Amateur Astrometric Contributions in Support of Flight Projects

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Abstract

There are seven flight projects that will visit 13 different comets and asteroids in the next thirteen years. In addition, several asteroids will be used as beacons for the autonomous navigation of some high technology spacecraft. For each target body and navigation beacon, the utmost in accurate orbits and ephemerides are essential for spacecraft navigation and the proper sequencing of science instruments upon arrival. Even with the use of on-board optical spacecraft navigation images to help improve the target body's ephemeris, the accuracy of the along track spacecraft position (time of target body flyby) remains dependent upon an ephemeris determined solely using ground-based data. The factors influencing asteroid ephemeris accuracy include the length of the observational data arc, the number of observations, the proximity to the Earth when these observations are made, and the data accuracy itself. Recent advances in the reference star catalogs, including the ACT catalog from the U.S. Naval Observatory, have allowed astrometric observations to be accurate to better than 0.1" and at least one amateur astronomer (G. Garradd) has routinely supplied data to this accuracy. A table is presented giving the future observing opportunities for the comets and asteroids that will be used as spacecraft target bodies in the near future. Astrometric data for all of these target bodies will be solicited from amateur and professional astronomers alike.

astrometry

Introduction

The space exploration of the solar system's small bodies began with the International Cometary Explorer (ICE) flythrough of comet 21P/Giacobini-Zinner's tail on September 11, 1985. A few months later, in March 1986, five separate spacecraft flew sunward of comet 1P/Halley and the Giotto spacecraft from the European Space Agency flew as close as 600 km from the comet's nucleus. Giotto was later re-targeted for a 200 km tail-side flythrough of comet 26P/Grigg-Skjellerup on July 10, 1992. On its way to a late 1995 encounter with Jupiter, NASA's Galileo spacecraft flew past two S-type, main-belt asteroids, 951 Gaspra and 243 Ida. The Gaspra encounter took place on October 29, 1991 at a close approach distance of 1620 km while the Galileo spacecraft flew within 2400 km of asteroid Ida on August 28, 1993. During the Ida encounter, the Galileo imager detected the presence of a small 1.5 km moon of Ida (subsequently named Dactyl). The Near-Earth Asteroid Rendezvous (NEAR) spacecraft has flown past two asteroids to date. The first NEAR encounter was the June 27, 1997 flyby of C-type asteroid 243 Mathilde and the second was the December 23, 1999 flyby of S-type asteroid 433 Eros. The spacecraft's close approach distances to Mathilde and Eros were 1212 km and 3827 km respectively. The NEAR spacecraft will once again encounter asteroid Eros in February 2000 and spend a number of months in close orbits about this body. To date, there have been spacecraft encounters of two periodic comets and four asteroids.

If current plans are carried out, there will be an additional 13 small body encounters in as many years. Launched on February 8, 1999, the Stardust spacecraft will flythrough the dust coma of comet 81P/Wild 2 in January 2004 and return a cometary dust sample to Earth two years later. The New Millennium DS1 mission, which was launched October 25, 1998, has been designated a NASA technology test flight. This DS1 mission will use its ion drive thrusters to fly past asteroid 9969 (1992 KD) on July 28, 1999 and if the necessary funding is made available, this spacecraft will fly past comet/asteroid 4015 Wilson-Harrington in January 2001 as well as comet 19P/Borrelly in September 2001. This DS1 spacecraft is also of interest because it observes the known positions of so-called "beacon asteroids" to automatically compute it's own inertial position in space. Once the positions of the beacons have been pre-determined using ground-based astrometric observations, this autonomous spacecraft navigation function can be done without any interaction from ground-based operators. After launching in July 2002, the Comet Nucleus Tour (CONTOUR) spacecraft will fly closely past three diverse comets. This spacecraft will encounter comet 2P/Encke on November 12, 2003, comet 73P/Schwassmann-Wachmann 3 on June 18, 2006 and comet 6P/d'Arrest on August 16, 2008. A joint project between the Japanese Space Agency and NASA will launch the MUSES-C spacecraft in 2002 to a near-Earth asteroid, land, and bring surface samples back to Earth in 2006. The potential target asteroids for this joint Japanese and American mission are 4660 Nereus or 1989 ML. Another of NASA's technology test flights (Space Technology 4) will launch in April 2003 and will attempt to land upon comet 9P/Tempel 1 three years later to analyze the chemical composition of subsurface materials. After a January 2003 launch, the European space Agency's Rosetta spacecraft will fly past two asteroids en route to the primary target, comet 46P/Wirtanen. Asteroids 4979 Otawara and 140 Siwa will be encountered in July 2006 and July 2008 respectively and the comet rendezvous and landing will begin in August 2012. The coming few years will be an extraordinarily busy time for comet and asteroid scientists.

