Mining the ESO WFI and INT WFC archives for known Near Earth Asteroids. Mega-Precovery software *

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Abstract: The ESO/MPG WFI and the INT WFC wide field archives comprising 330,000 images were mined to search for serendipitous encounters of known Near Earth Asteroids (NEAs) and Potentially Hazardous Asteroids (PHAs). A total of 152 asteroids (44 PHAs and 108 other NEAs) were identified using the PRECOVERY software, their astrometry being measured on 761 images and sent to the Minor Planet Centre. Both recoveries and precoveries were reported, including 143 encounters of known Near Earth Asteroids (NEAs) and Potentially Hazardous Asteroids (PHAs) which could be searched in any archive for serendipitous recoveries and precoveries (apparitions before discovery) including all known NEAs, PHAs, as well as all other numbered and provisionally named asteroids catalogued to date. Using this server, we searched the CFHTLS archive finding 143 encounters of known NEAs and PHAs (Vaduvescu et al., 2011a).

A recent similar initiative coordinated with the EURONEAR efforts includes a citizen-science project led by E. Solano from the Spanish Virtual Observatory (SVO, 2011) (Solano et al., 2011). Following its press announcement (Tristan, 2011), this Spanish service has registered more than 3,000 users who measured and reported recoveries and precoveries for all known asteroids. Using PRECOVERY, all known asteroids could be searched in any archive for serendipitous recoveries and precoveries (apparitions before discovery) including all known NEAs, PHAs, as well as all other numbered and provisionally named asteroids catalogued to date. Using this server, we searched the CFHTLS archive finding 143 encounters of known NEAs and PHAs (Vaduvescu et al., 2011a).

1 Introduction

Telescopes endowed with large field mosaic cameras having their images archived and stored for public online access are becoming very appealing nowadays to data mining work for many science aims. One of such aim involves the improvement of the orbital knowledge of the Near Earth Asteroids (NEAs) and Potentially Hazardous Asteroids (PHAs) which is one of the aims of the European Near Earth Asteroid Research (EURONEAR) project since 2006. To achieve this goal, few years ago we introduced the PRECOVERY software devoted to search all known asteroids to date in any archive uploaded as a simple observing log recorded in a standard format (Vaduvescu et al., 2009). This tool uses the SkyBoT web service (Berthier et al., 2006) to predict accurate positions for all known asteroids. Using PRECOVERY, all known asteroids could be searched in any archive for serendipitous recoveries and precoveries (apparitions before discovery) including all known NEAs, PHAs, as well as all other numbered and provisionally named asteroids catalogued to date. Using this server, we searched the CFHTLS archive finding 143 encounters of known NEAs and PHAs (Vaduvescu et al., 2011a).
more than 600 positions of some 150 NEAs (Solano, 2011). Besides its public outreach value, this work has a meritorious contribution to report moving sources not detected by the SDSS automated detection algorithm and not published in the SDSS moving source catalogues (Ivezić, 2008). The above number of detections could be compared with another SDSS NEO project which found 104 NEAs in the SDSS archive (Kent et al., 2009).

A similar focused tool of NASA was announced recently (Yau et al., 2011). The Moving Object Search Tool for NEOWISE and IRSA (MOST) is a new web-based server that enables researchers to look for serendipitously observed solar system objects (NEAs, asteroids and comets) contained in the images held by the NASA/IPAC Infrared Science Archive (IRSA), including single epoch exposures from WISE. MOST takes as input an object name or set of orbital parameters.

Part of a student bachelor project, the ESO/MPG WFI archive (1999 to 2003) was data mined for photometry of known asteroids using the Astro-WISE and SkyBoT servers (Bout, 2007). Taking into account three selection parameters, the author measured mostly two colour photometry from 354 occurrences of 144 asteroids (primarily Main Belt Asteroids - MBAs) on 1380 WFI images.

Another asteroid data mining tool was announced recently (Gwyn et al., 2011). The Solar System Object Search (SSOS) of the Canadian Astronomical Data Center (CADC) allows users to search for images from a variety of archives for single moving objects, accepting as input either an object designation, a list of observations, a set of orbital elements or a user-generated ephemeris for an object.

