

IRREGULAR SATELLITES OF THE OUTER PLANETS: ORBITAL UNCERTAINTIES AND ASTROMETRIC RECOVERIES IN 2009–2011

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ABSTRACT

More than 100 small satellites have been identified orbiting the giant planets in distant, inclined, eccentric orbits. Detailed study of these objects requires that their orbits be known well enough to permit routine observations both from the Earth and from spacecraft. Unfortunately, many of the satellites have very poorly known orbits due to a scarcity of astrometric measurements. We have developed a reliable method to estimate the future on-sky position uncertainties of the satellites and have verified that those uncertainties provide a correct measure of the true on-sky positional uncertainty. Based on the uncertainties, we identified a set of satellites that are effectively “lost” and another set that would be lost if additional observations were not obtained in the near future. We attempted recoveries of 26 of the latter group using the Hale 5 m and CFHT 3.6 m telescopes and found 23. This validated our method’s predictions and led to significant improvements in our knowledge of the orbits of the recovered moons. There remains a handful of irregular moons which are recoverable and whose orbits will benefit from additional observations during the next decade, while 16 moons of Jupiter and Saturn are essentially lost and will require a re-survey to be located again.

Key word: planets and satellites: individual (Jupiter, Saturn, Uranus, Neptune)

1. INTRODUCTION

The irregular planetary satellites are moons orbiting the giant planets in eccentric orbits inclined to the planetary equators and at distances beyond the planets’ major satellites (Nicholson et al. 2008). They comprise an interesting class of solar system objects worthy of scientific investigations because their orbital and physical characteristics provide constraints on the formation processes of the outer planets. As of 2012 January there are 87 recognized and 26 provisional irregular satellites; the International Astronomical Union (IAU) assigns permanent names and numbers to recognized satellites and temporary designations to provisional ones. The latter are those for which the IAU has concluded there are insufficient observations to produce well-determined orbits; in fact some of those orbits are so poorly known that the satellites are for all practical purposes lost. Among the recognized satellites there are also a number that have orbits of low enough quality (due to their meager observation sets) that they are in danger of being lost.

For the past few years, we have been attempting to observe those satellites with moderately uncertain orbits and improve those orbits utilizing the observations. To structure our work we have developed a procedure to quantify the on-sky position uncertainty, i.e., the uncertainty in the satellite position normal to the direction from the Earth to the satellite. These on-sky uncertainties guide us in carrying out our observations; based on the uncertainties we can disregard the hopelessly lost satellites and focus on those that, while on the verge of being lost, can likely be recovered. We have managed to observe a number of the “near lost” satellites in the Jovian, Saturnian, and Uranian systems. In the process we also acquired bonus astrometry for a number of the better known satellites and discovered two additional Jovians (Jacobson et al. 2011; Alexandersen et al. 2012). The Neptunian irregulars are the subject of a separate

analysis (Brozović et al. 2011) that incorporates the most recent astrometry, acquired in 2009.

In the following sections, we discuss the computation of the on-sky uncertainties, the current status of the orbits of all of the irregular satellites, our recovery procedure, and the results of recent recovery efforts.

2. ORBIT UNCERTAINTIES

Our model for the satellite dynamics (Peters 1981) takes into account the equatorial bulge of the central planet, perturbations from its major regular satellites, and perturbations from the Sun and the giant planets. We augment the mass of the Sun with the masses of the inner planets and the Moon. Our astrometric observation model is based on Murray (1983), The Astronomical Almanac (USNO 1987), and Seidelmann (1992). The completeness of the models allows us to easily produce orbit fits to the observations at their presumed error levels. Consequently, we believe that the orbit errors are dominated by random and systematic errors in the observations themselves. Desmars et al. (2009) and Emelyanov (2010) have also concluded that observational error currently limits the accuracy of satellite orbits and have proposed procedures for estimating that accuracy. For sparse observation sets, as in the case of the irregular satellites, Emelyanov found Desmars’s bootstrap method unsuitable; it tended to yield overly pessimistic error estimates. As alternatives, Emelyanov proposed two Monte Carlo type methods which assume that the observational errors are random with Gaussian statistics. Actual observations, however, are primarily corrupted by systematic errors in the instrumentation, the measurement reduction process, the reference star positions in the star catalog, and the relationship of the star catalog to the International Celestial Reference Frame. Moreover, the errors in the observations made on the same night at the same observatory can be expected to be correlated, i.e., not independent.

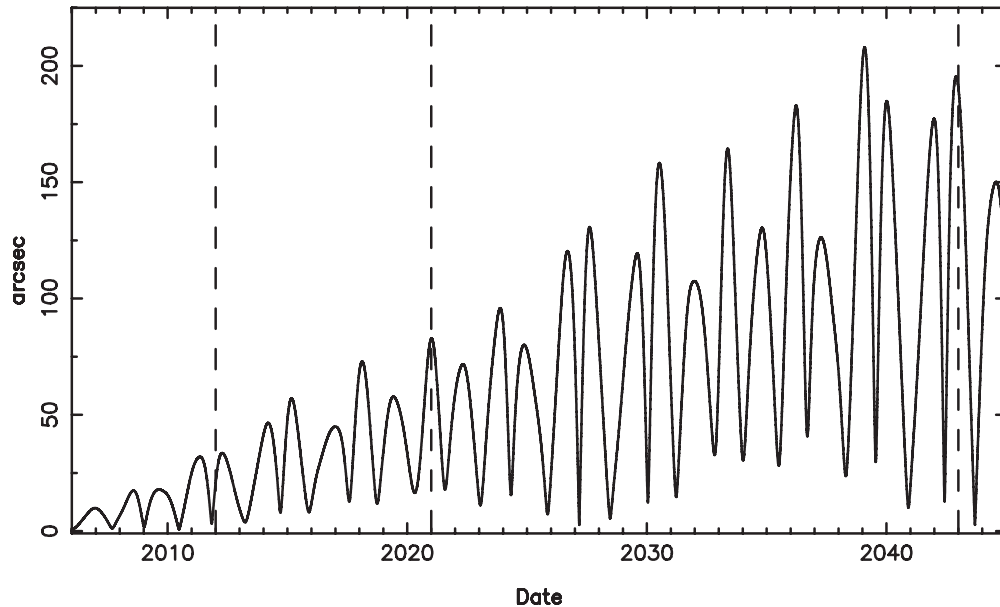


Figure 1. Time history of the on-sky position uncertainty for the Saturnian irregular Aegir. The last observation of this moon was in 2006. The on-sky uncertainty oscillates due to the projection of the three-dimensional orbital position uncertainty normal to the line of sight from Earth. The leftmost vertical dashed line marks 2012 January, the second and third lines mark three and ten sidereal satellite orbital periods later. The envelope of maximum uncertainty grows with time, and will be about 1/4 by 2021 and nearly 3/5 by 2043.

