An improvement of BeppoSAX LECS and MECS source positioning accuracy

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1 Introduction

This document reports a detailed study of the accuracy of *Beppo*SAX LECS and MECS sky position reconstruction.

This work has been motivated from the evidence of a ~ 40 arcsec discrepancy between LECS and MECS source positions, as noticed by various *Beppo*SAX users and in particular by Tim Oosterbroek (private communication).

2 Data analysis

A systematic comparison of LECS and MECS X-ray source positions with those collected from various optical catalogs is presented.

We have independently analyzed sky images of the four *Beppo*SAX X-ray telescopes (LECS, MECS1, MECS2 and MECS3) using event files processed at the ASI Science Data Center (ASDC).

We have restricted our analysis to observations performed after May 6th 1998, since before this date various calibration problems have affected the absolute spacecraft attitude reconstruction (see the Appendix for a detailed discussion on this topic).

This time selection has not been possible for MECS1, since this unit failed on May 6th 1997. We have therefore considered MECS1 observations from the beginning of the mission (May 1996) until the failure of the unit. Due to the worse spacecraft attitude reconstruction during this time interval, the MECS1 data are affected by larger systematic errors on the absolute sky position reconstruction.

LECS and MECS fields have been selected according to the following criteria:

- observation later than May 6th 1998 (with the exception of MECS1)
- exclusion of extended or confused target sources
- the target of the observation is sufficiently bright (count rate $> 10^{-2}$ cts s^{-1} for the LECS and the MECS units)
- the position of the optical counterpart of the target is known to within 1 arsec
- the whole range of spacecraft roll angle values (from $-90°$ to $+270°$) is covered

This selection results in a sample of **77** MECS1 images and **72** LECS, MECS2 and MECS3 images.

Source detection of the targets has been performed using the DETECT routine of the XIMAGE package (Version 2.66a).

Images were accumulated in the 2-10 keV energy band (channels 44-220) for the MECS and in the 0.1-10 keV (channels 10-950) for the LECS.

Special attention has been devoted to the quality of the detections. For each source different sizes of the slide-cell of the DETECT routine have been attempted and all detections have been checked interactively.

3 Comparison with optical positions

We have compared the *Beppo*SAX X-ray detections with the accurate positions obtained from various optical catalogs.

The results are shown in Figure 1 where the deviations in RA and Dec between the LECS and MECS X-ray sky positions and the optical positions are plotted. Note that differences have been computed subtracting the X-ray value from the optical one and that RA differences are corrected by the factor *cos(Dec)* and represent the true separation in the sky:

$$\Delta\mathrm{RA} = (\mathrm{RA}_{\mathrm{opt}} - \mathrm{RA}_{\mathrm{sax}})\cos(\mathrm{Dec})$$

$$\Delta\mathrm{Dec} = \mathrm{Dec}_{\mathrm{opt}} - \mathrm{Dec}_{\mathrm{sax}}$$

We have then computed the radial distance between the X-ray and optical position and the "radius" within which 68% and 90% of the objects are included. The results are summarized in Table 1.

Table 1: LECS and MECS 68% and 90% error radius values

Instrument	68% error radius	90% error radius
LECS	23"	29"
MECS1	38"	53"
MECS2	30"	42"
MECS3	32"	43"

From Figure 1 and Table 1 some issues can be pointed out.

First, MECS1 X-ray positions are significantly affected by larger errors than MECS2 and MECS3, as a result of the worse absolute attitude reconstruction of the spacecraft during the first two years of the mission. An analysis of MECS2 and MECS3 images from May 1996 to May 1997 confirms this interpretation: MECS2 and MECS3 error radius values during this period are nearly identical to those of MECS1.

Second, RA and Dec deviations for MECS2 and MECS3, and marginally for MECS1, are not uniformly distributed around the zero values, suggesting the presence of some problems in the telescopes misalignment calibrations.

