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Mining the CFHT Legacy Survey for known Near Earth Asteroids

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Abstract: The Canada-France-Hawaii Legacy Survey (CFHTLS) comprising about 25,000 MegaCam images was data mined to search for serendipitous encounters of known Near Earth Asteroids (NEAs) and Potentially Hazardous Asteroids (PHAs). A total of 143 asteroids (109 NEAs and 34 PHAs) were found on 508 candidate images which were field corrected and measured carefully, and their astrometry was reported to Minor Planet Centre. Both recoveries and precoveries (apparitions before discovery) were reported, including data for 27 precovered asteroids (20 NEAs and 7 PHAs) and 116 recovered asteroids (89 NEAs and 27 PHAs). Our data prolonged arcs for 41 orbits at first or last opposition, refined 35 orbits by fitting data taken at one new opposition, recovered 6 NEAs at their second opposition and allowed us to ameliorate most orbits and their Minimal Orbital Intersection Distance (MOID), an important parameter to monitor for potential Earth impact hazard in the future.

1 Introduction

Despite the continuous grow of the existing imaging archives and surveys taken with various telescopes around the globe, extremely little work has been devoted to data mining in order to ameliorate the orbits of known asteroids and Near Earth Asteroids (NEAs) and Potentially Hazardous Asteroids (PHAs).

Searching for known minor bodies in old imaging archives is not a new idea, such work being carried in the last two decades by a few authors in order to recover some asteroids and comets and improve their orbits (Bowell 1992; Haver et al. 1992; McNaught 1995; Boattini and Forti 2000; etc). During the last decade, some dedicated data mining work has been carried out to search for known NEAs in a few entire photographic plate archives, namely the projects AANEAS (Steel et al 1998, who introduced the term “precovery”), ANEOPP (Boattini et al. 2001) and DANEOPS (Hahn, 2002). Recently, we presented the public server PRECOVERY devoted to search *all* known asteroids (including NEAs and PHAs besides all other catalogued asteroids) in *any* archive uploaded by the user, given by a simple observing log recorded in a standard format (Vaduvescu et al 2009).

More than 7,400 NEAs are known today (Nov 2010) and some 1,170 of these are catalogued as PHAs according to the JPL NEO database (NASA 2010). Many of these bodies have been insufficiently observed, i.e. only during about one month of visibility at their first opposition. Some of these

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are classified as Virtual Impactors (VIs), while about 70 are considered lost due to their present very large uncertainty in their orbits and ephemeris and their very faint brightness, according to the NEODyS database (Milani et al 2010a). Based on the currently available observations, JPL Sentry System (NASA 2010) monitors more than 300 NEAs possibly to cause future Earth impact events during the next 100 years, although virtually all have almost zero probability to cause such impacts.

Thanks to five dedicated US-lead surveys searching for NEAs during the last two decades, we have discovered the tip of the iceberg of the entire NEA population consisting mostly in $\sim$ 1km and larger objects detectable with 1m class telescopes. Nevertheless, sub-km sized asteroids as small as 150m could still cause regional or global scale disaster in the eventuality of a catastrophic event (Morrison 2006), thus a common effort should be pursued not only to discover but also to recover and follow-up known NEAs.

During the past 4 years, part of the EURONEAR project we have observed about 200 selected NEAs using 10 non-dedicated 1-2m telescopes during about 50 nights obtained mostly through regular time allocation competition which has been difficult to obtain in the absence of a dedicated facility (Birlan et al 2010). Besides new observations, data mining of existing imaging archives represents another goal of the EURONEAR program, and a first paper introduced the method and software to perform the search of any archive for known NEAs, PHAs and other asteroids (Vaduvescu et al 2009).

In the present paper we will use the same method to data mine the entire Canada-France-Hawaii Legacy Survey (more than 25,000 wide field MegaCam images) for known Near Earth Asteroids. Section 2 briefly introduce the survey and present the data mining method. Section 3 will present the results grouped in five special classes, and Section 4 will conclude the paper, introducing two related projects in development.

2 Data Mining of the CFHTLS

2.1 CFHT Legacy Survey

Mounted at the prime focus of 3.6m Canada-France-Hawaii Telescope (CFHT) atop Mauna Kea in Hawaii, the wide-field imager MegaCam mosaic camera was dedicated in 2003 to become the largest field ($\sim$ 1 square degree) facility available worldwide until 2007 when the 1.8m Pan-STARRS survey opened, although this facility is still in engineering phase. MegaCam consists in 36 CCDs 2048×4612 pixel each (340 Mega-pixels total) having a resolution of $0.187''$/pix and producing a total field of view of $0.96\,\mathrm{deg} \times 0.94\,\mathrm{deg}$.

Canada and France joined a large fraction ($\sim$ 50%) of their dark and grey telescope time from mid-2003 to early 2009 for a large project, the CFHT Legacy Survey (CFHTLS). The data acquisition and calibration of the CFHTLS has been a major undertaking for the Canadian and French communities, with more than 450 nights over 5 years being devoted to this project by CFHT. Based on the diverse science interests of the large CFHT community, CFHTLS includes three components:

- The Very Wide survey observed shallow in 3 colours, covering a band of +/-2 degrees along the ecliptic for a total area of 410 square degrees, counting 5,980 images;
- The Wide survey observed deeper in 5 colours, covering 170 square degrees in four patches, counting 7,295 images;
- The Supernova and Deep survey (very deep and covering only 4 fields observed in 5 filters at many epochs, counting 12,289 MegaCam images.

