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An optimized detection technique for faint moving objects on a star-rich background

A search for the nucleus of comet 46P/Wirtanen⋆,⋆⋆

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Abstract. A novel method is proposed for the efficient detection of faint solar system objects moving in front of a star-rich field. After the removal of the background objects by means of seeing template frames and accurate image alignment on the moving object, subsets of frames selected by different criteria (e.g. seeing) are co-added to improve the signal-to-noise ratio for the image of the object. Requirements for the successful application of this procedure are discussed and verification checks for identified candidates are outlined. The procedure provides accurate astrometric positions and approximate magnitudes for identified objects.

The method was applied to a search for the ∼ 24-mag nucleus of comet 46P/Wirtanen, the prime target of ESA's ROSETTA mission, while at heliocentric distance 4.6 AU and located in a field near the direction to the Galactic Centre. A 24.2 mag candidate image was marginally detected in CCD frames totalling 176 min integration time and taken on June 26, 1995, with the 2.2-m telescope at ESO La Silla. However, because of insufficient, corroborating data from other nights (caused by adverse atmospheric conditions), an unambiguous confirmation of this detection is not possible. The corresponding upper limit of the radius (assuming albedo of 0.04) is only 0.8 km (the likely radius is 0.69 km), indicating that comet 46P/Wirtanen possesses one of the smallest cometary nuclei known so far.

Key words: comets: general; 46P/Wirtanen – methods: data analysis; observational

1. Introduction

Two classical methods are normally used for the detection of faint moving objects: 1) blinking of exposures taken of the same sky field at different epochs, and 2) long integration while the telescope tracking matches the sky motion of a particular object searched for. It is not uncommon that these methods are combined in order to improve the chances for a secure detection and thus an unambiguous identification of the object. For faint objects it may be necessary to co-add several frames to elevate the signal-to-noise ratio (S/N) of the object above the detection limit, which is empirically found to be ∼ 2. In this case, careful alignment of the frames at the sub-pixel level is crucial (cf. e.g., Hainaut et al. 1994).

However, for the detection of faint, moving objects located in front of star-rich sky regions (e.g., at low galactic latitude), the straightforward application of the above mentioned methods is often impossible because of the high likelihood that the object is overlapped by one or more stellar images. Such blends very significantly lower the achievable S/N ratio as compared to what would be the case on a clear sky background and will not lead to the detection of objects near the limiting magnitude, also when the classical frame-combining approach is used, cf. Fig. 1. The number of actual blends is in general proportionate to the angular distance covered by the moving object during the exposure, i.e. the exposure time, and in order to diminish the risk of blends, the exposure time may be shortened, but this of course in turn reduces the detection limit. Contrarily, long integrations and/or simple co-addition of shorter exposures drastically reduce the extent of blend-free areas which may be used for object detection. It is exactly in order to avoid these problems, that search programmes for faint solar system objects, whenever possible, are performed far away from star-rich sky areas.

In June 1995, we carried out an observing campaign on the prime target of ESA's upcoming ROSETTA mission, comet 46P/Wirtanen. After rendez-vouz with 46P/Wirtanen around 4.6 AU solar distance the spacecraft (S/C) will investigate the comet

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⋆ based on observations obtained at ESO La Silla within ESO programme No. 55-F-0337

⋆⋆ the comet was finally recovered on 25 April 1996, see comments under Note Added in Proof

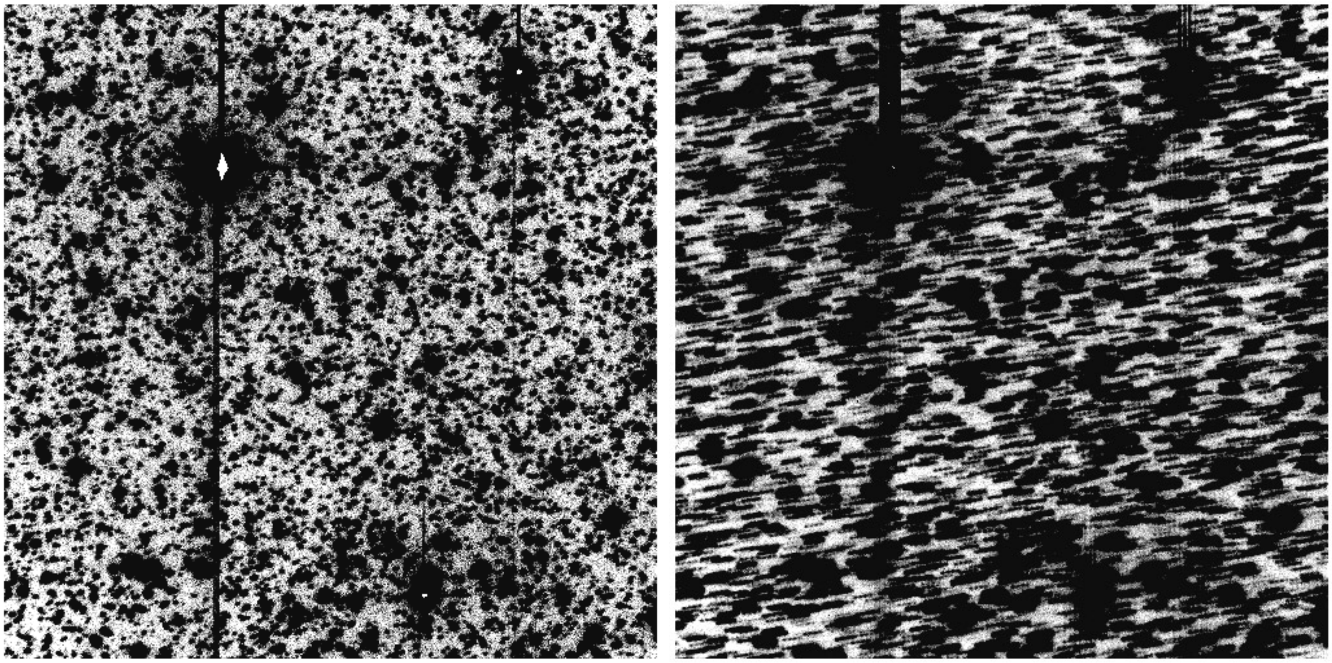

Fig. 1. Target field of comet 46P/Wirtanen on 26 June 1995. The field of view is 5.6 × 5.6 arcmin. North is up, east to the right. The images were taken through a Bessel R filter. Low cut level is 1 times the noise r.m.s. level below the mean background level, high cut level is 3 times the noise r.m.s. level above the mean background level. Left: single 4-min exposure with limiting magnitude around 22.5; Right: co-added frame based on four consecutive 4-min exposures without star removal.

