

# A Pencil-Beam Search for Distant TNOs at the ESO NTT

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**Abstract.** We used the image data set obtained during our NTT/EMMI observing campaign of the TNO 1996 TO66 at ESO La Silla (see our paper presented during this workshop) to start a pencil-beam search for very distant TNOs. During our 5 observing nights the exposures of the foreground TNO were centred at the same target position on the sky (apart from a small amplitude jittering). For the sampling of the light curve of 1996 TO66 a long series of R filter exposures was taken during 4 of the 5 nights. The individual R filter exposures of 15 min each reach a limiting brightness of about 24.5 mag, the aligned (using the background stars) and coadded R images of a single night go down to 26 mag. By blinking individual and coadded images a pencil-beam segment of  $8.5 \times 8.5$  arcmin could be searched for unknown solar system objects (several main belt asteroids were easily recognized). The blinking of the individual frames should have allowed us to identify TNOs with a typical diameter of 100 km at about 50 AU solar distance; the same procedure applied to the co-added images should allow to find objects of the same size at about 80 AU or 400km bodies at 150 AU distance.

This simple pencil-beam search in our narrow EMMI field of view was not successful, i.e. no distant TNO was found. According to Jewitt's and Luu's model assumption (AJ 112, 1996), one would expect about 0.2 TNOs in such a field, so our negative detection is not a surprise. However, refined search techniques are under development and, furthermore, the use of the 0.5 deg Wide Field Imager at the 2.2m telescope in La Silla will greatly improve the statistical significance of such deep search programmes.

## 1 A 'Search Included' TNO Programme

In late October 1997 a 5 night observing programme at La Silla Observatory targeted the Transneptunian object (TNO) 1996 TO66. The main goal of these observations was the physical characterization of this distant solar system body by means of multi-colour photometry and low-dispersion spectroscopy (for the results see this workshop's paper 'A Portrait of 1996 TO66' by Delahodde et al.). However, it also contained a small pencil-beam search for unknown

and more distant solar system objects utilizing the series of CCD images taken for the photometric rotation period analysis of 1996 TO66. In order to accomplish both goals with the same data set, i.e. the photometry of the rotational variability and the pencil-beam search for new objects, we tailored the concept for the observations such that we pointed the telescope to the same area of the sky while the TNO was moving very slowly (order of a few arcsec/h) across this region during a period of several nights. The number of nights during which the target TNO can be imaged on the same star background is basically determined by the field of view of the telescope/instrument equipment and by the velocity of the object used for the photometry. Of course, a 2-3m class telescope is needed to achieve accurate magnitudes for the 21-22 mag target and an even fainter limiting magnitude for the search programme. Although the detection of several foreground moving objects from the Asteroid Main Belt could be expected, the main aim of the search programme was to look for more distant solar system objects, and in particular for TNOs beyond 50 AU from the Sun.

In the following sections we describe in detail the observing strategy, the reduction technique applied to the data and the results of the search (at least of our first attempt). We finally discuss the requirements for our planned future search projects for objects in the outer solar system.

## 2 The Observation Strategy

The observations were performed during 21-24 Oct. 1997 at the New Technology Telescope (NTT) at the European Southern Observatory in La Silla/Chile (the fifth night - 25 Oct. 1997 - scheduled for this programme was used for spectroscopy of the foreground TNO 1996 TO66 and did not contribute to the image set of our search programme) using the EMMI multi-mode instrument at the Nasmyth focus of the telescope. The 'red' arm of the instrument allowed us to obtain BVR filter CCD imaging over a  $9.2 \times 9.2$  arcmin field of view (the Tektronix CCD has  $2048 \times 2048$  pixels of  $24 \mu\text{m}$  size which corresponds to 0.27 arcsec on the sky). For the sampling of the rotation period of 1996 TO66 and for the collection of a large number of images for the deep search project mostly broadband Bessel R

filter images were taken (a few Bessel B and V filter images were obtained for the determination of the colour index of 1996 TO66). The typical exposure time of the exposures was 15 min. The sky was photometric during most of the observing run with typical seeing better than 1 arcsec, and the moon was below the horizon during the TNO observing window for La Silla.

The pencil-beam search project required the following observing strategy:

1. to observe the same target field through the same filter with a very long total exposure time in order to increase the limiting magnitude for the search (also good seeing conditions are helpful for the success of the search)
2. to use sidereal tracking for the imaging in order to allow the proper alignment of the images during the data analysis (no tracking of the foreground TNO because of the refraction effects in the star images)
3. to jitter the telescope pointing in the target area for the superflating of the images and the removal of fixed patterns of the CCD detector

Long total integration times in a short observing period (as typically the case for many ESO programmes) can best be achieved if the object is in or close to opposition to the Sun when the observing window per night is longest. Apart from that, in our case the constraining factors for requirement 1 were the observing programme committee (OPC) of ESO (which decides on the observing time of the ESO proposals) and the motion of the foreground TNO for which we wanted to collect CCD photometry in the same field of view of the instrument. At the time of our observations the prime target 1996 TO66 moved with about +2.3 arcsec/h in right ascension and about -0.8 arcsec/h in declination. The typical transit time of this TNO for the EMMI field of view was about 10 days and, thus, the ESO OPC was somehow the limiting factor for our search project, since it allowed us only 4 half nights of observations, i.e. we had an observing window of about 3.25 days total duration.

