THE CHANDRA SURVEY OF THE COSMOS FIELD. II. SOURCE DETECTION AND PHOTOMETRY

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ABSTRACT

The Chandra COSMOS Survey (C-COSMOS) is a large, 1.8 Ms, Chandra program that covers the central contiguous ~0.92 deg² of the COSMOS field. C-COSMOS is the result of a complex tiling, with every position being observed in up to six overlapping pointings (four overlapping pointings in most of the central ~0.45 deg² area with the best exposure, and two overlapping pointings in most of the surrounding area, covering an additional ~0.47 deg²). Therefore, the full exploitation of the C-COSMOS data requires a dedicated and accurate analysis focused on three main issues: (1) maximizing the sensitivity when the point-spread function (PSF) changes strongly among different observations of the same source (from ~1 arcsec up to ~10 arcsec half-power radius); (2) resolving close pairs; and (3) obtaining the best source localization and count rate. We present here our treatment of four key analysis items: source detection, localization, photometry, and survey sensitivity. Our final procedure consists of a two step procedure: (1) a wavelet detection algorithm to find source candidates and (2) a maximum likelihood PSF fitting algorithm to evaluate the source count rates and the probability that each source candidate is a fluctuation of the background. We discuss the main characteristics of this procedure, which was the result of detailed comparisons between different detection algorithms and photometry tools, calibrated with extensive and dedicated simulations.

Key words: methods: data analysis – surveys – X-rays: general

Online-only material: color figures

1. INTRODUCTION

It is well known that X-ray surveys are an extremely efficient tool for selecting active galactic nuclei (AGNs), for example, in the XMM-Newton COSMOS survey, at the 0.5–2 keV limiting flux of 7 × 10⁻¹⁶ erg s⁻¹ cm⁻², the AGN surface density is ~1000 deg⁻² (Hasinger et al. 2007; Cappelluti et al. 2007), a factor of 2–4 greater than the AGN surface density in the most recent deep optical surveys, 250 deg⁻² in the COMBO-17 (Wolf et al. 2003), and 470 deg⁻² in VVDS Survey (Gavignaud et al. 2006). There are four main causes for the higher efficiency of X-ray surveys in finding AGNs: (1) X-rays directly trace the supermassive black hole (SMBH) accretion, while AGN classification through optical line spectroscopy may suffer incompleteness and/or misidentifications; (2) AGNs are the dominant X-ray population. In fact, most (~80%) of the X-ray sources in deep and shallow surveys turn out to be AGNs, unlike at optical wavelengths; (3) 0.5–10 keV X-rays (the typical Chandra and XMM-Newton energy band) are capable of penetrating column densities up to ~10²⁴ cm⁻², allowing the selection of moderately obscured AGNs; and (4) low-luminosity AGNs are difficult to select in optical surveys, because their light is diluted in the host-galaxy emission.

So far, Chandra and XMM-Newton have performed several deep, pencil beam, and shallower but wider surveys. Figure 1 compares the flux limit and area coverage of the main Chandra and XMM-Newton surveys. This figure shows that XMM-COSMOS and Chandra-COSMOS (C-COSMOS; Elvis et al. 2009, Paper I hereafter) surveys are the deepest surveys on large contiguous area. The coverage of larger areas at similar flux limits is today achieved only by serendipitous surveys using mostly non-contiguous areas (see, e.g., CHAMP; Kim et al. 2004a, 2004b; Green et al. 2004).

The Cosmic evolution survey (COSMOS; Scoville et al. 2007) is aimed at studying the interplay between the large-scale structure (LSS) in the universe and the formation of galaxies, dark matter, and the AGN. The COSMOS field is located near the equator (10h, 20° deg² as originally defined by the Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) imaging (Koekemoer et al. 2007), with subsequent deep and extended multi-wavelength coverage overlapping this area. The size of COSMOS was chosen to sample LSS up to a linear size of about 50 Mpc/h at z ~ 1–2, where AGN and star formation in galaxies are expected to peak. To study the role of the AGN in galaxy evolution the X-ray data are fundamental. Therefore, the central square degree of the COSMOS field has been the target of a Chandra ACIS-I 1.8 Ms Very Large Program: the C-COSMOS survey.
The C-COSMOS survey has a rather uniform effective exposure of ~160 ks over a large area (~0.45 deg²), thus reaching ~3.5 times fainter fluxes than XMM-COSMOS in both 0.5–2 keV band and 2–7 keV band. This flux limit is below the threshold where starburst galaxies become common in X-rays. The sharp Chandra point-spread function (PSF) allows nearly unambiguous identification of optical counterparts (F. Civano et al. 2009, in preparation, hereafter Paper III). Chandra secures the identifications of X-ray sources down to faint optical magnitude (i.e., I ~ 26), with only ~2% ambiguous identifications, significantly better than the ~20% ambiguous identifications in XMM-Newton (Brusa et al. 2007).

The C-COSMOS survey has a complex tiling (see Figure 2) compared with other X-ray surveys, in which the overlapping areas of the single pointings are small and with similar PSFs (see, e.g., the Extended Groth-Streep, AEGIS-X; Laird et al. 2009), or all the pointings are co-axial and nearly totally overlapping (see, e.g., CDFS; Giacconi et al. 2001; Luo et al. 2008). In the C-COSMOS tiling, the pointings are strongly overlapping and non-ccoasial. While this ensures a very uniform sensitivity over most of the field, each source is observed with up to six different PSFs, requiring the development of an analysis procedure for data observed with this mixture of PSF. The procedures presented in this paper are aimed at optimizing (1) source detection, (2) localization, (3) photometry, and (4) survey sensitivity. We have made detailed comparisons between different detection algorithms and photometry tools, testing them extensively on simulated data. We furthermore validate our results by detailed inspections of each single source candidate.

Our final analysis consists of two main steps:

1. A wavelet detection algorithm, PWDetect (Damiani et al. 1997), is first used to find source candidates. This algorithm is optimized to cleanly separate nearby sources, to detect point-like sources on top of extended emission, and to give the most accurate positions.
2. A maximum likelihood PSF fitting algorithm is then used to evaluate the source count rates and the probability that each source candidate is not a fluctuation of the background. We used the emldetect algorithm (Cappelluti et al. 2007, and references therein). emldetect works simultaneously with multiple overlapping pointings using PSFs appropriate to each one. This fitting method ensures accurate evaluation of the survey completeness and contamination, efficient deblending, and good photometry for close pairs, which may be partly blended even at the Chandra resolution.

As a third step, we also performed aperture photometry for each candidate X-ray source using 50%, 90%, and 95% encircled count fractions, using the PSFs appropriate to each observation. The aperture photometry is also used to check the results. Aperture photometry is preferable in all cases where the systematic errors introduced by PSF fitting are larger than the statistical errors, i.e., for bright sources (count rates ≥ 0.5 counts ks⁻¹).

The survey sensitivity is limited by both the net (i.e., including vignetting) exposure time, and by the actual PSF with which a given region of the area is observed. The latter issue is particularly relevant for the C-COSMOS tiling. We have developed an algorithm that evaluates the survey sensitivity at each position on C-COSMOS using a parameterization of the
Figure 3. Image of the same source (i.e., source-id 50 in the C-COSMOS catalog presented in Paper I) observed in four overlapping fields at different off-axis angles. The contours are drawn at 90%, 50%, 25%, and 10% of the peak counts. The red circles centered on the position of the source have a radius of 2 arcsec.