Unfortunately, we know of no direct way to characterize the systematic errors and introduce their effect into an orbit accuracy determination. For our satellite recovery efforts, however, we do not need to know the “actual” orbit errors. What we require is a reasonable bound on the predicted on-sky position error to characterize the quality of the orbit, i.e., known, recoverable, or lost, and to limit the search region for the recovery observations. To obtain this bound we adopt a variation of the method described in Emelyanov (2010) based on the covariance matrix of parameter errors. That is, we begin with the covariance on each satellite state obtained from the least-squares fit of the orbit to the observations, but rather than invoking a Monte Carlo process, we simply propagate that covariance via a linear mapping to two different times: 3 orbital periods and 10 orbital periods beyond the current opposition. We then transform each mapped covariance into a plane-of-sky coordinate system: one axis along the Earth satellite direction at the mapping time, one axis in the right ascension direction, and one axis in the declination direction. We define the predicted on-sky position error, i.e., the on-sky position uncertainty, to be the root sum of squares of the projections of the transformed covariance onto the right ascension and declination directions. The differences between the uncertainties at the two mapping times are a measure of the rate of degradation of our knowledge of the orbit of each satellite. Depending upon the robustness of a particular satellite’s data set, the errors in the satellite’s state represented by the covariance can range from small to large. For small errors the Monte Carlo process and the linear mapping yield effectively the same results. For large errors the Monte Carlo process accounts for nonlinear effects in the error propagation and will yield somewhat different results from the linear mapping depending on the degree of nonlinearity. However, if the errors are large enough to be affected by nonlinearities, we believe that the computed values of the orbit errors are probably meaningless. What is meaningful is simply that the errors are “large.” Consequently, the linearly mapped errors suffice for our needs.

In our standard least-squares orbit fitting process, we uniformly weight the observations at 1” and scale the resultant covariance by the factor

$$\sigma^2 = \frac{1}{n - m} \sum_{i=1}^n \zeta_i^2,$$

where n is the number of observations, m is the number of estimated parameters (e.g., 6 for Cartesian position and velocity), and ζ_i is a weighted observation residual. This scaled covariance represents the “formal” 1σ error in the satellite state under the assumption of independent random observation errors with Gaussian statistics. The unscaled covariance itself is a measure of the ability of the data set to determine the orbit. The $n - m$ factor further strengthens that measure as it is desirable to have many more observations than the number of parameters to be determined. Finally, the weighted residuals account for the data quality, i.e., high data noise levels or systematic observational errors will increase the weighted residuals. The uncertainties that we quote in the remainder of this paper are the formal 1σ errors.

As an example, Figure 1 displays the time history of the on-sky position uncertainty for a typical satellite having a poorly known orbit, the Saturnian irregular Aegir. This satellite was discovered in 2004 and was subsequently observed during the 2005 and 2006 oppositions; its observational time span is less than its ~ 3 year orbital period. The dotted vertical lines in the figure denote 2012 January (roughly the end of the 2011 opposition) and the times associated with 3 and 10 periods beyond that date. Clearly there is a general secular growth. However, there is also a significant periodic signature which is a consequence of a projection effect. The predicted orbital position error is not the same in all directions; the largest is along the satellite orbit and grows linearly with time (due to the uncertainty in mean motion), and the components normal to that direction are considerably smaller. In the figure, the peaks of the on-sky uncertainty curve occur when the satellite

is moving normal to the line of sight and the valleys occur when the motion is along the line of sight. As noted in Emelyanov (2010) the most powerful observations for orbit improvement are likely to be those obtained when the on-sky errors are the largest, i.e., when the motion is across the line of sight. However, it is also at those times that recovery is most difficult because of uncertainty as to where to point the telescope.

3. RECOVERY PROCEDURES

During 2009–2011, we identified a set of satellites that were not lost but had large on-sky positional uncertainties. These moons were the subject of our targeted observational recovery program. The satellite magnitudes for the chosen recovery targets ranged from roughly 22 to 26 in R band and their on-sky uncertainties varied from a few arcseconds to $20'$. Thus, the recovery work required a large-aperture telescope with a large field of view (FOV).

Our primary recovery instrument was the Large Format Camera (LFC) on the Palomar Hale 5 m telescope. The LFC has a cross-shaped FOV with a maximum east–west or north–south extent of $24'$. With a median seeing of about $1''.3$, the Hale is able to reach $R \simeq 24$ in 5 minutes of exposure time. Brighter satellites can thus be acquired in single images, with their motion detectable in short time baselines (a few tens of minutes to an hour, depending on the planetary rate of motion at the time of observation). Fainter satellites require longer integration times, but these cannot be much longer than the time it takes the satellite to move by the exposure's FWHM or the image will be trailed. This single-exposure limitation can be overcome by using the so-called shift and stack technique (Gladman et al. 1998) in which many sequential images are shifted in software so that the motion of the desired object is taken out, resulting in fixed stars and galaxies trailing but the moving object's signal accumulating as though the telescope was tracking the target. The advantage of this procedure, as opposed to tracking the telescope at the suspected non-sidereal rate of the target, is that the software recombination can be done at several different rates to hunt for more than one target in the data (since the planetocentric motion of the satellites, and thus resulting on-sky rates, may not be negligible).

The desire to ensure recovery of very faint satellites, e.g., Margaret and Ferdinand, or those with larger on-sky uncertainties, led us to also use the 3.5 m Canada–France–Hawaii Telescope (CFHT), with its 1×1 deg FOV Megaprime CCD mosaic (Boulade et al. 2003). Moreover, CFHT's greater FOV and better stray-light baffling allows for a deeper search when looking in the Jovian Hill sphere for faint satellites. In practice, the better median CFHT image quality ($0''.72$ median) compensates for its smaller aperture. Use of both telescopes during the important fall 2010 dark run when Jupiter and Uranus were available provided more robustness against weather loss at one of the sites.

