

## THE LAST OF *FIRST*: THE FINAL CATALOG AND SOURCE IDENTIFICATIONS

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### ABSTRACT

The *FIRST* survey, begun over 20 years ago, provides the definitive high-resolution map of the radio sky. This Very Large Telescope (VLA) survey reaches a detection sensitivity of 1 mJy at 20 cm over a final footprint of 10,575 deg<sup>2</sup> that is largely coincident with the Sloan Digital Sky Survey (SDSS) area. Both the images and a catalog containing 946,432 sources are available through the *FIRST* Web site (<http://sundog.stsci.edu>). We record here the authoritative survey history, including hardware and software changes that affect the catalog's reliability and completeness. In particular, we use recent observations taken with the JVLA to test various aspects of the survey data (astrometry, CLEAN bias, and the flux density scale). We describe a new, sophisticated algorithm for flagging potential sidelobes in this snapshot survey, and show that fewer than 10% of the cataloged objects are likely sidelobes, and that these are heavily concentrated at low flux densities and in the vicinity of bright sources, as expected. We also report a comparison of the survey with the NRAO VLA Sky Survey (NVSS), as well as a match of the *FIRST* catalog to the SDSS and Two Micron Sky Survey (2MASS) sky surveys. The NVSS match shows very good consistency in flux density scale and astrometry between the two surveys. The matches with 2MASS and SDSS indicate a systematic  $\sim 10$ – $20$  mas astrometric error with respect to the optical reference frame in all VLA data that has disappeared with the advent of the JVLA. We demonstrate strikingly different behavior between the radio matches to stellar objects and to galaxies in the optical and IR surveys reflecting the different radio populations present over the flux density range 1–1000 mJy. As the radio flux density declines, stellar counterparts (quasars) get redder and fainter, while galaxies get brighter and have colors that initially redden but then turn bluer near the *FIRST* detection limit. Implications for future radio sky surveys are also briefly discussed. In particular, we show that for radio source identification at faint optical magnitudes, high angular resolution observations are essential, and cannot be sacrificed in exchange for high signal-to-noise data. The value of a JVLA survey as a complement to Square Kilometer Array precursor surveys is briefly discussed.

**Key words:** catalogs – methods: data analysis – methods: statistical – radio continuum: general – surveys

### 1. INTRODUCTION

*Faint Images of the Radio Sky at Twenty-centimeters* (*FIRST*) were collected over a period of 18 years at the (now, Jansky) Very Large Array (VLA). The original proposal to use the world's premiere radio telescope for the relatively mundane task of surveying the sky was submitted in August of 1990. Pilot observations for the *FIRST* survey began in April of 1993, 50 years to the month after Grote Reber's original radio sky survey (Reber 1944). The final observations were completed in the Spring of 2011 in an expansion of the survey to cover the SDSS3 sky survey area. Over this extended period, a number of VLA hardware changes were implemented, not least being the transformation of the entire array into the JVLA. In addition, a number of changes to the data reduction software and processing algorithms also took place over the course of the survey. Furthermore, the lower-resolution NRAO VLA Sky Survey (NVSS) survey was completed during this interval, as were sky surveys at infrared (Two Micron Sky Survey, 2MASS) and optical (Sloan Digital Sky Survey, SDSS) wavelengths.