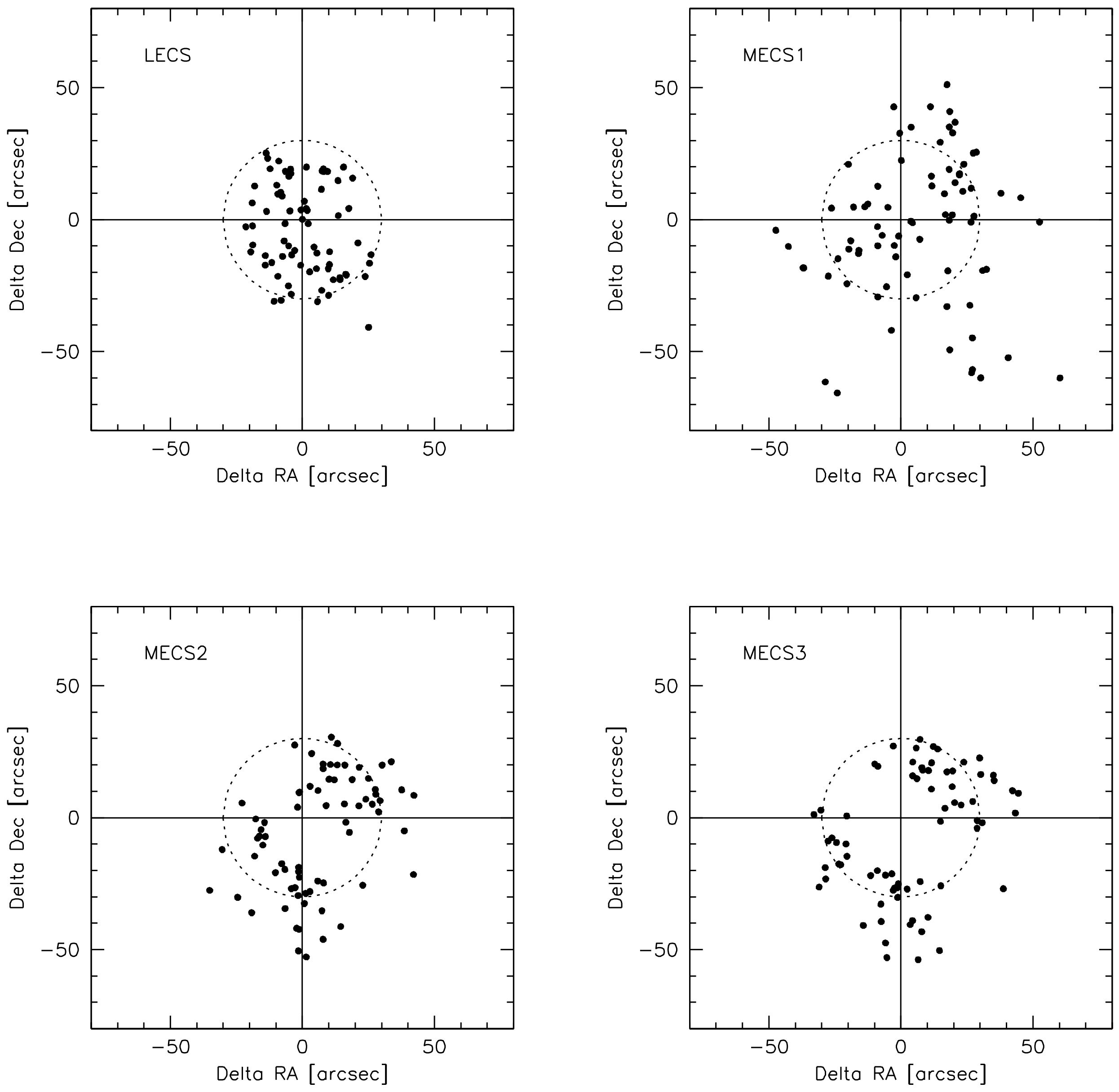

Figure 1: The deviation in RA and Dec between X-ray positions (LECS, MECS1, MECS2, MECS3) and optical positions. The short-dashed circle has a radius of 30 arcsec.

4 The dependence on roll angle

The non uniform distribution of RA and Dec differences is a clear indication that a systematic error is affecting the *Beppo*SAX NFI position accuracy, at least for the MECS units.

Figures 2 and 3 show the LECS and MECS RA and Dec deviations plotted as a function of the satellite roll angle. Clearly, both the LECS and MECS offsets are strongly correlated with the roll angle.