CCD data from both telescopes were debiased and flat-fielded using standard techniques. The astrometric flatness of the CFHT images is very good, while the Palomar LFC mosaic frames show significant nonlinearity (on the level of a several arcseconds over the $12'$ radius of the FOV). Astrometry was performed relative to the USNO A-2.0 stellar catalog. Typical astrometric scatter was $0''.3$, although due to the larger non-flatness of the astrometric field of the Palomar LFC camera, some solutions have $0''.5$ – $1''$ systematic offsets for all astrometric points.

4. RESULTS

4.1. Recoveries

Table 1 contains the complete list of targeted and untargeted recoveries from the Palomar and CFHT runs during our 2009–2011 observing campaign. Listed are the on-sky uncertainty for each satellite at the observation time and the rms of the difference between the satellite's predicted and observed on-sky positions, which hereafter will be referred to as the “discrepancy.”

We acquired our initial satellite recovery observations at Palomar in 2009 July and August during observational runs primarily targeted at trans-Neptunian objects. In July we targeted the named Jovian satellites with the largest predicted uncertainties: Kallichore, Helike, and Eukalade. We also attempted to find three of the unnamed satellites: S/2003 J 5, S/2003 J 17 (later named Herse), and S/2003 J 18 having uncertainties less than $10'$. All but satellite S/2003 J 5 were recovered. In August we targeted and recovered a second tier of named Jovian satellites, Euanthe, Sponde, Pasithee, Aoede, Thelxinoe, Carpo, and Cyllene, and acquired additional observations of S/2003 J 17 and S/2003 J 18. A significant portion of both nights in August was also devoted to recovering the faint Uranian satellites Setebos and Prospero. On the second night we attempted to recover the even fainter (25th magnitude) Ferdinand but were forced to abort the attempt due to time limitations and only average seeing. All of the targeted Jovian irregulars were sufficiently bright that two or three short images (three- or five-minute exposures) spaced at few-minute intervals were sufficient to detect motion. We used a series of “shift and stack” exposures, each five minutes long, for the Uranians; this approach is required on any telescope for the ~ 25 th magnitude Ferdinand except for an 8 m class telescope in excellent seeing.

In 2010 March at Palomar we directed our attention to Saturn and selected four of the satellites with poorly known orbits, two named (Hati and Greip) and two unnamed (S/2004 S 7 and S/2007 S 3), as well as two of the better known named ones (Tarqeq and Kari) which happened to be easily accessible (not too close to the planet and not too far from the other five). For these Saturnian satellites observations we employed a mix of short-exposure recoveries and “shift and stack” recoveries, depending on the target object magnitude. We failed to find two of our targets; however, we managed to locate five untargeted satellites in our images including one of the unnamed satellites, S/2006 S 3, with a rather large uncertainty.

During early 2010 September Jupiter was passing Uranus on the sky, allowing both Palomar and CFHT to look through the Hill spheres of *both* planets; a set of short exposures could be shifted and stacked at either planetary rate to search for faint satellites of either planet. We picked the two poorest known Uranians, Margaret and Ferdinand, as our primary targets and five of the Jovians as backup targets. The latter were those with large uncertainties that were far enough from Jupiter to be outside the glare from the planet. As before at Palomar, the Jovians were observed with a series of short images (two-to-three-minute exposures), and ~ 25 th magnitude Uranians were observed with a series of “shift and stack” exposures. At CFHT we acquired 60 sequential 140 s r -band exposures. At CFHT we also obtained observations of three other Uranians and four Jovians which happened to be in our targeted images; among the latter was one that had been presumed “lost,” S/2003 J 16. Moreover, at Palomar on the first night of the observing run, we serendipitously discovered an object (later designated

Table 1
Satellite Recoveries

| 2009 Jul–Aug | | | 2010 Mar | | | 2010 Sep | | |
|--------------|----------|-----------|--------------|----------|-----------|--------------|----------|-----------|
| Name | σ | rms | Name | σ | rms | Name | σ | rms |
| Jovians | | | Saturnians | | | Uranians | | |
| Euanthe | 3''1 | 4''3 | Hati | 9''8 | 6''9 | Margaret | 16''2 | 24''1 |
| Sponde | 8''8 | 1''6 | Tarqeq | 0''6 | 0''4 | Ferdinand | 26''6 | 7''2 |
| Pasithee | 7''0 | 0''3 | Greip | 6''3 | 9''8 | Caliban* | 0''1 | 0''4 |
| Aoede | 3''3 | 7''7 | Kari | 3''2 | 1''9 | Prospero* | 0''2 | 0''6 |
| Thelxinoe | 3''8 | 6''3 | S/2004 S 7 | 114'' | Not found | Trinculo* | 1''1 | 1''0 |
| Kallichore | 52''4 | 30''7 | S/2007 S 3 | 228'' | Not found | Jovians | | |
| Helike | 31''0 | 1''1 | Tarvos* | 0''2 | 0''5 | Hermippe | 3''3 | 2''1 |
| Carpo | 3''2 | 2''5 | Siarnaq* | 0''1 | 0''8 | Orthosie | 2''9 | 3''8 |
| Eukelade | 8''8 | 11''7 | Fornjot* | 0''5 | 0''6 | Kale | 15''6 | 7''5 |
| Cyllene | 6''4 | 6''0 | Hyrrokkin* | 1''8 | 2''4 | Kore | 8''4 | 11''6 |
| S/2003 J 5 | 244'' | Not found | S/2006 S 3* | 134'' | 144'' | Eurydome* | 2''3 | 7''0 |
| S/2003 J 18 | 246'' | 133'' | | | | Harpalyke* | 0''6 | 0''7 |
| Herse | 551'' | 211'' | | | | Erinome* | 0''2 | 0''5 |
| Uranians | | | | | | S/2003 J 16* | 552'' | 907'' |
| Prospero | 0''8 | 1''9 | | | | S/2010 J 1* | | Discovery |
| Setebos | 0''9 | 0''7 | | | | S/2010 J 2* | | Discovery |
| Ferdinand | 36''6 | Too faint | | | | | | |
| 2010 Oct | | | 2011 Jan–Sep | | | 2011 Oct | | |
| Name | σ | rms | Name | σ | rms | Name | σ | rms |
| Jovians | | | Jovians | | | Jovians | | |
| S/2010 J 1 | 342'' | 930'' | S/2010 J 1 | 43'' | 0''8 | Arche | 9''7 | 7''7 |
| S/2010 J 2 | 712'' | 215'' | S/2010 J 2 | 112'' | 3''0 | 2003 J 16 | 0''5 | 2''6 |
| S/2003 J 16 | 0''6 | 0''7 | Ananke* | 0''04 | 0''3 | 2003 J 18 | 0''7 | 2''2 |
| Harpalyke* | 0''2 | 0''7 | Callirrhoe* | 0''2 | 0''2 | 2010 J 1 | 0''8 | 2''7 |
| Iocaste* | 1''6 | 1''6 | Harpalyke* | 0''1 | 0''6 | 2010 J 2 | 0''3 | 0''6 |
| Erinome* | 0''4 | 0''9 | Iocaste* | 0''2 | 0''8 | Autonoe* | 3''0 | 5''9 |
| Hermippe* | 0''2 | 0''3 | Isonoe* | 0''2 | 0''6 | Aitne* | 2''4 | 0''7 |
| Eukelade* | 0''4 | 0''4 | Hermippe* | 0''4 | 1''7 | Pasithee* | 2''1 | 6''3 |
| S/2003 J 18* | 7''1 | 21''5 | Sponde* | 0''3 | 0''3 | Herse* | 1''8 | 0''8 |
| | | | Mneme* | 0''1 | 0''4 | | | |
| | | | Kore* | 0''4 | 0''2 | | | |

