ROSAT SCIENCE DATA CENTER

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Final Report

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This report provides a summary of the SAO ROSAT SCIENCE DATA CENTER (RSDC) activities for the recent years of our contract. Details have already been reported in the monthly reports.

1. HOPR: HRI/SASS SOFTWARE SUPPORT

The Smithsonian Astrophysical Observatory (SAO) was responsible for the High Resolution Imager (HRI) detector on ROSAT. We also provided and supported the HRI standard analysis software used in the pipeline processing (SASS). Working with our colleagues at the Max Planck in Garching Germany (MPE), we fixed bugs and provided enhancements. The last major effort in this area was the port from VMS/VAX to VMS/ALPHA architecture.

In 1998, a timing bug was found in the HRI standard processing system which degraded the positional accuracy because events accessed incorrect aspect solutions. The bug was fixed and we developed off-line correction routines and provided them to the community.

2. PROS: POST REDUCTION OFF-LINE SOFTWARE

The Post Reduction Off-line Software (PROS) package was developed by SAO and runs in the IRAF environment. Although in recent years PROS was not a contractual responsibility of the RSDC, we continued to maintain the system and provided new capabilities such as the ability to deal with simulated AXAF data in preparation for the NASA call for proposals for Chandra. Our most recent activities in this area included the debugging necessary for newer versions of IRAF which broke some of our software. At SAO we have an operating version of PROS and hope to release a patch even though almost all functionality that was lost was subsequently recovered via an IRAF patch (i.e. most of our problems were caused by an IRAF bug).

3. HOTSEAT: SERVICE TO PROS USERS

SAO/RSDC has had a long tradition of giving timely personal service to its users via the hotseat email service. Over the years, this commitment has served us well both in alerting us to problems with the software and in providing expert help to users. We were also the primary point of contact for definitive answers about the HRI detector, its capabilities, and in the interpretation of the scientific results of the standard processing. Hotseat activity peaked in the mid '90s with over 1000 emails per year from outside the Center for Astrophysics (SAO).

4. DOCUMENTATION

We maintained a complete array of documentation services. The so called "HRI Calibration Report" originally appeared in the early 90's, but was updated each year in support of the NASA AOs. Substantial additions such as that engendered by our better understanding of the cause of the UV leak, were included as well as time histories of the gain and other detector qualities.

The PROS Users Guide was another document available in hardcopy or via the web which was regularly updated and enhanced (e.g. inclusion of recipes for the use of HRI quantum efficiency and gain maps).

We also maintained an email list of PROS users and sent out newsletters ("Hints and Pointers for PROS users") with bug reports and fixes, notice of new releases, and other items which affected user's interpretation of their data. During the course of the mission, 28 newsletters have been issued.

We maintained a website which allowed users to access a large variety of documents about the HRI, PROS, other aspects of our ROSAT efforts. The latest update is listed as 2000 July 25. Our URL is: http://hea-www.harvard.edu/rosat/rsdc_www/ros_welcome.html.

5. UV CALIBRATION

One of our HRI related activities was to monitor the status and health of the HRI detector via examination of UV calibrations. These data were sent to us from MPE and throughout the mission, we checked the quality of the data by comparing these calibrations with standard templates.

6. HRI DETECTOR HOTSPOTS

Although some pores in the micro-channel plate of the HRI were known to be 'hot' and screened out in the standard software, in 1995 and 1996 3 additional 'hotspots' occurred near corners of the detector. We analyzed each of these as they were discovered and developed software to automatically monitor their sporadic behavior. We also provided users methods of excising these via detector coordinates although their presence had essentially no impact on the quality of the scientific results of the detector.

7. VV: VALIDATION and VERIFICATION of Standard Processing

During the early phases of the mission, VV was a major activity of the SAO/RSDC with detailed visual inspection of all data. Though VV, a large number of bugs were found and fixed in the standard software pipeline. As the software system matured and bugs were infrequent or absent entirely, the VV effort was modified to an automatic examination and report of the data. This process continued to the end of the mission.

8. ROSAT RESULTS ARCHIVE

With our colleagues at MPE, Potsdam (Germany), Leicester (UK) and GSFC, it was decided to provide a service to the community of collecting all the results on individual sources detected in the pipeline processing. The critical aspect of this effort was to re-examine each observation and provide a set of quality flags for the key parameters such as position and intensity. The detection algorithms employed in the standard processing were designed to locate unresolved sources and as such, they manifest various short-comings for actual data. The visual inspection and automatic evaluation provided the necessary extra information so that users of the resulting databases could evaluate the reliability of the SASS generated parameters.

