61 months ARN) 3 months duration (61 – 64 months ARN) 64 months ARN

B.8 Acronym List

arcmin	arc minute
arcsec	arc second
cm	centimeter
DC	direct current
deg	degree
ELV	expendable launch vehicle
EO-1	NMP Earth orbiting-1 spacecraft
FS	formation sensor
GEVS	general environmental verification specification
GRACE	gravity recovery and climate experiment
Hz	Hertz
ICS	intersatellite communication subsystem
ISS	international space station
Kbps	thousand bits per second
kg	kilogram
km	kilometer
L-1	Earth-Sun Lagrange point 1
LEO	low Earth orbit
LS-7	Landsat-7 spacecraft
m	meter
ms	millisecond
Mbps	million bits per second
MHz	megaHertz
N	number of S/C in a formation
nm	nanometer
PFF	precision formation flying
RF	radio frequency
PRS	point-to-point ranging sensor
s or sec	second
S/C	spacecraft
STS	space transportation system
TDRSS	tracking and data relay satellite system
TRL	technology readiness level
μm	micrometer
UTC	coordinated universal time
V	Volt
W	Watt
σ	standard deviation

Appendix C. System Technology For Large Space Telescope (LST)

C.1 Flight Validation Concept

Solicited Advanced Technology Capabilities: The technology advances needed to support a system-level flight validation of advanced technologies for Large Space Telescopes (LST) are:

- A high-performance deployable sunshade with one or more actively-cooled layers that will significantly reduce the thermal emissions impinging on the payload, and
- A mechanical two-stage cryocooler to provide greater than 150 mW of continuous active cooling at less than 25 K to cool the cold-side layer of the sunshade and greater than 20 mW of continuous active cooling at less than 15 K for cooling of simulated optics.

*Advanced Technology Description and Benefit***:** The Astronomical Search for Origins and Planetary Systems (ASO) and the Structure and Evolution of the Universe (SEU) themes in NASA's Space Science Enterprise (SSE) identify future large space-telescope missions as key elements of their strategic roadmap. The ASO long-range goal is to detect and characterize planets in orbit around nearby stars, while SEU's Beyond Einstein Initiative focuses on answering fundamental questions regarding the connections between space, time, and matter. These challenges are the drivers for large aperture systems. To achieve the highest possible signal-to-noise ratio for missions operating at long wavelengths, these large optics (and any support systems that fall into the beam pattern of an optical element) must be cooled to temperatures as low as 4 K in order to achieve performance limited by the background of space.

Ground-based thermal vacuum tests cannot easily provide the required low thermal background while simulating the thermal loads from the Sun, Earth, and warm spacecraft components. A complete thermal-control system that provides the necessary environment for a large optical system must be validated in space. The LST flight validation concept is based on the validation of two technologies required to meet these goals: a high-performance deployable sunshade with one or more actively-cooled layers that significantly reduces the thermal emissions impinging on the payload, and a mechanical cryocooler that provides the active cooling to both the sunshade layers and to the payload.

The active layer of the deployable sunshade will be temperature controlled by the mechanical cryocooler to the coldest achievable temperature based on the orbital environment. Because of ST9 resource constraints, the LST experiment intends to fly only a ROS and not a functioning imaging optical system. The ROS will only have the mechanical and structural characteristics of a scalable large aperture system and not the optical performance. The LST Study Team intends to provide the ROS measurement system for validating thermo-elastic stability and as a representative payload for validating the cryocooler performance.

The LST will be mounted to a host spacecraft that will provide supporting functions. In the optimal case, the spacecraft with the ST9 validation technologies will be launched to a high

Earth orbit or Lagrange Point 2 (L2) that provides a thermally stable environment and is traceable to targeted missions. However, a Sun-synchronous Low Earth Orbit (LEO) mission is an acceptable alternative. Notwithstanding the thermal, dynamical, and other differences at LEO, traceability to targeted missions can be demonstrated. A series of ground tests and in-space experiments will be performed for the validation of models and scaling laws to infer performances at targeted conditions.

Flight Validation Objectives: The minimum baseline objectives of this flight experiment, from which the experiment success is determined, include the following:

- Validate the capability of a high-performance, deployable sunshade and a mechanical cryocooler system that provides active cooling and is scalable to missions with a 10-meter class primary mirror requiring full aperture cooling at 4 K, and
- Validate and/or improve prelaunch models of critical related phenomena and enhance understanding of the associated physics between the model predictions and flight data.

The following is a secondary objective that increases the value of the overall experiment, but it is not essential to overall experiment success:

- Validate the thermo-elastic stability of an ROS produced using materials, fabrication, and verification processes scalable to 10-meter class primary mirrors or larger that are actively cooled to 4 K.

Technology Validation Rationale: The key factors for the overall LST experiment success are accuracy with which 1 g_e analytical models can predict on-orbit performance and the process by which these models are validated. Future large aperture systems such as Single Aperture Far InfraRed (SAFIR)-class projects will be verified by integrated analysis rather than by test because of their large size. Therefore, a strong and robust integrated modeling process will be the key factor for the overall experiment validation, and the LST experiment will prove that this approach is acceptable with well-anchored, scalable models. Modeling will utilize both simulation data and ground test data to generate or refine computer models and the LST experiment's predicted on-orbit performance. The flight data will be used to validate these prelaunch models and to enhance understanding of the associated physics.

A key objective is to determine modeling errors as a function of design/model/data fidelity over the life cycle of the future mission. The goal is that future projects such as SAFIR may then be undertaken with guidelines that help manage risk by a) increasing understanding of physics associated with the technologies; b) reducing modeling errors in the design process to an acceptable level; c) using demonstrated scaling laws for dimension, gravity, loads and thermal conditions; and d) specifying necessary and sufficient ground testing required to anchor models.

C.2 Science Missions Applicability

A high-performance deployable sunshade with one or more actively-cooled layers that significantly reduces the thermal emission impinging on the optical system will enable a number of future NASA science missions. Examples of applicable missions include the following:

- *Astronomical Search for Origins and Planetary Systems (ASO):* Single Aperture Far Infrared (SAFIR) observatory
- *Structure and Evolution of the Universe (SEU)*: Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), Cosmic Microwave Background Polarization (CMB-Pol) observatory.

C.3 Representative Space Experience

The most ambitious sunshade currently under development is that for the James Webb Space Telescope (JWST), which is scheduled to launch in 2011. While not yet flight validated, this implementation will be a passive, deployable sunshade to achieve the following key performance parameters:

- Radiation flux attenuation of ~3.5 orders of magnitude
- Innermost layer temperature of ≤ 100 K
- Instrument operating temperature of 30 K
- Multiple passively-cooled layers
- Primary mirror diameter ~5.6 m
- Orbiting at L2
- Three-hinge boom deployment system
- Total mass 345 kg
- Areal density of 1.5 kg/m^2.

For JWST, a half-scale sunshade deployment was demonstrated. Development of a full-scale pathfinder for thermal vacuum chamber testing is scheduled to occur early in the Formulation Refinement Phase. Its technology-readiness status is estimated to be at TRL 4, which implies that the component and/or breadboard has been validated in a laboratory environment.

The following missions characterize spaceflight experience representing temperatures achieved through deployable or fixed-geometry passive shielding:

- Space Infrared Telescope Facility (SIRTF) launched on August 2003, an Earth-trailing heliocentric orbit at 1 AU with an outer shell at ~40 K enabled by means of fixed geometry passive sunshading (TRL 9);

- Wilkinson Microwave Anisotropy Probe (WMAP) launched on June 2001, orbiting at L2 with primary reflectors at 68 K and microwave receiver at 90 K enabled by means of deployable passive shielding (TRL 9); and
- Cosmic Background Explorer (COBE) launched on November 1989, in a 6:00 AM, Sun-synchronous, low-Earth orbit, with an inner surface of Sun/Earth shield at 180 K and a dewar main shell at 150 K enabled by means of deployable passive shielding (TRL 9).

