Solar Sail GN&C Model Comparisons

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The Solar Sail Propulsion project is engaged in an ambitious program to raise the Technology Readiness Level of solar sails and prepare for a validation flight via a series of hardware ground demonstrations and development of a number of high fidelity simulations and models. Guidance, navigation, and control of solar sails is a key part of this effort. The large flexible structure and optical nature of solar sails create a considerable challenge for attitude control, thrust modeling, and navigation. In this paper, we present an overview and comparison of two recently delivered prototype solar sail guidance, navigation, and control software tools currently funded by the Solar Sail Propulsion project. The results of some key test cases are presented. Where possible, we also make comparisons to other software tools. We discuss the implications of the results of these comparative studies to the future direction and scope of development efforts for guidance, navigation and control software for solar sails, including the relationship to hardware test efforts such as the Thrust Vector Control Authority Demonstration.

I. Introduction

Solar sails require unique Guidance, Navigation and Control (GN&C) strategies and capabilities. The goal of the In-Space Propulsion (ISP) Solar Sail Propulsion (SSP) project is to bring various solar sail technologies to a Technology Readiness Level (TRL) of 6[1]. Figure 1 provides a description of the NASA definition of TRLs. TRL 6 is defined as a "System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)". Thus, the intent of the SSP is to bring all relevant technologies associated with solar sails, including GN&C, to a point just short of space flight validation via ground demos and detailed simulations. Solar sails would then be considered a mature enough technology for a flight validation.

As noted inGarbe, et al.[2], the standard TRL 6 definition does not really fit all that well with solar sails, due to their large-scale gossamer nature and the difficulty of simulating a microgravity environment on Earth (imagine fitting a 100x100 meter sail on a KC-135!). Although thermal, vacuum and optical effects are readily modeled on the ground, there is simply no easy way to measure solar radiation pressure or accurately test structural effects for a solar sail in a 1-g environment.

GN&C systems can be modeled with a high degree of fidelity via computer simulation for standard spacecraft, and for many facets of GN&C design for solar sails the current state-of-the-art tools are sufficient. However, solar sails present unique challenges which must be addressed with special tools and new research. A prime example is the controllability issue for solar sails. With such a large, flexible structure, control-structure interactions can lead to instability in the control system, and the unique nature of most solar sail Attitude Control System (ACS) designs cannot be modeled with existing tools.

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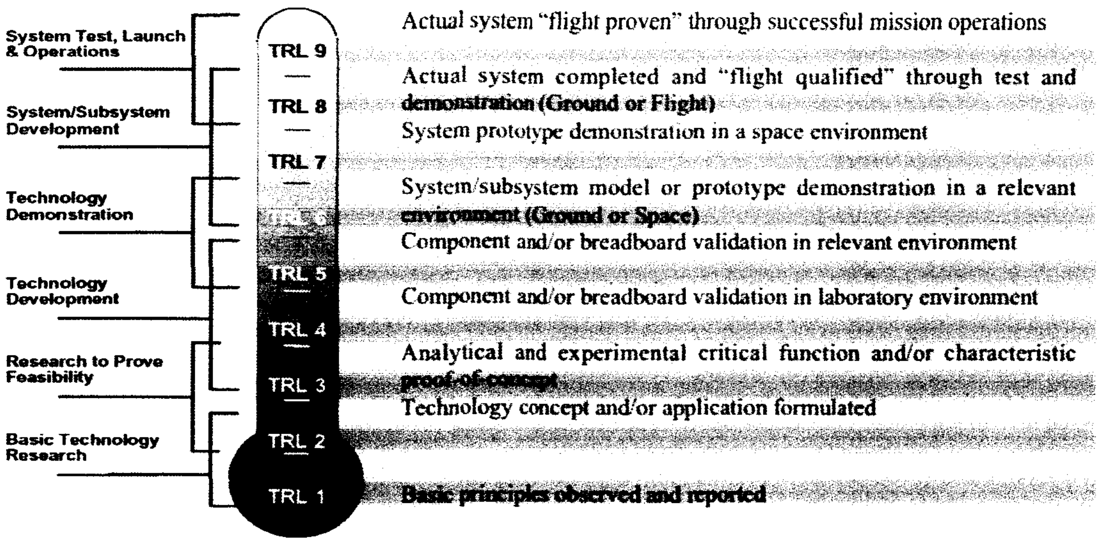

Fig. 1 NASA's Technology Readiness Level (TRL) Definitions

Another example is that the thrust of the solar sail is a function of its attitude relative to the sun and the shape of the sail. Different solar stresses are applied to the structure of the sail across a range of solar attitudes at a given distance from the sun, and so the sail shape could potentially vary as a result of the attitude of the sail, greatly complicating the life of the GN&C system designers. Many researchers are currently looking into the so-called "billow problem[3,4] " which refers to the fact that different segments of a sail could "billow" with the application of solar radiation pressure (and hence not present a normal surface to the sun), creating unbalanced torques and other undesirable effects.

