Solar Sail Models and Test Measurements Correspondence for Validation Requirements Definition

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ABSTRACT

Solar sails **are being developed as a mission-enabling technology in support of future NASA science missions. Current efforts have advanced solar sail technology sufficient to justify a flight validation program. A primary objective of this program is to test and validate solar sail models that are currently under development so that they may be used with confidence in future science mission development (*e.g.*, scalable to larger sails). Both system and model validation requirements must be defined early in the program to guide design cycles and to ensure that relevant and sufficient test data will be obtained to conduct model validation to the level required. A process of model identification, model input/output documentation, model sensitivity analyses, and test measurement correspondence is required so that decisions can be made to satisfy validation requirements within program constraints.**

INTRODUCTION

Solar sails are a mission-enabling technology to be used for future science missions such as Solar Polar Imager, Particle Acceleration Solar Orbiter, and L1 Diamond. Current advances made under the In-Space Propulsion Technology (ISPT) program have sufficiently progressed the technology far enough to go to the next step, flight validation. If chosen by the New Millennium Program (ST9), flight validation will reduce the risk (*i.e.*, increase Technology Readiness Level) associated with solar sail technology.

Due to the gossamer nature of solar sails, prototype ground testing is limited by the size of available test facilities (maximum ~400-m² sail) and by a "non-relevant" 1-*g* environment. Therefore, a primary objective is to test and validate solar sail models that are currently under development so that they may be used with confidence in future science missions (*i.e.*, scalable to 10,000 m² and larger). Validation requirements must be defined early in the flight validation program to ensure that relevant and sufficient flight test data is obtained to conduct model validation to the high level required. This includes a process of:

- *Model identification* - which models are needed?
- *Model input/output documentation* - what does it take to run the models?
- *Model sensitivity analysis* - how well do the inputs and outputs need to be known?
- *Test measurement correspondence* - what tests are needed and how accurate do they need to be made to validate the models?

Given this information, decisions can be made between what the modelers would need for complete validation and what the program, given money/time constraints, can deliver.

CURRENT MODELS

Model Name	Developer	Category	Platform
AEC-Able Structural	AEC-Able	Structural	ANSYS
L'Garde Structural	L'Garde	Structural	FAIM
Operational Sail Shape for Able	NASA-LaRC	Structural	NASTRAN
Operational Sail Shape for L'Garde	NASA-LaRC	Structural	ABAQUS
Structural Analysis & Synthesis Tools	NASA-JPL	Structural	MATLAB/C
Analytical Scaling Laws	Tenn. Tech	Structural	MATLAB
Advanced Computational Models	NASA-LaRC	Structural/ACS	ABAQUS
Solar Sail Propulsion Modeling Tool	SRS	Structural/ACS	PC/OpenGL
Solar Sail Spaceflight Simulation Software	NASA-JPL	GNC/ACS	MATLAB
Lightweight Sail Attitude Control System	Ariz. State	GNC/ACS	MATLAB
Gimbaled-Boom Mounted Bus	NASA-JPL	GNC/ACS	MATLAB
NASA Charging Analyzer Program 2000	NASA-MSFC	Environment	JAVA GUI
Plasma Interaction Model	Virginia Tech	Environment	-
NUMerical InTegration (charging)	NASA-JPL	Environment	FORTRAN

Currently, under the ISPT solar sail propulsion program, various modeling efforts (see table at right) are being tracked which define the current state of the art in solar sail spacecraft models. The NMP ST-9 Solar Sail Flight Validation (SSFV) study team is also taking advantage of this assessment to help define the requirements for a future solar sail flight validation. Models have been categorized into:

- *Structural* – membrane/boom static and dynamic
- *Attitude Control System (ACS) & Guidance, Navigation, and Control (GNC)* - attitude determination, thrust vector control, and orbit analysis
- *Environmental* – interaction with space environment

Some of the more sophisticated models overlap in functionality.

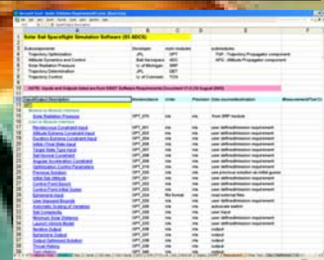
MODEL-MEASUREMENT MATRIX

Of the several model validation techniques available, validation by comparison to test data on prototypes (components, subsystems, and systems) is the most beneficial in technology development. Technology Readiness Level (used by NASA as a technology maturity metric) definitions are based on testing. A crucial step for validation requirements definition and model validation (once the data has been taken according to those requirements) is to catalog the correspondence among model inputs, outputs, and test measurements. Currently, an Excel® spreadsheet is being developed to address this need. Displayed is the input/output sheet for the S5 model which is currently being developed by NASA; tabs at the bottom select each of the other models.