(A color version of this figure is available in the online journal.)

2. OBSERVATIONS AND DATA REDUCTION

We give here a brief description of the observations and data reduction. The full details are given in Paper I. The C-COSMOS field covers a contiguous area of \( \sim 0.92 \) deg\(^2\), centered at \( 10^h 00^m 18.91 + 02^\circ 10' 33'34'\), near the center of the full COSMOS field. The survey is made up of 36 different heavily overlapping ACIS-I pointings, each with a mean exposure of \( \sim 50 \) ks, for a total exposure of 1.8 Ms. Twelve of the 36 pointings were scheduled as two or more separate observations, with very similar roll angles, thus resulting in 49 observations in total. Figure 2 shows the number of ACIS-I pointings per pixel. Note that the central \( \sim 0.45 \) deg\(^2\) area is covered by four to six overlapping pointings, while most of the outer \( \sim 0.47 \) deg\(^2\) area is covered by one to two overlapping pointings. As an example, Figure 3 shows the image of the same source observed in four overlapping fields at different off-axis angles.

The 49 observations were processed using the standard CIAO 3.4 software tools\(^{14}\) (Fruscione et al. 2006). Event files were cleaned of bad pixels, soft proton flares, and cosmic-ray afterglows, and were brought to a common reference frame by matching the positions of bright X-ray sources with the optical position of bright \( 18 < I < 23 \) point-like optical counterparts. The systematic shifts between the X-ray and optical positions are \( \Delta \text{R.A.} = 0'04 \) and \( \Delta \text{decl.} = 0'25 \) (see Paper I). Observations with the same aim points and consistent roll angles were merged together, producing 36 event files, one for each independent pointing.

\(^{14}\) http://cxc.harvard.edu/ciao/
The flux limits for source detection are influenced by three main factors: (1) net exposure time, (2) background per pixel, and (3) size of the source extraction region, which in turn depends on the size of the PSF at the given position. The Chandra ACIS-I on-axis PSF has a spatial resolution of 0.5 FWHM, equivalent to \(<4–4.5\) kpc at any redshift, and permits observations of up to \(\sim\)Ms to be photon limited. The adopted tiling produces a rather homogeneous exposure time over the C-COSMOS field (i.e., \(\pm 12\%\) in the central \(~0.45\) deg\(^2\) area) and a uniform background. In the vignetting-corrected exposure time, we clearly distinguish two main peaks at 80 and 160 ks (see Figure 7 of Paper I). Figure 4 shows the fraction of the C-COSMOS area with a given background per square arcsec in the three analyzed energy bands: 0.5–7 keV (full band, F), 0.5–2 keV (soft band, S), and 2–7 keV (hard band, H). We see two main peaks at 0.07 and 0.14 counts arcsec\(^{-2}\) in the F band and at 0.02 and 0.04 in the S band, corresponding to the two main peaks of the exposure time distribution. These peaks correspond to a level of \(\sim\)2 and \(\sim\)4 counts in the F band, and \(\sim\)0.6 and \(\sim\)1.2 counts in the S band over an area of 3 arcsec radius, a typical source detection region for off-axis angles less than 5–6 arcmin. Even the area with the largest exposure time has therefore relatively low background for point-source detection; this is important for the detection of the faintest sources.

3. GENERATION OF SIMULATED DATA

Extensive simulations were performed in order to test various source detection schemes. The simulations were used (1) to test the reliability of the source position reconstruction, (2) to verify the count rate reconstruction, and (3) to assess and validate the level of significance of each detected source at each given detection threshold and thus to evaluate the level of completeness of the source list as a function of flux.

3.1. Creating the Simulated Input Source Catalog

In order to include realistic source clustering into the simulated data, we sampled particles from a COSMOS Mock galaxy catalog (V3.0) derived by Kitzbichler & White (2008). They made use of the Millennium Simulation (Springel et al. 2005), a very large simulation that follows the hierarchical growth of dark matter structures from redshift \(z=127\) to the present. The simulation assumes the concordance \(\Lambda\) CDM cosmology and follows the trajectories of \(\sim 10^{10}\) particles in a periodic box 500 \(h^{-1}\) Mpc on a side, using a special reduced-memory version of the GADGET-2 code (Springel et al. 2001; Springel 2005). The formation and evolution of the galaxy population is simulated by using a semi-analytical model (Croton et al. 2006; De Lucia & Blaizot 2007). We randomly selected 10,000 mock galaxies per square degree in the ad hoc redshift range \(0.4 < z < 0.9\) and the \(i\) band magnitude range 17 < \(i\) < 26. The selected random sources in this redshift-magnitude range show the same angular correlation function (ACF) as the S band XMM-COSMOS sources (Miyaji et al. 2007), as shown in Figure 5, not taking into account that the clustering strength could depend on the survey flux limit (Plionis et al. 2008). The agreement between the ACF of the random sample and the XMM-COSMOS sample is good down to the 0.5 arcmin scale. Below 0.5 arcmin, the uncertainties in the ACF from literature (see, e.g., the Chandra Deep Field South; D’Elia et al. 2004) are too large to allow them to be sensibly compared with the one we derive. Each simulated galaxy was then assigned an S-band flux, randomly drawn from the number weighted log \(N\) – log \(S\) relation of the AGN population synthesis model by Gilli et al. (2007). The corresponding minimum S-band flux for the input particles was \(\sim 3 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\), which is a factor 100 below the detection limit of C-COSMOS. Hence, background fluctuations due to unresolved faint sources are included in the simulations.
The S-band flux of each source was then converted into an F-band flux assuming a power-law spectrum with an energy index of $\alpha_E = 0.4$.\(^{15}\) The simulated sources cover a 3 deg$^2$ sky area, which is enough to completely enclose the COSMOS field.

### 3.2. Creating the Simulated X-ray Event Files

Using the MARX simulator\(^{16}\) (version 4.2.1), we simulated a set of 49 *Chandra* ACIS-I pointings with the same exposure times, aim points, and roll angles as the real C-COSMOS pointings (see Paper I). The simulated source list was fed into each simulated pointing and net source counts $F$ recorded. This procedure returns 49 *Chandra* event files containing only source photons.

To include a background appropriate to each pointing, we used the *Chandra* X-ray Center (CXC) compilation of blank sky fields.\(^{17}\) These blank fields lie at high Galactic latitude, away from soft bright features such as the North Polar Spur, and have a median exposure of $\sim$70 ks. Point-like and extended sources down to fluxes that would be detectable in each exposure have been excluded, and the individual exposures have been stacked into different blank sky files. We chose the stacked blank sky file appropriate for ACIS-I data at the epoch of our observations,\(^{18}\) filtered to keep only photons detected in VFAINT mode observations. This blank sky field has a total effective exposure of $\sim$1.5 Ms.

We then extracted 49 background event files by randomly resampling the events out of the blank sky field scaling by the exposure time of each observation. Faint simulated sources with only a few counts would not be detected and increase the background level by $\sim$5% at the depth of the blank sky observations. Since these faint, unresolved sources are already included in the blank sky files, in order to avoid counting them twice, we removed 5% of the photons in each background event file.