The RRA project was hampered by the requirement that the data must pass into the public domain, and since a few observations had problems in the standard processing, dissemination of these to the principal investigators was delayed and thus also our ingestion into the database was delayed. However, both HRI and PSPC (Positional Sensitive Proportional Counter) lists have been made publically available

on the websites of the ROSAT consortium (ours can be found at URL: http://hea-www.harvard.edu/rosat/rsdc_www/rra.html).

9. CALIBRATION

The high voltage setting of the HRI detector determines the centroid of the pulse height analysis channels over which normal X-ray are distributed. During the mission, the status of this 'gain' was determined by regular observations of a celestial source and a slow reduction in gain was found with time. This situation required that from time to time the high voltage needed to be increased. A complete history of the gain and the voltage changes was reported in the HRI Calibration Report (and its revisions).

10. Other

One of the major problems with spatial analysis of sources with the ROSAT HRI is that the point-spread-function (PSF) is degraded by residual aspect errors of the satellite. This means that every observation has a somewhat different PSF making spatial analysis inaccurate. In consultation with colleagues at AIP (Potsdam) we developed scripts to make partial corrections for this effect if a reasonably strong point source is present near the field center. We published a paper[1] on this technique and provided the scripts to make the corrections with PROS/IRAF (and our colleagues developed and distributed similar scripts for use with EXSAS/MIDAS, the software system developed by ESO and MPE).

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[1] "Spatial corrections of ROSAT HRI Observations" 1998, A&AS, 133, 431 (copy attached).

Spatial corrections of ROSAT HRI observations

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Abstract. X-ray observations with the ROSAT High Resolution Imager (HRI) often have spatial smearing on the order of $10''$ (Morse 1994). This degradation of the intrinsic resolution of the instrument ($5''$) can be attributed to errors in the aspect solution associated with the wobble of the space craft or with the reacquisition of the guide stars. We have developed a set of IRAF/PROS and MIDAS/EXSAS routines to minimize these effects. Our procedure attempts to isolate aspect errors that are repeated through each cycle of the wobble. The method assigns a "wobble phase" to each event based on the 402 second period of the ROSAT wobble. The observation is grouped into a number of phase bins and a centroid is calculated for each sub-image. The corrected HRI event list is reconstructed by adding the sub-images which have been shifted to a common source position. This method has shown $\sim 30\%$ reduction of the full width half maximum ($FWHM$) of an X-ray observation of the radio galaxy 3C 120. Additional examples are presented.

Key words: techniques: image processing — X-rays: general

1. Introduction

Spatial analysis of ROSAT HRI observations is often plagued by poor aspect solutions, precluding the attainment of the potential resolution of about $5''$. In many cases (but not all), the major contributions to the degradation in the effective Point Response Function (PRF) come from aspect errors associated either with the ROSAT wobble or with the reacquisition of the guide stars.

To avoid the possibility of blocking sources by the window support structures (Positional Sensitive Proportional Counter) or to minimize the chance that the pores near the center of the microchannel plate would become burned out

from excessive use (High Resolution Imager), the satellite normally operates with a constant dither for pointed observations. The period of the dither is 402 s and the phase is tied to the spacecraft clock. Any given point on the sky will track back and forth on the detector, tracing out a line of length ≈ 3 arcmin with position angle of $135°$ in raw detector coordinates (for the HRI). Imperfections in the star tracker (see Sect. 2) can produce an erroneous image if the aspect solution is a function of the wobble track on the CCD of the star tracker.

This work is similar to an analysis by Morse (1994) except that we do not rely on a direct correlation between spatial detector coordinates and phase of the wobble. Moreover, our method addresses the reacquisition problem which produces the so-called cases of "displaced OBIs". An "OBI" is an observation interval, normally lasting for 1 ks to 2 ks (i.e. a portion of an orbit of the satellite). A new acquisition of the guide stars occurs at the beginning of each OBI and we have found that different aspect solutions often result. Occasionally a multi-OBI observation consists of two discrete aspect solutions. A recent example (see Sect. 7.1.2) showed one OBI for which the source was $10''$ north of its position in the other 17 OBIs. Note that this sort of error is quite distinct from the wobble error.

