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Near Earth Asteroid search and follow-up beyond 22nd magnitude

A pilot program with ESO telescopes

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Abstract. We have performed a Near Earth Asteroid search and follow-up test beyond 22nd magnitude with the 2.2-m MPG/ESO and the New Technology Telescope (NTT) facilities at La Silla. The experiment comprised a total number of 4 nights at the 2.2-m telescope and 3 nights at the NTT on two separate runs. In addition to the discovery of two NEAs and the recovery of many more, this pilot program has shown the advantages as well as the problems of a dedicated program using much larger facilities than the ones currently used worldwide. We confirm the results of Jedicke et al. (2003), that by observing at fainter magnitudes and finding objects at larger distances, such a system will discover km-sized NEAs with higher orbital e and i as well as a larger proportion of the smaller NEAs; moreover, it will shorten the time needed to reach 90% completeness for km-sized objects. The pilot program also evidenced the need for follow-up facilities compatible with the discovery telescopes.

Key words. solar system: general – minor planets, asteroids – astrometry – celestial mechanics – surveys

1. Introduction

In the past 12 years various studies have discussed the best strategy to discover Near Earth Asteroids (NEAs, Shoemaker et al. 1979) of 1 km or larger within a limited amount of time: impacts with objects of 1 km lead to the highest peak of casualties (Chapman & Morrison 1994). The *Spaceguard Survey* (Morrison 1992), for example, envisaged a battery of 6 telescopes in the 2/3-m size class, well distributed both in latitude and longitude: the goal of this project was to cover about 6000 square degrees around the opposition region on a monthly basis to the 22nd magnitude.

For various reasons, partly economic, a number of scientists opted for a network of smaller, 1m-or-less, existing facilities to be refurbished with state of the art (large format, high-quantum-efficiency, fast readout) CCDs. The most demanding requirement of the new approach (Shoemaker 1995; Harris 1998) was to cover the entire visible sky every month: the only way to meet this goal was to take short exposures, to a limiting magnitude of 19.

These efforts yielded remarkable success during the first few years of activity by increasing the NEA discovery rate by an order of magnitude. However, after 5 years of survey work, this approach is starting to show clear signs of a decline with a 20% decrease of the discovery activity of $H < 18$ NEAs in 2002, compared to 2000 and 2001, due to the fact that there are fewer unknown objects observable at any time brighter than a certain magnitude. This trend is going to continue in the future, so that a different approach at fainter magnitudes appears to be the natural choice from now on.

In this paper we present the results of an experiment using, though for a very short time, appropriate larger facilities that

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can reach magnitude 22 and beyond (the same magnitude limit envisaged for the original *Spaceguard Survey*).

1.1. The telescopes

To perform this pilot program we chose two facilities of the European Southern Observatory at La Silla (Chile): the 2.2-m MPG/ESO telescope equipped with the *Wide Field Imager* (WFI) as *search telescope*, and the 3.58-m New Technology Telescope (NTT) for *follow up* at fainter magnitudes.

The WFI, which consists of a CCD mosaic of eight 2048×4096 pixel chips (arranged in a 4×2 pattern), provides a total field of view (FoV) of $34' \times 33'$.

The data achieved with the NTT was obtained using the red-arm imager (RILD) of the ESO Multi-Mode Instrument (EMMI): the detector consists of two 2048×4096 chips which provide a total FoV of $9.1' \times 9.9'$. Both telescopes have non-sidereal tracking and autoguiding capabilities.

Since these facilities are neither dedicated nor optimized for NEA work, what we could achieve during this experiment was only a *snapshot* of what might be a deep Spaceguard Survey.

However, some encouraging results were obtained:

1. the discovery of two faint NEAs which would have escaped detection by the current surveys for years;
2. the follow-up of a number of faint objects, including many NEA recoveries (Boattini & Forti 2000);
3. a quantitative estimate of the possible results if these or similar facilities were used for dedicated work;
4. indications on how to make such work more efficient.

2. The observations

We performed two observing runs: the first one, from 2 to 8 June 2002, comprised two nights at the 2.2-m telescope and one night at the NTT and was badly affected by the weather conditions.

The second run, from 23 to 30 January 2003, with two nights at the 2.2-m telescope and two at the NTT, allowed us to perform practically all the necessary tests.

