NEOShield-2

Science and Technology for Near-Earth Object Impact Prevention

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WP 10.2 **Deliverable D10.6**	**Report on Photometry and Precovery Observations**		
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Table of Contents

1 Introduction

1.1 Scope

This document reports on work carried out under Work Package 10 of the NEOShield-2 project. The exact deliverable of task 10.2.3 as specified in the GA:
Precovery of NEOs and discovery apparition photometry
Perform precovery searches for high-priority NEOs through direct analysis of Pan-STARRS1+2 imaging data , leading to increased orbital accuracy and phase-curve coverage for Task 10.2.1
Provide accurate discovery apparition photometry of NEOs detected by Pan-STARRS 1+2, increasing the accuracy of published photometry by up to a factor 10.
Prepare proposals for telescope time allocation as coordinated by task 10.1 to meet the scheduled deadline and execute the observations when time is allocated.
Obtain photometry with 1.0 and 2.0m telescopes in support of Tasks 10.2.1, 10.2.2 and 10.4.

In summary, this task requires the searching and measurement of PS1+2 images to obtain new NEO astrometry and photometry of selected targets before they were first reported, and to obtain new photometry in support of WP 10.

1.2 List of Abbreviations

AD Applicable Document
AU Astronomical Unit
GA Grant Agreement
MOID Minimum Orbit Intersection Distance
NEO Near Earth Object
RD Reference Document
WP Work Package

1.3 Applicable Documents

[AD1] NEOShield-2: "Science and Technology for Near-Earth Object Impact Prevention", Grant Agreement no. 640351, 28.10.2014.

1.4 Reference Documents

[RD1] Gwin, S.D.J. et al., 2012. "*SSOS: A Moving-Object Image Search Tool for Asteroid Precovery*". PASP 124, p579.

[RD2] Berthier, J. et al., 2006. "*SkyBoT, a new VO service to identify Solar System objects*", Astronomical Data Analysis Software and Systems XV, 351, 367.

[RD3] NEOShield-2 D10.4: " *Report on Photometric Observations I (Colours, and Phase Functions)*", Issue 1.0, 30/06/2017.

[RD4] NEOShield-2 D10.4: " *Report on Photometric Observations II (lightcurves and rotational properties)* ", Issue 1.0, 12/07/2017.

[RD5] Chambers, K. et al., 2016. "*The Pan-STARRS1 Surveys*", eprint arXiv:1612.05560

[RD6] Wolf, C. et al., 2017. "*Skymapper Data Release 1*", DoI: 10.4225/41/572FF2C5EBD30.

[RD7] Magnier, E.A. et al., 2016. "*Pan-STARRS Photometric and Astrometric Calibration*", eprint arXiv:1612.05242

[RD8] Denneau, L. et al., 2013. "*The Pan-STARRS Moving Object Processing System*", PASP 125, p357.

[RD9] Abell, P. et al., 2009. "*LSST Science Book, Version 2.0*", eprint arXiv:0912.0201

[RD10] Veres, P. et al., 2015. "*Absolute magnitudes and* slope parameters for 250,000 asteroids observed by Pan-STARRS PS1 – Preliminary results", Icarus 261, p34.

[RD11] Warner, B. et al., 2009. "*The asteroid lightcurve database*", Icarus 202, p134.

2 Background – NEO orbit/absolute magnitude determination

2.1 Orbit determination and precoveries

The basic information obtained for any NEO are its orbital elements, which dictate the impact probability with the Earth, and its absolute magnitude that is a function of its size and albedo. The discovery rate of NEOs (https://cneos.jpl.nasa.gov/stats/totals.html) is now over 1800 per year Approximately 90% of all discoveries are made by the large dedicated surveys of Pan-STARRS and Catalina, along with highly efficient follow-up by associated and independent facilities. Once orbits are established for NEOs, the predicted positions can then be compared with previously unidentified objects, submitted to the MPC with too little data to either confirm a new object or associate it with a known object. As the longer arcs of observations are associated with a NEO, the orbit becomes more accurate and such precoveries can be extended further back in time.

