Navigation Strategies for Primitive Solar System Body Rendezvous and Proximity Operations

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Abstract: *A wealth of scientific knowledge regarding the composition and evolution of the solar system can be gained through reconnaissance missions to primitive solar system bodies. This paper presents analysis of a baseline navigation strategy designed to address the unique challenges of primitive body navigation. Linear covariance and Monte Carlo error analysis was performed on a baseline navigation strategy using simulated data from a design reference mission (DRM). The objective of the DRM is to approach, rendezvous, and maintain a stable orbit about the near-Earth asteroid 4660 Nereus. The outlined navigation strategy and resulting analyses, however, are not necessarily limited to this specific target asteroid as they may be applicable to a diverse range of mission scenarios. The baseline navigation strategy included simulated data from Deep Space Network (DSN) radiometric tracking and optical image processing (OpNav). Results from the linear covariance and Monte Carlo analyses suggest the DRM navigation strategy is sufficient to approach and perform proximity operations in the vicinity of the target asteroid with meter-level accuracy.*

Keywords: *Navigation, Asteroids, Rendezvous, Proximity Operations*

1. Introduction

Rendezvous missions to primitive solar system bodies (asteroids and comets) can provide a wealth of scientific information and insight into the composition and origins of the solar system because they remain largely unchanged. Precision navigation to approach, rendezvous, and perform proximity operations near a primitive solar system body presents unique challenges beyond traditional Earth-based and interplanetary missions. Obtaining knowledge of the mass, gravitational field, spin state, and precise ephemeris of a primitive body requires extensive proximity operations, in situ observations, and ground-based tracking [4]. Recent interest in primitive body rendezvous and sample return missions has generated a need for advanced navigation strategies designed to address such challenges.

This paper presents an analysis of a baseline navigation strategy for asteroid or comet rendezvous and proximity operations that can be applied to a diverse range of missions and targets. Elements of the baseline navigation strategy include traditional Earth-based Deep Space Network (DSN) radiometric tracking schedules and the utility and frequent utilization of spacecraft-based optical landmark tracking. Additionally, the baseline strategy defines the location and frequency of rendezvous maneuvers, as well as the trajectory design for the approach, survey, and orbit insertion. Linear covariance and Monte Carlo error analyses are performed on the baseline strategy using simulated data from a design reference mission (DRM).

2. Problem Definitions

Mission requirements, target asteroid parameters, spacecraft specifications and mission timeline are defined by the DRM. The objective of the DRM is to approach, rendezvous, and maintain a stable orbit about the near-Earth asteroid 4660 Nereus. For this analysis, the physical properties of the asteroid were estimated using available data on Nereus and similar asteroids (Tab. 1). The target body ephemeris was obtained via the Horizons system courtesy of the Jet Propulsion Laboratory's Solar System Dynamics Group*. Selection of an actual asteroid as the basis of the reference target is done primarily for clarity. The navigation strategy outlined in this paper and the resulting analyses are not fundamentally limited to this specific target asteroid and may be applicable to a diverse range of mission scenarios.

Table 1. Orbit and physical properties of the DRM target asteroid

Orbit Properties	
Semi-Major Axis [a]	1.489 AU
Eccentricity [e]	0.360
Inclination [i]	1.432 deg
Physical Properties	
Mean Radius	165 m
Density	1400 kg/m^3
Mass	2.66×10^{10} kg
Gravitational Parameter	1.78×10^{-9} km^3/s^2
Absolute Magnitude [H]	18.2
Geometric Albedo	0.55

Properties of the DRM spacecraft are given in Tab. 2. The spacecraft is modeled as a spherical bus with sun-fixed solar arrays.

Table 2. Properties of the DRM spacecraft.

Mass	1005 kg
SRP Area	13 m^2
Cr (nominal)	1.5

The DRM is separated into three mission segments: the approach phase, survey phase, and stable orbit phase. The outbound and Earth return cruise phases are assumed to be typical of any Deep Space mission, and hence are not analyzed this study.

Approach Phase

The approach phase begins after optical acquisition of the target asteroid at a distance of approximately two million kilometers in a heliocentric orbit. The spacecraft approaches the target asteroid on a hyperbolic trajectory with a relative velocity of 560 meters per second. Two Trajectory Correction Maneuvers (TCMs) target a close approach distance of ten kilometers on the sunward side of the target asteroid in the ecliptic plane.