The amplitude of this effect is $\sim$ **15** arcsec in the case of the LECS and $\sim$ **25** arcsec for the three MECS units.

The fact that RA and Dec differences are correlated with the satellite roll angle is a sure indication of a non perfect ($\sim$ **20** arcsec) calibration of the misalignment matrices of both LECS and MECS instruments.

Note that this correlation with the roll angle has also the effect of producing the radially asymmetric distributions shown in Figure 1.

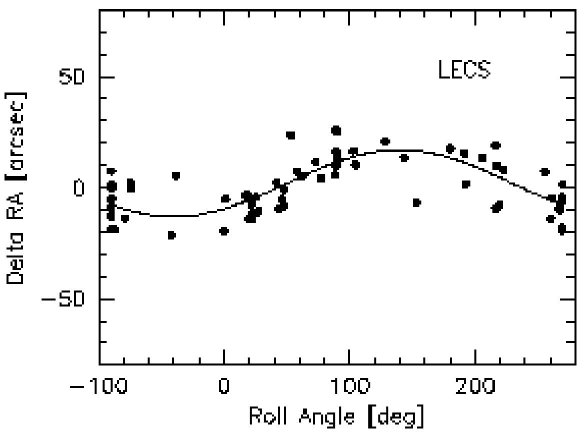

Figure 2: The differences in RA and Dec between LECS X-ray positions and optical positions plotted as a function of the spacecraft roll angle. The solid lines are best fits to the data and are discussed in the text.

