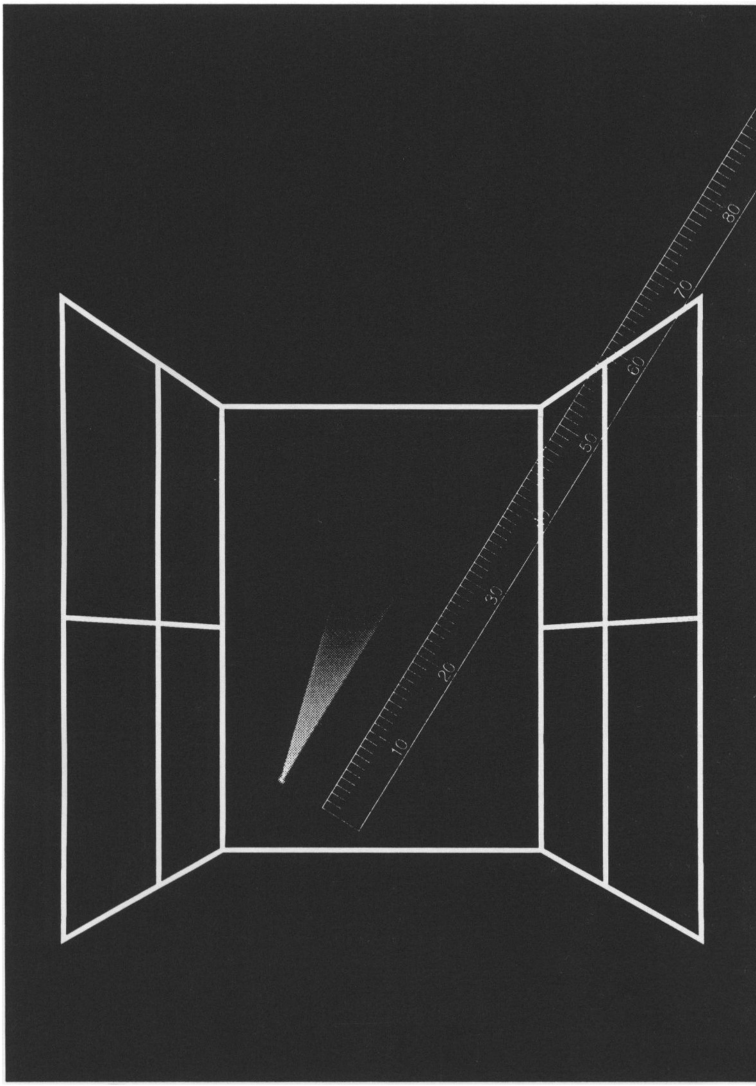

DYNAMICS and ASTROMETRY: PRESENT and FUTURE

COMET AND ASTEROID EPHEMERIDES FOR SPACECRAFT ENCOUNTERS

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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

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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.

Improving the quality of past and current observational data sets are of the utmost importance for accurately predicting the motions of target body candidates. Efforts were undertaken to re-reduce much of the existing 1909-11 data for comet Halley using more modern star catalogs (Roeser, 1987) and special reference star catalogs were prepared for accurate astrometric observations taken prior to the spacecraft arrivals at comet Halley and prior to the Galileo spacecraft arrivals at asteroids 951 Gaspra and 243 Ida. Details of these extensive efforts have been presented by Yeomans (1994a), Yeomans *et al.* (1993), Monet *et al.* (1994), and Owen and Yeomans (1994). Based upon only the ground-based astrometric observations, the plane-of-sky ephemeris accuracies at the encounter times for asteroids Gaspra and Ida were less than 80 km and 60 km respectively. Of particular interest were a group of 17 observations of Ida that were reduced using an overlapping plates technique applied to crossing-point CCD observations (Owen and Yeomans, 1994). Using a few Hipparcos reference star positions in the reduction process allowed an accuracy of $0.''06$ – unprecedented for asteroid astrometry. The Hipparcos reference star positions were kindly supplied by the Hipparcos project in advance of publication. Once the Hipparcos and Tycho star catalogs are widely available, asteroid astrometry to this level of accuracy may become common place. Although not as dense as the Hipparcos/Tycho star catalogs, the positions of radio reference sources are known to a comparable level of accuracy (1–2 milli-arcseconds). Using reference object positions in the extragalactic reference frame, Stone *et al.* (1996) have used drift scan observations to achieve inertial position accuracies of better than $0.''2$ for asteroids. Because the reference sources are so limited in number, global solutions must be made over an entire evening so that refraction effects limit this technique to accuracies of about $0.''14$ in right ascension and $0.''17$ in declination. However, at least a factor of three improvement can be expected when the Tycho reference star catalog becomes available.