We prefer to speak of the sail pointing for propulsive purposes as Thrust Vector Control or TVC in order to distinguish it from pointing for other purposes. The solar sail community generally agrees that any payload pointing must be accommodated by the sailcraft bus, and not the sail itself. Thus another key issue regarding solar sail GN&C design is how do we know where the sail is relative to the sailcraft bus? If all the instrumentation is on the bus, do we need more instrumentation for the sail itself? To what degree should we attempt to measure the shape of the sail in space with cameras or other instrumentation? A good GN&C modeling capability can shed light on these questions by helping to determine how much uncertainty in thrust vector pointing a sailcraft can sustain and still be viable.[5]

Solar sails also represent a class of low-thrust trajectories, but with the caveat that the thrust varies as a function of solar attitude and distance from the sun. Thus, solar sails also offer unique challenges in modeling solar sail trajectories.[6] Navigation of solar sails also presents unique challenges, if, for instance, accelerometers are included in the navigation updates.

The Solar Sail Propulsion project is currently sponsoring a variety of tasks designed to bring the TRL level of solar sail propulsion to TRL 6[1], among which are two major efforts to help model solar sail guidance, navigation and control.[7,8] In the next section, we give a brief description of these two software tools.

II. Solar Sail GN&C Software Tools

The SSP project is sponsoring a development effort for solar sail GN&C modeling that goes by the nameS5, for Solar Sail Spaceflight Simulation Software. This effort is led by the Jet Propulsion Laboratory (JPL) with partners at Ball Aerospace, the University of Colorado, the University of Michigan, Raytheon, and L'Garde. The purpose of S5 is to develop an integrated set of simulation tools will be able to predict, re-calibrate and optimize the trajectory, maneuvers and propulsive performance of a sail during a representative flight mission. A functional diagram of the S5 architecture appears in Fig. 2.[7]

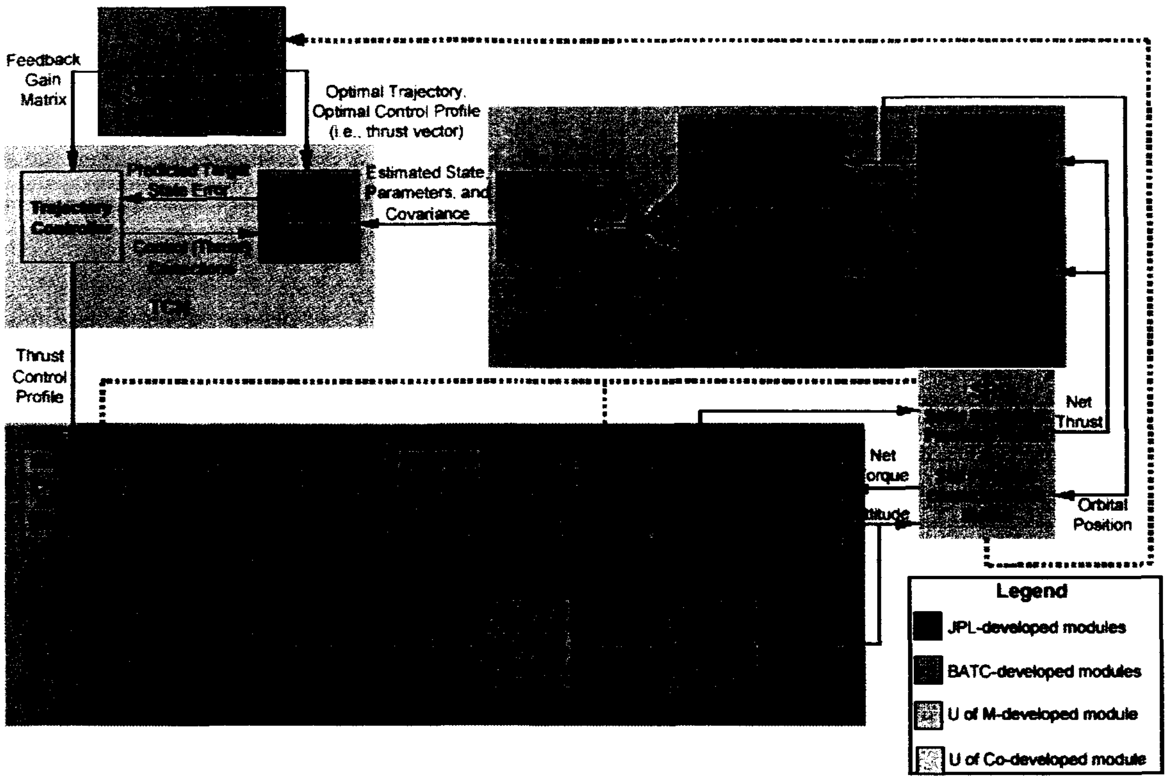

Fig. 2 S5 Architecture

There are five main modules in S5, and they are represented by the different large shaded blocks above labeled variously as OPT, ADC, DET, SRP, and TCN. A brief description of each of these follows[7]:

OPT - The Mission Design Module determines an optimal trajectory and sail control strategy which optimizes a given performance criteria (i.e. minimum time, control effort or sail dimension) subject to control and/or state constraints. A second order-gradient optimization algorithm is used to converge to the optimal trajectory. This module outputs the optimal control and control gain matrices which are used by the simulation and control modules.

SRP - The Solar Radiation Pressure Module is the source of the solar radiation pressure thrusts and torques for the OPT, ADC and DET modules. Using sail and spacecraft characteristics and knowledge of the spacecraft state and orientation, this module computes the thrust and the total torque due to solar radiation pressure. Structural dynamic effects, billowing, beam bending, and sail degradation are accounted for in the computation of forces and moments.

ADC - The Attitude Dynamics and Control Module simulates the rotational dynamics of a sailcraft, including torque induced by solar radiation pressure, other environmental disturbance sources (e.g., gravity gradient, aerodynamic, and magnetic moment), and conventional spacecraft actuators (e.g., reaction wheel assembly and thrusters). It models sailcraft attitude control using articulated control vanes located at the sail periphery or mass displacement (i.e., mass on a gimbaled boom altering center of mass location relative to the center of pressure). Simulated sensor measurements are processed to estimate attitude and angular velocity.

TCN - The Trajectory Control Module updates the thrust control profile based on the current estimate of the spacecraft state provided by the DET module. TCN uses the gain matrix from OPT in combination with previously designed control laws to update the control and predict the updated target conditions. The updated controls (thrusts) are input to the ADC module.

DET - The Orbit Determination Module simulates the navigation performance. DET propagates the equations of motion, simulates ground based and on board (optical and accelerometer) observations and processes the observables with a Kalman type filter to estimate the current state and statistics. It is designed to be used for covariance analysis or Monte Carlo studies.

S5 brings together these disparate modules in a single package that is capable of being run in a standalone or integrated fashion. S5 has recently completed Phase II of a 3-Phase development effort, and is scheduled to be finished in September of 2005. Version 1.0 has been delivered and is currently in Alpha testing. S5 is being developed by the individual providers primarily in Matlab, but legacy codes of various provenances have also been incorporated and some development is in C++.

S5 is integrated into the Python[9] environment. Python is a freeware platform available over the internet. The advantages of Python over a more typical environment are that it has great portability, does not require an end-user to possess or purchase a license, is suitable to object-oriented applications, and of course, is free. The particular S5 Python implementation will enable an end-user or customer to fashion his or her own simulation to the desired level of complexity by using scripts. The scripting environment is similar, but not identical to Matlab. The implementation provides high-level functions for solar sail GN&C as callable routines at the script level. For instance, a user can call functions to calculate solar radiation pressure or turn on gravity sources. For Version 1.0, the overhead associated with developing an S5 simulation is fairly high, but it is hoped that this will decrease for the final version of the software.

A partnership between Arizona State University and Princeton Satellite Systems (PSS) is developing another GN&C software package called the Solar Sail Control Toolbox, or **SSCT**[8]. The SSCT is more narrowly focused on the design of sailcraft control systems. SSCT roughly possesses the functionality of the ADC and SRP modules of S5; that is, it models sailcraft attitude dynamics and control as well as providing a solar radiation pressure module. The SSCT can model orbits but currently does not possess the capability to model or design low-thrust trajectories like the OPT module of S5. SSCT has some capability to develop trajectory control schema like the TCN module of S5.

While more limited in scope than S5, the SSCT as currently implemented has a greater amount of flexibility to design control systems, which is the primary purpose for which the ASU-PSS team is using it. The SSCT is actually only part of an effort by the same team called the Lightweight Attitude Control System for Solar Sails (LACSSS) project. This project is intended to help increase the TRL level of sailcraft in general, but is also working informally with AEC Able.

Here we should mention that the SSP project is sponsoring two major hardware development efforts for ground testing,[10,11] one led by Able and the other led by L'Garde. Since L'Garde is officially partnered with S5, the ongoing informal collaboration between the ASU/PSS team and Able is viewed positively by the SSP project. S5 has a charter to be more generally applicable to a wide range of solar sail designs, while SSCT is designed primarily to support the ongoing contract for the LACSSS. However, the SSCT will be fully delivered to the SSP project, and can be adapted as necessary.