During the last years we applied our PRECOVERY work to other large field archives, also applying our work to other data mining facilities (Vaduvescu et al., 2009; Vaduvescu et al., 2011a). In the same frame of the EURONEAR project, we introduced the Mega-Precovery project (Popescu et al., 2010; Popescu and Vaduvescu, 2010; Popescu and Vaduvescu, 2011), a web service dedicated to data mining of image archives for some given asteroids. Using this tool, one could search one or more existing archives for any given asteroid or a list of few asteroids (numbered or provisionally numbered).

In the present paper we present new data mining contributions carried out in the frame of EURONEAR project. Firstly, the ESO/MPG WFI and INT WFC archives observed between 1998 and 2009 are mined for all known NEAs and PHAs. We distributed this workload to a team of 13 Romanian students and amateur astronomers, thus the project has some educational aim, besides its main EURONEAR development role. Secondly, we present our public new EURONEAR data mining service Mega-Precovery, together with its associated Mega-Archive. Throughout this paper and conform with our two previous papers, we define “precoveries” as apparitions before discovery date (Steel, 1997).

The paper is structured in 5 sections. Section 2 presents the ESO/MPG WFI and INT WFC archives, giving an overview of their basic characteristics. Section 3 presents the data mining results, counting the encounters of NEAs and PHAs, listing the precoversies and recoveries at a new or the last opposition whose orbital improvement is analyzed. Section 4 presents Mega-Precovery software and its associated Mega-Archive. Section 5 lists the conclusions and a few related projects.

2 Data Mining the WFI and WFC Archives

Until the apparition of the SDSS 2.5m survey in 2000 and later the dedication of Pan-STARRS 1.8m survey telescope in 2007, the ESO/MPG 2.2m telescope equipped with the WFI mosaic camera and the INT 2.5m telescope endowed with the WFC mosaic camera have been two of the most powerful 2m class large field facilities in the world. Available since 1999 and 1998, respectively, and still operating partially devoted to survey work, these two facilities have given to European astronomers access to both hemispheres using mosaic cameras more than half degree field each.

2.1 ESO/MPG WFI Archive

The Max Planck Garching (MPG) 2.2m telescope is owned by the European Southern Observatory (ESO) in La Silla, Chile. In 1999 the Wide Field Imager (WFI) was mounted at the Cassegrain $F/5.9$ focus of the ESO/MPG (Baade et al., 1999). WFI is a mosaic camera consisting of a $2 \times 4$ CCDs $2K \times 4K$ pixels each, covering a total field of view of $34' \times 33'$ (0.30 square degrees) with a pixel scale of $0.24''/pix$.

In this paper we studied the ESO/MPG WFI archive during the period 25-10-1999 (first light) to 27-08-2009 (when we started this ESO project), although WFI has continued to be offered by ESO and MPG beyond this date. During this period, the WFI acquired 96,913 science images.

In Figure 1 (top) we plot in cyan (fainter dots) the WFI sky coverage during the above period. This shows random pointings between $\delta \sim -90^\circ$ and $\delta \sim +30^\circ$ driven by various science interests with some small patches covered by few extragalactic programs. We draw in magenta (fainter curve) the ecliptic, which has been followed by at least two NEA survey and follow-up programs led by Boattini et al., 2004; Vaduvescu et al., 2011b and other Solar System work led by other PIs.

2.2 INT WFC Archive

Owned by the Isaac Newton Group (ING), the 2.5m Isaac Newton Telescope (INT) is installed in the Northern European Observatory of Roque de los Muchachos (ORM) in La Palma, Canary Islands. Since 1998 the prime focus of the INT houses the Wide Field Camera (WFC) which
Fig. 1 The sky coverage of the ESO WFI and INT WFC archives whose observed fields are plotted as cyan (fainter) dots. Both hemispheres are covered randomly, including few sky patches and the galactic plane covered by a few surveys. We overlay with blue (larger) dots the NEAs and PHAs encountered in this work and with magenta (fainter curve) the ecliptic.

3 Results

3.1 Found Objects

Run with the two archives and assuming a safe limiting magnitude \( V = 23 \), PRECOVERY reported a total of 7,123 candidate images (1,535 for the ESO WFI archive and 5,588 for the INT WFC archive). These images were inspected, then astrometrically resolved and measured by our team in a distributed but homogenous manner. After inspection and search, only 761 images from the initial candidates resulted in reported positions, which represents only 11\%. This dramatic decrease could be explained by some factors, led by the optimistic limiting safer magnitude \( V = 23 \), the exposure time, proper motion, Moon phase, weather conditions, airmass, uncertainty in some ephemerides and magnitudes, used filters, etc.