Survey Phase

The objective of the survey phase is to estimate dynamic properties of the target asteroid for use in trajectory design and maneuver planning. The survey phase begins with a braking maneuver (FBM1) to reduce the spacecraft-asteroid relative velocity to one meter per second. Initial

* Available at: http://ssd.jpl.nasa.gov/?horizons. Accessed on March 2nd, 2010.

simulation and analysis results determined that a ten-kilometer flyby at a relative velocity of one meter per second was sufficient to estimate the gravitational parameter of the target asteroid for the stable orbit design. Immediately following the target asteroid flyby, a second survey phase maneuver (FBM2) initiates a return trajectory targeting the location of orbit insertion. Orbit insertion occurs five hundred meters south of the ecliptic in the terminator plane. Duration of the entire survey phase is approximately one day. The nominal stable orbit phase is plotted in Fig. 1.

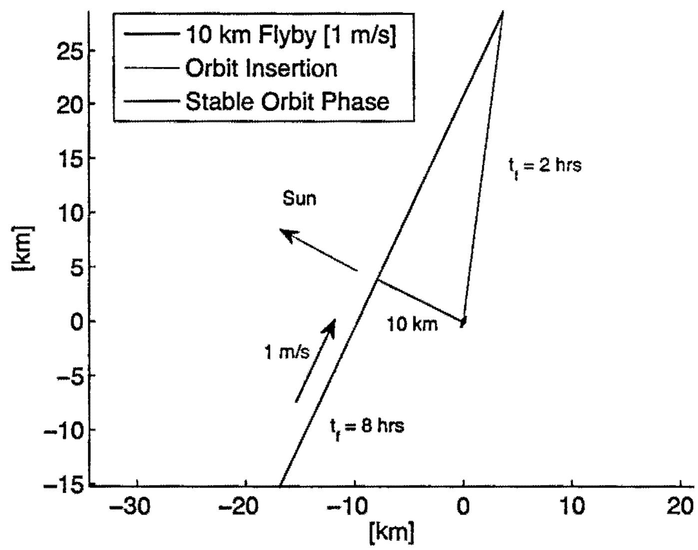

Figure 1. Plot of the nominal survey phase trajectory with flight times (t_f).

Stable Orbit Phase

Once the spacecraft has reached the targeted orbit insertion point, an Orbit Insertion Maneuver (OIM) initiates a five hundred meter circular orbit about the target asteroid in the terminator plane. A terminator plane orbit was chosen for long-term stability with respect to solar radiation pressure (SRP). The spacecraft remains in a stable orbit for one week without orbit correction maneuvers to refine estimates of target asteroid dynamic parameters. The nominal stable orbit trajectory including perturbations is plotted in Fig. 2.

Stable Orbit Phase (Nominal)

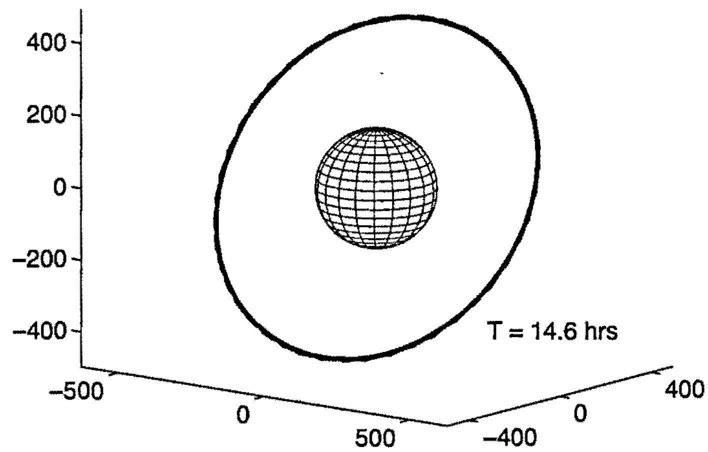

Figure 2. Plot of the nominal stable orbit phase trajectory [m].

7. Maneuvers

The spacecraft performs a total of five maneuvers during the DRM. Maneuver execution errors of 1 mm/s (1σ) in each axis were simulated for the Monte Carlo error analysis. Descriptions of each maneuver for the nominal trajectory are presented in Tab. 3.

Table 3. Summary of DRM maneuvers including magnitude and time of execution.