2.1. NEA search with the WFI

The search for new NEAs requires the blinking of exposures taken on the same field at different times: a sequence of n (typically 4 to 8) WFI adjacent fields are taken in quick succession one after the other; this operation is repeated between 3 and 4 times. With exposures ranging from 60 to 120-s a typical NEA search scan takes from 30 to 90 min. Our strategy was to observe at *small solar elongations* (SSE) during the first part of the night, move to the opposition region during the middle part and back to SSE in the morning sky towards the end of the night. The choice of the fields was done according to their ecliptic coordinates with respect to the sun, to avoid the presence of bright stars and, to some extent, the Milky Way. Another criterion was to minimize duplication of efforts with other NEA surveys. Observations at SSE with large facilities are important for two reasons:

1. There is an observing bias against the discovery of Aten and Inner Earth Object (IEOs, objects completely inside the orbit of the Earth) groups of NEAs since searches have concentrated towards the opposition region so far. Atens are very important because they show the highest frequency of close encounters with the Earth (Carusi & Dotto 1996). IEOs, on the other hand, are very interesting because of their dynamical evolution and their relationship with the Aten group (Michel et al. 2000). However, searches at SSE are difficult because objects appear fainter (Boattini & Carusi 1997) and require large facilities. Only one IEO has been discovered so far (2003 CP_{20});
2. The sky-plane density of NEAs increases at SSE and this is an advantage when the search is conducted above a certain threshold magnitude. The 2.2-m MPG/ESO has both the capability to go faint enough to become effective and to search low enough in the sky (up to 3.0 air masses).

2.1.1. Binning

One of the initial challenges of this test was to deal with large data formats: a full mosaic image with WFI is equivalent to a single chip of 8192×8192 pixels which results in a scale of $0.238''$ pixel^{-1}. Although for many astronomical applications this level of resolution, coupled with the average seeing of La Silla at $0.8''$, is very desirable, for NEA search work it is not needed.

In fact, it turns out to be better to observe in binned mode, either in a 2×2 or 3×3 combination, yielding a scale of $0.476''$ pixel^{-1} and $0.714''$ pixel^{-1}, respectively. Our experience with the WFI observing conditions (short-term tracking errors as well as seeing variability) suggests that 3×3 binning should be the normal operating mode. Pixel resolution should be increased only when the seeing becomes better than 3 pixel.

There is a number of practical advantages for this choice:

- the *trailing loss* (Rabinowitz 1991; Bowell & Muinonen 1994) which places a severe limit on the survey performance with large telescopes is limited: for example, in 3×3 bin mode main belt objects (MBOs) start to trail in the opposition region only with exposures longer than 120-s;
- the tracking system of the 2.2-m telescope generally needs the support of a guide star for the acquisition of very good quality images. However, when observing is done in binned mode the image degradation due to the lack of autoguiding is masked rather efficiently: without the autoguiding there is also a significant drop of the overheads;
- the readout time is shorter with binned images;
- both image download and the reduction process are faster.

2.2. Follow-up with the NTT

Although the WFI could be used also to follow-up the new discoveries, there are a few good reasons not to do it: i) follow-up observations do not require the same kind of FoV, necessary to perform a NEA survey, i.e. the WFI time is best spent at surveying more sky; ii) since NEAs tend to fade after discovery and will continue to fade, further observations will require larger facilities. A telescope like the NTT is one of the best choices for following-up the WFI discoveries; it also allows a substantial improvement of the follow up of other NEAs (Tholen 2002), with beneficial effects on the quality of their orbits.

The improvement acts in two directions since it can go to much fainter magnitudes than those attainable in the NEA community: i) to prolong the observing arc of the discovery apparition; ii) to anticipate the epoch of the first recovery opportunity. The NTT is an excellent facility because it brought the additional advantage of a fast preset capability and the ability to point at very low elevations: this is extremely important for work at SSE.

The NTT in this test was used in two ways:

- to confirm NEA candidates discovered with WFI: the need of the NTT will be quite frequent since most of these faint discoveries cannot be followed elsewhere. In this respect, the NTT meets a good empirical requirement for a follow-up facility: it goes two magnitudes fainter than the discovery instrument;
- to follow faint NEAs in urgent need of observations: the primary source of information was the *Faint NEO List*, and the *Faint Recovery List* that contains objects in the 21 to 25 mag range. These lists are two of the services of the *Spaceguard Central Node*, an international coordination center dedicated to NEAs (Boattini et al. 2000a).

2.3. Image analysis and astrometric reduction

After the usual data reduction steps, i.e. bias and dark current subtraction and flat-fielding, the frames were split into 8 single FITS files, one for each chip, and the reduction continued with *automatic object detection* and with these objects' *astrometry*. The calibration was done with IRAF. As for object detection, images were processed in two different environments: i) using a portable computer at La Silla, with the CCDAR software, by M. Carpino, and with the *Astrometrica* software package (Raab 2003); ii) a few images were also transferred to a workstation in Europe for additional astrometric reductions with *Adamo*, written by H. Scholl.

