IMPROVING MARS APPROACH NAVIGATION USING OPTICAL DATA

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Overview

An important objective of future Mars missions is to land spacecraft to ever increasing accuracies on the surface of Mars. This requires precise entry and descent phases, which in turn depend on navigating the spacecraft during the approach phase as accurately as possible. The current navigation techniques used to accomplish this rely primarily upon Doppler and range measurements to determine the spacecraft's state. Deviations from the nominal trajectory are then computed and maneuvers are executed to get the spacecraft back on course. However, the time required to process these radio measurements can restrict the final targeting maneuver to be more than a week before the encounter, before the Mars-centered trajectory can be precisely determined by the Doppler signature.

Additional navigation methods and data types during the approach phase are thus required to obtain the goal of precision landing. One data type which can help to meet this requirement is optical navigation imaging. These data consist of images of Phobos and/or Deimos, taken against a star background, that are used to pinpoint the spacecraft's Mars-centered procedure can be automated, allowing for quick turn-around times to implement maneuvers very late in the approach phase. These data can further supplement the radio observations by significantly improving our knowledge of the spacecraft state in the direction out of the equatorial plane, which is poorly determined from Earth-based radio data.

This paper presents the results of two procedures showing the results obtainable by the optical navigation procedure: (1) a covariance analysis showing that these data, taken in tandem with Doppler and range data, are capable of producing positional accuracies of better than a km at entry; and (2) simulations of a series of Phobos images, made with a realistic model, that validate the covariance results. These simulations also incorporate error sources which corrupt the solution, such as spacecraft and Phobos ephemeris mismodelings, shape distortions of Phobos, and errors in the rotational dynamics of Phobos.

The approach trajectory and camera parameters used in this case are those for the 2005 Mars Reconnaissance Orbiter, but the analytical methods described herein are applicable to any Mars orbiter or lander mission.

Covariance Analysis

A covariance analysis was performed on the approach phase, spanning the last few days before the entry date of 01 March 2006 at 00:00 UTC. The trajectory was initialized 4 days before entry, constrained by knowledge obtained from Doppler and range data. If these initial uncertainties are assumed to be 10 km along each position axis and 1 cm/sec along each velocity direction, the projected uncertainty at entry, if no further corrections are made, is an error ellipse of 23x24 km perpendicular to the trajectory and 24 seconds in time-of-flight.

Parameters estimated in the fit were the spacecraft state and Phobos ephemeris. While the spacecraft state was constrained by the radio solution, the Phobos ephemeris was constrained by its formal covariance multiplied by a scale factor of 3. The center-finding biases in pixel and line for Phobos were considered but not adjusted in the fit, with a-priori uncertainties taken to be 0.5% of the diameter of Phobos. The difference that would occur in the actual mission between the true and nominal spacecraft states was simulated by altering the camera pointing parameters used to create the original image, by values corresponding to the spacecraft state being in error by a given amount. It is this state error that we look to recover in the solution.

Simulated Phobos images (see below) are then used to triangulate the spacecraft's position roughly every 40 minutes during the approach. These data are then filtered using a least-squares process to obtain the complete spacecraft state at each time step and to map the every-decreasing uncertainty in position and velocity forward to the time of entry. This procedure shows that optical navigation data can be used to get obtain an entry-point error ellipse perpendicular to the trajectory with major axes under a km and a time-of-flight uncertainty of about 1 second.

Image Simulations

Software was used to simulate the series of Phobos images that would be taken with the on-board optical-navigation camera. The pictures were created using a 25,000-point model of the surface of Phobos, based on the latest topology and albedo information, projected into a 2-D image as would be seen by the camera, assuming a pixel size of 24.4 μrad.

At each picture time a "nominal" image and a "true" image are created. The true image simulates the actual image that will be taken by the spacecraft during the mission. The nominal image represents information that will be assumed when attempting to correct the center-of-brightness of the true image to the actual 2-D center-of-figure of Phobos. This simulates a worst-case scenario for the actual mission, in which center-of-brightness corrections must be made to the true images based on imperfect knowledge of factors that will determine the appearance of Phobos.

The difference between the two images results from the fact that several such errors are incorporated into the true image, including errors in the modeled ephemeris of Phobos, distortions to the shape of Phobos, and errors in the assumed rotational dynamics of Phobos, such as the longitudinal position, polar-axis tilt, and precession. The nominal picture does not incorporate these errors, assuming that they are not known. This image is used to determine the center-of-brightness correction, which is then applied to the true image. The true image is then compared to background stars and used to triangulate the position of the spacecraft in the Mars-centered frame. The filtering process mentioned above is shown to be able to correct for these errors by modeling them as errors in the center-finding bias.