In Figure 2 we overlay with blue (larger) dots the NEA and PHA fields measured in the two archives (ESO WFI above and INT WFC bellow). In both archives the NEA findings are spread randomly with respect to the ecliptic up to high ecliptic latitudes \( (\beta \sim 40^\circ) \), in agreement with the optimistic limiting safer magnitude \( V = 23 \), the exposure time, proper motion, Moon phase, weather conditions, airmass, uncertainty in some ephemerides and magnitudes, used filters, etc.
Fig. 2  Histograms showing the exposure time used in the ESO/MPG WFI archive (above) and the INT WFC archive (below). Relatively short exposures (less than 1-2 minutes) were mostly used, making the two archives suitable for searching NEAs affected by the trail loss effect.

with the known distribution of the inclinations of the NEA population. In total, 152 objects were measured and reported, namely 44 PHAs (15 in the ESO and 29 in the INT archive) and 108 other NEAs (40 in the ESO and 68 in the INT archive). 124 objects have datasets included within the timespan of their existing arcs. For a total of 28 objects we were able to prolong the existing arcs by new or last opposition datasets. From these, 18 objects represent precoveries (8 in the ESO archive and 10 objects in the INT one) and 10 objects represent recoveries at a new opposition or prolonged arcs at the last opposition (6 in the ESO and 4 in the INT archive).

Fig. 3  Histograms showing the predicted $V$ magnitude of the encountered NEAs and PHAs in the two surveys (ESO WFC top and INT WFC bottom). A limit around $V \sim 22$ was reached in both archives, consistent with 2m facilities.

Figure 3 shows the histogram of the predicted $V$ magnitude for the encountered objects in the two archives (ESO WFI above and INT WFC bellow). Both datasets show fainter objects around $V \sim 22$, according to the limiting magnitude of 2m-class telescopes imaging moving asteroids with relatively short exposures (less than \sim one minute).

Using PRECOVERY and Mega-Precovery (presented in Section 4), one could search the two archives for apparitions of any other given asteroid(s), including precoveries of new NEAs and PHAs catalogued after August 2009 (the end of our work). We plan to update soon these archives beyond 2009.
3.2 Astrometry

Like in our previous distributed work involving students and amateurs, we used the Astrometrica software (Raab, 2012) to resolve the astrometry of the fields. After resolving and aligning the multiple images of the same field, we searched for the asteroids in the candidate images by blinking the images, finally measuring manually the asteroid positions. We used quadratic sky-plate transformation and the USNO-B1 catalog that allowed in average identification of about 50-100 reference stars in each CCD which was resolved individually.

Figure 4 plots the O-C residuals (observed minus calculated positions) of the objects measured by us in the ESO WFI archive (above) and the INT WFC archive (below). Residuals are mostly clustered around origin for the ESO WFI archive (standard deviation $0.56''$ and average deviation $0.34''$), these being mostly dominated by catalog errors and measurements. The INT WFC residuals (right) show a larger spread (standard deviation $0.72''$ and average deviation $0.53''$) mostly due to the larger known WFC field distortion in the prime focus of the INT which is larger than that of the ESO WFI Cassegrain camera.

Because most exposure times were quite short (less than one-two minutes) most asteroid apparitions show stellar or small elliptical aspect easily fitted by Astrometrica which measures their centres in respect to mid-exposure time. We encountered also few longer trails caused by longer exposures for which we measured in the same manner the two ends, then we measured the average position corresponding to the mid-time exposure.

Using FITSBLINK asteroid residual server calculator (Skvarc, 2012) we checked the astrometry for possible errors which could include bad measurement of few faint targets, faint objects affected by nearby bright stars, possible confusion caused by larger sky uncertainties, etc. Then we reported the two datasets (one for each archive) to Minor Planet Center (MPC). These include 316 positions of 55 objects found in the ESO archive and 445 positions for 97 objects found in the INT archive. After minor revision from the MPC (Spahr & Williams, 2011) and our careful re-measurement of five objects (3% of the total), MPC accepted and published the astrometry (Elst et al., 2011 for the ESO archive and Fitzsimmons et al., 2011 for the INT archive).

