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Ground Imaging for Solar Sail Orbit Determination: A Proof of Concept

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Abstract

Solar sail propulsion systems enable a wide range of space missions that are not feasible with current propulsion technology. Hardware concepts and analytical methods have matured through ground development to the point that a flight validation mission can now be realized. Astronomical observations may play an important role in the flight validation of solar sail propulsion systems. Astrometric data and visual magnitude estimation has great potential for contributing to orbit determination, thrust performance verification, and optical model validation. This paper presents an overview of ground imaging techniques and proof of concept tests that are applicable to solar sail orbit determination. The concepts described here will demonstrate the benefit of collaboration between astronomical imagers and mission analysts for a flight validation mission.

1. Introduction

With very few exceptions, all spacecraft missions have been designed and conducted according to the principles established by Johannes Kepler in the early seventeenth century. Kepler had the genius to assimilate Tycho Brahe’s voluminous observational data into a radical new paradigm. No longer did the Greek notion prevail that the heavenly bodies moved in perfect circles. To make Tycho’s data fit, Kepler reasoned that planetary orbits were ellipses with the sun at a focus, which became the first of his three laws of planetary motion. Later, Isaac Newton brought mathematical formalism to Kepler’s description of planetary motion. Spacecraft missions today are still designed with Keplerian elements and Newton’s laws of motion.

Scientists often devise mission objectives that are difficult to accomplish with current state-of-the-art technology. Missions such as asteroid surveys, high inclination solar orbits, and comet rendezvous place enormous demands on a typical reaction-mass propulsion system. Other missions demand an entirely new class of non-Keplerian orbits. Exotic missions such as station-keeping at artificial Lagrange points and orbits displaced from the ecliptic require a continual thrusting for the duration of the mission. These important missions cannot be achieved with conventional expendable propellants. Solar sail propulsion systems have the potential to meet these mission demands.

2. Fundamentals of Solar Sailing

Solar sail propulsion utilizes the constant pressure exerted by the sun’s radiation to push the sailcraft along its path. Solar photons transfer momentum to an object during a collision, much like billiard balls colliding on a pool table. A photon’s momentum is the product of its mass and velocity, and while the latter is quite large, the vanishingly small mass means the photon momentum is quite small. The combined effect of a large number of photons is required to generate an appreciable momentum transfer, which implies a large sail area. And since acceleration is inversely proportional to mass for a given thrust force, the mass of the sailcraft must be kept to a minimum.

Figure 1 illustrates how the thrust force is utilized for propulsion. Incident rays of sunlight reflect off the solar sail at an angle θ with respect to the sail normal direction. For the model assuming perfect reflectivity, there are two components of force. The first is in the direction of the incident sunlight and the second is in a direction normal to incidence that represents the perfectly reflected photons. When the two components vectors are summed the result is that the two components of force along the sail surface cancel each other and the components normal to the surface add together to produce the thrust force in the direction perpendicular to the sail surface. For a 40 meter x 40 meter square sail at 1 AU from the sun, the solar radiation thrust force is 0.0296 Newtons.

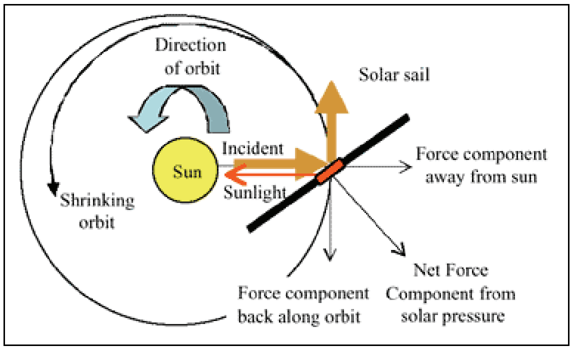


Figure 1. Solar Radiation Thrust Force (NASA/JPL).

Solar radiation pressure can be used to either increase or decrease the orbit energy. If the sail is oriented such that the thrust force is opposite the direction of motion, as in Figure 1 for a heliocentric orbit, the orbit spirals inward. Conversely, if the thrust is in the direction of motion, the sailcraft orbit spirals outward. Orbit inclination changes result when a component of the thrust force is oriented perpendicular to the orbit plane.