At the CFHT User's meeting which took place in 2007 in Marseilles we presented the opportunity to search the CFHTLS archives for known NEAs, PHAs and other asteroids (Vaduvescu and Curelaru 2007). In that work we searched the "candidate images" of the CFHTLS Very Wide component (the most interesting to produce most encounters of asteroids) to find serendipitous detections of NEAs, PHAs and all other known asteroids. Both recovery and "precovery" (apparitions before discovery date) were searched using a PHP script which queried the SkyBoT server (IMCCE 2010) and the CFHTLS observing log database available at the CFHT website (CFHT 2010). Overall for the CFHTLS Very Wide component alone, we predicted about 450 candidate images probable to hold precovery and recovery apparitions of NEAs and PHAs, while an average of 10 known Main Belt asteroids are visible in every observed CFHTLS field!

To search the candidate fields for predicted encounters and measure all such findings, we have joined in a team of eight people including five amateur astronomers and students and two professional astronomers, so this work is an example of a collaboration between professional and amateur astronomers. We present next the necessary steps to perform the entire work.

2.2 Searching for NEAs using PRECOVERY

To search for possible serendipitous encounters of all known NEAs, PHAs and other asteroids in the CFHTLS archive, we used PRECOVERY, a software written in PHP to perform searches and classify findings in any archive (Vaduvescu et al 2009). PRECOVERY uses an observing log holding the following basic information to define observations: the archive image identifier, observing date (calendar date and start UT time), telescope pointing (α, δ) at J2000.0 epoch, exposure time (sec), image field (degrees) and eventually other information. Besides this input file, the software uses the asteroid orbital elements database downloaded daily from the Minor Planet Centre (MPC), holding all known NEAs, PHAs, numbered and unnumbered asteroids. A dedicated option was built to search the CFHTLS/MegaCam archive and is available on site, taking into account the raw format of the CFHTLS archive and the geometry of the MegaCam (the position of each of the 36 CCDs forming the entire mosaic). For the search, we used the MPC asteroid database of 9 April 2009, thus the CFHTLS archive could produce new findings based on a new search to include the asteroids discovered after that date.

The three CFHTLS survey components add together a total of 25,564 images to search, a slow task for one user approach to transfer lots of data and queries between two servers (PRECOVERY and SkyBoT). Thus, we divided the big master archive log in batches of 250 images each, which were then run individually by the members of the team, one batch at a time by one person, during one session with PRECOVERY. Distributed between all members of the team, the search of the entire CFHTLS archive took some 20 days to run total time[1].

All candidate images were included in a table listing all data necessary for inspection and measurement: the image number and the CCD number, the encountered asteroid name, expected position (α, δ) and its associate uncertainty (in arcsec), expected V magnitude, observing date (start of exposure: calendar and Julian date), exposure time (sec) and filter. After applying a limiting magnitude $V = 24$ (compatible and safer than the survey specifications), we assembled these data in a master candidate images database holding about 1,000 images in total to be analysed in the next step.

2.3 Inspection of the Candidate Images

The master candidate images database was split between members of the team who downloaded from the Canadian Astronomical Data Centre (CADC) the processed MegaCam detrended images (already corrected by overscan, bias, mask and flat-fielding). Using the DS9 (to open MegaCam data cube) or IRAF[2] (to cut the appropriate image), we split the individual corresponding CCD predicted to hold NEAs. Then we used DS9 to inspect visually each candidate CCD image close to the predicted (α, δ) position, taking into account the positional uncertainty of the objects. The inspection task was easily performed by blinking subsequent images of the same field, usually found to hold the same object at different positions which was easily spotted to move between frames. If only one or two predicted images were available to hold a given asteroid, then we downloaded another image closed in time of the same field in the same filter to serve for the blinking process, in order to reject potentially mis-identification (other asteroids, image flaws, supernovae, galaxies, etc).

2.4 Uncertain Identification from Few Observations

The mining of the CFHTLS archive showed us how important the survey cadence and the search work-flow are, also revealing several limitations and possible failures of the precovery work. One of the major problems could appear for the objects which could be poorly identified only based on very few available images, defined as one or two apparitions only. The problem becomes even more difficult in case of poor detection (low S/N due to faint magnitude or/and poor weather). Moreover, the situation becomes critical for objects previously observed only at one opposition (a few weeks or months only), especially at one epoch very distant in time (a few years) from the available observational arc. In this last case, due to the relatively poorly determined orbit, the ephemeris uncertainty grows with time and it could reach from a few dozen arcsec to a few degrees, thus finding the object becomes much more difficult. Obviously, some major question rise in general related to uncertain identifications, namely how confident could be these detections and how often these situations arise?

The detailed answers to the above question are out of the scope of our paper and they depend on the survey strategy (number of visits, cadence, exposure time, surveyed area, etc) and also on the available statistics for the known NEA population at a given time. Here, we enumerate a few criteria to be taken into account for the correct identification in case of few observations, based on our CFHTLS data mining experience.