The background files were then reprojected to the coordinates of the real pointings by using the real aspect solution files, and then combined with the corresponding source event files. The final result is a set of 49 simulated ACIS-I fields that closely mirror the actual 49 observations.

### 4. CHOOSING THE C-COSMOS SOURCE DETECTION AND CHARACTERIZATION PROCEDURE

In order to fully exploit the large and deep C-COSMOS coverage, particular care had to be devoted to maximize areal coverage and produce uniform depth; C-COSMOS used a complex tiling, with four overlapping pointings in most of the central $\sim$0.45 deg$^2$ area with the best exposure, and two overlapping fields in most of the surrounding area, covering additional $\sim$0.47 deg$^2$ (see Figure 2). As a result, each source is observed at different off-axis angles, $\theta_i$ (i.e., the distance of the source position from the aim point in all overlapping fields), and thus with different PSFs. For some sources in the central area, the number of different $\theta_i$ is as high as six. This mixture of PSFs requires addressing three main issues: (1) maximizing the sensitivity when the PSF changes so widely between different observations of the same source (from $\sim$1 arcsec to $\sim$10 arcsec half-power radius); (2) maximizing the spatial resolution aimed at obtaining the best source localization and the effective deblending; and (3) obtaining accurate photometry, even in cases of partly blended sources. To solve these issues, a dedicated analysis procedure was developed, and the simulations were used to determine and validate it.

We tested sliding cell and wavelet algorithms to find and locate source candidates and both PSF fitting and aperture photometry. In particular, we compared the results obtained using the SAS *eboxdetect*\(^{19}\) and *emldetect*\(^{20}\) tasks, used for the XMM-COSMOS survey (Cappelluti et al. 2009), with those obtained using the *PWDetect* code (Damiani et al. 1997) and CIAO *wavdetect*\(^{21}\) (Freeman et al. 2002). We compared *PWDetect* and CIAO *wavdetect* on a data subset including eight ACIS-I fields and found consistent results. We adopt the *PWDetect* as the main wavelet algorithm because of its much faster processing time (i.e., factor of 40–50) with respect to the CIAO *wavdetect*.

#### 4.1. PWDetect

The *PWDetect* code (Damiani et al. 1997) was originally developed for the analysis of ROSAT data, and was then adapted for the analysis of *Chandra* and XMM-Newton data. This method is particularly well suited for cases in which the PSF varies across the image, as for *Chandra* images, since *PWDetect* is based on the wavelet transform (WT) of the X-ray image, i.e., a convolution of the image with a “generating wavelet” kernel, which depends on position and length scale, that is a free parameter. For the *Chandra* data, the length scale is varied from 0.35 to 16" in steps of $\sqrt{2}$. This choice spans the range from the smallest to the largest (for large $\theta_i$) *Chandra* PSFs. Both radial and azimuthal PSF variations are accounted for by *PWDetect*, which first assumes a Gaussian PSF and then corrects for PSF shape factor, calibrated on both radial and azimuthal coordinates. *PWDetect* was run on each of the 36 event files with a low significance level of $\sim$10$^{-3}$ to have entries with just five source counts (i.e., to pick up most of the input sources). The catalogs of source candidates from overlapping fields were then merged. The off-axis angle $\theta_i$ is recorded, and the source position measured at the smallest $\theta_i$ (i.e., with the best PSF) is adopted as the reported source position. If a candidate is not detected in one or more of the overlapping fields, the count rate is computed at the position of the source candidate and within a circle of radius $R_i$, corresponding to 90% of the encircled count fraction of the PSF at $\theta_i$. As calibrated by the CXC.\(^{23}\) Finally, a mean count rate that is weighted by the count rate errors, is associated at each source. Analysis of the simulated data showed that all candidates with a wavelet size smaller than the PSF size and less than five counts are spurious detections. These were then excluded from the candidate catalogs.

#### 4.2. eboxdetect and emldetect

Both *eboxdetect* and *emldetect* are part of the XMM-Newton SAS package and are based on programs originally developed for the detection in ROSAT images (see, e.g., Voges et al. 1999). *eboxdetect* is a standard sliding cell detection tool, which is run on each of the 49 single observations. *eboxdetect* produces a list

\(^{15}\) $f_E \propto E^{-\Gamma}$, with $\Gamma = \alpha_E + 1$.

\(^{16}\) http://space.mit.edu/CXC/MARX/

\(^{17}\) http://cxc.harvard.edu/contrib/maxim/acisbg/

\(^{18}\) http://cxc.harvard.edu/contrib/maxim/acisbg/data/, version file = acisi_D_01236_bg_evt_010205.fits

\(^{19}\) http://xmm.esac.esa.int/sas/current/doc/eboxdetect/index.html

\(^{20}\) http://xmm.esac.esa.int/sas/current/doc/emldetect/index.html

\(^{21}\) http://asc.harvard.edu/ciao/ahelp/wavdetect.html

\(^{22}\) $f_{\text{tot}}$ indicates a fraction of the source counts distributed in a circular area, following the PSF shape.

\(^{23}\) http://cxc.harvard.edu/caldb/
of candidate sources down to a selected low significance level. The list of source candidates is then passed to the emldetect task. emldetect performs a simultaneous maximum likelihood PSF fitting for each candidate to all the images at each position (see, e.g., Cappelluti et al. 2007 for more details on eboxdetect and emldetect). eboxdetect was run setting a low significance level (DET_ML = 3 or $P_{\text{random}} = 0.05$), to provide a list of source candidates to emldetect that recognizes all possible significant sources.

emldetect has been adapted to run on Chandra data by replacing the XMM-Newton PSF library with the Chandra PSF library (see footnote 23), and to work with many different PSFs simultaneously. The counts at each position were fitted using a model obtained by convolving the PSF at that position with a β model (Crudace et al. 1988). The program interpolates over the calibration library of Chandra PSFs to find the most appropriate PSF at the position of each source in each observation. The more crowded the field, the more candidates are fitted simultaneously. emldetect can provide either both source positions and source count rates, or only source count rates using fixed source positions. We ran it fitting for both source positions and count rates. The best-fit maximum likelihood, DET_ML, is related to the Poisson probability that a source candidate is a random fluctuation of the background ($P_{\text{random}}$):

$$\text{DET}_\text{ML} = -\ln(P_{\text{random}}).$$

Sources with low values of DET_ML, and correspondingly high values of $P_{\text{random}}$, are then likely to be background fluctuations.

4.3. Tests on Simulations

We ran both detection algorithms on the simulated data. Catalogs of candidates were produced with both eboxdetect and PWDetect. These lists were visually inspected to identify obviously spurious detections on the wings of the Chandra PSF around bright sources, and near the edges of the ACIS-I chips. For both detection algorithms, the number of these clearly spurious detections is rather small in all three bands ($<1\%$–$2\%$). These entries were deleted, and the “cleaned” lists used as input for the emldetect tool. The emldetect output catalog was then cut at a conservative value of $\text{DET}_\text{ML} = 12 (P_{\text{random}} < 6 \times 10^{-6})$ to ensure that the number of spurious detections in this catalog is practically zero, so that the results are not contaminated by spurious associations.