Maneuver	**ΔV (m/s)**	**Date**
Approach		
TCM 1	(Statistical)	06 APR 2023 20:00:00
TCM 2	(Statistical)	17 APR 2023 10:00:00
Survey		
FBM 1	517	22 APR 2023 14:00:00
FBM 2	6.0	22 APR 2023 22:00:00
Orbit		
OIM	4.3	23 APR 2023 00:00:00
Total	527.3	

3. Methodology

The Orbit Determination Toolbox (ODTBX)+ was used to perform linear covariance and Monte Carlo error analyses on simulated data from the DRM. The Navigation & Mission Design branch at NASA Goddard Space Flight Center developed ODTBX for use in early mission design and analysis. Data simulation and analysis utilized the sequential estimator function provided in

+ Available at: http://opensource.gsfc.nasa.gov/projects/ODTBX/.

ODTBX. The ODTBX sequential estimator is based on the Extended Kalman Filter (EKF) presented by Markley [2][3] and Carpenter [1]. Linear covariance analysis was performed using the nominal reference trajectory and simulated measurement data. Separate covariance partitions were utilized to analyze the contributions of a-priori, measurement, and process noise to the total covariance. For Monte Carlo simulations, perturbations were introduced to the true trajectory by random sampling from the a-priori covariance and the addition of process noise. The formal state estimate was updated using simulated measurement data from the perturbed true trajectory.

The filter states were selected to analyze the relative covariance and estimation error associated with the relative position and velocity of the spacecraft with respect to the target asteroid. Descriptions of the filter states are given in Tab. 4 and are based on previous mission experiences provided by Williams [5]. Simulation and analysis was performed in a Nereus-Centered, J2000 Cartesian reference frame.

Table 4. Description of filter states and associated a-priori uncertainties.

Estimated State	A-priori Uncertainty (1σ)
Spacecraft Position	50 km
Spacecraft Velocity	30 m/s
Asteroid GM Correction	200%
SRP Correction	10%

Measurement Schedule

The DRM measurement schedule consists of a combination of DSN radiometric tracking and spacecraft-to-asteroid optical image navigation (OpNav). Ground based measurements include DSN range and Doppler supplemented by Delta-Differenced One Way Range (DDOR) baselines. OpNav measurements are simulated as spacecraft to asteroid line-of-sight angles. A description of each measurement type and the corresponding measurement weight is given in Tab. 5.

Table 5. Description of each measurement type and corresponding measurement weight.

Measurement Type	Weight (1σ)
DSN Range	50 m
DSN Doppler	0.1 mm/s
DSN DDOR	20 cm
OpNav	25 μrad

At optical acquisition of the target asteroid, the DSN tracking schedule consists of three eight-hour passes per week and one DDOR baseline per week. DSN radiometric tracking increases to one eight-hour pass per day beginning one month from target asteroid close approach. Continuous DSN tracking occurs from two days before until one day after TCM 1, as well as from two days before TCM 2 until three days after OIM. OpNav image processing occurs once every seven hours throughout the entire simulation. Figure 3 is a graphical representation of the measurement schedule, where time is represented as days since optical acquisition.

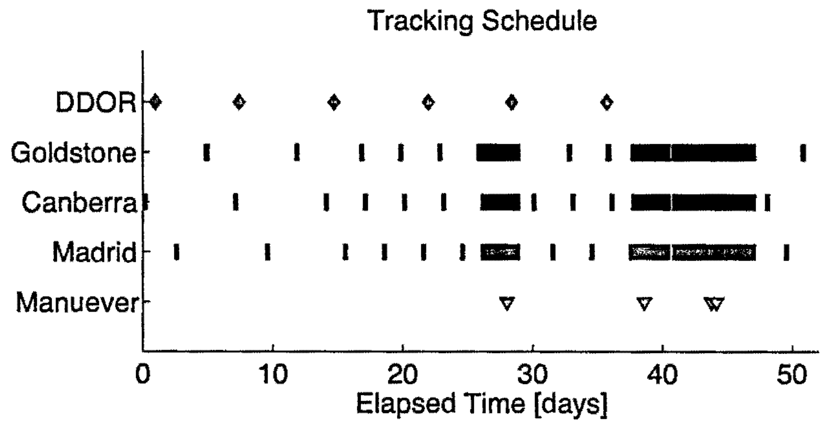

Figure 3. The baseline navigation strategy measurement schedule. OpNav image processing occurs once every seven hours.

4. Results

Approach Phase

Spacecraft position errors for the approach phase during a ten-case Monte Carlo simulation are plotted in Fig. 4. As expected, the ensemble mean of the spacecraft position errors and covariance decrease steadily during the approach phase. At the end of the approach phase, the ensemble mean of spacecraft position uncertainty is approximately five meters (RSS, 1σ).