Note. * Bonus satellites for which we obtained astrometry.

S/2010 J 1) that appeared to be a previously unknown Jovian irregular. The object was observed on the following night at both Palomar and CFHT. In addition, on that night at CFHT, C. Veillet discovered yet another potential unknown Jovian irregular (later designated S/2010 J 2). Given this discovery, we re-examined the previous night's observations at Palomar and managed to find this second object. For more details on the discoveries see Alexandersen et al. (2012).

To follow up on the discoveries and the recovery of S/2003 J 16, we were motivated to use CFHT to acquire some more short tracking exposure sequences in 2010 October. In those exposures we found the two moons discovered the previous month, S/2003 J 16, another nearly lost provisional satellite, S/2003 J 18, and five of the named Jovians.

In an effort to avoid “losing” the newly discovered Jovians, we continued observing them with CFHT in 2011 January, August, and September; in August nine of the named Jovians were also found in the exposures. Philippe Rousselot also recovered S/2010 J 1 in 2011 July with the Nordic Optical Telescope on the island of La Palma as part of the campaign to prevent the loss of the discoveries.

Our focus at Palomar in 2011 October was the Jovians discovered in 2010, the two provisionally designated satellites recovered that year, and the omitted backup target. As before

we also selected some easily accessible alternative targets which would benefit from additional observations. We recovered all of the targets and believe that we have definitively confirmed the 2010 discoveries.

Figure 2 compares our pre-recovery uncertainty on the recovery date for each satellite to the discrepancy between its predicted and observed position. Moons below the dashed line were found closer than the method's estimate of the uncertainty, while those above were found further away than the uncertainty indicated. A portion ($\sim 0''.3$ – $1''.0$) of the discrepancy can be attributed to systematic astrometric catalog or plate solution errors. Consequently, it is not surprising that the observed position error for a satellite with a well-determined orbit, e.g., Ananke ($< 1''$ predicted uncertainty), may be significantly larger than its predicted uncertainty. The data collected from the recovery runs have allowed us to evaluate how well the on-sky uncertainties computed from the method correlate with actual discrepancies between the ephemeris and the recovery positions. The results quoted in the table and displayed in the figure confirm the usefulness of the on-sky uncertainties for constraining the search region for recovery.

Three moons, S/2003 J 5, S/2004 S 7, and S/2007 S 3, which had large ($244''$, $114''$, $228''$, respectively) on-sky uncertainties at the time were not found. However, we have a plausible reason for

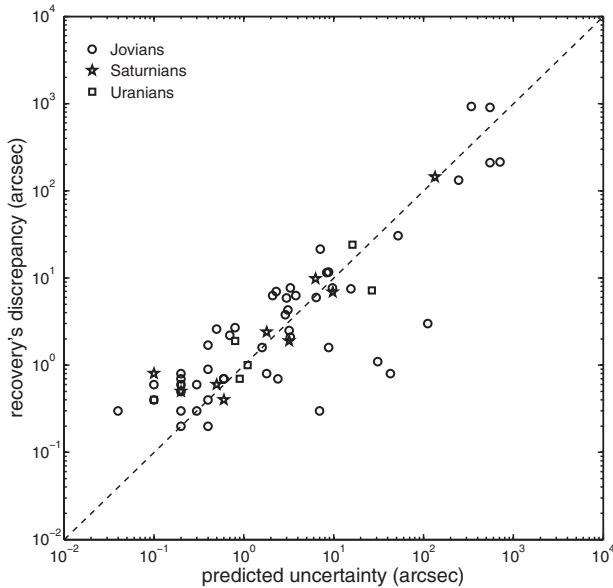


Figure 2. On-sky difference between the observed and predicted position at recovery compared to our method’s computed ephemeris uncertainty on the date of the observation. These results confirm that our method correctly estimates the on-sky uncertainties of irregular moons.

their non-recovery. With the LFC at Palomar we never point the center of the mosaic at the predicted satellite location because if the satellite is near that location its image would fall in the mosaic CCD gaps which run north–south and east–west. Instead, we offset the camera to the southeast by about $3'$ and move the pointing to the cosmetically best chip. In this configuration the coverage of the central four chips in the focal plane extends to at least $5'$ and in some directions may reach up to $12'$ with the exception of narrow strips of sky which fall within the gaps between the CCDs. The unrecovered moons most likely fell outside our working FOV. After reviewing the pointings that we used for these moons, we conclude that S/2007 S 3 had to be at least $1'$ away from its predicted ephemeris position and the other two had to be at least $5'$ away from their predicted positions. Position errors of these sizes are consistent with on-sky uncertainties at the 3σ level and suggests that a larger FOV search away from the current ephemeris will be required to find the satellites.