Although the EMMI field of view covers roughly the 3.25 days track length of a solar system object at about 17 AU distance from the Sun, it is obvious that the success of the search for unknown

objects in the instrument field of view by coadding the data from several nights (as described in section 4) will suffer from the loss of objects when they are located close enough to the edge of the image such that they can exit or enter the field of view of the instrument during the observing window. Thus, the 'horizon of complete coverage' of an instrument can be defined as the minimum distance of an object in a circular orbit around the Sun that stays in the instrument field of view for a given time interval if it is found there at the beginning of the observations. For our 3.25 days EMMI observations the 'horizon of complete coverage' was nominally about 40 AU (which is slightly less than the distance of our prime target 1996 TO66 at 45.7 AU from the Sun at the time of our observations), but effectively it was a few AU more because of the shrinking of the viewing field (due to the jittering mode used for our observations; see requirement 3 and discussion below).

For the search of distant and slowly moving TNOs it is advantageous to use sidereal tracking since a priori the velocity and direction of the potentially detectable objects are unknown and the trailing effects will be small during a 15 min exposure (for our prime target 1996 TO66 it was 0.6 arcsec, which was smaller than or of the order of the typical seeing during our observing interval). Beyond that the influence of the atmospheric refraction on the direction and length of star trails can be avoided. This is important if one aims for a removal of background objects using methods as described in Boehnhardt et al. (1997) and Hainaut et al. (1998).

Requirement (3) in principle widens the useful area for the search, but at the same time it reduces also the detection limit in the outer regions of the target field, since due to the jitter amplitude they are not longer covered by the same number of exposures (or in other words they differ in their total exposure time). For our imaging we applied a telescope jittering of 20 arcsec, i.e. in between the individual exposures the telescope pointing was offset in both directions according to a random-walk sequence with a maximum amplitude of 30 arcsec from the field centre. Thus, the total search area increases to about  $9.5 \times 9.5$  arcmin, but the area of optimum signal-to-noise (S/N) for the search decreases to about  $8.9 \times 8.9$  arcmin.

The coordinates of the target field for our search were close to the mid-time position of the prime target for our photometric part

of the observing programme, i.e.

Right Ascension (2000) 23h 52m 32s  
 Declination (2000) +01° 42' 30"

The observations were executed as a series of 15min R filter exposures per half night, interrupted only by a few images through the B and V filters (for the colour determination of 1996 TO66). During the 4 nights, 36 R filter images of the field were taken which gives a total integration time of 9 hours. Following requirements (2) and (3) telescope jittering and sidereal tracking were exercised for this programme. For the data reduction and flux calibration photometric standard stars (Landolt 1992), as well as bias, dark and twilight flatfield images, were obtained during the observing run.

### 3 The Data Reduction

The basic data reduction comprised bias and dark current subtraction, flatfield division, cosmic ray removal and photometric calibration. During the bias correction a 2dim bias frame was subtracted that was derived from a master bias constructed from the series of available bias exposures of this run and scaled to the bias level of the respective flatfield or object images using the overscan region of the frames. The flatfielding procedure followed the recipe of Hainaut et al. (1998), which uses both the object frames and twilight flats to calculate the optimum flatfield. This procedure delivers relatively calibrated images with background variations across the field of view of below 1 percent for large scale structures and below 0.1 percent for small scale variations. For the cosmic ray removal a standard routine of the ESO MIDAS image processing package was applied. The photometric calibration of the object frames was achieved using the standard star exposures. First order extinction and colour corrections were applied during the photometric reduction. Because of the excellent field overlap of the TNO exposure series all object frames could be flux calibrated (using relative photometry of field stars in case of images that suffered from rare, slightly non-photometric sky conditions during the observing run).

In a second step the object images were aligned to sub-pixel accuracy, i.e. the field stars had the same xy pixel coordinates in all images to within subpixel accuracy. Thereafter, the R filter images of a single night were coadded in stacks of 4-5 subsequent exposures. In that way, an increase of the S/N ratio of faint and unknown solar system objects in the field of view can be expected if their motion rate is not too fast that their images are smeared out along a longer trail length.

#### 4 The Results with a Short Discussion

The search for moving objects in the frame was exercised through blinking two or more single and coadded images of the target field on the computer. Moving objects could thus identified visually by the change in the pixel position in between the blinked exposures. Different combinations of images from the sets of single and coadded frames were used for the blinking. However, apart from several objects in the Main Asteroid Belt (which were already recognized as trailed objects in the images during the observing run) no further moving object was detected either in the single or in the coadded images.