The SSCT is implemented in Matlab, and provides specialized functions for solar sail GN&C. The SSCT has a CAD scripting capability that enables a user to design a sail and produce graphic images of the sail. As with S5, a user can script varying degrees of complexity into his or her simulation. The SSCT also includes some capability for thermal modeling, although this has not been tailored to solar sails at the present time, but is a general model inherited from Princeton Satellite Systems Spacecraft Control Toolbox (SCT).

The top-level functionality of the SSCT is as follows[8]:

Core - Orbit and attitude dynamics, computer-aided modeling, sensor and actuators
Attitude Control - Complete attitude control design examples
Orbit - Precision orbit propagator, mission planning, formation flying
Estimation: Attitude and orbit estimators
Propulsion - Propulsion system modeling
Thermal - Thermal system modeling
Link - Link and radar analysis
Spin Axis Attitude Determination - Attitude determination with horizon and sun sensors

AGNC - MATLAB implementation of an autonomous GN&C system

This architecture is further illustrated in Figure 3.

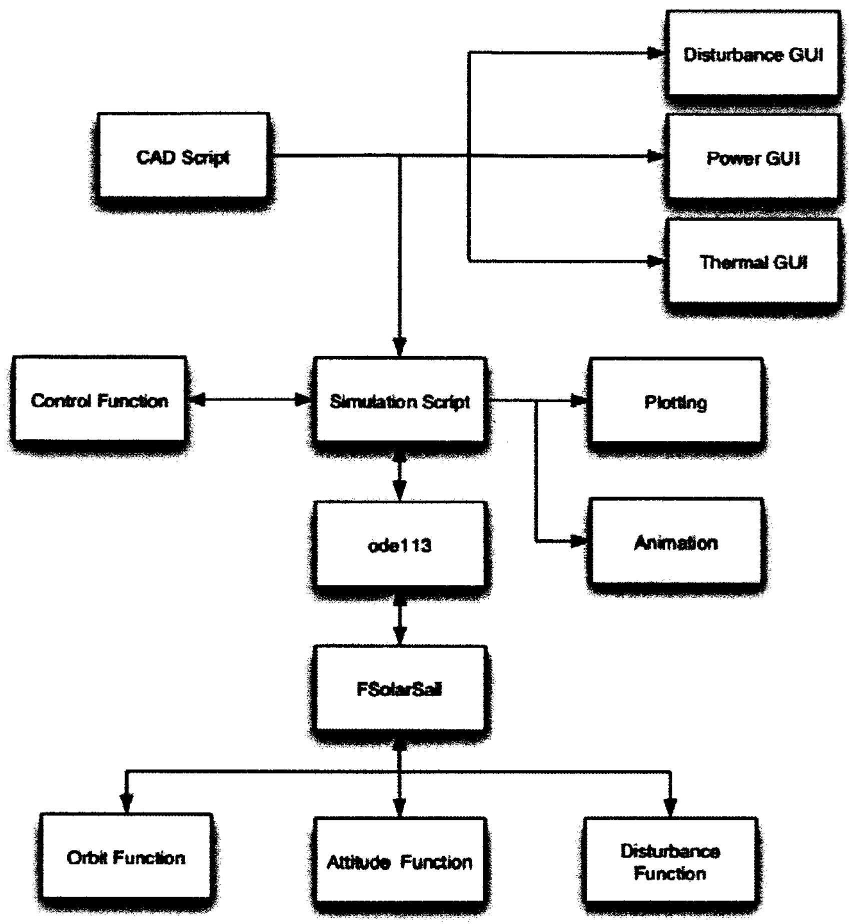

Fig. 3 SSCT Flow Diagram[8]

The SSCT as delivered has specific Able control system models, such as the spreader bars, translating masses, and optional Pulsed Plasma Thrusters (PPTs) that are unique to Able's current preferred ACS design[14]. On the other hand, S5 has more capability at the current time to model control vanes for solar sails, which is currently L'Garde's TVC of choice. S5 is developing a generic capability to model Center-of-Pressure/Center-of-Mass (CP/CM) methods of thrust vector control, which should be available soon.

III Test Cases

In order to have test cases, we must first have a sail model. The standard test case as defined in the 2002 NASA Research Announcement (NRA) appears in Table 1, with some information updated to reflect changes in project priorities.