The role of observational data in the orbit and ephemeris generation process

For simply trying to center a comet or an asteroid in the field of view of a wide field telescope, the target body's ephemeris need not be particularly accurate. However, for stellar occultation work, for spectroscopic observations, radar, and particularly for flight project support, the orbit and ephemeris uncertainties must be minimized. In general, the factors influencing asteroid ephemeris accuracy include the length of the observational data arc, the number of observations, the proximity to the Earth when these observations are made, and the data accuracy itself.

In most cases, the largest ephemeris uncertainty component for a comet or asteroid is in the object's along-track direction. That is, the object's mean motion, or semi-major axis, is often poorly determined. By basing an orbit on several observations over a long time interval, the error in the object's mean motion can be substantially reduced. Not surprisingly, the asteroids with low numbers generally have low ephemeris uncertainties because their orbits are based upon many observations over long intervals of time.

Because of the Galileo flight project's plans to fly past asteroids 951 Gaspra and 243 Ida prior to its December 1995 encounter with the planet Jupiter, special reference star catalogs were prepared for use in the reduction of the astrometric data. Under the direction of Arnold Klemola (Lick Observatory) and William Owen, Jr. (JPL) special reference star catalogs were prepared for two oppositions prior to the Gaspra encounter and for three oppositions prior to the Ida encounter. A small group of experienced observers agreed to reduce their astrometric data with respect to these reference star catalogs. Significantly, the same reference star catalog was used to support the final spacecraft terminal navigation; in the few weeks prior to encounter, the cameras on-board the spacecraft were used to image the asteroids on the star background and these optical navigation images were employed to refine the asteroid ephemerides just prior to the encounters. Some observations from the U.S. Naval Observatory at Flagstaff were reduced with respect to extragalactic radio sources and these observations were given increased weight in the orbit determination process because they were relatively unaffected by the systematic errors present in most star catalogs. Details of these extensive efforts have been presented by Yeomans (1994a), Yeomans et al. (1993), Monet et al. (1994), Owen and Yeomans (1994) and Stone et al.(1996). While asteroid images taken on-board the spacecraft can be used to correct ground-based ephemeris errors in the spacecraft's plane-of-sky, the asteroid's ephemeris error in the direction of the relative velocity vector between the spacecraft and asteroid remains a function of the ground-based ephemeris alone. Thus, the spacecraft's arrival time at closest approach is strictly dependent upon the accuracy of the asteroid's ephemeris as determined from ground-based astrometric data.

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 (Owens 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.

Now that reference star catalogs based upon the Hipparcos data are freely available to all, the level of astrometric accuracy available to observers is unprecedented. The ACT reference star catalog from the U.S. Naval Observatory is one such catalog with nearly one million stars down to about magnitude 11.5. The internal accuracy is about 0.03 arc seconds with proper motions good to about 0.003 arc sec. per year. Ron Stone and Alice Monet at the U.S. Naval Observatory in Flagstaff, Dave Tholen at Mauna Kea Hawaii, Bill Owen at JPL's Table Mountain Observatory, and the Australian amateur astronomer Gordon Garradd have routinely reached accuracy levels of 0.06 arc seconds or better in orbit residuals for particular asteroid targets. Hipparcos based observations of asteroid 253 Mathilde for the two months prior to the June 27 1997 encounter were upweighted with respect to the remaining data in the orbit solution. The use of these data in the final orbit solution provided an order of magnitude improvement in the asteroid's ephemeris uncertainties and they were, in part, responsible for the dramatic success of the NEAR images of Mathilde as the spacecraft flew by on June 27, 1997 (Veverka et al., 1997; Yeomans et al, 1997).

