

Solar Sail Models and Test Measurements Correspondence for Validation Requirements Definition

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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 activity 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.

Nomenclature

a_0	= characteristic acceleration (mm/s^2)
A	= sail area (m^2)
P	= solar radiation pressure ($4.56 \times 10^{-6} \text{ N/m}^2$)
η	= sail efficiency
m_B	= mass of spacecraft bus (kg)
m_S	= mass of sail assembly (kg)
σ_S	= sail loading (g/m^2)

I. Introduction

SOLAR sails are being developed as a mission-enabling technology in support of 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 progressed the technology far enough to go to the next step, flight validation. If chosen for the New Millennium Program (ST9), flight validation will reduce the risk (*i.e.*, increase Technology Readiness Level, TRL) 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 $\sim 400 \text{ m}^2$ 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 $10,000 \text{ m}^2$ 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/outputs need to be known), and 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 a program, given money/time constraints, can deliver.

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II. Current Models

Currently, under the ISPT solar sail propulsion activity, various modeling efforts 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. Table 1 summarizes the current modeling efforts and categorizes based on their primary function; some of the more sophisticated models overlap in functionality. Structural models focus on determination of sail membrane and support structure (booms) shape for both static and dynamic cases. Guidance, Navigation and Control (GNC) and Attitude Control System (ACS) models include those specific to attitude determination, thrust vector control, and orbit analysis. Environment models deal with the interaction of the solar sail with the space environment and include plasma interaction and spacecraft charging. The platform descriptor is an indicator of whether the model is finite element (FE) based or not; the majority of the structural models are FE-based. The status column represents a qualitative, comparative measure of model development progress and level of validation testing.

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

Table 1: Solar sail models included in the model-measurement matrix.

III. Model-Measurement Matrix

Of the several model validation techniques available [1], 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 [2]. 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. Figure 1 shows a screen shot of this model-measurement matrix illustrating the general format. Displayed is the input/output sheet for the S5 [3] model; tabs at the bottom select each of the other models. Each model will have a sheet giving details of each input/output parameter (*e.g.*, sail material properties, sail shape, trajectory) and which test measurement(s) would provide the respective input or output during the validation analyses. Links are provided to additional information describing a particular parameter or field. 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 for 10-m and 20-m sails, and eventually, data from the validation flight of a 40-m sail. It has also been proposed to link this model-measurement matrix directly with another ongoing effort by Adams [4] which focuses on the development of a complete reference database of technology development completed thus far within the solar sail program. Compilation of this information during the early stages of the 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.

Solar Sail Spaceflight Simulation Software (S5 ADCS)					
Subcomponents	Developer	main modules	submodules		
Trajectory Optimization	JPL	OPT	TGP - Trajectory Propagator component		
Attitude Dynamics and Control	Ball Aerospace	ADC	APG - Attitude Propagator component		
Solar Radiation Pressure	U. of Michigan	SRP			
Trajectory Determination	JPL	DET			
Trajectory Control	U. of Colorado	TCN			

Input/Output Description	Nomenclature	Units	Precision	Data source/destination	Measurement/Test Context
OPT					
Module-to-Module Interface					
Solar Radiation Pressure	OPT_070	n/a	n/a	from SRP module	
User-to-Module Interface					
Rendezvous Constraint Input	OPT_001	n/a	n/a	user defined/mission requirement	
Altitude Extrema Constraint Input	OPT_003	n/a	n/a	user defined/mission requirement	
Duration Extrema Constraint Input	OPT_004	n/a	n/a	user defined/mission requirement	
Initial / Final State Input	OPT_005	n/a	n/a	user defined/mission requirement	
Target State Type Input	OPT_007	n/a	n/a	user defined/mission requirement	
Sail Normal Constraint	OPT_008	n/a	n/a	user defined/mission requirement	
Angular Acceleration Constraint	OPT_009	n/a	n/a	user defined/mission requirement	
Optimization Control Parameters	OPT_019	n/a	n/a	user defined/mission requirement	
Previous Solution	OPT_020	n/a	n/a	use previous solution as initial guess	
Initial Sail Attitude	OPT_021	n/a	n/a	user defined/mission requirement	
Control Point Epoch	OPT_022	n/a	n/a	user defined/mission requirement	
Control Point Initial Guess	OPT_023	n/a	n/a	user defined/mission requirement	
Ephemeris Input	OPT_024	file format	n/a	read external files	
User Imposed Bounds	OPT_025	n/a	n/a	user defined/mission requirement	
Automatic Scaling of Variables	OPT_026	n/a	n/a	autoscale switch	
Sail Complexity	OPT_029	n/a	n/a	user input	
Minimum Solar Distance	OPT_030	n/a	n/a	user defined/mission requirement	
Launch Vehicle Model	OPT_033	n/a	n/a	user defined/mission requirement	
Iterative Output	OPT_036	n/a	n/a	output	
Ephemeris Output	OPT_037	n/a	n/a	output	
Output Optimized Solution	OPT_038	n/a	n/a	output	
Thrust History	OPT_039	n/a	n/a	output	
Turn History	OPT_040	n/a	n/a	output	