Table 1) Cycle 1 Integrated Software Tools Required Mission Characteristics

Dimensions:	100 meters x 100 meters or greater
Sail Subsystem Mass	120 kg
Spacecraft Mass	80 kg
Total Flight Mass	200 kg
Characteristic Acceleration @ 1 Au	0.35 mm/s^2
Sail Reflectivity	0.85
Mission Class	~ 1 AU Class

With a few minor modifications as noted, the sail appearing in Table 1 will be a general guideline for the sail models used as the basis of the comparisons in this section. To begin with, the sail is modeled as a flat plate for some simple test cases. We also need to introduce and define the following parameters in Table 2.

Table 2) Solar Sail Optical Parameter Description

Parameter	Description
r	Reflectance
$-_b$	Back Emissivity
$-_f$	Front Emissivity
$-_b$	Back non-Lambertian coefficient
$-_f$	Front non-Lambertian coefficient
S	Specular Reflectance

The above parameters in Table 1 are all non-dimensionalized coefficients between one and zero. Briefly, reflectance measures the amount of light reflected, and is set to 1.0 for a perfectly reflecting surface. A Lambertian surface is one equally bright when viewed from any aspect angle. Thus, the non-Lambertian coefficient determines how the surface varies from ideal brightness at different aspect angles. The emissivity coefficient measures the force from photons that have been absorbed and re-emitted as thermal radiation, and its ideal value is zero. The specular coefficient measures the scattering of light from a normal reflection and is ideally zero. This description of optical characteristics and approach to modeling sails using them is taken from McInnes.[12]

S5 also currently uses the approach espoused by McInnes. SSCT uses a similar approach as well, the one difference being that the effect of the Sun not being a point-mass is neglected (which is only a factor when very close to the Sun).

We note that the characteristic acceleration in Table 1 is a function of the optical parameters in Table 2 (as well as the mass of the sailcraft), and is not directly specified in the test cases presented in this section. Instead, the optical parameters in Table 2 are specified for the sail models compared in this section. We should also mention that the SSP project Design Reference Mission (DRM) sail is a 4-quadrant square sail that is 3-axis stabilized

We begin with a basic comparison using a sail model that appears in Table 3. The values in that table correspond to a perfectly reflecting, specular, "ideal" sail[12]. We begin with such a simple example to illustrate the models used by each tool, and to set the stage for more advanced comparisons.

The result of this comparison appears in Fig. 4, with the dashed line representing the SSCT result and the solid line the S5 result. The slight discrepancy occurs due to differences in how the solar flux is modeled in S5 and SSCT (and not the sail model itself). So the simple test is a success, and has been further validated by a comparison to SSMPT.[3] SSMPT is a tool developed by the SRS company (a partner of Able) to model sail shape with a great deal of fidelity, and is based on software known as IODA. SSMPT could potentially serve as a front-end to develop sail models and import them into S5 and SSCT.