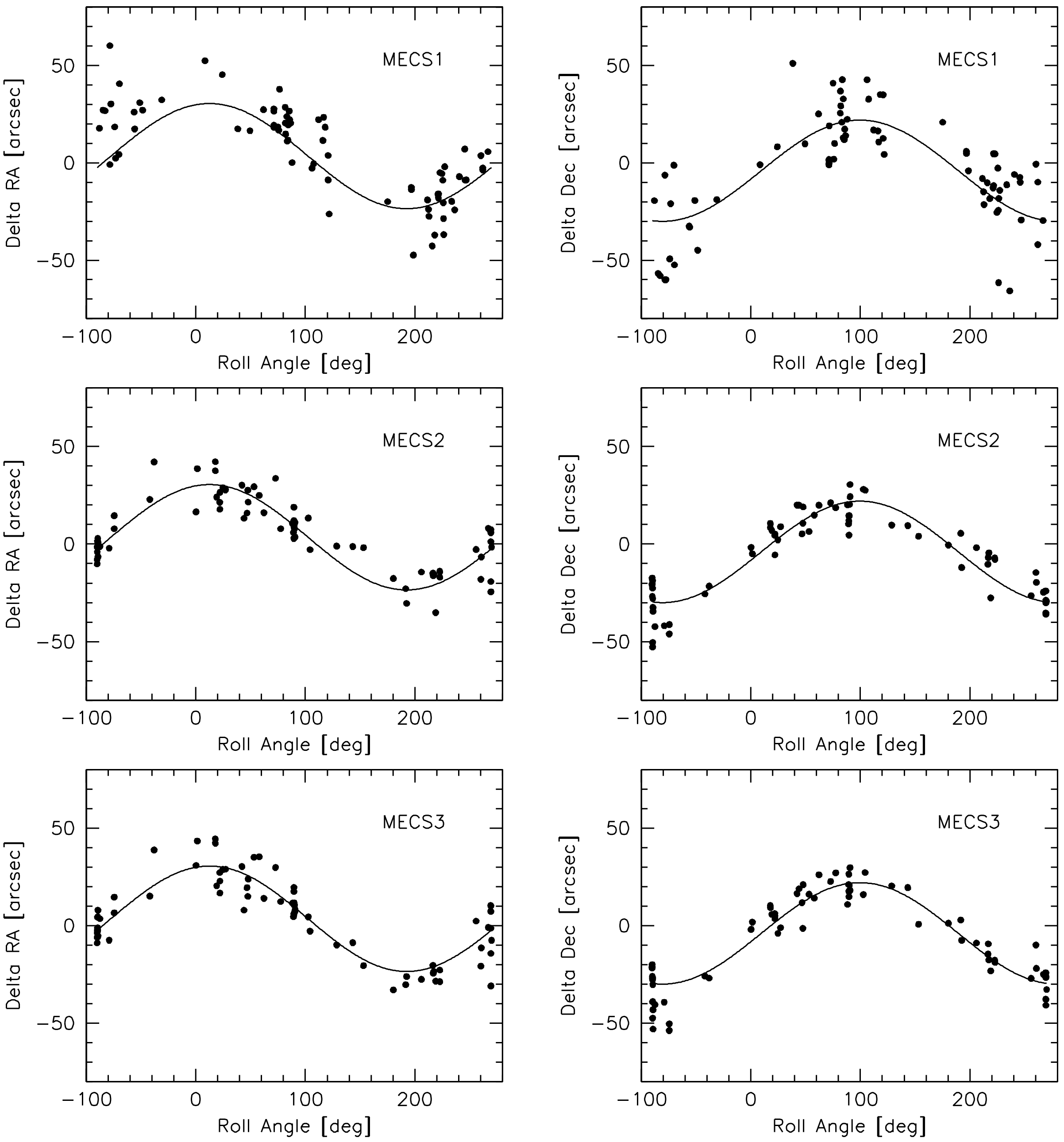

Figure 3: The differences in RA and Dec between X-ray positions and optical positions plotted as a function of the spacecraft roll angle (top: MECS1; middle: MECS2; bottom: MECS3). The solid lines are best fits to the data and are discussed in the text.

5 Origin of the error and how to correct it

In this section we investigate the origin of the non perfect ($\sim$ 20 arcsec) calibration of the misalignment matrices of the four X-ray telescopes on-board *Beppo*SAX.

LECS and MECS misalignment calibrations have been performed using observations carried out in summer 1996. As is discussed in the Appendix, during this period *Beppo*SAX pointings have suffered several attitude reconstruction problems which resulted in a non accurate ($\sim$ 20 arcsec) spacecraft attitude data.

The use of such data is most probably at the origin of the non perfect calibration of LECS and MECS misalignment matrices, as indicated also by the fact that the attitude inaccuracy is of the same order of the residual misalignment of *Beppo*SAX NFI instruments.

Moreover, LECS and MECS misalignment calibrations have been performed independently from two distinct teams and this makes very unlikely an error in the procedure used to compute the misalignment matrices.

Two different procedures can be adopted to correct the NFI misalignment calibration: 1) a new computation of LECS and MECS misalignment matrices and 2) a correction of the NFI event files coordinates.

While the first solution seems the most natural one, it requires a greater effort and new dedicated *Beppo*SAX pointings. Moreover, a complete reprocessing of all *Beppo*SAX observations would be needed to produce a new complete archive of LECS and MECS images.

We have therefore decided to adopt the second option. With this procedure is in fact possible to correct very quickly all the present NFI images, and to include the correction in the *Beppo*SAX data processing software, without any degradation of the scientific results obtained.

6 Correction algorithm

From Figures 2 and 3 it is evident that the residual misalignment of LECS and MECS coordinates can be described in terms of sinusoidal functions of the satellite roll angle.

We have fitted the RA and Dec deviations as a function of roll angle obtaining the following best fits:

$$\Delta\mathrm{RA}_{\mathrm{LECS}} = 15\ \cos(\phi - 140) + 2 \qquad [\mathrm{arcsec}] \tag{1a}$$
$$\Delta\mathrm{Dec}_{\mathrm{LECS}} = 19\ \cos(\phi - 236) - 4 \qquad [\mathrm{arcsec}] \tag{1b}$$

$$\Delta\mathrm{RA}_{\mathrm{MECS}} = 27\ \cos(\phi - 12.5) + 3.5 \qquad [\mathrm{arcsec}] \tag{2a}$$
$$\Delta\mathrm{Dec}_{\mathrm{MECS}} = 26\ \cos(\phi - 99.5) - 4.0 \qquad [\mathrm{arcsec}] \tag{2b}$$

where ϕ is the value of the roll angle expressed in degrees.

These best fits have been plotted as solid lines in Figures 2 and 3 respectively.

A separate fit of MECS1, MECS2 and MECS3 data has been performed. Since very small differences (of the order of 2-3 arcsec) between the three units have been found, we have adopted a single correction formula for MECS data, obtained averaging the best fit parameters of the three units.