3.3 Orbital Improvement

The mined data for the 152 found objects was used to ameliorate orbits of the encountered NEAs and PHAs. Most of the data improved the density within the existing arcs, the observing date being contained in the existing orbital arc timeframe. For 28 objects we prolonged the existing orbital arcs by new oppositions or last opposition datasets, adding 18 precovers and 10 recoveries. In the Appendix Table A1 we list these 28 cases of NEA and PHA encounters representing precovers and recoveries at a new or the last opposition. Four of these objects (2005 CG41, 1996 XX14, 2003 MK4 and 2002 DH2) were previously reported to MPC in 2005, being observed by other PIs. We mark these objects with an asterix in Table A1 and Table A2. In the third column we list the orbital arc length before and after our datamining work. A few cases represent major encounters, namely:
precoversies at the first opposition: 2005 TU45 (arc prolonged by 5 years), 2005 MB (extended by 2 years), 2009 TG10 (extended by 6 years), 2009 NA (from 5 months to 9 years), 2006 PW (from 1 year to 5 years), 2009 HW2 (from 3 days to 2 months), 2009 SP171 (from 2 months to 2 years), 2009 FU23 (a very desirable PHA whose arc was prolonged from 2 months to 7 years) and 2006 KA (from 2 years to 6 years);

recoveries at the last opposition: 1996 XX14 (arc prolonged from 2 months to 8 years), 2003 MK4 (PHA very desirable, extended arc from 2 months to 2 years), 2002 DH2 (from 4 months to 3 years) and 1994 JX (arc increased by 5 years).

We compare the orbits of the precovered and recovered objects fitted with FIND ORB software (Gray, 2012) using their published positions (full orbital arc) available via MPC. In the Appendix Table A2 we list the orbital elements obtained excluding our data (first line) and including our data (second line). Orbits of most asteroids were improved using our mined data, namely the $\sigma$ residuals in last column decreased for most. In only 3 cases $\sigma$ residuals increased, namely: 2009 HW2 (from the INT archive, from $\sigma = 0.43''$ to $\sigma = 0.48''$), extended arc from 3 days to 2 months), 2001 XK105 (ESO archive, from $\sigma = 0.61''$ to $\sigma = 0.63''$, for which only two images were encountered), and 2006 KA (ESO archive, from $\sigma = 0.49''$ to $\sigma = 0.53''$, for which only one image was available showing a long trail for which we reported the middle and the two ends taking into account the predicted proper motion).

4 Mega-Precovery

Despite some recent data mining efforts, the vast collection of CCD images and photographic plate archives still remains insufficiently exploited. PRECOVERY covers all catalogued asteroids (including all known NEAs and PHAs), but the search of an entire archive could take quite a long time, typically about 10 hours for some 10,000 square degrees sky coverage of a single archive. Therefore, some dedicated tool to target one or very few selected objects is necessary to speed up data mining of asteroids, including important NEAs and PHAs.

In this sense we designed Mega-Precovery, with the aim to fasten and target the search of one or some few important objects, such as PHAs or Virtual Impactors (VIs). Given this, we propose to search very large collections of archives for images which include one or a few selected known asteroids in their field. There are two components of this project:

– the database (named Mega-Archive) which includes the individual instrument archives, namely the observing logs for their science CCD images or plates available from a collection of instruments and telescope around the globe. The Mega-Archive is an open project allowing other instrument archives to be added later for exploration by anybody who would like to contribute;

– the Mega-Precovery software for data mining the Mega-Archive for the images containing one or a more desired catalogued objects (NEAs, PHAs or other asteroids) included in a local daily updated MPC database;

The input of Mega-Precovery consists of: 1. a selection of the instrument archives to be searched (including the option to search either one or all the existing archives in the same time) and 2. the specified asteroid or list of few asteroids given by their names, numbers or provisional designations. The output of Mega-Precovery consists of a list of candidate images in which the searched object is expected to be visible based on two main thresholds, namely the expected limiting magnitude of the archive and the expected positional uncertainty of the searched object (provided by the user based on the currently known orbit).

The definition file containing the instrument archives includes the following data: the filename keeping the telescope observing logs, the observatory code, the width and height of the field (both in degrees, in the direction of $\alpha$ and $\delta$, respectively), the start and end Julian Date defining the timespan of the archive and the limiting magnitude $V$ expected from the given telescope and instrument.