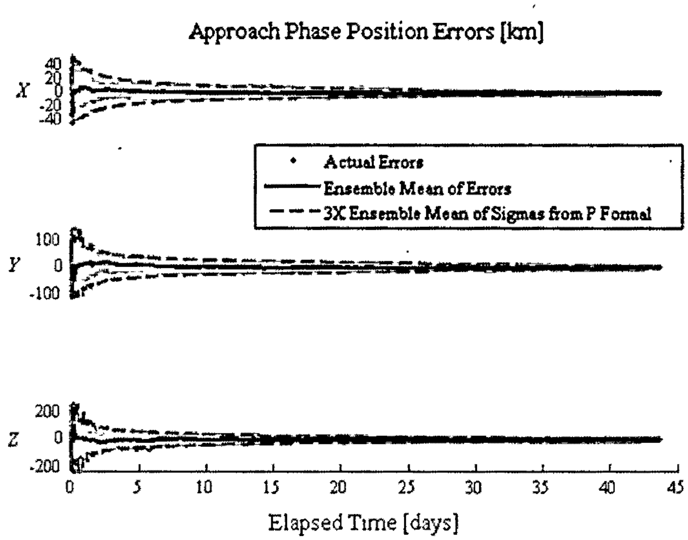

Figure 4. Approach Phase 10-case Monte Carlo error analysis results for spacecraft position [km].

Contributions of the a-priori, measurement, process, and maneuver execution noise to the spacecraft total position covariance are shown in Fig. 5. During the approach phase, contributions from a-priori uncertainty dissipate and measurement error becomes the dominant contributor to the total uncertainty.

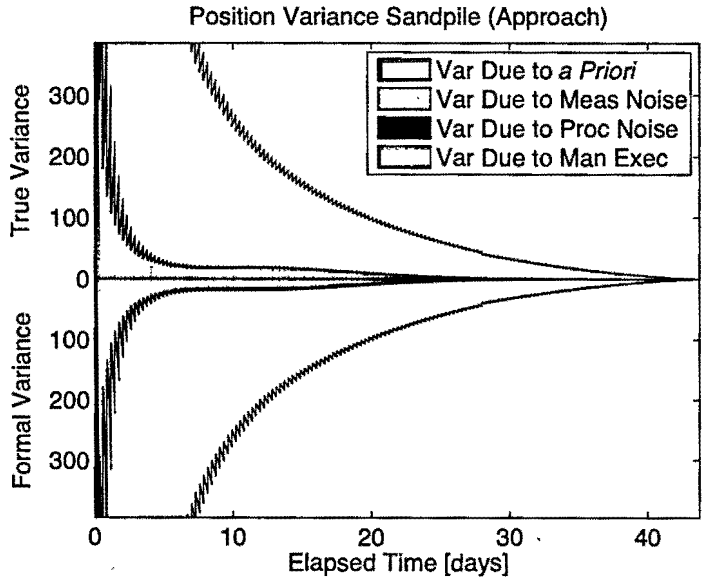

Figure 5. Approach Phase linear covariance analysis results for spacecraft position [km^2].

Survey Phase

Monte Carlo error analysis results for the survey phase are presented in Fig. 6. Spacecraft position errors and covariance remain at the meter level throughout the Survey Phase. An OpNav measurement on the 44th day decreased the ensemble mean errors and covariance.

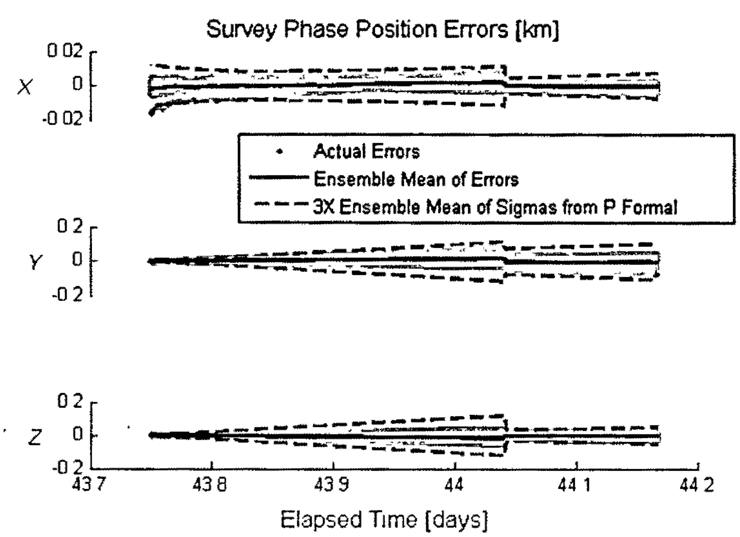

Figure 6. Survey Phase 10-case Monte Carlo error analysis results

for spacecraft position [km].

