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

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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 prolonged orbital arcs for 18 precovered objects and 10 recoveries. We analyze all new opposition data by comparing the orbits fitted before and after including our contributions. We conclude the paper presenting "Mega-Precovery", a new online service focused on data mining of many instrument archives simultaneously for one or a few given asteroids. A total of 28 instrument archives have been made available for mining using this tool, adding together about 2.5 million images forming the "Mega-Archive".

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).

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

* Using ESO/MPG WFI images served by the ESO Science Archive Facility and INT WFC images served by the CASU Astronomical Data Centre.

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3000 users who measured and reported 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 (Ivezic 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 & Vaduvescu 2010; Popescu & 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 et al. 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 precoveries 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 2.5-m survey in 2000 and later the dedication of Pan-STARRS 1.8-m survey telescope in 2007, the ESO/MPG 2.2-m telescope equipped with the WFI mosaic camera and the INT 2.5-m 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 and 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) 2.2-m 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 $2{\times}4$ CCDs with $2\mathrm{k}{\times}4\mathrm{k}$ 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 Fig. 1 (top) we plot in cyan (fainter dots) the WFI sky coverage during the above period. This shows random pointings between $\delta \sim -90°$ and $\delta \sim +30°$ 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 2.5-m 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

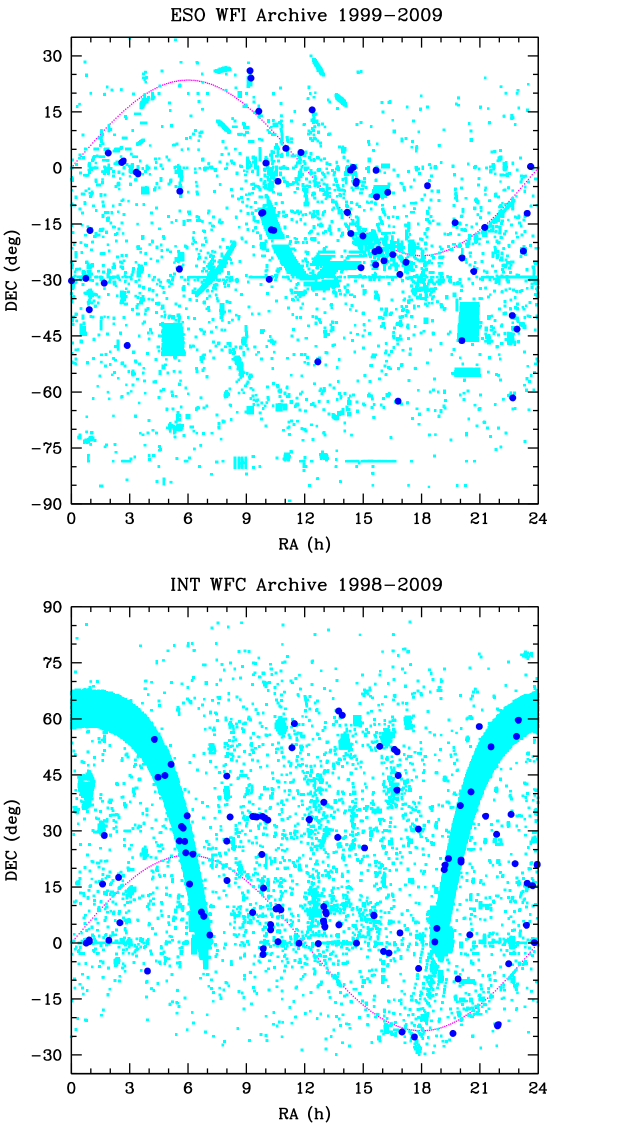

Fig. 1 (online olour at: www.an-journal.org) The sky coverage of the ESO WFI and INT WFC archives whose observed fields are plotted as cyan (fainter) dots. Both hemispheres are covered randomly, including few sky patches and the galactic plane covered by a few surveys. We overlay with blue (larger) dots the NEAs and PHAs encountered in this work and with magenta (fainter curve) the ecliptic.

the INT houses the Wide Field Camera (WFC) which consists of 4 CCDs with 2k×4k pixels each, cove ring an L-shape $34' \times 34'$ (0.28 square degrees) with a pixel scale of $0.33''$/pix.