Our recovery observations, together with almost all of the previous irregular satellite observations, are documented in the Minor Planet Circulars issued by the IAU Minor Planet Center and may be obtained from the Center’s database (MPC 2011b). Jacobson (2000) discusses additional observations of the original eight Jovian irregulars. Much of the data can also be found in the Natural Satellites Astrometric Database (Arlot & Emelyanov 2009).

4.2. On-sky Position Uncertainties

Tables 2–5 contain the maximum on-sky position uncertainties for all of the irregular satellites at roughly 3 and 10 orbital periods beyond 2012 January (the end of the 2011 opposition). For reference we have also included very approximate apparent magnitudes, a geometric description of the orbits in the form of mean orbital elements, the time span over which the satellites have been observed, and the number of observations (right ascension and declination positions are counted separately): Mag is the magnitude, a is the semimajor axis, e is the eccentricity, i is the inclination to the ecliptic, and P is the orbital period. We

derived the elements by fitting a precessing ellipse to each orbit. The magnitudes do not account for phase or rotational variation and should only be used as guide to possible observability with a particular instrument.

The on-sky uncertainties for most of the unnamed Jovian and Saturnian satellites are of the order of thousands of arcseconds and are clearly meaningless; some are actually larger than the Hill spheres of 14,000 and 5000 arcsec, respectively. Because the dominant portion of the orbital uncertainties is “along-track,” the large uncertainties indicate that all orbital phase information is gone, i.e., the satellite could be anywhere along its orbit. In our judgement, satellites with uncertainties exceeding a thousand arcseconds are effectively “lost;” their entries in the table appear in italics.

At the present time, a few moons are not lost but their on-sky uncertainty will exceed $1'$ within 3 or 10 of the moon’s orbital periods after 2012 January. After that point, typically the uncertainties grow rapidly. Table entries given in boldface identify the satellites that have moderate but worsening uncertainties and should be the focus of any near-term observing program. Fortunately, relatively few satellites fall into this category: two Jovians, seven Saturnians, one Uranian, and two Neptunians. Of these, the Jovians discovered in 2011 (Sheppard 2012) are most at risk and must be recovered in the next couple of oppositions. At Saturn, the unnamed satellite, S/2004 S 12, is in the most danger, but the named satellite Aegir is also on the verge of being lost. Its on-sky uncertainty could grow to more than $3'$ in less than 10 years. Ferdinand’s orbit is significantly less well known than the other outer Uranians, but there is ample time to recover it. Its period is more than seven years, consequently its uncertainty should remain under an arcminute for the next century. Similarly, the situation with the Neptunians is not as dire as the table entries might suggest. The problem with Psamathe and Neso is that the observation set does not yet cover a complete orbital period of either; they have orbital periods of 25 and 27 years, respectively.

5. CONCLUDING REMARKS

We have verified our method for estimating the uncertainties on future on-sky positions of the irregular satellites of the giant planets. Our uncertainties guided our efforts to recover several Jovian, Saturnian, and Uranian irregulars, leading to significant improvements in their orbits. As a consequence of our recoveries in 2009–2011, the provisional Jovian S/2003 J 17 was officially recognized and named Herse. We believe that three additional provisional satellites should be considered for recognition; the orbits of 2003 J 16 and 2003 J 18 are now actually better known than a number of the named Jovians, and the orbit of the Saturnian 2006 S 3 is now more certain than that of Aegir. We have also identified a remaining handful of satellites which will be lost in the near future (few decades) without further observation; we strongly recommend that attempts be made to observe them in the next few years because only a small number of additional observations are needed to dramatically reduce their uncertainties to an acceptable level. For the two Neptunians with orbital periods of more than 20 years, it would be desirable to acquire observations spaced over the next couple of decades to provide complete orbital coverage. Last, we have identified the satellites that are effectively lost, i.e., we have very little idea where to point a telescope to observe them; they could be almost anywhere in the planet’s Hill sphere. A new survey of the planetary environs will be required to find them. If “rediscovered” and tracked for several months, however, the

Table 2
Jovian Satellite Mean Ecliptic Orbital Elements, Magnitudes, Observation Time Span and Number, and On-sky Uncertainties