Typical spaceflight experience representing the state of technology of mechanical cryocoolers is represented by the following:

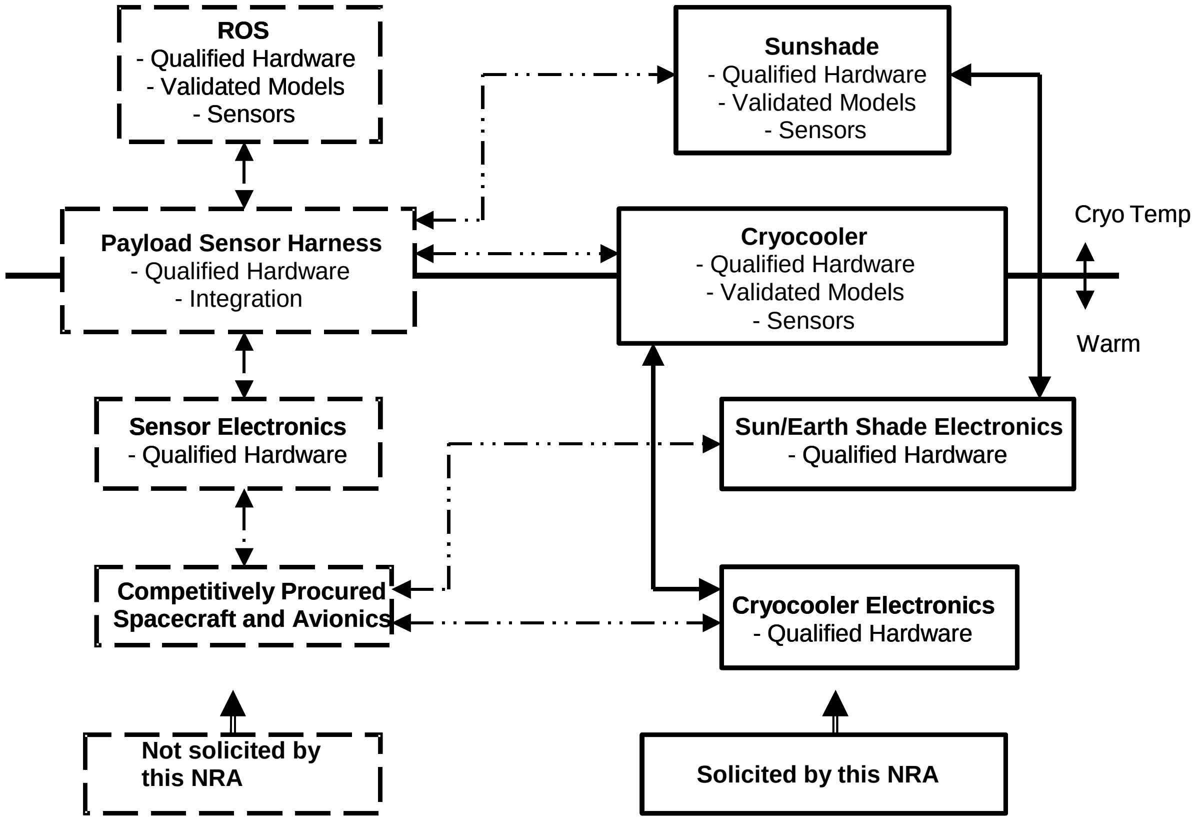
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS) Cooling System on Hubble Space Telescope launched in March 2002 with 7 W of cooling power at 80 K, achieved with a Creare Reverse Turbo-Brayton cryocooler plus circulator (TRL 9); and
- Atmospheric Infrared Sounder (AIRS) on EOS Aqua launched in May 2002 with 1.5 W of cooling power at 55 K, achieved with TRW pulse-tube cryocoolers, two redundant units (TRL 9).

In addition to the above missions, the following are pending near-term flights involving space-qualified cryocoolers:

- Tropospheric Emission Spectrometer (TES) on EOS Aura to be launched in 2004 with 1 W of cooling power at 57 K, achieved with two pulse-tube cryocoolers cooling separate focal planes (TRL 8); and
- High Resolution Dynamics Limb Sounder (HIRDLS) on EOS Aura to be launched in 2004 with 0.72 W of cooling power at 55 K, achieved with a single-stage Stirling-cycle cryocooler (TRL 8).

C.4 Flight Experiment Concept

Experiment Concept Description: The objectives of the LST validation experiment are to validate the integrated performance of the sunshade and mechanical cryocooler and, if possible, to validate the performance of the integrated thermo-opto-mechanical system as predicted by models validated in 1 g_e. This includes monitoring of the temperatures and mechanical motions of the sunshade, cryocooler assembly, and ROS. Figure C-1 illustrates the major functions, interfaces, advanced technology providers and NASA responsibilities.



<u>Figure C-1</u>. ST9 Large Space Telescopes Block Diagram.

Because of ST9 resource constraints, the LST experiment intends to fly a ROS only as a surrogate for an actual imaging system. The ROS will have the mechanical and structural characteristics of a scalable large aperture system; however, it will be based on technology envisioned for far-infrared large-aperture missions, but will not be science-grade quality and may not acquire images.

The LST experiment will be fitted with sensors such that thermo-elastic stability can be quantified. The objective is to take measurements that will establish optical system thermo-elastic stability traceable to a 10-meter class (or larger) deployable telescope that is to be actively cooled to 4 K. This representative optical system will comprise a simulated optical surface and its mount, an aperture support structure, and an instrumentation suite for taking measurements.

The optical system's forced dynamic response to vibration inputs from the reaction wheels and cryocooler will be measured with accelerometers, and these same accelerometers will also monitor the system for transient dynamic events (e.g., thermal snap and spontaneous microdynamics) at other times. The disturbance forces and torques imparted by the reaction wheels and cryocooler will be measured using load cells along with the accelerometers. The quasi-static response of the ROS to time-varying thermal loads—periodic variations as a function of Sun angle and forced variations through the discrete location of heaters—will be measured with strain gauges and noncontact displacement sensors.

The sunshades will also be instrumented with accelerometers and temperature sensors for performance verification and for model validation of the full thermo-mechanical system. In addition, the temperature and cooling power for each of the thermal stages of the cryocooler will be measured or calculated from other performance data. A nominal flight experiment sensor package is presented in Table C-1.

Table C-1. Sensors Required for On-Orbit Measurements.

Location	Instrumentation	Minimum Number
Sunshade (solicited by NRA)	To be defined by proposer, see Sec. C.5.1.	To be defined by proposer, see Sec. C.5.1.
Mechanical Cryocooler (solicited by NRA)	To be defined by proposer, see Sec. C.5.2.	To be defined by proposer, see Sec. C.5.2.
Representative Optical System (not solicited by NRA)	Thermal sensors Dynamic accelerometers Capacitance sensors Heaters	20 Thermal 20 Accelerometers 6 Capacitance sensors 8 Heaters
Spacecraft (not solicited by NRA)	Dynamic accelerometers Video camera to monitor shield deployment and ROS	2 Accelerometers 1 Video camera
Spacecraft/Payload Interface (not solicited by NRA)	Thermal sensors Dynamic accelerometers Load cells	20 Thermal 6 Accelerometers 6 Load cells
Spacecraft Reaction Wheel Assembly (not solicited by NRA)	Dynamic accelerometers Load cells	12 Accelerometers 12 Load cells

C.5 Advanced Technology Performance Requirements

The advanced technologies solicited for the ST9 LST flight validation experiment are a high-performance sunshade and mechanical cryocooler refrigerator. The principal objectives for this flight validation experiment are to acquire measured performance on the ground, use the validated ground models to predict the system performance once on orbit, and perform post-launch characterization and verification of predicted performance in a relevant space environment. The ST9 LST will be equipped with a suite of flight sensors to verify the on-orbit performance of the advanced technology components and the predictability of their models. The proposer shall be capable of providing the flight sensors, associated electronics, and cables required for validation of the on-orbit predictive models. The hardware (mechanical cryocooler and sunshade) shall be delivered with the flight instrumentation package fully integrated. The flight instrumentation system shall have sufficient accuracy and sensitivity to measure:

- The interface loads and system vibrations of the cryocooler up to 200 Hz and of the sunshade up to 25 Hz,

- Temperatures down to 6 K measured with an absolute accuracy of 0.1 K and a relative accuracy of 0.01 K, and
- The shield thermal deformations for validation of the predicted on-orbit states.

Along with the flight sensors required for model validation, the proposer shall be capable of performing ground tests to measure and verify the performance of the flight sensors mounted on the flight hardware. Auxiliary ground sensors are expected to be used for performance verification. The ground test data and all associated analyses and verified models will be delivered at the time of delivery of the flight hardware.

