RADIO OBSERVATIONS OF THE HUBBLE DEEP FIELD–SOUTH REGION. II.
THE 1.4 GHz CATALOG AND SOURCE COUNTS
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ABSTRACT
This paper is part of a series describing the results from the Australia Telescope Hubble Deep Field–South (ATHDFS) survey obtained with the Australia Telescope Compact Array. This survey consists of observations at 1.4, 2.5, 5.2, and 8.7 GHz, all centered on the Hubble Deep Field–South. Here we present the first results from the extended observing campaign at 1.4 GHz. A total of 466 sources have been cataloged to a local sensitivity of 5σ (11 μJy rms). A source extraction technique is developed that (1) successfully excludes spurious sources from the final source catalogs and (2) accounts for the nonuniform noise in our image. A source catalog is presented, and the general properties of the 1.4 GHz image are discussed. We also present source counts derived from our ATHDFS 1.4 GHz catalog. Particular attention is given to ensuring that the counts are corrected for survey incompleteness and systematic effects. Our counts are consistent with other surveys (e.g., the Australia Telescope ESO Slice Project, VIRMOS, and the Phoenix Deep Field), and we find, in common with these surveys, that the HDF-N counts are systematically lower.

Key words: catalogs — radio continuum: galaxies — surveys

Online material: machine-readable table

1. INTRODUCTION
Early radio surveys found that classical radio galaxies (S \geq 1 Jy) evolve strongly with time in both density and luminosity and are relatively rare in the local universe (Longair 1966). More recent surveys that probe to fainter flux densities have shown that the normalized source count flattens below a few millijanskys (Windhorst et al. 1985). This flattening corresponds to a rapid increase in the number of faint radio sources and has been interpreted as being due to a new population of sources that do not show up at higher flux density levels—the so-called submillijansky population. The existing submillijansky samples are generally small due to the large amount of observing time required to reach these faint levels.

Several models, involving different classes of objects, have been developed to explain the observed submillijansky source counts. These include a strongly evolving population of normal spiral galaxies (Condon 1984, 1989) or actively star-forming galaxies (Windhorst 1984; Windhorst et al. 1985; Rowan-Robinson et al. 1993). A nonevolving population of local (\z < 0.1) low-luminosity radio galaxies has also been proposed to explain the submillijansky population (Wall et al. 1986). It is now thought that the submillijansky population comprises low-luminosity active galactic nuclei (AGNs), normal spirals, and ellipticals, as well as starbursts, but the exact mix is unknown.

The nature of the submillijansky population is still not clear because of the difficulty of obtaining optical photometry and spectra for complete radio samples. The follow-up optical identification and spectroscopy of submillijansky radio samples require a lot of telescope time because these sources generally have very faint optical counterparts. Conclusions about the submillijansky sample have been inferred from surveys of varying radio sensitivity and different depths of optical follow-up.

Approximately 41% of submillijansky (S_{1.4 GHz} > 0.2 mJy) radio sources are identified with optical counterparts to \m_{B} \sim 23.7, and these are mostly faint blue galaxies with optical-infrared colors indicative of active star formation (Windhorst et al. 1985). This result is confirmed by a spectroscopic study of optical counterparts (B < 22) to faint (S_{1.4 GHz} > 0.1 mJy) radio sources, which found that most of the submillijansky sources have spectra similar to star-forming IRAS galaxies (Benn et al. 1993). However, this result is obtained from spectroscopy of only 10% of this study’s whole radio sample.

A more spectroscopically complete sample is the Marano field, where spectra were obtained for 50% of the 68 faint (S_{1.4 GHz} > 0.2 mJy) radio sources (Gruppioni et al. 1999). Contrary to the previous results of Benn et al. (1993), the majority of the spectra are identified with early-type galaxies. Gruppioni et al. attribute this discrepancy to the fainter magnitude limit reached in their spectroscopic identifications, since the fraction of radio sources identified with early-type galaxies increases abruptly at B \sim 22.5, which is the limit of the Benn et al. sample.

About 60% (219/386) of the faint (S_{1.4 GHz} > 0.5 mJy) radio sources in the Australia Telescope ESO Slice Project (ATESP; Prandoni et al. 2000a) are identified to I = 22.5. The spectra obtained for 70 sources with I < 19 are dominated by early-type galaxies (60%). Starbursts and poststarburst galaxies become
important in the submillijansky \((S_{1.4\text{GHz}} < 1\ \text{mJy})\) regime, where they make up 39% of the \(I < 19\) sample (Prandoni et al. 2001b). Nevertheless, Prandoni et al. find that early-type galaxies still constitute a significant fraction (25%) of the submillijansky radio sources and that submillijansky samples with fainter spectroscopic limits become increasingly sensitive to early-type galaxies.

The Phoenix Deep Field (PDF) survey covers 4.5 deg\(^2\) at 1.4 GHz and has an rms noise of 12 \(\mu\)Jy over the most sensitive region (Hopkins et al. 2003). A subregion covering about 1' has been imaged to \(R \approx 24.5\), and optical counterparts have been found for 76% of radio sources within the imaged area (Sullivan et al. 2004). Spectra of the radio sources revealed that at least 32% of the submillijansky population is made up of star-forming galaxies, and 21% are quiescent galaxies (Afonso et al. 2005). However, Afonso et al. (2005) only have spectra for 17% of their radio sources, and the spectral completeness is biased to the optically brighter radio sources \((R \lesssim 21)\).

The most complete result in photometry is in the Hubble Deep Field—North (HDF-N), for which the Very Large Array (VLA) was used to follow-up observations of a patch of sky observed by the Hubble Space Telescope (HST) to depths of about 30 mJy in the four HST broadband filters, F300W, F450W, F606W, and F814W (approximately \(U, B, V,\) and \(I\)). Eighty percent of the 79 faint \((S_{1.4\text{GHz}} \geq 0.04\ \text{mJy})\) radio sources in the HDF-N region were identified by HST and ground-based images reaching \(F_{AB} = 25\) (Richards et al. 1998; Richards 2000). Using optical and radio morphologies, along with radio spectral index arguments, Richards et al. concluded that 60% of the HDF-N radio sources with optical counterparts were star-forming galaxies, 20% were classified as AGNs, and the remainder were ambiguous.