In this paper we studied the INT WFC during the period 20-06-1998 (first light) to 10-07-2009 (when we started the INT project), although WFC is continuing to be offered by the ING beyond this date. During the above period, the WFC acquired 237 768 science images. Figure 1 (bottom) plots the sky coverage of the WFC archive during this period. The plot shows random distribution between $\delta \sim -30°$ and $\delta \sim +90°$ and clearly some 10° wide band around the galactic plane which represents the two major galactic INT surveys, namely The INT/WFC Photometric Hα Survey of the Northern Galactic Plane (IPHAS, Drew et al. 2005) and The UV-Excess Survey of the Northern Galactic Plane (UVEX, Groot et al. 2009) to be completed soon. We draw with magenta the ecliptic, which has been followed sporadically by few solar system runs led by A. Fitzsimmons (NEAs and comets), J. L. Ortiz (TNOs), J. Licandro (MBCs), O. Vaduvescu (NEAs) and possibly other PIs.

2.3 Exposure time and filters

Figure 2 plots the histogram of the exposure times used in the ESO WFI archive (above) and the INT WFC (bellow). Most images were taken with exposures shorter than 200s in both archives, therefore they are suitable for findings of NEAs affected by a small trail effect caused by their fast proper motion ($\mu > 1''$/min). Few other maxima in exposure times are visible on both histograms for longer exposures, up to 2500 s in both archives.

We also studied the usage of filters in the two archives. The ESO WFI archive counts 44 filters, while INT WFC counts 20 filters (both broad and narrow band). For the ESO WFI archive, 93 % represent 13 broad band filters (led by Rc, I, B, V, and no filter), while 30 other filters representing narrow band and others count for only 7 %. For the INT WFC archive, 73 % represent 14 broad band filters (led by r, i, g, V, and no filter) while 6 narrow band filters count for 27 %. In conclusion, both ESO WFI and INT WFC archives are appropriate for asteroid detection in most of their broad band images.

3 Results

3.1 Found objects

Run with the two archives and assuming a safe limiting magnitude $V = 23$, PRECOVERY reported a total of 7123 candidate images (1535 for the ESO WFI archive and 5588 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 Fig. 1 we overlay with blue (larger) dots the NEA and PHA fields measured in the two archives (ESO WFC above and INT WFC bellow). In both archives the NEA findings are spread randomly with respect to the ecliptic up to high ecliptic latitudes ($\beta \sim 40°$), in agreement with the known distribution of the inclinations of the NEA population. In total, 152 objects were measured and reported, namely 44

