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KLENOT Project 2002–2008 contribution to NEO astrometric follow-up

Jana TICHA[1*], Milos TICHY[1], Michal KOCER[1], and Michaela HONKOVA[1]

[1]Klet Observatory, Zatkovo nabrezi 4, CZ-370 01 Ceske Budejovice South Bohemia, Czech Republic
[*]Corresponding author. E-mail: jticha@klet.cz

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Abstract–Near-Earth object (NEO) research plays an increasingly important role not only in solar system science but also in protecting our planetary environment as well as human society from the asteroid and comet hazard. Consequently, interest in detecting, tracking, cataloguing, and the physical characterizing of these bodies has steadily grown. The discovery rate of current NEO surveys reflects progressive improvement in a number of technical areas. An integral part of NEO discovery is astrometric follow-up crucial for precise orbit computation and for the reasonable judging of future close encounters with the Earth, including possible impact solutions. The KLENOT Project of the Klet Observatory (South Bohemia, Czech Republic) is aimed especially at the confirmation, early follow-up, long-arc follow-up, and recovery of near-Earth objects. It ranks among the world's most prolific professional NEO follow-up programs. The 1.06 m KLENOT telescope, put into regular operation in 2002, is the largest telescope in Europe used exclusively for observations of minor planets and comets, and full observing time is dedicated to the KLENOT team. In this paper, we present the equipment, technology, software, observing strategy, and results of the KLENOT Project obtained during its first phase from March 2002 to September 2008. The results consist of thousands of precise astrometric measurements of NEOs and also three newly discovered near-Earth asteroids. Finally, we also discuss future plans reflecting also the role of astrometric follow-up in connection with the modus operandi of the next generation surveys.

INTRODUCTION

There are various kinds of small bodies orbiting the Sun. The near-Earth objects (NEOs) are the closest neighbors of the Earth-Moon system. NEO research is an expanding field of astronomy, important both for solar system science and for protecting human society from the asteroid and comet hazard. NEOs are sources of impact risk and represent usually a low-probability but potentially a very high-consequence natural hazard. Studies of NEOs contributed significantly to our overall understanding of the solar system, its origin, and evolution.

Near-Earth objects are asteroids and comets with perihelion distance q less than 1.3 AU. The vast majority of NEOs are asteroids, referred to as near-Earth asteroids (NEAs). NEAs are divided into four groups (Amors, Apollos, Atens, and IEOs) according to their perihelion distance, aphelion distance, and their semi-major axes. There are currently more than 5700 known NEAs.

Potentially hazardous asteroids (PHAs) are NEAs whose minimum orbit intersection distance (MOID) with the Earth is 0.05 AU or less, and whose absolute magnitude H is H = 22.0 mag. or brighter, i.e., whose estimated diameter exceeds about 140 meters. Currently, almost 1000 PHAs are known.

NASA proposed the Spaceguard goal of discovering 90 percent of all NEOs with a diameter greater than 1 km by the end of 2008. In 2007, the Spaceguard goal was modified to detect, track, catalogue, and characterize 90 percent of all potentially hazardous objects (PHOs) larger than 140 m by the end of 2020. One can estimate that there may be about 100,000 NEAs with diameters exceeding 140 m.

Virtual impactors (VIs) are asteroids for which possible impact solutions, compatible with the existing observations, are known, and a very small but definitely non-zero, probability of collision with Earth exists. Virtual impactors are listed on the Sentry Impact Risk page hosted by the NASA Jet Propulsion Laboratory (Chamberlin et al. 2001) and on the NEODys Risk Page maintained by the University of Pisa which operates the impact risk monitoring system CLOMON2 (Milani et al. 2005). As new positional observations become available, the most likely outcome is that the object's orbit is improved, uncertainties are reduced, impact solutions are ruled out for the next 100 years, and the object will eventually be removed from these lists.

Astrometric follow-up is essential also for targets of future radar observations, space mission targets and other observing campaigns.