In 1998 HST observed a region of sky in the southern continuous viewing zone as a complementary observation to the HDF-N (Williams et al. 1998). This field is known as the Hubble Deep Field—South (HDF-S; Williams et al. 2000). A region containing a quasar suitable for the search of \(\text{Ly}\alpha\) absorption systems was chosen. The main WFPC field of the HDF-S observations reaches a magnitude limit of \(\sim 30\) mag in the four HST broadband filters. Simultaneous observations with the other HST instruments, NICMOS and STIS, reach similarly deep levels in the near-infrared and ultraviolet. In addition to the main HST deep fields, a mosaic of nine flanking fields were imaged to shallower levels of \(\sim 25\) mag in \(I\) (F814W). From the ground, deep wide-field images have been obtained, reaching depths of \(\sim 25\) mag in \(UBVRI\) in a 44' \(\times\) 44' region centered on the HDF-S (Teplitz et al. 2001). Spectroscopically, 194 galaxies in the main HDF-S and its flanking fields were targeted by the Very Large Telescope (VLT), and reliable redshifts were obtained for 97 targets (Sawicki & Mallén-Ornelas 2003). In addition, optical spectroscopy is available for 225 bright \((R < 24)\) sources in a 9' \(\times\) 3' region containing the STIS and WFPC fields (Glazebrook et al. 1998).

The HDF-S was selected as a region for deep radio follow-up to take advantage of the wealth of publicly available optical/ near-infrared photometric and spectroscopic data. Observations over 1998–2001 were performed by the Australia Telescope Compact Array (ATCA) at all four available frequency bands. Approximately 100 hr of observing at each band yielded images at 1.4, 2.5, 5.2, and 8.7 GHz with sensitivities of approximately 10 \(\mu\)Jy rms. A detailed description of observations, catalogs, and analyses of these Australia Telescope Hubble Deep Field—South (ATHDFS) images is given in Norris et al. (2005, hereafter Paper I).

The radio source counts at the faintest flux density levels \((S_{1.4\text{GHz}} < 1\ \text{mJy})\) are not well determined due to the small number of surveys reaching this sensitivity regime. The sensitivity of our radio survey allows us to determine the source counts down to \(\sim 0.05\) mJy. Only the PDF (Hopkins et al. 2003) and the HDF-N (Richards 2000) reach similarly deep levels.

This paper describes the image analysis and source extraction technique of the full 1.4 GHz ATHDFS survey. This paper is organized as follows. In §2 we summarize the 1.4 GHz observations and data reduction. Various image properties are discussed in §3, and the source extraction and catalog are detailed in §4. Section 5 contains an analysis of the accuracy of our source parameters. The survey completeness is investigated in §6, and the ATHDFS 1.4 GHz differential radio source count is presented in §7.

2. OBSERVATIONS AND DATA REDUCTION

Paper I discussed in detail the observations and data reduction steps used to obtain the ATHDFS images. Here we provide a brief summary.

The 1.4 GHz observations were carried out over 4 years from 1998 to 2001. They consist of single pointings centered on R.A. = 22\text{h}33\text{m}35\text{s}06, decl. = −60°38'09" (J2000.0). A wide variety of ATCA configurations were employed to ensure maximum \(u-v\) coverage. The correlator was set to continuum mode (2 \(\times\) 128 MHz bandwidth), with each 128 MHz bandwidth divided into 32 \(\times\) 4 MHz channels. The primary flux density calibrator used was PKS B1934–638, while secondary gain and phase calibrations were performed through observations of either PKS B2205–636 or PKS B2333–528.

The data were inspected using the MIRIAD interactive task \texttt{tsflag}. After flagging, the 1.4 GHz data were split into the three observing bands (1.344, 1.384, and 1.432 GHz) before imaging and cleaning. This allowed the cleaning process to do a much better job of removing all the flux of a source. Two iterations of both phase and amplitude self-calibration were then performed to improve the image quality.

3. IMAGE ANALYSIS

In this section we discuss two systematic effects that have to be taken into account in deriving source flux densities, the clean bias and bandwidth smearing. We use methods similar to those outlined in Prandoni et al. (2000b) to investigate clean bias and bandwidth smearing. A master equation to derive flux densities corrected for these effects is given in the Appendix.

3.1. Clean Bias

When the \(u-v\) coverage is incomplete, the cleaning process can redistribute flux from real sources to noise peaks, producing spurious sources. This effect is generally only a problem for snapshot observations in which \(u-v\) coverage is poor. Although our \(u-v\) coverage is very good, tests were performed to check the magnitude of the clean bias in our image.

We performed a clean bias check by injecting point sources into the \(u-v\) data at random positions. The \(u-v\) data were then cleaned to the same rms level as our original image, and source peak fluxes after cleaning were compared to input values. The flux density distribution of injected sources was chosen to be similar to that of the real sources in the image; 40 at 5 \(\sigma\), 15 at 6 \(\sigma\), 15 at 7 \(\sigma\), 15 at 8 \(\sigma\), 15 at 9 \(\sigma\), 10 at 10 \(\sigma\), 3 at 20 \(\sigma\), 2 at 30 \(\sigma\), 1 at 50 \(\sigma\), and 1 at 100 \(\sigma\). This simulation was repeated 50 times to get reliable number statistics.

The results from this process are shown in Figure 1. The average source flux measured after the cleaning process \((S_{\text{out}})\)
normalized to the true source flux ($S_{\text{inp}}$) is shown for various values of the input source signal-to-noise ratio ($S/N$) ($S_{\text{inp}}/\sigma_{\text{loc}}$). It is evident that clean bias only affects the faintest sources. There is a sudden increase in the clean bias at a flux density of about 10 $\sigma$, but even at the faintest bin (5 $\sigma$) the clean bias is only 4%.

An analytical form of the clean bias effect was obtained by a least-squares fit to the function

$$
S_{\text{out}}/S_{\text{inp}} = a + b \frac{1}{S_{\text{inp}}/\sigma_{\text{loc}}},
$$

The best-fit values for $a$ and $b$ are 1.00 and $-0.23$, respectively. The resulting best-fit curve is plotted in Figure 1.

3.2. Bandwidth Smearing

Bandwidth smearing, the radio analog of optical chromatic aberration, is a well-known effect caused by the finite width of the receiver channels. It reduces the peak flux density of a source while correspondingly increasing the source size in the radial direction such that the total integrated flux density is conserved. The amount of smearing is proportional to the distance from the phase center, and the bandwidth of the observations. In the simplest case of a Gaussian beam and passband, the bandwidth smearing can be described by (Condon et al. 1998)

$$
\frac{S_{\text{peak}}}{S_{\text{peak,0}}} \approx \frac{1}{\sqrt{1 + [(2 \ln 2)/3][(\Delta \nu/\nu)(d/\theta_b)]^2}},
$$

where the ratio $S_{\text{peak}}/S_{\text{peak,0}}$ represents the attenuation of the source peak flux density with respect to that of an unsmeared source, $\Delta \nu$ is the passband width, $\nu$ is the observing frequency, $d$ is the distance from the phase center, and $\theta_b$ is the synthesized beam FWHM.