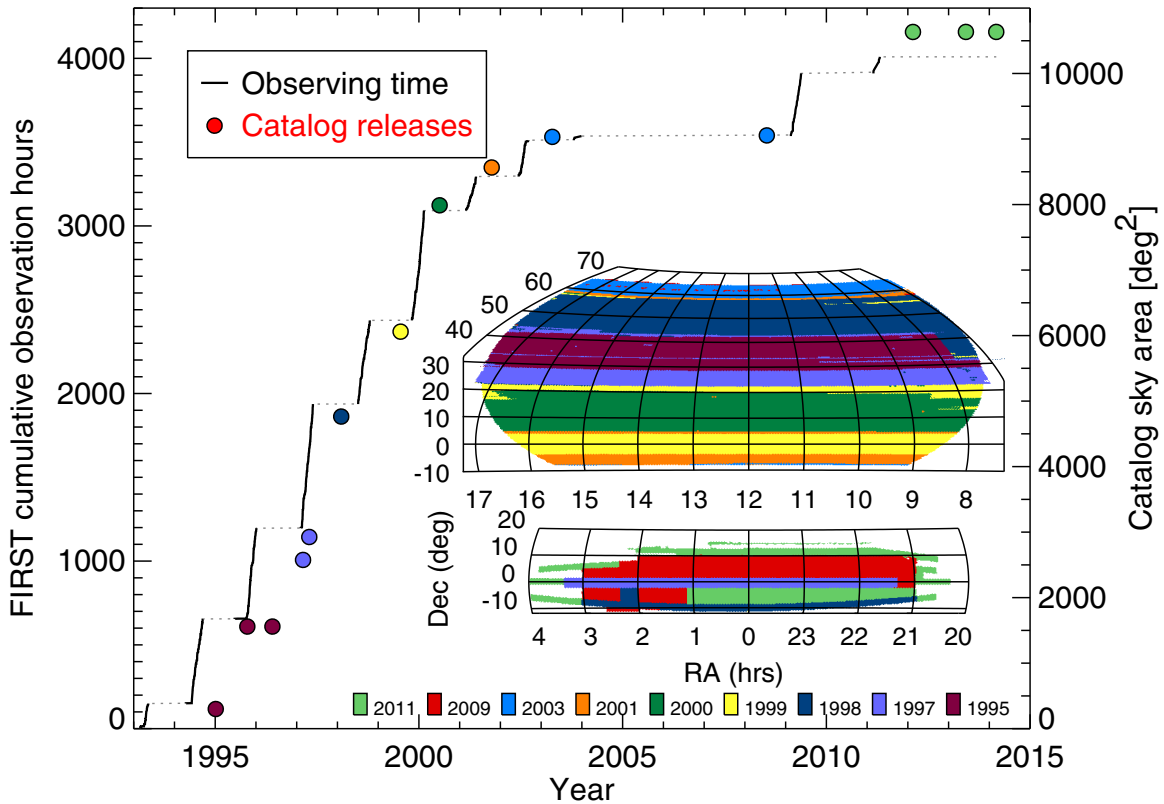
In this paper, we describe the final products of the *FIRST* survey. The *FIRST* images and catalogs are distributed through the *FIRST* Web site,<sup>6</sup> the Mikulski Archive for Space Telescopes<sup>7</sup> and other archival sites.

A history of the hardware and software changes during the project is provided to alert users to possible systematics in the survey images and catalog (Section 2); we also note various rare anomalies in the VLA system that have been discovered as a consequence of examining over 75,000 snapshot images. In some of this work, we make use of matches of the *FIRST* catalog to other all-sky surveys, the science from which is reported later in the paper. We assess the astrometric accuracy of the *FIRST* catalog, which reveals some small systematic offsets in the positions (Section 3). We go on to describe the algorithm developed to assign to each source a probability that it is a spurious catalog entry resulting from a sidelobe of a bright source elsewhere in the field (Section 4). Various tests of this algorithm using radio and optical catalog matching provide an assessment of the algorithm's reliability.

We compare the *FIRST* survey catalog with the results of three other major sky surveys that cover most or all of the same  $>10,000$  deg<sup>2</sup> of sky: the NVSS (Condon et al. 1998), the 2MASS survey (Skrutskie et al. 2006), and the SDSS (York et al. 2000) plus its more recent extensions (Ahn et al. 2014). In particular, we use the NVSS match (Section 5) to quantify the accuracy of the *FIRST* flux density scale and the degree to which faint sources are missed as a consequence of the increased noise level near bright sources, as well as the incompleteness of *FIRST* for very extended objects. The 2MASS (Section 6) and SDSS (Section 7) matches provide information on the astrometric accuracy of the respective surveys, as well as insight into the

<sup>6</sup> <http://sundog.stsci.edu>

<sup>7</sup> <http://archive.stsci.edu/vlafirst/>



**Figure 1.** Twenty-year history of the *FIRST* survey showing the sky coverage (nearly vertical dark lines) as a function of time. The right axis shows the sky area in square degrees and the left axis shows the cumulative observing time. The insert shows the sky coverage color-coded by the catalog release dates, which are also indicated by circles colored to match the coverage map. The final project, representing an investment of 4009 hr of VLA time, generated a survey covering 10,575 deg<sup>2</sup> of sky.

classes of sources that populate the radio sky at milliJansky flux densities. We conclude with a commentary (Section 8) on the survey's utility and on the lessons learned from this undertaking that can be used to inform the next generation of radio sky surveys. In particular, we examine critically the effect of survey resolution on optical/IR identification programs for radio sources.