from cometo-centric orbit during its approach to perihelion and will also drop a lander with surface science experiments on the nucleus. Unfortunately, the orbit of 46P/Wirtanen is such that this object is always located in front of dense Milky Way fields when it is beyond heliocentric distance $r \sim 3.9 - 4.7$ AU. This will make supporting ground-based observations during the S/C approach difficult. Moreover, it is only at this distance that the as yet unknown cometary parameters, like the size of the nucleus and its rotational state, as well as the presence or absence of initial or remnant activity, can be measured from the ground; all of these are extremely important for the on-going design of the S/C scientific experiments. Furthermore, astrometric positions are needed at large heliocentric distance for the improvement of the orbital parameters, especially in preparation of and during the complex rendez-vouz operations of ROSETTA. This observational difficulty has certainly contributed to the fact that comet 46P/Wirtanen has never been studied beyond r = 2.55 AU, and that accordingly our knowledge about the properties of this cometary nucleus is still very poor, cf. Jorda & Rickman (1995), A'Hearn et al. (1995).

Faced with this problem, we have devised a novel technique for the detection of faint solar system objects in front of a star-rich background. If the object can be detected at all, the new method permits the measurement of accurate astrometric positions and some approximate photometry. This approach was first applied to our June 1995 observations of comet 46P/Wirtanen when it was at about r = 4.6 AU pre-perihelion and located near the Galactic Centre at $(l, b) = (10°, -10°)$. In what follows, we describe the observations (Sect. 2), the new methodology (Sect. 3) and its application in the case of the present observations (Sect. 4).

2. The observations

The observations of comet 46P/Wirtanen were performed with the EFOSC2 instrument attached to the 2.2-m MPG/ESO telescope at the European Southern Observatory (ESO) at La Silla (Chile) during four consecutive nights (June 23–26, 1995). All frames were obtained through a Bessel R filter. Unfortunately, only the last night provided a long stretch with the atmospheric conditions required for our programme, i.e. the sky was nearly photometric and the seeing was slowly variable with values around 0.8–1.5 arcsec; the total integration time on the comet field was 220 min. During two earlier nights (June 23–24 and 25–26), the observations of 46P/Wirtanen were heavily affected by cirrus clouds and bad seeing so that only exposures with a total of about 90 and 30 min integration time, respectively, could be collected under seeing conditions better than 1.5 arcsec. The fourth night was completely lost due to clouds.

The orbital elements and ephemeris of 46P/Wirtanen were kindly provided by F. Hechler (European Space Operations Centre ESOC, Darmstadt, Germany) and B. Marsden (Centre for Astrophysics (CFA), Cambridge, Mass., USA) in the form of private communications (1995). The observing geometry for 46P/Wirtanen as well as further information about the observations are listed in Table 1.

Table 1. Observing conditions for comet 46P/Wirtanen

Date	Sun Distance (AU)	Earth Distance (AU)	Phase (deg)	Elongation (deg)	Atmospheric Conditions	Seeing (arcsec)	Exposure Time per Frame (sec)	Number of Frames
23/6/95	4.630	3.624	2	171	cirrus	1-2	180	29
25/6/95	4.624	3.614	2	173	nearly photometric	2-3	240	8
26/6/95	4.621	3.610	2	174	nearly photometric	1-1.5	240	55

The magnitude of the nucleus of 46P/Wirtanen was in principle unknown, but was assumed to be around 22–24. The target fields were extremely crowded (see Fig. 1), and the observations were therefore, as far as possible, performed as required by the detection method described below, cf. Sect. 3.

3. Methodology of detection

As feared, visual inspection, blinking and simple co-addition of the obtained (bias-subtracted and flat-fielded) exposures of the very crowded 46P/Wirtanen target field did not reveal an image of the comet above the detection limit of the individual exposures ($\sim$ 22 $-$ 22.5 mag). Thus the primary goal of an efficient detection method under these special circumstances, i.e. the identification of a known solar system object (implying known rate and direction of the motion) in front of a star-rich background, must aim both at an *optimum suppression of light from the background objects* and at a *coherent amplification of the S/N ratio for the observational target*. The latter condition can only be achieved by co-adding a sufficient number of properly aligned target frames, while the former requires a special treatment of the individual images before co-addition. For this reason, our method for signal enhancement of a faint moving object in front of a star-rich region consists of two separate steps:

– Step 1 - removal of background objects in the individual exposures by means of template frames sorted by seeing. These “seeing template frames” are constructed by aligning and averaging target field frames obtained under similar seeing conditions. The weak signal of the moving object must be preserved as far as possible during the background object cleaning process. A detailed description is given in Sect. 3.1.

– Step 2 - co-addition of “cleaned frames” with the moving object properly centered, i.e. by taking all contributing motions into account. Pixel areas with brightness level higher than a suitable user-defined threshold above sky background are masked during the image co-addition and do not contribute to the final result. This process is described in Sect. 3.2.

It is important to note that the detection technique described here imposes certain requirements on the observation technique used to obtain the frames, on the initial data reduction and in particular on the critical procedure of image alignment. These requirements are further described in Sect. 3.3.