Although the observational bandwidth is 4 MHz, the MIRIAD task `atlod` effectively doubles the channel bandwidth. So, with the ATHDFS channel width ($\Delta \nu$) of 8 MHz and an observing frequency ($\nu$) of 1.4 GHz, equation (1) simplifies to

$$
\frac{S_{\text{peak}}}{S_{\text{peak,0}}} \approx \frac{1}{\sqrt{1 + (2 \ln 2/91,875)(d/\theta_b)^2}}.
$$

The bandwidth smearing as a function of distance from the center is plotted in Figure 2, calculated with the appropriate ATHDFS beam size parameter. The majority of our radio sources lie within the inner $10'' \times 10''$ region, where the bandwidth smearing is less than 5%. The attenuation increases rapidly, however, and is $\sim 18\%$ at a radial distance of $20''$ from the phase center.

4. SOURCE EXTRACTION

4.1. The Noise Map

To investigate the noise characteristics of our 1.4 GHz image we constructed a noise map. The noise map, which contains the pixel by pixel rms noise distribution, was made using the SExtractor package (Bertin & Arnouts 1996). SExtractor initially estimates the local background in each mesh from the pixel data, and the local background histogram is clipped iteratively until convergence is reached at $\pm 3 \sigma$ around its median. The choice of mesh size is very important. When it is too small, the background will be overestimated due to the presence of real sources. When it is too large, any small scale variations of the background are washed out.

We ran SExtractor with a mesh size set to 30 $\times$ 30 pixels, approximately 8 $\times$ 8 beams. A gray-scale image of the SExtractor noise map is shown in Figure 3. As expected, the noise is lowest in the center and increases with radial distance. Figure 4 (left) shows the average noise as a function of distance from the center. This increase in noise is roughly a parabolic shape due to the primary beam attenuation. A histogram of the noise map pixel values is shown in Figure 4 (right). This distribution peaks at a value of 10 $\mu$Jy but has a large wing at high noise values ($\geq 15 \mu$Jy) due to the radially increasing noise.

There are also regions of increased noise (white pixels) around bright sources, which are clearly evident in the gray-scale image (Fig. 3). The increased noise around these sources is due to dynamic range effects, as discussed in Paper I. The most affected region is noticeable as a high-noise bump at approximately 6$''$ from the image center in Figure 4 (left). This corresponds to the area surrounding the brightest source ($S_{1.4 \text{ GHz}} = 155 \text{ mJy}$). The noise in this region is up to 3 times that of the surrounding unaffected region.

Although SExtractor was developed for the analysis of optical data, the noise image obtained with it has been found to be
reliable for radio images (Bondi et al. 2003). We confirmed the accuracy of the SExtractor noise map by comparing pixel values against rms values directly measured from our radio image. The directly measured values were obtained by selecting a set of random positions in the 1.4 GHz image and calculating the rms in the surrounding 30 $''$ 30 pixel box. Each box was examined for any sources above 3 $''$/C27 before inclusion in the analysis to ensure that flux from real sources did not effect the statistics. Figure 5 shows the mean and standard deviation of the difference between the SExtractor pixel values and the directly measured values as a function of distance from the center. The difference is very close to zero, and there is no systematic effect as a function of radial distance. We therefore concluded that the SExtractor noise map is reliable and used it to perform the source extraction.

4.2. Source Detection and Fitting

We determined a sensible maximum radial distance for the source cataloging taking into account the following factors:

1. The radial noise distribution.
2. The primary beam attenuation effect.
3. The bandwidth smearing effect.

These three factors determine the efficacy of detecting a source with a particular flux density at different radial distances from the center. The primary beam response at a radial distance of 20 $''$ is approximately 39%, resulting in an increased noise of $\sim$20 $''$/C27, compared to $\sim$10 $''$/C27 at the image center. Furthermore, the bandwidth smearing effect is 18% at this distance and rapidly degrading, as discussed in § 3.2. On this basis we choose to catalog to a maximum distance of 20 $''$ from the image center.

To begin the source extraction we divided the original 1.4 GHz map by the noise map generated by SExtractor, obtaining an S/N map. SExtractor is useful for obtaining S/N maps, but it has not been reliably used for extracting sources from radio images. The commonly used routines are sfind (Hopkins et al. 2002) and imsad. Although sfind may result in fewer false detections (Hopkins et al. 2002), there are no systematic differences in the source parameters found by either routine (Schinnerer et al. 2004). We used the MIRIAD task imsad to derive a preliminary list of source “islands.” This task searches for islands of pixels above a specified cutoff and attempts to fit Gaussian components to them. We executed imsad on the S/N map to detect all islands with a peak flux density level of 4 $''$/C27. This resulted in a list of 688 source islands for further investigation.

Each source island found by imsad was examined and refitted with an elliptical Gaussian to derive source flux densities and sizes. This refitting procedure was performed on the “real” image (not the S/N map). All sources and fit parameters were visually inspected to check for obvious failures and poor fits that needed further analysis. Following Prandoni et al. (2000b), a reference peak value was derived from a second-degree interpolation of the source (MIRIAD task maxfit). If the difference between the fitted peak and reference peak was less than 20% of the reference value and the fitted position was inside the 0.9 $''$/C27 flux density contour, then these sources were assigned a fit quality flag of 1. Gaussian integrated fluxes were also compared to the ones directly measured by summing the pixels greater than 3 $''$/C27 in the source area. In most cases the Gaussian fit provided good values for the position and peak flux densities but not integrated flux densities. These sources are given a quality flag of 2 in the catalog.

Fig. 3.—Gray-scale image of the noise map obtained by SExtractor. The image is 40 $'$ 40 $'$, and darker regions indicate lower noise.

Fig. 4.—Left: Noise (radially averaged) as a function of radial distance for the SExtractor noise map. The broad peak around 5 - 7 $'$ is due to the noise region around the bright 155 mJy source (ATHDFS J223355.6-604315). Right: Distribution of the pixel values of the SExtractor noise map.
There were some problematic cases, which were classified as follows:

1. Sources fitted by \textit{imsad} with a single Gaussian but better described by two or more Gaussians (\(C24\%\)).
2. Non-Gaussian sources not well fitted by a single Gaussian, i.e., fit exceeding the tolerance criteria described above (\(C24\%\)).
3. Obviously spurious sources that correspond to artifacts or noise peaks (\(C24\%\)).

In the first case above, the \textit{imsad} islands were split into two or three Gaussian components. The number of successfully split islands is 19 in total (18 with two components and 1 with three components). The individual components of these sources are listed in the catalog.

The reference positions and peak flux densities from \textit{maxfit} were adopted for the two non-Gaussian sources. The source position angle (P.A.) was determined by the direction along which it was most extended. The FWHM size of the axes was defined by the distance between two points on the 3 \(\sigma\) contour parallel to (major) and perpendicular to (minor) this direction. These sources are flagged “n” in the catalog.

After accounting for the multiple components, non-Gaussian sources, and noise artifacts, we have a list of 693 sources or source components. Figure 6 shows the peak flux density and S/N distributions of the 4 \(\sigma\) sample. The spurious sources were of low S/N and make up about 4\% of the 4–5 \(\sigma\) sources. So, to ensure that we have a source catalog of high reliability we apply a cut of 5 \(\sigma\), which includes 12 multiple-component sources. There are clear signs of physical association between the individual components of these sources, as shown by the postage stamps in Figure 7. The final 5 \(\sigma\) catalog has 466 sources.

