Transneptunian object ephemeris service (TNOEPH)

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Abstract. We present a web service called TNOEPH (http://asteroid.lowell.edu/) for ephemeris uncertainty prediction and dynamical classification for short-arc transneptunian objects (TNOs). User-supplied observations are transformed to a rigorous sky-plane uncertainty map using the technique of statistical orbital ranging. We show examples of the growth of ephemeris uncertainty with time, and give the probabilities of different dynamical classifications for a few short-arc TNOs.

1. Introduction

The availability of rigorous ephemeris uncertainty predictions is crucial for efficient recovery and follow-up observations of short-arc transneptunian objects (TNOs). Ephemeris uncertainty estimations for TNOs are provided either as services (e.g. the Minor Planet Center[1]), or by sharing the software needed for the computations (e.g. Bernstein and Khushalani, 2000).

The limitations and disadvantages of the existing ephemeris uncertainty estimation techniques for TNOs have been discussed by Virtanen et al. (2003). The common limiting factor of all these methods is that they are approximations; more rigorous methods should be used for TNOs having very short observational arcs (of, say, a few weeks or less) to derive the orbital uncertainties properly.

We present a web service called TNOEPH[2] (Transneptunian Object Ephemeris), which computes and displays a geocentric astrometric ephemeris for a TNO using user-supplied observations. It is based on an inversion method termed statistical [orbital] ranging (Virtanen et al., 2001; Muinonen et al., 2001), which is a powerful orbit computation

[1] See http://cfa-www.harvard.edu/cfa/ps/mpc.html
[2] See http://asteroid.lowell.edu/cgi-bin/virtanen/tnoeph

tool for sparsely observed objects and/or short observational arcs—criteria that the majority of the known TNOs meet (Virtanen et al., 2003; Tancredi and Virtanen, 2003). Muinonen and Bowell (1993) laid out the theoretical basis for a statistical Bayesian treatment of the orbital inversion problem, and used it for long-arc objects. Statistical ranging is built on the same theoretical basis, but it is particularly suitable for short-arc objects.

In what follows, we first give a short description of the technique of statistical ranging in Section 2. In Section 3, we describe the output of `TNOEPH`. We explain how the various plots can be used to maximize the efficiency of recovery and follow-up observations. We also show some examples of the evolution of ephemeris uncertainty with time, and some examples of dynamical classification. Our conclusions are summarized in Section 4.

2. Statistical orbital ranging

The probability density of TNO orbital elements is examined using Monte Carlo selection of orbits in orbital element space in the following way:

- Two observations are chosen, and angular deviations in right ascension (R.A.) and declination (Dec.) are introduced.
- Topocentric ranges (distances) are assumed corresponding to the observation dates.
- A trial orbit is computed and compared to all observations. If the trial orbit fits the observations to predefined accuracy, it is added to the sample of possible orbits.

Topocentric range intervals are determined from the 3-σ cutoff values of the range probability density. By increasing the number of generated sample orbits ($10 \rightarrow 200 \rightarrow n$) , the range intervals are improved and an unbiased phase space region of possible orbits is found.

3. Ephemeris prediction and dynamical classification

The projection of the orbital element distribution onto the sky at a given date results in sky-plane uncertainty regions. Since every sample orbit is assigned a probability depending on how well it fits the observations, the ephemeris uncertainty region is not just a two-dimensional

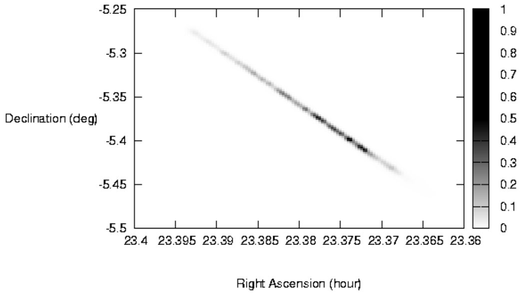

Figure 1. Ephemeris probability density function for 2001 QE_{298} at time of the follow-up observation. The object was observed in the area where probability peaks. The maximum value of the colour coded probability has been normalized to unity.