In what follows, we shall refer to the moving object as the “target”. While this procedure has been specifically developed for the reduction of the present observations of 46P/Wirtanen, it is equally applicable to other, similar cases. We shall, however, in some places refer to the practical experience obtained in the current case.

3.1. Step 1: Removal of background objects

The basic goal of the background object removal is to obtain (isolate) a signal from the target, even when it is located within the halo of scattered light from a (much brighter) background object; in the present investigation, this is the case in almost every frame. Ideally, this requires knowledge of the exact point spread function (PSF) of the background objects so that they may be subtracted, leaving a uniformly flat background on which the target image may then be recognized. It is in principle possible to deduce the mean PSF of a particular frame by averaging many (stellar) images and then to scale it for each individual background object. Nevertheless, this subtractive method also requires a time-consuming and error-prone search algorithm in order to identify the faintest background objects. Moreover, it cannot properly handle halos of extended objects. We therefore decided to use an empirical approach to model the background objects.

After adjustment of the sky background in the frames (cf. Sect. 3.3.3), template frames of the background objects are constructed by *median averaging* of several frames of the target field. For this method to be efficient, the frames must first be sorted by seeing, their sky fields must significantly overlap and they must be carefully aligned by means of measured pixel coordinates of suitable stars (see Sect. 3.3.1). The resulting “template frame” contains the pattern of the background objects at improved S/N, while - as long as the number of combined frames is reasonably large - the faint target signal is effectively suppressed because of its motion with respect to the background objects. Experience has shown that only frames obtained under very similar seeing conditions should be co-added for the generation of the template frame. It is also important to note that this procedure requires essentially identical image quality of the background objects, i.e. also the length and orientation of the star trails due to the telescope tracking must be identical for all frames in a certain "seeing batch". For our 46P/Wirtanen application, (see Sect. 3.3.2), we found that batches of five, as far as possible consecutive, CCD exposures could be used for the construction of one template frame.

In the next step, the individual frames in a particular seeing batch are divided with the corresponding template frame, again after careful alignment of the pixel coordinates of the background objects. We refer to the resulting frames as "target-only (TO) frames", since they in principle only contain the target image. However, they do display artifacts from incompletely removed central cores of bright background objects and these core regions must be "neutralized" prior to the subsequent co-addition of the TO frames (Step 2; see Sect. 3.2). This is achieved by masking (and thus, "marking") those areas in the TO frames where the fluxes are above a defined level above background. In practice, the pixel values in these zone-of-avoidance areas are not taken into account for the co-addition of the TO frames described below. We have found that a suitable "neutralization threshold" is $\sim 3-4$ times the noise r.m.s. level above the mean background level. This threshold must be sufficiently high to ensure that the target image is in any case below the limit and thus remains unaffected.

The resulting TO frames are then normalized and thus contain pixel values close to unity in the areas between the background objects and in the wings of their straylight haloes, while they are marked as "unusable" in the areas of the high level seeing cores.

3.2. Step 2: Co-addition of the aligned TO frames

The next step of this procedure is the co-addition of the aligned TO frames and subsequent normalisation of the summed frame. For this process, the alignment procedure (Sect. 3.3.1) must guarantee that the frame shifts are such that the target is located at the same pixel position. On the other hand, any remnant structure from incompletely removed background objects will now be located at different pixel coordinates in each frame and will therefore be smeared out by incoherent co-addition of the signal. For statistical reasons, this process obviously requires a large number of frames.

It is evident that each pixel of the summed frame (hereafter, the STO frame) will have its own contribution record from the individual TO frames used, and thus the individual original frames contribute to different pixels in the final STO frame. It is therefore necessary to normalize the STO frame result pixelwise by the number of contributing frames, i.e. the number of images for which the respective pixel coordinates was not marked after the star-cleaning to be ignored in the TO frame co-addition.

We also experimented in applying subtraction (instead of division) of seeing template files from the individual images of our dataset - before co-addition of the STO frame. While subtraction better preserves the photometry of the comet when placed in front of a seeing disk halo from a background star, the co-addition of the respective TO frames leads to a very noisy STO image (this would have made the detection of the comet candidate as described in Sect. 4.1 impossible). In fact, using seeing template file subtraction for background star removal is very sensitive to alignment errors of the pixel coordinates of the star images. Hence, for exposures taken under good seeing conditions misalignment of the seeing disks of background objects in the subtracted images on a sub-pixel level unavoidably results in relatively large signal differences in the halo regions. These unwanted effects increase with decreasing distance from the centre of the seeing images of the stars, i.e. they are largest in the inner halo parts, but small in the outer wings and negligible in the star-free background areas. The corresponding STO image of a crowded field appears very "uneven" because of the "remanence" of the incomplete star removal by subtraction. The coherent co-addition of a weak signal from a moving foreground object can easily be extinguished by a single or a few strong background star "remanences". On the other hand, STO frames from seeing template file division are much less affected by remnant counts from a small star misalignment, since the count ratio of the individual frame and the seeing template image converges to unity with decreasing distance from the centres of star images. Similarly, the photometry of the foreground target becomes less accurate the deeper it is placed in the halo regions of background objects and more such regions contribute to the pixel area of the STO frame in which the moving object is located.

For the 46P/Wirtanen frames, the S/N ratio of the background was nearly the same in all original frames because of the equal exposure time and, to some extent, also of the seeing conditions for the complete series of frames (see Sect. 2).

3.3. Data processing and special requirements

3.3.1. Image alignment

The signal enhancement by star cleaning and co-addition as described above relies on the prior, proper alignment of the CCD frames, both for the star-cleaning (Sect. 3.1) and for the target signal co-addition (Sect. 3.2). The accuracy of the alignment procedures must be better than one pixel.