4.3. Deconvolution

The ratio of integrated flux to peak flux is a direct measure of the extension of a radio source:

\[
\frac{S_{\text{int}}}{S_{\text{peak}}} = \frac{\theta_{\text{maj}}\theta_{\text{min}}}{b_{\text{maj}}b_{\text{min}}},
\]

where \(\theta_{\text{maj}}\) and \(\theta_{\text{min}}\) are FWHMs of the source axes and \(b_{\text{maj}}\) and \(b_{\text{min}}\) are the FWHMs of the synthesized beam axes. We therefore use this relation to determine whether our sources are resolved or unresolved (see, e.g., Prandoni et al. 2000b; Bondi et al. 2003).

In Figure 8 we plot the ratio of the total integrated flux density \((S_{\text{int}})\) and peak flux density \((S_{\text{peak}})\) as functions of S/N \((S_{\text{peak}}/\sigma)\) for all the sources in the catalog. If the values of \(S_{\text{int}} < S_{\text{peak}}\) are purely due to errors introduced by noise in our image, we can derive a criterion for extension by assuming that these statistical errors are also present for \(S_{\text{int}} > S_{\text{peak}}\) sources. We determined the lower envelope in Figure 8, which contains 90\% of the sources \(S_{\text{int}} < S_{\text{peak}}\) and mirrored it above the \(S_{\text{int}} = S_{\text{peak}}\) line. The upper envelope is characterized by the equation

\[
\frac{S_{\text{int}}}{S_{\text{peak}}} = 1 + \frac{100}{(S_{\text{peak}}/\sigma)^2}.
\]

Only sources lying above this upper envelope and successfully deconvolved by MIRIAD are considered resolved. From this analysis we conclude that 221/466 (47\%) of the sources are resolved. Deconvolved sizes are only given in the catalog for resolved sources, and other sources have deconvolved sizes set to zero.

4.4. Multiple-Component Sources

Radio sources can be made up of a nucleus with hot spots along, or at the end of, one or two jets. The individual components of a single source are often cataloged separately by
Gaussian fitting routines. This will skew number statistics, so a method must be devised to identify multiple components as belonging to a single source.

Similar to the technique of Magliocchetti et al. (1998), we plot the sum of the fluxes of the components of each nearest neighbor pair versus their separation, as shown in Figure 9. The high density of points to the lower right of the $\theta$–flux density plane is made up of the general population of single-component sources. The pairs with a separation of about $10\,^\prime\!0\,^\prime$ are most likely subcomponents of single sources. This is evident from Figure 9, where the sources that were successfully split into multiple components in § 4.2, shown as circled large dots, cluster around this separation.

We apply a maximum separation that increases with the summed flux density, $S_{\text{tot}}$.

$$\theta = 100 \left( \frac{S_{\text{tot}}(\text{mJy})}{10} \right)^{0.5} \text{arcsec.}$$

This maximum separation is shown as a dashed line in Figure 9. By varying the allowed separation with summed flux, bright components may be considered a single source even at large separations, while faint sources are kept as single sources.

As a further constraint we apply a flux ratio cut to the nearest neighbor pairs. Since the flux densities of real double sources are correlated, this gives us another criterion to restrict the
matched pairs to physically associated sources. We combine pairs only if their flux densities differ by a factor of less than 4. The sources that meet this further requirement are marked in Figure 9 by large filled circles. For sources that lie to the left of equation (5), 20/23 pairs with separations less than 20'' pass the flux ratio cut, while only 3/21 pairs with larger separations are passed. Thus, this procedure seems to be successful in that almost all pairs with small separation are considered single sources, while very few distant pairs are passed.

From this analysis we identify an additional 11 possible multiple sources. All these sources were visually inspected, and only five pairs appear to be real double sources with lobe-lobe or core-lobe morphology. The postage stamps of these pairs are shown in Figure 10. These sources are accepted as double sources and flagged in the catalog. The other six pairs are shown in Figure 11. They are rejected as double sources, as they show no sign of physical association.

4.5. The Catalog

The full 5 $\sigma$ catalog is presented in Table 1. The description of Table 1 is as follows:

- **Column (1).**—Source identification.
- **Column (2).**—Source name.
- **Columns (3) and (4).**—Right ascension (J2000.0), with 1 $\sigma$ uncertainty in arcseconds. The uncertainty is calculated following Condon (1997) and Prandoni et al. (2000b).
- **Columns (5) and (6).**—Declination (J2000.0), with 1 $\sigma$ uncertainty in arcseconds. The uncertainty is calculated following Condon (1997) and Prandoni et al. (2000b).
- **Column (7).**—Source 1.4 GHz peak flux density, in millijanskys. The values given here are not corrected for the systematic effects described in § 3. The Appendix describes how to obtain source peak flux densities corrected for the systematic effects.
- **Column (8).**—Source 1.4 GHz integrated flux density, in millijanskys.
- **Columns (9) and (10).**—The deconvolved major and minor axes (FWHM) of the source, $\Theta$, in arcseconds. Zero values refer to unresolved sources (see § 4.3).
- **Column (11).**—The deconvolved P.A. (measured from north through east) of the source, in degrees. Zero values refer to unresolved sources (see § 4.3).

Column (12).—The S/N of the detection, calculated as $\text{imisad}$ fitted peak flux density.

Column (13).—Gaussian fit quality flag: “1” refers to very good fits, “2” refers to poor integrated flux density, and “n” refers to non-Gaussian sources. See § 4.2 for more details.

Column (14).—Notes on associated sources; components of a multiple source are indicated with the name of the other source(s) with which they are associated. See § 4.4 for more details.

5. ACCURACY OF SOURCE PARAMETERS

5.1. Internal Accuracy

We performed Monte Carlo simulations to check the internal accuracy of our Gaussian fits to the ATDFS radio sources. First, a residual map was produced by removing all the sources detected above 5 $\sigma$. Gaussian sources were injected into the residual image at random positions, and the MIRIAD Gaussian fitting task $\text{imfit}$ was used to extract fitted parameters. The injected point sources had peak flux densities between 5 and 100 $\sigma$. Fifty sources were injected at each peak flux density level per simulation (500 in total), and the simulation was repeated 20 times to get a sample size of 1000 sources per flux density level. By comparing the input to fitted output parameters we tested the reliability of our source parameters and obtained an estimate of the fit errors.