Various configurations have been proposed for solar sail vehicles. One of the earliest concepts was a Halley's Comet rendezvous mission using a heliogyro (middle of Figure 2). Heliogyros have reflecting surfaces formed by long blades rotating about a central axis and pitch controlled like a helicopter to provide attitude control. Another approach that is currently in development is a square sail comprised of four triangular sail quadrants. These systems are typically three-axis stabilized, as opposed to spinning, with attitude control torques provided either by articulating tip vanes or varying the center of pressure/center of mass offset. Spinning disk sails have also been proposed.

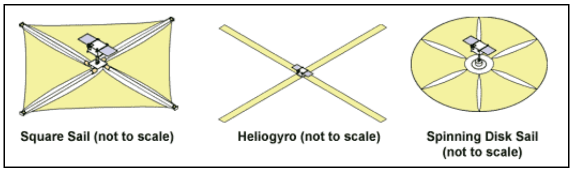


Figure 2. Solar Sail Design Concepts (NASA/JPL).

3. Solar Sail Flight Validation

For the past several years NASA has been investing in several aspects of solar sail propulsion technology. Teams have conducted research on analytical methods for modeling the shape and motion of the sail and support structures under solar radiation pressure loading. Others have developed prototype solar sail hardware systems including the sail membranes, structural supports, deployment mechanisms, and control actuation systems. This work has been converging toward a ground test of the prototype 20 meter square solar sail systems and the correlation of test data with analytical tools. Verifying the design processes and analytical tools on a scale system is a step in the process of validating the technology in a larger scale flight experiment. The first generation of science missions call for 80 meter square sails, so the intermediate goad for a flight validation mission in earth orbit is likely to be a 40 meter square sail.

A fundamental question is how one would go about verifying the performance of a solar sail as a propulsion system. The resultant thrust produced by a solar sail is a function of many variables that are difficult to measure on the ground or predict from analysis. The parameters can be loosely grouped into two categories: one associated with the thrust vector direction (i.e. pointing orientation of the sail) and the other associated with the thrust vector magnitude (i.e. reflectivity of the sail). Factors such as sail shape, both global and local, support structure deformations, disturbance torques such as atmospheric drag and gravity gradient, and the spacecraft attitude control system all influence the direction of the thrust vector. Likewise many factors such as membrane topology (wrinkles, billow, etc), specular and diffuse reflectivity, absorptivity, emissivity, and sail temperature affect the magnitude of the resultant thrust.

Two approaches can be used to estimate thrust performance – indirect methods and direct methods. Indirect methods utilize ground tracking station data and Global Positioning System (GPS) measurements for orbit determination from which the thrust profile that results in the measured trajectory is estimated. Orbit determination is the process whereby the spacecraft position and velocity is obtained, and in some cases also estimates errors in the analytical model of the spacecraft and measurement systems.

Another approach would be to utilize acceleration measurements to directly measure the thrust performance. Enabling both approaches requires a navigation system architecture comprised of direct inertial measurements aided by GPS and ground station tracking data.

Several issues complicate the orbit determination and thrust estimation problem. Environmental forces, torques, and instrument biases all contribute to errors in direct thrust measurement. GPS measurement accuracy is a function of the orbit (altitude primarily) and hence may be useful for only certain times. Ground tracking data is a function of the availability, cost, and location of the tracking station. Hence a range of measurement data types combined with a judicious choice of orbit and attitude profiles is necessary to potentially isolate and eliminate error sources, model the sailcraft properties that affect the thrust vector, and accurately estimate the thrust performance.

4. Pro-Am Collaboration

One additional data source that can potentially be of significant utility for thrust estimation is ground astronomical observations. Two types of ground observations are particularly beneficial: astrometric data and visual magnitude data.

Astrometric data is typically used to estimate the six constant Keplerian elements of satellite, comet, and asteroid orbits. In the case of solar sails, the Keplerian elements are functions of time. Hence the aggregation of astrometric data will be beneficial to reconstruct the trajectory and estimate the thrust vector time history. Likewise visual magnitude data will be useful to correlate spacecraft optical properties as a function of vehicle attitude. It bears repeating that these properties directly affect the sail's performance as a propulsion system and are quite difficult to accurately predict or test on the ground. This astronomical data has the potential to directly impact the quality of the thrust estimation and model validation and hence may significantly contribute to the success of a solar sail flight validation mission.

The orbit chosen for flight validation is a compromise between affordable launch access and acceptable environmental constraints. One orbit under consideration is a 1500km circular near-polar orbit. This orbit is high enough to effectively eliminate atmospheric drag, minimize gravity gradient disturbance torques, and guarantee no eclipses. Another alternative is a highly elliptical orbit with longer dwell times at apogee during which the effect of solar thrust can be maximized.