Equations (1) and (2) can been used to correct LECS and MECS event files coordinates. The correction is obtained *adding* ΔRA and ΔDec to the LECS and MECS coordinates:

$$\mathrm{RA_{corrected}} = \mathrm{RA} + \Delta\mathrm{RA}/\cos(\mathrm{Dec})$$

$$\mathrm{Dec_{corrected}} = \mathrm{Dec} + \Delta\mathrm{Dec}$$

A specific task (**saxposcor**) that corrects LECS and MECS event files has been developed and is available at http://www.asdc.asi.it/bepposax/coord_correction.html

7 Results

The coordinates of LECS and MECS detections obtained in Section 2 have been corrected using equations (1) and (2).

The deviations in RA and Dec between the corrected LECS and MECS positions and the optical positions have then been computed and plotted in Figure 4.

From the new radial deviations between corrected NFI X-ray positions and optical ones we obtain the 68% and 90% error radius values reported in Table 2:

Table 2: LECS and MECS 68% and 90% error radius values after correction

Instrument	68% error radius	90% error radius
LECS	12”	16”
MECS1	23”	38”
MECS2	12”	18”
MECS3	13”	22”

As can be seen, after correction the accuracy of LECS and MECS positions has improved by a factor of 2.

Note that the non uniform distribution of RA and Dec deviations before the correction (see Figure 1) is no longer present.

As already mentioned in Section 3, the larger MECS1 position uncertainties are due to the worse spacecraft attitude data of all *Beppo*SAX observations performed in the first two years of the mission (May 1996-May 1998).