1. Location - In the first step, the search should start closely and around the position predicted by some very accurate ephemeris (SkyBoT in this case), taking into account the line of variation and the confidence ellipse assumed by some (usually linear) orbital uncertainty model (e.g., Milani and Gronchi 2009);
2. Apparent Motion - This represents probably the most important criterion for the correct identification of a searched object. The observed apparent motion could be assessed only from multi-apparitions (if available usually on neighbour images), the predicted motion in both α and δ directions and the time interval between successive exposures. The motion information fails in case that only one image is available, and in this case other factors should be taken into account;
3. Magnitude - Another important identification criterion is the expected apparent magnitude of the object, but two factors usually impede the correct assessment of the magnitude, namely the longer exposures (resulting in long trails) and the mostly unknown spectral class of the object and its colour (in order to reduce the correct magnitudes);
4. Aspect - Especially when sparse data is available, a very important identification factor is the expected aspect of the searched object. Taking into account the pixel scale, exposure time, magnitude and the apparent movement of the searched object, its aspect could appear either as a

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[1] Following this work, SkyBoT server improved significantly its speed by adding new hardware and an improved search method, so the entire job is expected to take much less now.

[2] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation

long trail (linear, with a thickness compatible with stellar FWHM), a small trail (compatible with a slightly elliptical PSF, in which case the trail orientation is a very important criterion to be compared with the expected movement direction) or a point-like "stellar" object (in which case the identification should take into account other criteria). If possible, the inspection of the field must be combined with other deep-sky images in order to avoid confusions with background galaxies.

Due to the CFHTLS cadence (at least 4 visits of each field from which at least 3 taken in the same night), most of our present work involved multi-apparition objects (measurable each on at least 3 positions), which total 99 objects (about 70% of the total number of apparitions). In these cases, we inspected the fields visually (aligning the images centred on the central predicted position, then using the blink) so that the object recognition was obvious, taken into account the expected proper motion and magnitude from at least 3 apparitions. The rest of 44 objects represent few observations objects, with 20 objects appearing only in one image (14% of total) and 22 objects appearing in two images (15%). For all these cases we applied the above search criteria, so that only 2 objects could not be measured (about 1% from the total reported) due to their faint magnitude resulting in a very high risk of bad detection. In case of very faint objects (closed to the limit of CFHTLS detection, about $V \sim 23$) or poor S/N due to bad weather conditions, we applied *boxcar* in IRAF binning 2×2 in order to improve the S/N for an easier detection.

2.5 Field Correction and Measurement

The detrended CADC images do not include astrometric field correction of the original MegaCam images. Field correction is necessary to fix the optical distortion of any wide field camera which reaches up to $\sim 2''$ towards the margin of the raw MegaCam field. To remain compatible with our past EURONEAR astrometric accuracy ($\sim 0.2''$) and also to take full advantage of MegaCam's capability, we had to correct the raw detrended images for the field distortion effect. In this sense, we used the available software written at TERAPIX Data Centre, specially built to correct MegaCam images and reduce CFHTLS data.

The field correction process and semi-automatic measurement of the asteroid positions consists in five steps, given a CADC CCD distorted field image with header astrometric coefficients in the USNO catalogue system. First, we applied SWARP to correct the field distortion using the same USNO astrometric system. Second, we used SExtractor to extract sources with USNO positions. Third, we applied SCAMP to correct the astrometry from USNO to UCAC catalogue system (known to have better accuracy than USNO). Fourth, we used MISSFITS to update the header of the corrected image to include UCAC astrometric coefficients. Finally, we used again SExtractor to extract all sources from the corrected field image in the UCAC reference system. Among all extracted sources (mostly stars and galaxies), the coordinates (α, δ) of the searched asteroid were extracted from the final catalogue.

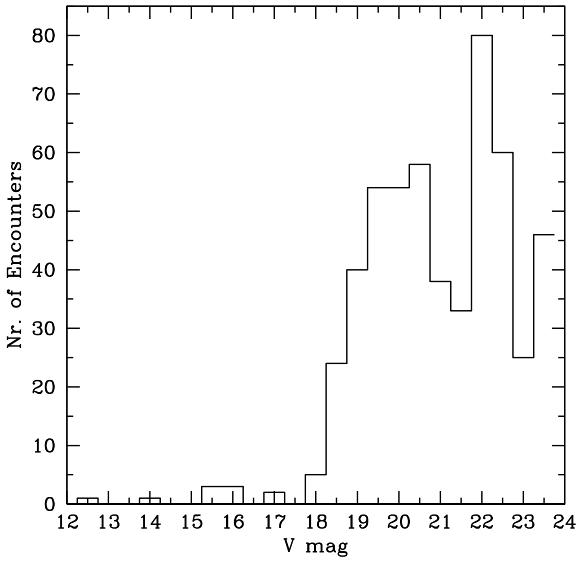

Fig. 1 Histogram showing our total number of asteroid encounters (NEAs and PHAs). Two main bulks are visible at $V \sim 20$ and $V \sim 22$ and are discussed in the text.

Most encounters were found in the Wide field (ecliptic) component for which most exposures were small, thus most asteroids appear stellar-like or slightly elliptical, possible to measure automatically by SExtractor. Some exposures took longer (e.g., those coming from the two deeper surveys) and some asteroids moved faster close to opposition, thus some encounters resulted in trails necessary to be measured visually in DS9. We checked all SExtractor findings by inspecting the final resulted catalogues overlaid on the DS9 final corrected images. For the bad SExtractor findings, we either visually measured the centres of the trails (for the shorter ones) or we calculated the centre of the trails by averaging the two ends. Finally, we recorded all measured positions together with the observational data in our asteroid master catalogue.