Astronomical imaging for mission analysis in either the circular or elliptical orbits will be a challenging endeavor. For the circular orbit, the angular velocity in the orbit plane is 2.98 degrees/sec and the angular size of the sail is 55 arcseconds. Figures 3 and 4 show the angular rate and size of the sail, respectively, as a function of apogee height in representative elliptical orbits. This is a much smaller angular rate than the circular orbit, but nonetheless this rate may pose a challenge for accurate tracking.

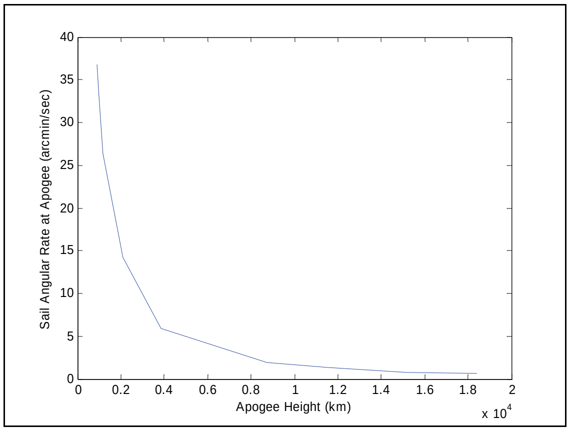


Figure 3. Sail Angular Velocity at Apogee Passage

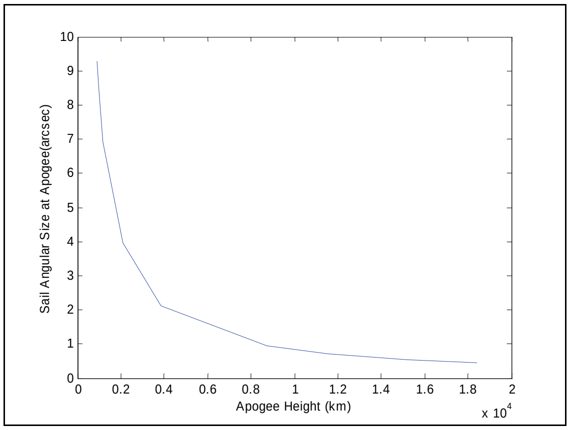


Figure 4. Angular Size of Sail at Apogee Passage

More than the tracking rate, the greater challenge will be contrast ratio between the bright solar sail and background stars. Several factors influence the visual magnitude: the angle of the sail with respect to the sun ("cone angle"), the angle of the sail with respect to the observer's line of sight ("look angle"), the altitude of the sail, atmospheric seeing, and the sail's optical properties, among others. For a 1500km circular orbit, Figure 5 shows the visual magnitude of a sail with 60% reflectivity for various look angles and cone angles. Figure 6 shows the visual magnitude as a function of altitude for the elliptic orbits with the sail oriented perpendicular to the incident sunlight. Obviously this corresponds to the sail at opposition and all look angles are not feasible, but this represents a limiting case.