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 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 had 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.

Because of their gas and dust atmospheres, astrometric observations of comets will not be as accurate as those for asteroids. One observes the comet's center-of-light and this is not necessarily the object's center-of-mass. To minimize the uncertainty introduced by this offset between the comet's center-of-light and its center-of-mass, observers should try to use the minimum possible integration time that still allows suitable reference stars to be in the field of view along with the smallest possible cometary image (Yeomans, 1994b).

The ephemeris improvement efforts for asteroid 433 Eros prior to the NEAR spacecraft's arrival in December 1998 provides a vivid example of all the elements necessary to create the utmost in ephemeris accuracy. The data arc for Eros was over one hundred years and there were a substantial number of observations (3244). Eros was often observed during Earth close approaches and in January 1975 and December 1982 during two of these approaches there were radar data taken. As a result, the data set for Eros was about as good as it gets and when the NEAR spacecraft arrived at Eros, the error of the ground-based ephemeris was found to be only 20 km or less!

Possible amateur astrometric contributions to flight project support

Amateur astrometric contributions are sought to aid the ephemeris development efforts for those comets and asteroids that are of interest to the flight projects. The use of the ACT reference star catalog is strongly encouraged and observers should try to observe the targets of interest when they are closest to the Earth (usually near opposition). The spacecraft of the future are likely to rely more and more upon bright beacon asteroids for autonomous navigation. Hence, observers are encouraged to make occasional observations of the first 100 numbered asteroids because it is these relatively bright objects that will be used by future spacecraft to autonomously determine their positions in space. As well as providing astrometric positions of beacon asteroids, observers are requested to provide high quality astrometric data for the comets and asteroids that have been identified as future spacecraft target bodies. Table 1 gives the observing opportunities for those comets and asteroids that have been designated as targets for upcoming space missions. Although many of the target body observing opportunities listed in Table 1 will be impossible for modest telescope apertures, there are several relatively bright target bodies for which accurate astrometric data are solicited.

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Table 1. Observing opportunities for targets of approved (or planned) space missions to comets and asteroids. For each mission target, the approximate dates (beginning, mid-point, end) of the optimal observation periods are given. These dates are followed by the Earth-Object distance in AU, the declination in degrees, the apparent magnitude, and solar elongation angle (sun-Earth-object) in degrees. Detailed ephemerides for these, and all other, solar system bodies can be generated and downloaded from the JPL web site; http://ssd.jpl.nasa.gov

Ground-based Observing Opportunities for Small Body Mission Targets

Mission	Target Body (Encounter Date)	Observing Date	Geocen. Distance (AU)	Decl. (deg.)	Appar. Magn.	Solar Elong. (deg.)
NEAR	433 Eros	1998 Feb 19	0.60	-35	11.9	98
	(Jan. 1999)	1998 May 20	0.55	-44	11.4	149
	(S spec. type)	1998 Oct 27	2.08	-24	14.9	59
New Millennium	1992 KD	1999 Mar 02	1.12	-35	18.3	123
DS-1	(July 28,1998)	1999 May 13	1.08	-18	18.2	91
		1999 Jul 28	1.25	-06	18.4	71
	4015 Wilson-	2000 Apr. 01	2.46	-20	21.2	145
	Harrington	2000 May 16	2.14	-16	20.6	160
	(Jan. 16, 2001)	2000 Aug. 29	2.77	-15	21.2	62
	9P/Borrelly	2001 Jul 20	1.87	+04	10.3	54
	(Sep. 23, 2001)	2001 Aug 14	1.41	+11	9.3	57
		2001 Sep 23	1.47	+21	8.7	63
Stardust	81P/Wild 2	2002 Sep 21	2.99	+19	16.5	104
	(Feb. 8, 2003)	2002 Dec 30	1.99	+16	14.6	143
		2003 Feb 8	2.23	+17	14.4	101
MUSES-C	4660 Nereus	1999 Jun 14	1.45	-10	21.9	107
	(May 26, 2003)	1999 Aug 23	0.83	-12	19.4	177
	(C spec. type?)	1999 Oct 22	1.02	-15	20.8	106
	1989 ML	1999 Mar. 15	0.34	+08	18.7	151
	(Oct. 20, 2003)	1999 Apr. 24	0.25	+18	18.1	144
	(C spec. type?)	1999 May 14	0.26	+16	18.4	126
	1989 ML	2002 Sep 25	0.39	+06	19.4	120
	(Oct. 20, 2003)	2002 Oct 25	0.34	+04	18.7	152
	(C Spec. type?)	2002 Dec 14	0.51	+07	19.9	136
New Millennium	9P/Tempel 1	2000 Jul 19	1.79	-11	16.0	111
DS-4	(Jan. 2006)	2000 Aug 28	1.66	-14	16.9	149
		2000 Oct 17	2.00	-17	18.4	144
	9P/Tempel 1	2005 Jan 04	1.90	+09	15.7	98
	(Jan. 2006)	2005 May 04	0.71	+11	10.1	142
		2005 Oct 21	1.91	-32	13.5	70