4.1 Mega-Precovery Archive

For easier identification of the images, the Mega-Archive is split into more instrument archives, each corresponding to a given telescope and camera. Table A3 lists the available instrument archives and their basic characteristics. Besides these standard archives, Mega-Precovery leaves the user the flexibility to add his/her own instrument archive given in the same standard format, by loading the file to be run by the server. As of August 2012, the Mega-Archive counts about 2.5 million images from 28 instrument archives available for search via Mega-Precovery. This collection includes all archived ESO imaging instrument, most archived NVO imaging instruments (National Virtual Observatory of the United State), the INT WFC, CFHTLS, Subaru SupimeCam and the AAT WFC archives.

4.2 Mega-Precovery Software

The Mega-Precovery software is written in PHP, being embedded on the EURONEAR website (EURONEAR, 2012) as a public access application under the Observing Tools section. Figure 5 presents the flowchart of this software. To run Mega-Precovery application, the user needs to load the webpage using any internet browser (block User interface in Figure 5). In order to create the query, one needs to provide the following information to the web interface:

1. http://archive.eso.org/eso/eso_archive_main.html
2. http://portal-nvo.noao.edu
3. http://casu.ast.cam.ac.uk/casuadc/archives/narchive/@@query.html
4. http://www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/cadcdbin/cfht/cfht/quick/form
5. http://smoka.nao.ac.jp/search.jsp
6. http://apm5.ast.cam.ac.uk/arc-bin/wdbaast_database/observation_log/make
A list of names, numbers or provisional designations of the asteroid(s) to search;

- The selection of the instrument archives to be searched for (the first default option ALL allowing to search the entire Mega-Archive);

- The field Uncertainty used to accommodate for the uncertainty in telescope pointing plus the uncertainty in position of the searched object due to its (sometime more insecure) orbit. Based on extended tests, for this parameter we recommend the default value 0.02° but this should be increased in case of poorly known objects or less accurate pointing. Increasing too much this parameter (more than ~ 1°) would result in selection of false candidate images (false detections);

- The email address where Mega-Precovery could announce the user about the end of long runs and the FTP space where the user should download the data; this includes the same information given in the web browser after the end of the run.

After the user submits the query, this is processed by Mega-Precovery in the block Processor of the input, then the accurate ephemerides for each archive dates and the given body (bodies) are calculated in the Ephemerides query block. This step uses the IMCCE’s ephemeris service Miriade [Berthier et al., 2009] [IMCCE, 2012a] which is queried for some discrete times covering the entire queried telescope archive(s), then accurately interpolated the positions for the observing dates given in the archive (the block Interpolator).

We used a five order Bessel interpolation model [IMCCE, 2012b], choosing for the Miriade ephemerides a step based on the asteroid proper motion, namely 1 day for objects moving slower than 2 degrees daily and 1 hr for objects faster than this limit. Using this fine time step we ensure sufficient accuracy (< 1′) for most NEAs and PHAs passing close to Earth affected by very fast proper motion. For NEAs and PHAs away from close encounters with the Earth, and also for MBAs, the interpolator precision is very accurate (about 1′). The parameters for the interpolation where established as a tradeoff between processing time and predicted position accuracy and were validated by extensive tests.

Each image of the archive is defined by a rectangular box given by the telescope pointing, the width and height field of view stored with each instrument archive entry. If the predicted position falls within the field of the current image bounded by the Uncertainty area, then the current entry is selected as a candidate image to hold the queried asteroid. This step is done in the Selector block.

Like in PRECOVERY, the format of each instrument archives follows the same standard format listing one observation (telescope pointing) on each line which includes the image ID (name of the image file), the Julian date (start of observation), exposure time (sec), telescope pointing (α and δ at J2000 epoch), width and height of the field of view (towards α and δ axis frame, both in degrees), and a eventually comment (which could include the filter, etc), all separated by "|

The output of Mega-Precovery consists in a list including the images and the corresponding CCD number predicted to contain the queried object(s). The results are displayed both in the web interface (visible only at the end of the run) and sent via e-mail to the user (in case this option was selected). The user can search the images in the online instrumental archive, then download, inspect and measure the data related to this asteroid based on his/her own scientific interest (astrometry, photometry, etc).