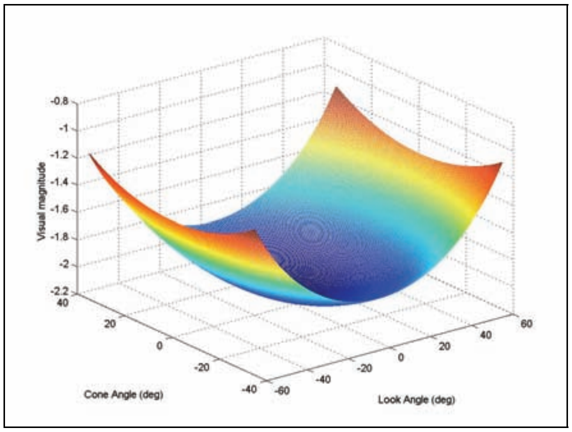


Figure 5. Visual Magnitude at 1500 km

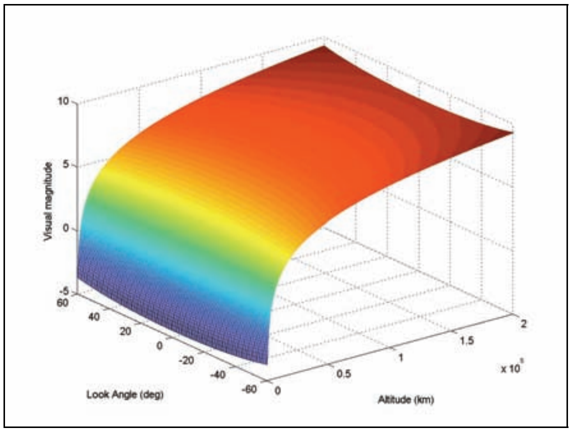


Figure 6. Visual Magnitude as a function of altitude and clock angle

5. Solar Sail Orbit Determination Methods

Several methods offer promise for the determination of the orbital elements for a spacecraft powered by solar sails. Each method is summarized in terms of the equipment and level of participation that might be required, organizational structures necessary and methods for mobilizing the required cadre of observers. We propose that these methods can be used to demonstrate the concept using various candidate objects such as the International Space Station.

5. 1. Method 1: Still Photography, Multi-Observer

This method employs multiple geographically separated observers with still cameras capable of 5 second to 60 second exposures.

5. 1. 1 Requirements

1. Precise knowledge of observer latitude and longitude. This can easily determined with a GPS receiver or from many web sites where the street address is provided.
2. Precise knowledge of the time of the satellite passage at their location. This information is easily obtained from web sites such as www.heavens-above.com, or can be calculated with several freeware orbital calculators such as STS-Orbit available through NASA.
3. A tripod mounted still camera with a cable release.
4. A method for accurately determining time to ±0.5 seconds. The accurate determination of time can be achieved in several ways:
    1. The participant can use a cell phone or cordless phone, if at home, and call the local time service or the NIST Boulder time service number and listen to the time signals.
    2. Tune a shortwave radio to WWV or WWVH.
    3. Synchronize a portable PC with the NBST atomic clock via a network connection using NISTTIME software supplied free by NIST and subsequently run the PC Clock or utilize readily-available software to generate a audio time code using the computer's sound card.
    4. Synchronize a portable PC with a GPS/NEMA signal via free geodesy software available from the web site www.ssccorp.com (follow the Observatory link to Geodesy).

5. 1. 2 Observational Procedure

Each observer is instructed to take one daylight exposure to mark the start of roll and framing interval, and a second of a cue card containing the observer's name and the roll index number. The observers then take 15 second exposures of the satellite on the start of each minute and half minute during their passes.

The film is subsequently processed to negatives. The negative and the observing journal page for that roll are submitted to the data reduction team. Users of digital still cameras can simply save their images in any uncompressed format, TIFF being the recommended standard, and can be transmitted on digital archival media to the data reduction team.

5. 1. 3 Data Reduction and Analysis

These images, taken with a normal 50mm lens will cover a field of view of approximately 45 degrees. The satellite should have transited about 10 degrees of the field. The exact start and end points of the arc can be determined from the image. Typical 35mm film, scanned at 2400dpi will resolve positions to about 1-2 arcminute accuracy. The background star field and local sidereal time and geodesy together will allow the satellite's azimuth and altitude to be solved. For more precise calculations atmospheric refraction can be used in the solutions. Off the shelf astrometric software such as "ASTROMET" can perform these reduction or IRAF scripts can be generated relatively easily. With this technique a moderate elevation pass (say 30 degrees for both observers) should allow observers on a 50km baseline to locate the satellite to within a 15km radius circle of error. The time standard is the critical value. If timing can be held to within ±100msec, the error circles diameter drops to 3km.

5. 2. Method 2: Still Photography, Multi-Exposure

This method requires only a single observer, but more sophisticated math. The idea is that the observer makes photos as in the multi-observer method. The data reduction team computes the precise Az, El and Time of the start and end point of each track on several images from the same pass. To the first order, these passes are Keplarian orbits precessed by the Earth's gravitation field. Using an iterative method one can compute a least squares fit of the [Az, El, Time] observations to adjust to the initial NASA two-line elements to best match the observed pass. The most interesting method for adjusting the two-line elements is to treat the drag term as a vector rather than a scalar. By allowing it to have a direction relative to the direction of motion, rather than treating it as a scalar against the direction of the motion, one effectively models the sum of drag and acceleration resulting from the sail. By adjusting only this quantity and fitting the observations, one directly solves for the acceleration of the sail.