The discovery rate of current NEO surveys reflects an incremental improvement in a number of technical areas, such as detector size and sensitivity, computing capacity and availability of larger telescope apertures. This has resulted in an increase in the NEO discovery rate. There are currently a dozen telescopes ranging in size from 0.5 to 1.8 meters carrying out full or part time systematic surveying in both hemispheres. Several new larger projects are in various stages of preparation.

An integral part of NEO discovery is rapid early follow-up. Extensive follow-up on time scales of weeks and months is usually required for subsequent return recoveries, and may become critical in ensuring that PHAs and VIs are not lost. Calculation of precise orbits and determination of impact probabilities require enough precise astrometric measurements covering appropriate orbit arcs. For brighter objects, many amateur volunteer observers use small or moderate-size telescopes all over the world to help accomplish this task. For fainter objects, just several professional telescopes of 1 m class or larger are used regularly for astrometric follow-up, mainly the JPL Table Mountain 0.6 m, Mt. John 0.64 m, Klet Observatory KLENOT 1.06 m, Spacewatch 1.8 m, and Mt. Lemmon 1.5 m telescopes (Larson 2007).

Considering the urgent need for astrometric follow-up of fainter and fast-moving objects, we decided to use resources of the Klet Observatory for building a 1-meter-size telescope for such purposes. This KLENOT telescope was put into operation in 2002 (Ticha et al. 2002). We report the results obtained during six years of regular KLENOT operation as well as future plans based on technical improvement of the KLENOT system and also inspired by the planned next generation surveys.

KLENOT GOALS

The KLENOT project is a project of the Klet Observatory Near-Earth and Other Unusual Objects Observations Team (and Telescope). Our observing strategy is to concentrate particularly on fainter objects, up to a limiting magnitude of m(V) = 22.0 mag. Reasonable object selection is a key part of the observation planning process. Therefore. the main goals of The KLENOT Project have been selected as follows.

Confirmatory Observations of Newly Discovered Fainter NEO Candidates

The majority of newly discovered objects which, on the basis of their motion or orbit, appear to be NEOs as well as objects that are suspected to be comets go on promptly to the NEO confirmation web page (NEOCP) maintained by the Minor Planet Center (MPC) (Marsden et al. 1998). Such NEO candidates need rapid astrometric follow-up to confirm both their real existence as a solar system body and the proximity of their orbits to that of the Earth. Some of new search facilities produce discoveries fainter than m(V) = 20.0 mag. (for example, 1.5 m Mt. Lemmon, 1.8 m Spacewatch II) which need a larger telescope for confirmation and early follow-up. A 1-meter-class telescope is also very suitable for confirmation of very fast moving objects and our larger field of view enables to search for NEO candidates having a larger ephemeris uncertainty.

Follow-Up Astrometry of Poorly Observed NEOs

Newly discovered NEOs need astrometric data obtained over a longer arc during the discovery opposition when they get fainter. The highest priority has been given to virtual impactors and PHAs. Special attention is also given to targets of future space missions or radar observations. It is necessary to find and use an optimal observing strategy to maximize orbit improvement of each asteroid along with efficient use of observing time, because reasonable object selection is a key part of the observation planning process.

Recoveries of NEOs at the Second Opposition

For the determination of reliable orbits it is required to observe asteroids at more than one opposition. If the observed arc in a discovery apparition is long enough, the chance for a recovery at the next apparition is good. If the observed arc at a single opposition is not sufficient and the ephemeris of selected target is uncertain, then we usually plan to search along the line of variation based on data from Minor Planet Center databases (Marsden, Williams, Spahr), Lowell Observatory databases (Bowell, Koehn), and Klet Observatory databases (Tichy, Kocer). For this purpose, a larger field of view is an advantage.

Analysis of Cometary Features

The majority of new ground-based discoveries of comets comes from large surveys devoted, predominantly, to NEAs. The first step in distinguishing these newly discovered members of the population of cometary bodies consists of confirmatory astrometric observations along with detection and analysis of their cometary features (Tichy et al. 2005). Timely recognition of a new comet can help in planning future observing campaigns. The following step is to pursue the behavior of cometary bodies, i.e., to obtain observation data of comet outbursts and fragmentation or splitting of cometary nuclei.