In Figure 12 the ratio of the fitted peak flux density ($S_{\text{inp}}$) to the input peak flux density ($S_{\text{out}}$) is shown as a function of the source S/N. There is an evident systematic effect (known as “noise bias”) in the fitted peak flux density for sources with S/Ns less than about 10 $\sigma$. Here the ratio of fitted to input peak flux density deviates from unity due to incompleteness at the lower S/N bins. If an injected source is coincident with a noise dip, either its peak flux density is underestimated or it falls below the source detection threshold. This biases the fitted flux density to higher values because only sources that fall on noise peaks, and therefore have extra flux, are detected and measured.

Figure 13 shows the ratio of output to input source sizes for both major and minor axes. There may be a marginal systematic overestimation of the source major axis for sources with a S/N less than about 20 $\sigma$. Although the output major axis sizes are
increasingly overestimated from 20 to 5 \( \sigma \), the overestimation is less than the standard deviation in the measurements. In contrast, there is no systematic effect present on the measurement of the minor axis.

The accuracy of source positions was also checked in the simulations. The mean difference between output and input positions (\( \Delta \alpha \) and \( \Delta \delta \)) is plotted in Figure 14 as a function of source S/N. No systematics are present, and we note that rms values for the two axes (\( \alpha \) and \( \delta \)) are similar. The positional accuracy of our catalog is therefore derived as 1\( \sigma \) at the limit of our survey (5\( \sigma \)), improving to 0\( \sigma \)6 at 10\( \sigma \) and 0\( \sigma \)1 at 100\( \sigma \).

5.2. Absolute Accuracy

Ideally, our survey would be checked against an independent radio survey to determine the absolute accuracy of the source parameters. Unfortunately, there are no radio surveys in the region that reach the required depth. The Parkes-MIT-NRAO (PMN) survey (Griffith & Wright 1993) has a flux density limit of only 30 mJy at 4.85 GHz, while the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003) reaches a peak flux density limit of 6 mJy at 843 MHz. The SUMSS source positions are not useful as a comparison because the
### TABLE 1
ATHDFS 1.4 GHz Catalog

| ID   | Source       | R.A.  | $\sigma_\alpha$ (arcsec) | Decl. | $\sigma_\delta$ (arcsec) | $S_{peak}$ (mJy) | $S_{int}$ (mJy) | $\theta_{maj}$ (arcsec) | $\theta_{min}$ (arcsec) | P.A. (deg) | S/Nlocal | Flag | Notes   |
|------|--------------|-------|--------------------------|-------|--------------------------|-----------------|-----------------|------------------------|------------------------|------------|----------|-------|---------|
| 1    | ATHDFS J223303.6–605751 | 22 33 03.62 | 0.12 | $-60$ $57$ $51.6$ | 0.41 | 0.297 | 0.508 | 0.00 | 0.00 | 0.0 | 16.4 | 2 |
| 2    | ATHDFS J223325.8–605729 | 22 33 25.88 | 0.55 | $-60$ $57$ $29.3$ | 1.28 | 0.092 | 0.162 | 7.81 | 5.90 | $-5.3$ | 5.1 | 2 |
| 3    | ATHDFS J223255.6–605656 | 22 32 55.62 | 0.48 | $-60$ $56$ $56.5$ | 0.76 | 0.159 | 0.375 | 9.35 | 6.32 | $-0.5$ | 7.7 | 2 |
| 4    | ATHDFS J223246.3–605654 | 22 32 46.30 | 0.28 | $-60$ $56$ $54.0$ | 0.50 | 0.170 | 0.254 | 6.92 | 2.24 | 18.6 | 10.0 | 2 |
| 5    | ATHDFS J223403.4–605640 | 22 34 03.43 | 0.54 | $-60$ $56$ $40.3$ | 0.66 | 0.126 | 0.210 | 5.63 | 5.20 | $-7.8$ | 6.6 | 2 |
| 6    | ATHDFS J223243.8–605608 | 22 32 43.80 | 0.60 | $-60$ $56$ $08.8$ | 0.62 | 0.149 | 0.363 | 8.55 | 7.33 | 57.1 | 7.8 | 1 |
| 7    | ATHDFS J223244.8–605603 | 22 32 44.89 | 0.43 | $-60$ $56$ $03.7$ | 0.84 | 0.119 | 0.176 | 7.41 | 7.41 | 1.01 | 19.2 | 6.2 | 1 |
| 8    | ATHDFS J223410.5–605545 | 22 34 10.58 | 0.05 | $-60$ $55$ $45.4$ | 0.09 | 1.284 | 2.106 | 7.28 | 3.47 | $-3.9$ | 58.7 | 1 |
| 9    | ATHDFS J223409.5–605559 | 22 34 09.50 | 0.05 | $-60$ $55$ $59.6$ | 0.10 | 1.302 | 2.443 | 8.88 | 3.75 | 8.6 | 59.6 | 1 |
| 10   | ATHDFS J223308.5–605544 | 22 33 08.50 | 0.03 | $-60$ $55$ $44.3$ | 0.04 | 2.056 | 3.643 | 6.70 | 5.06 | $-1.1$ | 112.2 | 1 |

**Notes.**—Table 1 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
SUMSS resolution is about 45" and source positional uncertainties are up to 10", which are much greater than the ATHDFS internal positional uncertainties. Flux density comparisons are not possible, since these two surveys are at different frequencies and there is no a priori knowledge of the source spectral energy distributions.

The absolute positional accuracy of our survey will depend on how well the positions of the phase calibrators are known. The calibrator PKS B2333−528 has been observed by VLBI, and its position in the FK5 reference system is known to within 0"005 in each coordinate (Ma et al. 1998). The position of the second calibrator, PKS B2205−636, is known to within 0"1–0"25. Thus, we expect the absolute accuracy of our source positions to be 0"25. This absolute uncertainty in position is not included in the catalog (Table 1) and needs to be added in quadrature to the source positional uncertainty. This affects mainly the brighter sources, as the positional uncertainty of sources with S/N less than 10 are dominated by the internal accuracy of our survey.

6. SURVEY COMPLETENESS

In the ATHDFS, sources were included in the catalog if the measured peak flux density exceeded 5 times the local noise. This can lead to incompleteness at faint flux density levels, which has to be taken into account when deriving source counts. In this section we discuss the various possible sources of incompleteness in the source catalog.

6.1. Visibility Area

Any source extraction method that relies on the ratio of peak flux density to the local noise will be affected by the variation of noise in the image. The area over which a source of a given flux density can be detected, also known as the visibility area, depends on the source peak flux density and the homogeneity of the noise distribution. The noise in our image is 11.0 μJy at the center and is a function of the primary beam response, increasing toward the edges of the field as quantified in § 4.1. Local variation in image noise is also caused by bright sources, which can increase the noise in their vicinity by up to 3 times that of an unaffected region (see § 4.1 for details).