5 Conclusions and Future Work

Two wide field 2m class telescope archives, ESO/MPG WFI and INT WFC, comprising about 330,000 images were mined to search for serendipitous encounters of known NEAs and PHAs. Two master archives were built based on the observing logs of the two facilities. Using the PRECOVERY software, a total of 152 asteroids (44 PHAs and 108 other NEAs) were identified and measured on 761 images and their astrometry was reported to Minor Planet Centre (MPC). Both recoveries and precoveries were reported, including prolonged orbital arcs for 18 precovered asteroids and 10 recoveries, plus other 124 recoveries. We analyze all recoveries and recoveries at a new or last opposition by comparing the orbits fitted before and after including our datasets. Following the PRECOVERY project, we present Mega-Precovery, a new search engine focused on data mining of many instrument archives simultaneously for one or few given asteroids. A total of 28 instrument archives have been made available for mining, adding together about 2.5 million images forming the Mega-Archive.

Few other projects are in plan within the frame of EU-RONEAR data mining of NEAs. Few months ago we started datamining of the Subaru SuprimeCam archive using PRECOVERY. Another important project will be to extend the mining capabilities of the Mega-Precovery. Another project plans to apply Mega-Precovery to search the entire Mega-Archive in order to recover and improve orbits of some important VIs, PHAs and NEAs. Finally, we plan to continue to enlarge the Mega-Archive, adding new instrument archives, including CCD cameras and photographic plates.

In this sense, any observatories, especially those endowed with large field imaging instruments, are welcomed to contribute to this open source project.

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developed at IMCCE and accessed by PRECOVERY and Mega-Precovery, respectively. Acknowledgements are also due to Bill Gray, the author of FINDORB software, for his very prompt assistance in order to upgrade his very robust and user-friendly code for fitting orbits. Mega-Precovery archive is based on data obtained from the ESO Science Archive Facility, the NOAO Science Archive served by the National Virtual Observatory of the United States, Subaru-Mita-Taka-Kiso Archive (SMOKA), the Canadian Astronomy Data Centre (CADC) and CASU Astronomical Data Centre (United Kingdom). This work has made use of SAOImage DS9 developed by Smithsonian Astrophysical Observatory. We are thankful to Minor Planet Centre, specifically to Tim Spahr who pointed out a few errors in the reported positions. Final acknowledgements are due to the referee David Asher for careful reading and advice to improve our paper.

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A Appendix: Data Tables
Table A1 28 objects found in the ESO and INT archives include 18 precovered asteroids and 10 recovered objects whose arcs were prolonged by a new opposition or at the last opposition. Besides the asteroid name we give its MPC classification (acc. to Jan 2012 database), the number of positions, the length of the orbital arc (before and after our astrometry) and the archive. Four objects marked with an asterix were reported also by other PIs in 2005.

| Asteroid          | Classification          | Nr. pos. | Arc (before/after) | Archive |
|-------------------|-------------------------|----------|--------------------|---------|
| Extended Arcs at First Opposition (Precoveries): |
| 2005 CG41 *       | NEA desirable           | 12       | 3d/4d              | ESO     |
| 2005 TU45 (231134)| NEA desirable           | 4        | 3y/8y              | ESO     |
| 2005 MB           | NEA very desirable      | 3        | 3y/5y              | ESO     |
| 2004 XP164 (216707)| NEA desirable           | 5        | 4y/5y              | ESO     |
| 2009 TG10         | NEA very desirable      | 6        | 3y/9y              | ESO     |
| 2009 NA           | NEA very desirable      | 3        | 5m/9y              | ESO     |
| 2002 HQ11 (159677)| NEA desirable           | 2        | 5y/6y              | ESO     |
| 2001 XK105        | NEA extremely desirable | 2        | 2m+10d             | ESO     |
| 2006 WT1          | PHA very desirable      | 6        | 4m/5m              | INT     |
| 2002 TY57 (250162)| NEA desirable           | 7        | 5y+2m              | INT     |
| 2006 PW           | NEA very desirable      | 2        | 1y/5y              | INT     |
| 2009 HW2          | NEA extremely desirable | 8        | 3d/2m              | INT     |
| 2009 SP171        | NEA very desirable      | 2        | 2m/2y              | INT     |
| 2005 BY1          | NEA very desirable      | 12       | 10m/11m            | INT     |
| 2009 FU23         | PHA very desirable      | 2        | 2m/7y              | INT     |
| 2005 VC2          | NEA very desirable      | 5        | 3m/4m              | INT     |
| 2006 KA           | NEA very desirable      | 3        | 2y/6y              | INT     |
| 2000 FL10 (86666)| NEA desirable           | 3        | 8y/9y              | INT     |