Search for New Asteroids

The primary goal of the KLENOT Project is astrometric follow-up of NEOs and comets. Moreover, all of obtained CCD images are processed not just for targeted objects, but also examined visually for possible unknown moving objects. This can be achieved because the effective field of view, observing time and limiting magnitude of m(V) = 22 mag. of the KLENOT telescope enable us to find new objects.The obtained CCD images are processed with special attention to objects showing unusual motion.

KLENOT TELESCOPE

The KLENOT telescope is located at the Klet Observatory in the Czech Republic. The IAU/MPC observatory code is (246) Klet Observatory-KLENOT. The geographical position of the observatory is longitude = +14°17′17″ E, latitude = +48°51′48″N, h = 1068 m above sea level. It is situated at a rather dark site in the middle of a protected landscape area.

The KLENOT telescope was built between 1996–2002 using an existing dome and infrastructure of the Klet Observatory. An original mount dating from 1960s was upgraded. A new control and computer room was built on the ground floor of the dome.

The KLENOT telescope was completed using a 1.06 m primary mirror and a primary focus corrector. The main mirror was fabricated by Carl Zeiss Jena using Sital glass (Zerodur type) and is f/3.0. The primary focus corrector was designed by Sincon, Turnov, Czech Republic, and was fabricated by the Optical Facility of Charles University, Prague, Czech Republic, led by Jindrich Walter. The corrector consists of four spherical lens elements. The resulting optical configuration is f/2.7 folded prime focus where the CCD camera is located.

The CCD camera used for the KLENOT telescope is Photometrics Series 300. The CCD chip sensor SITe SI003B contains 1024 × 1024 pixels, pixel size 24 microns, and is back illuminated with high quantum efficiency, Q.E. >80% in range 5500–8000 Angströms. Imaging array size is 24.6 × 24.6 millimeters. The CCD camera includes a 16 bit digitizer with full-frame readout time of 5.4 seconds and liquid nitrogen cryogenic cooling. Cryogen hold time for our 1.1 liter dewar is over 6 hours. Dark current is virtually non-existent in this camera due to operating chip temperature of 183 K.

The field of view of the KLENOT telescope is 33 × 33 arcminutes using the CCD camera mentioned above. The image scale is 1.9 arc seconds per pixel. The limiting magnitude is m(V) = 21.5 mag. for 120 second exposure time in standard weather conditions.

The KLENOT telescope is the largest telescope in Europe used exclusively for observations of minor planets and comets. All the observing time is dedicated to the KLENOT team.

KLET SOFTWARE

There has been developed a special software package for KLENOT at Klet. The package combines observation planning, data-acquisition, camera control and data processing tools running on Windows and Unix platforms (recently we have been using FreeBSD-amd64). The system uses client-server architecture where appropriate and most of the software is associated with a SQL database.

The SQL database stores orbital elements and other information on minor planets updated on daily basis from text-based databases; the MPC Orbit Database (MPCORB), maintained by the Minor Planet Center, and from the Asteroid Orbital Elements Database (ASTORB), created and maintained by E. Bowell at the Lowell Observatory. The asteroids listed in the Spaceguard system The Priority List and objects listed as a virtual impactors by SENTRY (JPL) or by CLOMON (NEODys) are flagged in the database as well for more convenient search. In addition, the database holds orbital elements and other useful data on all solar system objects discovered at Klet (database K_KLET) and also information on comets (database COMETS) created and updated from more sources by Klet. The database also contains positions, times, and observed objects on all of the processed photographic plates and CCD images.

All data are stored locally in the local network of the observatory, so the system works also in off-line mode; i.e., in cases when online services are not available. Besides regular updates, it is possible to trigger updates for all locally stored data from external sources at any time.