C.5.1 High-Performance Sunshade with Actively-Cooled Layer(s)

Objectives and Requirements for High-Performance Sunshade with Actively-Cooled Layer(s):

Sunshade Flight Validation Objectives

- Validate the ability to package and deploy a sunshield while in orbit,
- Validate the capability to achieve a solar radiation flux reduction of approximately six orders of magnitude by means of a multilayer sunshade,
- Validate the capability to sustain a substantial period in space without significant degradation of the performance of the shield, and
- Validate mathematical models of both the thermal and the dynamic behavior of this sunshade in the absence of gravity and atmosphere.

Sunshade Technology Performance Requirements

Sunshading is the primary means of cooling large payloads to the desired operating temperatures. Science observation in wavelength bands of 30 – 600 μm requires effective cooling in order to attain usable signal-to-noise ratios. This is accomplished by reducing nonsignal noise created by thermal radiation of the telescope optics and structure itself. Effective sunshading also reduces the need for inefficient refrigeration hardware, thus reducing resource requirements and enabling larger science payloads.

The successful proposer must work with the ST9 LST team to develop a usable sunshade design that achieves all thermal, mechanical, and spacecraft control requirements. To accomplish this, the successful proposer must demonstrate knowledge of techniques for active cooling of large surfaces comprised of thin membranes and be capable of performing the required design, manufacturing, integration, verification, and validation of the proposed sunshade. It is incumbent on the proposer to present appropriate justification that the proposed system design will be at TRL 4 or greater by the end of the Study Phase.

Previous experience has indicated that the required level of energy-flux attenuation will likely necessitate having one or more sunshade layers capable of transporting substantial thermal energy in the plane of the sunshield layer at cryogenic temperatures. The heat energy transported within the sunshield layer is expected to be removed from the shield by means of a cryocooler.

The proposer shall be capable of providing a sunshade implementation that involves active cooling of successive sunshade layers to temperatures of 35K and 15K, respectively, with the colder surface being that in closest proximity to the optics. Alternative designs not using at least one of these options are acceptable, but they must be strongly justified.

The proposer shall describe a candidate sunshade thermo-mechanical design that meets the requirements listed in Table C-2, which will be used as the starting point for the Study Phase.

Table C-2. Technology Validation Requirements for the Sunshade.

Parameter	ST9 Requirement	Scalability Target	Comments
Thermal Radiation Flux Attenuation	≥ six orders of magnitude from the incident solar input.	> six orders of magnitude from incident solar input.	Driven by need to eliminate thermal load on optics. Payload must not see surfaces with temperatures exceeding 25 K (15 K goal).
Sunshade-Layer Cooling	Active cooling to < 25 K, plus an intermediate-layer actively cooled to 35 K for intercepting a limited amount of radiation and conduction heat load, if needed.	Same as ST9 for larger–sized radiator.	See cryocooler requirements in Table C-3.
Size and Shape	Appropriate to shield cylindrical payload of nominal 1 m diameter by 0.75 m length with cylindrical axis parallel to Earth gravity vector while occupying Sun-synchronous orbit at a minimum altitude of 500 km with ascending node occurring at dawn or dusk.	Applicable to any spacecraft requiring low-temperature large optics (≥ 10m).	Driven by probable orbital constraints during technology validation flight.
Pointing Compatibility	Compatible with 3-axis spacecraft pointing control of 1 deg rms and pointing knowledge of 1 deg rms	Compatible with 3-axis spacecraft pointing control of < 1 deg rms and pointing knowledge of < 1 deg rms.	
Stowed Volume	≤ 0.35 m^3	Mission specific	Driven by packing constraints of probable carrier.

Parameter	ST9 Requirement	Scalability Target	Comments
Stowage Diameter	≤ 1.1 m	Mission specific	Driven by packing constraints of probable carrier.
Subsystem Mass	≤ 28 kg	Mission specific	Driven by need to reduce mass.
Areal Density	≤ 1.5 kg/m^2	1.0 kg/m^2	Exclusive of deployment hardware used to stow and contain sunshield, but includes booms, hinges, etc., that are part of the deployed sunshield.

Representative Measurements, Parameters, and Model Verification for High-Performance Sunshade with Actively Cooled Layer(s): Proposals for this technology advance should discuss the predictive models and measurements to be used in validating an actively-cooled sunshade; existing and planned models; measurements to be made during ground-based testing, with an emphasis on those used to achieve TRL 5 where a component and/or breadboard has been validated in its relevant environment; measurements to be made during the space experiment; how these measurements would be used to verify or calibrate the existing models; how they would validate the technology; any applicable scaling or extension of the validated model and its domain of applicability; and any ground and flight models, instrumentation, and measurements required for the sunshade to validate any integrated system-level, thermo-elastic models including the ROS.

The proposer shall be capable of providing the following sunshield radiation-shield modeling information or its equivalent upon delivery of the experiment hardware:

- A CAD model in Pro/E™, Ideas™, or STEP™, format;
- A materials list;
- A thermal geometric model developed using the Thermal Synthesizer System (TSS) or Thermal Model Generator (TMG) and a global coordinate system;
- A thermal mathematical model of the sunshield that satisfies a set of basic validation checks and has been validated in a thermal vacuum test;
- Documentation of either the thermal models, including a list of all assumptions and references to establish the accuracy and uncertainty bounds for all material properties or, if none is available, data from tests on material samples (along with documentation of the test, measurement, and analysis procedures), predictions of both steady-state and transient temperatures in the test environment, and corresponding temperature measurements used to establish the validity of the model;

- A structural Finite Element Method (FEM) model of the deployed sunshield that satisfies the following conditions in order to allow system-level, free-free dynamics analysis:
  - Compatible with NASTRAN™ to allow basic NASTRAN validation checks and be validated via a fixed-base modal survey;
  - Discusses nonlinear mechanical effects and the impact of 1-g to zero-g environment (e.g., membrane effects of the sunshield as well as any deployment mechanism or gimbal), ground testing and model validation for characterization of nonlinearities, and thermo-mechanical deformation models, predictions, and ground validation; and
  - Includes predictions of both fixed-base frequencies and mode shapes in the test environment, and the corresponding sensor measurements used to establish the validity of the model;
- Either a list of all assumptions and references to establish the accuracy and uncertainty bounds for all material properties, or if none is available, provide data from tests on material samples (along with documentation of the test, measurement, and analysis procedures);
- Documentation of other mechanical tests that may be necessary for predicting the behavior of the sunshade in zero gravity; and
- A list of all assumptions used in the development of the thermal and mechanical mathematical models, including an assessment of the accuracy and uncertainty bounds on the ground-validated models to performance in zero gravity.

C.5.2 Mechanical Cryocooler

Mechanical Cryocooler Flight Validation Objectives:

- Validate the capability of achieving scalability to 4 K cooling of the sunshade, including initial cool down from room temperature and any degradation of performance during the three-month experiment lifetime;
- Validate the integrated thermal and structural model of the complete cooling system; and
- Validate thermal and mechanical mathematical models of the cooler performance characteristics in zero gravity and the vacuum of space.

Mechanical Cryocooler Technology Performance Requirements:

Microgravity and the space thermal environment, both of which affect the sunshade and hence the cryocooler performance, cannot be adequately simulated on the ground. Therefore, in addition to verifying thermal and structural models, cryocooler testing in space is required not only to validate successful cooling technology but also to quantify vibration levels and the effects of external molecular contamination on the overall thermal control system.

In 2001, NASA initiated a new program referred to as the Advanced Cryocooler Technology Development Program (ACTDP). The program objective is to produce mechanical cryocoolers with two primary cooling stages at 6 K and 18 K, and it builds on NASA's successful prior developments of Stirling, pulse-tube, and turbo-Brayton technologies. The best current understanding of the state of the art is reflected by the ACTDP effort. However, for the LST experiment, the cryocooler must be able to cool a ROS remotely, as well as to provide cooling to the deployable sunshade. An additional higher temperature fixed-shield stage may also be used to intercept a limited amount of radiation and conduction heat load.

Therefore, proposals for a Mechanical Cryocooler technology validation must include discussions of the current state-of-the-art as represented by the ACTDP cryocoolers; the tradeoff space in which the cryocoolers that are now in development would be integrated into a system for the ST9 LST; and the scaling laws for power or temperature that will be required for a future large-aperture telescope cooler. In particular, a candidate mechanical cryocooler must meet the requirements listed in Table C-3, which will be used as the starting point for the Study Phase.

Table C-3. Technology Validation Requirements for the Mechanical Cryocooler.