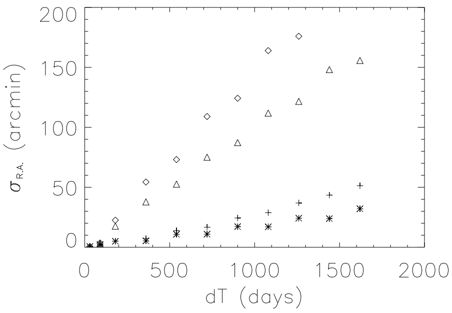

Figure 2. The standard deviation of the predicted R.A. as a function of the time elapsed from the last observation. Different symbols correspond to different objects and different observational arcs (in days): 2002 PK_{149}: 1 (diamond), 2002 PD_{149}: 30 (triangle), 2001 $QE_2 98$: 63 (plus), 2002 CX_{224}: 110 (star).

map of the sky, but a three-dimensional map containing both the sky-plane coordinates and the corresponding probabilities (Fig. 1).

The standard deviation of the predicted R.A. grows nearly linearly with time (Fig. 2). Usually, an object most in need of additional observations also has a wide distribution of current and future ephemeris uncertainty. `TNOEPH` offers the user two means to narrow down the distribution: orbital element filtering and dynamical classification.

3.1. Orbital element filtering

The user can make use of the computed orbital element distribution to search for correlations between the position uncertainty and the orbital elements (the uppermost plots in Fig. 3). Noting that the se-

Table I. Probabilities for different dynamical classes after follow-up observations (prior values in parenthesis). In these cases, the classical belt probability increase, while the overrepresented scattered disk probability (see Virtanen et al. (2003)) decrease as a function of the observational arc.

Object	Obs. arc (days)	Probability for dynamical classification (%) Classical belt	Outer belt	Scattered disk	Plutino
2001 QE_{298}	360 (63)	29 (5)	0 (6)	50 (87)	0 (0)
2001 QT_{322}	358 (74)	50 (23)	0 (7)	0 (43)	1 (2)
2002 CX_{224}	288 (110)	44 (17)	4 (13)	51 (67)	0 (0)

mimajor axis, eccentricity, and inclination are often highly correlated with position, one can impose limits to these orbital elements, which considerably shrink the region to be searched.

Bearing in mind that the majority of known TNOs are on low- to moderate-eccentricity orbits, the user can center the search at the position corresponding to the minimum eccentricity orbit.

3.2. Dynamical classification

The classification of orbital type is a straightforward application of the orbital element probability densities. We have adopted the dynamical classification of the transneptunian region from Virtanen et al. (2003).

`TNOEPH` computes the sky-plane uncertainty regions and the probabilities for each dynamical class (the lowermost plots in Fig. 3). As a trade-off for faster calculations, the user is only allowed to compute a relatively small number of sample orbits. Due to this limitation, the probabilities remain just order of magnitude estimates. Probabilities for different dynamical classes for a few TNOs before and after follow-up observations are given in Table I.

4. Conclusion

The service now offered should be considered as a precursor of future services. We are planning to offer real-time services based on an observational database and located in Helsinki. These new services are planned to offer rigorous solutions not only for short-arc objects, but also for long-arc objects. The novel methods needed to achieve this goal are under development. With the help of the supercomputing facilities available, the new services will be significantly faster than the present `TNOEPH`, which is running on a workstation.