As well as the quality and number of the astrometric observations, and the time interval over which they are available, the proximity of the object to the Earth during the observations is important. Astrometric observations of an asteroid or comet at relatively large geocentric distances are not particularly helpful in the orbit refinement process. For example, an astrometric observation with an accuracy of one arc second represents a linear error of 725 km at a distance of one AU but only 72.5 km when the object is 0.1 AU from the observer. A close Earth approach of a target body not only provides an opportunity for powerful optical astrometric observations but radar observations may be possible as well. The benefits of radar data in the asteroid and comet orbit determination process have been discussed in detail elsewhere (Yeomans *et al.*, 1987; Ostro *et al.*, 1991; Yeomans *et al.*, 1992). Typical radar Doppler and time-delay measurements correspond to line-of-sight astrometric measurements of better than 2 cm/s and 150 meters respectively. During an Earth approach of a target body, the combination of optical observations (plane-of-sky angles) and radar measurements (radial velocity and distance) form a particularly powerful data set in that all three components of the object's ephemeris uncertainty ellipsoid are dramatically reduced. These circumstances will be demonstrated with error analysis case studies in section 4.

3. Cometary Orbit Determination

Even after all the gravitational perturbations of neighboring planets and asteroids are taken into account, the observations of many active comets cannot be well represented without the introduction of additional so-called nongravitational effects into the dynamic model. These nongravitational effects are brought about when momentum is transferred to the cometary nucleus by the sublimation of its ices. In an attempt to model the effects of these nongravitational forces upon the motions of active comets, Marsden *et al.* (1973) introduced what has become the standard, or symmetric, nongravitational acceleration model for cometary motions; a rapidly rotating cometary nucleus is assumed to undergo vaporization from water snow that acts symmetrically with respect to perihelion. That is, at the same heliocentric distance before and after perihelion, the cometary nucleus experiences the same nongravitational acceleration. In this model, a radial sun-comet nongravitational parameter (A1) and a transverse nongravitational parameter (A2) are included in the orbital solution along with the six orbital parameters at epoch. This model was used to successfully represent the nongravitational accelerations affecting the motions of comets Giacobini-Zinner and comet Halley. An asymmetric model for these nongravitational effects was suggested by Yeomans and Chodas (1989) whereby the comet's peak vaporization rate could occur a certain number of days before or after perihelion. A review of the subject is given by Yeomans (1994b).

Neither the symmetric nor the asymmetric models are completely accurate representations of a comet's true behavior. For example, short term changes in these effects are not taken into account. The errors introduced by imperfect modelling of these nongravitational effects can account for relatively large uncertainties in a comet's future ephemeris positions. Errors introduced by improper modelling of the nongravitational effects will act in a secular fashion; these errors can be expected to become larger as extrapolations of the comet's ephemeris, beyond the orbital observation interval, grow longer. As a result of imperfectly modelled nongravitational effects, the future ephemerides of active comets must often be based upon orbits that include only recent observational data.

In addition to the imperfect modelling of an active comet's outgassing accelerations, there are ephemeris errors introduced because cometary astrometric observations correspond to the object's photometric center, rather than its center of mass. For the very active comet Halley, it was necessary to model the offset between the observed photometric center of the comet's image and the comet's unseen center-of-mass. This offset was assumed to vary along the comet-sun line with an inverse square dependence on the heliocentric distance. An estimate for this offset at one AU from the Sun was determined to be 848 km sunward (Yeomans, 1994b).