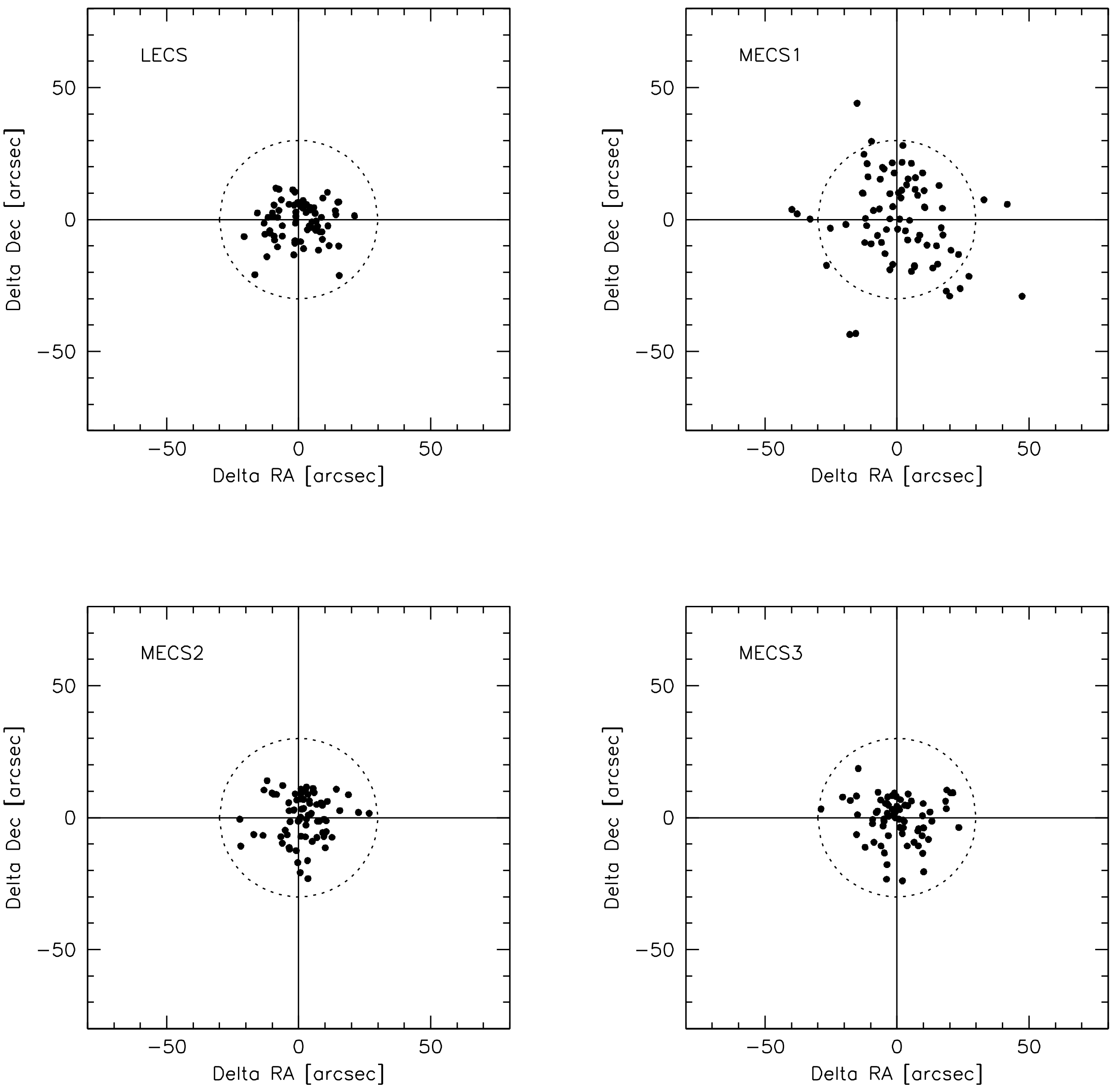

Figure 4: The deviation in RA and Dec between the corrected X-ray positions (LECS, MECS1, MECS2, MECS3) and optical positions. The short-dashed circle has a radius of 30 arcsec.

8 Coadded MECS and MECS23 sky images

As already mentioned, our study has been conducted analyzing independently the sky images of the four X-ray telescopes on board BeppoSAX (LECS, MECS1, MECS2, MECS3).

We have also studied the coadded MECS1+MECS2+MECS3 (named ”MECS”) and MECS2+MECS3 (named ”MECS23”) images.

The corresponding RA and Dec deviations from optical positions (before and after the coordinate correction) are shown in Figure 5.

The 68% and 90% error radius values for MECS and MECS23 instruments are reported in Table 3 and Table 4:

Table 3: Coadded MECS and MECS23 68% and 90% error radius values before correction

Instrument	68% error radius	90% error radius
MECS	37”	53”
MECS23	30”	41”

Table 4: Coadded MECS and MECS23 68% and 90% error radius values after correction

Instrument	68% error radius	90% error radius
MECS	19”	38”
MECS23	11”	17”