Our observers are using a web-based tool called “ephem” for observation planning. The tool allows the user to get an ephemeris for one minor planet and/or for known minor planets in specified field in the sky at given time. The objects in the output list can be reduced to objects of given magnitude and/or type; i.e., to NEAs, PHAs, TNOs, virtual impactors, Klet discoveries, critical list objects, unusual or distant minor planets, Trojans, Spaceguard Priority List objects, and comets. Besides the designation, position in the sky, magnitude, and other usual ephemeris data, the output list also includes information on object type, ephemeris uncertainty, date of last observation, length of orbital arc used in orbit computation.

Another tool, also used in observation planning, is Program KLAC—KLENOT Atlas Coeli. This GUI program shows stars and solar system objects with a line showing their daily motion across the sky in a selected region in the sky. The size of the region usually corresponds to the FOV of the telescope used so it is also used to check the telescope position during an observation. The USNO-B1.0, USNO-A2.0 and GSC star catalogues can be used within KLAC as a source of positions, magnitude estimates and proper motion of stars.

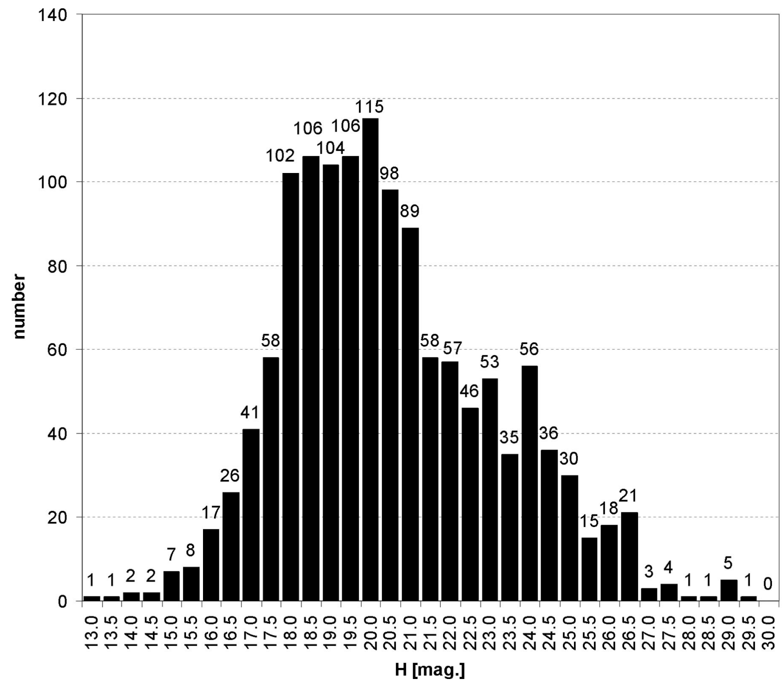

Fig. 1. Histogram of absolute magnitudes H of NEAs observed by KLENOT since 2002.

We use V++ for CCD camera control. The V++ is a precision digital imaging system developed by Digital Optics, a standard program for Photometrics CCD cameras on the Win32 platforms. For exposure control and data-acquisition a set of scripts in VPascal (build-in programming language in V++) has been written. The scripts store a sequence of several CCD frames (images) in one file in TIFF format. In the header of the sequence file information about the number of frames in the sequence, time, exposure time, equipment used, and other information is included.

Programs “Blink and “SumViewer” are used for blinking and manipulating RAW CCD multi-image TIFFs. Two or more selected frames from the sequence can be alternatively displayed on the monitor and visually inspected. Besides blinking, the program also allows smoothing, inverting, shifting, simultaneously adding and zooming of the image frames.

The images taken by CCD camera are then processed through the program “Astrometry,” which has been developed for the reduction of CCD images and automatic identification of stars with USNO-B1.0, USNO-A2.0 or GSC star catalogues. The images are reduced and all objects with given conditions for signal to noise ratio are found on the image. These objects are then identified with stars from the selected star catalogue. Equatorial coordinates of objects are then determined, and at the same time stars with residuals greater than 1 arcsecond are excluded automatically or/and manually and magnitude of the objects is determined. The user then selects the desired object on the image, and the program gives appropriate output data for that object directly in the MPC format. The time of observation and other information needed for the output are derived from the data stored in the header of the image file. Information about the processed CCD image (time, filename, frame number, equatorial coordinates of the center of the frame, telescope used, exposure time, position of objects on frame, etc.) are stored in the database of processed CCD images for later use, e.g., for automated recovery program.