Table 3) Simple Sail Model Optical Properties

Parameter	Value
r	1.0
$_b$	0.0
$_f$	0.0
$_b$	2/3
$_f$	2/3
S	1.0

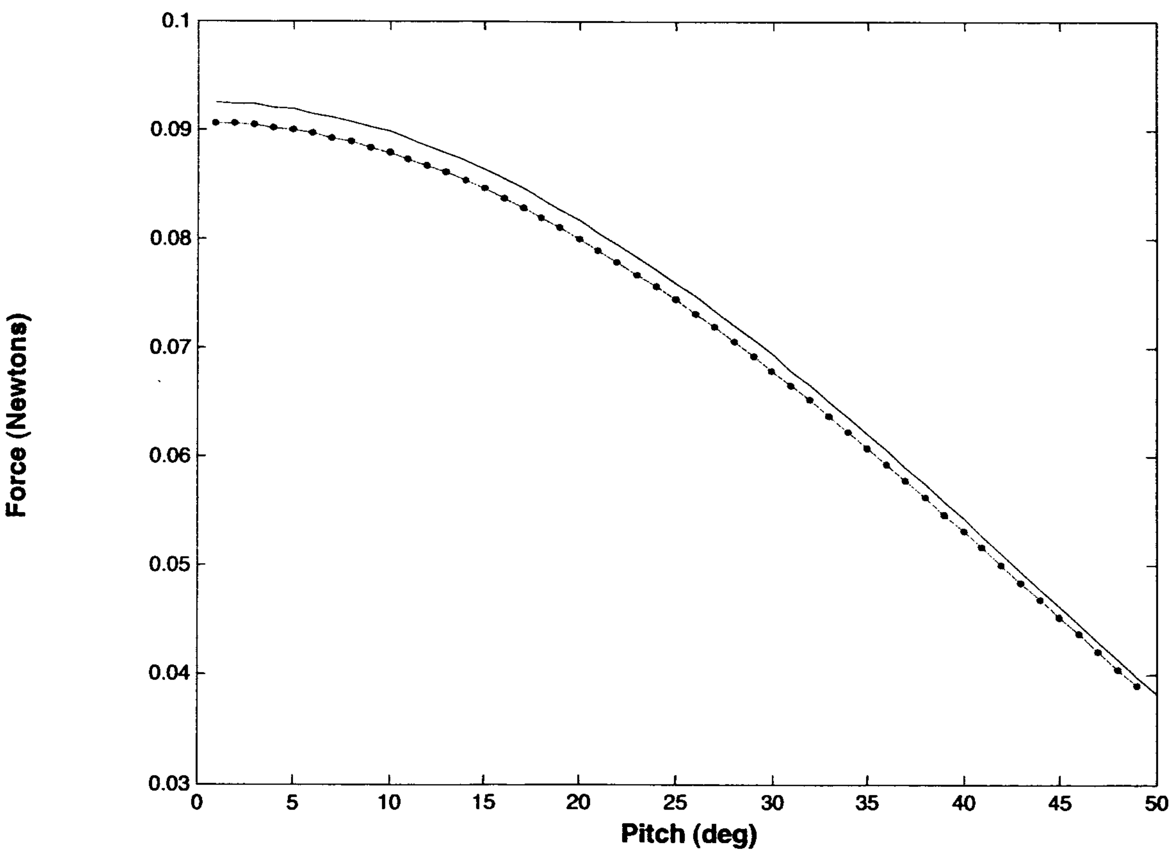

Fig. 4 Simple Sail Model Thrust Comparison

As mentioned earlier, the optical properties model favored by McInnes[12] is used by S5. This optical model is represented by

$$f_n = PA\left((1+rs)\cos^2\alpha) + B_f(1-s)r\cos\alpha + (1-r)\frac{\varepsilon_f\beta_f - \varepsilon_b\beta_b}{\varepsilon_f + \varepsilon_b}\cos\alpha\right)n \qquad (1).$$
$$f_t = \left(PA(1-rs)\cos\alpha\sin\alpha\right)t$$

InEq. (1), the optical properties are as defined in Table 1, while P is the photon pressure from the sun, A is the reference area of the sail, _ is the pitch angle, $\boldsymbol{n}$ is a unit vector indicating the direction normal to the sail, $\boldsymbol{t}$ is a unit vector indicating the direction tangential to the sail, f_n is the normal force, and f_t is the tangential force. The pitch angle occurs around the tangential axis (see Fig. 5). Since the sail in this case is symmetric about the normal body axis, the pitch angle could be able either the X or Y axis in Fig. 5, but we prefer the Y axis. If we rotate only about the Y axis, which is perpendicular to the edge of the sail, then all the tangential force is directed in the X direction (and with a pitch angle of zero, there would be no tangential force for an ideal sail).

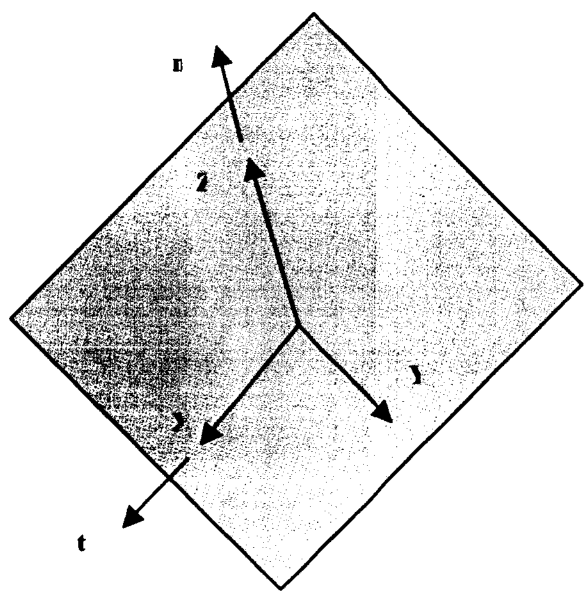

Fig. 5 Sail Body Coordinates

The cos^2_ term in Eq. 1 is a result of multiplying the angle of reflection with the projected area (both of which are functions of the cosine of the angle with respect to the Sun. A common oversight of researchers is to miss the variation of the projected area and model that term (which is the term that results from absorption) as a simple cosine function.

The thrust model in SSCT currently does not include optical properties. The reason for the omission is that since the SSCT is aimed primarily at control system design, a simpler model is all that is needed to model disturbance torques. As with any disturbance torque in spacecraft control system design, it is only necessary to model the worst-case torque to assure sufficient control authority for your design. More refined models are possible, but may not be necessary.