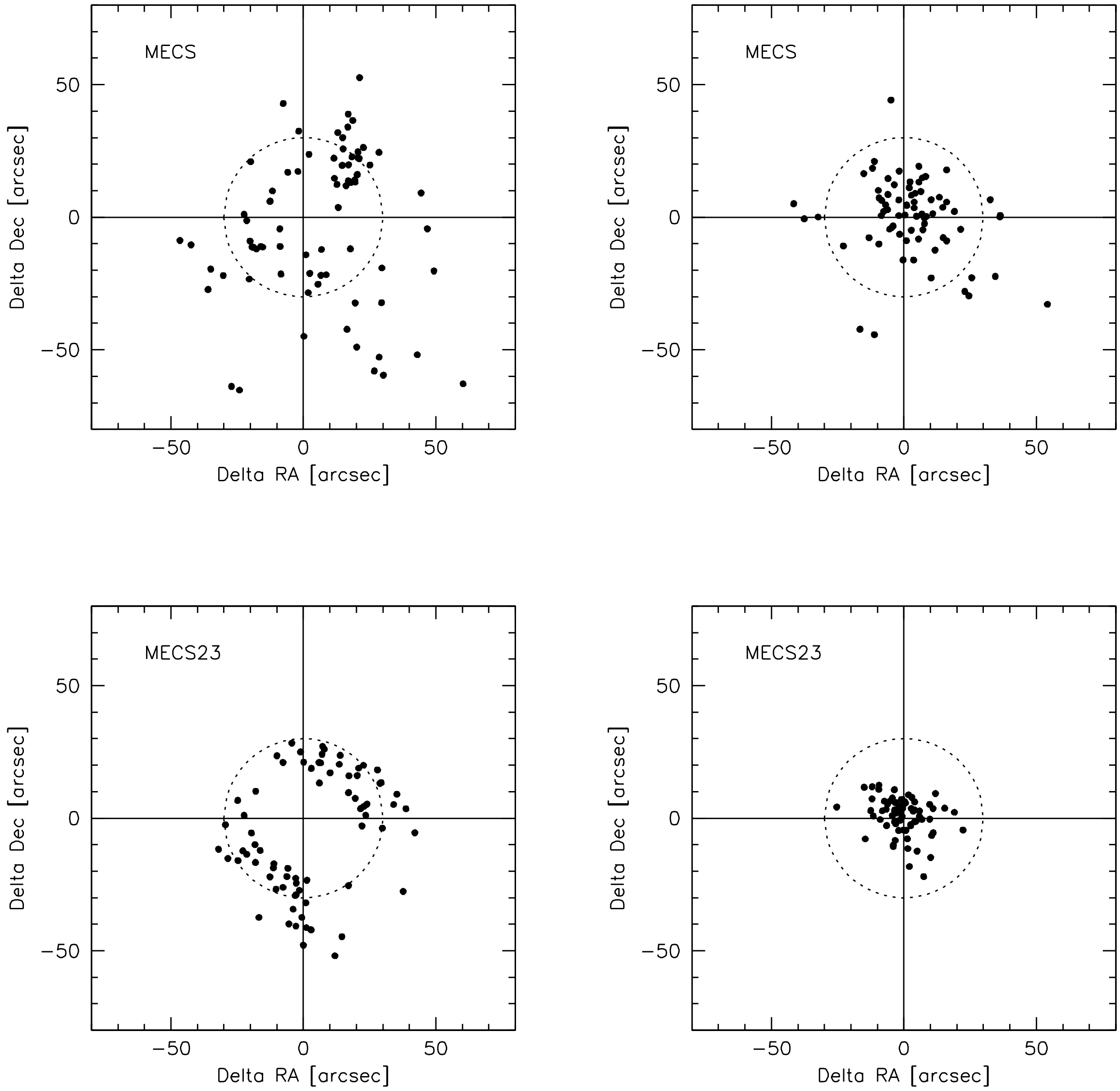

Figure 5: RA and Dec deviations from optical values for uncorrected (left) and corrected (right) X-ray positions as obtained from the coadded MECS and MECS23 images. The short-dashed circles have a radius of 30 arcsec.

9 Off-axis sources

The analysis presented in the previous sections has pointed out that both LECS and MECS images are shifted in RA and Dec by an amount of $\sim$ 20 arcsec, which corresponds to a rotation around the X and Y axes of the spacecraft reference frame.

The non perfect calibration of the misalignment matrices may also concern the rotation around the Z axis, the one co-aligned with the NFI instruments. Since this corresponds to a rotation of the X-ray images, the analysis of LECS and MECS on-axis sources is not useful to investigate this issue.

The residual misalignment around the Z axis is expected to have a similar amplitude to those around the X and Y axes ($\sim$ 20-30 arcsec). As the following simple argument shows, the effect of the Z misalignment on the image coordinates is negligible. If we consider a 30 arcsec rotation of the image around its center the effect on the coordinates of a source located at an off-axis angle of 30 arcmin is a very small shift ($\sim$ 0.3 arcsec).

We have verified this conclusion comparing the *Beppo*SAX X-ray and optical positions of a small sample of off-axis sources. In all cases we found that there is no need of a rotation of the image and that the RA and Dec coordinate correction described by Equations (1) and (2) corrects very well also the positions of off-axis sources. An example of a MECS3 image before and after the correction is shown in Figure 6.