Throughout this discussion, we use the term "PRF" in the dynamic sense: it is the point response function realized in any given situation: i.e. that which includes whatever aspect errors are present. We start with an observation for which the PRF is much worse than it should be. We seek to improve the PRF by isolating the offending contributions and correcting them if possible or rejecting them if necessary.

2. Model and method

The "model" for the wobble error assumes that the star tracker's CCD has some pixels with different gain than others. As the wobble moves the de-focused star image across the CCD, the centroiding of the stellar image gets the wrong value because it is based on the relative

response from several pixels. If the roll angle is stable, it is likely that the error is repeated during each cycle of the wobble since the star's path is over the same pixels (to a first approximation if the aspect "jitter" is small compared to the pixel size of ≈ 1 arcmin). What is not addressed is the error in roll angle induced by erroneous star positions. If this error is significant, the centroiding technique with one strong source will fix only that source and its immediate environs.

The correction method assigns a "wobble phase" to each event; then divides each OBI (or other suitably defined time interval) into a number of wobble phase bins. The centroid of the reference source is measured for each phase bin. The data are then recombined after applying x and y offsets in order to ensure that the reference source is aligned for each phase bin. What is required is that there are enough counts in the reference source to obtain a reliable centroid. Variations of this method for sources weaker than approx 0.1 count/s involve using all OBIs together before dividing into phase bins. This is a valid approach so long as the nominal roll angle is stable (i.e. within a few tenths of a degree) for all OBIs, and so long as major shifts in the aspect solutions of different OBIs are not present.

3. Diagnostics

Our normal procedure for evaluation is to measure the $FWHM$ (both the major and minor axes) of the observed response on a map smoothed with a $3''$ Gaussian. For the best data, we find the resulting $FWHM$ is close to $5.7''$. While there are many measures of source smearing, we prefer this approach over measuring radial profiles because there is no uncertainty relating to the position of the source center; we are normally dealing with elliptical rather than circular distributions; and visual inspection of the two dimensional image serves as a check on severe abnormalities. It has been our experience that when we are able to reduce the $FWHM$ of the PRF, the wings of the PRF are also reduced.

3.1. Wobble errors

If the effective PRF is evaluated for each OBI separately, the wobble problem is manifest by a degraded PRF in one or more OBIs. Most OBIs contain only the initial acquisition of the guide stars, so when the PRF of a particular OBI is smeared, it is likely to be caused by the wobble error and the solution is to perform the phased "de-wobbling".

3.2. Misplaced OBI

For those cases where each OBI has a relatively good PRF but the positions of each centroid have significant disper-

sion, the error cannot be attributed to the wobble. We use the term "misplaced OBI" to describe the situation in which a different aspect solution is found when the guide stars are reacquired. In the worst case, multiple aspect solutions can produce an image in which every source in the field has a companion displaced by anywhere from 10 to 30 arcsec or more. When the separation is less than 10 arcsec, the source can appear to have a tear drop shape (see Sect. 7.1.1) or an egg shape. However, depending on the number of different aspect solutions, almost any arbitrary distortion to the (circularly symmetric) ideal PRF is possible. The fix for these cases is simply to find the centroid for each OBI, and shift them before co-adding (e.g., see Morse et al. 1995).

4. IRAF/PROS implementation

The ROSAT Science Data Center (RSDC) at SAO has developed scripts to assist users in evaluating individual OBIs and performing the operations required for de-wobbling and alignment. The scripts are available from our anonftp area: sao-ftp.harvard.edu. Then change directory to pub/rosat/dewob.

An initial analysis needs to be performed to determine the stable roll angle intervals, to check for any misalignment of OBIs and to examine the guide star combinations. These factors together with the source intensity are important in deciding what can be done and the best method to use.

4.1. OBI by OBI method

If the observation contains a strong source (≥ 0.1 counts/s) near the field center (i.e. close enough to the center that the mirror blurring is not important), then the preferred method is to dewobble each OBI. The data are thus divided into $n \times p$ qpoe files (n = number of OBIs; p = number of phase bins). The position of the centroid of the reference source is determined and each file is shifted in x and y so as to align the centroids from all OBIs and all phase bins. The data are then co-added or stacked to realize the final image (qpoe file).