In any case, since it is not possible at the present time to compare more sophisticated optical models between the two toolkits, instead we provide a comparison of the simple sail described in Table 3 and a more complex model described in Table 4 using only S5. The result appears in Fig. 6 and gives one example of how a "real" sail compares to an "ideal" one. The properties in Table 4 are taken from McInnes (and McInnes obtained them from an old JPL design). The shape of the curves in Fig. 6 matches those of the similar Fig. 2.9 in McInnes closely, but note that the Force scale (*Y* axis) in McInnes is off by a factor of two.[13]

The comparisons in this section are rather basic, but they serve a two-fold purpose. First, the SSP project does have a strong interest in cross-checking the various models under development to assure that they agree at the most basic level. Second, these simple comparisons serve to introduce the casual reader to the basics of solar sailing.

Table 4 Complex Sail Model Optical Properties

Parameter	Value
r	0.88
$—_b$	0.55
$—_f$	0.05
$—_b$	0.55
$—_f$	0.79
S	0.94

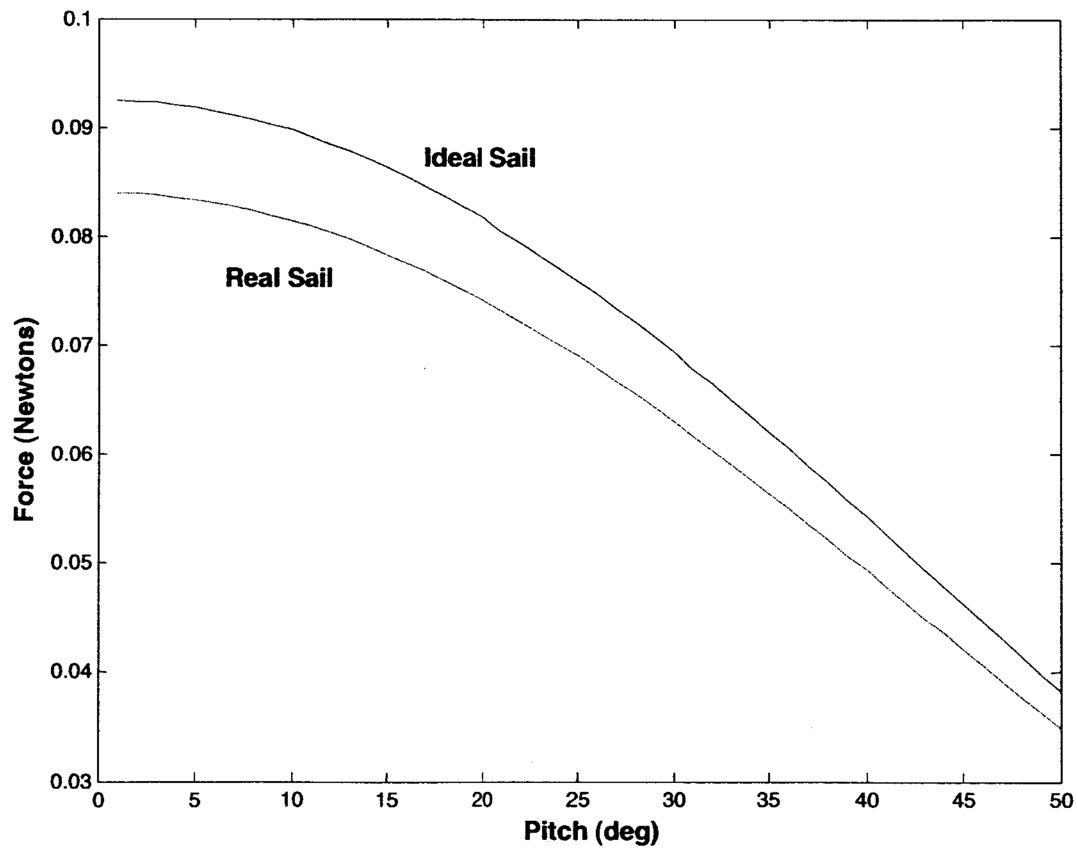

Figure 6 Ideal vs. Real Sail Comparison

Speaking of basicEq. 1 currently comprises something of a standard sail optical model for the solar sail community (at least, in the GN&C neighborhood). However, there is nothing that says Eq.1 is sacrosanct; in fact, the S5 team currently has considered other models and has "hooks" in the software to easily incorporate them. Part of the reason the SSP project is funding efforts such as S5 and SSCT is precisely to consider and test items like optical characteristics models. A future goal is to compare optical models to optical data from the ground demo test program.