The residuals of the measured astrometric positions are checked before they are made available to the astronomical community. The calculation of residuals is based on osculating orbital elements of the object near the current epoch, so they are acceptable mainly for the evaluation of observations. In addition the Delta-T variation of the mean anomaly is determined. Checking of both residuals and the Delta-T variation in mean anomaly helps verify object identification.

All the programs in the system are using The Planetary and Lunar Ephemerides DE405 provided by JPL for exact determination of planetary positions.

KLENOT RESULTS

The Klet Observatory is one of the world’s most prolific professional observatories producing follow-up astrometry of NEOs (Ticha et al. 2007). The results presented here of the KLENOT Project were obtained during the first phase of the KLENOT Project from March 2002 to September 2008. The KLENOT telescope was out of operation due to dome reconstruction between May 2005–December 2005.

Near-Earth Asteroids

We have measured and sent to the Minor Planet Center 52,658 positions of 5,867 objects, including 13,342 positions of 1,369 NEAs, 157 of which were VIs in the time of observations.

The majority of measured NEAs were confirmatory observations and early follow-up observations of newly discovered objects presented on the NEO Confirmation Page (NEOCP) maintained by the Minor Planet Center. These astrometric observations helped both to confirm new discoveries and to extend their observed arc. Confirmatory observations were centered on newly discovered NEO candidates fainter than magnitude m(V) = 19.5 mag. and faster moving objects. Long-arc follow up astrometry is devoted also to NEAs fainter than magnitude m(V) = 19.5 mag.

Special consideration is given to Virtual Impactors coming from SENTRY and CLOMON automatic monitoring systems. In many cases data obtained by the KLENOT Team alone enabled to remove predicted impact solutions. These observations were included in 561 Minor Planet Electronic Circulars.

Figure 1 shows absolute magnitudes of NEAs observed by KLENOT from March 2002 to September 2008. Most of the near-Earth asteroids observed have absolute magnitude H between 18 and 21, but some asteroids as intrinsically faint as H = 30 have been observed by the 1.06 m KLENOT telescope.

Figure 2 shows apparent motions distribution for NEAs observed by KLENOT from March 2002 to September 2008. We count all the observations of one NEA during the same night as one entry for the purpose of the graph. The range of motions of our targets is remarkably broad, NEAs moving as fast as 160″/min were successfully observed by the KLENOT telescope.

Recovery of NEOs at the second opposition is another important goal of the KLENOT Project. In the framework of the KLENOT Project we recovered 16 NEAs (including 2 PHAs) and 4 comets. These are shown in Table 1.