The visibility area of the ATHDFS 1.4 GHz image is shown in Figure 15. As expected, the fraction of the total area over which a source of a given peak flux density can be detected increases between 0.05 and 0.1 mJy and reaches 0.96 at 0.1 mJy. The rise in the visibility function is not as rapid as in the ATESP (Prandoni et al. 2001a) or VIRMOS (Bondi et al. 2003) surveys. This is because these surveys used a mosaicking technique, which results in a more uniform noise distribution than single-pointing surveys such as the ATHDFS. The visibility area also shows that sources with a peak flux density greater than 0.1 mJy can be detected over more than 95% of the whole image. The visibility area reaches 100% of the image at a peak flux density of 0.23 mJy.

6.2. Systematic Effects

Two additional effects that could be responsible for partial incompleteness in the source catalog are bandwidth smearing and clean bias. These two effects have been extensively discussed in § 3. Bandwidth smearing can lead to an underestimation of
peak flux densities by up to \( \sim 18\% \), although the amount is \( 5\% \) or less for the majority of our sources. The clean bias affects both peak and integrated flux densities. It leads to an underestimation of flux densities by \( \sim 5\% \) for the faintest sources (5 \( \sigma_{\text{local}} \)) but has no effect on sources brighter than 10 \( \sigma_{\text{loc}} \).

In the Appendix we propose a formula (eq. [A1]) to correct the measured peak and integrated flux densities for these two systematic effects. The correction depends on the source S/N, as well as on the source distance from the image center. However, peak flux densities are underestimated by \( \sim 23\% \) at most due to the combined effects of both clean bias and bandwidth smearing. Since the highest level of noise is \( \sim 50 \mu\text{Jy} \), it follows that clean bias and bandwidth smearing do not affect sources brighter than \( 5 \times 50 \mu\text{Jy} / 0.77 \sim 0.32 \text{ mJy} \).

6.3. Resolution Bias

Resolution bias is an effect in which weak extended sources may have peak flux densities that fall below the cataloged 5 \( \sigma \) limit, yet still have total integrated flux densities above the survey limit. To derive a source count that is complete in terms of total flux density, the number of “missing” sources has to be estimated. Given a maximum detectable angular size and knowledge of the intrinsic source size distribution as a function of flux density, this so-called resolution bias can be corrected. Here we follow the procedures of Prandoni et al. (2001a) to correct the resolution bias.

Assuming a Gaussian beam, the maximum size (\( \theta_{\text{max}} \)) a source of total flux density \( S_{\text{tot}} \) can have before it drops below the 5 \( \sigma_{\text{local}} \) detection limit can be calculated from the equation

\[
\frac{S_{\text{tot}}}{5 \sigma_{\text{loc}}} = \frac{\theta_{\text{max}}^2}{b_{\text{maj}} b_{\text{min}}}. \tag{6}
\]

In Figure 16 we plot the angular size (\( \theta \)) of the ATHDFS sources as a function of the measured total flux density. The angular sizes are defined as the geometric mean of the major and minor deconvolved axes of the sources. We assume \( S_{\text{tot}} = S_{\text{peak}} \) for point sources. We calculate \( \theta_{\text{max}} \) from equation (6) with a full
range of noise values from 5 to 30 μJy. The distribution of pixel values in the noise image of § 4.1 is used to determine the relative weight of each noise value, and a weighted average \( \sigma_{\text{max}} \) is calculated. Figure 16 shows that the angular sizes of the largest ATHDFS sources are in good agreement with this weighted average \( \theta_{\text{max}} \) function.

As discussed in § 4.3, the deconvolution efficiency depends on the S/N of the source. An estimate of the minimum angular size \( (\theta_{\text{min}}) \) that a source can have is derived from equations (3) and (4),

\[
\frac{S_{\text{tot}}}{S_{\text{peak}}} = 1 + \left[ \frac{100}{(S_{\text{tot}}/\sigma_{\text{loc}})^2} \right] = \frac{\theta_{\text{min}}^2}{\theta_{\text{maj}} \theta_{\text{min}}}. \tag{7}
\]

Similar to the derivation of \( \theta_{\text{max}} \), a weighted average \( \theta_{\text{min}} \) is calculated using the noise distribution of our image. The resulting average \( \theta_{\text{min}} \) is plotted in Figure 16 as a dashed line. We note that the \( \theta_{\text{min}} \) constraint is important at low flux density levels where \( \theta_{\text{max}} \) becomes unphysical (\( \sim 0 \)). Also, the minimum deconvolved size is about 10″ at the detection limit, whereas sources as small as \( \sim 1″ \) are reliably deconvolved at higher S/N.

Using the two constraints described above, an overall angular size upper limit, \( \theta_{\text{lim}} \), as a function of flux density \( S_{\text{tot}} \) is defined as

\[
\theta_{\text{lim}} = \max (\theta_{\text{max}}, \theta_{\text{min}}). \tag{8}
\]

The incompleteness of the ATHDFS survey due to \( \theta_{\text{lim}} \) can be estimated with knowledge of the true source angular size distribution as a function of flux density. We assume an exponential form for the integral angular size distribution, \( h(\theta) \) (Windhorst et al. 1990),

\[
h(\theta) = \exp \left[ -\ln 2(\theta/\theta_{\text{med}})^{0.62} \right], \tag{9}
\]

with

\[
\theta_{\text{med}} = 2S_{1.4\text{GHz}}^{0.30}, \tag{10}
\]

where \( S_{1.4\text{GHz}} \) is in mJy and \( \theta_{\text{med}} \) is the estimated median source size at a given flux density. Equations (9) and (10) together with equation (8) allow us to estimate the fraction of sources larger than the maximum detectable size and therefore missed by our survey. The correction factor, \( c \), is then simply calculated as

\[
c = \frac{1}{1 - h(\theta)}. \tag{11}
\]

In Figure 17 we show both \( h(\theta) \) (left) and \( c \) (right). The resolution bias peaks at about 0.1 mJy but decreases at lower flux densities due to the \( \theta_{\text{lim}} \) constraint.

7. THE ATHDFS 1.4 GHz SOURCE COUNTS

In this section we construct the differential radio source counts from the 5 σ ATHDFS catalog. In computing the source counts we have used the integrated flux density for resolved sources and peak flux densities for point sources. The counts were calculated by dividing the number of sources in each flux density bin by the total survey area and the bin width and then normalizing by the Euclidean slope of \( S^{-2.5} \). The reason for the normalization is historical, relating to the early use of radio source counts to test various cosmological models against the number of sources that would be expected in a steady state Euclidean universe (Longair 1966; Ryle 1968).