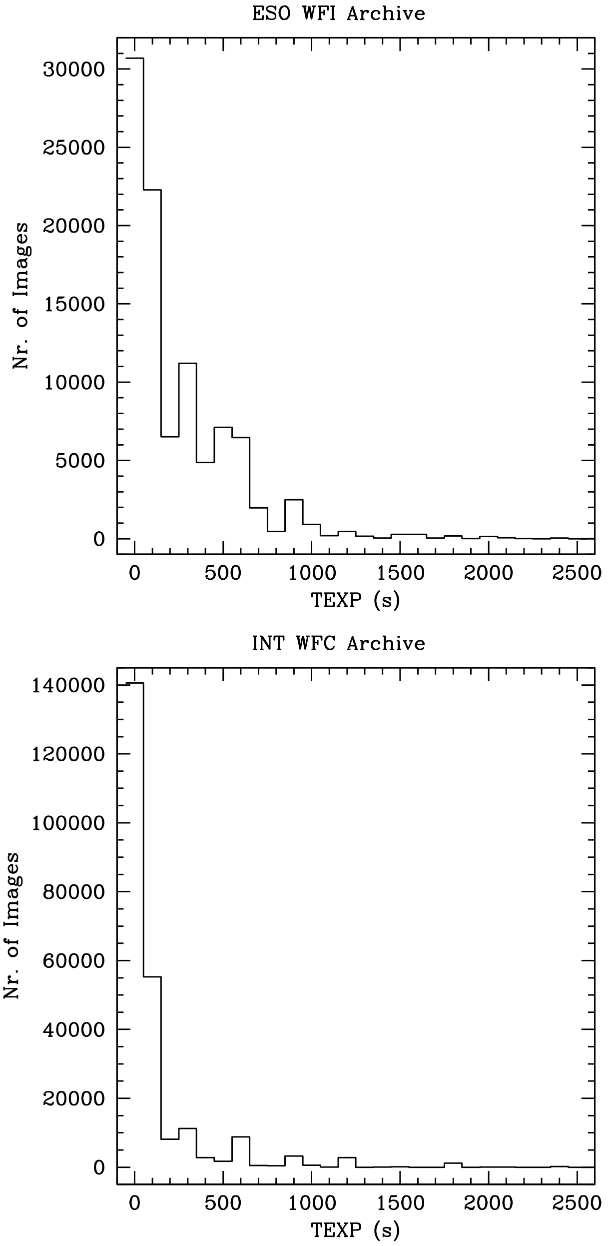

Fig. 2 Histograms showing the exposure time used in the ESO/MPG WFI archive (above) and the INT WFC archive (bellow). Relatively short exposures (less than 1–2 min) were mostly used, making the two archives suitable for searching NEAs affected by the trail loss effect.

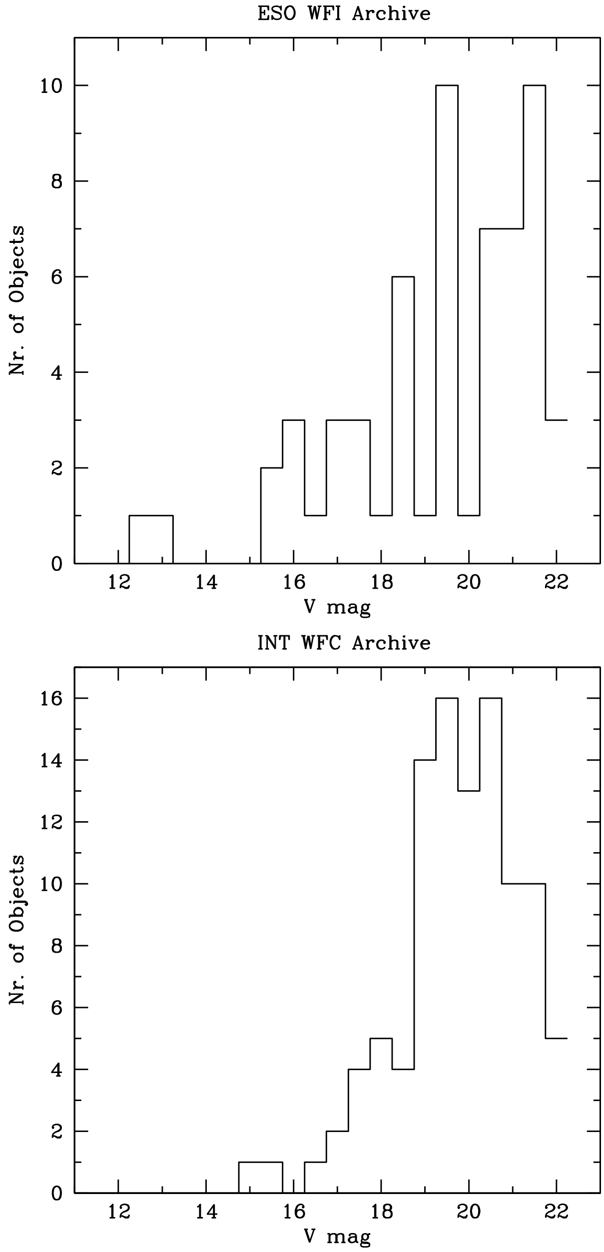

Fig. 3 Histograms showing the predicted V magnitude of the encountered NEAs and PHAs in the two surveys (ESO WFC top and INT WFC bottom). A limit around $V \sim 22$ was reached in both archives, consistent with 2-m facilities.

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).

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 Sect. 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 (bellow). 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).