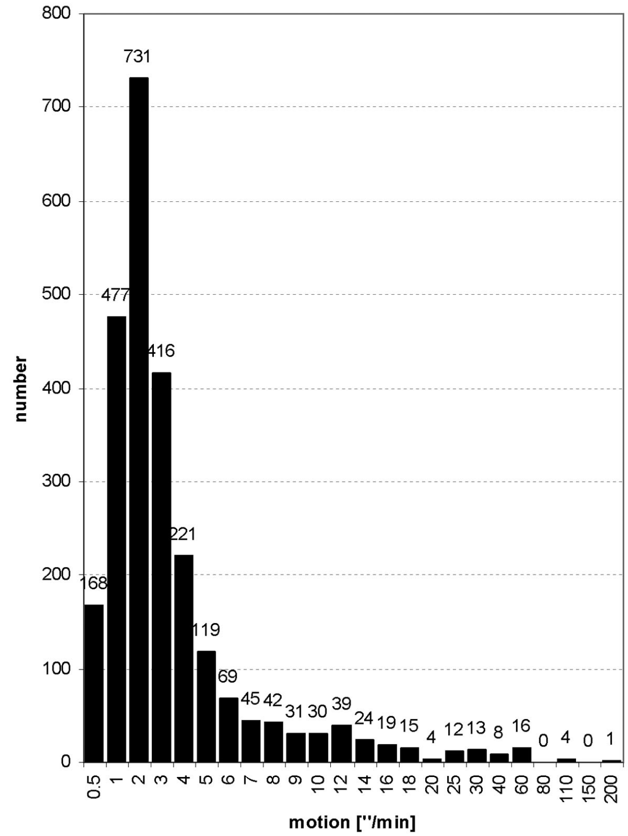

Fig. 2. Histogram of apparent motions of NEAs observed by KLENOT since 2002.

Comets

A smaller though significant part of the near-Earth object population consists of comets. 2,728 astrometric measurements of 216 comets have been obtained and sent to the Minor Planet Center.

The next step in recognizing this comet fraction of NEO population is an analysis of possible cometary features of newly discovered bodies. We have confirmed 34 newly discovered comets (i.e., we have found cometary features of objects with unusual motion presented mostly on the NEO Confirmation Page) up to now. A further step is to watch the behavior of such cometary bodies i.e., to obtain observation data of near-Earth comets outbursts, fragmentation, splitting and so on. Within the framework of the KLENOT Project we detected nucleus duplicity of comet C/2004 S1 (Van Ness) (Sekanina et al. 2005) and provided astrometric measurements of 17 fragments of comet 73P/Schwassmann-Wachmann 3 including the independent detection of several new fragments during its 2006 close approach to the Earth.

Discoveries

Although searching for unknown NEAs is just a complementary goal of the KLENOT project, all obtained images are checked for possible new objects. Within the framework of this project 750 small solar system bodies have been discovered up to now. These new discoveries are processed with a special reference to objects with unusual motion. Understandably, the majority of them belong to typical main-belt minor planets, although there are several Hungarias, Mars-crossers and asteroid 2004 RT109 orbiting the Sun on a Jupiter-family comet orbit. The 3 NEAs can be considered the most important discoveries of the KLENOT Project. Their orbital elements, absolute magnitudes, approximate diameters and closest Earth approaches during discovery apparition are given in Table 2.

Table 1. Recoveries of NEOs and comets made by KLENOT.

Designation	Orbit type	Dis. opp. arc (days)	Last. obs. in disc. Opp.	Recovery date	Delta-T (days)	Reference
P/2008 C2	Comet	86	2001 Feb. 16	2008 Feb. 03.73	–0.16	IAUC 8917
2001 GQ_2	Apollo	14	2001 Apr. 28	2005 Mar. 31.95	+0.009	MPEC 2005-G09
2003 MA	Amor	83	2003 Sept. 7	2005 Jan. 18.05	+0.00000	MPEC 2005-B29
2002 PQ_{142}	Apollo	41	2002 Sept. 21	2004 Sept. 4.91	–0.36	MPEC 2004-R25
2003 EN_{16}	Amor	145	2003 Apr. 27	2004 July 17.01	–0.032	MPEC 2004-O24
2001 YF_1	Apollo	250	2002 Aug. 23	2004 July 16.98	0.0046	MPEC 2004-O20
2003 LP_6	Apollo	30	2003 July 12	2004 Feb. 17.15	0.005	MPEC 2004-D02
2001 SG_{276}	Amor	56	2001 Nov. 21	2003 Sept. 5.13	–0.025	MPEC 2003-R34
1999 VS_6	Apollo	181	2000 May 5	2003 Sept. 5.12	+0.00028	MPEC 2003-R31
2002 RR_{25}	Aten	56	2002 Oct. 30	2003 Sept. 5.05	+0.0010	MPEC 2003-R30
2000 RS_{11}	Apollo (PHA)	290	2001 June 19	2003 Aug. 27.10	–0.0076	MPEC 2003-R28
2002 SR_{41}	Apollo	31	2002 Oct. 31	2003 Aug. 24.88	–0.0019	MPEC 2003-Q31
2001 FB_7	Amor	118	2001 July 14	2003 Aug. 24.04	+0.0059	MPEC 2003-Q24
1999 TF_{211}	Apollo (PHA)	36	1999 Nov. 11	2003 Aug. 4.01	+1.7	MPEC 2003-P10
1993 FS	Amor	86	1993 June 13	2003 Mar. 25.09	+0.24	MPEC 2003-F38
2001 FT_6	Aten	26	2001 Apr. 18	2003 Mar. 25.03	–0.15	MPEC 2003-F37
100 P	Comet	–	1997 June 29	2003 Feb. 27.08	–	MPEC 2003-E23
2001 FZ_6	Amor	76	2001 June 2	2003 Feb. 26.10	+0.0074	MPEC 2003-D31
C/2002 A1	Comet	55	2002 Feb. 6	2003 Feb. 25.95	–	MPEC 2003-D29
C/2002 A2	Comet	137	2002 Apr. 5	2003 Feb. 22.94	–	MPEC 2003-D23

