Orbit Determination Performance Evaluation of the Deep Space 1 Autonomous Navigation System

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NASA's New Millennium Program is a series of missions designed specifically to demonstrate new technologies for space exploration which can then be baselined for use by subsequent scientific missions. Deep Space 1 is the first of the interpl anetary mission set and will validate about a dozen new technologies, including the first use of a solar electric ion propulsion system (SEP) as its main thrusting element, and a fully autonomous onboard navigation system to guide the spacecraft to its targets. Some of the additional new technologies include an advanced solar array used for onboard power, a miniature imaging camera and spectrometer (MICAS), and a small deep-space transponder. The mission plans call oral launch in July of 1998, a flyby of the asteroid Mcaulliffe in January 1999, a gravity assist flyby of Mars in April 2000, and finally, a flyby of the comet West-Kohoutek-Ikemura in June 2000. Although not a primary goal, science data will be collected using the MICAS instrument during the asteroid and comet flybys.

The DS-1 navigation system is quite unique in that it is designed to be almost completely self-contained onboard the spacecraft in its nominal configuration. Unlike all deep-space missions of the past which used radio (Doppler and range) signals as its primary navigation data type, the 11 S-1 system uses optical images of asteroids as its sole data type. The basic principle behind this technique is relatively straightforward. An image of an asteroid is taken against a star background; determining the center location of the asteroid in the image fixes the line-of-sight direction to that asteroid. Two such line-of-sight measurements effectively pinpoints the three-dimensional cartesian position of the spacecraft. By stringing together a series of such line-of-sight measurements and processing them in a filter, the full state of the spacecraft (position and velocity) as well as other parameters can be estimated. The accuracy of this procedure depends on several factors, including the accuracy of the centerfinding, the accuracy of the asteroid ephemerides, and the amount of noise which corrupts the dynamics of the system. The latter is an especially important factor for the IJS-1 system because the SEP engine imparts a fair amount of unmodelled noise in the form of thrust variations which must be accounted for in the filter. The evaluation of the performance available from the orbit determination (OD) is critical because it impacts the planning and execution of the maneuvers needed to achieve the flyby targets. In particular, if the accuracy obtainable by the OD is poor, an inordinate amount of fuel may be needed to correct these errors, or worse still, there may not be enough delta-v available from the thrusters to achieve the desired flyby. This paper describes the OD algorithm and then assesses its performance through the usc of covariance analyses and Monte Carlo simulations for all phases of the mission up to Mcaulliffe encounter, including post-launch injection error corrections, interplanetary cruise, and the approach and flyby of the asteroid.

The OD system is comprised of several main elements: trajectory and variational equation propagation, computed observable and partials generation, and filtering. Trajectory and variational equation propagation is accomplished via a Runge-Kutta 7-8th order integrator with variable stepsize and error control. The dynamical equations of motion to be integrated include the central body force from the sun, third body perturbations from all nine planets and the Moon, solar radiation pressure model ling the spacecraft as a sphere, acceleration due to thrusting from the SEP engine, and impulsive delta-vs arising from thruster firings to maintain attitude. The computed observables are needed to form residuals with the observable obtained from the image. The observable is computed by first determining the inertial relative line-of-sight vector from the spacecraft to the asteroid in question, rotatating the vector into the camera frame coordinates, and then projecting and scaling the vector into the camera focal plane. Thus, the 3-D line-of-sight vector is converted into 2-D pixel and line camera coordinates. Residuals are formed by differencing the predicted location of the asteroid with the actual location as determined by processing the image. Partial derivatives can be computed of the pixel and line center location values with respect to the state parameters by first computing the geometric partials with respect to the instantaneous position and then mapping these back to the epoch via the state transition matrix. Finally, the filtering is performed in batch mode using the U-D decomposed form of the covariance matrix.

The estimated parameters in the filter include the spacecraft state (position and velocity), three acceleration parameters for each batch, and a variable number of thrust scale factors in each batch. The batch in this case is a data arc of about 28 days in length. It was found during tbc analysis that this is an optimal length because shorter batches do not provide enough information, and in longer batches, the system noise tends to cancel out the improvement caused by additional data. Within each batch are subsegments which are nominally seven days in length during most of cruise, but will shorten down during encounter. These subsegments correspond to SEP engine on/off cycles. in a given cycle during cruise for example, the SEP engine is turned on for about 6.5 days and the turned off for half a day to allow for observations and telecommunication activities. Thus, thrust scale factors are estimated for each SEP on/off cycle with a maximum of four over the data batch. The accelerat ion parameters estimated arc used to account for any residual errors in either the thrust, delta-vs, or the solar radiation pressure model.

Because the filter parameters were deliberately chosen to be a subset of tbc the full dynamics which affect spacecraft motion in order to keep the algorithm as simple as possible, using covariance analysis alone is not sufficient to fully assess OD performance. Thus, Monte Carlo simulations were also performed, incorporating as many error sources as possible into the "truth" model, and compared with the covariance results. From simulations, the final delivery at asteroid encounter is predicted to be around 1 km, which is sufficient to meet the mission requirements.