In all cases image reduction, detection and astrometry were made separately for each chip of the mosaic because of the different pixel properties: for this reason we had to use different settings for each chip (FoV of about $16.5' \times 8'$) in order to find a balance in the number of discovery candidates to be verified by the observer.

3. The MPG-WFI observing runs and results

Only a modest amount of data was obtained in 2002 (on June 2/3, the first night) because of adverse weather conditions while the second night (June 3/4) was completely cloudy. Images were taken in unfiltered mode, except in the presence of strong moonlight: in such cases an *R* filter became useful to lower the level of the sky background.

Table 1. Various statistics regarding the data obtained with the 2.2-m MPG-WFI system on three nights (2/3 June 2002, 23/24 and 24/25 Jan. 2003): i) the number of fields and the total sky coverage; ii) the limiting magnitude in 3×3 binning mode and the seeing conditions during the three nights; iii) the total number of asteroid detections in all binning modes. They are followed by two groups: the ONS (One Night Stands) are observations of unidentified asteroids made in the course of only one night. The second group are known asteroids; the sum of these two groups is smaller than the number of detections because some fields from the first night were repeated on the second; iv) the total number of discoveries during the two runs: these are the subset of the known asteroids that were previously unknown and that were observed on two nights, a necessary condition established by the MPC in order to receive credit. It is interesting to notice that a large number of detections comes from unknown asteroids (ONS): the relative number of objects was especially high during the June run because we observed regions south of the ecliptic which are not easily accessible to northern observers. The numbers from the June run are affected by rapid moving clouds during the exposures.

	2/3 June	23/25 January
Number of fields	13	71
Sky covered	3.9 sq.deg.	24.1 sq.deg.
Limiting mag	21.0–22.0	21.0–21.5 (23/24)
		22.0–22.8 (24/25)
Aver. seeing	1.7–2.0″	1.8–2.0″(23/24)
		0.7–0.8″(24/25)
Total detections	122	661
ONS	93	282
Known asteroids	29	235
Discov.	1	75

During the second run at WFI, allocated on Jan. 23/24 and 24/25, the observing nights occured in good weather conditions. Both in the June and January runs typical exposures ranged from 60 to 120 s: given an overhead of about one minute per image, it was possible to cover 6–7 fields (or 2 square degrees) per hour with three passes. There was no benefit in shortening the exposure time under 60-s since it would not be very effective in terms of increasing the sky coverage.

The first night was affected by poor seeing conditions and only one interesting object (at mag 21) was detected, but unfortunately was not recovered (it might have been a false detection). A total of 31 search fields (WFI FoVs) were observed.

The second night at the WFI, with seeing of about $0.7{-}0.8''$, showed that a valid compromise between depth and trailing loss consists of exposures between 60 and 90-s: objects fainter than magnitude 22 were detected in unfiltered, 3×3 bin mode near opposition as well as with an *R* filter. The exposures ranged from 60 to 150-s. The night was initially affected by cirrus clouds on the western horizon so that the search work at SSE was partially compromised. A total of 40 WFI FoVs were obtained (all within 15 deg from the ecliptic) and led to the discovery of two NEAs, 2003 BC_{46} and 2003 BH_{84} (see later). The seeing improvement with respect to the first night (see Table 1) resulted in a gain of more than one magnitude.

A small number of WFI fields were taken in differential tracking mode for search purposes at SSE; a recent analysis (Masi 2003) has shown that the Aten and IEO populations display a relatively constrained range of apparent motions (about 1 deg/day), so that it would be more effective to track at this *average* motion rate than sidereally. Longer exposures can be taken to discover such objects at fainter magnitudes.

3.1. The NEA discoveries and their follow-up

During the 3 nights at the 2.2-m, a total of 783 asteroids were detected. Almost all of them were MBOs, that are recognizable from their characteristic motion. The discrimination between NEAs and MBOs was done by simulating asteroid motion numerically with a reliable sample of orbits of asteroids from different populations. The motion rates in ecliptic coordinates $(\dot{L}, \dot{B})$ of every detected asteroid was compared to the ranges of $(\dot{L}, \dot{B})$ from the different asteroid populations for the given position $(L - L_{\odot}, B)$ of the search field ($L_{\odot}$ is the ecliptic longitude of the Sun).

Three detections called for immediate attention due to their non-MBO motion; all of them were communicated to the Minor Planet Center, and were put on the NEO Confirmation Page. Due to their faintness, none of them was followed up by other telescopes. One was not recovered even by ourselves, and has to be considered a possibly spurious detection; the remaining two turned out to be NEAs.