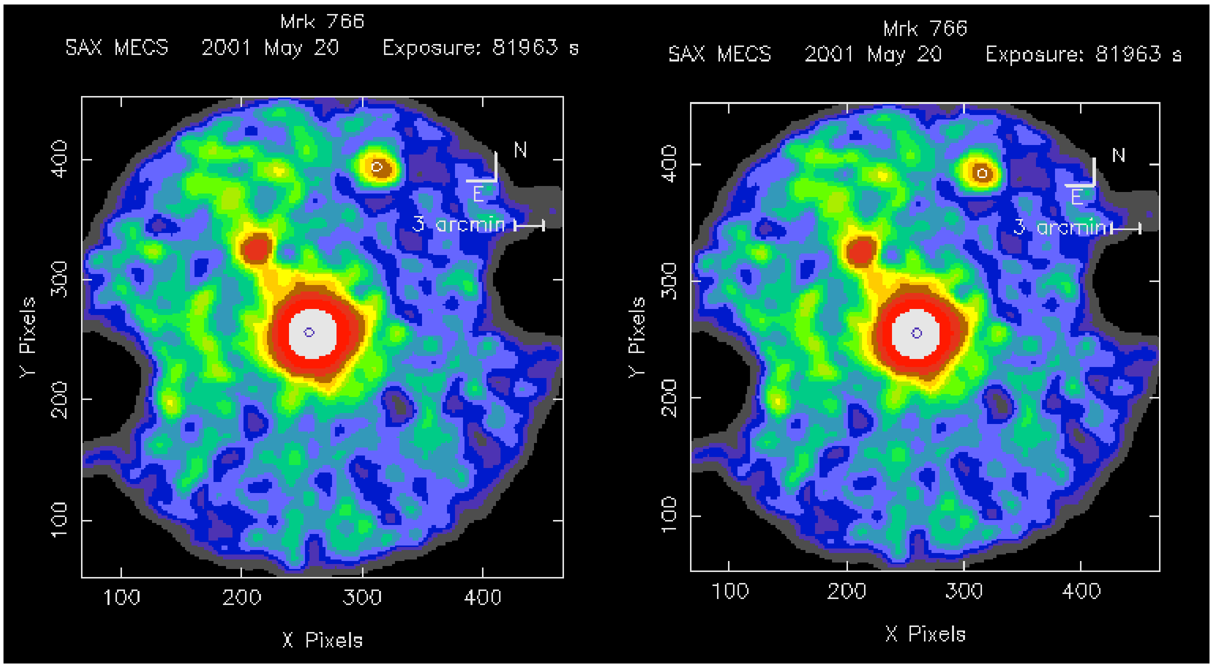

Figure 6: Left: MECS3 image of the Seyfert galaxy Mrk 766 (target) and the BL Lac object ON 325 (NW source) before the RA and Dec correction described by Equations (1) and (2). The small circles indicate the optical positions of the two sources. Right: MECS3 image after the correction. The improved accuracy of the X-ray position of both sources is evident.

Appendix: the spacecraft attitude reconstruction

In this Appendix we investigate in some details the problems that affected the absolute attitude reconstruction of *Beppo*SAX during the first two years of the mission.

In summer 1997, during the commissioning of the *Beppo*SAX Single Gyro Pointing Mode, an error of about 20 arcsec in the misalignment matrices of the three star-trackers, used to control the spacecraft attitude, was discovered.

As the following investigation revealed, the error originated because the coordinates of the stars used by the spacecraft star-trackers were not corrected for the annual aberration due to the heliocentric motion of the Earth.

This error was soon corrected (August 1997), but this led to even greater problems: rather large movements of the spacecraft (up to about 2 arcmin) was in fact observed when the attitude control was switched between different star-trackers. The inspection of this problem, in spring 1998, revealed that the correction for the annual aberration was applied with the wrong sign. The error was finally fixed on May 6 1998 with a new and exact computation of star coordinates and star-trackers misalignment matrices.

To summarize, we can define 3 distinct time intervals with respect to *Beppo*SAX attitude reconstruction:

- **Period 1** (May 1996 - May 1997): $\sim$ 20 arsec error on both star-trackers alignment matrices and target star positions (due to a missing correction for annual aberration).

- **Period 2** (August 1997 - May 6 1998): $\sim$ 40 arcsec error on both star-trackers alignment matrices and target star positions (due to a wrong correction for annual aberration).

- **Period 3** (May 6 1998 - present): the spacecraft attitude data is unaffected by errors related to the annual aberration.

The effects of the satellite attitude reconstruction problems on the positioning accuracy of *Beppo*SAX NFI instruments is discussed in Section 3, 4 and 5 of this document.