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The importance of Near Earth Object detections on archival images: recent results and future potential

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Abstract. Astronomical archives represent an immense source of information for the detection of past images of Near Earth Objects. Archives are very important for NEO work because the identification of suitable images leads to the acquisition of very good orbital information, which, in turn, allows astronomers to perform more accurate studies of their dynamical evolution and characterization, as well as improve assessments of their impact hazard. After a brief historical introduction we present recent results from current activities and we outline future directions.

Key words. Asteroids – Astrometry – Metods: numerical – Tecniques: photometric

1. Introduction

In recent years discussions regarding searches for *Near Earth Objects* (NEOs - asteroids and comets, NEAs refers just to asteroids) (Shoemaker et al. 1979) have concentrated on the *hazard* aspect of these bodies. In addition to theoretical studies, various publications have discussed the best methods to discover a significant fraction of the larger NEOs within a limited amount of time. These achievements convinced NASA to invest some resources on a mid-term survey, the so-called *Spaceguard Survey* whose goal is to achieve 90% discovery of km-sized NEOs in about 10 years. A dedicated NEO Program Office was also set up at NASA-JPL to coordinate the search work. The preliminary results of such efforts can be best understood by looking at fig. 1, which shows a great increase in the NEO discovery rate starting in 1998.

However, hazard mitigation requires much more than just discovery: above all, we need very good orbits and this can be achieved by obtaining astrometric positions over a long period of time. Orbital improvements are obtained both with follow-up observations immediately after discovery for the calculation of a reliable orbit and, subsequently, with recovery observations at other convenient apparitions years later. Recovery observations are a very important step of the process. There are generally four methods for obtaining astrometric data at a

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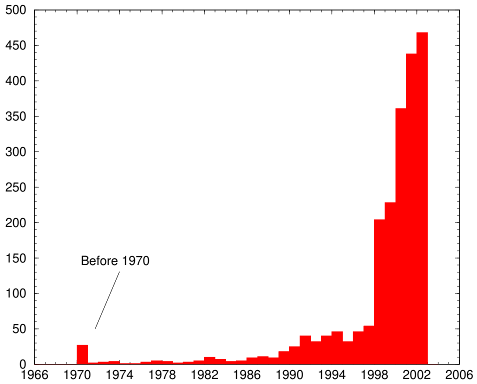

Fig. 1. The NEO discovery rate over the past 30 years.

second apparition: i) direct recovery at the telescope at some future epoch (for simplicity we will define these as **R**); ii) identification of the object with data already existing (**I**); iii) accidental rediscovery of the object (**A**); iv) direct recovery search on archival material (photographic or CCD - **P**).
This last type of recovery is called *precovery* and there are several good arguments to support this activity: i) it is often the quickest method to obtain very good orbits of newly-discovered bodies: this is a great opportunity in case of objects that possess non zero collision probabilities; ii) it saves a lot of telescope time and money too; iii) it is a day-time activity, not affected by the weather.

1.1. Historical background

Precovery searches for minor bodies (comets and asteroids) are not a new activity, and in the recent past they led to scientifically valuable results even beyond the astrometric work: for example, the identification of the Amor-type object (4015) = 1979 VA with the periodic comet Wilson-Harrington (1949 III) on two plates from POSS-I showed clear evidence that the distinction between asteroids and comets is not very straightforward. After some regular activity carried out in Australia in 1990-1996 as part of the AANEAS project (Steel et al. 1997) and, to a smaller extent in the USA, NEO precovery work was restarted systematically in 1999 when two dedicated teams, *DANEOPS* in Germany and *ANEOPP* in Italy, begun their activities. These initiatives as well a few others were heavenly stimulated by the following factors:

- *A much higher NEO discovery rate* (due to the NASA search programs): it simply means that if there are more discoveries, there are more opportunities for precovery identifications.
- *Development of the WWW (easier access to various databases)*: this technology is avoiding to us expensive visits to the places where archives are stored. For example, the *Digital Sky Survey* (DSS) represents an excellent, widely used, database where photographic archival images are stored and retrievable. Other databases are releasing data in near real time, such as *SkyMorph* (especially for CCD work by the NEAT program).
- *Improvements of the services of the Minor Planet Center*: all NEO astrometric observations are freely disseminated on a daily basis through their *MPEC-DOUs (Daily Orbit Updates)*. Other orbit calculation centers are processing the astrometric data in near real time (see next).
- *Improvements in orbital computations and collision analysis*: fueled in large part by observational efforts to discover NEOs, recent theoretical studies allow i) to calculate the object sky uncertainty; ii) to develop tools for finding objects with poor orbits; iii) to locate collision orbits, compatible with the data available, in near real time as soon as the data of a new object become available: since we don't know *a priori* if these orbits are the real ones, the virtual objects associated with them were defined as *virtual impactors* (Milani et al. (2000)). The main centers making such calculations are NEODyS in Pisa, Italy, Sentry at NASA JPL facil-

ity, California and Lowell Observatory in Arizona (though not every center performs all these tasks).

2. Steps to search for a NEA on an archival image

The *Arcetri NEO Precovery Program*, (*ANEOPP*), is a dedicated project started in mid-1999 at the Arcetri Observatory in Florence, by A. Boattini and G. Forti taking advantage of the photographic plate copy collection available at the observatory (Boattini et al. (2001)). At various stages other people became involved with this initiative: Roy Gal, Germano D'Abramo, Mike Read, Maura Tombelli and Luciano Tesi. The *modus operandi* that we have been using with ANEOPP can be summarized as follows:

- As soon as a preliminary orbit of an object becomes available, we produce a set of fully perturbed n-body ephemerides with the *Orbfit* software (see later).
- These ephemerides are *crossed-checked* with the catalog file of each archive to produce a list of suitable plates/films/images (some description of the process is provided in 2.2).
- The third step consists in separating the list of suitable images depending both on the difficulty to retrieve them, and, once available, on the likelihood of finding the object.
- Every reliable candidate, with motion vector and magnitude close to the predictions is considered and measured using the USNO A2.0 astrometric catalogue.
- As soon as we have astrometric data for one or more candidates, we proceed to attempt an orbital linkage between the two (or more) sets of positions obtained at different apparitions.

2.1. Search strategies and techniques

This paragraph provides a quick overview about the search techniques. In the real work we have to deal with two main problems:
- The *sky uncertainty* (*SU*) of the object on a particular image taken at a specific epoch.
- Devise efficient ways to cover the sky uncertainty region.

To address the first issue we need to remind that each set of astrometric data, which is thought to belong to a specific object, contains a certain amount of error. From this data it is generally possible to calculate a preliminary orbit. It is also possible to represent the uncertainty of this orbit by a *confidence region* in the six-dimensional space of orbital elements. In order to derive the *SU* from this region, either a linear and non-linear theory can be used. In addition to the work done in the 90' at Lowell Observatory by E. Bowell and K. Muinonen, a team led by A. Milani at the University of Pisa has developed increasingly complex algorithms to deal with cases of intrinsic difficulty. These algorithms have been implemented in a software package called *Orbfit*, which has been used in our precovery program. In the classic approach (i.e. in the framework of the linear theory - small uncertainties), asteroid recovery was performed following a line in the sky, obtained by slightly varying the object's *mean anomaly* from the nominal orbit. By doing so we obtain a line in the sky plane and this is called *line of variation* (*LOV*). Actually, this line is a confidence ellipsoid, whose projection in the sky is an ellipse. Usually this ellipsoid is elongated only in the direction of the mean anomaly, so that it appears essentially as a straight line segment. The *multiple solution* method (Milani et al. (2000)) appears as the most effective approach to search for objects whose orbital information is too poor to rely on a single orbit: the *effectiveness* refers to a compromise between heavy and time consuming calculations (required by a full nonlinear theory) with the computation time. The method consists in sampling the confidence region into a swarm of *virtual asteroids*, with a family of differing orbits, all compatible with the observations (unlike before here we are more interested in locating the real object rather then checking for collision orbits). Since the confidence region contains a continuum of orbits, each virtual asteroid is representative of a small region, due to its own orbital uncertainty, but to a much smaller degree. The multiple solution approach gives uniformly spaced (in σ units) solutions along the LOV.