| Satellite | a (Mkm) | e | i (deg) | P (yr) | Mag (R) | Time Span | No. | σ_3 (arcsec) | σ_{10} (arcsec) |
|------------------|--------------|-------|--------------|-------------|----------------|-----------|------|------------------------|---------------------------|
| Himalia | 11.46 | 0.159 | 28.49 | 0.69 | 14.2 | 1894–2012 | 3514 | 0.03 | 0.03 |
| Elara | 11.74 | 0.211 | 27.80 | 0.71 | 16.0 | 1905–2012 | 2230 | 0.04 | 0.05 |
| Pasiphae | 23.63 | 0.405 | 151.34 | 1.94 | 16.8 | 1908–2012 | 3258 | 0.04 | 0.06 |
| Sinope | 23.94 | 0.254 | 158.16 | 1.98 | 18.2 | 1914–2011 | 1708 | 0.07 | 0.11 |
| Lysithea | 11.72 | 0.116 | 27.58 | 0.71 | 18.1 | 1938–2011 | 862 | 0.07 | 0.08 |
| Carme | 23.40 | 0.254 | 165.01 | 1.92 | 18.1 | 1938–2011 | 1946 | 0.09 | 0.15 |
| Ananke | 21.25 | 0.232 | 148.66 | 1.67 | 19.1 | 1951–2011 | 1200 | 0.10 | 0.15 |
| Leda | 11.16 | 0.162 | 27.99 | 0.66 | 19.2 | 1974–2011 | 356 | 0.15 | 0.16 |
| Callirrhoe | 24.10 | 0.280 | 147.08 | 2.08 | 20.8 | 1999–2011 | 190 | 0.3 | 0.6 |
| Themisto | 7.51 | 0.252 | 42.72 | 0.36 | 21.0 | 1975–2011 | 110 | 0.3 | 0.4 |
| Megaclite | 23.81 | 0.416 | 152.83 | 2.06 | 21.7 | 2000–2003 | 100 | 3.6 | 9.0 |
| Taygete | 23.36 | 0.252 | 165.26 | 2.01 | 21.9 | 2000–2003 | 106 | 1.7 | 4.9 |
| Chaldene | 23.18 | 0.251 | 165.16 | 1.98 | 22.5 | 2000–2003 | 100 | 1.6 | 4.7 |
| Harpalyke | 21.11 | 0.229 | 148.75 | 1.71 | 22.2 | 2000–2011 | 168 | 0.3 | 0.6 |
| Kalyke | 23.56 | 0.248 | 165.13 | 2.03 | 21.8 | 2000–2003 | 144 | 1.5 | 3.5 |
| Iocaste | 21.27 | 0.213 | 149.37 | 1.73 | 21.8 | 2000–2011 | 148 | 0.6 | 0.8 |
| Erinome | 23.29 | 0.266 | 164.92 | 1.99 | 22.8 | 2000–2010 | 124 | 0.8 | 1.3 |
| Isonoe | 23.23 | 0.247 | 165.26 | 1.99 | 22.5 | 2000–2011 | 168 | 1.1 | 1.7 |
| Praxidike | 21.15 | 0.228 | 148.93 | 1.71 | 21.2 | 2000–2010 | 118 | 0.7 | 1.4 |
| Autonoe | 24.04 | 0.315 | 152.39 | 2.08 | 22.0 | 2001–2011 | 86 | 1.0 | 1.5 |
| Thyone | 21.20 | 0.229 | 148.54 | 1.72 | 22.3 | 2001–2003 | 60 | 2.4 | 5.4 |
| Hermippe | 21.30 | 0.210 | 150.77 | 1.74 | 22.1 | 2001–2011 | 98 | 0.3 | 0.6 |
| Aitne | 23.32 | 0.263 | 165.06 | 2.00 | 22.7 | 2001–2011 | 74 | 0.9 | 2.1 |
| Eurydome | 23.15 | 0.275 | 150.23 | 1.96 | 22.7 | 2001–2011 | 70 | 0.3 | 0.6 |
| Euanthe | 21.04 | 0.234 | 148.98 | 1.70 | 22.8 | 2001–2009 | 46 | 0.7 | 1.4 |
| Euporie | 19.34 | 0.142 | 145.69 | 1.51 | 23.1 | 2001–2011 | 54 | 1.1 | 2.0 |
| Orthosie | 21.16 | 0.278 | 145.90 | 1.70 | 23.1 | 2001–2010 | 52 | 1.3 | 1.6 |
| Sponde | 23.79 | 0.311 | 150.98 | 2.05 | 23.0 | 2001–2011 | 60 | 1.5 | 3.1 |
| Kale | 23.30 | 0.259 | 164.96 | 2.00 | 23.0 | 2001–2010 | 62 | 1.3 | 2.3 |
| Pasithee | 23.09 | 0.268 | 165.12 | 1.97 | 23.2 | 2001–2011 | 48 | 1.8 | 2.1 |
| Hegemone | 23.57 | 0.346 | 154.21 | 2.03 | 22.8 | 2002–2011 | 78 | 2.0 | 3.5 |
| Mneme | 21.03 | 0.227 | 148.63 | 1.70 | 23.3 | 2002–2011 | 102 | 1.7 | 4.0 |
| Aoede | 23.97 | 0.432 | 158.25 | 2.08 | 22.5 | 2002–2009 | 70 | 1.6 | 3.7 |
| Thelxinoe | 21.16 | 0.219 | 151.37 | 1.72 | 23.5 | 2002–2011 | 64 | 2.2 | 4.6 |
| Arche | 23.35 | 0.250 | 165.02 | 2.00 | 22.8 | 2002–2011 | 78 | 0.9 | 1.7 |
| Kallichore | 23.27 | 0.250 | 165.11 | 1.99 | 23.7 | 2003–2010 | 58 | 1.0 | 2.2 |
| Helike | 21.07 | 0.150 | 154.84 | 1.71 | 22.6 | 2003–2010 | 88 | 0.7 | 1.4 |
| Carpo | 17.06 | 0.429 | 51.67 | 1.25 | 23.0 | 2003–2009 | 78 | 0.8 | 1.4 |
| Eukelade | 23.32 | 0.262 | 165.24 | 2.00 | 22.6 | 2003–2011 | 76 | 0.7 | 1.2 |
| Cyllene | 23.79 | 0.416 | 150.33 | 2.06 | 23.2 | 2002–2009 | 48 | 1.6 | 2.2 |
| Kore | 24.48 | 0.330 | 145.15 | 2.13 | 23.6 | 2003–2011 | 70 | 0.3 | 1.2 |
| Herse | 23.41 | 0.254 | 164.96 | 2.01 | 23.4 | 2003–2011 | 96 | 2.9 | 4.3 |
| 2003 J 16 | 21.10 | 0.227 | 148.67 | 1.71 | 23.3 | 2003–2011 | 196 | 0.1 | 0.3 |
| 2003 J 18 | 20.51 | 0.096 | 146.16 | 1.64 | 23.4 | 2003–2011 | 80 | 0.5 | 1.1 |
| 2010 J 1 | 23.45 | 0.248 | 164.94 | 2.02 | 22.8 | 2003–2011 | 332 | 0.5 | 1.1 |
| 2010 J 2 | 21.00 | 0.223 | 148.58 | 1.69 | 23.2 | 2010–2011 | 232 | 3.5 | 10.4 |
| 2011 J 2 | 23.48 | 0.363 | 153.71 | 2.01 | 23.5 | 2011–2011 | 44 | 98. | 438. |
| 2011 J 1 | 23.45 | 0.260 | 165.16 | 2.02 | 23.7 | 2011–2011 | 34 | 580. | 2529. |
| <i>2003 J 19</i> | 23.53 | 0.256 | 165.12 | 2.03 | 23.7 | 2003–2003 | 20 | <i>1058.</i> | <i>2250.</i> |
| <i>2003 J 5</i> | 23.49 | 0.247 | 165.25 | 2.02 | 22.4 | 2003–2003 | 44 | <i>1223.</i> | <i>3271.</i> |
| <i>2003 J 15</i> | 22.63 | 0.189 | 146.47 | 1.89 | 23.5 | 2003–2003 | 24 | <i>1291.</i> | <i>2699.</i> |
| <i>2003 J 9</i> | 23.38 | 0.263 | 165.05 | 2.01 | 23.7 | 2003–2003 | 34 | <i>3265.</i> | <i>9676.</i> |
| <i>2003 J 23</i> | 23.56 | 0.273 | 146.37 | 2.01 | 23.6 | 2003–2003 | 32 | <i>7664.</i> | <i>14384.</i> |
| <i>2003 J 4</i> | 23.93 | 0.362 | 149.59 | 2.07 | 23.0 | 2003–2003 | 22 | <i>14255.</i> | <i>27641.</i> |
| <i>2003 J 10</i> | 23.04 | 0.430 | 165.10 | 1.96 | 23.6 | 2003–2003 | 22 | <i>16371.</i> | <i>28627.</i> |
| <i>2003 J 12</i> | 17.83 | 0.490 | 150.98 | 1.34 | 23.9 | 2003–2003 | 22 | <i>31124.</i> | <i>59286.</i> |
| <i>2003 J 2</i> | 28.38 | 0.413 | 157.11 | 2.68 | 23.2 | 2003–2003 | 16 | <i>75545.</i> | <i>164913.</i> |
| <i>2003 J 3</i> | 20.22 | 0.198 | 147.54 | 1.60 | 23.4 | 2003–2003 | 30 | <i>81538.</i> | <i>136650.</i> |