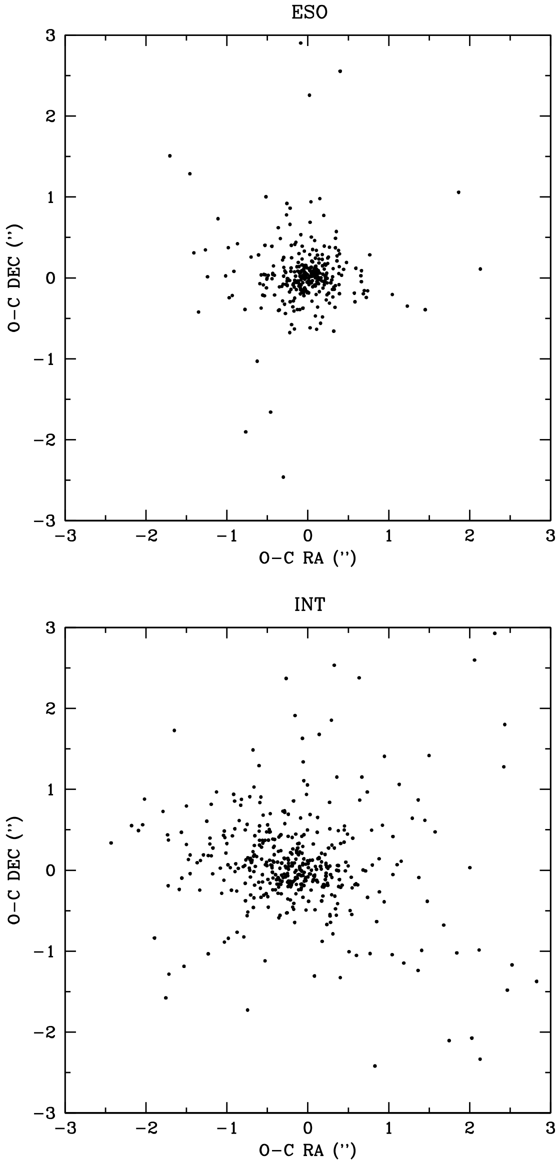

Fig. 4 $O-C$ residuals (observed minus calculated) for the NEAs and PHAs found in the the ESO/MPG WFI (above) and INT WFC archives (bellow). For the ESO WFI, the standard deviation is $0.56''$ and the average deviation $0.34''$, mostly due by catalog errors. For the INT WFC, the standard deviation is $0.72''$ and the average deviation $0.53''$, mostly dominated by astrometric errors due to the uncorrected field of the camera mounted in the prime focus of the INT.

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 time frame. For 28 objects we prolonged the existing orbital arcs by new oppositions or last opposition datasets, adding 18 precoveries and 10 recoveries. In Table A1 we list these 28 cases of NEA and PHA encounters representing precoveries 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 asterisk in Tables A1 and A2. In the third column we list the orbital arc length before and after our data mining work. A few cases represent major encounters, namely:

– precoveries 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 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 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 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 σ residuals in last column decreased for most. In only 3 cases σ 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 file name keeping the telescope observing logs, the observatory code, the width and height of the field (both in degrees, in the direction of α and δ, 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 instruments[1], most archived NVO imaging instruments (National Virtual Observatory of the United States[2]), the INT WFC[3], CFHTLS[4], Subaru SuprimeCam[5] and the AAT WFI[6] 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 input interface" in Fig. 5). In order to create the query, one needs to provide the following information to the web interface:

- A list of names, numbers or provisional designations of the asteroid(s) to search;

[1] http://archive.eso.org/eso/eso_archive_main.html
[2] http://portal-nvo.noao.edu
[3] http://casu.ast.cam.ac.uk/casuadc/ingarch/query
[4] http://www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/cadcbin/cfht/wdbi.cgi/cfht/quick/form
[5] http://smoka.nao.ac.jp/search.jsp
[6] http://apm5.ast.cam.ac.uk/arc-bin/wdb/aat_database/observation_log/make