It has long been recognized that imaging archives from Earth and space-based observatories can hold useful additional data in performing astrometry and photometry of solar system objects. Currently the most useful facility for searching these datasets is the Solar System Object Image Search at the CADC (http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/ssois/index.html) [RD1]. This allows searches of the pointings associated with over 8 million images from a variety of astronomical cameras. These include large-scale sky surveys such as SDSS, through to pointed observations obtained with wide field instruments like MegaCam on the CFHT, to narrower field instruments such as WFPC2 on HST. Additional tools for performing such searches include the SkyBoT service at IMCCE for searching local and on-line ground-based images (http://vo.imcce.fr/webservices/skybot/) [RD2] and the in-development ESASky2.0 for space-mission images (http://sky.esa.int/beta/).

2.2 Absolute magnitude determination

At the same time, photometry performed on detection, follow-up and precovery images allow an accurate measurement of the phase curve of the NEO and hence its absolute magnitude. This process is vital as a good determination of the phase curve is necessary for an accurate absolute magnitude. It can also lead to an indication of the taxonomic type, as demonstrated in D10.4 of WP10 [RD3]. This can be difficult for NEOs, as unlike most main-belt asteroids, observations near zero degrees phase angle may not be obtainable. So observations over as large a range of phase angle as possible are important.

Historically, the MPC central repository of minor planet astrometric data has been the primary source of photometric data for NEOs, outside dedicated photometric studies such as those reported in D10.5 [RD4]. These brightness measurements are held to one decimal place –10% accuracy – to take into account previous uncertainties in submitted photometry. But there now exist accurate all-sky catalogues of stellar magnitudes from Pan-STARRS [RD5] and Skymapper [RD6]. Both major NEO surveys actually measure magnitudes to two decimal places. Hence the intrinsic accuracy of NEO survey data should allow more precise determination of absolute magnitudes and phase functions, as long as there are no systematic biases in the calibrations of these surveys.

3 Pan-STARRS Precovery Studies

QUB is part of the Pan-STARRS 1 Science Consortium (PS1SC), and as such has access to the non-public image database from both the PS1 and PS2 facilities. At the time of writing this contains 656,786 images obtained during both the 3.5-year 3-Pi sky survey (3PI [RD7]) plus the 7-year Solar System Survey (SSS). As the primary goal of the SSS is the discovery and tracking of NEOs, moving objects are automatically detected, measured and reported to the Minor Planet Centre via an Image Processing Pipeline (IPP) and Moving Object Processing System (MOPS) [RD8].

Unfortunately, there are natural limitations on this process. First, detections are made at a cut-off of 5-sigma above sky background. This is primarily to remove the large number of false detections that would otherwise occur. However, this means that lower brightness images of many NEOs will definitely exist in the data but are not detected and reported.
Second, and more nuanced, is the effect of the linking process within MOPS. 4 images are obtained at each sky position with a cadence of approximately 15 minutes. Detections are assigned into "tracklets", with each tracklet containing up to 4 detections of a given object as it moves over ~45 minutes. However, some frames may not contain a detection due to contamination by background objects, seeing variations bringing the signal to noise below 5 sigma, or the object falling into a gap between the detectors or on a bad set of pixels. The latter is a particular problem, as while the filling factor of the detectors in the PS1 camera is 90%, there are significant areas of poor detector response. Overall, the detection efficiency as measured from bright asteroids is only ~75%. This means that even if a NEO is above the detection threshold, less than 4 detections will often be made and the likelihood of the individual detections being recognised as a real object is significantly reduced.

Due to these limitations, it is probable that many additional NEO detections are present in the Pan-STARRS images. (We note that the frequency of non-detections in Catalina Survey data is likely to be significantly less, because of their larger effective fill factor, but more importantly detections are recorded at a lower signal to noise). To assess the importance of such unrecognised detections, we first made a search for low delta-v H-constrained NEOs with physical data but uncertain orbits, identified through WP9 D9.2. No new detections were identified. This was primarily due to targets being too faint for detection when in the Pan-STARRS field of view. Subsequently, we searched the existing Pan-STARRS image archive for unreported detections of two additional sets of NEOs.