Parameter	ST9 Requirement	Scalability Target	Comments
Optics Cooling Power	> 20 mW at < 15 K	30 mW at 6 K	For cooling simulated optics.
Sunshade Cooling Power	> 150 mW at < 25 K	250-400 mW at 15 K	For cooling cold-side layer of sunshade.
Interstage Cooling	Available capability		Interstage cooling capability must be available if needed to meet primary cooling requirement.
Mass	< 50 kg	Mission specific	Driven by need to reduce mass.
Input Power	< 250 W rms at end of life	Mission specific	Driven by need to minimize power needs.

Representative Measurements, Parameters, and Model Verification for Mechanical Cryocooler: Proposals for the Mechanical Cryocooler technology advance should discuss the predictive models and measurements to be used in validating the mechanical cryocooler technology; how these measurements would be used to verify or calibrate the existing models; how they would validate the technology; any applicable scaling or extension of the validated model and its domain of applicability; and ground and flight models, instrumentation, and measurements required for the mechanical cryocooler in order to support the secondary experiment objective of validating integrated, system-level dynamics and thermo-elastic models including the ROS.

In addition, proposals are expected to demonstrate that the following information on the mechanical cryocooler can be provided upon delivery of the experiment hardware:

- An external CAD model in Pro/E, Ideas, or STEP format of the cryocooler (supports, heat rejection plates, casing and interfaces) including mass properties (mass, mass moments of inertia);
- A materials list;
- A thermodynamic performance model of the cryocooler that includes cooling capacity, power dissipation, and distribution as a function of cooling temperature, heat rejection temperature, and cooler operating parameters (including stroke, etc.); and
- A mechanical vibration disturbance model of the cryocooler that provides the exported vibration as a function of frequency and axis.

C.6 Technology Selection Opportunities and Planned Funding Levels

The planned number of technology provider selection opportunities and funding for the Study Phase is indicated in Table C-4.

Table C-4. Award Levels for Concept Definition Study Phase.

Technology Area	Selection Opportunities	Maximum Funding*
Sunshade	1	$200,000
Mechanical 4 K Cryocooler	1	$75,000

* Proposals with budgets in excess of these amounts may be selected only if they exhibit exceptional merit and breadth of objectives.

C.7 Representative Project Schedule (for use as a reference only)

The representative Project schedule for the LST system technology validation is presented in Table C-5 below.

Table C-5. Large Space Telescope Project Schedule.

Milestone	Months After Release of NRA (ARN)
• Concept Definition Study Phase - Concept Definition Study Team Forms - Deliver Study Report	8 months duration (5 – 13 months ARN) 5 months ARN 11 months ARN
• Formulation and Refinement Phase - Systems Requirements Review - Preliminary Design Review	12 months duration (13 – 25 months ARN) 15 months ARN 23 months ARN
• Confirmation Review	25 months ARN
• Implementation Phase - Critical Design Review - Pre Environmental Test Review - Launch - Flight Operations - Validation Data Analysis - Final Report	26 months duration (25 – 51 months ARN) 29 months ARN 36 months ARN 40 months ARN 6 months duration (40 – 46 months ARN) 5 months duration (46 – 51 months ARN) 51 months ARN

C.8 Acronym List

ACT	advanced technology center
ACTDP	advanced cryocooler technology development program
AIRS	atmospheric infrared sounder
ASO	astronomical search for origins (one of four OSS science themes)
AU	astronomical unit
CAD	computer aided design
CMB-Pol	cosmic microwave background-polarization
COBE	cosmic background explorer
EOL	end of life
EOS	Earth observing system
FEM	finite element model
g_e	gravitational acceleration at Earth surface
HIRDLS	high resolution dynamics limb sounder
JWST	James Webb space telescope
K	Kelvin
kg	kilogram
L2	Earth-Sun Lagrange point 2
LEO	low Earth orbit
LST	large space telescope
m	meter
mW	milliWatt
NASTRAN	NASA structural analysis system
NICMOS	near infrared camera and multiobject spectrometer
OSS	Office of Space Science, NASA Headquarters
rms	root mean square

ROS	representative optical system
SAFIR	single aperture far infrared
SEU	Structure and Evolution of the Universe (one of four OSS science themes)
SI	Le Système International d'Unités
SPECS	Submillimeter Probe of the Evolution of Cosmic Structure
SSE	Space Science Enterprise, NASA Headquarters
SIRTF	Space Infrared Telescope Facility
STEP	standard for the exchange of product
TES	Tropospheric Emission Spectrometer
TMG	thermal model generator
TSS	thermal synthesizer system
W	Watt
WMAP	Wilkinson Microwave Anisotropy Probe

Appendix D. Terrain-Guided Automatic Landing System for Spacecraft (TGALS)

D.1 Flight Validation Concept

Solicited Advanced Technology Capabilities: The technology advances needed to support an in-space, system-level validation of a Terrain-Guided Automatic Landing System for Spacecraft (TGALS) should have the following capabilities:

- Advanced terrain sensing and terrain recognition technologies, both hardware and software, that identify terrain features consistent with a 100 m navigation accuracy objective via comparison with a reference map, and that identify terrain features that could pose landing hazards to a spacecraft having a surface footprint from 3 to 10 m; and
- Advanced propulsion technologies that provide a powered flight maneuvering capability sufficient to deliver a space vehicle to a safe target landing site, where safety is defined through a modeling approach characterizing landing hazard properties as a function of landing site environment and landing vehicle configuration.

Advanced Technology Description and Benefit: NASA's plans to explore the Solar System include landing on a number of bodies at locations of greatest scientific interest, and returning samples from some. Mars, the Moon, Europa, and many comets and asteroids are being considered for missions designed to perform *in situ* science investigations or sample return where accurate landing relative to terrain features of maximum scientific interest is essential for success. On Mars, for example, landing near sites identified as containing hematite may optimize the chances of finding past life. On Europa, landing at previously identified vents or newly created surfaces may provide the best opportunity to understand potential under-ice oceans. In addition to pinpoint landing accuracy, identification and characterization of terrain such as craters, steep slopes, ice ridges, crevasses, soft soil, and rocks are needed to assure the safest possible landing.

The ST9 TGALS experiment will validate two advanced technologies critical to highly accurate and safe landings on Solar System bodies: (1) terrain sensing and recognition and (2) pinpoint propulsive landing. Current descent and landing technology for planetary missions, such as landing on Mars, is characterized by at least a 30 x 100 km landing dispersion ellipse, with no hazard avoidance technology utilized to date. Related goals for this decade include achieving terrain-relative navigation accuracy of 100 m, leading to "pinpoint" landing accuracies at that level, and recognition of small scale (0.3 to 1.0 m) hazards over ranges of 40-1000 m with a propulsive traverse capability of 100-200 m for hazard avoidance. These capabilities are sufficient to support NASA's candidate solar system exploration mission set for the next 10-20 years.

System-Level Flight Validation Objectives: The objectives of TGALS are to test advanced technologies in flight to validate the following capabilities:

- A terrain-relative navigation system capable of 100 m (99% probable) accuracy consistent with the flight dynamics envelope of future missions;
- A terrain sensing and recognition capability a) to identify terrain features on a scale consistent with the 100 m system accuracy objective, and b) to identify terrain features that could pose landing hazards for future landing vehicles with a surface “footprint” in the 3 to 10 m range;
- A modeling capability that characterizes landing hazard properties as a function of landing site environment and landing vehicle configuration; and
- A powered flight maneuvering capability sufficient to deliver a space vehicle to a safe target landing site where safety is defined through the modeling approach noted above.

Advanced Technology Validation Rationale: The process of automated descent and landing on remote bodies imposes demanding requirements on guidance, navigation, and control (GN&C) and powered maneuvering capability. The descent and landing technology must be capable of delivering a spacecraft to a desired target site safely within a very short period of time, often in a highly variable environment. The landing spacecraft’s GN&C and propulsion subsystems must accomplish this task in an uncertain environment, encompassing both the flight dynamics experienced by the vehicle and the terrain properties in the vicinity of the target landing site. The key to validating such systems is to conduct tests across a flight regime that envelopes the regime anticipated in the class of science missions of interest, while acquiring both onboard and external measurements to construct a highly accurate “ground truth” allowing detailed evaluation of system performance.