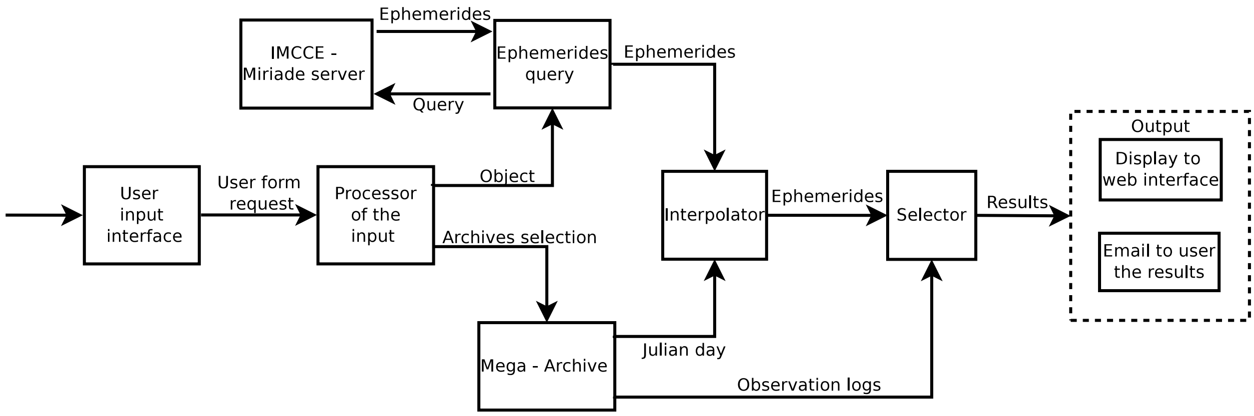

Fig. 5 The flowchart of the Mega-Precovery software.

- 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 $\sim 1^\circ$) 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 hour 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 2-m 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 precoveries 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 EURONEAR data mining of NEAs. Few months ago we started data mining 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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A 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 January 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 asterisk 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 FIND_ORB at epoch JD = 2 456 000.5 listing the asteroid name, semimajor axis a, eccentricity e, inclination i, longitude of the ascending node Ω, argument of pericenter ω, and mean anomaly M, followed by the minimal orbital intersection distance MOID, number of fitted observations Obs and the root mean square residual of the fit σ. Four objects marked with an asterisk were reported also by other PIs in 2005.