Table 2. KLENOT NEO discoveries.

Designation	A (AU)	e	i (deg)	H (mag.)	Type	Arc	Approx. diameter (m)	Earth approach (AU)
2006 XR_4	1.04	0.27	10.9	26.2	Apollo	1 day	20	0.00401
2003 UT_{55}	0.98	0.15	16.7	26.8	Aten	1 day	15	0.00740
2002 LK	1.10	0.15	25.1	24.2	Apollo	6 days	75	0.023

The absolute majority of astrometric measurements have been sent to the Minor Planet Center immediately.

CONCLUSIONS AND PERSPECTIVES

This paper summarizes the first phase of the KLENOT Project from March 2002 to September 2008. It resulted in an important contribution to the international NEO effort.

The next generation surveys, such as Pan-STARRS, LSST and the Discovery Channel Telescope, could revolutionize solar system dynamic studies and will therefore change requirements for astrometric follow-up. The role of astrometric follow-up in connection with the new generation of all-sky deeper surveys should move towards faint(er) NEOs which are in urgent need of astrometric position determinations over a longer arc. Additional follow-up observations with other telescopes would also help make linkages in their archives (McMillan et al. 2007). Another important study would be the search for and analysis of possible cometary features of newly discovered bodies especially in the case of bodies showing unusual orbit.

A fundamental improvement of the KLENOT telescope was started in autumn 2008. It represents installation of a new computer-controlled equatorial mount for the KLENOT telescope allowing a better sky coverage, including lower solar elongations. The new mount is designed and it is in the process of being built. The original high-quality optics of the KLENOT telescope mentioned above will be used. The construction, first light and testing observations of this "new" KLENOT are planned in winter 2008/2009. This new mount will substantially increase telescope time efficiency, the number of observations, their accuracy and limiting magnitude.

It is rather demanding to teach a computer to recognize moving bodies on astronomical images. Thus, this task is left to the astronomer, but there is still room for improving limiting magnitude by co-adding of KLENOT multi-TIFF images.

The program developed at the Klet Observatory has been designed to support a human eye, facilitating search for fainter objects in the solar system on our images—even for those not detectable by eye. The images are initially processed for obtaining their center coordinates, then co-added on their common centre, effectively lenghtening the exposure time of the compound image. This strategy may prove useful in a search for fainter slowly moving bodies like TNOs.

Faster moving objects require a different approach. Specifying the apparent motion and position angle of such an object permits us to move the images against its predicted motion, and the object emerges from the background noise, much like faint stars on a longer exposure time image. For astrometry of the object to be possible, only a chosen area of the image can be co-added this way. Then the first position is found with respect to the reference stars of the first image and every other is computed based on the target body's movement.

Furthermore, since this method allows us to compensate for the target movement, it can also be used to detect cometary features or to search for new fainter cometary fragments.

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