The first NEA, designated by the Minor Planet Center 2003 BC_{46}, was discovered very close to the opposition point on January 25 and immediately caught our attention since it was moving perpendicularly to the direction of the ecliptic, though rather slowly. After follow-up with the NTT on January 29 and 30, it was possible to calculate a preliminary orbit and to find out that it is a very small Amor. Of magnitude 22.3 at discovery, it was detected automatically on 120-s exposures taken with an *R* filter under moon light.

The second NEA, 2003 BH_{84}, was imaged at magnitude 21.6 on Jan. 25; its motion, nearly parallel to the ecliptic ($\dot{B} \simeq 0$), was a bit too fast to be compatible with that of an MBO. However, the software to identify moving objects failed to detect 2003 BH_{84}, because the fringing patterns of the images were still too strong. Thus, it was detected by visual inspection only four days after the images were taken, and at that point it could be followed up only on the last night available at the NTT. The data from two nights were still insufficient to compute a complete orbit with the standard algorithm (Gauss' preliminary orbit followed by differential corrections). Since the object was faint, to the point of not being observable elsewhere, a *Target of Opportunity* (ToO) request was issued, and an additional set of NTT observations were obtained by O. R. Hainaut on February 6. An orbit determination using the observations of three nights revealed it as an Apollo type asteroid.

A final remark: to follow an object, one has usually a predicted position together with an error ellipse or an error estimate: both new NEAs were recovered after 4–5 days at only about 60–120″ from the nominal ephemeris. Of the same amount was the offset at which 2003 BH_{84} was recovered on the third night. This shows that the use of the NTT and the timing of its observing session after that of WFI was appropriate.

However, in the future a more flexible schedule is highly recommended: a reasonable solution for a typical run of a few nights at WFI consists of a full night with the NTT plus a number of hours with the same telescope to be used in service mode depending on the productivity of the WFI run. After the immediate actions following the discovery of new objects, a little bit of time is necessary on a regular basis during the following weeks to secure their orbits. We estimate that a new NEA requires a total of 45–60 min of time at the NTT.

4. The NTT observing runs and results

The first observing night at the NTT, June 7/8, 2002, was clear, and yielded very interesting results. Unfortunately, the seeing conditions were not very good (an average value of 1.4″), but this night was still very useful to evaluate the practical perfomance of the EMMI system both in unfiltered and *R*-filter mode.

Similarly to the WFI run, both nights at the NTT on the second run (Jan. 28/29 and 29/30) were clear. During the first night sky conditions were pretty satisfactory, with an average seeing of 0.8″. NEAs up to magnitude 24 were detected and measured and a few comets were also observed.

Unlike the WFI experiment, differential tracking was very effective in recovering some of the faint/faster moving objects. In several cases, the observations prevented the objects from becoming lost and in the case of 2002 XY_{38} they contributed to eliminate a *virtual impactor* (Milani et al. 2000a).

On the second night the workload for follow-up of already known objects was smaller, but the visual discovery of the second NEA candidate on the WFI images at the beginning of the night and the variations of the seeing (from 1.1″, to a peak of 5.0″, during the middle of the night and then 1.0″, towards the end of the night) made the organization of the observations rather challenging.

Beside the use of the EMMI imager, we performed a test with the *Superb Seeing Imager – 2* (SuSI2) system on Jan. 24/25 at the NTT on 2003 AL_{73}. Although the results were satisfactory as far as camera performance is concerned, its limited FoV (about 5′ on a side) makes this system less appealing than EMMI.

As shown in Table 3 the overall results at the NTT were very encouraging. A good number of NEAs were observed at faint magnitudes and some recovered rather easily. Besides the asteroid program some comets were also observed for astrometric purposes, such as C/1995 O1 (Hale-Bopp) and C/1999 K8 (LINEAR), both located at large heliocentric distances (17.9 AU and 9.5 AU, respectively).

A number of other NEAs scheduled with the NTT were searched for but not detected for a few reasons. Possible reasons for the missing detections are:

1. sky uncertainty larger than EMMI FoV and/or uncertainty in the object magnitude;
2. insufficient exposure time for the sky conditions;

Table 2. Orbital elements of the two new NEAs, epoch, distance from Earth at the epoch of discovery, observed arclength. The last line gives the absolute magnitude *H*: a value of 23.8 corresponds to an object of about 45−105 m, while $H = 17.3$ indicates a body between 1 and 2 km.

O. E.	**2003 BC$_{46}$**	**2003 BH$_{84}$**
a	2.021 AU	1.951 AU
e	0.388	0.713
i	4.53°	23.15°
Ω	154.12°	283.39°
ω	314.15°	35.20°
M	71.62°	174.81°
epoch* (MJD)	52 850	52 850
Δ	0.280 AU	1.984 AU
arc	89 days	12 days
H	23.8	17.3

3. crowded field due to low galactic latitude;
4. interference with trailed stars (differential tracking).