The limiting magnitude of about 24.5 mag for single frames translates to an object radius of about 100km at 50 AU solar distance (assuming an albedo of 0.04), the 26 mag limit for the coadded frames to the same object radius at 80 AU or to a radius of 400 km at 150 AU. Since our observations fulfill the criterion for the 'horizon of complete coverage' for objects beyond about 40 AU from the Sun, we conclude that there were no slowly moving objects in the outer solar system in our EMMI field of view at the time of observations. This applies to objects with suitable size for detection with EMMI (i.e. to be brighter than 24.5 mag) with an upper limit for very, very distant bodies which are not longer recognizable by blinking, since they are too far away and thus do not move more than about 1 arcsec during our whole observing interval of 3.25 days (i.e. objects beyond about 10000 AU). A similar conclusion for the 26 mag limit of the coadded frames can only be done with caution since, from the point of view of data reduction, we may not have achieved the optimum S/N for moving objects due to our simple coaddition of frames which

are aligned for the stars (see discussion in section 5).

Applying Jewitt et al.'s (1996) assumption about the object distribution and sizes of TNOs to our observing conditions (EMMI field of view, limiting magnitude of 26 mag in R), we arrive at a probability of 20 percent for the detection of an Edgeworth-Kuiper-Belt (EKB) object in our data. Therefore, the non-detection we have as a result of our data analysis (although biased by the fact that the coadded images are not corrected for anticipated motion of the objects searched for) is not too much a surprise. Unfortunately, it does not provide much constraint on the structural and size models of the EKB.

## 5 Our Plans for Doing Better

The search for TNOs in our EMMI data as described above was only a by-product that we could get for free from our imaging campaign of the prime target 1996 TO66. Although the outcome of the TNO search was negative, we find it a challenging enterprise to do better - and more work in this area of research - in the future. So, what are our plans?

Distance range scanning by shift-and-add examination of the images: of course, the coaddition of frames aligned to the star background is too simple to achieve the optimum S/N for the detection of slowly moving objects in our EMMI images of 1996 TO66. The images should be systematically shifted in x and y assuming a particular speed and direction of motion for the objects being sought. Thereafter, the images should be coadded to improve the S/N of the potential TNO, the image of which should then fall in the same pixel area in all frames. The object detection can be done by looking for a point source in the data while the stars will appear as trails. However, blinking two or more such images may help to ascertain the identification. The velocity parameter for the shift basically represents a certain range of heliocentric distance for the sought objects. One can thus systematically scan through the whole outer solar system looking for new distant objects in the same data set. At present our EMMI data of 1996 TO66 are evaluated by applying such a shift-and-add search algorithm (colaboration with Watanabe group in Japan).

Background object removal: the shift-and-add approach, as well as the use of deep exposures, leads to a crowding of the images by background objects (either stars, or more normally galaxies, are the objects of concern). This implies that the useful pixel area (i.e. free from background objects) gets less the more images are coadded and/or the deeper the exposures are. Therefore, we are thinking of the removal of background objects in a more self-consistent way, i.e. it uses the image data themselves. Such processing for the removal of background objects has successfully been applied in the past for the detection of very faint comets on a crowded background (Boehnhardt et al. 1997, Hainaut et al. 1998), and one can expect that it will work for the distant TNO search also.

Wide and deep field searches: at present new telescope and CCD technology is being introduced world-wide that will hopefully advance the exploration of the outer solar system in a quantum step (as is promised also for other fields of astronomy). Wide-field CCD imaging of 0.5 to 1 deg is becoming available at 2-3m class telescopes at different observatories (ESO, Hawaii, La Palma). These telescopes will certainly allow one to reach 24-26 mag limiting magnitude in wide area search campaigns for TNOs that will fill in the gaps that we have right now in the wide-field coverage of the Kuiper-Belt region. Beyond 25-26 mag pencil-beam searches on 8-10m class telescopes (FORS at the ESO VLT, LRIS at Keck, FOCAS at Subaru) can explore more in a "spotlight" approach the greater distances and a smaller range of the solar system bodies, down to 30 mag and beyond. The ultimate step, however, will be achieved if we can go wide and deep at the same time, i.e. if wide-field CCD imaging becomes possible on these large telescopes. VMOS at the ESO VLT and the prime focus camera of the Subaru telescope will be the workhorses for such applications.

As a final remark, we should like to point out that all approaches mentioned above will have one point in common, i.e. they will need significant computing power and disk storage for the data reduction and evaluation. An image of the 0.5 deg Wide Field Imager (WFI) at the 2.2m telescope at ESO La Silla (this instrument will become operational in January 1999) is about 130 MegaBytes of FITS data, and a single observing night at the WFI is expected to deliver about 20-30 GigaByte of FITS images. Numerical manipulation of such

images requires fast computers with large RAM storage to deal with the images efficiently (i.e. in a finite time of a few hours or so). The ultimate step in this respect will be the automatic detection of moving objects in wide-field imaging data using computers and sophisticated search algorithms on TeraBytes of data.

## References

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