Mission	Target Body (Encounter Date)	Observing Date	Geocen. Distance (AU)	Decl. (deg.)	Appar. Magn.	Solar Elong. (deg.)
CONTOUR	2P/Encke	2003 Sep 27	1.05	+30	16.7	128
	(Nov. 12, 2003)	2003 Oct 17	0.52	+40	14.5	149
		2003 Nov 06	0.30	+43	13.6	124
	73P/Schwassmann-	2006 Feb 22	0.87	+12	15.1	129
	Wachmann 3	2006 May 13	0.08	+22	6.6	85
	(June 18, 2006)	2006 Jun 02	0.20	-07	8.1	63
	6P/D'Arrest	2008 May 27	0.80	+13	15.5	127
	(Aug. 16, 2008)	2008 Jul 06	0.47	+12	12.1	145
		2008 Aug 05	0.36	-08	10.6	163
Rosetta	4979 Otawara	2000 Jul 02	0.98	-16	16.6	140
		2000 Aug 11	0.90	-19	15.8	174
	(Jul 10, 2006)	2000 Sep 20	1.14	-20	17.1	132
	4979 Otawara	2003 May 08	1.01	-23	16.7	139
		2003 Jun 17	0.85	-24	15.5	177
	(Jul 10, 2006)	2003 Jul 27	1.00	-24	16.7	134
	4979 Otawara	2006 Mar 13	1.27	-14	17.4	130
		2006 May 12	0.97	-12	16.3	162
	(Jul 10, 2006)	2006 Jun 21	1.18	-11	17.3	121
	140 Siwa	1999 Mar 2	2.06	+03	12.8	158
	(May 2008)	1999 Mar 22	1.97	+05	12.4	175
	(P spec. type)	1999 Apr 11	2.00	+07	12.8	153
	140 Siwa	2000 Jul 14	1.20	-16	11.2	150
	(May 2008)	2000 Aug 03	1.14	-18	10.6	172
	(P spec. type)	2000 Sep 12	1.29	-21	11.5	143
	140 Siwa	2004 Apr 04	1.70	-14	12.3	143
	(May 2008)	2004 May 14	1.48	-12	11.5	170
	(P spec. type)	2004 Jun 23	1.64	-11	12.3	127
	46P/Wirtanen	2003 Feb 6	1.72	+01	15.2	104
	(Aug 2012)	2003 Mar 18	1.61	+05	16.0	145
		2003 Jun 26	2.86	+04	18.8	100
	46P/Wirtanen	2007 Oct 24	1.06	-33	12.4	107
	(Aug 2012)	2008 Feb 01	0.94	+06	9.2	67
		2008 Apr 01	1.10	+35	11.0	77

Notes:

1. The New Millennium DS-1 targets 4015 Wilson-Harrington and 9P/Borrelly are possible follow-on target bodies but they have not been given official approval.
2. The DS-4 mission has not yet received official NASA approval.
3. The MUSES-C primary target is asteroid 4660 Nereus. Asteroid 1989 ML is a backup target.