Matched catalogs between the input simulated catalog and the emldetect and PWDetect output catalogs were produced using two methods: (1) a conservative approach, using a fixed matching radius of 0.5 arcsec. This produces matched catalogs that probably miss a fraction of real associations, but are virtually free from spurious associations. (2) A maximum likelihood algorithm, to find the most probable association between an input source and an output detected source. We used the catalogs produced using the first method to study the accuracy of source localization and flux reconstruction, while we used the catalogs produced by the second method to study the completeness and reliability of the detection algorithms (see Section 5).

Table 1 summarizes the comparison of the results of the application of eboxdetect+emldetect and PWDetect on simulated data.

| Table 1 | Comparison Between eboxdetect+emldetect and PWDetect |
|----------|--------------------------------------------------|
| Parameter | eboxdetect + emldetect | PWDetect |
| (1) | (2) | (3) |
| **Comparison on Source Position** | | | |
| $|\Delta R.A.|^a$ | 0.17 ± 0.16 | 0.02 ± 0.15 |
| $|\Delta \text{decl.}|^a$ | −0.18 ± 0.15 | 0.003 ± 0.15 |
| $\Delta R.A. \text{ rms}^b$ | 0.32 | 0.31 |
| $\Delta \text{decl. rms}^b$ | 0.35 | 0.34 |
| **Comparison on completeness of close pairs** | | | |
| % of missed pairs$^c$ | ~75% | | |
| **Comparison on source photometry** | | | |
| $\frac{F_{\text{F}}(\text{FW})}{F_{\text{H}}(\text{FW})}$ | 0.97 ± 0.11 | 0.86 ± 0.12 |
| $\frac{F_{\text{F}}(\text{SB})}{F_{\text{H}}(\text{SB})}$ | 1.00 ± 0.12 | 0.94 ± 0.14 |
| $\frac{F_{\text{F}}(\text{DS})}{F_{\text{H}}(\text{DS})}$ | 1.05 ± 0.16 | 0.88 ± 0.17 |

**Notes.** Column (1) shows the parameters used to test the accuracy of source localization, the completeness in the recovery of close pairs, and the flux reconstruction of the two detection algorithms, which we used. Columns (2) and (3) show the results for the eboxdetect+emldetect and the PWDetect algorithm, respectively.

$^a$ The median and interquartile of the shifts between the R.A. or decl. of the input sources and the R.A. or decl. of the detected sources. See also Figure 6.

$^b$ The rms of the R.A. or decl. shifts between input and detected positions. See also Figure 6.

$^c$ Percentage of the pairs with a separation smaller than 4 arcsec that are missed in comparison to PWDetect. See also Figure 6.

$^d$ The median and interquartile of the ratio between the output detected and input simulated count rates in the F, S, and H bands. See also Figure 8.

are similar for the two detection algorithms; however, we find a small systematic median shift between input and detected R.A. and decl. (see also Figure 6) using emldetect. We conclude that PWDetect provides positions of higher quality.

As a second step, we focused on the ability of the detection algorithms to separate close pairs of sources in Chandra data, comparing the numbers of pairs found by emldetect and PWDetect (see Figure 7 and Table 1). The two algorithms are equivalent for large (>4") separations, but there is a deficiency in the number of pairs recovered by emldetect at small (<4") separations. We verified that all the ~75% of the pairs with a separation smaller than 4 arcsec missed by emldetect are in the input source list, and not spuriously created by the splitting of a single source. Analysis of the eboxdetect candidate list and emldetect final list shows that the majority (>70%) of these pairs are missed in the emldetect step, where the program finds a best fit including one significant source only, while the second falls below the detection threshold. We conclude that PWDetect is more efficient than emldetect at resolving close pairs with separations <4" and greater than ~1"8.

Finally, we compared the emldetect and PWDetect best-fit count rates with the input count rates in the F, S, and H bands (see Figure 8 and Table 1). The PWDetect reconstructed count rates were systematically smaller than the input count rates by 10%–20%. A similar problem was found by Puccetti et al. (2006) using a similar detection algorithm on XMM-Newton data. PWDetect reconstructs much better count rates in all the bands.

The accuracy of the count rate reconstruction of the emldetect algorithm is also good at all count rates, without any large systematic shifts, both at low count rates and at high count rates (see the left panel of Figure 9). The right panel of Figure 9 shows the difference between the emldetect count rate and the...
input simulated count rate divided by the \textit{emldetect} error on the count rate as a function of the \textit{emldetect} count rate. We see that the distribution is approximately centered around zero for count rates smaller than \(\sim 0.5\) counts ks\(^{-1}\), but becomes positive for larger count rates. This suggests that at high count rates, there is a non-negligible systematic error in the \textit{emldetect} count rate determination due to the uncertainties in the PSF model becoming comparable to, or higher than, the statistical error. For this reason we also performed aperture photometry (see Section 6.4), which should be free from this systematic error.

\subsection*{4.3.1. Error on the Positions}

The source positional error is proportional to the PSF at the position of the source, and inversely proportional to the square root of the source number counts. We evaluated the errors on the positions by dividing the PSFradius by (1) the square root of the total source plus background counts \((T; \text{PosError} = \text{PSFradius}/\sqrt{T})\) and (2) the square root of the net, background-subtracted, source counts \((C_s; \text{PosError} = \text{PSFradius}/\sqrt{C_s})\). We used different PSFradius, from 50\% to 90\% of the \(f_{\text{psf}}\) at the position of each source in the field where the source is detected at the smallest \(\theta_i\) (i.e., with the best PSF).

These errors were then compared with the deviations between the X-ray positions and input positions in the simulations. Method (2) gave the best match using a PSFradius corresponding to 50\% \(f_{\text{psf}}\) at the \(\theta_i\) of each source and the counts included.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{Left panel: shift between the input simulated source positions and the source positions by \textit{emldetect} using a matching radius of 2 arcsec (black solid dots). The solid black lines represent the zero shifts. The red circles have a radius of 0.5, 1, and 2 arcsec, respectively. Right panel: shift between the input simulated source positions and the source positions by \textit{PWDetect} using a matching radius of 2 arcsec (black solid dots). Symbols as in the left panel. (A color version of this figure is available in the online journal.)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7}
\caption{Top panel: number of pairs in the F band detected by \textit{PWDetect} (black empty histogram) and \textit{emldetect} (green solid histogram), as a function of the separation. Bottom panel: ratio between the difference between the number of pairs detected by \textit{PWDetect} and \textit{emldetect}, and the pairs detected by \textit{PWDetect} as a function of the separation. (A color version of this figure is available in the online journal.)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{\textit{PWDetect} (red dashed histogram) and \textit{emldetect} (solid black histogram) best-fit count rates over the input count rates in the F (left panel), S (center panel), and H (right panel) bands. The dotted vertical line corresponds to the exact match between the evaluated count rates and the input count rates. Note that the \textit{emldetect} count rates are in good agreement with the input count rates. (A color version of this figure is available in the online journal.)}
\end{figure}
in a circular region with the same radius. We used the \( f_{\text{psf}} - \theta_i \) calibration provided by CXC (see footnote 23). Larger PSF radii provided implausibly large position errors for bright sources. Including background counts (method 1) produces very small errors for faint sources, where the background is not negligible. For \( \sim 60 \) sources with more than \( \sim 120 \) counts, the errors on R.A. and decl. are formally smaller than 0.07 arcsec (i.e., errors on source position smaller than 0.1 arcsec). In these cases, the error in the source position was conservatively set to 0.1 arcsec to account for possible small systematic errors in the astrometric corrections (see Sections 2 and 4.3). Figure 10 shows the distribution of the ratio between the deviation between the \( \text{PWDetect} \) positions and input positions and the X-ray error on the position evaluated as in method (2). The distributions in the three detection bands are similar and peak at a value of \( \sim 0.7-0.8 \).