Figure 1: Screen shot of model-measurement matrix showing general format. Each model (tabs at bottom) has a worksheet with links to current or planned test measurements.

IV. Model Sensitivity Analyses

Once the inputs and outputs of each model have been cataloged, some 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 (*i.e.*, degree of need for validation) 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 (*e.g.*, FEA-generated vibration modes vs. laser vibrometer measurement data), model 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. Determining the acceptance level of a measurement can be determined by this type of analysis. A simple example is presented here for illustration purposes. The example is taken from McInnes [5], reformulated for a design proposed for the 40-m flight validation program [6]. A primary performance metric for solar sails is the characteristic acceleration a_0 given by

$$a_0 = \frac{2\eta P}{\sigma_s + (m_B/A)}, \quad \sigma_s = \frac{m_s}{A}$$

where η is the sail efficiency (0.85 used here), P is the solar radiation pressure constant for a perfectly absorbing surface ($4.56 \times 10^{-6} \text{ N/m}^2$), σ_s is the mass per unit area of the sail assembly (membrane and booms), and m_B is the mass of the spacecraft bus. For this example, the spacecraft bus includes all other components not included in the sail assembly such as power, electronics, communications, and instrumentation (payload). Splitting the spacecraft into two subsystems, the “engine” and “everything else” allows the examination of how separate subsystems affect characteristic acceleration. The “X” in Fig. 2 locates a solar sail design (40-m, state-of-the-art) in the center of

surface representing the response of characteristic acceleration to changes ($\pm 50\%$) 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. However, the example is here to illustrate the concept of sensitivity. Note that the response surface has a much steeper slope (higher sensitivity) in the direction of the bus mass axis as compared to

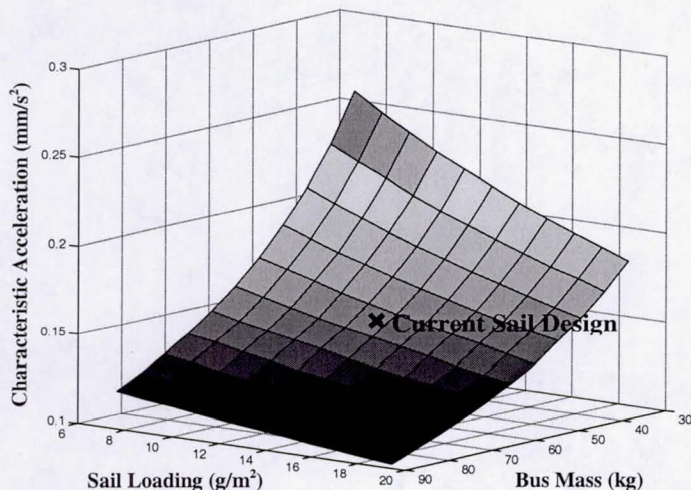


Figure 2: Solar sail characteristic acceleration as a function of sail loading and bus mass with the design point for a 40-m flight validation shown with an X.

sail loading axis for a given percentage change. 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. Particularly, to a flight validation program, sensitivity analyses can help define what requirements are needed specifically for model validation so that they can be incorporated early into the program to assist in test planning and hardware development.

V. 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 here are the New Millennium Program's (ST9) Solar Sail Flight Validation study team's validation goals:

Goal 1. Validate processes and design tools for solar sail fabrication

- ☒ Verify processes for fabrication and scaling
- ☒ Verify sail system design tools
- ☒ Verify sail system packaging

Goal 2. Validate controlled deployment

- ☒ Validate sail deployment on the ground
- ☒ Validate sail deployment in space
- ☒ Validate attitude control during deployment

Goal 3. Validate in-space structural characteristics

- ☒ Validate sail shape model
- ☒ Validate structural loads model
- ☒ Validate sail thermal model
- ☒ Validate sail dynamics model

Goal 4. Validate solar sail attitude control

- ☒ Validate a method for identifying all torques

- ☑ Verify ACS methodology
- ☑ Validate model for attitude maneuvering and pointing control

Goal 5. Validate solar sail thrust performance

- ☑ Validate models of thrust vector magnitude and direction
- ☑ Validate models for sailcraft trajectory correction and maneuvers

Goal 6. Characterize the sail's electromagnetic interaction with the space environment

- ☑ Characterize induced magnetic fields
- ☑ Determine electrostatic charging

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. Figure 3 lists a few representative measurements 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.