4.2. Stable roll angle intervals

For sources weaker than 0.1 counts/s, it is normally the case that there are not enough counts for centroiding when 10 phase bins are used. If it is determined that there are no noticeable shifts between OBIs, then it is possible to use many OBIs together so long as the roll angle does not change by a degree or more.

4.3. Method for visual inspection

On rare occasions, it may be useful to examine each phase bin visually to evaluate the segments in order to decide if some should be deleted before restacking for the final result. We have found it useful to do this via contour diagrams of the source. This approach can be labor intensive if there are a large number of OBIs and phase bins but scripts we provide do most of the manipulations.

5. MIDAS/EXSAS implementation

The X-ray group at the Astrophysical Institute Potsdam (AIP) has developed some MIDAS/EXSAS routines to correct for the ROSAT wobble effect. The routines can be obtained by anonymous ftp from ftp.aip.de at directory pub/users/rra/wobble. The correction procedure works interactively in five main steps:

- Choosing of a constant roll angle interval.
- Folding the data over the 402 s wobble period.
- Creation of images using 5 or 10 phase intervals.
- Determining the centroid for the phase resolved images.
- Shifting the photon X/Y positions in the events table.

We have tested the wobble correction procedures for 21 stars and 24 galaxies of the ROSAT Bright Survey using archival HRI data. The procedures work successfully down to an HRI source count rate of about 0.1 counts/s. In the case of lower count rates the determination of the centroid position failed because of the few photons available in the phase-binned images. The number of phase bins which can be used is of course dependent on the X-ray brightness of the source.

6. Limitations

We briefly describe the effects which limit the general use of the method. In so doing, we also indicate the process one can use in deciding if there is a problem, and estimating the chances of substantial improvement.

6.1. Presence of aspect smearing

The $FWHM$ of all sources in the field should be $\geq 7''$ (after smoothing with a $3''$ Gaussian). If any source is smaller than this value, it is likely that aspect problems are minimal and little is to be gained by applying the dewobbling method.

If there is only a single source in the field, without a priori knowledge or further analysis it is difficult to determine whether a distribution significantly larger than the ideal PRF is caused by source structure or aspect smearing. The best approach in this case is to examine

Table 1. ROSAT clock resets

Year	Day
90	151.87975 (launch)
91	25.386331
92	42.353305
93	18.705978
94	19.631352
95	18.169322
96	28.489871
97	16.069990
98	19.445738

the image for each OBI separately to see if some or all are smaller than the total image (i.e. OBI aspect solutions are different).

6.2. Wobble phase

It is important that the phase of the wobble is maintained. This is ensured if there is no "reset" of the space craft clock during an observation. If an observation has a begin and end time/date that includes a reset, it will be necessary to divide the data into two segments with a time filter before proceeding to the main analysis. Dates of clock resets (Table 1) are provided by MPE: http://www.ROSAT.mpe-garching.mpg.de/~prp/timcor.html.

6.3. Characteristics of the reference source

In most cases, the reference source (i.e. the source used for centroiding) will be the same as the target source, but this is not required. Ideally, the reference source should be unresolved in the absence of aspect errors and it should not be embedded in high brightness diffuse emission (e.g. the core of M 87 does not work because of the bright emission from the Virgo Cluster gas). Both of these considerations are important for the operation of the centroiding algorithm, but neither is an absolute imperative. For accurate centroiding, the reference source needs to stand well above any extended component.