These distributions are compared with the expectation based on Gaussian statistics, which peaks at unity. This comparison shows that the assumed errors on the positions, although very small, are, on average, somewhat larger than the deviation between input positions and detected positions. However, to account for small systematic errors in the astrometric corrections, which are not included in the input positions though they certainly affect the observed data, we use in the following the conservative errors on the positions computed as described above.

4.4. The Final C-COSMOS Source Detection and Characterization Procedure

In summary, the comparison of the two methods \( \text{PWDetect} \) and \( \text{eboxdetect+emldetect} \) on the simulated C-COSMOS field shows that \( \text{PWDetect} \) is superior in separating closely spaced sources and in localizing sources, and relatively poor at photometry. Conversely, \( \text{emldetect} \) is poor at separating closely spaced sources, while it is good at estimating source reliability, completeness, and photometry. These results suggested the following source detection and characterization procedure:

1. \( \text{PWDetect} \) is run first with a low threshold to produce a catalog of source candidates with the best localization.

2. This catalog of source candidates is used as input for \( \text{emldetect} \), which performs a PSF fitting to find the best-fit maximum likelihood source count rate and the probability that each source candidate is a fluctuation of the background. In \( \text{emldetect} \), the coordinates used to fit each source are those provided by \( \text{PWDetect} \) for the most on-axis observation.

3. Aperture photometry is used to get good photometry for bright sources.

This combined approach allows us to obtain both the best possible position determination and reliable photometry for all sources.
5. COMPLETENESS AND RELIABILITY

The threshold for source detection must be set by balancing completeness (the fraction of true sources detected, i.e., ratio between the number of the detected sources and the number of input simulated sources) versus reliability (1 minus the fraction of spurious sources detected, i.e., 1 minus the ratio between the number of spurious sources and the number of input simulated sources). Our simulations allow us to choose a threshold which has a known completeness and reliability. The three panels of Figure 11 show the completeness in the F, S, and H bands as a function of the significance level for sources with at least 12 counts (solid lines) and 7 counts (dashed lines). The latter value refers to the counts of a typical source close to our flux limit, where we expect a rather large incompleteness. The former value (12 counts) ensures significantly higher completeness. Figure 11 also shows the reliability as a function of the significance levels for the same two cases. We chose a significance level of $2 \times 10^{-5}$ (or DET_ML = 10.8), which represents a reasonable compromise between high completeness and high reliability. Higher significance levels give higher completeness but lower reliability. At the chosen threshold, we have 87.5% and 68% (F band), 98.2% and 83% (S band), and 86% and 67% (H band) completeness for sources with at least 12 and 7 counts, respectively. At the same significance level and the same count limits, the reliability is $\sim 99.7\%$ for the three bands and both source count limits. This implies about 5, 4, and 3 spurious detections with $\geq 7$ counts in the F, S, and H bands, respectively, and 3, 4, and 3 spurious detections with $\geq 12$ counts in the same bands.

Figure 12 shows the completeness for a significance level of $2 \times 10^{-5}$ as a function of the flux for the F, S, and H bands. Table 2 gives the flux limits corresponding to four completeness fractions in the F, S, and H bands.

We have also evaluated the completeness of the method in the detection of close pairs. Figure 13 compares the number of pairs having one member with at least 7 and 12 counts in the simulated data with the detected number of pairs. The number of pairs in the simulated data has been corrected, dividing them by the square of the completeness expected at their count thresholds (87.5% for the pairs with at least 12 counts and 68% for the pairs with at least 7 counts). In fact, to correctly compare the number of pairs in the simulated data and the detected number of pairs, it is necessary to take into account that the detected number of pairs is not complete at the chosen significance level, and moreover, that each pair must be corrected for the completeness of both sources in pair, that is, the square of completeness. We see that at distances smaller than 5 arcsec, we miss between 50% and 70% of the pairs with at least 12 counts and between 70% and 80% of the pairs with more than 7 counts. The reason is that it is increasingly difficult to detect a faint (7 or 12 counts) source near a bright source because of the wings of the PSF of the latter. Indeed, all pairs recovered have a count ratio $< 3$, while about 40% of the input pairs have a count ratio $> 3$, none of which is detected in our analysis.

6. OBSERVED DATA: SOURCE DETECTION AND COUNT RATES

Source detection and characterization were performed on the real, observed event files using the approach described in...
Section 4.4. The three energy bands, F, S, and H, were used. The candidate catalogs produced by PWDetect, used as input for emldetect, were cut at a low threshold of $\sim 10^{-12}$, corresponding to 5 counts. The number of PWDetect source candidates in each of the three bands was between 2500 and 3500. These lists were visually cleaned to identify obviously spurious detections on the wings of the Chandra PSF around bright sources and near the edges of the ACIS-I chips, following the same procedure adopted for the simulated data (see Section 4). As for the simulations, the number of clearly spurious detections is small in all three bands ($<1\%$–$2\%$).

At the chosen probability (i.e., significance level $2 \times 10^{-5}$ or DET_ML = 10.8), the number of spurious detections is presumably $<12$ in the total catalog (i.e., F, S, and H bands). The total catalog is obtained by the cross-correlation of the three single band (i.e., F, S, and H) catalogs, in this way the number of spurious sources in the single F, S, and H bands, evaluated by the detailed analysis of the simulations (see Section 5), are no longer independent. As a result, the number of the total spurious sources is less than the sum of the spurious sources in each of three single bands.

Figure 14 (left panel) shows the positional error, evaluated using the empirical technique described in Section 4.3.1, as a function of the off-axis angle. The notch in the figure depends on the fact that at a fixed off-axis angle, the PSF$_{\text{radius}}$ is $\sim$constant, while $\sqrt{C_i}$ is a discrete variable, since $T$ are integer numbers and $B$ are small. The error is typically less than $\sim 0.5$ arcsec at the smallest off-axis angles, $\theta_i < 2$ arcmin, and then increases to 1–2 arcsec for $\theta_i \geq 2$ arcmin. Most of the scatter at a given off-axis angle in this figure is due to the range of count rates in the sources. Figure 14 (right panel) shows the positional error in the F band as a function of the source count rate in four off-axis bins. Both figures show that the quality of the data is good enough to provide positions with sub-arcsec accuracy, except for $\leq 12\%$ of F-band sources (i.e., 202 sources), and for $\sim 13.5\%$ of the entire source catalog (see Paper I for more details). These small positional errors are the key to the high identification rate of the C-COSMOS sources with optical and infrared counterparts (F. Civano et al. 2009, in preparation, Paper III).

### 6.2. Count Rates

Vignetting corrected count rates for each source are obtained by dividing the best-fit counts derived from emldetect for each band and in each single field by the net exposure time, reduced by the vignetting at the position of each source, as in the exposure maps. The exposure maps are computed averaging over an area of 8 pixels to smooth out CCD gaps and cosmetic defects, and are weighted with an absorbed power-law spectral model with an energy index $\alpha_E = 0.4$ and the Galactic column density of the COSMOS field, $N_H = 2.7 \times 10^{20}$ cm$^{-2}$.