3.1 NEOShield-2 spectroscopic targets

We took the NEOs with spectroscopy reported from WP10 at the mid-term review. As we were focused on the potential of precoveries, we selected the 20 NEOs from this list that had been discovered after the start of Pan-STARRS surveys at the end of 2010. To search the archive there was no point in using automated software, as the IPP/MOPS pipeline has already been tuned to high efficiency over 6+ years of operation. Instead, for each object we calculated which exposures might contain the object when it had a predicted magnitude of V<25 i.e. approximately 3 magnitudes below the best effective limiting magnitude in the normal survey. This is equivalent to a factor ~10 in flux or a signal to noise of < 2. Several arcminutes of each image around the predicted position were then retrieved from the archive and searched manually via blinking in display software.

Out of the 20 NEOs searched for, 8 NEOs (40%) were found to have precovery images in the PS1 survey data. The precovery of one object – 2014 YS34 - was found in pre-survey test data obtained in October 2010, 4 years before discovery. If this high rate of unreported detections is usual, we should expect there to be a similar number of unreported post-discovery images. Indeed, we found images of 7 NEOs (35%) in data obtained post-discovery but not detected by the IPP/MOPS software. The NEOs detected in this study are listed in table 3-1.

Table 3-1 NEOs with NEOShield-2 WP10 spectroscopy identified by us in precovery and post-discovery imaging by Pan-STARRS.

NEO	Precovery detection?	Unreported post-discovery detection?	Number of precovery images?	Days before earliest existing data	Precovery Filter
2011AK5	N	Y			
2011AM24	N	Y			
2011BT15	N	Y			
2012XD112	N	Y			
2013XV8	Y	Y	3	30	i
2014AY28	N	Y			
2014EK24	N	Y			
2014HS184	N	Y			
2014OV3	Y	Y	2	24	w
2014RQ17	Y*	N	3	43	w
2014VP35	N	Y			
2014YS34	Y	N	2	1520	i
2015BY310	Y	N	6	731	g,w
2015CN13	Y	N	4	12	i
2015RG36	Y	N	2	42	i
2015SZ	Y	N	4	41	w

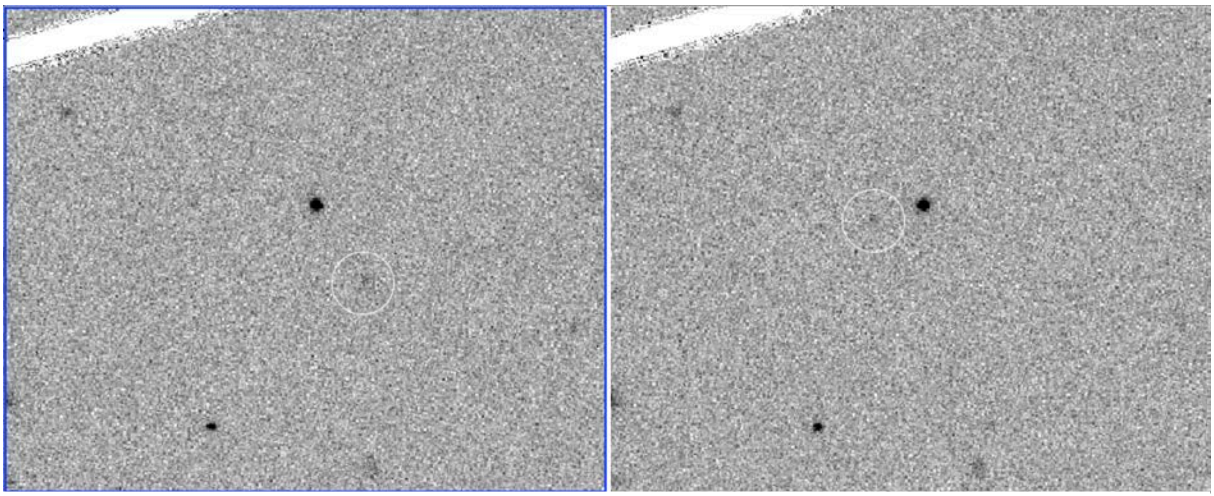

Figure 3-1 Precovery images of NEO 2014YS34 identified in PS1 images obtained on 29 October 2010, 4 years before discovery. Images are 1.5 arcminutes across.