3 Results

We encountered 508 candidate images holding a total of 143 NEAs and PHAs whose positions (α, δ) were measured and reported to Minor Planet Centre (MPC). From these, we found 109 NEAs (20 NEAs precovered and 89 NEAs recovered) and 34 PHAs (7 PHAs precovered and 27 PHAs recovered). In average, each asteroid was measured on 3.5 images, which is consistent with the Very Wide component which holds most encounters. In the Very Wide component alone we found a total of 111 NEAs and PHAs (78% from total number), in the Wide component 33 NEAs and PHAs

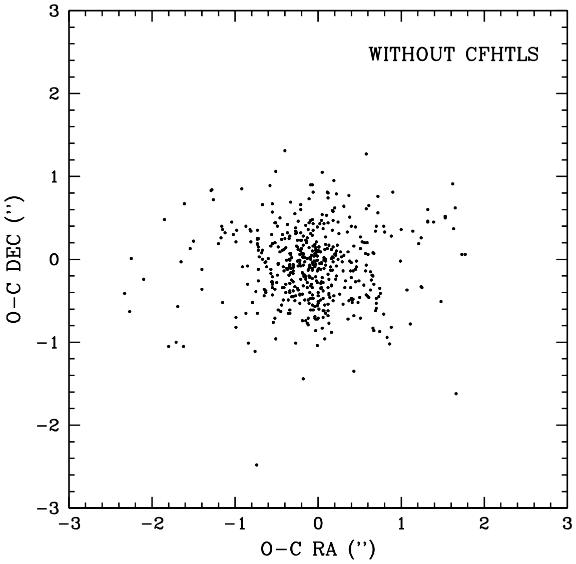

Fig. 2 O-C (Observed minus Calculated) residuals in α and δ, where the calculated positions refer to orbits which do not include our data. The average standard deviation is $0.97''$ and the sample standard deviation is $2.91''$ and the plot includes all 508 measured positions. A few points referring to orbits with larger residuals are outside the limits.

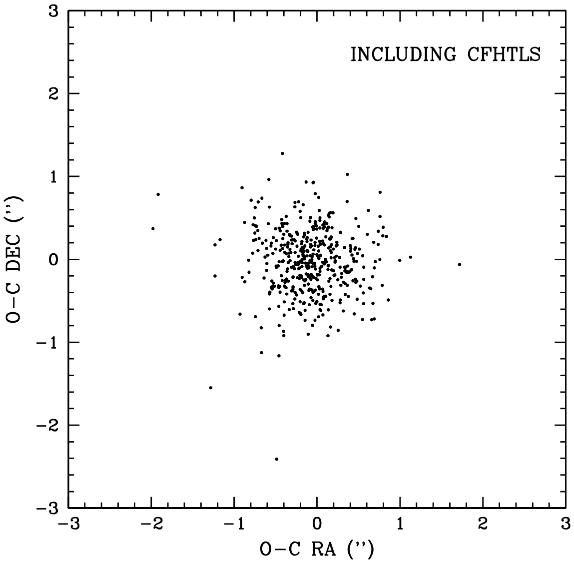

Fig. 3 O-C (Observed minus Calculated) residuals in α and δ, where the calculated positions refer to orbits which include our data. The average standard deviation is $0.24''$ and the sample standard deviation is $0.38''$. The plot includes all accepted positions and all points are inside the limits.

(22% which confirms that NEAs should be searched all over the sky) and in the Supernova and Deep survey none.

In Figure 1 we plot the histogram showing our total number of encounters (images) as a function of the object predicted V magnitude, using a bin of 0.5 mag. Most asteroids have magnitudes fainter than $V \sim 18$, although a few were found at brighter regime, as bright as $V \sim 12$. On the plot there are two apparent bulks visible. The first bulk peaks around $V \sim 20$ and probably represents the objects observed close to their opposition accessible to other established 1m surveys. The second bulk peaks around $V \sim 22$ and correspond to objects inaccessible to the other dedicated surveys, possibly representing objects either fainter or not observed at opposition, and in this regime the CFHTLS could bring a more important contribution.

3.1 Astrometry

We submitted 508 measured positions to Minor Planet Centre (MPC) and most of them (99%) were accepted. They were included in the MPC, NEODyS and other databases and they were taken into account by major providers for the amelioration of the orbits. Only two objects (positions) were rejected by the MPC, to which we will refer in Section 3.2.5.

In Figure 2 we plot the O-C residuals (Observed minus Calculated in α and δ) resulting from orbits which do not include our data. One could observe some relatively large spread of the residuals around the origin, with a larger spread in the right ascension, consistent with the proper motion of most asteroids. The average standard deviation is $0.97''$ and the sample standard deviation is $2.91''$ and the plot includes all 508 measured positions. Some points are located outside the visible limits of the plot which focuses on the central region for a better view. In Figure 3 we plot the same data resulted from orbits fitted with all available data set including our CFHTLS accepted observations. Most points are better confined around the origin, dropping the average standard deviation to $0.24''$ and the sample standard deviation to $0.38''$. The points are better grouped around the centre in Figure 3 compared with Figure 2, probing the fact that the majority of the initial orbits could be well adjusted after including our data. Compared with previous statistics, the deviations obtained from the orbits which include our data probe that our work contributed to the refinement of the orbits. We will discuss these findings further.