The errors on count rates at 68% confidence level were then computed using the equation:

$$\text{Error} = \frac{\sqrt{C_i} \times (1 + a) \times B}{0.9 \times T_{\text{expo}}},$$

where $C_i$ are the source net counts estimated by emldetect corrected to an area including 90% of the PSF (see footnote 23), $B$ are the background counts from the emldetect background maps (counts/pixel$^2$) multiplied by a circular area of radius corresponding to $f_{\text{psf}} = 90\%$, and $T_{\text{expo}}$ is the vignetting corrected exposure time at the position of the source from the exposure maps. $a$ is a parameter which accounts for the fact that the background at the source position is not known with infinite precision. $a = 1$ corresponds to the situation of a background area equal to the source extraction area, which for Chandra is always very small because of the very good PSF. $a = 0$ would correspond to assuming no uncertainty on the estimate of the average value of the background. Unfortunately, emldetect provides neither the $B$ errors nor the information on the size of the region used to measure the background counts. Because of the way emldetect estimates the background counts, i.e., by a fit, using a sophisticated background modeling (Cappelluti et al. 2007), we are in an intermediate situation between the two extreme cases $a = 0$ and $a = 1$. For this reason, we chose to adopt $a = 0.5$. This ensures that we are not underestimating the error on the background, even for sources close to problematic areas like the edge of the field or CCD gaps. We chose an area corresponding to $f_{\text{psf}} = 90\%$ because this is the typical

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24 http://hea-www.harvard.edu/~elvis/CCOSMOS.html
25 http://irsa.ipac.caltech.edu/data/COSMOS/
size of the area where emldetect works for relatively bright sources. We checked that the errors computed using Equation (2) agree well with the errors evaluated from aperture photometry (Section 6.4).

Figure 15 plots the signal-to-noise ratio\(^\text{26}\) of each source as a function of DET_ML. Note the regular behavior of the signal-to-noise ratio, which increases smoothly and monotonically with increasing DET_ML, or with decreasing \(P_{\text{random}}\) (see Equation (1)), with a small dispersion around the correlation. The six diagonal black lines show the expectations computed for six values of the background in the detection cell, from 0.5 counts to 8 counts. This range is centered on \(\sim 4\) counts, a value typical for the C-COSMOS survey (see Section 2), and accounts for two effects: (1) the differences in exposure time and (2) the different sizes of the source extraction region as a function of the off-axis angle, due to the variation of the Chandra PSF with the off-axis angle. This range of background counts explains most of the observed dispersion in Figure 15, especially for the faintest sources. For the brightest sources in the F band, the best-fit DET_ML, is somewhat smaller than expected based on the signal-to-noise ratio, even for the case of a background of 8 counts per detection cell. This can be explained if the fit of bright sources is performed over an area significantly larger than the 90\% f_{\text{90}} area and so does not fully optimize the signal-to-noise ratio. This shift is smaller for the S-band sources because of the smaller background in this band with respect to the F band.

6.3. Fluxes

The emldetect count rates \((R)\) were converted to fluxes \((F_x)\) using the formula \(F_x = R/(\text{CF} \times 10^{11})\), where \(\text{CF}\) is the energy conversion factor that is evaluated by using spectra simulated through Xspec\(^{27}\) including the appropriate on-axis response matrix and the chosen spectral models. We used energy conversion factors of 0.742 counts erg\(^{-1}\) cm\(^{-2}\), 1.837 counts erg\(^{-1}\) cm\(^{-2}\), and 0.381 counts erg\(^{-1}\) cm\(^{-2}\) appropriate for a power-law spectrum with energy index \(\alpha_E = 0.4\) and Galactic column density for the COSMOS field \((N_H = 2.7 \times 10^{20} \text{ cm}^{-2})\), to convert the F count rate into the 0.5–10 keV flux, the S count rate into the 0.5–2 keV flux, and the H count rate into the 2–10 keV flux, respectively. We extend the F and H bands up to 10 keV to allow an easier comparison with the results of literature. The conversion factors are sensitive to the spectral shape: for \(\alpha_E = 1\), they change by \(\sim 40\%\) in the F band, by less than 5\% in the S band, and by less than 25\% in the

\(^{26}\) Ratio between the source count rate and the error on the source count rate at 68\% confidence level.

\(^{27}\) http://xspec.gsfc.nasa.gov/
Table 3

| $\alpha_E$ | $N_H$ | $\alpha$ | $C_F(F)$ | $C_S(S)$ | $C_H(H)$ |
|------------|-------|----------|----------|----------|----------|
| 0.4        | 0.027 | 0.742    | 1.837    | 0.381    |
| 1          | 0.027 | 1.042    | 1.759    | 0.474    |
| 0.4        | 1     | 0.508    | 2.12     | 0.561    |
| 1          | 1     | 0.712    | 2.151    | 0.447    |

Note.

$^a$ Energy conversion factor to convert the F count rate into the 0.5–10 keV flux (CF(F)), the S count rate into the 0.5–2 keV flux (CS(S)), and the H count rate into the 2–10 keV flux (CF(H)) using the formula $F_x = R/\alpha_E$ and appropriate for a absorbed power-law spectra with the listed $N_H$ and $\alpha_E$.

H band. For absorbed power-law spectra with $N_H = 10^{22}$ cm$^{-2}$ and $\alpha_E = 0.4$ or $\alpha_E = 1.0$, the conversion factors change by up to $\sim 46\%$ in the F band, by up to $\sim 17\%$ in the S band, and by up to $\sim 18\%$ in the H band (see Table 3). The conversion factor for the F band depends more strongly on the spectral shape because of the wider band.

6.4. Aperture Photometry

In addition to PSF fitting photometry, we have also performed standard aperture photometry on the sources included in the final emldetect catalog. We find an overall consistency between the two estimates, with the emldetect count rates slightly larger, less than 10%, than the count rates by aperture photometry. For each source in the catalog, aperture photometry was performed in the F, S, and H bands with the yaxx tool. The aperture photometry values are derived from event data for each individual Chandra observation where a source is located. Then, for sources being located in multiple observations, the aperture photometry is performed in each of the multiple observations, and the corresponding multiple aperture photometry values are combined to produce a single set of values, using the appropriate method shown in Table 4.

To extract source counts, circular regions of radii corresponding to 50%, 90%, and 95% f$_{psf}$, centered on each source location, are used for each observation where the source is located. The radii are calculated using the off-axis and azimuthal angles of the source in each observation and interpolating the circular f$_{psf}$ table provided by the CXC calibration group to the nearest angles. Mean energies 2 keV, 1.2 keV, and 3.6 keV were chosen for the F, S, and H bands, respectively. To extract background counts, annuli with the inner edge at the 95% f$_{psf}$ radius plus 8 pixels, and with a width of 40 pixels, are used. To limit contamination, all sources that overlap with the source or background regions are masked by using circular exclusion regions with the 95% f$_{psf}$ radius. Exclusions can also come from the CCD edge, with an 8 pixel padding inward from the edge. Aperture fluxes for which the net source extraction area was less than 75% of the available area (i.e., the original circle prior to exclusions) are not given in the catalog.