| Extended Arcs at Last Opposition (Recoveries): |
| 1996 XX14 *       | NEA very desirable      | 7        | 2m/8y              | ESO     |
| 2003 MK4 *        | PHA very desirable      | 7        | 2m/2y              | ESO     |
| 2002 DH2 *        | NEA very desirable      | 8        | 4m/3y              | ESO     |
| 1994 JX           | NEA very desirable      | 8        | 9y/14y             | ESO     |
| 2004 RS25         | NEA very desirable      | 2        | 3y+1m              | ESO     |
| 1999 WK11 (102873)| NEA desirable           | 6        | 28y+1m             | ESO     |
| 2005 GN59 (164400)| PHA desirable           | 2        | 31y+3m             | INT     |
| 2002 EQ9 (163191) | NEA very desirable      | 2        | 5y+10d             | INT     |
| 2007 DK           | NEA very desirable      | 4        | 5y+7m              | INT     |
| 2005 CA (189263)  | NEA desirable           | 4        | 30y+4d             | INT     |
### Table A2

Extended arcs of NEAs and PHAs at first opposition (precoveries) and last opposition (recoveries). Comparison of the orbits fitted without our data (first line) and including our data (second line). Orbital elements fitted with FINDORB at epoch $JD = 2456000.5$ listing the asteroid name, semimajor axis $a$, eccentricity $e$, inclination $i$, longitude of the ascending node $\Omega$, argument of pericenter $\omega$, and mean anomaly $M$, followed by the minimal orbital intersection distance MOID (AU), number of fitted observations $\text{Obs}$ and the root mean square residual of the fit $\sigma$. Four objects marked with an asterisk were reported also by other PIs in 2005.

| Asteroid | $a$ (AU) | $e$ | $i$ (deg) | $\Omega$ (deg) | $\omega$ (deg) | $M$ (deg) | MOID (AU) | $\sigma$ ($\sigma$) |
|----------|----------|-----|----------|---------------|---------------|-----------|-----------|------------------|
| 2005 CG41 $^*$ | 1.0007879 | 0.2845687 | 19.09737 | 137.74366 | 233.38300 | 89.72675 | 0.0902 | 8 | 0.98 |
| 2005 TU45 | 1.9737518 | 0.4959595 | 28.53919 | 120.24291 | 76.86254 | 154.0739 | 0.2669 | 808 | 0.31 |
| 2005 MB | 0.9852658 | 0.7927082 | 41.39802 | 86.66029 | 42.80966 | 53.24388 | 0.0840 | 80 | 0.40 |
| 2005 CA | 2.7290438 | 0.5890431 | 16.75355 | 72.67897 | 202.31389 | 202.31389 | 0.0845 | 212 | 0.5 |

**Extended Arcs at First Opposition (Precoveries):**

- **Asteroid**
- **$a$ (AU)**
- **$e$**
- **$i$ (deg)**
- **$\Omega$ (deg)**
- **$\omega$ (deg)**
- **$M$ (deg)**
- **MOID (AU)**
- **$\sigma$ ($\sigma$)**

**Extended Arcs at Last Opposition ( Recoveries):**

- **Asteroid**
- **$a$ (AU)**
- **$e$**
- **$i$ (deg)**
- **$\Omega$ (deg)**
- **$\omega$ (deg)**
- **$M$ (deg)**
- **MOID (AU)**
- **$\sigma$ ($\sigma$)**

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Table A3  28 instrument archives available in August 2012 in the *Mega-Archive* used by *Mega-Precovery* adding together about 2.5 million images. We list the telescope, instrument, number of images (thousands rounded), archive start and end date, field of view (in arcmin), number of CCDs (for mosaics) and estimated $V$ limiting magnitude suitable to detect NEAs.