5. Discussion

We now discuss some issues that this pilot program has raised:

- the scientific impact of a dedicated program with these facilities on the Spaceguard Survey;
- a comparison with other survey approaches;
- the limits of a system not built to look for NEAs;
- the margins for its improvement.

5.1. Implications of the NEAs discovered with the WFI

There are essentially two lessons learned from the two NEAs discovered at 22nd magnitude (see Table 2):

- Tunguska size class objects, like 2003 BC$_{46}$, are discovered at larger distances than with smaller telescopes. Although this specific object is not on an orbit which poses a threat, other hazardous ones in this size range can be detected before they come very close to the Earth and followed for much longer. This body was followed on two additional nights, on March 8 at the NTT (mag 23.6 V) and on April 24 at the VLT (mag 25.6 V) in order to obtain an accurate orbit for a future recovery. This example shows that such a deep survey can provide a considerable contribution to the inventory of small objects.
- The discovery of 2003 BH$_{84}$ at large geocentric distance shows that a deep survey accelerates the time required to reach the full inventory of the km-sized NEAs. Objects like this one, with large eccentricity and inclination, require more *survey time* to be discovered with current surveys since they spend a greater percentage of time at large distances where they are faint (Jedicke et al. 2003), while, with a limiting magnitude of more than 22, km-sized NEAs can be discovered at heliocentric distances larger than 3 AU. With currently operating facilities this NEA would have not been discovered before the end of 2007.

Table 3. A listing of all the NEAs and comets successfully followed-up with the NTT. The upper part of the table refers to the first run in June 2002: a total of 19 NEAs and 2 relatively bright comets were identified. The *Rec* in the third column stands for *recovery* and means that the object was located for the first time after the discovery apparition. In the second run in January 2003 (lower part of the table) 30 NEAs and 6 comets were successfully followed-up. The predicted magnitude ranged between 15 and 24.0 V. Most of these objects were observed in unfiltered mode, a few with an *R* filter. A (*) indicates that the object was observed at less than 60 deg elongation from the sun.

Object	Visual magn.	Notes	Object	Visual magn.	Notes
1998 ST$_{49}$	21.3	*	2002 LK	20.9	
2002 AC	20.5		2000 SF$_{8}$	22.6	Rec
2002 AE$_{9}$	21.2	* Rec	2000 TO$_{64}$	23.4	Rec
2002 DH$_{2}$	21.5		2002 GP$_{5}$	21.8	
2000 GS$_{146}$	21.6	*	2002 ES$_{11}$	21.9	
2001 CQ$_{36}$	22.4	Rec	C/2001 Q4	17	
2001 FX$_{9}$	23.5	Rec	C/2001 W2	18	
2000 YM$_{29}$	23.4	Rec	2002 GZ$_{8}$	21.7	
1998 ST$_{4}$	22.9		2002 AA	22.7	
2001 QO$_{142}$	22.5	Rec	2002 JQ$_{100}$	21.3	
1998 QR$_{15}$	22.9	Rec			
1978 CA	16.9		2002 WP$_{11}$	22.2	
1998 ST$_{49}$	22.6	Rec	2002 XB	22.7	
1999 RC$_{32}$	23.4	Rec	2002 XM$_{14}$	23.7	
1999 TB$_{5}$	21.9	Rec	2002 XS$_{14}$	21.9	
2000 AD$_{6}$	21.8	Rec	2002 XY$_{38}$	23.0	
2001 FF$_{7}$	23.4	Rec	2002 XY$_{39}$	22.1	
2001 SK$_{9}$	24.0	Rec	2002 XO$_{40}$	22.8	
2001 BP$_{61}$	23.0	Rec	2002 YG$_{4}$	21.3	
2002 FA$_{6}$	21.7	Rec	2002 YD$_{12}$	20.2	
2002 LW	22.7	Rec	2003 AL$_{73}$	18.5	
2002 LG$_{3}$	22.3	Rec	2003 BC$_{46}$	22.1	
2002 LS$_{32}$	21.9	Rec	2003 BH$_{84}$	21.7	
2002 RP$_{137}$	23.2		C/1995 O1	20	
2002 SR	21.1		C/1999 K8	19	
2002 TV$_{55}$	20.6		C/1999 Y1	18	
2002 TS$_{69}$	23.7		C/2001 N2	15	
2002 VO$_{85}$	22.1		C/2001 Q1	20	*
2002 VC$_{92}$	19.8		C/2001 W2	22	

5.2. A comparison of survey approaches

A useful analysis to help visualize the impact of a deep survey is to compare the ratio between the detection of new NEAs with that of known ones found accidentally.

