The Role of Structural Models
In the Solar Sail Flight Validation Process

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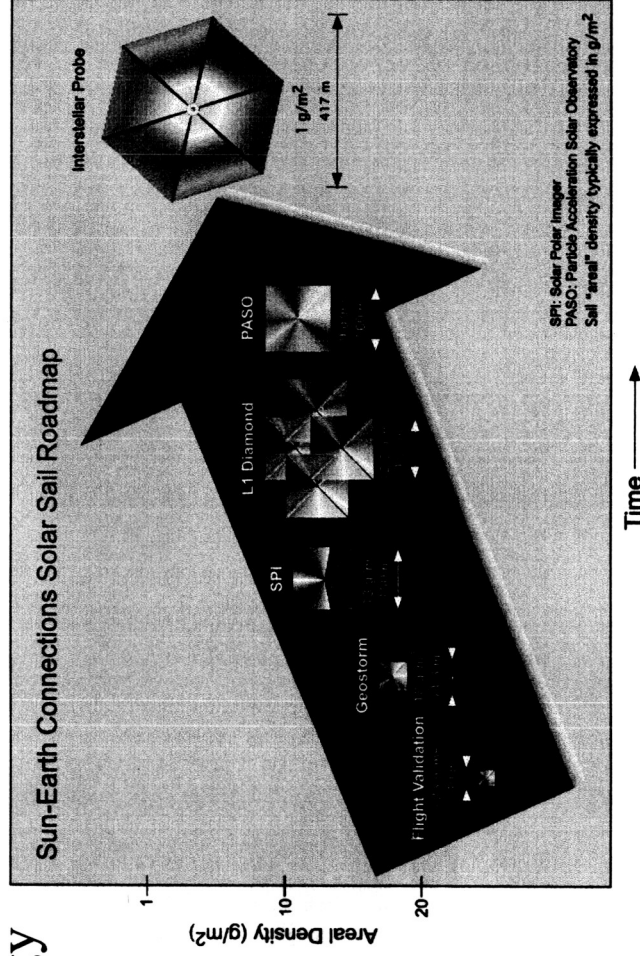Solar Sail Technology and Applications Conference
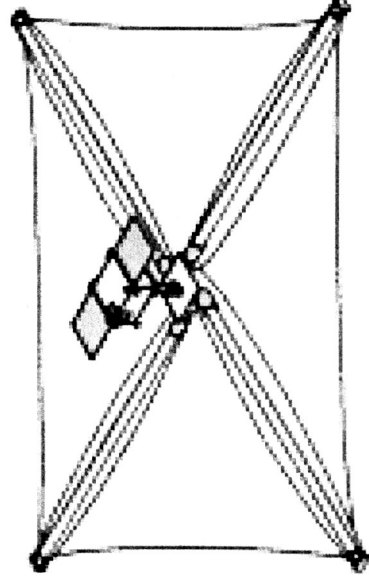
Greenbelt, MD

September 28, 2004

Solar Sail Overview

Sun-Earth Connections Solar Sail Roadmap

Interstellar Probe

1 g/m² 417 m

Areal Density (g/m2)

PASO

L1 Diamond

SPI

Geostorm

Flight Validation

Time →

SPI: Solar Polar Imager
PASO: Particle Acceleration Solar Observatory
Sail "areal" density typically expressed in g/m²

Square Solar Sail Concept

- Solar sails are an enabling technology for future NASA science missions.

- Solar sails provide propellantless propulsion by gaining momentum from solar photons:

  - Large reflective surface areas are required to generate useful accelerations

  - Post-deployment structural performance is critical to mission success since sail surface flatness directly impacts thrust performance

- Square solar sail design concept:

  - Four thin-film membrane quadrants supported by deployable booms.

  - Most mature design concept. Examples include NASA's ST-5&7 and ISP concepts.

  - Overall size of ~40 m is envisioned for flight validation mission

Solar Sail Flight Validation Experiment

- NASA is currently soliciting proposals via the New Millennium Program ST-9 opportunity for a potential Solar Sail Flight Validation (SSFV) experiment to develop and operate in space a deployable solar sail that can be steered and provides measurable acceleration.*

- The approach planned for this experiment is to test and validate models and processes for solar sail design, fabrication, deployment, and flight. These models and processes would then be used to design, fabricate, and operate scaleable solar sails for future space science missions.