In the first case, the alignment parameters can easily be determined from the (x, y) pixel coordinates of several stars of suitable magnitudes and locations in the frames. These stars should ideally appear in all frames used or at least in a majority of them. If the time intervals between the individual exposures of the target field are relatively short, the field overlap in subsequent exposures will be sufficient to find many stellar objects that may be used for the calculation of the geometrical alignment parameters.

In the second case, the pixel coordinates of the target must be aligned in an indirect way, since it is not visible (detectable) in the individual frames and thus cannot be used as a reference. Offsets of the moving object from the á priori unknown, nominal pixel coordinates will be caused (a) by inaccurate CCD alignment and telescope tracking (even though the observer may have used the predicted target velocity for the guideprobe/telescope control) and (b) by the daily parallax motion of the object. We now discuss these corrections.

CCD alignment and telescope tracking

Incorrect CCD alignment (for instance CCD columns are inclined to the north-south, N-S, direction) can finally affect the coherent co-addition of the target signal in the STO frame. By means of astrometry of background stars the CCD alignment with the N-S direction can easily be verified and appropiate corrections can be applied for the pixel coordinates of the images to be co-added. For our 46P/Wirtanen observations the CCD was inclined less than 1 degree to the N-S direction which had a negligible effect on the target offsets in the exposures (for a detailed discussion of CCD alignment effects in image co-addition see, for instance, Hainaut et al. 1994).

The telescope tracking performance can be assessed by measuring the pixel coordinates (x_{sm},y_{sm}) of a suitable number of reference stars in each frame (e.g., 7 stars were measured in the 46P/Wirtanen frames). A comparison of the measured coordinates with the expected ones (x_{se},y_{se}), calculated from the predicted target tangential velocity, allows the determination of the off-sets (x_{soff},y_{soff}) caused by incorrect telescope tracking:

$$x_{soff}(t) = x_{sm}(t) - x_{se}(t) \quad (1)$$

$$\text{with } x_{se}(t) = x_{se}(t=0) + cos\ \delta * x_{speed} * t/x_{scale} \quad (2)$$

$$y_{soff}(t) = y_{sm}(t) - y_{se}(t) \quad (3)$$

$$\text{with } y_{se}(t) = y_{se}(t=0) + y_{speed} * t/y_{scale} \quad (4)$$

It is here assumed that the CCD (x,y) axes are aligned with East-West and South-North, respectively; if not, appropriate modifications to Eqs. 2 and 4 must be made. Moreover,

t = exposure mid-epoch,
δ = declination of object at time t,
x_{speed}= object velocity in x direction on sky at time t,
y_{speed}= object velocity in y direction on sky at time t,
x_{scale}= pixel scale in x direction on CCD at time t, and
y_{scale}= pixel scale in y direction on CCD at time t.

x_{speed} and y_{speed} are obtained from the target ephemeris, while x_{scale} and y_{scale} must be derived by means of accurate astrometry of the CCD frames. If there are not enough astrometric standard stars in the narrow-field CCD frames, accurate positions of a sufficient number of secondary astrometric standards in the CCD frames must be determined by interpolation of primary standards on a separate wide-field exposure (normally a Schmidt plate). The plate scale factors x_{scale} and y_{scale} must be determined with an accuracy that guarantees exact alignment of the pixel coordinates over the maximum shift range used during the star-cleaning process and the co-addition of the TO frames.

For our search for 46P/Wirtanen, we used PPM stars measured on the POSS plate of the respective sky region. The required plate scale accuracy was typically of the order of 1%. As a useful side benefit of this analysis, the performance of the telescope tracking and autoguider control can be evaluated a posteriori (it is very likely that a major contribution to the deviation of the telescope tracking from nominal values as measured in our data set is caused by plate-scale errors and non-linearities in the optics of the autoguider which are not properly corrected by the telescope control software).

Daily parallax

If it is not included in the telescope tracking rates (and this is actually recommended for objects not too close to Earth), the daily parallax of the comet must be taken into account during the data processing. This is in particular the case, if geocentric target velocities were used for the tracking. These effects can be modelled by the following approximations:

$$\Delta\alpha = -\pi * cos\ \phi * sin\ \tau / cos\ \delta \quad (5)$$

$$\Delta\delta = \pi * sin\ \phi * sin\ (\delta - \gamma) / sin\ \gamma \quad (6)$$

where

$$tan\ \gamma = tan\ \phi / cos\ \tau \quad (7)$$

$$sin\ \pi = R/\Delta \quad (8)$$

In the formula above the following abbreviations are used:

$\Delta\alpha$ = parallax in R.A.
$\Delta\delta$ = parallax in Decl.
π = parallax amplitude
ϕ = latitude of observer
τ = hour angle at mid exposure time t
δ = declination of object observed
R = Earth radius
Δ = geocentric distance of object

The appropriate pixel shifts are then calculated from the plate scale factors of the CCD frames. On one hand, the correction of the telescope tracking rates for daily parallax effects of closer objects may somewhat improve the image quality of the target searched for. On the other hand, however, it will at the same time degrade the quality of the seeing template files which require star trails of equal length and direction. One may hence use shorter exposure times when observing near-Earth objects with geocentric tracking rates.

3.3.2. Observational requirements

In addition to the normal observational requirements as bias level, flat field, dark current and standard star exposures, the observation of faint moving targets demand special precautions. It is important to ensure that as much light as possible is concentrated within the seeing disk. Hence, even for short exposures, differential telescope tracking on the object must necessarily be applied. In the ideal case, the tracking rate is smooth and corresponds exactly to the actual motion of the target. However, when the exposure series is extended, minor deviations will necessarily occur which can however be effectively corrected for by the procedure described in Sect. 3.3.1. It is usually sufficient to apply the geocentric motion rates of the object for the telescope tracking and to correct for the daily parallax changes during data processing.