4. Ephemeris Error Analyses Studies for Mission Targets

Successful spacecraft flybys of three comets and two asteroids have already taken place and because of their accessibility and intrinsic science interest, there are a number of future missions to comets and asteroids that are either in progress, or in various stages of the planning process. To demonstrate some of the points made in the previous sections, we have conducted covariance error analyses for five target bodies of existing, or potential, space missions.

Table 1 presents the existing observations for each target body as well as the simulated, or expected, future observations. For example, from the table we note that for asteroid 1989 UR, there are only 15 existing observations covering the interval October-November 1989. In the future, we have assumed that there will be an additional 16 optical simulated observations over the interval from August 1996 through November 1998. We assumed simulated optical observations taken every 10–20 days during those times when the object was relatively near the Earth and when the solar elongation angle was large enough to allow observations in a dark sky. Finally for 1989 UR, we have assumed 22 simulated Doppler observations and 22 simulated time-delay measurements made in November 1998, just prior to the spacecraft encounter one month later.

The error analyses undertaken here utilize standard covariance techniques whereby noise values for both existing and simulated observations, as well as dynamic model uncertainties, are used to compute expected 1-sigma position uncertainties at particular times (Yeomans *et al.*, 1987). For all the simulated optical observations, we have assumed measurement noise values of 1 arc second in both right ascension and declination. For the Doppler and time-delay (range) measurements for asteroid 1989 UR, appropriate noise values were supplied by Steve Ostro based upon preliminary signal-to-noise estimates for the November 1998 radar observation opportunity. For the simulated radar data for asteroid 4660 Nereus during the December 2001 and January 2002 opportunities, we assumed noise values of one Hertz at X-band (1.76 cm/s) and one microsecond round trip light time (150 m range error). The optical and radar noise values are purposely conservative to account for unmodelled error sources such as observatory location errors and errors in the planetary masses and positions. For the two comets, an additional unmodelled error source includes time dependencies in the outgassing acceleration model. For both comets, we assumed that the transverse nongravitational parameter (A2) would be in the solution set along with the six orbital elements at epoch. Although they were not included in the solution set, the errors associated with the radial nongravitational parameter (A1) and the offset between the comet's center-of-light and its center-of-mass at one AU were "considered" in the sense that their errors affected the comet's ephemeris uncertainties at encounter. The errors associated with A1 for these error analyses were assumed to be three times the formal uncertainty associated with A1 when this parameter was included in the solution set for the current orbit. By not including A1 as a "solve for" parameter in our error analysis, even though it is included in the orbital solution set of parameters, we have provided quite conservative estimates for the cometary ephemeris errors at the respective encounters.

NASA's Near-Earth Asteroid Rendezvous (NEAR) mission was launched on February 17 1996 and after a flyby of asteroid 253 Mathilde in June of 1997, the spacecraft will rendezvous with asteroid 433 Eros and spend a year in orbit about that object. The NEAR rendezvous target, Eros, has been selected for an error analysis study as an example of an object that has been well observed for more than a century. In addition, periodic close Earth approaches have allowed optical and radar data during close Earth approaches in 1975 and again in 1988. Eros' ephemeris uncertainties at encounter are the lowest for any of the test cases considered here (see Figure 1).

Asteroid 2660 Nereus is the current target body of the Japanese Muses-C mission. This project is planning a spacecraft launch in January 2002 with a rendezvous in September of 2003. After spending two months in orbit about this asteroid, the Muses-C spacecraft will return a sample of Nereus to Earth in January 2006. The target body of this mission, Nereus, is a good example of an object with only a modest set of existing optical observations but whose close Earth approach in late 2001 and early 2002 will enable powerful optical and radar data to be taken; from Figure 2, we note that these data keep the ephemeris errors to a few tens of kilometers at the time of the spacecraft encounter.

The Clementine 2 mission, supported by the U.S. Department of Defense, plans to impact each of three small asteroids with a micro-satellite. After a launch in May 1998, the Clementine 2 spacecraft will fly closely past asteroid 1987 OA (and deploy one of three micro-satellite impactors)

TABLE 1. Ephemeris error analysis for mission target bodies.