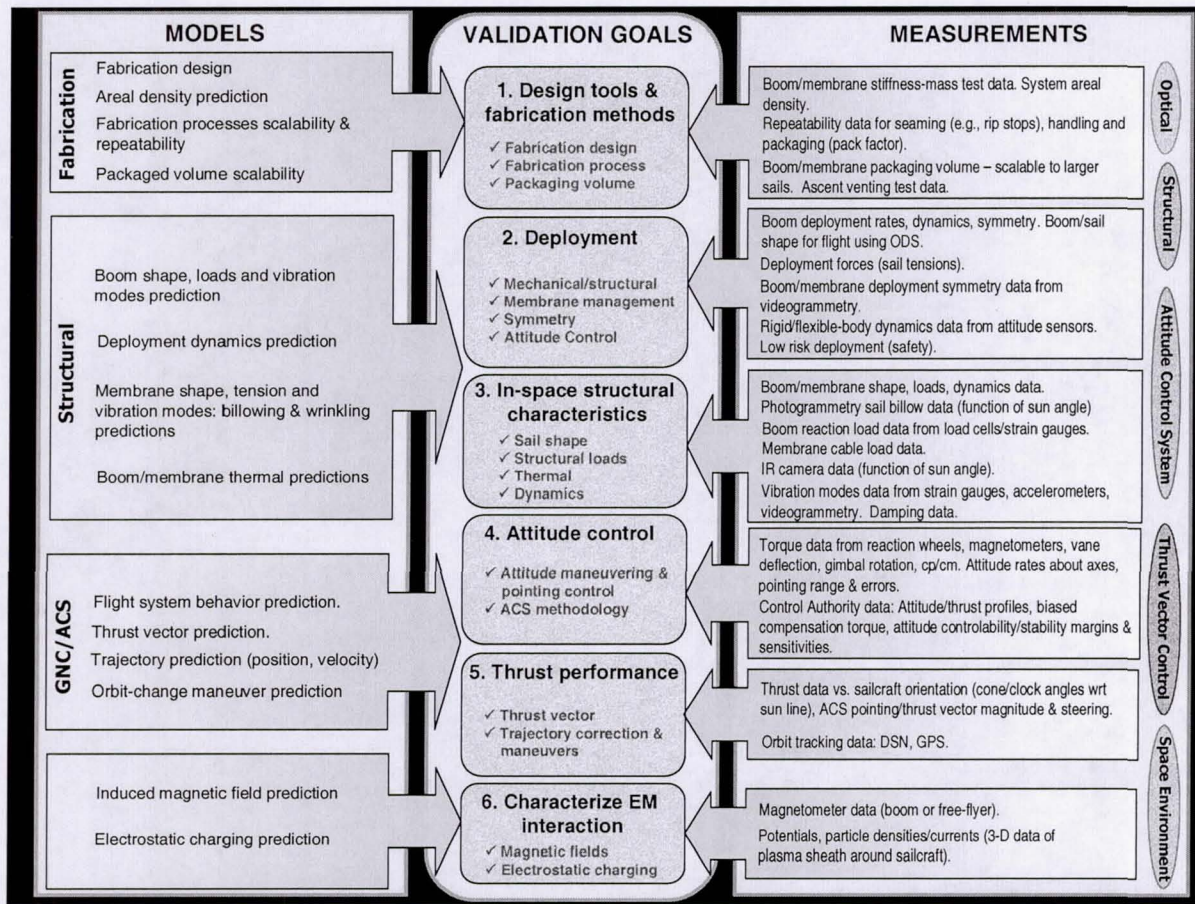


Figure 3. Solar sail models and measurement data correspondence to meet validation goals.

VI. 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. The program objective is to develop in-space propulsion technologies that can enable or benefit near and mid-term NASA space science missions by significantly reducing cost, mass and travel times.

Anthony Ewing would also like to thank Gregory Garbe of MSFC for the opportunity to work in this very interesting (and exciting!) solar sail technology development program.

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