The construction of the seeing template frames requires exposures with equal trail length and orientation for the background star images. This can usually, i.e. for a target whose velocity remains constant during the night, be achieved by using the same exposure time and telescope tracking rate throughout the observation interval. In any case, several images of the same target fields should be taken under identical or very similar seeing conditions, e.g. typically about 5 or more images of similar seeing quality are required for the respective seeing template frames (see Sect. 3.1). In practice, the frames are sorted into groups over the range of seeing quality in steps of about 0.2 arcsec or better. As expected, the experience shows that for targets close to or below the detection limit of an individual exposure, only frames obtained during periods of good to excellent seeing should be used. It is also important to collect enough frames each night to guarantee a good coverage of the seeing range as well as a large number of contributing frames for each pixel of the STO frame in order to achieve a high S/N ratio for the target image.

The actual exposure time moreover depends on the target velocity and the star density in the field of view. For the 46P/Wirtanen observations we used exposure times which produced star trails about twice as long as the typical seeing width of the trails. Longer exposures improve the detection limit, but reduce the pixel areas free of stellar blends. Furthermore, short-term tracking errors, seeing variability and CCD saturation effects by bright stars will degrade the quality of such exposures. On the other hand, short exposures produce a significant overhead of CCD read-out time and reduce the S/N level of the individual exposures. Hence, a comparatively large number of images is needed to obtain a good S/N value in the co-added frame.

In conclusion, stable atmospheric conditions, combined with constant exposure time and the collection of a large number (50 or more) of target field images are the best prerequisites for a successful application of the reduction procedure decribed above. Furthermore, the variation of the S/N ratio over the dataset should be small in order to allow a reasonably quantitative photometry of the target, if detected in the co-added frame (see Sect. 4.2).

3.3.3. Basic data reduction

After the usual data reduction steps, i.e. bias and dark current subtraction, flat-fielding and exposure time normalisation, all frames of the target field must be scaled to the same count level for the mean background intensity. This is an important requirement for the subsequent median averaging during the construction of the seeing template frames described in Step 1 above and this at the same time improves the neutralization process of the bright star blends in Step 2.

In the case of the 46P/Wirtanen exposures, the mean background level was determined from statistics of the count rates as measured in 500 arbitrarily chosen pixels in the image and subtracted from the respective frame. Thereafter each frame received a constant artificial sky offset of +30 counts. Usually, cosmic ray cosmetics are not required since the median averaging for the seeing template frames and the neutralization procedure for bright star blends automatically deletes such artifacts, as long as they exhibit count levels above the neutralization threshold.

3.4. Verification of the object identification

If the observations and the data processing were executed correctly, the resulting STO frame may then be inspected in order to identify the image of the moving target, which in the case of asteroids and inactive cometary nuclei should resemble that of a star. An error box around the nominal object (R.A.,Decl.) position in the STO frame (based on the formal uncertainty of the orbital elements) may help to limit the search area, in particular for the detection of a marginal target signal. The CCD frame astrometry described in Sect. 3.3.1 allows to accurately define the (x, y) coordinates of the corners of this error box.

In the case of a very crowded star field (as for 46P/Wirtanen) the method described above requires a large number of images (in practice, at least 40 frames) in order to achieve an almost uniform, star-free background and to enhance a faint object above detection limit (see Figs. 2 and 3). If too few frames are used for co-addition or some regions are overloaded with many bright objects, substructures will appear in the STO frame which may simulate the target searched for. But even if the STO frame appears uniform and only one single image shows up, it is necessary to perform a critical verification of the reality of that signal in order to exclude all possible artifacts, before the identity with the target can be established with any certainty.

As indicated above, image artifacts are mainly produced by incomplete removal of background objects, in particular overexposed stars. It is therefore necessary to inspect the individual TO frames for such features which might produce artifacts in the final STO frames. For verification purposes, it is desirable to compare possible target identifications resulting from different datasets obtained on one or more nights. Since direct reference via background objects is impossible in the STO frames, this can only be done by means of accurate astrometry of the presumed target images, i.e. by consistent off-sets of the measured target positions from those predicted by the orbital calculations.

A further, effective and independent check of the correct performance of the present enhancement procedure is by means of implantation of a series of artificial "test comets" (TC's) into the original frames. These TC's should resemble perfectly tracked comets of different brightness, but with seeing disk properties typical for the analysed dataset. The series of TC's should be placed in a suitable area of the original frame so that they co-add perfectly during the enhancement procedure and appear cleanly in the STO frame. Due to their different, but well-known flux levels the TC's can also be used to assess the brightness of identified targets and to determine the limiting magnitude of the STO frame reached by this enhancement procedure (see Sect. 4.2).

4. The search for comet 46P/Wirtanen in the Milky Way

The enhancement procedure outlined above was applied for the search of comet 46P/Wirtanen. The observing procedure followed the recipe described in Sect. 3.3.2. The telescope tracking was adjusted to the geocentric velocity of the comet (about 28 arcsec/h). Constant exposure times were used throughout the nights: 3 min on June 23 (29 frames) and 4 min on June 25 (8 frames) and 26 (55 frames), respectively. In addition to the usual calibration exposures (biases, flats and dark current frames), images of flux standard stars were taken, although under slightly variable (5% level) photometric conditions. We then applied the detection procedure as follows:

– basic data reduction, including sky level offset (Sect. 3.3.3);
– determination of star alignment and of seeing parameters (Sect. 3.3.1: first case);
– sorting of frames by seeing;
– image alignment for seeing template frame construction;
– construction of seeing template frames (Sect. 3.1);
– image alignment for seeing template frame division (Sect. 3.3.1: first case);
– star removal in individual frames (Sect. 3.1);
– masking of bright star blends in TO frames (Sect. 3.1);
– alignment of TO frames for moving target (Sect. 3.3.1: second case); and
– co-addition of TO frames to produce STO frames (Sect. 3.2)

For comet 46P/Wirtanen, the amplitude of the daily parallax at the Earth equator was 2.4 arcsec during the June 1995 observing period, and the parallax variations for La Silla (geographical latitude -29.5 deg) were between ± 1.7 arcsec in R.A. and $0.0 - 0.3$ arcsec in Decl.