	433 Eros	4660 Nereus	1989 UR	P/Wild 2	P/Wirtanen
Existing Optical Observations					
Number	3041	28	15	347	15
Interval	1893–1996	9/81–5/95	10/89–11/89	1/78–1/96	2/75–12/91
Simulated Optical Obs.					
Number	14	42	16	25	65
Interval	2/98–7/98	1/02–8/03	8/96–11/98	11/96–2/03	6/96–7/11
Existing Radar Observations					
Doppler, Delay	4,1	None	None	None	None
Interval	1975–1988				
Simulated Radar Observations					
Doppler, Delay	None	5,5	22,22	None	None
Interval		12/01–1/02	11/98		
Min. Dist. [AU]		0.03	0.07		
Date of Min. Dist.		1/22/02	11/27/98		
Outgassing Effects Considered?	No	No	No	Yes	Yes
Spacecraft Encounter	NEAR	Muses-C	Clementine	Stardust	Rosetta
Date	2/1999	9/2003	12/1998	01/2004	8/2011
Helio. Dist. [AU]	1.7	1.13	0.96	1.86	4.8
Geo. Dist. [AU]	2.6	1.07	0.08	2.60	4.1
S-E-O angle [Deg]	15	66	75	33	125
Position Uncertainties at Encounter (1-sigma, [km])					
R (Sun-Obj.)	5	13	21	739	2400
T (Transverse)	23	12	15	2421	1103
N (Normal)	11	29	20	90	479

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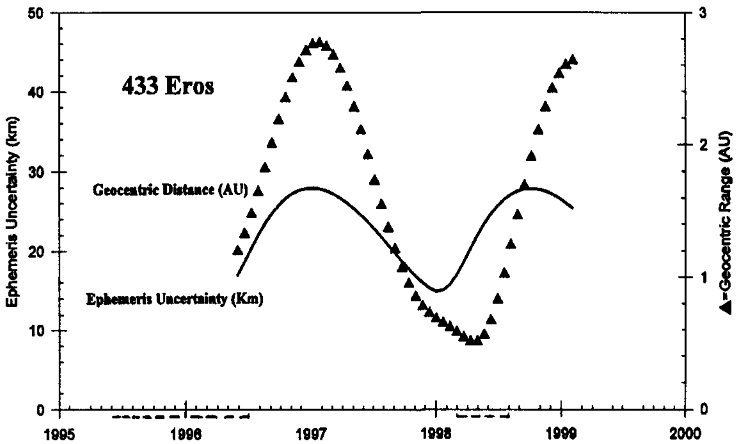

Figure 1. For the NEAR target body, asteroid 433 Eros, the predicted 1-sigma position uncertainty and its geocentric distance are plotted against calendar date. Each curve terminates at the time of the proposed spacecraft encounter.

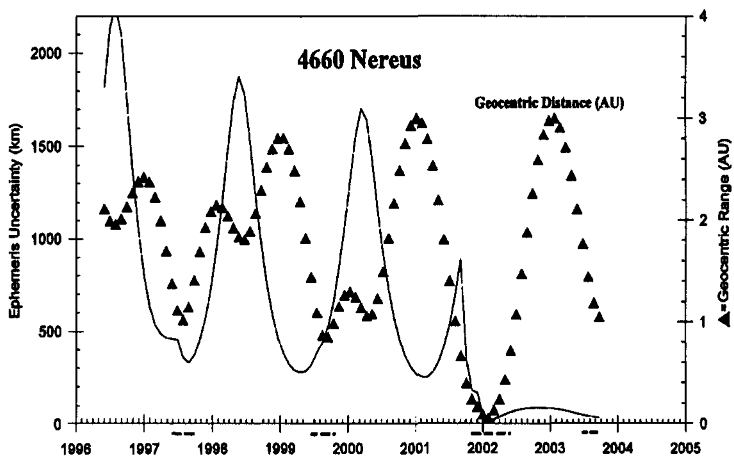

Figure 2. For the Muses-C target body, asteroid 4660 Nereus, the predicted 1-sigma position uncertainty and its geocentric distance are plotted against calendar date.