Contributions of the survey phase maneuver execution error were observed in the covariance analysis for spacecraft position (Fig. 7). As with the approach phase, the dominant contributor to the total uncertainty for the Survey Phase was measurement error.

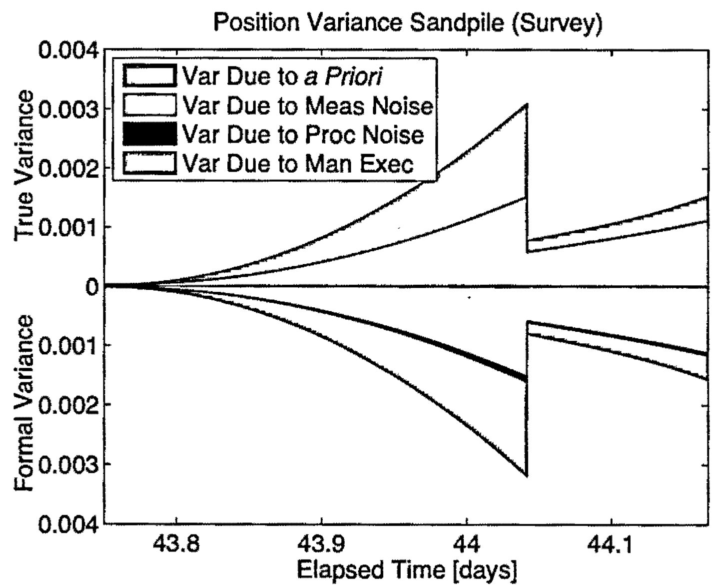

Figure 7. Survey Phase linear covariance analysis results for spacecraft position [km^2].

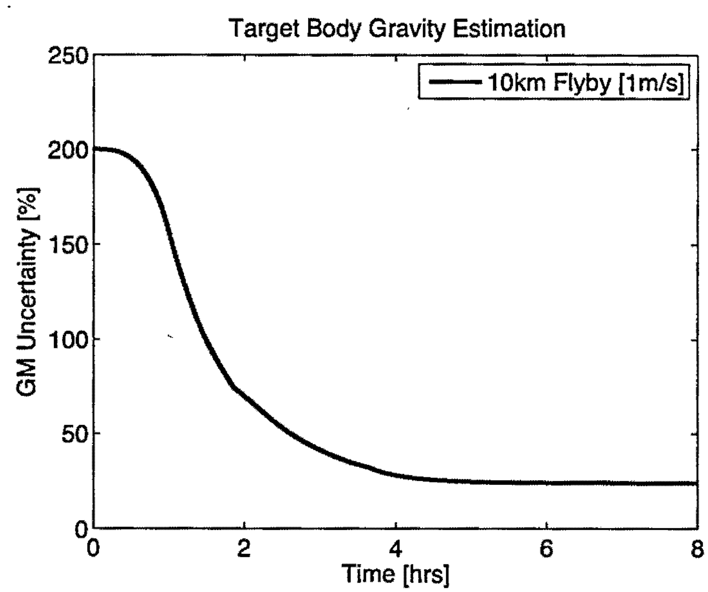

Figure 8. Uncertainty of the target asteroid gravitational parameter from the beginning of the survey phase.

The ensemble mean of the uncertainty in the target asteroid gravitational parameter is plotted in Fig. 8. The ten-kilometer flyby at a relative velocity of one meter per second was sufficient to estimate the target asteroid gravitational parameter to within 25% of the true value (1σ).

Stable Orbit Phase

Spacecraft position errors from the stable orbit phase are plotted in Fig. 9 in the Velocity-Normal-Bi-Normal (VNB) reference frame. The spacecraft position estimates remain at meter-level accuracy throughout the stable orbit phase. Position errors in the velocity direction were larger than the normal and bi-normal components, a result of the relative geometry of the terminator plane orbit with respect to the Earth line-of-sight. The cyclical variation in the spacecraft position uncertainty was caused by the frequency of OpNav image processing. The reduced DSN tracking schedule caused an increase in spacecraft position error and covariance after the third day in the stable orbit.