In this respect, we have analyzed four NEO observing programs: LONEOS, LINEAR, CINEOS and this test with the WFI (Table 4), taking the data from the databases of the Minor Planet Center and of NEODyS (Milani et al. 1999). Since each survey has a different rate of productivity, we reported statistics from different intervals. Although the LINEAR team does a more complete coverage of the whole available sky, it regrettably does not publish data on single night

Table 4. In this table we report: i) the number of ONS which we defined in Table 1; ii) the total number of designated objects, old and new *Desig. objs*; iii) the number of new NEAs; iv) the number of known NEAs detected accidentally during the survey; v) the ratio between new and known NEAs detections; vi) the total list of discoveries (essentially, MBO discoveries); vii) the nominal limiting magnitude of the system; viii) the initial time and ix) the final time for the statistics; x) the total number of clear nights (even clear for just one hour) in which these observations were obtained.

	LONEOS	**LINEAR**	**CINEOS**	**WFI**
ONS	1666	unpubl.	2235	375
Desig. objs	38212	23678	9522	264
New NEAs	14	13	5	2
Known NEAs	112	97	14	0
Ratio	0.125	0.134	0.357	>1.0
All discov.	1283	1625	1152	76
Lim. magn.	19.3 V	19.4 V	20.5 V	22.0 V
Start time	20/11/02	20/02/03	10/06/02	02/06/02
End time	18/03/03	18/03/03	17/10/03	25/01/03
No. of nights	40	27	63	3

observations (ONS). We are then forced to make the comparison with LONEOS.

The most important parameter is the ratio between new and known NEAs. This ratio is low for LONEOS and LINEAR, which are very similar systems, while it increases for CINEOS, since this smaller survey goes a full magnitude fainter, and it becomes larger than 1 (it cannot be fully evaluated with such small numbers) for the ESO/WFI system.

5.3. Expected number of NEA discoveries with the WFI

For a very short time (two nights) the WFI worked as a deep survey, resembling in part the original Spaceguard Survey. Of course, two new NEAs discovered in that period are almost negligible when compared to about 40 such objects discovered each month, but we can estimate i) what could be achieved with, say 10 nights per month at WFI, extrapolating some information from the pilot run, and ii) the amount of time for follow-up needed with the NTT. Here we neglect the contribution from the June 2002 run since it was very modest and not fully reliable because of the weather.

For this purpose, we have compared the WFI data with the 1.8-m Spacewatch II survey (SW-II) performance (McMillan et al. 2002) between Jan. 17 and Feb. 17, 2003. Such an evaluation is possible using pointing history information of this survey. For simplicity, the comparison was made only with data coverage taken in the opposition region. We chose to use SW-II data since the latter is the only NEA discovery program which has a comparable visual limiting magnitude to that of WFI. In the given period, SW-II discovered 6 NEAs. Taking the average sky covered per NEA discovered by SW-II, rescaling and correcting it for the slightly different charateristics of ESO telescopes, we obtained a conservative estimate of the

Table 5. SW-II observing performance between Jan. 17 and Feb. 17, 2003.

Sky covered	160.3 sq. deg.
Discovered object	*V* at discovery
2003 BN_4	20.4
2003 BQ_{35}	21.7
2003 CC	20.3
2003 BC_{44}	21.9
2003 BK_{47}	21.9
2003 BM_{47}	21.3

expected number of NEA discoveries for a typical observing night at ESO. This is useful to understand whether or not the two NEA discoveries in two clear nights is a typical result.

5.3.1. A comparison with Spacewatch II

Table 5 shows the amount of sky covered by SW-II and the visual magnitude range of its 6 NEA discoveries.

All SW-II published discoveries are objects automatically detected on CCD frames; the experience of the SW-II team is that the automatic detection finds about 2/3 of the objects that visual inspection of their CCD images can find. We take this into account by introducing a correction factor of 3/2 for the automatic/visual detection discrepancy. Thus, the number of SW-II NEA discoveries would have been ~10 if visual detection had been used.

The first night at the WFI experienced bad seeing, with $V_{\rm lim} = 21.4$. The sky covered was 5.4 sq. deg, and no discoveries were made. The expected number of discoveries for this night is

$$E_{\rm NEAs,\,1st} \simeq \frac{5.4}{160.3} \cdot 5 \simeq 0.2, \quad (1)$$

where $E_{\rm NEAs,\,1st}$ is the expected number of discoveries in the 1st night, ~5 is the number of NEAs discovered by SW-II below $V = 21.4$ (see Table 5) and 160.3 is the total sky coverage in sq. deg.