4.1. Outcome of the search for 46P/Wirtanen

The enhancement method was applied separately to the frame sets of 46P/Wirtanen obtained during the two best nights, i.e. June 23 and 26; there were too few exposures of 46P/Wirtanen during the third night. In the STO frame resulting from the co-addition of forty-four (eleven additional frames were made with a new telescope setup and are not used for our present analysis), cleaned 4-min exposures obtained on June 26 (see Fig. 2), the many star trails in the original frames have been effectively removed and are barely visible as subtle grainy streaks on the widely uniform background. Only one, isolated and almost stellar image, indicated by a circle in Fig. 3, is apparent close to the centre of the STO frame, and near the predicted position of 46P/Wirtanen. This rather faint image has an appearance that is somewhat different from those of other substructures in the frame and could therefore be assumed to be that of the comet. In order to verify the reality of this image, we have performed the three checks described in Sect. 3.4 with the following outcome:

- the implanted TC's (with a pattern as a "string of pearls") appear clearly in the STO frame (see Fig. 2), thus proving that the numerical procedure works correctly;

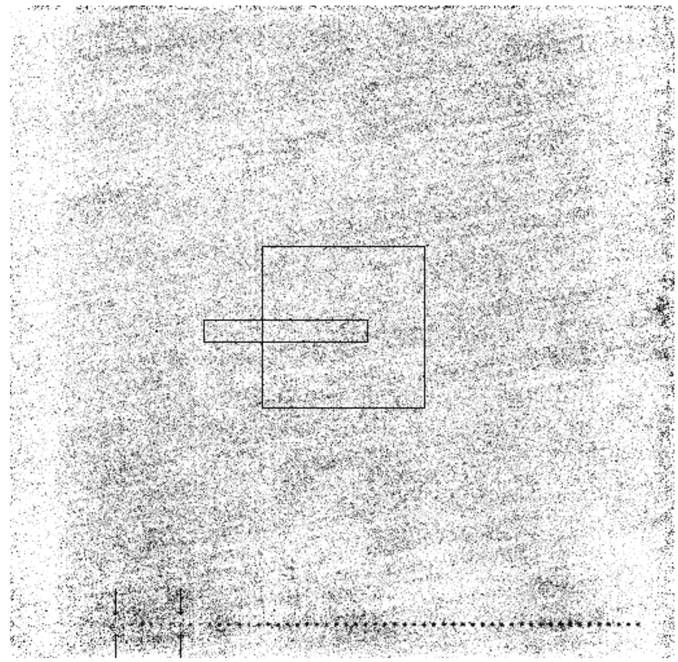

Fig. 2. Co-added frame (STO) of the 46P/Wirtanen field of June 26, 1995, after star removal, etc. as explained in this paper. A total of forty-four 4-min exposures were used for co-addition. The field of view is 5.9×5.7 arcmin. North is up, and east to the right. Since the telescope was tracking (blindly) on the comet during the exposures, the STO frame covers a larger sky area than the individual frames. The shaded areas at the eastern and western sides have less good signal statistics since they are not covered by all frames obtained. The rectangle indicates the error box corresponding to an uncertainty of the perihel transit time $\Delta T = \pm 0.15$ days around the nominal position of the comet. The square box is centered on the position of the 24.2 mag candidate image described in the text and indicates the field of view in Fig. 3. The offset from the predicted position of 46P/Wirtanen corresponds to a shift in perihelion transit time of $\Delta T \sim -0.1$ days. The "test comets" (TC's) appear as a "string of pearls" in the southern part of the frame. The two "test comets" used for the determination of the lower and upper detection limit are marked by arrow pairs.

- a thorough search for artifacts from incomplete removal of stars in a single or small subset of frames effectively excluded an origin of this type; and

- the image re-appears at the same, relative position, i.e. at the same offset from the position predicted by the orbit of 46P/Wirtanen, when different frame subsets from this night are co-added, albeit at lower S/N as expected. The STO frames resulting from the subsets have stronger substructure patterns than those visible in the STO frame of the complete frame set, clearly demonstrating the improvement in detectability of faint objects that can be achieved by using a large number of aligned TO images.

The detected candidate image is close to the predicted position of comet 46P/Wirtanen. The estimated off-set is Δ(O–C) = (+30,+2) arcsec in R.A. and Decl., respectively, and corresponds to a change of perihelion transit time of $\Delta T \sim -0.1$

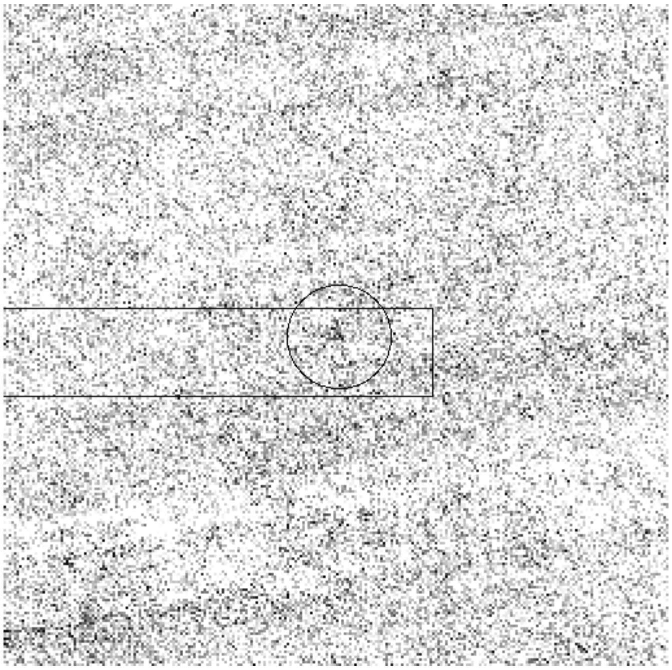

Fig. 3. Central part (square box) of Fig. 2. The field of view is 1.4×1.4 arcmin. North is up, and east to the right. The candidate object near the predicted 46P/Wirtanen position is indicated by a circle. Other substructures close to the background level are artifacts from incomplete star-cleaning. The lines mark the limits of the error box corresponding to an uncertainty of perihel transit time ΔT = ± 0.15 days (see also caption to Fig. 2).