Table 2 lists the final ATHDFS source counts, corrected for the visibility area, clean bias, bandwidth smearing, and resolution bias as discussed above. For each flux density bin, the mean flux density \( \langle S \rangle \), the number of detected sources \( N \), the number of effective sources after applying the corrections \( N_{\text{eff}} \),

\[
(\text{dN}/\text{dS}) S^{-2.5} \quad (\text{Jy}^{-1} \text{sr}^{-1})
\]

| Range in S (mJy) | \( \langle S \rangle \) (mJy) | \( N \) | \( N_{\text{eff}} \) |
|------------------|--------------------------|------|----------------|
| 0.050–0.064      | 0.059                    | 28   | 226.1          |
| 0.064–0.082      | 0.073                    | 53   | 149.8          |
| 0.082–0.106      | 0.094                    | 70   | 143.0          |
| 0.106–0.136      | 0.119                    | 54   | 87.06          |
| 0.136–0.174      | 0.154                    | 52   | 79.85          |
| 0.174–0.224      | 0.197                    | 43   | 59.43          |
| 0.224–0.287      | 0.253                    | 26   | 33.49          |
| 0.287–0.368      | 0.328                    | 24   | 29.18          |
| 0.368–0.473      | 0.417                    | 22   | 25.18          |
| 0.473–0.607      | 0.541                    | 14   | 15.10          |
| 0.607–0.779      | 0.667                    | 10   | 10.75          |
| 0.779–1.000      | 0.905                    | 7    | 7.56           |
and the corrected normalized differential radio source count \((dN/dS)\) are given. We show the counts before and after corrections in Figure 18. We note that the corrections are most important in the flux density range 0.09–0.3 mJy, where they can increase the source count by up to approximately 30%.

Sources classed as “multiple component” (see § 4.4) only make one contribution to the source count. At these flux density levels, the difference between incorporating multiple-component sources as single objects and deriving counts from the “full-component” catalog is negligible. If all components are used, then the most significant change is in the \((S) = 0.119\) mJy bin, where there are four additional sources. For this bin the difference is ~7%, which is less than the Poisson error.

7.1. Comparison to Other Deep Radio Source Counts

The ATHDFS source counts are compared to those derived from other 1.4 GHz surveys in Figure 19. The source counts from the Faint Images of the Radio Sky at Twenty cm survey (FIRST; White et al. 1997) are shown, as well as counts from the ATESP survey (Prandoni et al. 2001a), the PDF (Hopkins et al. 2003), and the HDF-N (Richards 2000). The solid line in Figure 19 is the linear least-squares sixth-order polynomial fit to this compilation of source counts. FIRST counts below 2.5 mJy were removed from the fit, since FIRST is incomplete at this limit. PDF counts above 2.5 mJy and ATESP counts above 76 mJy were also excluded from the fit, since the sampling is sparse in the higher flux density bins of these surveys. The resulting polynomial fit is given by

\[
\log \left( \frac{dN}{dS} \right) S^{-2.5} = \sum_{i=0}^{6} a_i \left[ \log \left( \frac{S}{\text{mJy}} \right) \right]^i,
\]

with \(a_0 = 0.841, a_1 = 0.540, a_2 = 0.364, a_3 = -0.063, a_4 = -0.107, a_5 = 0.052,\) and \(a_6 = -0.007\). For comparison, a third-order fit to source counts from 0.1 to 10,000 mJy by Katgert et al. (1988) and a sixth-order fit by Hopkins et al. (2003) to the PDF and FIRST source counts between 0.06 and 1 mJy are shown as dashed and dotted lines, respectively. A

![Figure 18](image1.png)

**Figure 18.**—The 1.4 GHz normalized differential radio source counts derived from the ATHDFS catalog. The source counts before correcting for clean bias, bandwidth smearing, and resolution bias are shown as squares. Triangles indicate the counts after correcting for clean bias and bandwidth smearing but not resolution bias. Source counts with full corrections are shown as circles.

![Figure 19](image2.png)

**Figure 19.**—Normalized 1.4 GHz differential radio source counts for FIRST (asterisks; White et al. 1997), the original Phoenix Deep Field survey (crosses and triangles; Hopkins et al. 1998), the latest Phoenix Deep Field survey (diamonds and filled stars; Hopkins et al. 2003), the ATESP survey (open circles; Prandoni et al. 2001a), the Hubble Deep Field–North (open squares; Richards 2000), the ATHDFS (filled circles), and the VIRMOS survey (open stars; Bondi et al. 2003). The solid line is a sixth-order polynomial fit described in the text. The sixth-order fit from Hopkins et al. (2003; dotted line) and the third-order fit from Katgert et al. (1988; dashed line) are shown for comparison.
third-order polynomial is insufficient to account for the curvature below 0.1 mJy suggested by both the HDF-N and PDF surveys. A fourth-order polynomial does not adequately model the point of inflection around 0.5 mJy (Hopkins et al. 2003), while fifth-order polynomials do not reproduce the concave curvature seen at about 1 Jy (e.g., Windhorst et al. 1990; Katgert et al. 1988). Hence, the sixth-order polynomial is necessary. The fitted polynomial has no physical basis but is useful in quantifying the differential radio source count.

There is a high level of consistency between the source counts derived from both small- and large-area surveys at flux densities $S_{1.4\,\text{GHz}} > 0.5$ mJy (Figs. 19 and 20). The differential source counts diverge at fainter flux density levels ($S_{1.4\,\text{GHz}} < 0.5$ mJy). The source count from the HDF-N has been previously noted as being particularly low because of inadequate completeness corrections, as well as cosmic variance (Richards 2000; Hopkins et al. 2003). In contrast, the count from the ATHDFS lies higher than all other counts at $S_{1.4\,\text{GHz}} < 0.4$ mJy, although within statistical agreement for $S_{1.4\,\text{GHz}} < 0.3$ mJy. The excess is significant for the ATHDFS at 0.37 mJy < $S_{1.4\,\text{GHz}} < 0.47$ mJy, compared to the latest (2003) PDF results and the counts from the VIRMOS survey. Over the $0.35\,\text{deg}^2$ area cataloged by the ATHDFS survey, we have 22 sources in this flux density range, compared to 44 in the VIRMOS field ($1\,\text{deg}^2$) and 150 in the latest PDF catalog ($4.5\,\text{deg}^2$). We designate the variation in the ATHDFS as real given the small area of the ATHDFS, with a probable overdensity of $3–8$ sources compared to the “average” field.

It has been suggested that the differential radio source count steepens at the faintest flux density levels ($S_{1.4\,\text{GHz}} < 0.1$ mJy) (Hopkins et al. 2003; Richards 2000). Although there is little real confirmation, since in every case it relies on the faintest source count bin, this steepening is expected, as the “flat” region of the count between 0.08 and 0.3 mJy cannot continue infinitely because the implied surface density of radio sources would exceed the number of host galaxies (Windhorst et al. 1993). The differential count from the ATHDFS is in agreement with the general trend around $S = 0.08$ mJy, although the last data point at 0.059 mJy lies well above those from the HDF-N and PDF. Thus, we cannot confirm the downturn in the differential radio source count and will have to wait for a deeper source catalog to supply these data.