Obviously the prime concern is that there be enough counts in a phase bin to successfully measure the centroid. The last item is usually the determining factor, and as a rule of thumb, it is possible to use 10 phase bins on a source of 0.1 counts/s. We have tested a strong source to see the effect of increasing the number of phase bins. In Fig. 1, we show the results of several runs on an observation of HZ 43 (12 counts/s). This figure demonstrates that ten phase bins is a reasonable choice, but that there is little to be gained by using more than 20 phase bins.
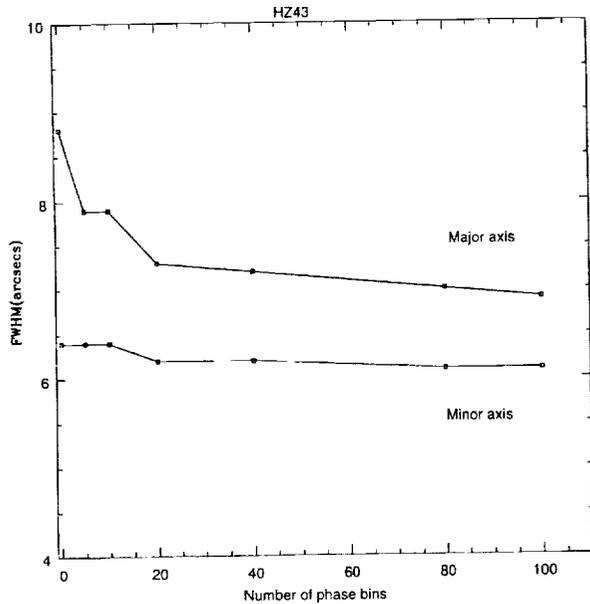
Fig. 1. The $FWHM$ of a HZ43 (observation number rh142545) observation was measured for multiple dewobble runs while increasing the number of phase bins
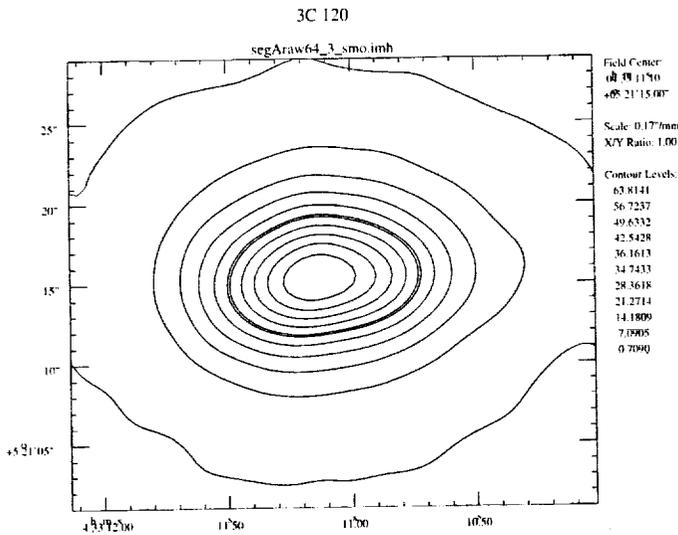
Fig. 2. The original data for 3C 120 (segment A, rh702080n00), smoothed with a Gaussian of $FWHM = 3''$. The peak value on the map is 70.9 counts per $0.5''$ pixel. Contour levels are 1, 10, 20, 30, ... 90% of the peak value, with the 50% contour, doubled. The nominal roll angle is $-167°$ and the wobble direction is at PA $= 122°$. The $FWHM$ of this smoothed image is $11.6'' \times 7.4''$
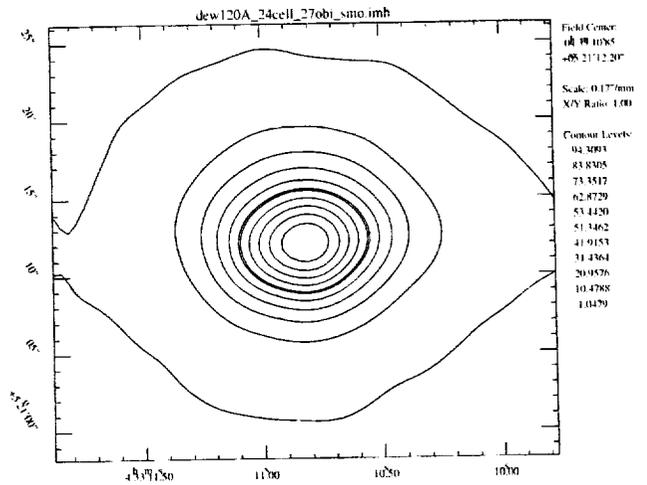
Fig. 3. The results after dewobbling 3C 120A, smoothed with a Gaussian of $FWHM = 3''$. The peak value on the map is now 104.8 counts per $0.5''$ pixel. Contour levels are 1, 10, 20, 30, ... 90% of the peak value, with the 50% contour, doubled. The $FWHM$ of this smoothed image is $8.1'' \times 6.7''$

7. Examples

7.1. 3C 120

3C 120 is a nearby radio galaxy ($z = 0.033$) with a prominent radio jet leaving the core at PA $\approx 270°$. The ROSAT HRI observation was obtained in two segments, each of which had aspect problems. Since the average source count rate is 0.8 count/s, the X-ray emission is known to be highly variable (and therefore most of its flux must be unresolved), and each segment consisted of many OBIs, we used these observations for testing the dewobbling scripts.