2.2. Candidate plates

As regards to the second problem, the identification of the objects, we start with an evaluation of the effort required to achieve a reasonable chance of success, though there are no guarantees that an image of the object will be found. In order to obtain a list of plates/films/images where the target could be located we need to define a *search window (SW)* which is a square window of a size to be defined,which is always centered on the target's nominal position in the sky. The *cross-checking* process defines the SW by comparing the position of the center of each plate from the catalogue with the nominal position of the target at the time the plate was exposed. If the angular distance between these two points is smaller than a certain number, which depends on the size of the Schmidt field of View ($SFOV$), then the object's position will be inside the $SFOV$ and the target can be detected if it is brighter than a specific threshold (see next also). When a plate meets these requirements it is defined as a *candidate plate.* In order to be sure that no candidate plates are left undetected, the size of the SW must be as large as the $SFOV$. For each object we generate an *output file* listing all of its candidate plates. Unfortunately a real search is always more difficult because we must keep into account the object SU. In particular, when we need to use the multiple solutions approach, if n is the number of orbital solution considered, then the cross-checking process is repeated n times, resulting in n output lists of candidate plates. By combining the contribution of all the candidate plates from these lists we can estimate our chances of finding one or more precovered images.

2.3. Proposing attributions

Acquiring *astrometric data* and *securing attributions* are the final important steps of the process. We use some general criteria to propose a *reliable attribution* or identification to the *Minor Planet Center* (MPC): i) the object must be located near the LOV; ii) the predicted and measured angular rates and magnitudes must agree; iii) the measured angular rates should allow the observer to discriminate it from objects belonging to more common orbital classes. If this is not the case it becomes of even higher priority to search for additional image to confirm the candidate. Before moving further additional minor factors need to be considered; iv) the orbital linkage between the new data (which provides the starting orbit) and the old data must be successful; v) finally, in case of an insecure identification, the data could be held either by the working group or the MPC before being released.

2.4. Trailing loss and filters

There are other important issues to deal with: the *trailing loss*, is the loss in limiting magnitude due to the target's angular rate. For long photographic exposures it may account easily 3 to 5 magnitude loss respect to fixed objects. CCD images suffer much less for this problem due to their shorter exposures and higher sensitivity. The use of different *filters* has an impact as regards to the deepness of the image and the expected limiting magnitude.

3. Results and statistics

Out of a total known NEA population of 2150 bodies (here we discriminate the cometary component), about 700 NEAs

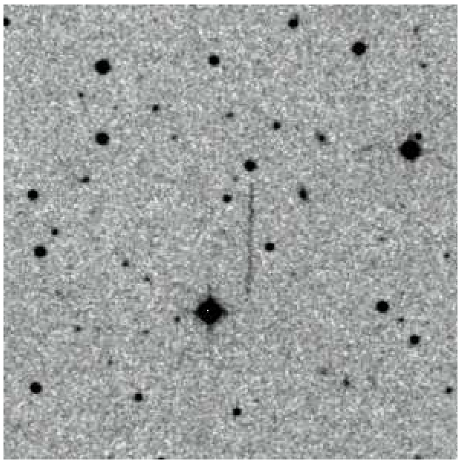

Fig. 2. An example of the trailing loss effect: the precovery image of 2000 BF_{19} as it appears on a red plate taken in the course of the POSS-II survey on October 4, 1991. Located by the ANEOPP team, this object is of visual magnitude 18 on this picture.

have been observed at two or more apparitions. According to the scheme outlined in par. 1, the recovery circumstances can be summarized as follows:

- **R** > 300
- **A** $= 30$
- **I** $= 50$
- **P** < 250

As can be seen the contribution of precoveries (**P**) has been very remarkable: more than 80% of this contribution was provided only in these last three years. This includes the results of ANEOPP whose contribution accounts for the identification of about 100 NEAs previously observed only in the course of one apparition. A similar number of objects was precovered by the DANEOPS team.