Key features that require end-to-end flight validation are: (1) autonomous, terrain-aided inertial navigation, (2) terrain sensing and recognition during descent prior to landing, (3) a modeling approach to characterizing landing hazard properties, and (4) powered flight maneuvering capability tied to the modeling approach. Ground-based field tests support the design of the GN&C and propulsion subsystem elements, while flight tests validate the ability of the complete GN&C software, sensors, and computing platform and propulsion subsystem to operate an actual landing vehicle in an end-to-end manner under flight conditions.

D.2 Science Missions Applicability

Terrain recognition and pinpoint landing are primary capabilities needed to optimize science return and reduce mission risk in a large number of planned planetary and small body missions. For example, pinpoint landing on Mars is a key need of the Mars Exploration Program. It fulfills a requirement to emplace rovers where they can access surface features of the highest scientific interest. These missions include Mars Science Laboratory (launch proposed in 2009) and Mars Sample Return (second decade). Farther into the future, probes for landing on Jupiter’s icy moons will be more demanding applications for autonomous descent, including terrain acquisition and identification and powered maneuvering capability.

Preliminary mission concepts include a lunar sample return mission to a location such as the Aitken Basin. This mission was identified as a high priority in the 2002 Solar System

Exploration Decadal Study and will explore for water. Comet Surface Sample Return could utilize TGALS terrain recognition technology, as could the Europa Geophysical Explorer, both of which were recommended by the 2002 Decadal Study.

D.3 Representative Space Experience

Automated landing systems have been flown successfully as part of NASA Lunar and Mars exploration missions such as *Surveyor*, *Apollo* Lunar Module, *Viking* and *Mars Pathfinder* Landers, and on Soviet lunar and Martian landers. However, none of these vehicles had a capability for terrain-relative guidance and navigation, although several of them did have very limited propulsive maneuvering capability. There is a more significant experience base, however, in operational terrain-relative GN&C systems, including propulsive maneuvering capability in military and, to a lesser extent, civilian Earth-based applications. For example, weapon systems such as the *Tomahawk* cruise missile have successfully used a combination of TERrain COntour Matching (TERCOM) for navigation, coupled with a Digital Scene Matching Area Correlation System (DSMACS) for guidance, with delivery accuracies of 30 m or better over flight distances of up to 2,000 km. Previous NASA deep space missions have used remote terrain sensing such as infrared and visible wavelength imaging from orbit to select target landing sites. On a larger scale, the landing site for the Huygens probe attached to the Cassini mission was selected by radar mapping of Titan's surface from Earth.

D.4 Flight Experiment Concept

The TGALS system experiment will validate terrain-relative guidance and navigation technology and pinpoint propulsive landing technology using a sounding rocket as the experiment carrier. The experiment package will be fully contained within a fairing mounted atop the rocket during launch and ascent. This payload, an automated descent/landing system, will be launched into space on a suborbital trajectory, then reenter the Earth's atmosphere using a combination drag device/parachute system to achieve a targeted landing approach velocity. Sensors on board will determine the vehicle's flight path in real time, and, upon reaching a predesignated height above the ground, the vehicle will begin scanning the terrain for identifying features. Upon separation from the subsonic parachute, the propulsion subsystem will maneuver the lander to a safe target landing site designated by the lander's guidance system. The flight path followed during ascent and descent is designed to subject the vehicle's GN&C system to a dynamic environment spanning a range representative of several different target body environments.

D.5 Advanced Technology Performance Requirements

A list of performance requirements based on the TGALS flight experiment concept that must be met by proposers for a successful validation experiment has been developed. In Section D.5.1, terrain technology refers to the advanced terrain sensing and recognition (TSR) technology package, both hardware and software. Section D.5.2 refers to advanced propulsion systems technology. Finally, Section D.5.3 lists requirements applicable to both the terrain and propulsion technologies. These advanced technologies will provide interfaces to experiment-provided elements including the lander flight software, lander avionics, and lander mechanical configuration.

D.5.1 Advanced Terrain Sensing and Recognition Technologies

Terrain Sensing and Recognition Technology Performance Requirements: The proposer to this opportunity shall be capable of providing a terrain sensing and recognition technology that:

- Senses terrain features including rocks and slopes and correlates their location to a reference map, and
- Satisfies requirements in Table D-1.

Resource Allocations for TGALS Terrain Sensing and Recognition Technology: The proposer shall be capable of providing a terrain technology that:

- Is capable of operating with power input voltage range of +22 V to + 34 V,
- Does not exceed power usage of 100 W;
- Has the capability to receive serial commands and transmit serial telemetry and engineering data not exceeding 5 Mbps;
- Provides three levels of enable switches to transmitter devices, including a mechanical plug;
- Operates in a radiation environment not to exceed 1 krad (Si) Total Ionizing Dose (TID) behind 100 mils of aluminum; and
- Does not exceed the mass and volume constraints given as two options in Table D-1.

Table D-1. Terrain Sensing and Recognition Technology Validation Requirements.

Parameter	ST9 Requirement	Scalability Target	Comments
Size of feature for recognition	1 m at a range of 1000 m	< 30 cm at a range of 1000 m	Desire operation on bodies both with and without atmospheres.
Altitude at initiation of TSR technology	2000 m	5000 m	
Minimum operating altitude	10 m	10 m	Depends on mission.
Maximum vertical velocity for which TSR technology must be applicable	100 m/s	100 m/s	Values given are for planets; small bodies will have lower limits.
Maximum horizontal velocity for which TSR technology must be applicable	50 m/s	50 m/s	Values given are for planets; small bodies will have lower limits.
Mass and volume constraints for TSR electronics pkg	10 kg, fit in envelope 23 x 21.5 x 30 cm dictated by sounding rocket requirements	Mission-dependent	ST9 requirements address most anticipated mission needs.

Parameter	ST9 Requirement	Scalability Target	Comments
Mass and volume constraints for TSR antenna and/or external optical elements	1.5 kg, fit in envelope 10 x 10 x 20 cm; or in envelope 30 cm dia x 10 cm; dictated by sounding rocket requirements*	Mission-dependent	ST9 requirements address most anticipated mission needs.

*The options for antenna/external element volume relate to whether the technology hardware is located in either the main diameter of the vehicle (30 cm dia x 10 cm, essentially looking through the plume), or on a leg (10 cm x 10 cm x 20 cm, trying to minimize looking through the plume).

Verification/Validation, including extrapolation to diverse target bodies: The terrain technology proposer shall be capable of providing the following capabilities:

- Flight-like operation in the ambient environment for testing;
- Support by analysis and test of the technology's ability to achieve terrain sensing and recognition objectives on diverse planetary bodies, including the Moon, Mars, Europa, Titan, comets, and asteroids;
- Software written in ANSI C or C++;
- Delivery of two (2) protoflight model units in January 2007 having a minimum design life (non-operating) of two years for each unit;
- Delivery of a protoflight model specification document;
- Delivery of at a minimum of one preliminary flight software build, one final flight software build, and one set of flight software source code;
- By analytical justification, scalable in the following parameters: altitude/velocity envelope, resolution, and field-of-view; and
- Low sensitivity to the following operating environments: day/night illumination, exhaust plumes from main or reaction control system (RCS) propulsion systems, atmospheric conditions such as clouds and wind, dust, vibration during operations, and oscillation during operations.

Minimum Instrumentation Requirements: The proposer to this opportunity shall be capable of providing a terrain sensing and recognition technology that has the capability for external engineering telemetry including at least four temperature monitors, one input power current monitor, and six discrete bilevel outputs (switch status monitoring). In addition, the technology shall provide fully serviceable data sets from the terrain technology to the lander in digital format at a continuous sample rate $\geq$ 45 Hz.