7.1.1. Segment A: Two aspect solutions, both found multiple times

The smoothed data (Fig. 2) indicated that in addition to the X-ray core, a second component was present, perhaps associated with the bright radio knot $4''$ west of the core. When analyzing these two components for variability, it was demonstrated that most of the emission was unresolved, but that the aspect solution had at least two different solutions, and that the change from one to the other usually coincided with OBI boundaries. The guide star configuration table showed that a reacquisition coincided with the change of solution.

The 24 OBIs comprising the 36.5 ksec exposure were obtained between 96Aug16 and 96Sep12. Because 3C 120 is close to the ecliptic, the roll angle hardly changed, and our first attempts at dewobbling divided the data into 2 "stable roll angle intervals". This effort made no noticeable improvement.
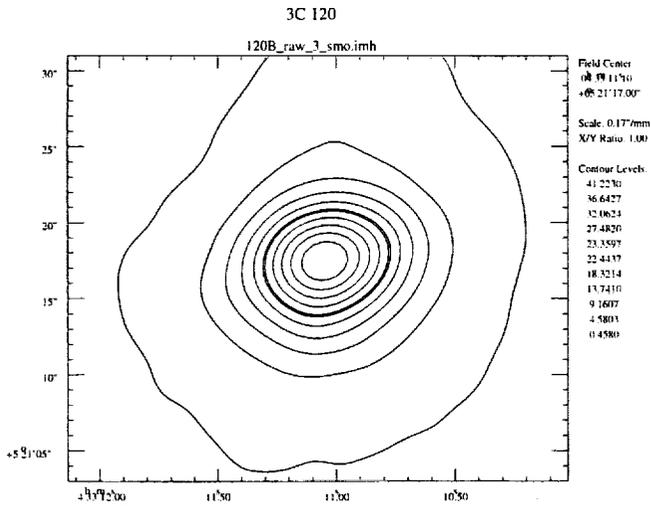
Fig. 4. The original data of 3C 120 (segment B, rh702080a01), smoothed with a Gaussian of $FWHM = 3''$. The peak value on the map is 45.8 counts per $0.5''$ pixel. The contour levels are the same percentage values as those of Fig. 2. The roll angle is 8° and the wobble PA is 127°. $FWHM$ for this image is $8.0'' \times 6.7''$
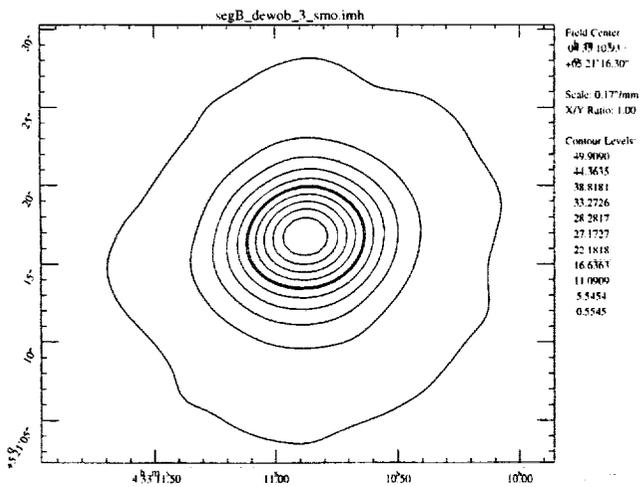
Fig. 5. The results of 3C 120 (segment B) after dewobbling. The contour levels are the same percentage values as those of Fig. 4, but the peak is now 55.4. The $FWHM$ is $7.2'' \times 6.5''$

We then used the method described in Sect. 4.1. The results are shown in Fig. 3. It can be seen that a marked improvement has occurred, but some of the E-W smearing remains.