- There are six validation objectives planned for the ST9 SSFV experiment:

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

- This poster presents a top-level assessment of the role of structural models in the validation process for in-space structural characteristics.

* Reference: New Millennium Program Space Technology-9, NASA Research Announcement, August 25, 2004.

The Role of Structural Models
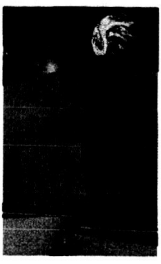
- Structural models will be used in the solar sail design process to verify structural integrity and to support prediction of system-level performance.

- Specific aspects of structural performance predicted by the models includes:

  - Static deflections, internal loads, strains, and stresses under combined loading from mechanical preloads, thermal loads, and solar pressure loading.

  - Dynamic characteristics (frequencies and mode shapes) and response to transient excitation.

- Additionally, structural model predictions will support multi-disciplinary system-level performance analyses related to Guidance, Navigation, and Control:

  - Thrust vector analysis requires predictions for the deformed geometry of the sail.

  - Attitude control simulations require flexible body dynamic characteristics.

- Validated models from SSFV mission will subsequently be used in the design process for solar sails needed for operational science missions.
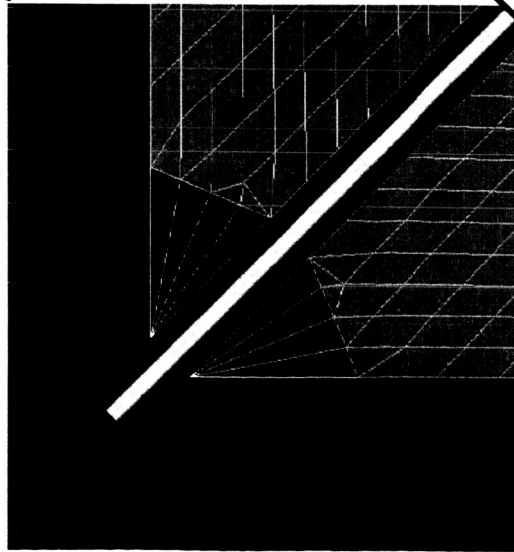
Overview of Solar Sail Structural Models
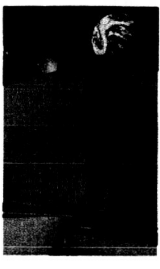
- Structural modeling and analysis of solar sails is challenging due to the nonlinear behavior exhibited by both the thin-film membranes and the long, slender deployment booms. Examples of this behavior include:

  - Wrinkling and billowing of the membranes
  - Nonlinear load-displacement behavior in the compressively loaded booms

- Structural models of solar sails are typically developed using the finite element method:

  - Commercially available finite element analysis programs such as NASTRAN, ABAQUS, ANSYS, and ALGOR have all been used to model and analyze the performance of these structures.
  - Nonlinear solution approaches are required to deal with the aforementioned nonlinearities.

- Solar sail structural models will include representations of the following key components:

  - Thin-film membranes
  - Deployable booms
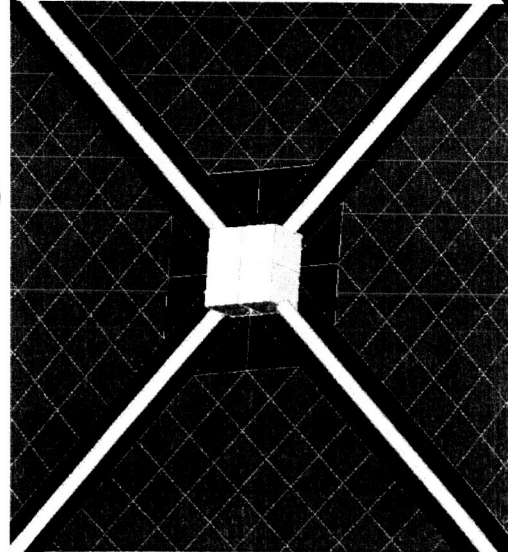 - Membrane management hardware (edge cables, halyards, etc.)
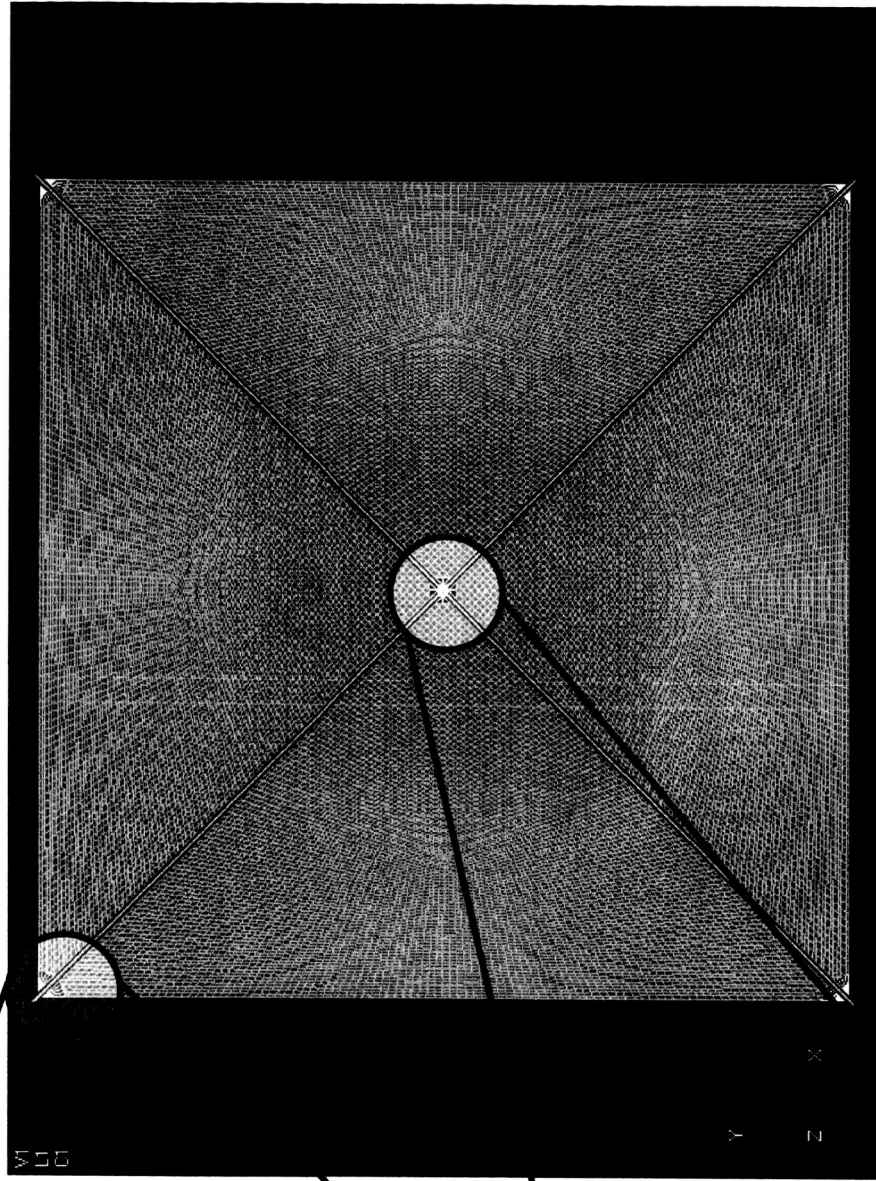
Representative Solar Sail Model

40 m Class Solar Sail Structural Model

**Boom Tip Region**

Central Region

Model Validation

- Structural models must be validated through correlation with experimental data in order to provide confidence in sail designs for future missions.

- The general model validation process involves the following steps:

  - Develop validation requirements:
    - Model requirements
    - Measurement requirements
    - Correlation criteria

  - Characterize structural performance:
    - static shape (global, local scales)
    - loads (mechanical and thermal)
    - dynamics (frequencies, mode shapes, damping)

  - Correlate model predictions with experimental measurements
  - Update model as needed to match experimental measurements

- The overall approach will likely involve progressive model validation at successively higher levels of assembly:

  - Materials (basic properties measurements via ground tests)
  - Components (booms, membrane characterization via ground tests)
  - Subsystem, e.g. single membrane quadrant + two deployment boom, and/or Sub-scale System (ground tests)
 - Full-scale System (In-space testing)

Accuracy Issues Related to Model Validation
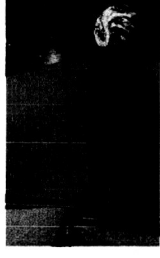
- The required accuracy for the structural models will be tied to system-level performance requirements and determined through multi-disciplinary systems analyses.