The second night was much better, with $V_{\rm lim} = 22.4$. The sky covered was of 7.6 sq. deg. and yielded 2 discoveries. The corresponding expected number of discoveries is

$$E_{\rm NEAs,\,2nd} \simeq \frac{7.6}{160.3} \cdot 10 \cdot 2 \simeq 0.9, \quad (2)$$

where $E_{\rm NEAs,\,2nd}$ is the expected number of discoveries in the 2nd night and ~10 is the corrected number of NEAs discovered by SW-II, and 2 is the correction factor due to the deeper limit than SW-II of about 0.5 mag.

The latter factor has been estimated as follows: the visual magnitude of a minor planet near opposition is related to its absolute magnitude by the equation

$$V = H + 5\log(1 + \Delta) + 5\log\Delta, \quad (3)$$

where Δ is the geocentric distance of the object. For an asteroid with a given absolute magnitude, the reduction in visual magnitude, ΔV, due to the increase in geocentric distance, from Δ_1 to Δ_2, can be expressed in the following way, through Eq. (3),

$$\frac{\Delta_2 + \Delta_2^2}{\Delta_1 + \Delta_1^2} = 10^{\frac{\Delta V}{5}}. \quad (4)$$

As a rough approximation, we assume that the correction factor we are searching for is the fraction of increased explorable volume due to the WFI deeper magnitude and is proportional to $(\Delta_2/\Delta_1)^3$.

If we assume that a) $\Delta_2 \simeq \Delta_1 > 1$ AU, and b) $\Delta_2 \simeq \Delta_1 < 1$ AU, then Eq. (4) could be approximated by

$$\text{a)}\ \frac{\Delta_2^2}{\Delta_1^2} \simeq 10^{\frac{\Delta V}{5}}, \qquad \text{b)}\ \frac{\Delta_2}{\Delta_1} \simeq 10^{\frac{\Delta V}{5}}, \quad (5)$$

and the correction factors become, respectively

$$\text{a)}\ \left(\frac{\Delta_2}{\Delta_1}\right)^3 \simeq 10^{\frac{3\Delta V}{10}}, \qquad \text{b)}\ \left(\frac{\Delta_2}{\Delta_1}\right)^3 \simeq 10^{\frac{3\Delta V}{5}}. \quad (6)$$

With $\Delta V = 0.5$, Eqs. (6) give correction factors of $\sim$1.4 and $\sim$2, respectively. Note that Eq. (6b) provides an upper limit to the true correction factor rigorously derivable from Eq. (4). These values not being very different, in our analysis we choose to use the latter.

The cumulative expected NEA discoveries by ESO from the data of two nights is then

$$E_{\text{NEAs}} \simeq 1 \pm 1, \quad (7)$$

where the uncertainty comes from assuming Poisson statistics.

As a matter of fact, this estimate is compatible with the actual performance for these two specific nights of the pilot program. If we assume that a future typical night at La Silla is similar to the second one, we find that the estimate in Eq. (7) is expected to be reachable in one single night (see Eq. (2)). Of course, there are various significant uncertainties: i) a test run, by definition, cannot be as efficient as a routine run for which a *best observing strategy* has been defined; ii) there are margins to improve the automatic detection software, testing different settings so that objects like 2003 BH_{84} can be detected *automatically*; iii) there is room to improve the image calibration in order to reduce the contribution of fringing; iv) a few fields of the first night were repeated on the second; although this approach led to the discovery credit of a number of MBOs and could help to locate NEAs that mimic MBO motion rates, it is more convenient to cover only *fresh sky* on consecutive nights.

After evaluating the various trade-offs, we estimate that, on a total of 120 nights per year, of which about 90−100 would be clear, about 100 new NEAs could be discovered.

5.4. WFI and NTT suitability for NEA search and follow-up

As it is, the 2.2-m WFI system is not optimized to look for NEAs. The main issues that reduce its efficiency with respect to a hypothetical facility are:

- there are relatively long overheads between two consecutive images (readout and other tasks); some steps could be automated to save many seconds per image;
- the calibration and reduction analysis could be faster;
- the scale and the FoV are not optimized for NEA work, for the reason explained in Sect. 2.1.1. In particular the large matrix provided by the WFI mosaic could be used to obtain a much larger FoV at lower resolution (this would eliminate the need for binning). However, since the *WFI* already efficiently exploits the telescope focal plane, a different facility should be used to obtain a larger FoV.