on August 14, 1998, then continue its mission with a close encounter with asteroid 1989 UR on December 4, 1998, and finally terminate the mission with a close encounter with asteroid 6489 Golevka (1991 JX) on June 2,

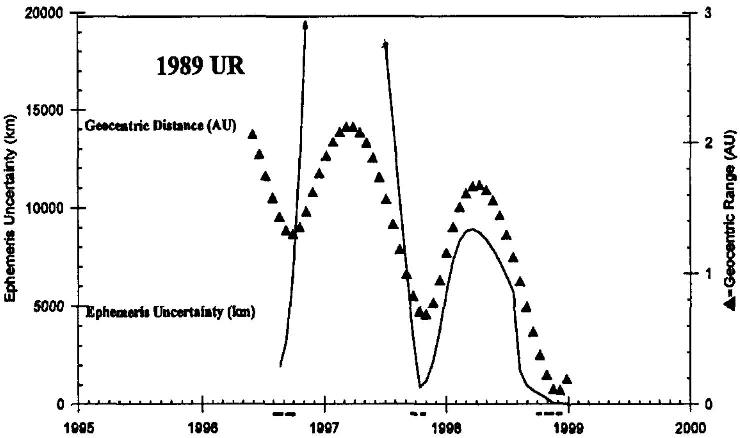

Figure 3. For the Clementine 2 target body, asteroid 1989 UR, the predicted 1-sigma position uncertainty and its geocentric distance are plotted against calendar date.

1999. Asteroid 1989 UR has been selected as an example of a target body with a very sparse optical data set but with a superb opportunity for optical and radar data immediately prior to the spacecraft encounter in December 1998 (see Figure 3).

Periodic comet Wild 2 will be the target body of NASA's Stardust mission, scheduled for launch in February 1999. During the fast flyby of the comet in January 2004, dust samples from the comet's coma will be captured in an under-dense (aerogel) medium on board the spacecraft and this sample will then be returned to Earth in January 2006. For this comet, only the observations during a limited number of apparitions can be used in the orbit determination process because of unmodelled temporal changes in the comet's outgassing accelerations. In addition, there are no opportunities prior to the spacecraft encounter when observations (optical or radar) could be taken during an Earth close approach. To make matters worse, there will be an eleven month interval between the time of the last astrometric observation and the scheduled time of the spacecraft encounter. As a result, this target body will have the largest a-priori ephemeris uncertainties of any of the test cases considered here (see Figure 4).

ESA's Rosetta mission will launch in January 2003 and finally rendezvous with its target body, periodic comet Wirtanen, in August 2011. As an active periodic comet, Wirtanen shares some of the same problems as the Stardust target body, comet Wild 2. Only a limited portion of the existing observations can be used, the nongravitational accelerations are imperfectly

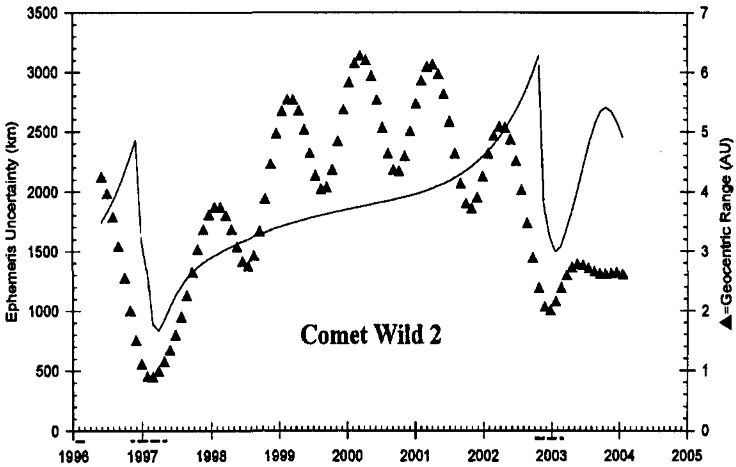

Figure 4. For the Stardust target body, comet Wild 2, the predicted 1-sigma position uncertainty and its geocentric distance are plotted against calendar date.

modelled, and there are no close Earth approaches that would allow powerful astrometric data to substantially refine the comet's orbit. However, unlike the case for Wild 2, there are ground- based observing opportunities just prior to the August 2011 encounter so that the ephemeris extrapolation time is very short (see Figure 5).