3.1. Most prolific archives

For several reasons some archives have been much more prolific than others in providing precovery images of NEOs: limiting magnitude, survey observing mode, strategies, data easily accessible and well maintained are some of the important keys to success. Here we provide a brief overview (**P** stands for photographic, **C** for CCD):

– **UK Schmidt Telescope** 1.2-m - Siding Spring, Australia - part of *DSS* - (**P**). So far, the most productive photographic resource.
– **Palomar Sky Survey - I - II** 1.2-m - Mount Palomar, California, part of *DSS* - (**P**).
– **PCAS and PACS** 0.46-m Schmidt, Mount Palomar, California, *old* NEO survey programs - (**P**).
– **NEAT** program, two 1.2-m telescopes at Palomar and Maui (Hawaii) - (**C**). It is currently the most productive CCD resource.
– **Other collections**: CFHT, SLOAN, HST (all **CCD**), Lowell Observatory archives and the 1.1-m Schmidt at ESO - (all **P**).

Going beyond the above list, we need to remind that many additional archives are not accessible in any comfortable way. The most desiderable collection is from the 1.2-m Schmidt at Mount Palomar obtained between the two sky surveys, *POSS-I* and *POSS-II.*

3.2. The Spaceguard Central Node

A fairly complete inventory of archival resources and general information on the precovery activities of the teams involved is described on a specific web site of the *Spaceguard Central Node* (*SCN*). Set up in 1999 with a financial contribution by ESA, the SCN is an international center dedicated to the coordination of the follow-up astrometric activities on NEOs and has been operating regularly for the past three years.

4. Archive management

There are more than two million astronomical plates/films (professional collections) to

be exploited. It is often quite difficult to access the data, sometimes there is no catalog file available. CCD archives are quickly developing (some come from the same NEO survey programs), international collaboration and exchange of information. The important question is how to make full use of past and present archives, and to characterize the future ones. In order to answer to this problem it is essential to address these issues:
a) **Huge amount of data** (*terabytes*): there is a need for the creation of an astronomical institution that could collect and organize all the digital material of photographic and CCD archives, as well as more basic information such as catalog files. A viable path is to investigate the support of space agencies. They have enough experience with databases of this size and might be interested in forms of collaborations.
b) **Lack of information on several archives**: it remains still of primary importance to fund many single projects in order to make their archival information available in a comfortable, non-expensive way to the community.

5. Concluding remarks

Although any survey/archival resource could be very useful for NEO astrometric work, we need to outline the following remarks:

- *NEOs can appear anywhere in the sky.*
- *To discover NEOs* it is necessary to cover a lot of sky on a regular frequent schedule.
- *Faint magnitudes must be reached with short exposures*
- *Avoid the use of filters* or limit to the use of R or V bands.
- *Discriminate minor planets from fixed objects*

The continuous synergy between observers and orbit computers, each driving advances in the other's research, is the key to success to various activities in the NEO field, including the archival work.

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Appendix

This is a list of related web sites. For any other useful reference, please refers to Boattini et al. (2001). *The Arcetri NEO*

Precovery Program
`www.arcetri.astro.it/science/aneopp`

DANEOPS projects
`earn.dlr.de/daneops`

The Spaceguard Central Node
`spaceguard.rm.iasf.cnr.it`

The Minor Planet Center
`cfa-www.harvard.edu/iau/mpc.html`

NEODyS database
`newton.dm.unipi.it/neodys`

NEO Program Office - JPL, NASA
`neo.jpl.nasa.gov`

Lowell Observatory - asteroid services
`asteroid.lowell.edu`

SkyMorph
`skyview.gsfc.nasa.gov/skymorph/`

The Spaceguard Foundation
`spaceguard.rm.iasf.cnr.it/SGF/`

References

Boattini, A., D'Abramo, G., Forti, G. & Gal, R. 2001, A&A 375, 293
Milani, A., Chesley, S. R., Boattini, A. & Valsecchi, G. B. 2000, Icarus 145, 12
Shoemaker, E. M., Williams, J. G., Helin, E. F. & Wolfe, R.F. 1979, in Asteroids, ed. T. Gehrels, 253