3.2 Amelioration of Orbits

We evaluated our contribution to the final orbital solution which includes our data. In this sense, we used NEODyS observational data available to date 10 Jan 2010. From the total of 143 asteroids found in the survey, 58 orbits resulted to be interesting to be studied (40%), and we group them in 5 special classes based on the existing observing data available before our data mining. We include these results in

Table A1. Besides the asteroid name, we include the MPC classification, the number of CFHTLS observations, the orbital arc before and after adding our data (where "w" stands for weeks, "m" for months and "y" for years), the number of covered oppositions before and after adding our data, and some comments showing how our data improved the available orbits. These special cases are presented in the next sections.

We compared the orbits fitted with and without our observations, using all other available observations taken from the NEODyS (.rwo) database. To fit orbits, we used the ORBFIT package (Milani et al 2010b) running first ORBFIT to fit the available observations using full differential corrections and the nonlinear least squares method, then running FITOBS to propagate the orbit to the same epoch and perform a close approach analysis which includes an iterative calculation of MOID (Minimal Orbital Intersection Distance) in 10 steps. A similar comparison using the ASTERPRO software (Rocher 2007) and FIND_ORB software (Gray 2010) produced similar results.

Table A2 includes the most notable cases of orbits ameliorated with our CFHTLS data. We calculated with ORBFIT the six Keplerian orbital elements for the epoch $MJD = 55400.0$: the semi-major axis (a), eccentricity (e), inclination of the orbit (i), longitude of the ascending node (Ω), argument of the pericenter (ω) and the mean anomaly (M). To assess the potential impact hazard and the goodness of the fit we include the calculated MOID, the number of fitted observations and the residual mean square RMS of the fit. For each asteroid we give in the first line the orbital fit including our data and in the second line the orbital fit excluding our observations.

Comparing the orbital elements, one could observe that most orbits were improved slightly: a and e change mostly at the 4-5th decimal (representing up to 15,000 Km in semi-major axis), the angles i, Ω, ω change at their 3-4th decimal in most cases, and M changes mostly at its 1st or 2-nd decimal. Comparing the goodness of the fit (counted by the RMS in the σ column), the majority of the orbits improved after including our data, namely σ decreased by $0.01 - 0.02''$ and in some cases up to $0.04''$ (PHA 1993 BX3) and $0.05''$ (NEA 2004 QE20) - both objects being observed only by us at their last opposition. Looking at the MOID column, most of the orbits became less chaotic after fitting our data, converging faster in our 10 step iterative process calculated by ORBFIT - the MOID intervals became narrower, e.g. for 2003 TG2 of the second set in Table A2 the initial MOID obtained without our data varies between 0.19460 and 0.19565 AU (an interval 0.00105 AU), while after fitting our data it varies between 0.19497 and 0.19551 (an interval 0.00054 AU), so in this case we constrained MOID by 0.00051 AU = 76,500 Km. In some cases MOIDs were changing at their 5-th or 4-th decimal (representing up to 15,000 Km), although in many cases they remain unchanged.

We present next the five special classes derived from the existing observing data and orbital arcs available before our work.

3.2.1 Extended Arcs at First Opposition (Precoveries)

A total of 21 asteroids (15 NEAs and 6 PHAs) were precovered, i.e. found on 75 images taken before their discovery date (as recorded by MPC) and we include them in the first group of Table A1. From these, 7 asteroids (5 NEAs and 2 PHAs) have their 1st or 2-nd opposition covered only by the present work (reported as X/(X+1) in the "Opp" column). For the rest of 14 asteroids (11 NEAs and 3 PHAs) we have prolonged their arcs with data at first opposition and we give in the Comments column the extended interval. We improved the existent orbits and MOIDs by fitting our data to the previous observations and this can be observed in the columns σ and MOID in the Table A2. As one can see comparing the first line (including our observations) versus the second, MOIDs converge better while RMS' decrease after including our data for the majority of the objects. Six cases deserve to be evidenced based on their extended Arc column: 2008 ED69 (having an orbital arc data prolonged from 9 months to 4 years), 2005 OW and 2005 QN11 (having their short arcs prolonged by one month), 2008 AF4 (PHA very desirable having a MOID = 0.00281 and the orbital arc extended from 4 months to 6 years), 2007 FS35 (arc extended from 3 months to 8 years) and 2008 CR118 (with the arc extended from 8 months to 5 years). In two other cases we could constraint the MOIDs (2007 RM133 and 2005 UU3). We compare the fitted orbits in Table A2.

3.2.2 Extended Arcs at Last Opposition (Recoveries)

A total of 14 asteroids (9 NEAs and 5 PHAs) were recovered by us at their last opposition. From these, 7 objects (4 NEAs and 3 PHAs) have their last opposition covered only thanks to our work. All orbits were improved by fitting our CFHTLS data. At least four objects deserve to be noted based on the extending time coverage (given in the Arc column): 1998 VD35 (PHA desirable with the orbital arc prolonged with 5 years), 2005 WA1 (PHA extremely desirable having the short arc improved from one month to 7 months), 2003 TG2 and 2004 XG29 (NEAs having the very short arcs of 18 and 25 days prolonged by 6 and 10 days, respectively). For two other objects we decreased the RMS, namely for 1993 BX3 (a numbered object) by $0.04''$ and for 2004 QE20 (NEA very desirable) by $0.05''$. We compare the fitted orbits in Table A2.