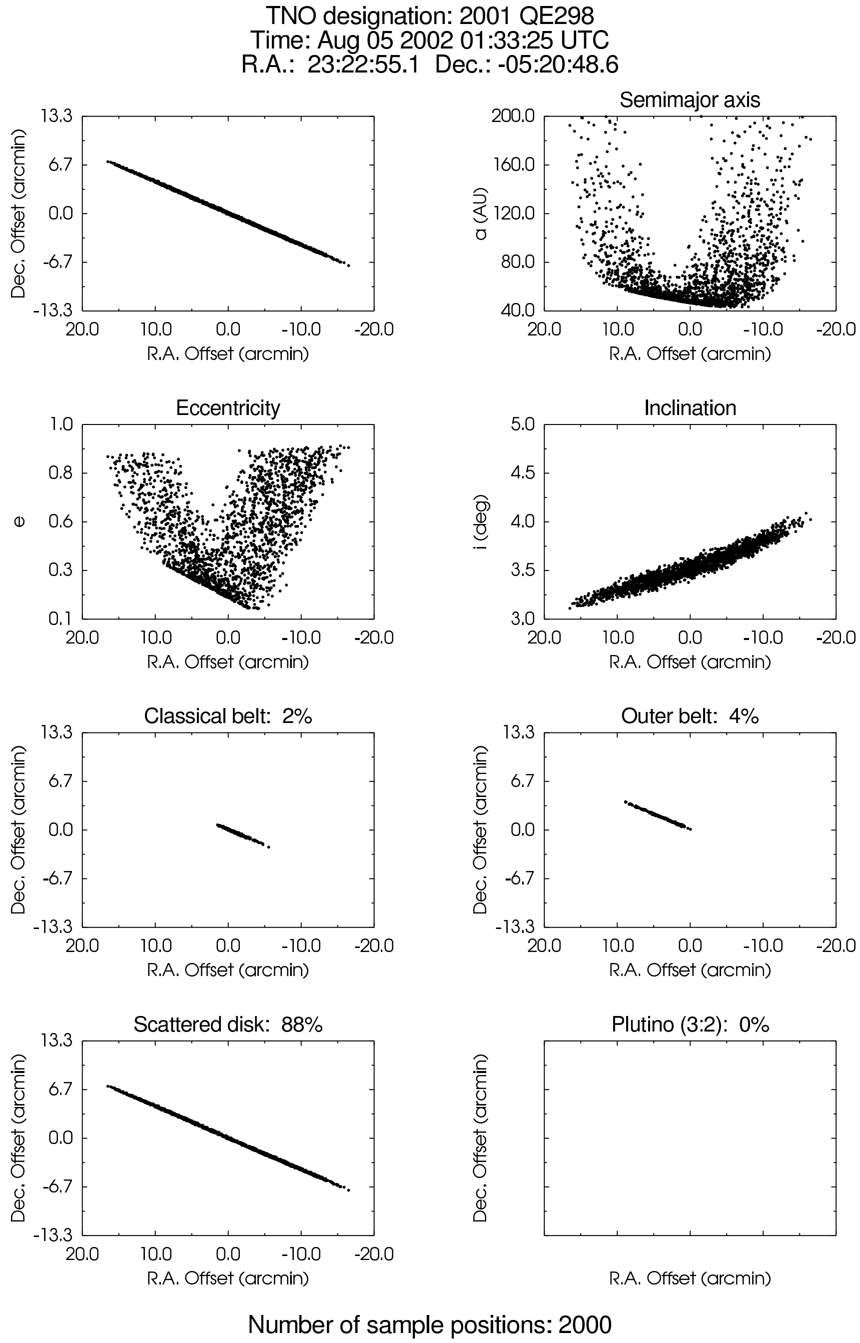

Figure 3. **TNOEPH** output for 2001 QE_{298} (9 observations spanning 63 days). The user can narrow the sky-plane ephemeris uncertainty by applying *a priori* knowledge on the orbital element distribution and/or dynamical classification.

In future services, visualization will be changed from two-dimensional plots with dots (Fig. 3) to contour plots (Fig. 1) containing information on the probability. We will also perform dynamical filtering of the orbits, i.e. exclude orbits with small minimum orbital intersection distances with respect to planets.

Statistical ranging does not contain any assumptions of the target body, as long as the orbit is Keplerian. Therefore, it can be used on other minor planets (e.g. near-Earth objects) as well. We are currently upgrading the techniques so that the user does not need to have prior knowledge of the dynamical class of the object.

Linkage software using statistical ranging is also under development. The software, which is particularly suitable for very short-arc objects, is potentially to be used in connection to both space missions such as the European Space Agency's GAIA, and groundbased surveys such as the Lowell Observatory Near-Earth-Object Search, Búsqueda Uruguaya de Supernovas, Cometas y Asteroides, and the potential Nordic survey of near-Earth objects.

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