Currently S5 has two ways of modeling the thrust on the sail. The first is part of the SRP module and involves a method of modeling shapes that depends on tensors[14]. The second method[4] was developed by L'Garde to protect information about the shape of their sailcraft that was proprietary (although it is not currently). This method involves non-dimensionalized coefficients that are similar to the familiar drag and lift coefficients for terrestrial aircraft. The S5 team has received one set of such coefficients from L'Garde to model a square 10,000 square-meter sail at 1 AU, and is in the process of incorporating them into the integrated software package.

S5 and SSCT also contain detailed torque models that incorporate mass properties as well as optical properties into the modeling process. Since a basic comparison between the two models for torque would largely be a repeat of the thrust comparison above, the details of the comparison will be omitted.

IV. Future Direction and Scope of Solar Sail GN&C Tools

While they both have great potential, much work remains for GN&C modeling tools for solar sail technology development. S5 in particular has only recently delivered a version of the software for Alpha testing. SSCT has an edge in maturity due to the fact that it is based on a legacy tool, but the solar sail specific portions of it could also use further development. Fortunately, both efforts have a year's development time remaining. S5 recently was approved for the final year of funding, while the project that is funding SSCT has a review approaching in October of 2004.

While the tests conducted so far with the software are basic, they do demonstrate commonality of models and methods. Further testing is underway with more complex modeling capabilities. A Beta version of S5 will be delivered in or around February of 2005. The development path for SSCT is less clear, as it depends on the needs of the LACSSS project of which it is part, but certainly some improvements will be made in the second phase of that effort.

Each tool has great potential to continue to raise the TRL level for solar sail GN&C. Given the similarities between Matlab and Python, the possibility of importing parts of S5 into SSCT and vice versa is promising, providing that there are no issues with proprietary software or licensing. Licensing is one of the challenges facing the effort to raise the TRL level of GN&C software, as the SSP project has an interest in "seeding" industry for solar sails by distributing software, which can conflict with the proprietary or licensed software of some of the providers.

Another item of interest to the SSP project is to model flight data from existing spacecraft as a means of checking the sail solar radiation models. The Chandra spacecraft has been identified as an early test candidate and some preliminary results obtained. The Chandra operations community needs a fairly accurate solar radiation model because it is used to predict and schedule reaction wheel momentum dumps (which interrupt science). Chandra makes a good test case because its solar radiation model has been updated fairly recently[15], and the solar torques calculated from the model disagreed with the flight data by a factor of almost 2. The investigation of Chandra as an "inefficient solar sail" will continue as S5 and SSCT grow more mature.

The SSP project is also interested in evaluating the effects of sail shape on thrust and torque. The SSMPT tool of SRS mentioned earlier allows a user to enter a sail model and calculate thrust and torque. Thus, it can be used to study phenomena such as billowing. SSCT also allows great flexibility to the user in modeling a sail shape. S5 is a bit more limited in this area, but the ongoing tensor model development is promising[14].

Also of great interest is the ability of these tools to model different sail TVC designs. The current Able design favors spreader bars, translating masses and optional micro-Pulsed Plasma Thrusters (PPTs)[16]. The SSCT currently can model this design, while S5 will only offer a generic CP/CM TVC modeling which is still under development. On the other hand, the ADC portion of S5 has a fairly high fidelity model of a vane TVC. In the future, it is anticipated that many issues pertaining to TVC for solar sails can be investigated with a high degree of fidelity with SSCT and S5.

Recently the contracts of Able and L'Garde have also been modified to support something called the Thrust Vector Control Authority Demonstration, or TVCAD. The TVCAD is designed to be a ground demonstration of a solar sail system that incorporates GN&C actuators. The intent is to encourage the hardware manufacturers to begin coming to grips with some of the issues of integrated the TVC into the solar sail system, such as increased mass and power requirements and structural dynamics. The tests will combine hardware-in-the-loop with software. Some output or even code from either S5 or SSCT may be included as part of the test, which are currently being designed.

S5 and SSCT will also in the future fulfill a role that is common to GN&C software for spacecraft, which is to serve as testbeds for the actual flight control software. Many current flight programs compile the flight software into high-fidelity simulations and test it prior to flight. In some cases, flight cards are also tested with the simulation containing flight code in order to simulate the timing of commands properly. S5 and SSCT can certainly serve this purpose for the flight code of the future. They will also serve as primary tools for the development of the flight code.

V. Conclusions

Two primary software tools that model solar sail GN&C have been developed for the NASA In-Space Propulsion project, and are being evaluated. Each tool has its unique strengths and weaknesses. Together they complement each other well. The tools are still under development, but testing has been promising so far. An early start to testing should help inform the remaining development process. These tools should contribute significantly to the effort to improve GN&C technology for solar sails in the future, and eventually contribute to a flight demonstration of solar sails.

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