3.2.3 Refined Arcs at one Intercalated Opposition

A total of 15 asteroids (all NEAs from which 10 are considered desirable or very desirable) were recovered by us in the CFHTLS at one intercalated opposition, and our data represent the only available observational set at the indicated opposition (given in the Comments column). Most objects had observed data at many oppositions, so their orbits could be improved only marginally, nevertheless one object merits its attention, namely 1998 QB28 (NEA very desirable) for which we could constrained the MOID by 0.00007 AU, as can be observed in Table A2.

3.2.4 Refined Very Small Arcs

Two NEAs have their very short orbits improved thanks to our work. 2005 YD was observed only for two weeks (26 observations) for which we reported two more observations weighting about 7% from the entire data set, while 2008 RZ24 was observed for two months being found by us in the Very Wide survey in 11 images which weight for about 17% of the entire data set. Their orbits could be improved using our data, as one can see in the σ column in Table A2.

3.2.5 Extended Arcs at Second Opposition (Major Recoveries)

A total of six asteroids (all NEAs extremely desirable) were observed previously only at one opposition, only for a few months. They were found by us in 13 CFHTLS images within $2''$ to $50''$ distance from their predicted positions, consistent with their orbital 1σ uncertainty ellipse calculated at their observing date by NEODyS. Two of them (2006 UD17 and 2007 VX137) appeared only on one image each, so we dropped them due to high risk of misidentification from noise. These were the only objects rejected by MPC (Spahr 2010). The other four objects appear on multiple (2 or 3) images and they had systematic O-C residuals. Their apparitions verified most of the criteria presented in Section 2.4, so we reported them to MPC who accepted the data. These notable cases of major recoveries are: 2005 OJ3 (precovered by us 2 years before its discovery in 2005), 2008 CJ70 (precovered 3 years before discovery), 2000 SZ44 (recovered by us 5 years after its oldest discovery in 2000) and 2002 VR94 (recovered by us after 2.5 years following discovery in 2002). All orbits and MOIDs could be improved with our data for all reported objects, as one could check in Table A2.

4 Future Work

We continue to offer PRECOVERY to the community for other data mining projects (Vaduvescu et al 2010), and our server will offer soon new focused search capabilities. Recently we have proposed two similar projects to expand our data mining work.

4.1 The Archives ESO/WFI and INT/WFC

In a team of about 10 people including mostly students and amateur astronomers, in autumn 2009 we have embarked in a project to data mine the 2.2m ESO/MPG Wide Field Imager archive and the INT 2.5m Wide Field Camera archive. These comprise of about 100,000 and 230,000 images respectively, taken during the last decade by two similar wide field ($34' \times 34'$) cameras mounted on similar 2m class telescopes located in both hemispheres. This project is about half completed, and has already built the two databases from the off-line nightly observing logs of the ING and on-line ESO Data Archive for the ESO/MPG. We have run PRECOVERY on both these archives, inspecting about 1,500 ESO candidate images and measuring a few hundred positions, and this project continues.

4.2 MEGA-PRECOVERY and the Mega-Archive

Recently we have started to write a code (named MEGA-PRECOVERY) to address a new data mining method focused on a list of a few specified known objects (NEAs or PHAs) to search a “mega-archive” comprising in a number of given archives whose observing logs will be available soon on the EURONEAR website. To start this “mega-archive”, we will join the CFHTLS, ESO/WFC, INT/WFI and Bucharest plate archives, and we plan to add soon the DSS, SDSS, and later the Wide Field Plate Database (WFPDB, www.skyarchive.org) which stores the archive pointings of about one thousand plate archives existing worldwide (Tsvetkov 1991, Tsvetkov 2005). Empowered by this new tool to data mine this proposed “mega-archive”, we plan to propose to international forums such as IVOA and IAU to ask every observatory to make available in a first phase their observing logs in a standard VO format to be data mined for any poorly known asteroid. Besides the available existing data, we consider that the continuous exponential grow due to recent and new surveys could make such a data mining tool more than rewarding, and we consider that our present paper proved this.

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A Appendix: Data Tables

Table A1 Five special classes including 58 NEA and PHA asteroids data mined in the CFHTLS. Besides the asteroid name we give its MPC classification, the number of CFHTLS observations, the orbital arc and the number of covered oppositions before and after adding our data, and some comments showing how our work improved the orbits.

