Abstract. To a significant degree, the success of spacecraft missions to comets and asteroids depends upon the accuracy of the target body ephemerides. In turn, accurate ephemerides depend upon the quality of the astrometric data set used in determining the object’s orbit and the accuracy with which the target body’s motion can be modelled. Using error analyses studies of the target bodies for the NEAR, Muses-C, Clementine 2, Stardust, and Rosetta missions, conclusions are drawn as to how to minimize target body position uncertainties at the times of encounter. In general, these uncertainties will be minimized when the object has a good number of optical observations spread over several orbital periods. If a target body lacks a lengthy data interval, its ephemeris uncertainties can be dramatically reduced with the use of radar Doppler and delay data taken when the body is relatively close to the Earth. The combination of radar and optical angle data taken at close Earth distances just before a spacecraft encounter can result in surprisingly small target body ephemeris uncertainties.

1. Introduction

Space missions to comets and asteroids began when the International Cometary Explorer (ICE) spacecraft flew approximately 7800 km tail-ward of comet Giacobini-Zinner on September 11, 1985. A few months later in March 1986, five separate spacecraft flew sunward of comet Halley and one of them (Giotto) flew as close as 600 km from the comet and was later re-targeted for a 200 km tail-side flyby of comet Grigg-Skjellerup on July 10, 1992. On its way to a late 1995 encounter with Jupiter, the Galileo spacecraft flew past two S-type, main-belt asteroids, 951 Gaspra and 243 Ida. The Gaspra encounter (1620 km at closest approach) took place on October 29, 1991 while the spacecraft passed within 2400 km of asteroid.
243 Ida on August 28, 1993. During the latter encounter, the Galileo images revealed the presence of Ida's 1.5 km satellite, Dactyl. To date, there have been three comets and two main-belt asteroids visited by spacecraft.

In general, the ephemeris uncertainty of a target body at the time of the spacecraft encounter will depend upon the quality of the available astrometric data set and how well the target body's motion can be modelled. The quality of a particular target body's data set depends upon the time interval over which astrometric data are available, the number of existing observations, the accuracy of these observations, and the proximity of the target body to the Earth when these observations were taken. Section 2 outlines the factors that must be considered in an effort to form a high quality data set for a target body. Because active comets are often affected by rocket-like outgassing thrusts (nongravitational accelerations), it is generally more difficult to accurately predict their long-term motions. Section 3 outlines the problems encountered when modelling the long term motions of active comets. Section 4 will emphasize the points made in sections 2 and 3 by presenting error analysis case studies for ongoing, and future, missions to comets and asteroids. These case studies include asteroid 433 Eros as the target body of NASA's Near-Earth Asteroid Rendezvous (NEAR) mission, 4660 Nereus as the target body of the Japanese Muses-C mission, and asteroid 1989 UR as one of three asteroid targets for the planned U.S. Clementine 2 mission. These case studies will also include periodic comets Wild 2 and Wirtanen as the target comets of NASA's Stardust and ESA's Rosetta missions. Section 5 will draw together some of the most important conclusions resulting from the efforts to improve the ephemeris accuracies of comets and asteroids prior to their intercept, or rendezvous, by spacecraft.

2. Building a High Quality Astrometric Data Set for a Mission

In terms of the necessary orbital refinement for accurate ephemeris predictions, the number of available observations is important as is the length of the interval over which these observations are available. In most cases, the largest ephemeris uncertainty component for a comet or asteroid is in the object's along-track direction; the object's mean motion, or semi-major axis, is often poorly determined. By basing an orbit on several observations over many oppositions, the error in the object's mean motion can be substantially reduced. Not surprisingly, asteroids with low numbers generally have low ephemeris uncertainties because their orbits are based upon many observations over long intervals of time. In section 4, an ephemeris error analysis for asteroid 433 Eros shows this object's ephemeris uncertainties are only a few tens of kilometers because the existing orbit is based upon three thousand observations spread over a 103 year time interval.