7.1.2. Segment B: A single displaced OBI

The second segment of the 3C 120 observation was obtained in 1997 March. In this case, only one OBI out of
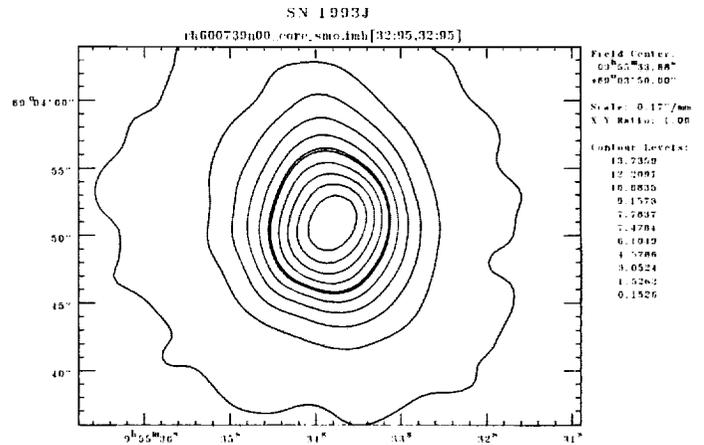
Fig. 6. The original M 81 data (rh600739), smoothed with a Gaussian of $FWHM = 3''$. The peak value on the map is 15.3 counts per $0.5''$ pixel. The contour levels are 1, 10, 20, 30, 40, 50 (the 50% contour, doubled), 60, 70, 80, and 90 percent of the peak value. The nominal roll angle is 135° and the wobble direction is 0°. The $FWHM$ of this smoothed image is $10.4'' \times 7.5''$

17 was displaced. It was positioned $10''$ to the north of the other positions, producing a low level extension (see Fig. 4). After dewobbling, that feature is gone, the half power size is reduced, and the peak value is larger (Fig. 5).

7.2. M 81

M 81 is dominated by an unresolved nuclear source. The count rate is 0.31 count/s. The observation has 14 OBIs for a total exposure of 19.9 ks. Figure 6 shows the data from SASS processing. After running the "OBI by OBI" method, the source is more circularly symmetric, has a higher peak value, and a smaller $FWHM$ (Fig. 7).

7.3. NGC 5548

This source was observed from 25 June to 11 July 1995 for a livetime of 53 ks with 33 OBIs. The average count rate was 0.75 counts/s and the original data had a $FWHM = 8.2'' \times 6.8''$. Most of the OBIs appeared to have a normal PRF but a few displayed high distortion. After applying the OBI by OBI method, the resulting $FWHM$ was $6.3''$ in both directions and the peak value on the smoothed map increased from 138 to 183 counts per $0.5''$ pixel.

7.4. RZ Eri

The observation of this star was reduced in MIDAS/EXSAS. The source has a count rate of 0.12 count/s. The reduction selected only a group of
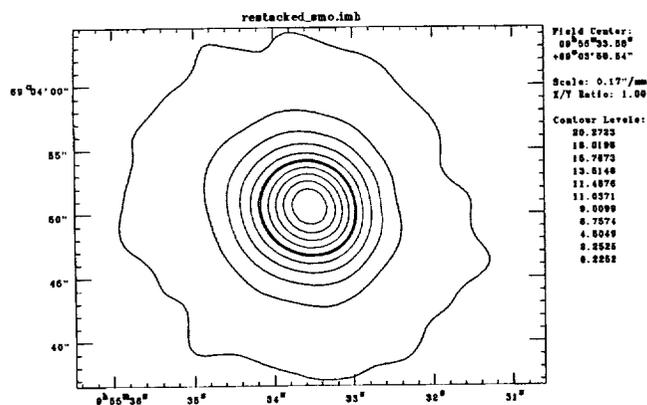
Fig. 7. The results after dewobbling of M 81 smoothed with a Gaussian of $FWHM = 3''$. The peak value on the map is 22.5 counts per $0.5''$ pixel. The contour levels are 1, 10, 20, 30, 40, 50 (the 50% contour, doubled), 60, 70, 80, and 90 percent of the peak value. Ten phase bins have been used. The $FWHM$ of this smoothed image is $7.2'' \times 6.5''$

the OBIs which comprised a "stable roll angle interval"; almost half the data were rejected. The original smoothed image had a $FWHM = 8.4'' \times 6.6''$. After dewobbling, the resulting $FWHM$ was $6.9'' \times 5.8''$.

8. Summary

We have developed a method of improving the spatial quality of ROSAT HRI data which suffer from two sorts of aspect problems. This approach requires the presence of a source near the field center which has a count rate of ≈ 0.1 counts/s or greater. Although the method does not fix all bad aspect problems, it produces marked improvements in many cases.

Note added in proof. The "displaced OBI" example of 3C 120 appears to be caused by a bad boresight file since a recent reprocessed image does not have this problem. However, the original data still serve as a valid example.

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