It is a simple process to use the elapsed time since the ephemeris time, and with knowledge of the spacecraft mass, determine the mean force vector generated by the sail. Any earth orbit prediction program can be modified to make this calculation.

Distribution of this program to participants allows observers to perform their own analysis, provided they have the means to:

1. Get their images in digital format.
2. Perform the astrometric reductions on their image.
3. Convert [RA,DEC,Time] from their images to [AZ,EL,Time]
4. Obtain an initial orbital element set.

5. 3. Method 3: CCD Multi-Observer

This method is similar in philosophy to the Photographic Multi-Observer Method, but instead of film this method utilizes an integrating CCD imager with short focal length lenses mounted upon tracking telescopes.

5. 3. 1 Requirements

1. Precise knowledge of the observer's latitude and longitude.
2. Precise knowledge of the time of the satellite passage at their location.
3. A CCD Camera with imaging software equipped to image a FOV from 4 to 20 degrees mounted piggyback on a tracking telescope.
4. 4) A method for accurately determining the exposure time to ±0.1 seconds.

5. 3. 2 Observational Procedure

Each observer slews his telescope to the center of the predicted satellite pass. Prior to the pass, the observer will make a long duration exposure of the field of view, assuring that at least 10 stars of sufficient S/N ratio are imaged to ensure good astrometry of the images. During the pass, the observer will take a series of images of approximately 1-second duration during the pass until the satellite has transited the field.

Observers should submit these images in FITS format with their observing journals on archival media to the data reduction team. Among the challenges of this method is the recording of the image time with very high accuracy. Provided that the PC clock is synchronized with the NIST timeserver, it should be possible to get ±0.1 second accuracy for exposure times.

5. 3. 3 Data Reduction

As with the Photo-Multi-Observer method, astrometry is performed on images and the potential accuracy of these measurements is again time limited, but can be within ±3km.

5. 4. Method 4: CCD Multi-Pass

This method uses the same procedures as the CCD Mulit-Observer method but measures the satellite position on successive passes. The same software and methodology as described for the Photo Multi-Exposure method can be used to solve for orbital acceleration.

6. Experimental Procedure Validation

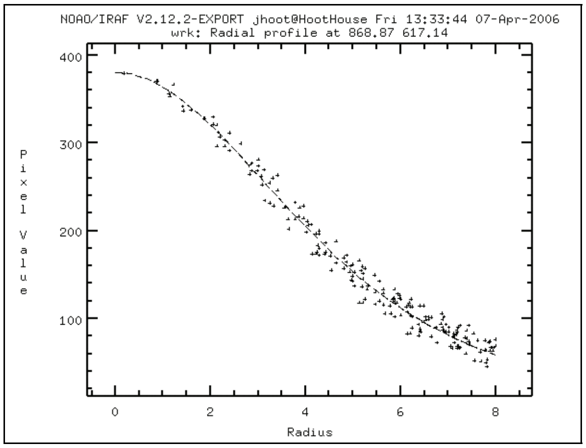
We have begun tests to validate the experimental methods proposed above. To validate our method, we have been applying the proposed photographic and CCD imaging methods to bright satellites. Our imaging targets have been satellites making passes with apparent magnitudes of 2.5 brighter. Targets have included ISS, HST, TRMM and serendipitous targets occurring during other CCD imaging projects.

Figure 7: 15-second ISS Exposure at high air mass.

We have verified that satellites are easily photographed from suburban environments with the proposed setup. Even in the presence of significant light pollution, both the track and enough background stars are detectable to assure accurate astrometry.

Analysis of the image in Figure 7, scanned at 2400 dpi, yield a plate scale of 44.2”/pixel. FWHM of stars in the image averaged 7.8 pixels. This indicates a psf of 5.75’.

Performing precise astrometry on wide field images proved a challenge. It could not be peformed with Astrometrica. The latest generation of the program is optimized for deep field minor planet work. As such, it uses USNO A.1, USNO A.2 and USNO B catalogs that do not include bright stars. Reversion to the older DOS based program succeeded in working with GSC 1.1 and ACT-GSC catalogs, but did not provide reasonable fits.