Asteroid	Classification	Obs	Arc	Opp	Comments
Extended Arcs at First Opposition (Precoveries):					
2008 ED69	NEA very desirable	6	9m/4y	2/3	Arc prolonged by 3 yrs
2005 CJ	PHA very desirable	3	5/8m	2	Arc prolonged by 3 mths
2006 PA1	PHA very desirable	1	4y	3	Arc prolonged by one month
2008 OX2	PHA	4	2y	2	Arc prolonged by 1.5 mths
2003 WO151	NEA very desirable	3	2y	2	Arc prolonged by 1.5 mths
2005 LW	NEA very desirable	2	4/5y	3/4	Arc prolonged by 8 mths
2005 OW	NEA extremely desirable	3	4/5m	1	Short arc prolonged by 1 mth
2005 QN11	NEA extremely desirable	3	4/5m	1	Short arc prolonged by 1 mth
2005 QS10	NEA very desirable	3	4y	2	Arc prolonged by 1.5 mths
2005 SS4	NEA very desirable	4	3y	3	Arc prolonged by 2 weeks
2004 BE86	NEA very desirable	4	5y	2	Arc prolonged by one month
2007 RM133	NEA	8	3y	2	Arc prolonged by one week
2008 SQ1	NEA	5	5y	2	Arc prolonged by one month
2008 AF4	PHA very desirable	1	4m/6y	2/3	We only at 2nd opp, Goldstone radar target
2007 FS35	NEA very desirable	4	3m/8y	2/3	We only at 2nd opp
2008 CR118	PHA	1	8m/5y	2/3	We only at 2nd opp
2006 SV19	NEA	3	6y	3/4	We only at 2nd opp, numbered (212546)
2006 SU49	PHA very desirable	3	7y	3/4	We only at 2nd opp
2005 RN33	NEA very desirable	6	4y	2	We first at 2nd opp
2008 XE3	NEA	4	4y	2	We 2nd set at 1st opp
2005 UU3	NEA very desirable	4	2y	2	We 2nd set, only just 4 hrs after discovery
Extended Arcs at Last Opposition (Recoveries):					
1998 VD35	PHA desirable	1	2/7y	3/4	Arc prolonged by 5 yrs, numbered (20425)
1993 BX3	PHA desirable	6	11/13y	3/4	Arc prolonged by 5 yrs, numbered (65717)
1999 GS6	PHA desirable	3	7/8y	4/5	Arc prolonged by 1 yr, numbered (152754)
2005 RR6	PHA very desirable	4	2y	2	Arc prolonged by 2 weeks
2005 WA1	PHA extremely desirable	3	1/7m	1	Initial 3 week arc prolonged by 6 months
2003 TG2	NEA for survey recovery	3	18/24d	1	Very small arc prolonged by one week, old object
2004 XG29	NEA extremely desirable	1	25/35d	1	Very small arc prolonged by 10 days
1998 XA5	NEA very desirable	3	4/8y	3/4	Arc prolonged by 4 yrs
2002 TY57	NEA very desirable	1	3/5y	2/3	Arc prolonged by 2 yrs
2002 AA	NEA very desirable	6	5y	3	Arc prolonged by 1 week
2007 DL8	NEA very desirable	4	2y	2	Arc prolonged by 2 mths
2003 TX9	NEA very desirable	6	3y	2	Arc prolonged by 6 mths
2002 AC29	NEA very desirable	3	7y	3/4	Arc prolonged by 3 mths
2004 QE20	NEA very desirable	3	5/7y	3/4	Arc prolonged by 2 yrs, numbered (164221)
Refined Arcs at one Intercalated Opposition:					
2001 OE84	NEA	2	8y	3/4	We alone at 3rd opp
1997 GH3	NEA desirable	10	13y	4/5	We alone at 3rd opp, numbered (19356)
2002 LS32	NEA very desirable	1	8y	5/6	We alone at 4th opp
1998 QB28	NEA very desirable	3	9y	2/3	We alone at 2nd opp
1999 RP36	NEA	3	10y	3/4	We alone at 3th opp, numbered (217683)
2003 CJ11	NEA desirable	4	4y	3/4	We alone at 2nd opp, numbered (154453)
1998 ST4	NEA very desirable	3	11y	5/6	We alone at 4th opp
2000 YM29	NEA	4	10y	5/6	We alone at 4th opp, numbered (153219)
2002 TS67	NEA very desirable	2	8y	3/4	We alone at 2nd opp
2005 WS55	NEA	3	7y	3/4	We alone at 2nd opp, numbered (209924)
2008 LW8	NEA very desirable	2	12y	3/4	We alone at 3rd opp
2000 DH8	NEA	4	15y	5/6	We alone at 3rd opp, numbered (231792)
1993 TQ2	NEA very desirable	5	15y	2/3	We alone at 2nd opp
2000 UP30	NEA very desirable	8	7y	2/3	We alone at 2nd opp
2001 WL15	NEA very desirable	4	9y	4/5	We alone at 4th opp
Refined Very Small Arcs:					
2005 YD	NEA for survey recovery	2	2w	1	
2008 RZ24	NEA extremely desirable	11	2m	1	
Extended Arcs at Second Opposition (Major Recoveries):					
2005 OJ3	NEA extremely desirable	3	8m/2y	1/2	O-C=6″ V=23.6, precovery 2 yrs before discovery
2008 CJ70	NEA extremely desirable	2	3m/3y	1/2	O-C=50″ V=23.1, precovery 3 yrs before discovery
2000 SZ44	NEA extremely desirable	3	4m/5y	1/2	O-C=13″ V=22.4, recovery 5 yrs after discovery
2002 VR94	NEA extremely desirable	3	6m/3y	1/2	O-C=30″ V=23.6, recovery 2.5 yrs after discovery

Table A2 Comparison of the orbits fitted with (first line) and without our observations (second line). Keplerian orbital elements fitted with ORBFIT at epoch $MJD = 55400.0$: 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 and the squared mean residual RMS of the fit.