Using the region described above, photometry was extracted using the CIAO tool dmextract. The source net counts were then corrected for the fraction of f$_{psf}$, dmextract was also run on the exposure maps with exactly the same regions in order to compute the vignetting corrected exposure times that are needed to compute the source count rates.

Table 4

| Parameter | Symbol | Merge Method |
|-----------|--------|--------------|
| Exposure time corrected for the vignetting | $T_{expo}$ | $\sum_i T_{expo,i}$ |
| Counts | $T$ | $\sum_i T_i$ |
| Background counts | $B$ | $\sum_i B_i$ |
| Net counts | $C_i$ | $\sum_i C_{ij}$ |
| Errors on counts | $\text{err}_T$ | $\sqrt{\sum_i \text{err}_T,i^2}$ |
| Errors on background counts | $\text{err}_B$ | $\sqrt{\sum_i \text{err}_B,i^2}$ |
| Errors on net counts | $\text{err}_C_i$ | $\sqrt{\sum_i \text{err}_C_{ij}^2}$ |
| Count rates | $R$ | $\sum_i R_i / T_{expo,i}$ |
| Net count rates | $R_i$ | $\sum_i R_i / T_{expo,i}$ |
| Count rate errors | $\text{err}_R_i$ | $\sqrt{\sum_i \text{err}_R_i^2 / T_{expo,i}}$ |
| Net count rate errors | $\text{err}_R_i$ | $\sqrt{\sum_i \text{err}_R_i^2 / T_{expo,i}}$ |

Note. The index $i$ indicates each of the observations where a source is located.

Figure 16 compares the count rates evaluated by emldetect with the count rates evaluated by the aperture photometry. The median and interquartile of the count rate ratios are 1.03 ± 0.16, 1.08 ± 0.19, 1.07 ± 0.18 in the S, H, and F bands, respectively.

6.5. Upper Limits

If a source is not detected in one band, we give 90% upper limits to the source count rates and fluxes in this band. The upper limits are computed as follows: if $T$ is the total number of counts measured at the position of a source not satisfying our detection threshold, $B$ are the expected background counts, and $X$ are the unknown counts from the source, the 90% upper limit on $X$ ($X(90\%)$) can be defined as the number of counts $X(90\%)$ that gives a 10% probability to observe $T$ (or less)
counts. Applying the Poisson probability distribution function, \(X(90\%)\) is therefore obtained by iteratively solving for different \(X\) values in the following equation:

\[
0.1 = e^{-(X+B)} \sum_{i=0}^{\infty} \frac{(X + B)^i}{i!}.
\]

(3)

(see, e.g., Narsky 2000). We collected the counts \(T\) both from a region of 5 arcsec radius and from the aperture photometry discussed in Section 6.4. The results were always statistically consistent with each other. The \(X(90\%)\) upper limits derived with Equation (3) do not take into account the statistical fluctuations in the expected number of background counts. In order to take the background fluctuations into consideration, we used the following procedure: if \(\sigma(B)\) is the root mean square of \(B\) (e.g., \(\sigma(B) = \sqrt{B}\) for large \(B\)), we estimated the 90% lower limit on \(B\) as \(B(90\%) = B - 1.282 \cdot \sigma(B)\) and, as a consequence, the “correct” 90% upper limit on \(X\) becomes

\[
X_{\text{corr}}(90\%) \sim X(90\%) + 1.282 \cdot \sigma(B).
\]

(4)

We used \(X_{\text{corr}}(90\%)\) as upper limits for C-COSMOS sources. We also evaluated the upper limits following the method described in Kashyap et al. (2009). Comparing the upper limits obtained using the two methods, we found that our upper limits are generally more conservative (i.e., higher) than those which would be derived using the method of Kashyap et al. (2009).

7. SURVEY SENSITIVITY AND SKY COVERAGE

7.1. Survey Sensitivity

In X-ray observations, the sensitivity, i.e., the flux limit, is not uniform in the field of view (FOV) due to two main reasons: (1) the variable size of the PSF, which determines the background counts that limit the source detection; and (2) the vignetting of effective area. In C-COSMOS, where we have used multiple overlapping pointings giving different PSFs and vignetting factors for each observation of each source, the problem of assessing the sensitivity at each position in the FOV is more complex than normal. To evaluate the C-COSMOS survey sensitivity, we have developed a dedicated procedure by adapting the analytical method, used for the easier case of the ELAS-S1 mosaic (Puccetti et al. 2006 and references therein), to the more complicated C-COSMOS mosaic. In this procedure, the full C-COSMOS field is divided into a grid of positions with spacing of 4 pixels, i.e., 2 arcsec. This bin size is a suitable balance between the spatial resolution in the C-COSMOS survey and the ram memory required for computing the sensitivity maps. At each point of the 2 arcsec grid, we evaluated the minimum number of counts \(C_{\text{min}}\) needed to exceed the fluctuations of the background, assuming Poisson statistics with a significance level equal to that used for the catalog (i.e., \(2 \times 10^{-5}\); see Section 6.1), according to the following formula:

\[
P_{\text{Poission}} = e^{-B} \sum_{k=C_{\text{min}}}^{\infty} \frac{B^k}{k!} = 2 \times 10^{-5},
\]

(5)

where \(B\) is the total background count computed at the position of each point \(P_i\) of the grid by \(B = \sum_{i=1}^{n} B_i\), where \(i\) runs from 1 to the number of overlapping fields at the position of each \(P_i\), and \(B_i\) are the background counts computed using the background map of each Chandra pointing covering the position, in a region centered at \(P_i\) and of radius \(R_i\). \(R_i\) corresponds to a fixed value of \(f_{\text{psf}}\) and is evaluated from the distance of \(P_i\) and the aim point of each single Chandra pointing covering the position using the CXC calibration. We solved Equation (5) iteratively to calculate \(C_{\text{min}}\). The count rate limit, \(R_{\text{lim}}\), at each point of the grid is then computed by

\[
R_{\text{lim}} = \frac{C_{\text{min}} - B}{f_{\text{psf}} T_{\text{expo}}},
\]

(6)

where \(T_{\text{expo}}\) is the total, vignetting corrected, exposure time at each position of the grid, read from the merged C-COSMOS exposure map (see footnotes 24 and 25).

Finally, the flux limits at each \(P_i\) are computed using the same conversion factor used for the real C-COSMOS sources. This procedure is applied to the S, H, and F bands to produce binned sensitivity maps.

7.2. Sky Coverage

The “sky coverage” is the integral of the survey area covered down to a given flux limit as a function of the flux in the sensitivity map. The solid lines in Figure 12 are the normalized sky coverages, computed using the procedure described above and adopting \(f_{\text{psf}} = 0.5\). We studied how the sensitivity maps and the sky coverage depend on the assumption on \(f_{\text{psf}}\) and found that they change by less than a few percent for \(f_{\text{psf}}\) values up to 0.90. We also studied how the sensitivity maps change using different \(f_{\text{psf}}\) values at different off-axis angles where a single source is observed, finding again very little change. The reason for this behavior is the relatively low background within each \(R_i\), even at large off-axis angles.