- The sensitivity of thrust performance to structural deformations needs to be analytically established in order to define structural model accuracy requirements for static shape:

  - Lower-order deformations (billowing / twist, first-order effects)
  - Higher-order deformations (wrinkling / creasing, presumed second-order effects)

- The sensitivity of attitude control system (ACS) performance to structural dynamics will be established in order to define structural model accuracy requirements for dynamics:

  - Frequency range of interest
  - Controls-Structures Interactions (CSI) considerations

- Note that the model validation process will likely involve correlation to measurements from both the ground test and in-space environments:

  - These environments differ dramatically primarily due to the presence of gravity loads, consequently deformations will be much larger in ground test than under operational loads.
  - Model accuracy requirements will need to consider both environments.

Scalability for Solar Sail Structures
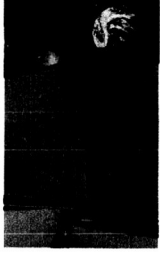
- There are numerous approaches to scalability for solar sail structures, including:

  - Scaling laws – Uniform global scaling of all dimensions is impractical due to minimum thickness limits for membranes and some deployable booms.

  - Specialized scaling laws – All global dimensions are scaled uniformly except for membrane and wall thicknesses. Constant thickness scaling laws were developed by Greshchick, et. al.* specifically for the application to thin-film membrane structures.

    *Reference: Greschik, G. and Mikulas, M.M., "Scaling of Nonlinear Phenomena With Emphasis on Thin Film Deployable Structures," IUTAM-IASS Symposium on Deployable Structures: Theory and Applications, Cambridge, UK, September 1998.
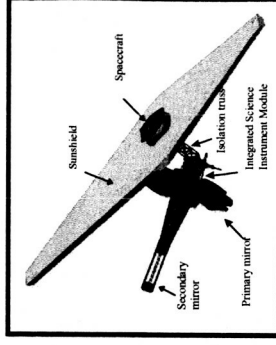
  - Truncated full-scale structures – This approach uses full-scale hardware, but at truncated lengths (e.g. a ½ scale truncated sail would have booms with the same cross-section, but ½ the length of the full-scale structure). The advantage is that the full-scale flight hardware is test validated. However the extrapolation to full-scale systems is less rigorous than with scaling laws and this approach requires increased reliance on validated mathematical models.

- Validated models will play a key role in solar sail design scalability:

  - Serve as a link between sub-scale and full-scale designs

  - Provide confidence in predicted performance of full-scale designs

Benefits of Validated Structural Models

Solar Sails ⟷ **Sunshields**

Sunshield

Spacecraft

Isolation truss

Integrated Science Instrument Module

Secondary mirror

Primary mirror

Major Principal Stresses

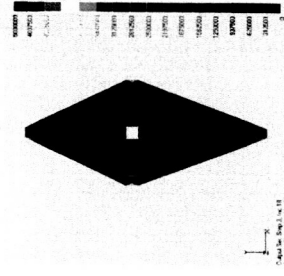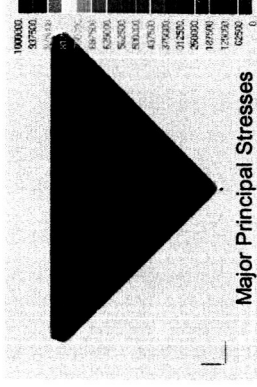Subscale Tests ⟷ Models ⟷ Flight Projects

- Validated solar sail structural models will provide improved confidence and reliability for future solar sail missions.

- The validation process envisioned for solar sail structural models is applicable to other 'gossamer' (i.e. very large, ultra-lightweight) space structures envisioned for future NASA science missions, including:

  – Sunshields
  – Antennas
  – Solar arrays