Asteroid	a (AU)	e	i (°)	Ω (°)	ω (°)	M (°)	MOID (AU)	Obs	σ (″)
Extended Arcs at First Opposition (Precoveries):									
2005 CG41 *	1.0007879	0.2846587	19.09737	137.74366	233.38300	89.72675	0.0902	8	0.98
	1.0589380	0.3535199	25.29019	137.82014	238.16912	75.88581	0.1170	20	0.68
2005 TU45	1.9737518	0.4959559	28.53919	120.24291	76.86254	149.07339	0.2669	808	0.31
	1.9737518	0.4959559	28.53919	120.24291	76.86254	149.07339	0.2669	812	0.31
2005 MB	0.9852658	0.7927082	41.39802	88.66029	42.80966	53.23488	0.0840	80	0.40
	0.9852658	0.7927081	41.39805	88.66032	42.80964	53.23494	0.0840	83	0.40
2004 XP164	2.1784898	0.4125130	22.64397	127.01048	310.26942	109.80532	0.3836	104	0.52
	2.1784898	0.4125130	22.64397	127.01048	310.26940	109.80534	0.3836	109	0.51
2009 TG10	1.9737117	0.4239201	40.88903	210.71935	12.08752	87.39857	0.1389	47	0.39
	1.9737149	0.4239234	40.88867	210.71941	12.08990	87.39260	0.1389	53	0.37
2009 NA	2.6600451	0.5529338	10.08911	269.50371	98.88855	206.85431	0.2669	498	0.41
	2.6600088	0.5529283	10.08907	269.50366	98.88858	206.85853	0.2669	501	0.41
2002 HQ11	1.8504197	0.5955217	6.04556	153.36013	322.08227	4.04716	0.0555	139	0.43
	1.8504197	0.5955216	6.04556	153.36013	322.08227	4.04716	0.0555	141	0.43
2001 XK105	2.1303469	0.5004268	7.63156	79.92045	6.99267	104.77324	0.0811	25	0.61
	2.1304028	0.5004399	7.63171	79.92043	6.99257	104.72642	0.0811	27	0.63
2006 WT1	2.4717312	0.6011840	13.68475	244.92276	170.58186	131.36247	0.0039	79	0.46
	2.4717312	0.6011840	13.68474	244.92276	170.58186	131.36247	0.0039	85	0.45
2002 TY57	1.9221114	0.3273811	3.45506	119.03691	259.77000	194.64386	0.3018	134	0.42
	1.9221114	0.3273805	3.45507	119.03677	259.77024	194.64380	0.3018	141	0.42
2006 PW	1.3813093	0.6516800	35.87687	132.98690	325.07629	88.37690	0.3654	56	0.40
	1.3813093	0.6516801	35.87686	132.98690	325.07629	88.37691	0.3654	58	0.40
2009 HW2	2.2061742	0.5266663	2.90017	211.42013	350.74180	320.03523	0.0419	24	0.43
	2.1826121	0.5214024	2.87655	211.42082	350.69936	325.37582	0.0422	32	0.48
2009 SP171	1.3557430	0.3559500	25.62158	223.14972	285.17007	87.36382	0.0613	54	0.46
	1.3557449	0.3559509	25.62172	223.14955	285.17012	87.36292	0.0613	56	0.46
2005 BY1	3.1548620	0.6909590	17.02151	298.02275	282.16258	73.64347	0.1962	36	0.51
	3.1548619	0.6909590	17.02150	298.02271	282.16260	73.64349	0.1962	48	0.51
2009 FU23	0.8371147	0.2820307	13.89992	57.82262	315.14072	121.64228	0.0344	106	0.45
	0.8371171	0.2820245	13.89955	57.82290	315.14067	121.63625	0.0344	108	0.45
2005 VC2	2.7670888	0.5871642	36.78132	222.08193	166.90560	136.56584	0.1599	95	0.40
	2.7670893	0.5871642	36.78130	222.08193	166.90566	136.56569	0.1599	100	0.40
2006 KA	1.6331499	0.5614647	31.02218	236.08104	244.60796	323.01311	0.0693	69	0.49
	1.6331500	0.5614619	31.02231	236.08099	244.60830	323.01310	0.0693	72	0.53
2000 FL10	1.4629016	0.4268866	29.01712	186.99620	258.80260	319.18251	0.0815	218	0.55
	1.4629011	0.4268877	29.01714	186.99619	258.80242	319.18377	0.0815	221	0.55
Extended Arcs at Last Opposition (Recoveries):									
1996 XX14 *	2.5469021	0.6518068	10.58772	195.71905	184.95389	289.92264	0.1036	52	0.68
	2.5493643	0.6501978	10.56587	195.57444	185.06938	281.52481	0.0997	59	0.66
2003 MK4 *	1.0803203	0.1811634	22.30645	282.63278	109.56148	181.78607	0.0017	218	0.57
	1.0804562	0.1812333	22.31694	282.63460	109.53443	181.29420	0.0018	225	0.57
2002 DH2 *	2.0507005	0.5417798	20.97315	345.75458	231.59884	134.88238	0.0686	160	0.53
	2.0506639	0.5417709	20.97292	345.75456	231.59892	134.91606	0.0686	165	0.53
1994 JX	2.7631468	0.5726370	32.16385	52.49705	193.44617	319.74146	0.1798	92	0.58
	2.7631468	0.5726371	32.16383	52.49705	193.44625	319.74147	0.1798	100	0.59
2004 RS25	2.1268859	0.4795878	6.64886	179.03636	145.29544	160.50845	0.1140	133	0.48
	2.1268858	0.4795879	6.64886	179.03636	145.29543	160.50849	0.1140	135	0.47
1999 WK11	2.1342937	0.4652704	7.46410	72.67897	220.35355	57.77729	0.1482	187	0.54
	2.1342937	0.4652704	7.46409	72.67897	220.35355	57.77729	0.1482	193	0.54
2005 GN59	1.6565831	0.4678204	6.62763	219.03615	202.90753	203.39329	0.0501	570	0.43
	1.6565831	0.4678204	6.62763	219.03615	202.90753	203.39329	0.0501	572	0.43
2002 EQ9	1.8356544	0.4651654	16.30670	179.23417	44.14087	347.65988	0.0626	362	0.45
	1.8356544	0.4651654	16.30670	179.23417	44.14086	347.65988	0.0626	364	0.45
2007 DK	1.3961987	0.5503815	5.17549	290.95892	354.89948	311.16457	0.0894	85	0.55
	1.3961987	0.5503811	5.17550	290.95910	354.89925	311.16454	0.0894	89	0.55
2005 CA	2.7290438	0.5890431	16.75355	202.13893	203.97095	242.81789	0.1495	82	0.60
	2.7290438	0.5890431	16.75355	202.13891	203.97096	242.81791	0.1495	86	0.59

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