days (compared to the best set of orbital elements provided by B. Marsden in private communication). Unfortunately, it is not possible to verify the identification by means of the STO frames from the other night (June 23) since the total integration time of this dataset is much smaller. The June 23 STO frame exhibits significantly more "noisy" substructures which make the secure identification of an image of about the same magnitude impossible.

We conclude that there is some evidence for the presence of a very faint object close to the predicted position of comet 46P/Wirtanen on June 26, 1995. However, this is based on observations from one night only and does not permit an unambiguous confirmation of the detection of the nucleus of the ROSETTA target comet at 4.6 AU solar distance. Nevertheless, a new orbital determination after the expected recovery of the comet in 1996/97 should allow to settle definitively the question whether or not this candidate is identical with comet 46P/Wirtanen (see comment in Note Added in Proof). If it is not, then the achieved limiting magnitude for the STO frame places important constraints on the size of the cometary nucleus.

4.2. Accurate astrometry and photometry

Accurate astrometry, as described in Sect. 3.3.1, was performed for the determination of secondary astrometric standards and of

Table 2. Astrometric position of the 46P/Wirtanen candidate

Date(UT)	26.23167 June 1995
α_{2000}	18^h 39^m 59.34^s
δ_{2000}	-27^o 14' 07.9"
Timing accuracy	1 sec
Pos. accuracy	1 arcsec
Measured by	R. West and H. Boehnhardt
Calculated by	R. West

the exact alignment parameters of the individual CCD frames. This also makes it possible to transform the (x, y) pixel coordinates of the image tentatively identified with 46P/Wirtanen into celestial coordinates. The resulting, accurate astrometric position of the candidate is given in Table 2.

The first step of the photometric calibration of the observed frames was performed by means of exposures of photometric standard stars obtained each night. For the 46P/Wirtanen images, we performed a careful assessment in order to estimate the limiting magnitude achieved by the present method and also the magnitude of the candidate image detected in the STO frame of June 26, 1995.

The limiting magnitude is estimated in two slightly different ways.

a. The limiting magnitude of a single exposure is estimated by using standard stars as well as flux measurements of very faint objects, just identifiable in the exposures. The counts for such objects are usually a factor of 1.3 above the count rate at the typical noise level above mean background. In parallel, we calculated the limiting magnitude from the usual S/N formula (see for instance: ESO VLT Instrumentation Plan: Preliminary proposal and Call for Responses, June 1989, p. 76).

We find from these two methods as the limiting magnitude of a single exposure 22.5 mag (faint objects) and 22.3 mag (S/N formula), respectively. Both values vary with the actual seeing, but for the June 26 observations the measured values remained relatively constant. However, stellar photometry, performed simultaneously with other telescopes at La Silla, shows slightly variable atmospheric transparency (at the 5% level) due to faint cirrus clouds in the sky.

The image counter of the co-addition procedure indicates that typically about thirty-five out of forty-four frames have contributed to each pixel in the STO frame. Therefore, the limiting magnitude of this frame should be about $2.5 \log(\sqrt{(35)}) = 1.93$ mag fainter than that of a single 4-min exposure from this night. In summary, the limiting magnitude of the present method is $\sim 24.5 - 25.0$ mag, the fainter limit corresponding to all fifty-five 4-min exposures of that night being used.

b. In a second approach, the two objects in the series of "test comets" (TC's) were identified which are barely and definitely detectable above the background in the STO frame resulting from the co-addition of all TO frames. An absolute safe detection was found possible for an object with a central intensity of about 13 counts and a very marginal detection for one with 6

Table 3. Photometry of the 46P/Wirtanen frames of 26 June 1995. The table lists the magnitude and the corresponding equivalent radius of a cometary nucleus with albedo 0.04 for the 46P/Wirtanen candidate image identified in the STO frame, as well as for the established detection limits (see text). All magnitudes are for Bessel R filter.

	Brightness (mag)	Radius (km)
46P/Wirtanen candidate	24.2	0.69
Detection limit single 4-min frame	22.5	1.53
Upper detection limit co-addition frame	23.8	0.84
Lower detection limit co-addition frame	24.9	0.51

counts above mean sky background (see Fig. 2). From this and the measured count rate of known standard stars, we find 23.8 mag for a guaranteed detection and 24.9 mag for a marginal one. Of course, the accuracy of this estimate depends somewhat on the local star background which affected the area of the implanted TC's. The relative brightness of the TC's originally increase by 1 count at maximum level from 0 counts (faintest TC) to 60 counts (brightest TC) above background, but, as can be seen in Fig. 2, the enhancement procedure somewhat modifies this. This main cause is most certainly the star-cleaning procedure. However, the overall brightness slope in the TC series survives well the severe treatment by our enhancement method and the derived limiting magnitude is probably good to a few tenths of a magnitude.

In summary, both estimations of the limiting magnitude of the STO frame lead to similar values; in what follows, we assume the actual value to be between 24.5 and 24.9 mag.