D.5.2 Advanced Propulsion Subsystem Technologies

Propulsion Technology Performance Requirements: The proposer shall be capable of providing an advanced technology propulsion subsystem that:

- Consists of four main engines and four RCS engines per unit;

- Satisfies requirements in Table D-2;
- Supports two-axis translation thrusting;
- Supports controllable thrust levels between the maximum and minimum values;
- Operates in either throttled or pulsed mode (main engines or RCS engines);
- Has a throttle or pulse response time of 500 ms from command epoch to 90% of commanded thrust (both main engines and RCS);
- Has a thrust vector alignment within 1.0 deg from the nominal pointing angle (total error);
- Supports a firing duration of approximately 30 sec (worst case) each for both main engines and RCS engines each time they are fired;
- Has throttle valves (if used) with fuel/oxidizer flow valves with highly comparable response times and a 28 VDC nominal operating voltage;
- Has tanks with a burst pressure at least four times greater than the maximum design pressure, a design which supports offloading propellants within four hours, and a design which supports onloading propellants in four hours or less;
- Supports safety by allowing pressure relief to all pressurized components "on command" or after a 300 sec time-out after vehicle touchdown, and, by proof testing, of all components to at least 1.5 times the maximum design pressure;
- Supports operational safety by providing at least two mechanical seals per valve to prevent external leakage and providing at least two electrical inhibits on each thruster prior to firing;
- Is capable of operating with power input voltage range of +22 V to + 34 V;
- Operates in a radiation environment not to exceed 1 krad (Si) TID behind 100 mils of aluminum; and
- Does not exceed the mass and volume constraints given as two options in Table D-3.

Table D-2. TGALS Propulsion System Technology Validation Requirements.

Parameter	ST9 Requirement	Scalability Target	Comments
Altitude at initiation of propulsion technology	500 m	All altitudes, all bodies	May initiate on orbit for small bodies.
Main engine subsystem thrust range	1160 N – 7209 N	Mission-dependent	ST9 requirements address most anticipated mission needs.
RCS subsystem thrust range, net thrust for two-axis translation	0 N – 445 N	Mission-dependent	ST9 requirements address most anticipated mission needs.

<u>Table D-3</u>. Mass and Volume Constraints for TGALS Propulsion Technology.

	Mass (kg)	Volume (cylindrical sections)
Thruster	< 30 kg dry mass*	597 mm dia. x 166 mm high
Tanks		597 mm dia. x 269 mm high

*includes all thrusters, tanks, valves, etc. (less propellants and guidance electronics)

Verification/Validation, including extrapolation to diverse target bodies: Proposals for the TGALS advanced propulsion subsystem shall describe a subsystem having the following capabilities:

- Provides flight-like operation in the ambient environment for testing, and
- Can support by analysis and test the technology's ability to achieve propulsive landing objectives on diverse planetary bodies, including the Moon, Mars, Europa, Titan, comets, and asteroids.

Implementation: Proposals shall demonstrate that the proposer is experienced and capable of providing an advanced technology propulsion subsystem that:

- Has engines (main and RCS) that can be used two or more times each;
- Supports a two-week turnaround between engine firings;
- Supports the following in the case of a scrubbed launch: a 24-hour turnaround, and up to 8 hours "on-the-pad" time, fully fueled;
- Has a minimum of two years "dry storage" capability;
- Delivers two protoflight model units in January 2007;
- Delivers a protoflight model specification document; and
- Has low sensitivity to the following operating environments: day/night illumination, atmospheric conditions such as clouds and wind, dust, vibration during operations, and oscillation during operations.

Representative Propulsion Measurements: The proposal shall demonstrate that the proposer is capable of providing an advanced propulsion subsystem that has the capability for at least the following engineering measurements:

- Temperatures of the fuel, oxidizer and pressurant tanks, each pressure regulator valve, and each thruster flow valve using either Type K thermocouples or 100 ohm resistance thermal device (RTDs) with an accuracy of ± 2 deg C or better; and
- Pressures of each tank and downstream of each pressure regulator on each thruster using sensors that cover the entire operating pressure range (to burst pressure) that operate with 5 VDC excitation (supply) voltage and output between –10 VDC and +10 VDC, and that have an accuracy of ±1 psi or better.

D.5.3 Environmental Requirements for Both the Terrain and Propulsion Technologies

Proposals shall describe advanced technologies that:

- Have low sensitivity to radiated or conducted emissions due to the operation of other subsystems;
- Minimize the potential for interference with the other flight subsystems;
- Operate within a pressure range of 101.3 kPa (1 std. Atm) and 2.37 kPa (18 torr);
- Maintain full capability at a minimum pressure of 1.6 mPa (0.01 torr) nonoperating;
- Are capable of operating at launch loads (non-operating) consistent with sounding rocket requirements as given in Table D-4 and Table D-5 (Ref: "Sounding Rocket Program Handbook," Wallops Flight Facility, available at http://www.wff.nasa.gov/~code810/docs/SRHB.pdf); and
- Are capable of operating at temperatures consistent with the expected environment given in Table D-6.

Table D-4. Design Loads for TGALS Technologies.

Design Loads	Min	Max
Moment about 0-180 deg axis*	150,000 lb_f-in (= 16947.72 N-m)	3000,000 lb_f-in (= 33895.45 N-m)
Moment about 90-270 deg axis*	150,000 lb_f-in (= 16947.72 N-m)	3000,000 lb_f-in (= 33895.45 N-m)
Acceleration in thrust levels	$25g_e$	$50g_e$

*applicable to structural load-bearing members only

Table D-5. Vibration Loads for TGALS Technologies.

Vibration Loads			
Sine (All Axes)		**Random (All Axes)**	
Sweep Rate: 4 octave/minute Test Profile:		Duration: 10 sec/axis Spectrum:	
3.84 in/s 1.53 g_e 3.50 g_e 10.0 g_e	5-24 Hz 24-110 Hz 110-800 Hz 800-2000 Hz	12.7 g_e rms 0.01 g_e^2/Hz 0.10 g_e^2/Hz* 0.10 g_e^2/Hz	 20 Hz 1000 Hz 1000-2000 Hz

*on 1.8 db/octave slope

Table D-6. Temperature Requirements for Technologies.

	Min Temp (°C)	Max Temp (°C)
Electronics		
Operating	-10	+50
Nonoperating	-50	+80
Antenna or External Optical Elements		
Operating	-50	+100
Nonoperating	-100	+150

D.6 Technology Selection Opportunities and Planned Funding Levels

There are two TGALS technology provider opportunities and funding for the Study Phase as listed in Table D-7. During the Study Phase, the technology providers will also delineate the adaptations needed to meet future mission landing requirements.

Table D-7. Award Levels for Concept Definition Study Phase.

Technology Area	Selection Opportunities	Maximum Funding*
Terrain sensing and recognition hardware and software	1	$75,000
Propulsion subsystem	1	$75,000

* Proposals with budgets in excess of these amounts may be selected only if they exhibit exceptional merit and breadth of objectives.

D.7 Representative Project Schedule (for use as a reference only)

A preliminary TGALS project schedule is given in Table D-8.

Table D-8. Terrain-Guided Automatic Landing System Project Schedule.

Milestone	Months After Release of NRA (ARN)
• Concept Definition Study Phase	8 months duration (5 – 13 months ARN)
- Concept Definition Study Team Formed	5 months ARN
- Deliver Study Report	11 months ARN
• Formulation and Refinement Phase	12 months duration (13 – 25 months ARN)
- Systems Requirements Review	15 months ARN
- Preliminary Design Review	23 months ARN
• Confirmation Review	25 months ARN
• Implementation Phase	30 months duration (25 – 55 months ARN)
- Critical Design Review	37 months ARN
- Pre Environmental Test Review	41 months ARN
- Protoflight Models Delivered	43 months ARN
- Launch Opportunities	7 months duration (45 – 52 months ARN)
- Validation Data Analysis	3 months duration (52 – 55 months ARN)
- Final Report	55 months ARN

D.8 Acronym List

ANSI	American National Standards Institute
cm	centimeter
deg	degree
DSMACS	digital scene matching area correlation system
g	gram
GN&C	guidance navigation and control
Hz	Hertz
kg	kilogram
kPa	kiloPascals
Krad	thousand rads
lb_f-in	pound-inches
m	meter
Mbps	million bits-per-second
mm	millimeter
mPa	milliPascals
ms	millisecond
N	Newton
rad	radiation accumulated dose
s	second
sec	second
Si	silicon
RCS	reaction control system
RTD	resistance thermal device
TERCOM	terrain contour matching
TID	total ionizing dose
TGALS	terrain-guided automatic landing system

torr	1 mm Hg
TRL	technology readiness level
TSR	terrain sensing and recognition
V	Volts
VDC	Volts direct current
W	Watt

Appendix E. Aerocapture System Technology (AST) for Planetary Missions

E.1 Flight Validation Concept

Solicited Advanced Technology Capabilities: Appendix E describes needed technology advances to support in-space, system-level validation of an Aerocapture System Technology (AST) for Planetary Missions:

- Aerocapture Guidance Algorithm and Software,
- Advanced Aerocapture Instrumentation, and
- Advanced Thermal Protection Materials.