Figures 1 through 5 give the 1-sigma, root-sum-square, position uncertainties as a function of time for five mission targets. On each plot, the broken curve denotes the geocentric distance of the target body in AU (see right hand y-axis) while the solid curve gives the position uncertainties in kilometers (see left hand y-axis). Below the x-axis on each plot, the heavy broken lines indicate the approximate times for which simulated observational data were processed.

5. Conclusions

To meet the often demanding spacecraft and mission science requirements, a successful spacecraft encounter with a comet or asteroid requires an accurate ephemeris for the target body. For an asteroid with a long data interval (e.g., 433 Eros), its orbit and in particular, its mean motion, is well determined so that the ephemeris predictions that depend upon this orbit are relatively accurate. For the few oppositions of the target body that take place prior to a spacecraft encounter, special reference star catalogs can be generated for use by experienced astrometric observers. These data are

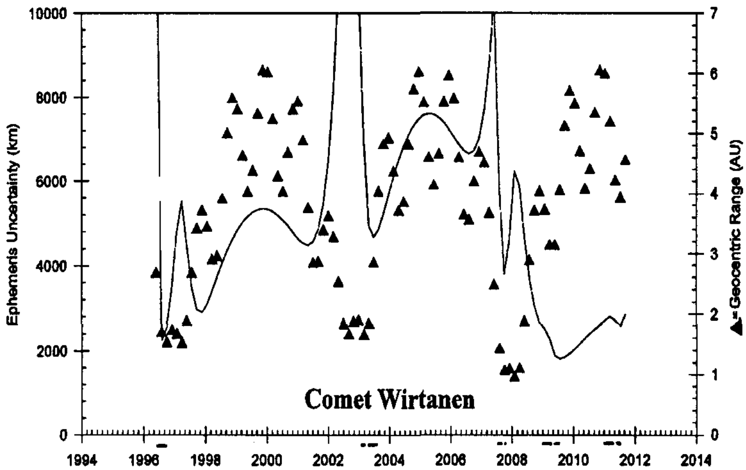

Figure 5. For the Rosetta target body, comet Wirtanen, the predicted 1-sigma position uncertainty and its geocentric distance are plotted against calendar date.

then upweighted with respect to the older data. Such efforts proved very successful for the spacecraft flyby of comet Giacobini-Zinner in September 1985, for the comet Halley flybys in March 1986, and for the Galileo spacecraft flybys of asteroids 951 Gaspra and 243 Ida in October 1991 and August 1993.

For asteroids with sparse astrometric data sets over short time intervals, an accurate ephemeris can still be achieved if the body passes closely by the Earth prior to the planned encounter: during these close encounters, traditional, optical angle data become very powerful in the orbit determination process. In addition, a close Earth approach may allow radar Doppler and delay measurements and these data, when used in combination with the optical data, can dramatically improve a target body's ephemeris (e.g., 4660 Nereus and 1989 UR).

For active comets like Wirtanen and Wild 2, additional perturbative effects can arise from the sublimation of the comet's ices. Rocket-like outgassing thrusts, or so-called nongravitational accelerations, then develop. Largely due to temporal changes in these outgassing effects, these perturbations are imperfectly modelled – a fact that normally restricts the data interval over which the comet's orbit can be successfully computed. Thus, for an active comet and an asteroid with the same orbital characteristics and observational histories, the comet can have ephemeris uncertainties an order of magnitude larger than the asteroid.

For future missions to comets and asteroids, carefully planned observing campaigns, using both optical and radar techniques, will allow ephemeris

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uncertainties of only a few tens of kilometers for the asteroidal targets of the NEAR, Muses-C and Clementine 2 missions. However because of the data interval constraints, imperfectly modelled outgassing accelerations, and poor astrometric observing opportunities prior to their encounters, the cometary targets of the Stardust and Rosetta missions could have ephemeris uncertainties at encounter at least an order of magnitude larger.

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