Notes. σ_3 is the on-sky uncertainty 3 orbital periods beyond 2012 January, and σ_{10} is the uncertainty 10 orbital periods beyond 2012 January. Entries in boldface identify the satellites that are in danger of being lost, and entries in italics identify those that are effectively lost.

Table 3
Saturnian Satellite Mean Ecliptic Orbital Elements, Magnitudes, Observation Time Span and Number, and On-sky Uncertainties

| Satellite | a (Mkm) | e | i (deg) | P (yr) | Mag (R) | Time Span | No. | σ_3 (arcsec) | σ_{10} (arcsec) |
|------------------|--------------|-------|--------------|-------------|----------------|-----------|------|------------------------|---------------------------|
| Phoebe | 12.94 | 0.163 | 175.77 | 1.50 | 16.4 | 1898–2011 | 6957 | 0.1 | 0.1 |
| Ymir | 23.13 | 0.334 | 173.50 | 3.60 | 21.9 | 2000–2007 | 98 | 0.5 | 1.0 |
| Paaliaq | 15.20 | 0.333 | 46.23 | 1.88 | 21.1 | 2000–2012 | 164 | 0.3 | 0.6 |
| Tarvos | 18.24 | 0.538 | 33.73 | 2.54 | 22.7 | 2000–2010 | 96 | 0.7 | 1.5 |
| Ijiraq | 11.41 | 0.272 | 47.48 | 1.24 | 22.6 | 2000–2007 | 108 | 0.6 | 0.8 |
| Suttungr | 19.47 | 0.114 | 175.81 | 2.78 | 23.9 | 2000–2007 | 112 | 0.6 | 1.4 |
| Kiviuq | 11.38 | 0.332 | 46.77 | 1.23 | 22.1 | 2000–2007 | 92 | 0.6 | 0.9 |
| Mundilfari | 18.65 | 0.210 | 167.45 | 2.61 | 23.8 | 2000–2007 | 74 | 0.8 | 2.5 |
| Albiorix | 16.39 | 0.480 | 34.06 | 2.14 | 20.5 | 2000–2012 | 274 | 0.3 | 0.9 |
| Skathi | 15.64 | 0.272 | 152.63 | 1.99 | 23.6 | 2000–2007 | 92 | 0.7 | 1.5 |
| Erriapus | 17.60 | 0.472 | 34.48 | 2.38 | 23.4 | 2000–2007 | 102 | 1.4 | 3.6 |
| Siarnaq | 18.18 | 0.280 | 45.81 | 2.45 | 19.9 | 2000–2012 | 478 | 0.1 | 0.4 |
| Thrymr | 20.42 | 0.466 | 177.66 | 2.99 | 23.9 | 2000–2007 | 96 | 0.7 | 2.2 |
| Narvi | 19.35 | 0.429 | 145.73 | 2.75 | 23.8 | 2003–2007 | 94 | 0.8 | 2.6 |
| Bebhionn | 17.12 | 0.468 | 35.10 | 2.29 | 24.1 | 2000–2007 | 68 | 1.3 | 3.5 |
| Bergelmir | 19.34 | 0.142 | 158.56 | 2.75 | 24.2 | 2004–2007 | 60 | 5.3 | 12.6 |
| Bestla | 20.14 | 0.520 | 145.16 | 2.98 | 23.8 | 2004–2007 | 62 | 8.6 | 21.4 |
| Fenrir | 22.45 | 0.135 | 164.96 | 3.45 | 25.0 | 2004–2007 | 44 | 10.7 | 25.2 |
| Fornjot | 25.15 | 0.208 | 170.37 | 4.09 | 24.6 | 2004–2010 | 66 | 5.7 | 17.3 |
| Hati | 19.87 | 0.371 | 165.81 | 2.85 | 24.4 | 2004–2010 | 42 | 4.1 | 11.4 |
| Hyrokkin | 18.44 | 0.336 | 151.54 | 2.55 | 23.5 | 2004–2010 | 76 | 0.9 | 2.2 |
| Kari | 22.09 | 0.476 | 156.07 | 3.37 | 23.9 | 2004–2010 | 60 | 2.8 | 8.0 |
| Tarqeq | 17.96 | 0.168 | 46.29 | 2.42 | 23.9 | 2005–2010 | 66 | 0.5 | 1.4 |
| Surtur | 22.94 | 0.446 | 169.69 | 3.55 | 24.8 | 2004–2007 | 42 | 8.9 | 23.6 |
| Greip | 18.46 | 0.315 | 174.80 | 2.57 | 24.4 | 2006–2010 | 48 | 9.5 | 26.8 |
| Skoll | 17.67 | 0.464 | 161.01 | 2.40 | 24.5 | 2004–2007 | 42 | 11.3 | 29.9 |
| Loge | 23.06 | 0.186 | 167.69 | 3.59 | 24.6 | 2004–2007 | 48 | 14.3 | 37.2 |
| Farbauti | 20.39 | 0.241 | 156.52 | 2.98 | 24.7 | 2004–2007 | 50 | 15.5 | 52.4 |
| Jarnsaxa | 19.35 | 0.218 | 163.65 | 2.76 | 24.7 | 2006–2007 | 42 | 23.0 | 81.2 |
| 2006 S 3 | 22.43 | 0.379 | 158.63 | 3.44 | 24.6 | 2006–2010 | 26 | 44.3 | 144.8 |
| Aegir | 20.75 | 0.252 | 166.67 | 3.06 | 24.4 | 2004–2006 | 40 | 82.1 | 208.0 |
| 2004 S 12 | 19.89 | 0.327 | 165.26 | 2.86 | 24.8 | 2004–2005 | 20 | 441. | 1134. |
| <i>2006 S 1</i> | 18.78 | 0.141 | 156.18 | 2.63 | 24.6 | 2006–2006 | 36 | <i>1078.</i> | <i>2284.</i> |
| <i>2004 S 7</i> | 21.00 | 0.529 | 165.69 | 3.12 | 24.5 | 2004–2005 | 20 | <i>2171.</i> | <i>6450.</i> |
| <i>2004 S 17</i> | 19.45 | 0.180 | 168.24 | 2.78 | 25.2 | 2004–2005 | 24 | <i>2175.</i> | <i>5622.</i> |
| <i>2007 S 3</i> | 18.94 | 0.185 | 177.59 | 2.68 | 24.9 | 2007–2007 | 32 | <i>2838.</i> | <i>7695.</i> |
| <i>2007 S 2</i> | 16.72 | 0.179 | 174.06 | 2.21 | 24.4 | 2007–2007 | 28 | <i>3740.</i> | <i>10011.</i> |
| <i>2004 S 13</i> | 18.41 | 0.259 | 168.80 | 2.56 | 24.5 | 2004–2005 | 20 | <i>3762.</i> | <i>8823.</i> |