Technology Description and Benefit: Aerocapture is a flight maneuver executed upon arrival at a planet in which atmospheric drag is used to decelerate the spacecraft into orbit during only one atmospheric pass. It consists of an automatically-guided atmospheric flight followed by one or more in-vacuum propulsive maneuvers to raise the periapsis and correct for delivery errors. This technique contrasts with the conventional alternatives of propulsive insertion directly into the desired orbit, or propulsive insertion into a large elliptical orbit followed by a long period of aerobraking to reduce the apoapsis altitude. Although aerocapture has not yet been attempted, it has long been recognized that this maneuver can greatly reduce the amount of propellant carried by the spacecraft, thereby enabling either larger payload mass fractions or smaller launch vehicles from Earth. The propellant mass savings of aerocapture become especially significant for missions requiring large velocity changes for orbit insertion either because a low circular orbit is required or because the approach velocity is high.

In addition to the primary application of aerocapture, this aerocapture flight validation experiment will benefit atmospheric entry missions of probes and landers. In particular, the benefits encompass aspects of improved thermal protection materials, advanced instrumentation, and the ability to do guided entries for precision landing missions.

An aerocapture test vehicle is comprised of a mixture of standard spacecraft components that are adapted from existing aeroentry technology and from specialized advanced technology components unique to aerocapture. Relative to this latter category, this NRA solicits proposals for only the three advanced technologies listed above, each of which is described in more detail below. The proposed architecture of the ST9 flight validation experiment is described in Section E.4.

Flight Validation Objectives: The systems level objectives of the aerocapture flight validation experiment are to demonstrate satisfactory performance of the flight vehicle and to acquire sufficient experimental data to validate and improve the efficacy of the simulation and design tools and processes. Inherent to these objectives is an efficient integration of the standard spacecraft and aerocapture-specific advanced components into a robust aerocapture flight vehicle.

AST objectives at the component level include, but are not limited to the following:

- To quantify performance of the atmospheric flight mechanics and correlate with expected behavior for all three phases: entry, energy dissipation and exit;
- To evaluate guidance algorithm performance via trajectory reconstruction and confirm that it and its simulation tools perform as expected;
- To quantify performance of the autonomous postaerocapture periapsis raise maneuver and correlate with expected behavior;
- To quantify performance of the thermal protection system and validate its design and simulation tools; and
- To quantify performance of the vehicle aero/aerothermodynamics and validate their design and simulation tools.

Technology Validation Rationale: Existing wind tunnels and other ground test facilities can only match a small subset of the aerocapture flight regime that features very high speeds, significant thermochemistry, and high Reynold's numbers. Furthermore, only an in-space investigation can validate the design and simulation tools and thereby significantly reduce the risk of future aerocapture missions.

E.2 Science Missions Applicability

Aerocapture provides significant mass benefits for spacecraft orbit insertion at any of the eight worlds in the Solar System with appreciable atmospheres: Venus, Earth, Mars, Jupiter, Saturn, Titan, Uranus, and Neptune. Studies have shown that several missions in NASA's Space Science Strategic Plan are either enabled or greatly enhanced by the propellant savings afforded by aerocapture technology, such as orbiters around Titan and Neptune, and sample return missions to Venus and Mars. Other severely mass-constrained planetary missions in the Discovery, Mars Scout, New Frontiers, and secondary payload programs would also benefit from the availability of aerocapture technology.

E.3 Representative Space Experience

Aerocapture leverages technology developed and flown for atmospheric entry missions over the past few decades including Apollo, Shuttle, Viking, Mars Pathfinder, Pioneer Venus, Galileo probe, and Huygens. Various simulation and design tools can be used in whole or in part in the critical disciplines of hypersonic aerodynamics, aerothermal chemistry and heating, guidance algorithms, and trajectory design and simulations.

E.4 Flight Experiment Concept

Concept Description: The funding available for ST9 necessitates an Earth orbit flight test rather than going to another planet. Ideally, the flight vehicle would be brought in on a hyperbolic trajectory at Earth to simulate a true aerocapture maneuver, namely "capturing" the vehicle by using drag to alter the trajectory from a hyperbola to an ellipse. However, the essential characteristics of aerocapture flight can be evaluated without a hyperbolic to elliptic orbit change. Therefore, the ST9 AST experiment will use an elliptical starting orbit whose elements will be finalized during the Study Phase.

The baseline ST9 AST flight concept is as follows:

- Launch into orbit of a 3-axis controlled spacecraft enclosed in a protective aeroshell having a probable aeroshell geometry of a 60 or 70 degree half-angle sphere cone with a maximum diameter in the range of 1.0 to 1.4 m and an approximate vehicle mass in the range of 100 to 200 kg;
- In-space propulsion and navigation to achieve the desired inbound trajectory;
- Hypersonic flight through the atmosphere with active guidance, navigation, and control to deliver the vehicle into the desired postaerocapture orbit:
  - The entry speed will be approximately 10 km/s with a corresponding speed change (ΔV) due to atmospheric drag of –2 km/s,
  - Minimum altitude during the atmospheric pass will be approximately 50 km, and
  - A communications blackout is expected during the high heating portion of this flight, which means that most of the onboard flight test data will be stored and transmitted afterwards;
- Vehicle coast after the atmospheric flight out to an apoapsis altitude of approximately 200 km, at which point data playback may start;
- Propulsive maneuver at apoapsis to raise the periapsis up to approximately 130 km to prevent the vehicle from reentering the atmosphere on the next orbit, in order to allow complete playback of engineering data collected during aerocapture; and
- Deorbit burn to bring the vehicle to Earth and end the flight experiment.

E.5 Advanced Technology Performance Requirements

E.5.1 Aerocapture Guidance Algorithm and Software

Objectives and Requirements for Aerocapture Guidance Algorithm and Software: The validation requirements for aerocapture guidance algorithm and software are provided in Table E-1. A key component in the aerocapture system is the hypersonic flight guidance algorithm and software used to steer the vehicle actively along the desired flight path through the atmosphere. The proposed investigations shall be capable of providing a robust, high performance algorithm and software implementation for the ST9 aerocapture flight vehicle whose approximate vehicle and experiment characteristics are described in Section E.4 above.

Table E-1. Validation Requirements for Advanced Technology Aerocapture Guidance Algorithm and Software.

Parameter	ST9 Requirements	Scalability Target	Comments
Domain of Applicability	The guidance algorithm shall be designed to control the ST9 test vehicle from atmospheric entry interface to the desired exit apoapsis and exit inclination using bank angle control only.	Same as for ST9.	
Capture of Theoretical Entry Corridor	> 90%	Same as for ST9.	> 90% metric must be demonstrated in high fidelity Monte-Carlo trajectory simulations.
Tolerance to Atmospheric Density Uncertainties	Constant offset: ± 30% Additional cases: +15% before periapsis and −15% after periapsis and vice versa	Similar to ST9 except customized for each target planet.	With all other variables nominal.
Tolerance to Aerodynamic Parameter Uncertainties	L/D ratio: ± 10% Trim angle of attack: ± 2 deg	Similar to ST9 except customized for each target planet.	With all other variables nominal.
Tolerance to Approach Navigation Flight Path Angle Uncertainties	± 0.2 deg	Similar to ST9 except customized for each target planet.	With all other variables nominal.

The proposer shall be capable of providing the guidance algorithm and code as a single, stand-alone, ground-validated module to be integrated with the rest of the flight software.

With participation from the selected technology provider, a well defined application program interface (API) will be established early in the software development phase to define the interface between the technology provider's guidance code and remaining flight code. This interface will specify the requirements on data type, format, and communication rate needed for successful execution of the entire software system.

The guidance algorithm must be adaptable to various conditions by only changing the initialization quantities with no executable changes. These conditions include entry atmospheric interface velocity and position, desired target apoapsis and inclination, and vehicle mass properties. It is desired that proposed algorithms have software implementations of less than approximately 1000 lines of code, no recursive programming, and run in less than 0.1 Central Processing Unit (CPU) seconds on an 100+ MIPS PPC750 processor.

Representative Measurements, Parameters, and Model Verification for Aerocapture Guidance Algorithm and Software: Proposals for Aerocapture guidance algorithms and software must discuss the predictive models and measurements to be used in validating the guidance algorithm and software technology; existing and planned models; measurements to be made during ground-based testing, with an emphasis on those used to achieve TRL 5 where a component and/or breadboard has been validated in its relevant environment; measurements to be made during the space experiment; how these measurements would be used to verify or calibrate the existing models; and how they would validate the technology, including any applicable scaling or extension of the validated model and its domain of applicability.