7.2. Source Counts and Galaxy Evolution

Source counts are important because they can be used to constrain the evolution of the radio population. The source count above 10 mJy is dominated by giant radio galaxies and QSOs, which we group together in this discussion as AGNs. At submillijansky levels ($0.1–1$ mJy) there is an increasing number of blue galaxies with star-forming spectral signatures. Condon (1989), Rowan-Robinson et al. (1993), Hopkins et al. (1998), and others have concluded that the source count at these faintest levels requires two populations, AGNs and star-forming galaxies, both of which undergo strong evolution.

To derive a local luminosity function of star-forming galaxies, Hopkins et al. (1998) start with the IRAS 60 $\mu$m luminosity function (Saunders et al. 1990) and convert that to radio using the well-known far-infrared–radio correlation (Helou & Bicay 1993; Yun et al. 2001). Assuming that luminosity evolves as $(1+z)^q$, Hopkins et al. (1998) found that $q = 3.3 \pm 0.8$ best matches the radio source counts.

We perform a similar test to determine the rate of evolution of the local star-forming galaxies required to match the radio source counts. We use the local radio luminosity function (RLF) of star-forming galaxies determined by Condon et al. (2002) for the 4583 Uppsala Galaxy Catalogue (UGC; Nilson, 1987, UGC).
1973) galaxies cross-matched with the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). The UGC-NVSS local RLF is the most comprehensive to date, very local ($z < 0.02$), and probes the low-luminosity end of star-forming galaxies to log ($L_{1.4 \text{ GHz}}$) $= 18.8$ W Hz$^{-1}$. The UGC-NVSS local RLF, $\rho_n(L)$, is described by the local visibility function, $\phi \equiv L^{5/2} \rho(L)$, where

$$\log (\phi) = \log [\rho_n(L)] + \frac{3}{2} \log (L) + 28.43.$$ 

Fitting the visibility function directly instead of the RLF results in a better fit because the $L^{5/2}$ weighting prevents the visibility function from steepening as fast as the luminosity function at high luminosities. Condon et al. (2002) approximate the visibility function with a hyperbolic function,

$$\log (\phi) = Y - \left\{ B^2 + \left[ \frac{\log (L) - X}{W} \right]^2 \right\}^{1/2},$$

with $Y = 3.06$, $B = 1.9$, $X = 22.35$, and $W = 0.67$ for star-forming galaxies. For the AGN component we use the AGN counts from Jackson (2004).

The observed source count is shown in Figure 21 along with several models for the counts of the local star-forming population. We have explored a variety of evolution scenarios: pure luminosity evolution going as $(1 + z)^q$, pure density evolution going as $(1 + z)^p$, and a no-evolution model. We confirm that two distinct populations, the star-forming galaxies and AGNs, are required to account for the faint source counts. The counts are best fitted by star-forming galaxies undergoing $(1 + z)^{2.7}$ luminosity evolution. This amount of evolution means that the number of star-forming galaxies exceeds the number of AGNs at about 0.25 mJy. The counts rule out the stronger luminosity evolution of $q > 4$. A modest amount of density evolution is also allowed, but if it is large (e.g., $p > 6$) the source counts are too high at the microjansky level. A downturn in radio source counts is needed at these levels so that the number of radio sources does not exceed the number of host galaxies (Windhorst et al. 1993). Thus, the radio source counts rule out large amounts of density evolution in the star-forming galaxy population.

Similar values for the evolution of star-forming galaxies have been found by Hopkins (2004) and Seymour et al. (2004), who find $q = 2.7$ and 2.5, respectively. These two studies use the local RLF of star-forming galaxies from Sadler et al. (2002). Despite different assumptions for the luminosity functions of both star-forming and AGN galaxies, there is good agreement between our work and these previous studies.

Redshift information is required to break the degeneracy between luminosity and density evolution. Little density evolution is expected, however. For example, Hopkins (2004) jointly constrains the evolution parameters $q$ and $p$ to find $q = 2.7$ and $p = 0.15$. We have obtained spectra of our radio sources that will allow us to explore galaxy evolution in detail. This further work will be discussed in a future paper.

8. SUMMARY

We have presented the extended observations of the Hubble Deep Field–South with the Australia Telescope Compact Array at 1.4 GHz. The new 1.4 GHz image reaches a maximum sensitivity of $\sim 11 \mu$Jy rms at a resolution of $\sim 6.5$ arcsec. The clean bias and bandwidth smearing effects have been investigated and quantified for our 1.4 GHz image. A catalog of all sources brighter than $5 \sigma_{\text{loc}}$ within 20 arcmin of the image center has been compiled, comprising 466 sources.
The 1.4 differential radio source counts from the ATHDFS survey have been presented. We have corrected the counts for survey completeness and systematic effects, including visibility area, clean bias, bandwidth smearing, and resolution bias. We find that the source counts in the ATHDFS are in general consistent with those from previous surveys, although the ATHDFS counts are greater than that found in the HDF-N by a factor of 1.2–2. Other deep surveys have also found the HDF-N counts to be low (e.g., Phoenix; Hopkins et al. 2003; VIRMOS; Bondi et al. 2003). Thus, the HDF-N counts are probably underestimated, or the HDF-N samples a relatively underdense region of radio sources. We find that the radio source counts are best fitted by the local star-forming population with luminosity evolution of the form $(1 + z)^{2.7}$, although small amounts of density evolution are not ruled out.

The ATHDFS survey has obtained radio images at 2.5, 5.2, and 8.7 GHz in addition to 1.4 GHz. The next paper in the series will provide radio spectral indices and a detailed analysis of the ATHDFS sources across this radio spectrum. The HDF-S has also been the target of deep multicolor optical photometry and spectroscopy. Future papers in this series will present the optical identifications and spectroscopy of the ATHDFS radio sources.

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APPENDIX

FLUX DENSITY CORRECTIONS FOR SYSTEMATIC EFFECTS

As discussed in §3, the two systematics that affect the peak flux densities of the ATHDFS sources have been analyzed. These two effects are the clean bias and bandwidth smearing. The flux densities given in the ATHDFS catalog (Table 2) are not corrected for these effects. Corrected flux densities can be obtained using the formula

$$S_{\text{corr}} = \frac{S_{\text{meas}} \sqrt{1 + [(2 \ln 2)/(91875)](d/\theta_b)^2}}{1.00 - 0.23(S_{\text{meas}}/\sigma)^{-1}}, \quad (A1)$$

where $S_{\text{meas}}$ is the flux density actually measured and cataloged, $S_{\text{meas}}/\sigma$ is the cataloged source $S/N$, $d$ is the source distance from the pointing center (R.A. = 22h33m37s, decl. = $-60^\circ33'29'\arcsec$), and $\theta_b$ is the synthesized beam FWHM ($6'\arcsec$). The term in the numerator of equation (A1) corrects for the bandwidth smearing, while the term in the denominator represents the clean bias correction. For integrated flux densities, the term in the numerator of equation (A1) should be set to 1.

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