Unlike the 2.2-m WFI, the NTT is very close to an ideal follow-up instrument. The only significant improvement that could be made to it consists in a wider FoV, especially beneficial in two cases: i) confirmation of faint NEA candidates reported on the NEO Confirmation Page; ii) extension of recovery searches to objects with larger sky uncertainties.

Compared to the search work, the follow-up is more time consuming because of the need for direct interaction with the observer to confirm the recovery and check the astrometric results.

5.5. Feasible improvements

There are various areas with room for improvements:

- we need to optimize the rapid access to the data. The goal is to reduce all the data well before the start of the following night at the NTT, so that there is time to organize targeted follow-up observations of the objects with non-MBO motion found with WFI;
- the image acquisition overheads can be shortened by creating an ad hoc *Observing Block (OB)* for survey work. This *OB* will execute all the p frames of a whole search scan (with $p = n_1 \times n_2$, n_1 = number of FoVs, n_2 = number of repetitions);
- part of the reduction tasks could be performed with remote assistance in Europe;
- there are also issues related to atmospheric conditions: the inclusion of a large follow-up telescope like the NTT does not guarantee that follow-up observations will always be provided when needed, but the survey should occasionally involve other facilites in the 2−4 m class. When a search night occurs under excellent seeing conditions, its particular productivity can be put at high risk by follow-up nights with bad seeing. For example, 2003 BC_{46} could not be detected with the NTT for several hours during the last night of the run, while it was a relatively easy detection when it was discovered with WFI. A remedy used by astronomers consists of requesting ToO observations with specific observing constraints to make sure that their scientific goals are met. This approach can be implemented for the follow-up work, but there is a limit to the number of hours that can be requested in this mode and a need to find *balance* between ToO time and allocated time on fixed dates.

5.5.1. Astrometry and orbital accuracy

The quality of NEA orbits depends on various factors. Two of the most important are: i) the intrinsic accuracy of the observations; ii) their correct weighting.

It has been demonstrated that CCD observations allow relative positions of objects of stellar or quasistellar appearance with accuracy better than 0.1 pixels (Pravec et al. 1994), though not close to the detection limit. Thus, given the tracking accuracy of the NTT, it is reasonable to expect astrometric precision of the order of 0.05″, under good seeing conditions. Of course, it is crucial to link the *temporal* accuracy to the *spatial* one: a time accuracy of 0.1-s is always satisfactory.

At this stage the main impediment to CCD astrometry with such facilities is the lack of astrometric star catalogs with sufficient precision to exploit their full potential, and it would certainly help if all the data from the NTT were remeasured when better astrometric catalogues are produced.

The astrometric star catalogue we have used is the *USNO A2.0*. Although its photometric accuracy is of marginal quality, we used this source of information to provide first order magnitude estimates of all the detected asteroids: a general check was made with the expected brightness of known objects at various magnitudes. The astrometric accuracy of our observations tends to approach the limit of the USNO catalogue, namely 0.3″ to 0.5″. However, for the near future we expect to use better catalogs, such as the *USNO B1.0* whose residuals drop by a factor of two.

6. Conclusions

The 2.2-m WFI and NTT systems have been shown to be potentially competitive, even in the presence of surveys covering very large sky areas. NEA search work at very faint magnitudes is a new field whose potential has not been fully exploited as yet. This is underscored by the fact that no other facility in the NEA community was able to follow our two discoveries. This calls for special attention because, with this new *modus operandi* the follow-up support cannot be easily organized or expected for granted elsewhere, not even at the very preliminary stages. There is strong motivation to organize and optimize the distribution of observing efforts with one or more (local) large facilities, represented by the NTT in this case.

The facilities of ESO were chosen because La Silla offers appealing observing conditions (good seeing, large fraction of clear nights, dark sky), and because it is located in the Southern hemisphere where no NEA search programs were operating.

This test teaches us some lessons:

1. a large search facility must work in synergy with at least one larger follow-up facility;
2. the vagaries of seeing conditions play a very important role for the successful confirmation/identification of NEA candidates: a flexible schedule is the key to dealing with rapid seeing changes;
3. one new NEA per clear night seems a reasonable estimate for the WFI system after further improvements in image calibration and detection software; part of the work could be done remotely to increase its efficiency.

The combination of poor seeing, cirrus clouds or moon light, did not allow full evaluation of the potential of this system for searches at SSE. Nevertheless, if a program like this could be conducted on a large number of nights, all the requirements would be fulfilled to contribute to the discovery of Atens and IEOs.

Summarizing, we find a well defined *niche* in which the pair WFI-NTT can play an important role for several years to come. The use of these facilities can represent the transition between the current NEA NASA surveys and future ground-based surveys with larger telescopes, as well as space based facilities.

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