Guidance commands and vehicle state data will be recorded by the vehicle's data handling system during the flight experiment for postflight evaluation of the guidance algorithm and its software implementation. These onboard measurements may be augmented with ground tracking data depending on the details of the final experiment design and availability of suitable tracking stations. This postflight analysis will both quantify the performance of the aerocapture guidance system and validate the simulation tools used to predict that performance.

E.5.2 Advanced Aerocapture Instrumentation

Objectives and Requirements for Advanced Aerocapture Instrumentation: The ST9 AST flight investigation will require a significant amount of engineering data to evaluate properly the performance of the aerocapture test vehicle and validate its design tools and methodologies. Proposed flight instrumentation may be a mixture of proven, off-the-shelf devices to guarantee a minimum data return on the vehicle dynamics and temperature response, as well as advanced devices that offer either substantial mass, power or accuracy improvements over proven devices, or that can provide additional, but difficult to obtain, information on the surrounding flow field. For advanced devices, the proposals shall describe the capability to provide a flight prototype of their integrated sensor/instrument for inclusion on the ST9 aerocapture vehicle.

Accordingly, AST proposals are expected to contain design and performance estimates for candidate new technology engineering sensors that are applicable to the ST9 flight measurement needs and indicate their technological maturity and the development path that will yield a flight prototype instrument consistent with the ST9 Project experiment schedule. Such sensors must include sufficient electronics to yield a standard 0-5 V analog or RS 422 digital output. A development plan must include ground testing and calibration of each instrument prior to flight. Applicability of the candidate instrument to future planetary missions is desirable but not required, and any multidestination claims are expected to be substantiated in the proposal with analyses and data.

Sensors are desired in the following areas:

- Pressure sensor for aeroshell surface locations,
- Heat flux sensor for surface and embedded aeroshell locations, and
- Remote sensing or direct sampling sensors for measuring the bow shock heated gas composition around the vehicle.

The validation requirements for each sensor type are given in Tables E-2, E-3, and E-4.

Table E.2. Technology Validation Requirements for Aft-Body Pressure Sensor.

Parameter	ST9 Requirements	Scalability Target	Comments
Measurement Range	0.1 to 10 Pa	Similar to ST9 requirement, except customized for each target planet.	
Measurement rate	1 Hz	Same as ST9 requirement.	
Measurement System Mass	< 100 g	Same as ST9 requirement.	
Measurement System Power	< 5 W	Same as ST9 requirement.	

Table E-3. Technology Validation Requirements for Heat Flux Sensors.

Parameter	ST9 Requirements	Scalability Target	Comments
Measurement Range	1 – 300 W/cm^2	Similar to ST9 requirement for small planets; up to 20,000 W/cm^2 for gas giant planets.	
Measurement rate	1 Hz	Same as ST9 requirement.	
Measurement System Mass	< 50 g	Same as ST9 requirement.	
Measurement System Power	< 2 W	Same as ST9 requirement.	

Table E-4. Technology Validation Requirements for Bow-Shock Gas Sensors.

Parameter	ST9 Requirements	Scalability Target	Comments
Key Gas Species	N_2+, O_2+, N, and O	Different species are required for different planetary destinations.	Preference given to sensors that are less sensitive to the contaminating presence of ablation products in the flow field.
Measurement System Mass	< 4 kg	Same as ST9 requirement.	
Measurement System Power	< 20 W	Same as ST9 requirement.	

Representative Measurements, Parameters, and Model Verification for Advanced Aerocapture Instrumentation: Proposals to provide AST Advanced Aerocapture Instrumentation should discuss the predictive models and measurements to be used in validating the advanced aerocapture instrumentation technology, how these measurements would be used to verify or calibrate the existing models, how they would validate the technology advance, and any applicable scaling or extension of the validated model and its domain of applicability.

All instrument data generated during the flight will be recorded for postflight analysis. Each advanced instrument will be crosschecked against preflight test data and, where possible, against data from other instruments on the vehicle. Once verified, the instrument data will be used to help quantify vehicle aerodynamic and aerothermodynamic performance and validate the associated design and simulation tools.

E.5.3 Advanced Thermal Protection Materials

Objectives and Requirements for Advanced Thermal Protection Materials: To take maximum advantage of the opportunity to obtain flight performance data, the ST9 aerocapture experiment plans to incorporate samples of advanced thermal protection system (TPS) materials into the forebody and afterbody of the vehicle. Up to six different TPS samples may be selected through this solicitation, and providers are allowed to propose multiple materials. Preference will be given to materials that represent substantial improvements in current TPS state-of-the-art densities for the expected environments while offering clear infusion paths for use in future aerocapture and aeroentry missions throughout the solar system. The performance requirements for candidate, advanced technology, TPS materials are listed in Table E-5.

Table E-5. Technology Validation Requirements for Advanced Technology Thermal Protection System Samples.

Parameter	ST9 Requirements	Scalability Target	Comments
Peak forebody heat flux	100-300 W/cm^2	Similar to ST9 for small planets, up to 20,000 W/cm^2 for gas giant planets.	Both ablators and nonablators are allowed.
Peak aft body heat flux	10-50 W/cm^2	Similar to ST9 for small planets, up to 2000 W/cm^2 for gas giant planets.	Both ablators and non-ablators are allowed.
TPS Sample Size	8 to 15 cm in diameter	Up to 4 m diameter complete aeroshells.	Proposers shall justify that their material can be fabricated for full-scale aeroshells.
Number of TPS Samples	10 of each candidate selected	N/A	6 for arc-jet testing, 2 for integration studies, 1 for flight and 1 flight spare.
TPS Sample Instrumentation	Thermocouples at 3-5 locations through the thickness	Similar to ST9.	

Representative Measurements, Parameters, and Model Verification for Advanced Thermal Protection Materials: Proposals to provide advanced technology AST thermal protection materials should discuss the predictive models and measurements to be used in validating the advanced technology for advanced thermal protection materials; how these measurements would be used to verify or calibrate the existing models; how they would validate the technology advance; and any applicable scaling or extension of the validated model and its domain of applicability.

All thermocouple data generated from TPS samples during the flight will be recorded for postflight analysis and will be combined with the overall aerodynamic and aerothermodynamic assessment of the vehicle to yield a quantitative measure of the TPS coupon performance.

E.6 Technology Solicitation Opportunities and Planned Funding Levels

The planned number of technology-provider opportunities and funding for the Study Phase is provided in Table E-6.

Table E-6. Award Levels for Concept Definition Study Phase.

Technology Area	Selection Opportunities	Maximum Funding*
Aerocapture Guidance Algorithm and Software	1	$100K
Advanced Aerocapture Instrumentation	up to 2	$75K each
Advanced Thermal Protection Materials	up to 6	$25K each

* Proposals with budgets in excess of these amounts may be selected only if they exhibit exceptional merit and breadth of objectives.

E.7 Representative Project Schedule

The representative aerocapture system technology project schedule is presented in Table E-7 below.

Table E-7. Aerocapture System Technology Project Schedule.

Milestone	Months After Release of NRA (ARN)
• Concept Definition Study Phase	8 months duration (5 – 13 months ARN)
- Concept Definition Study Team Forms	5 months ARN
- Deliver Study Report	11 months ARN
• Formulation and Refinement Phase - Systems Requirements Review - Preliminary Design Review	12 months duration (13 – 25 months ARN) 15 months ARN 23 months ARN
• Confirmation Review	25 months ARN
• Implementation Phase - Critical Design Review - Pre Environmental Test Review - Deliver Protoflight Models - Launch - Flight Operations - Validation Data Analysis - Final Report	28 months duration (25 – 53 months ARN) 28 months ARN 38 months ARN 43 months ARN 46 months ARN 1 month duration (46 – 47 months ARN) 6 months duration (47 – 53 months ARN) 53 months ARN

E.8 Acronym List

API	application program interface
AST	aerocapture system technology
cm	centimeter
CPU	central processing unit
deg	degree
g	gram
Hz	Hertz
kg	kilogram
MIPS	million instructions per second

L/D	lift to drag
Pa	Pascal
TPS	thermal protection system
TRL	technology readiness level
W	Watt