Notes. σ_3 is the on-sky uncertainty 3 orbital periods beyond 2012 January, and σ_{10} is the uncertainty 10 orbital periods beyond 2012 January. Entries in boldface identify the satellites that are in danger of being lost, and entries in italics identify those that are effectively lost.

Table 4
Uranian Satellite Mean Ecliptic Orbital Elements, Magnitudes, Observation Time Span and Number, and On-sky Uncertainties

| Satellite | a (Mkm) | e | i (deg) | P (yr) | Mag (R) | Time Span | No. | σ_3 (arcsec) | σ_{10} (arcsec) |
|------------------|--------------|-------|--------------|-------------|----------------|-----------|-----|------------------------|---------------------------|
| Caliban | 7.23 | 0.181 | 141.53 | 1.59 | 22.4 | 1984–2010 | 270 | 0.3 | 0.5 |
| Sycorax | 12.18 | 0.522 | 159.42 | 3.53 | 20.8 | 1984–2011 | 474 | 0.2 | 0.4 |
| Prospero | 16.28 | 0.444 | 151.82 | 5.42 | 23.2 | 1999–2010 | 208 | 0.6 | 1.5 |
| Setebos | 17.42 | 0.591 | 158.23 | 6.09 | 23.3 | 1999–2009 | 114 | 1.1 | 4.1 |
| Stephano | 8.01 | 0.225 | 143.85 | 1.85 | 24.1 | 1999–2004 | 82 | 2.4 | 3.5 |
| Trinculo | 8.50 | 0.219 | 166.97 | 2.05 | 25.4 | 2001–2010 | 68 | 1.8 | 2.5 |
| Francisco | 4.28 | 0.132 | 147.25 | 0.73 | 25.0 | 2001–2004 | 28 | 2.6 | 3.6 |
| Margaret | 14.07 | 0.679 | 57.58 | 4.53 | 25.2 | 2001–2010 | 56 | 4.2 | 10.0 |
| Ferdinand | 20.71 | 0.398 | 169.80 | 7.69 | 25.1 | 2001–2010 | 50 | 13.7 | 30.2 |

Notes. σ_3 is the on-sky uncertainty 3 orbital periods beyond 2012 January, and σ_{10} is the uncertainty 10 orbital periods beyond 2012 January. Entries in boldface identify the satellites that are in danger of being lost.

observations could be linked with the existing ones to obtain definitive orbits.

Ephemerides for all of the satellites are available electronically from the JPL Horizons online solar system data and ephemeris computation service (Giorgini et al. 1996), NASA's

Navigation and Ancillary Information Facility (Acton 1996), the Natural Satellites ephemerides facility at the Sternberg Astronomical Institute (Emelyanov & Arlot 2008), or the Natural Satellites Ephemeris Service of the IAU Minor Planet Center (MPC 2011a).

Table 5
Neptunian Satellite Mean Ecliptic Orbital Elements, Magnitudes, Observation Time Span and Number, and On-sky Uncertainties

| Satellite | a (Mkm) | e | i (deg) | P (yr) | Mag (R) | Time Span | No. | σ_3 (arcsec) | σ_{10} (arcsec) |
|-----------------|--------------|-------|--------------|-------------|----------------|-----------|------|------------------------|---------------------------|
| Nereid | 5.51 | 0.751 | 5.03 | 0.99 | 19.2 | 1949–2008 | 1432 | 0.08 | 0.09 |
| Halimede | 16.68 | 0.291 | 112.90 | 5.15 | 24.5 | 1999–2009 | 116 | 0.9 | 2.5 |
| Sao | 22.62 | 0.283 | 49.91 | 7.99 | 25.5 | 2001–2009 | 90 | 1.6 | 4.4 |
| Laomedea | 23.61 | 0.434 | 34.05 | 8.69 | 25.5 | 2001–2009 | 76 | 1.8 | 5.0 |
| Psamathe | 46.70 | 0.462 | 137.68 | 24.99 | 25.5 | 2001–2009 | 72 | 42.6 | 174. |
| Neso | 50.26 | 0.424 | 131.27 | 27.05 | 24.6 | 2002–2009 | 76 | 200. | 401. |

Notes. σ_3 is the on-sky uncertainty 3 orbital periods beyond 2012 January, and σ_{10} is the uncertainty 10 orbital periods beyond 2012 January. Entries in boldface identify the satellites that are in danger of being lost.

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