A relatively large uncertainty in the sensitivity maps and sky coverage computation is, instead, the unknown spectrum of the sources near the detection limit. The magnitude of this uncertainty depends on the width of the energy band, and therefore is largest in the F band. To estimate the magnitude of the uncertainty, we calculated the sky coverage for power-law spectra with \(\alpha_E = 1.0\), and for absorbed power-law spectra with \(\alpha_E = 0.4\) or \(\alpha_E = 1.0\) and \(N_H = 10^{22}\) cm\(^{-2}\), in addition to the baseline case (\(\alpha_E = 0.4\), \(N_H = 2.7 \times 10^{20}\) cm\(^{-2}\); see Figure 17). At the flux limits corresponding to 90% completeness (see Table 2), the deviations are less than 3%, 3%, and 16% for the S, H, and F bands, respectively. This uncertainty relates to the unknown spectrum of the sources becomes significant only at fluxes below the 50% completeness.

7.3. The log \(N - \log S\)

We used the catalogs of the sources detected in the simulations in the S, H, and F bands and the sky-coverage curves computed in Section 7.2 to obtain the number counts (log \(N - \log S\)) of the sources detected in the simulations. We cut the catalogs in the S, H, and F band at a signal-to-noise ratio higher than 2, 2.5, and 2.8, respectively. These cuts are introduced because: (1) we do not correct for the Eddington bias, which may be strong (up to 30%–50%) at the lowest flux limits; (2) low signal to noise implies a large statistical uncertainty in the flux, which in turn would introduce a large uncertainty on the number of counts at the lowest fluxes; (3) at the lowest fluxes,
The flux limits implied by the signal-to-noise thresholds are smaller than 5%. The log $S$ curves of the sources detected in the simulations: bottom left panel, 0.5–2 keV band; bottom middle panel, 2–10 keV band; bottom right panel, 0.5–10 keV band. Ratio between log $N$ – log $S$ curves of the sources detected in the simulations: bottom left panel, 0.5–2 keV band; bottom middle panel, 2–10 keV band; bottom right panel, 0.5–10 keV band.

(A color version of this figure is available in the online journal.)

8. COMPARISON WITH AEGIS-X

Chandra was used to perform a survey somewhat similar to C-COSMOS in the AEGIS-X (Laird et al. 2009). The 1.6 Ms AEGIS-X survey is made of eight ACIS-I pointings, each of a nominal 200 ks exposure, with very little overlap, covering $\sim 0.67$ deg$^2$. While the effective exposure time and area coverage are similar to C-COSMOS (see Figure 19), the tiling is completely different. In C-COSMOS, each source in the central area is observed at four to six different off-axis angles, while in AEGIS-X, each source is observed only at one off-axis angle.

To compare the two surveys quantitatively, we cut the C-COSMOS catalog at the same significance level used for AEGIS-X (i.e., $4 \times 10^{-6}$ or DET_ML = 12.4; Laird et al. 2009). We also recomputed the C-COSMOS sky coverage using the same significance level. Figure 19 compares the C-COSMOS sky coverage to the AEGIS-X one computed without the Bayesian correction for the Eddington bias. The C-COSMOS sky coverage has a significantly sharper drop toward lower fluxes than the AEGIS-X sky coverage. This means that the sensitivity in C-COSMOS is more uniform over the field than in AEGIS-X, while the AEGIS-X tiling reaches fainter limiting fluxes than C-COSMOS. The estimated AEGIS-X flux limit in the S band is 50% deeper than C-COSMOS, while the flux limits in the H and F bands are about twice as deep as C-COSMOS, albeit in small areas. The deeper AEGIS-X flux limit in the H and F bands with respect to the S band depends on the higher internal background in these bands and on the smaller typical source extraction regions in the areas of best sensitivity of AEGIS-X with respect to C-COSMOS. In fact, AEGIS-X has a PSF better than $\sim 1$ arcsec over an area of $\sim 0.15$ deg$^2$, while the complex C-COSMOS tiling implies effective source extraction regions of radii of $\sim 3$ arcsec over most of the area.

The more characteristic flux limits corresponding to 90% completeness in the F, S, and H bands are similar in C-COSMOS and AEGIS-X, while the AEGIS-X flux limits corresponding to 50% completeness in the F, S, and H bands are lower than C-COSMOS by a factor of $2\sim 3$ (see Table 5).
The more uniform sensitivity of C-COSMOS over the field reaches a higher source density (see Table 5).

For C-COSMOS, we estimate a slightly lower number of spurious sources at a higher significance level (i.e., $2 \times 10^{-5}$ versus $4 \times 10^{-6}$; see Table 5) with respect to AEGIS-X survey. The number of spurious sources is roughly given by the product of the significance level times the number of independent detection cells in the field. The combination of different PSFs at each C-COSMOS position produces an effective source extraction region of $\sim 3$ arcsec radius, i.e., significantly wider than the Chandra PSF at off-axis angles smaller than 5–6 arcmin. This means that the number of independent cells per unit area is smaller in C-COSMOS than in AEGIS-X. In conclusion, the lower number of spurious detections in C-COSMOS with respect to AEGIS-X at a given significance level is due to the fact that each field is observed more than once at different off-axis angles, and therefore, with different PSFs.

9. CONCLUSION

The complex tiling of the C-COSMOS survey required the development of a tailored multistep procedure to fully exploit the data. Detailed simulations were used to test different detection (sliding cell and wavelet) and photometry (PSF fitting and aperture photometry) algorithms. In particular, we compared the results obtained using the SAS `eboxdetect` and `emldetect` tasks, used for the XMM-COSMOS survey (Cappelluti et al. 2007, 2009), with those obtained using the `PWDetect` code (Damiani et al. 1997). Through these tests we selected a procedure consisting in first identifying source candidates using `PWDetect`, and then performing accurate PSF fitting photometry and evaluating aperture photometry for each source candidate. In this way, we obtained sub-arcsec source localizations and accurate photometry even for partly blended sources.

We set the threshold for source detection to $P = 2 \times 10^{-5}$, which implies a completeness of 87.5% and 68% for sources...
with at least 12 and 7 F band counts, respectively, and 3 to 5 spurious detections in the F band at the same count limits, respectively.

We evaluated the survey sensitivity and the sky coverage through an analytical method, tuned using simulations. We then evaluated the log $N - \log S$ of the detected sources in the simulations down to F-, S-, and H-band flux limits of $F_x \sim 2.3 \times 10^{-16}$, $\sim 1.6 \times 10^{-15}$, and $\sim 9.6 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, respectively.

Finally, we compared the C-COSMOS survey to the AEGIS-X survey, a Chandra survey with similar sky coverage and total exposure time, but using non-overlapping ACIS-I pointings. We found that the complex tiling of C-COSMOS helps in obtaining a contiguous area with uniform sensitivity and somewhat higher source density. The overlap of several pointings with different PSFs at the same position produces an effective source extraction region of $\sim 3$ arcsec radius, i.e., significantly wider than the Chandra PSF at off-axis angles smaller than 5–6 arcmin. This produces a number of independent detection cells per unit area smaller than in a single ACIS-I pointing survey like AEGIS-X, which in turn implies a smaller number of spurious sources at each given detection threshold.

This research has made use of data obtained from the Chandra Data Archive and software provided by the Chandra X-ray Center (CXC) in the application packages CIAO and Sherpa.

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