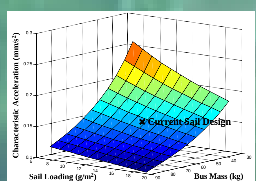
This format provides:

- Listing and details of model input/output parameters
- Correspondence to test measurements for validation analyses
- Links to information on a particular parameter or field
- Links to other NASA solar sail technology reference databases

Measurement data available for model validation will include; in-house testing done by the sail provider, NASA in-house testing, ground system demonstration (GSD) testing at various NASA facilities and, eventually data from the validation flight of a 40-m sail. Compilation of this information during the early stages of the flight validation program aids in determination of test plans and in decision making when having to make trade-off comparisons between what measurements are desired and what can actually be done within program cost and schedule constraints.



MODEL-SENSITIVITY ANALYSES



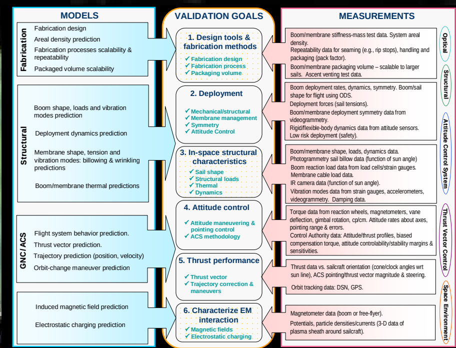
$$a_0 = \frac{2\eta P}{\sigma_S + (m_B/A)}$$

η = sail efficiency (0.85)
P = solar pressure constant = $(4.56\times10^{-6}\ N/m^2)$
A = sail area (m^2)
m_S = mass of sail assembly (kg)
m_B = mass of spacecraft bus (kg)
σ_S = sail loading or areal density $= m_S/A\ (kg/m^2)$

Once the inputs and outputs of each model have been cataloged, an approach is required to determine how important a measurement is or how accurately the measurement needs to be taken. The dependence of a model on a particular measurement has to be weighed against feasibility, cost, mass, technical development, and schedule constraints, just to name a few. A common approach to quantify this dependence is to conduct sensitivity analyses on the model to identify which outputs are highly sensitive to small perturbations in inputs. If a model has a highly-sensitive output parameter, the corresponding input variables must be well known or accurately measured. Even when comparing model outputs to test data directly, inputs must reflect precisely the test conditions, especially for high-sensitivity outputs. And measurement data cannot be so noisy as to be useless for model-output comparison.

To illustrate the concept of sensitivity analysis, an example is taken from McInnes, reformulated for a state-of-the-art 40-m flight validation design. A primary performance metric for solar sails is the characteristic acceleration a_0. The figure at left shows the 40-m solar sail design in the center of a surface representing the response of characteristic acceleration to changes (± 50%) in sail loading and bus mass. As expected, decreasing sail loading (*i.e.*, decreasing membrane and boom mass) or decreasing bus mass increases characteristic acceleration. The main feature to point out here is that the response surface has a much steeper slope (higher sensitivity) along the direction of the bus mass axis as compared to the sail loading axis for a given percentage change. In other words, reducing bus mass by 10% will yield more performance gain (higher acceleration) than the same percentage change in sail loading. This may lead one to make the decision to direct more design and test effort towards reduction of bus mass rather than towards thinner sails. Although this is a simplistic example, it illustrates the process required to identify sensitivity of outputs to changing inputs. Applying this technique to the parameter space of each of the solar sail models can guide design, testing, and validation processes.

VALIDATION REQUIREMENTS



With the relevant models identified, their inputs/outputs catalogued, and sensitivity analyses done to determine critical parameters, initial requirements can now be defined specific to model validation. Although much more rigorous validation and verification procedures will eventually be implemented for each model, this preliminary framework, utilizing a model-measurement matrix to map model inputs/outputs to specific measurement data and then conducting first-level sensitivity analyses to help quantify the importance of the measurement and how accurately the measurement needs to be made, can assist in initial requirements definition and program decision making in support of meeting these requirements. Listed in the figure above are the New Millennium Program's (ST9) Solar Sail Flight Validation study team's validation goals. These are currently undergoing initial definition review with expected refinement occurring during program development. With model validation being a primary goal, implementation of a process, such as the one presented in this paper, is vital to program success. The figure shows measurements representative of those that will be used to validate the various models and how both models and measurements will have to correspond to satisfy validation goals. Development of scalable, robust, high-confidence level models is absolutely required to advance solar sail technology for integration into space systems; high confidence can only be achieved through proper validation.

SUMMARY

Solar sails are being developed as a mission-enabling technology in support of future NASA science missions. Current advances have progressed solar sail technology far enough to justify a flight validation program. Due to the gossamer nature of solar sails, prototype ground testing is limited. Therefore, a primary objective is to test and validate solar sail models that are currently under development so that they may be used with confidence when scaled to the larger sizes required by future missions. Both system and model validation requirements must be defined early in the program to guide design cycles and to ensure that relevant and sufficient test data will be obtained to conduct model validation to the level required. This paper presents a basic framework or process of model identification, model input/output documentation, model sensitivity analyses, and test measurement correspondence to assist in requirements definition and program decision making to meet those requirements within program constraints.

ACKNOWLEDGMENTS

The work described in this paper was funded by the In-Space Propulsion Technologies Program, which is managed by NASA's Science Mission Directorate in Washington, D.C., and implemented by the In-Space Propulsion Technology Projects Office at Marshall Space Flight Center in Huntsville, AL.