We next estimate the brightness of the comet candidate located within the error box for 46P/Wirtanen on June 26. By aperture photometry the TC with relative flux closest to that of the candidate image at the center of the STO frame (see Fig. 2) was identified; possible influences on the brightness level due to the enhancement method were not taken into account. From the known, relative brightness of this TC above sky background, the approximate magnitude of the target image is found to be 24.2 ± 0.3 mag; the error estimate is conservative, taking also the variable sky conditions during the observations into account.

The various brightness estimates are summarized in Table 3. In addition, we also list the respective equivalent radius for a comet as calculated from the semi-empirical formula given by H. Spinrad et al. (1979), assuming an albedo of 0.04 and a phase darkening coefficient of 0.03 mag/deg. It is evident that the radius of comet 46P/Wirtanen must be well below 1 km, i.e. more than a factor 2 smaller than the upper limit estimated by Jorda & Rickman (1995).

5. Discussion and concluding remarks

A new approach for the efficient detection of faint moving (solar system) objects on CCD frames in front of a star-rich sky region is described. This method allows to remove background objects from the frames by a semi-empirical numerical procedure in which the frames are cleaned for background objects, aligned and co-added to increase the S/N ratio of the target.

There are several requirements for the successful application of this method: the construction of seeing template frames for the star removal needs a broad reservoir of target frames with equal exposure times or, in general terms, with the same length and orientation of the background star trails, obtained under adequate (i.e. good to excellent) seeing conditions. The image alignment for the co-addition of the target signal (which essentially resembles the calculation of accurate x-y pixel coordinates for the topocentric positions of the comet on the chip) involves accurate astrometric measurements of the CCD frames and careful corrections for telescope tracking errors and daily parallax of the object. A large number of frames must be co-added in order to provide a "smooth and flat" background on which the faint target may be identified. The possible identification of images of the moving target must be carefully verified in order to exclude artifacts from the star cleaning process (possible systematic effects not corrected by bias subtraction and flatfield division can be cancelled out by random offsets of the telescope as discussed by Hainaut et al. (1994) and references therein). For the identified objects accurate positions can be obtained and a coarse estimate of its brightness can be made.

This method has been used to search for comet 46P/Wirtanen in front of a rich Milky Way field close to the Galactic Centre. An image was marginally detected at R = 24.2 ± 0.3, close to the predicted comet position, in the cleaned and co-added frame, based on forty-four 4-min exposures obtained in late June 1995 at ESO La Silla. Due to adverse weather conditions this detection cannot be confirmed by observations from a second night during this run.

Orbital analyses for 46P/Wirtanen by F. Hechler (ESOC) and B. Marsden (CFA; both in private communication, 1995), including the position of our candidate image from June 26, 1995, also does not allow a firm conclusion as to the identity (see comment in Note Added in Proof). On one side, the position of the candidate is in good agreement with a short-arc solution for the 46P/Wirtanen orbit, including only the last two apparitions of the comet. However, it apparently cannot be matched to longer orbit arcs which include also the close encounters with Jupiter in 1972 and 1984 (Belyaev et al. 1995). These passages of the comet at the massive gas planet drastically changed its orbit (e.g. decrease of perihelion distance from 1.63 to 1.06 AU), but are badly sampled by astrometric observations. The final assessment of our possible identification can therefore only be made when updated orbital elements become available after the unambiguous recovery of the comet, after the onset of activity expected in 1996 or 1997 (see comment in Note Added in Proof).

The brightness of our 46P/Wirtanen candidate and the detection limit achieved with the present method indicate a nucleus radius of 0.8 km or less for the comet (assuming an albedo of 0.04). Therefore, 46P/Wirtanen must be at least a factor of 2 smaller than previously estimated (Jorda & Rickman 1995) and may in fact be one of the smallest cometary nuclei known so far (see O'Ceallaigh et al. 1995). Its nucleus may therefore exhibit a high degree of activity per surface area and, considering the production rates determined by A'Hearn et al. (1995), more than 25 percent of the nuclear surface may contribute to the activity of the comet.

The present indication of a small, but highly active nucleus for 46P/Wirtanen is at least qualitatively supported by the strong non-gravitational forces exhibited by this comet as pointed out by Jorda & Rickman (1995).

We moreover conclude from the outcome of the analysis of our 46P/Wirtanen observations in June 1995 that the detection of the ROSETTA target comet 46P/Wirtanen in front of the Milky Way and close to the rendez-vouz distance with the spacecraft will probably require the use of ground-based telescopes of the 4-m class with excellent optics and under good atmospheric conditions; full night exposure series may be necessary for a safe detection, even by means of the present, optimised method.

We finally note that while this method is particularly suitable for detection of faint moving targets on a star-crowded background, it is is not restricted to the removal of star-like sources. The method may thus also be suitable for very deep searches for distant solar system objects, e.g. Transneptunian objects (TNO's) or debris bodies in the asteroid belt, also on a galaxy-rich background as seen in very long exposures of the HST and (existing or future) 8–10-m class telescopes. The method can also be applied to faint, extended targets, for instance active comets at large distances.

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Note added in proof: Comet 46P/Wirtanen was recovered by Boehnhardt, Rauer, Motolla, and Nathues (see IAU Circular No. 6392, 1996) on 25 April 1996 during an observing campaign at the Danish 1.54m telescope at ESO La Silla. The comet brightness was 21.5 mag through a Bessel R filter, and it exhibited a 4 arcsec tail. The immediate orbit determination by Brian Marsden (CFA, private communication) confirmed that the candidate object identified in our images of 26 June 1995 was indeed 46P/Wirtanen. Apart from the unexpectedly large offset from the predicted position - indicating strong non-gravitational effects on the orbit - the non-stellar appearance of the comet in April 1996, when it was 3.2 AU from the Sun, also suggests an early onset of nucleus activity. This would also explain the differences between our radius estimate at 4.6 AU (when the comet was most likely still inactive) and that of Jorda and Rickman (1995) based upon observations of the comet closer than 2.6 AU from the Sun (where coma contamination of the nucleus photmetry are now likely).

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