3.2 Potentially Hazardous Asteroids

To further investigate the rate of precovery imaging, we selected the 90 PHAs discovered in 2016, and searched the Pan-STARRS dataset in a similar manner to above. Precovery images were found of 23 PHAs, or 26% of the selected targets. The earliest precovery made was of extremely faint g-filter images of 2016 BZ14 in data taken on 5 January 2011, 5 years before discovery. The PHAs with detected precovery images are given below in table 3-2.

Table 3-2 Precoveries of PHAs discovered in 2016 via searches of archival Pan-STARRS imaging data.

NEO	Number of precovery images	Days before earliest existing data	Precovery Filter
2016AC65	2	18	w
2016AZ8	4	195	w
2016BE1	2	178	w
2016BZ14	2	1839	g,i
2016CB194	6	1527	r, w
2016CJ195	6	10	r
2016CL32	4	688	w
2016CL264	11	543	g, i
2016CO247	4	34	w
2016CR247	2	30	w
2016CU193	4	27	w
2016DP	2	416	w
2016EH157	2	9	r
2016EJ56	5	23	i,w
2016EZ157	11	61	w
2016GT220	10	1443	w
2016HV3	4	26	r,w
2016JU33	15	126	I,w
2016NV	2	48	w
2016PQ39	2	3	w
2016PR38	2	21	w
2016SJ1	3	14	w
2016TZ17	4	100	w

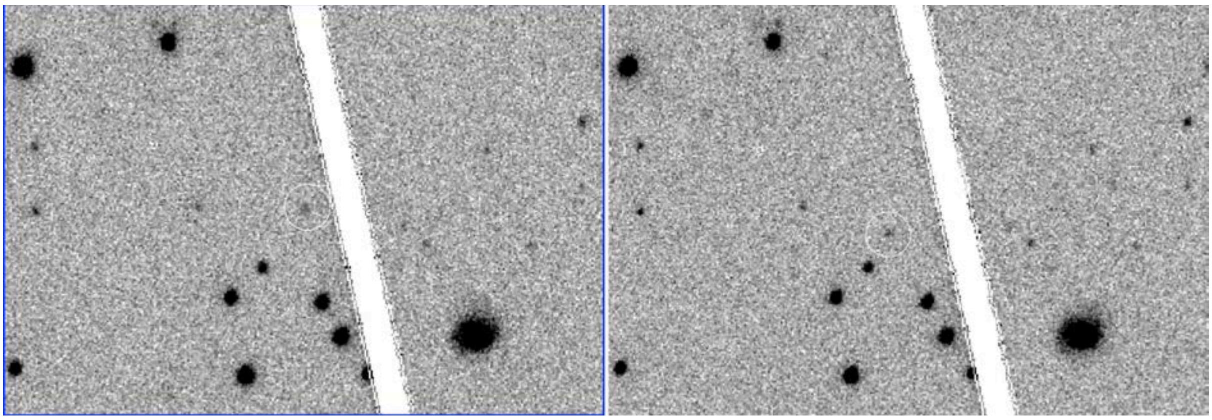

Figure 3-2 Precovery images of NEO 2016 GT220 identified in PS1 images obtained on 30 January 2012, 4 years before discovery.

3.3 Discussion

The difference between the precovery rates for the NEOShield-2 sample (40%) and the 2016 PHAs (26%) seems large at first glance. However, the former is affected by low-number statistics. Also, the IPP and MOPS software were continuously tuned in the first 3 years of survey to improve detection efficiency. Another important factor is that many of the

NEOShield-2 sample had significantly better orbits with which to constrain the area for precovery searches. This is a natural bias, as without good orbits it would not be possible to easily locate the NEO for subsequent spectroscopic observations. Some PHAs discovered in 2016 had large orbital and subsequent positional uncertainties at the epoch of Pan-STARRS observations, of order of several degrees. This made locating the PHA in the images impractical at best.