| Telescope       | Instrument | Nr. images | Start Date   | End Date   | FOV′  | CCDs | $V$ |
|-----------------|------------|------------|--------------|------------|-------|------|-----|
| **ESO Instruments:** |            |            |              |            |       |      |     |
| VLT 8.2m        | FORS1      | 36,000     | 23-01-1999   | 26-03-2009 | 6.8 x 6.8 | 2   | 26  |
| VLT 8.2m        | FORS2      | 111,000    | 30-10-1999   | 25-02-2012 | 6.8 x 6.8 | 2   | 26  |
| VLT 8.2m        | HAWKI      | 69,000     | 01-08-2007   | 24-02-2012 | 7.5 x 7.5 | 4   | 26  |
| VLT 8.2m        | ISAAC      | 199,000    | 01-03-1999   | 25-02-2012 | 2.5 x 2.5 | 1   | 26  |
| VLT 8.2m        | NACO       | 275,000    | 02-12-2001   | 29-02-2012 | 1.0 x 1.0 | 1   | 26  |
| VLT 8.2m        | VIMOS      | 66,000     | 30-10-2002   | 28-02-2012 | 12.8 x 16.0 | 4   | 26  |
| VLT 8.2m        | VISIR      | 67,000     | 11-05-2004   | 26-02-2012 | 0.5 x 0.5  | 1   | 26  |
| VISTA 4.1m      | VIRCAM     | 230,000    | 16-10-2009   | 22-06-2011 | 46.3 x 46.3 | 16  | 25  |
| VST 2.6m        | OmegaCam   | 19,000     | 01-04-2011   | 15-03-2012 | 58.4 x 58.4 | 32  | 24  |
| NTT 3.5m        | EMMI       | 18,000     | 17-03-2004   | 01-04-2008 | 9.1 x 9.1  | 2   | 25  |
| NTT 3.5m        | SOFI       | 126,000    | 30-03-2006   | 15-02-2012 | 4.9 x 4.9  | 1   | 25  |
| NTT 3.5m        | SUSI2      | 17,000     | 02-04-2004   | 29-12-2008 | 5.5 x 5.5  | 2   | 25  |
| ESO 3.6m        | EFOSC2     | 47,000     | 03-07-2004   | 16-03-2012 | 4.1 x 4.1  | 1   | 25  |
| ESO 3.6m        | TIMMI2     | 64,000     | 08-05-2004   | 28-06-2006 | 1.6 x 1.2  | 1   | 25  |
| ESO/MPG 2.2m    | WFC        | 124,000    | 20-06-1998   | 25-02-2012 | 33.6 x 32.7 | 8   | 23  |
| **AURA NVO Instruments:** |            |            |              |            |       |      |     |
| KPNO 4m         | MOSAIC     | 33,000     | 01-09-2004   | 27-06-2012 | 36 x 36  | 8   | 25  |
| KPNO 4m         | NEWFIRM    | 130,000    | 30-06-2007   | 10-07-2012 | 28 x 28  | 4   | 25  |
| WIYN 3.5m       | Mini Mosaic | 6,000     | 17-03-2009   | 19-07-2012 | 10 x 10  | 2   | 25  |
| WIYN 3.5m       | WHIRC      | 89,000     | 04-04-2009   | 11-04-2012 | 3.3 x 3.3 | 1   | 25  |
| WIYN 0.9m       | MOSAIC     | 9,000      | 27-05-2009   | 03-05-2012 | 59 x 59  | 8   | 21  |
| CTIO 4m         | MOSAIC-2   | 67,000     | 11-08-2004   | 20-02-2012 | 37.0 x 37.5 | 8   | 25  |
| CTIO 4m         | NEWFIRM    | 74,000     | 18-05-2010   | 17-10-2011 | 28 x 28  | 4   | 25  |
| CTIO 0.9m       | Cass Img   | 228,000    | 27-03-2009   | 24-07-2012 | 13.5 x 13.5 | 1   | 21  |
| SOAR 4m         | OSIRIS     | 60,000     | 17-03-2009   | 20-07-2012 | 3.3 x 3.3 | 2   | 25  |
| **Other Instruments:** |            |            |              |            |       |      |     |
| CFHT 3.6m       | CFHTLS     | 25,000     | 22-03-2003   | 02-02-2009 | 57.6 x 56.4 | 36  | 25  |
| INT 2.5m        | WFC        | 230,000    | 20-06-1998   | 10-07-2009 | 34.1 x 34.5 | 4   | 23  |
| Subaru 8.3m     | SuprimeCam | 60,000     | 05-01-1999   | 31-12-2010 | 35.1 x 27.6 | 10  | 26  |
| AAT 3.9m        | WFC        | 5,000      | 21-08-2000   | 05-02-2006 | 31.4 x 31.4 | 8   | 25  |