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NOAO/IRAF V2.12.2-EXPORT jhoot@HootHouse Fri 13:33:44 07-Apr-2006
wrk: Radial profile at 868.87 617.14
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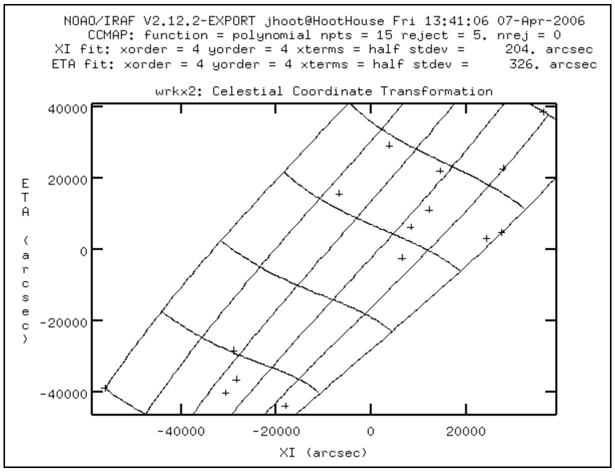
Figure 8: PSF Radial Profile

There are several factors that make photographic plate solutions challenging. First, the fields themselves are very large and the pixel scale, at 44”, is atypical for most astronomy. The second challenge is that wide field photographic lenses suffer from not only field curvature, but also from barrel distortions and astigmatisms as a result of their design for wide fields of view. Additionally, the film scanning process can introduce additional distortions, notably skew. Finally, images taken in ALT-AZ with tripods always contain significant field rotations. These higher order corrections require more complex fitting than typical second-order plate scale solutions.



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CCMAP: function = polynomial npts = 15 reject = 5. nrej = 0
XI fit: xorder = 4 yorder = 4 xterms = half stdev =     204. arcsec
ETA fit: xorder = 4 yorder = 4 xterms = half stdev =     326. arcsec
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Figure 9: IRAF Plate Scale Solutions

After looking into several alternatives, acceptable results were obtained using IRAF, now available running in native mode under Windows using the Cygwin library. Using 4th order plate solution polynomials, fits were obtained with residuals compatible with PSF of the plates. The 1-sigma RA error was 3.4’ and the Declination 1-sigma error was 5.4’. Both are smaller than the PSF of the image. A script to automate the IRAF fitting routine is under development.

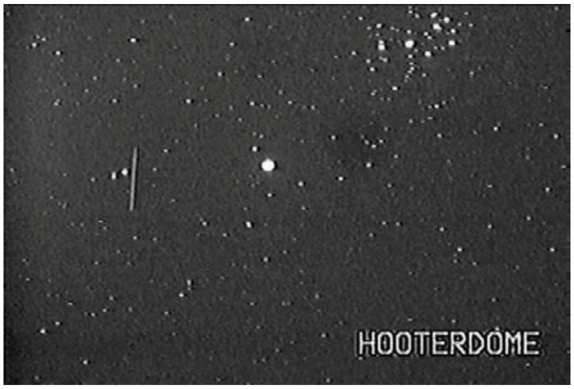

Figure 10: Wide Field 2 Second CCD Exposure

Similarly, wide field CCD images have proved the feasibility of their use. The image in Figure 10 was a 2-second exposure from a time lapse series that was produced during Mar's recent occultation of SAO76327. This 2-second exposure, and those bounding it, shows the passage of a high inclination angle satellite through the frame. Analysis of the image shows a plate scale of 42.414"/pixel and a FWHM of 3.6, yielding a PSF of 2.55'. This would indicate that short exposure, wide field CCD images should be able to provide about twice the positional accuracy of photography with comparable time resolution. With computer triggering of exposures and precision timing, even better results should be obtainable. Furthermore, flatter fields should also lead to better astrometry from all digital images.

These results have convinced us that the photographic methods are viable within the error ranges projected. These methods will reach the broadest audience of potential participants.

We are now in the process of taking further imagery and modifying SSC orbital prediction software to solve for satellite acceleration and orbits

7. Where We Go From Here

NASA, academia, and industry are working together to advance the technology of solar sail propulsion systems with the goal of validating the technology in flight. An important part of that flight validation will be the gathering of data to support the analysis for thrust estimation and model validation. A collaboration between the astronomical imaging community and the mission analysis team will be a synergistic effort that may advance the state of the art for both communities.

This proof of concept demonstration will add significant merit to the flight validation mission concept proposal. If selected, this concept will be implemented as part of a solar sail flight validation mission. In either event, the astronomical imaging community will have contributed substantially to the technology by demonstrating the feasibility of ground observations for solar sail low-earth orbit determination

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