It is clear that for many NEOs, and in particular PHAs, there is approximately a 1-in-4 chance of finding precovery detections in Pan-STARRS images. This is an important number to take into account in future studies. It may also be possible to semi-automate this process in the future, as for most objects the apparent motion vector and sky-plane uncertainty ellipse is well constrained.

Perhaps the most important significance is for future surveys. The Large Synoptic Survey Telescope (LSST) will commence its NEO searches in 2022, and the limiting signal-to-noise for detections will also be 5-sigma [RD9]. Direct comparison is difficult, as LSST will be at a better site with more stable seeing. Also, the camera fill factor of ~91% should not be additionally affected by large areas of detector insensitivity. However, this study demonstrates that directed precovery efforts will be worthwhile for important NEOs such as high impact risk PHAs and potential space mission targets.

4 Precovery and discovery-epoch photometry of NEOs

4.1 Pan-STARRS photometry

Along with astrometric measurements, all NEO surveys report photometry of their detections. With Pan-STARRS, the accepted assessment is that this photometry is accurate to the photometric precision of the measurements i.e. there appear to be no significant biases in the photometry. This was shown after the start of the NEOShield-2 project by Veres et al. (2015) [RD10], where we analysed sparse photometry for 250,000 main-belt asteroids to derive absolute magnitudes and phase functions.

Along with the precovery and post-discovery detections and astrometry reported above, we independently performed photometry on the NEOShield targets in the Pan-STARRS images. This allowed us to compare manually measured PS1 magnitudes to predicted magnitudes and independently assess their accuracy. In this exercise, there are three important factors to consider.

First, the predictions are based on the MPC absolute magnitudes and phase functions. In the past, there have been significant biases in the MPC magnitudes of main-belt asteroids due to inaccurate calibration of early Solar system surveys (see figure 8 in [RD10] and references therein). However, most NEOs should be free of these biases. Second, accurately converting the Pan-STARRS filter magnitude to the standard V-band requires a composition-dependent magnitude correction. For example, converting from i(PS) to V-band requires a correction of 0.47 magnitudes for an S-type NEO, but only 0.31 magnitudes for a C-type NEO. Hence there is an additional uncertainty of up to ±0.1 magnitudes for measurements of individual NEOs. Third, lightcurve variations will impose variations in the observed magnitude for each measurement. While combining many measurements of many NEOs should remove any systematic offset, this will also affect the dispersion of magnitude measurements. The mean amplitude of 100-300m NEOs is ~0.3 magnitudes [RD11]. Hence from colour and lightcurve variations we might expect a dispersion between observed and predicted magnitudes of ~0.2 magnitudes.

For the primary gri filter observation of the NEOShield-2 targets we found a mean difference between the observed equivalent V-band magnitudes and predicted V-band magnitudes of 0.06±0.15. This absolute offset is relatively small, and may diminish with inclusion of further observations. The standard deviation matches expectations from the lightcurve and transformation uncertainties. An open question remains the accuracy of the w-band photometry, as this requires transforming field-star gri magnitudes from the 3PI survey Data Release 1 (December 2016) to w-band. Assessment of this photometry is currently being done by personnel outside NEOShield-2 (via a UK STFC grant), but will not be completed by the end of NEOShield-2.

4.2 1-m & 2-m photometry

At the time of grant application, we expected to have use of the 1-m SAFT telescope on La Palma for NEO photometry throughout the NEOShield-2 project. Unfortunately, although some limited early test observations were taken by another science team from the facility lead institute, there were continued significant problems with the optics and the mount drive mechanism. This prevented use of the telescope for NEOShield-2 observations. These problems were only mostly rectified in early 2017, and the 1-m was finally inaugurated on 3 July 2017.

5 Summary

We successfully obtained >30 precovery detections of PHAs and NEOShield-2 WP10 targets in archival Pan-STARRS images. The resulting extensions to the arc of orbital astrometry ranged from 3 days to 5 years. This study clearly demonstrated the importance of availability of archival data for precoveries of specific NEOs, with precovery rates of ~25% for recently discovered PHAs. A significant implication is that similar precovery searches for specific NEOs should be productive for the LSST in 2022 onwards. Planned observations with the 1-m SAFT facility could not take place due to an unexpected delay in bringing the telescope to operational status.