Asteroid	a (AU)	e	i (deg)	Ω (deg)	ω (deg)	M (deg)	MOID (AU)	Obs	σ ($''$)
Extended Arcs at First Opposition (Precoveries):									
2008 ED69	2.88704287	0.74949654	36.27922752	149.89327262	172.73282884	149.61802749	0.28316	116	0.43
	2.88695213	0.74948772	36.27908600	149.89317168	172.73280795	149.62504553	0.28316	110	0.42
2005 OW	2.66552267	0.60163695	1.63921135	271.76312432	62.27499199	46.31259102	0.05759	196	0.62
	2.66553757	0.60163914	1.63921642	271.76315442	62.27495821	46.30915905	0.05758	193	0.63
2005 QN11	2.17394532	0.40379176	5.61935281	223.87836246	134.99008565	184.49056673	0.30336	121	0.46
	2.17393231	0.40378871	5.61933855	223.87834461	134.99036525	184.49533346	0.30330-38	118	0.46
2007 RM133	2.21037753	0.44000603	10.74595065	106.19581007	181.01826765	347.88273273	0.22113-18	56	0.51
	2.21036767	0.44000347	10.74591063	106.19601557	181.01822181	347.88492253	0.22112-19	48	0.53
2008 AF4	1.38256104	0.41072419	8.91934131	109.42271956	293.32280895	231.52478785	0.00281	609	0.35
	1.38256494	0.41072640	8.91938330	109.42273385	293.32278690	231.52224732	0.00281	606	0.35
2007 FS35	1.92227709	0.39022490	0.31760987	183.27038985	107.04010819	31.13370375	0.15568-71	60	0.45
	1.92238624	0.39026668	0.31758960	183.26936559	107.03613297	31.10509908	0.15565-72	53	0.43
2008 CR118	1.83875731	0.51066465	3.92343947	121.63512526	156.91147019	286.31967420	0.02816	81	0.44
	1.83879655	0.51067494	3.92353435	121.63581110	156.91013530	286.31072755	0.02815-6	74	0.43
2005 UU3	1.28261561	0.47819728	13.93810052	36.53446656	128.56296260	27.45528293	0.14251-303	44	0.41
	1.28263495	0.47820262	13.93815480	36.53441590	128.56421885	27.45518844	0.14250-306	40	0.41
Extended Arcs at Last Opposition (Recoveries):									
1998 VD35	1.56459680	0.47673984	6.98207379	227.41633118	296.12600123	294.06492318	0.00321	51	0.58
	1.56459674	0.47673982	6.98209499	227.41637403	296.12599271	294.06499563	0.00321	50	0.58
1993 BX3	1.39463215	0.28060259	2.79020747	175.58505195	289.94925112	233.79801622	0.04843	53	0.74
	1.39463214	0.28060257	2.79020832	175.58505307	289.94925038	233.79802668	0.04843	47	0.78
2005 WA1	2.00712579	0.58526544	10.93346025	247.38964489	241.55518760	212.65535613	0.02070	118	0.62
	2.01068769	0.58610164	10.94631051	247.39020632	241.55363801	211.12777389	0.02049-88	115	0.62
2003 TG2	0.90787297	0.31598894	25.44938968	200.70288030	355.13821055	109.12183940	0.19497-551	35	0.58
	0.90782816	0.31593624	25.43375232	200.70922357	355.13053872	109.34478265	0.19460-565	32	0.59
2004 XG29	1.40962299	0.31319954	0.15454852	302.84078467	109.89518303	141.58385674	0.00205	130	0.73
	1.40960282	0.31318696	0.15454391	302.83963116	109.89759837	141.63226231	0.00205	129	0.74
2004 QE20	1.50507593	0.20534407	6.48274424	272.66090730	74.16056708	67.14803071	0.22006	130	0.57
	1.50507608	0.20534454	6.48272684	272.66089645	74.16057837	67.14785564	0.22006	129	0.62
Refined Arcs at One Intercalated Opposition:									
1998 QB28	2.07448980	0.37976447	1.07717741	341.64613291	297.97833026	23.54298808	0.27085-47	42	0.37
	2.07448933	0.37974343	1.07719064	341.64645854	297.97695080	23.54609416	0.27093-48	39	0.34
Refined Very Small Arcs:									
2005 YD	1.65283640	0.42520216	4.78305977	90.65373286	314.23849158	73.57127069	0.02261	28	0.52
	1.65241013	0.42504894	4.78167561	90.65428349	314.23914129	73.87912964	0.02260	26	0.53
2008 RZ24	2.17784533	0.56163149	13.93533754	165.75988542	122.24834247	228.94219608	0.07838-40	63	0.41
	2.17787177	0.56163720	13.93543395	165.75996916	122.24824768	228.93803259	0.07838-40	52	0.43
Extended Arcs at Second Opposition (Major Recoveries):									
2005 OJ3	2.71013672	0.53762893	4.44043486	239.00829721	154.97116812	11.35563295	0.26280-1	65	0.45
	2.71021194	0.53764106	4.44045440	239.00783784	154.97121905	11.34024651	0.26280-2	62	0.46
2008 CJ70	1.40566635	0.15171298	17.33745102	145.71702268	69.89141510	109.41544705	0.28369-70	75	0.54
	1.40568600	0.15171773	17.33805493	145.71693753	69.89010832	109.40607845	0.28367-74	73	0.54
2000 SZ44	2.44314896	0.50419701	5.69470263	128.83931580	250.57411766	203.53577984	0.23621-22	46	0.76
	2.44313484	0.50419447	5.69468409	128.83919426	250.57433239	203.54361778	0.23618-25	43	0.78
2002 VR94	2.38103120	0.55880939	5.57530694	57.06182464	326.87070923	37.18697396	0.07397	107	0.58
	2.38096936	0.55879728	5.57523792	57.06197398	326.87061638	37.21641152	0.07397-6	104	0.58