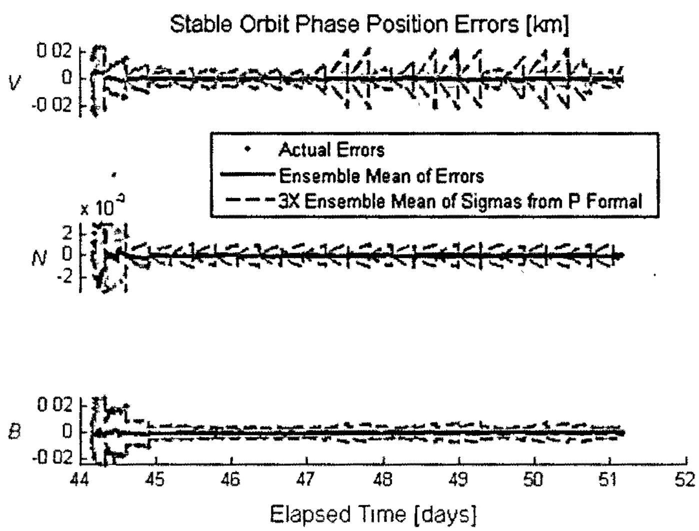

Figure 9. Stable Orbit Phase 10-case Monte Carlo error analysis results for spacecraft position [km].

Results from the stable orbit phase linear covariance analysis are presented in Fig. 10. Setting a larger process noise spectral density in the formal filter parameters during tuning caused a larger contribution of process noise in the formal variance compared to the true variance. Slight contributions from the OIM execution error are observed at the beginning of the Stable Orbit phase and quickly dissipate within the first few hours.

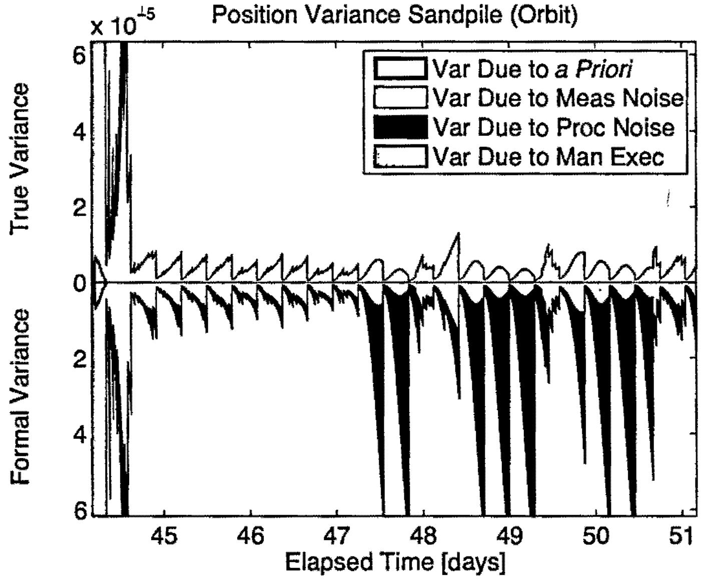

Figure 10. Stable Orbit Phase linear covariance analysis results for spacecraft position in the direction of the velocity vector [km^2].

5. Conclusion

Linear covariance and Monte Carlo analyses suggest the DRM navigation strategy is sufficient to approach and perform proximity operations in the vicinity of the target asteroid. The DSN radiometric tracking schedule and OpNav image processing were capable of reducing spacecraft-asteroid relative position errors to meter-level accuracy. After the seven-day stable orbit phase, the target asteroid gravitational parameter was estimated with an uncertainty of less than 0.2 percent. This analysis has shown that the navigation strategy is adequate with respect to spacecraft-asteroid relative errors for a rendezvous mission to 4660 Nereus and similar near-Earth asteroids.

6. Future Work

Future efforts will focus primarily on optimization of the baseline navigation strategy to reduce spacecraft-asteroid relative errors and tracking schedule resource requirements. The addition of a surface contact phase to the DRM will facilitate analysis of the surface contact error ellipse for controlled descent or sample collection. Trade studies will be performed through variations in the baseline navigation strategy, including the optimal navigation strategy in between proximity operations phases, an orbit approach to surface contact compared to a powered approach, and the utility of a spacecraft-based laser ranging instrument. Additional filter states and consider parameters will be added to investigate the linear sensitivity of various dynamic and local parameters, such as the target asteroid spin state, planetary ephemeris errors, and DSN media errors.

7. References

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