A Giant Step: from Milli- to Micro-arcsecond Astrometry
Proceedings IAU Symposium No. 248, 2007
W. J. Jin, I. Platais & M. A. C. Perryman, eds.

doi:10.1017/S1743921308020115

Astrometric data for NEAs extracted from the infrared DENIS survey

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Abstract. When astrometric data can be extracted from archives, this generally allows us to get very strong constraints for the orbital modeling of Solar System objects. This is particularly important for Near-Earth Asteroids. We have developed tools in the Virtual Observatory framework in order to carry out such a task. We have applied them to the DENIS survey. This survey has been performed from 1995 to 2001 in the I, J, K' spectral bands with a 1m telescope at ESO La Silla. Many sources associated to Solar System Objects have been identified and we present our preliminary results.

Keywords. astrometry, surveys, asteroids

1. Introduction

The orbital models of Near Earth Objects (NEO) can be drastically improved when a long enough time of astrometric observations is available for a fit. In case of detection of new objects, we know that any old observation can be very important for this improvement and consequently for estimating the risks of collision. Nowadays, the numerous sky surveys available provide with a huge amount of astronomical observational data for which their mining requires fast and reliable processing tools in order to detect and identify Solar System objects, in particular to seek for precovery observations. With this goal, we have developed some specific tools within the Virtual Observatory (VO) framework: SkyBoT, and its data-mining pipeline counterpart AstroId wich performs an automatic identification of the Solar System Objects present in astronomical archives. We have applied this VO workflow on the sources catalogue of the infrared survey DENIS, obtaining valuable astrometric results related to many asteroids.

2. The DENIS survey

The DENIS infrared survey was operating between 1995 and 2001 from the 1 meter telescope at ESO La Silla (Epchtein *et al.* 1999). Three bands were used -I, J K'- and a specific observation strategy was established in order to get a wide scan of the southern sky: 5206 strips (a column-like scan of the sky at a fixed right ascension), each containing 180 12x12 arcmin frames. The limiting magnitudes were 18.5 (I), 16.5 (J) and 14 (K'). As a result of the survey, a large catalogue of sources (around 355 mill. point sources) was generated and made available. The initial goal of the DENIS survey was to produce one of the first large infrared catalogues directly digitized, allowing the study of several

astrophysical objects, in particular the distribution of various stellar populations in our Galaxy and the research on the "missing mass". Initially, it was not addressed for the study of Solar System Objects and much less for the astrometry or the dynamics of such objects. Nevertheless, a preliminary study done in 2001 (Baudrand *et al.* 2001) and 2004 (Baudrand *et al.* 2004) showed that valuable asteroids observations could be extracted from it despite its low astrometric accuracy at about 1 arcsec. However, this work was very limited due to the lack of specific, automatic tools and to the low number of asteroids known at that time.

3. SkyBoT, a VO tool for Solar System objects identification

The fast and accurate identification of Solar System objects on a given stellar field at a certain epoch is not a trivial problem. In order to give an answer to that question, we have developed a powerful tool -SkyBoT (Sky Body Tracker)- within the Virtual Observatory (VO) framework. This tool is based on the pre-computation of a large database of asteroid ephemerides. To this date, more than 380 000 asteroids have been identified. Their orbital elements are regularly computed and stored on the publicly-accessed "Astorb" database from the Lowell Observatory (Bowel 2007). SkyBoT computes the asteroids ephemerides in advance for a period of time within 1949-2009, and then a PHP/MySQL software deals with these data. First, it divides the celestial sphere in boxes of about 20 arcmin in size and determines in advance all the asteroids present in each box on a 10-days interval basis. The equatorial and heliocentric coordinates are associated to each box and asteroid for further interpolations. This computation is based on an accurate numerical integration weekly updated in sync with the update of the Astorb database of orbital elements. Furthermore, we also provide ephemerides for the planets and for 33 of their natural satellites by means of an on-line connection to their dynamical models. Therefore, a query providing the date (on the 1949-2009 interval) and the coordinates of the FOV center, the characteristics of the Solar System objects identified in that field are returned after a few seconds of time (depending on the FOV size). SkyBoT implementation as a web service permits any external software using standard VO protocols to include it as part of its VO workflow. It has already been implemented in Aladin -the CDS (Centre de Donnes de Strasbourg) Sky Atlas (Bonnarel *et al.* 2000)- and is publicly available through this software since 2006, as well as through the address skybot.imcce.fr

4. AstroId, a VO Workflow for data mining

One of the key concepts behind the Virtual Observatory framework is interoperability, which in fact makes this platform well adapted for instance to cross correlations of data between multiple VO users or VO data centers. In this context, we have developed a pipeline based on the use of the SkyBoT tool. This VO workflow, called AstroId, furnishes the users with the capability of data-mining extensive archives with the purpose of identifying the Solar System objects (SSO) contained in them. AstroId's input comprises, on one hand and for SkyBoT identification purposes, information on the date, coordinates of the centre and FOV of the different images from the archive; and, on the other hand, the extracted sources catalogue for correlation purposes. This correlation part consists of a cross-matching of "SSO candidates" with point sources by means of a Chi-square statistical test (based on angular distance as well as astrometric accuracies) and a comparison of magnitudes (although this latter will require a more extensive development in the future). At this point the user disposes of a certain amount of choice to tune up the correlation based on his particular needs. The "SSO candidates" come from

https://doi.org/10.1017/S1743921308020115 Published online by Cambridge University Press

Table 1. Number of asteroids detected in the analysis of the DENIS survey.

	Number of associations	Number of objects
Correlated objects	16 993	15181
Correlated NEO	308	273
Precovery objects	9975	9221
Precovery NEO	198	176

the catalogued celestial bodies that our VO web service SkyBoT furnishes as an output for each FOV (ephemeris computation). Moreover, on this correlation module we also do a pre-matching of sources with "non-SSO" objects in order to eliminate some stars from the cross-matching pipeline. For these "non-SSO" objects we have made use of the NOMAD catalogue (a compilation of the Hipparcos, Tycho-2, UCAC2 and USNO-B1.0 catalogues) accessed through the VizieR VO service from the CDS. Finally, as for the output, AstroId provides a set of lists (VOTable documents) containing the identified and unidentified SSO with respect to their reference sources.

5. Mining the DENIS survey: first results

We have applied a first prototype of AstroId to explore the DENIS survey in search for Solar System objects. In this sense, the previous work done by Baudrand (Baudrand *et al.* 2004) provided some promising results by detecting 1931 asteroid positions from the DENIS sources catalogue thanks to conventional means and a limited list of 9000 known objects. In comparison, our workflow has made use of 40 times more catalogued SSO as well as of several stellar catalogues. This work has allowed us to detect numerous asteroids and, in particular, various Near-Earth asteroids. Our results are given in Table 1 where we show the number of observations (point sources) associated to SSO (among those catalogued in SkyBoT) and the resulting number of SSO identified (once we take into account the multiple observations).

These results are giving us the opportunity to improve the dynamical models of several asteroids, specially those that have been recently discovered and have not been observed for a long period of time. While this application is still in progress, we have already made multiple tests on several detected objects. Let us consider for the sake of illustration, the main belt asteroid 2005 ED93. On one hand we have identified 3 DENIS observations of this body (all dating back from 1998) and, on the other hand, we have had at our disposal about 51 other astrometric observations made between 2003 and 2007. Our dynamical model fitted on these 51 old observations gave a preliminary orbit in large discrepancy with the DENIS observations, with the O-C being around 5-6 arcsec in right ascension and declination at the time of the DENIS observations (1998). Therefore these new observations furnished by DENIS appear to be a strong constraint for the orbit as the comparison between the preliminary orbit and the orbit fitted on the whole set of observations exhibits differences in R.A. and declination as large as 8 arcsec in 1999 and 2002. These differences correspond to a shift of around 12000 km in space in 10 years of time. We note that the discrepancy is small in the time period where observations were already available and so used in the model's fit. Therefore, this example perfectly illustrates the usefulness of data mining on improving orbits of asteroids and in particular for NEOs.

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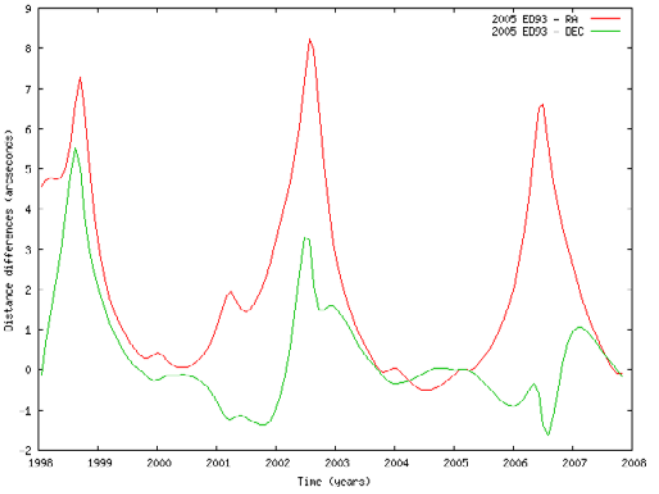

Figure 1. Asteroid 2005ED93: Shift in right ascension and declination between the orbital model fitted on the observations available before this analysis and the orbital model obtained by including the DENIS observations. This shift corresponds to about 12,000 km over a 10-year period

6. Conclusion

Thanks to a set of Virtual Observatory compliant tools, we have explored the DENIS sources catalogue, performing an identification of the Solar System objects present in that survey. The first of this tools -SkyBoT- is a VO web service which can be implemented on a user's software and which is also publicly available either through our web site or through the CDS service Aladin. The second tool -AstroId- which is still in the prototype phase, is also aimed to become a publicly available service. AstroId is a VO workflow dedicated to the data mining of large surveys in search for Solar System Objects (and so it makes use of SkyBoT). In this case, we have applied AstroId to exploit the DENIS infrared survey which was done on the 1995-2001 period at ESO-La Silla. As a result, we have detected 15181 Solar System objects, including 273 Near-Earth Objects including about around 170 NEO precoveries which must be now confirmed. The first test that we have made to test the applications of this concept has proved to be very encouraging as the new data discovered has provided some strong constraints that can be applied to the orbital modeling of these objects.

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https://doi.org/10.1017/S1743921308020115 Published online by Cambridge University Press