Readers uninterested in the detailed technical history and/or the subtle catalog biases useful only for those using *FIRST* in large, statistical surveys should skip to the science results, which begin in Section 5.

## 2. THE SURVEY HISTORY

The VLA<sup>8</sup> pilot observations in 1993 aided us in designing the pointing grid for the survey (also adopted by the NVSS) and in developing the basic data reduction algorithms for turning snapshot visibilities into final survey images. These basic attributes of the project are described in detail in Becker et al. (1995) and the catalog, constructed as detailed in White et al. (1997); those papers should remain the primary references when making use of *FIRST* results. Here, for the record, we document the technical history of the project and describe all factors that might affect the character and integrity of the data products.

In Figure 1, we show the time allocated and the sky coverage achieved over the 18 years of survey observations. A total of

eleven observing sessions in the B-configuration led to the accumulation of just over 4000 hr (5.5 months) of observing time that resulted in 10,575 deg<sup>2</sup> of sky coverage (8444 deg<sup>2</sup> in the north Galactic cap and 2131 deg<sup>2</sup> in the southern cap). A coverage map, color-coded by observation epoch, is displayed in the inset to Figure 1; the catalog-release points are colored to match the relevant coverage areas.

As originally envisioned, all data were released to the public archive on the day they were taken, and all images were fully reduced and put on a public Web site before a new set of observations commenced. More than a dozen catalog releases were issued; they are located in Figure 1 by date and sky coverage (right axis). A summary of the catalog releases is given in Table 1. The final 2014 December 17 release contains 946,432 entries. A history of catalog format changes and error corrections can be found at <http://sundog.stsci.edu/first/catalogs/history.html>.

### 2.1. Hardware and Observing Mode Changes

The only major hardware change over the period of the survey was occasioned by the transition of the array from its original configuration to the JVLA. During the 2009 observing session, roughly half the array had the original 20 cm receivers, while half had been changed to the JVLA receivers. The center frequencies of the two IFs were held constant, but the shapes of the receiver bandpasses were different. In the 2011 session, the JVLA transition was complete. We observed at a different center frequency (1335 MHz versus two narrow bands centered at 1365 MHz and 1435 MHz) with a 128 MHz total bandwidth comprised of 64 2 MHz channels (versus  $2 \times 7$  3 MHz channels for the remainder of the survey); data taken in a second 128 MHz

<sup>8</sup> The Very Large Array is an instrument of the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

**Table 1**  
Summary of *FIRST* Catalog Releases

Release Date	Number of Sources	North Galactic Cap Area (deg <sup>2</sup> )	South Galactic Cap Area (deg <sup>2</sup> )	Total Area (deg <sup>2</sup> )
(1)	(2)	(3)	(4)	(5)
1995 Jan 6	26,892	300	0	300
1995 Oct 16	138,665	1559	0	1559
1996 May 28	138,665	1559	0	1559
1997 Feb 27	236,040	2576	0	2576
1997 Apr 24	268,047	2576	350	2926
1998 Feb 4	437,429	4153	611	4764
1999 Jul 21	549,707	5448	611	6060
2000 Jul 5	722,354	7377	611	7988
2001 Oct 15	771,076	7954	611	8565
2003 Apr 11	811,117	8422	611	9033
2008 Jul 16	816,331	8444	611	9055
2012 Feb 16	946,464	8444	2191	10635
2013 Jun 5	971,268	8444	2191	10635
2014 Mar 4 <sup>a</sup>	946,432	8444	2131	10575
2014 Dec 17 <sup>a</sup>	946,432	8444	2131	10575

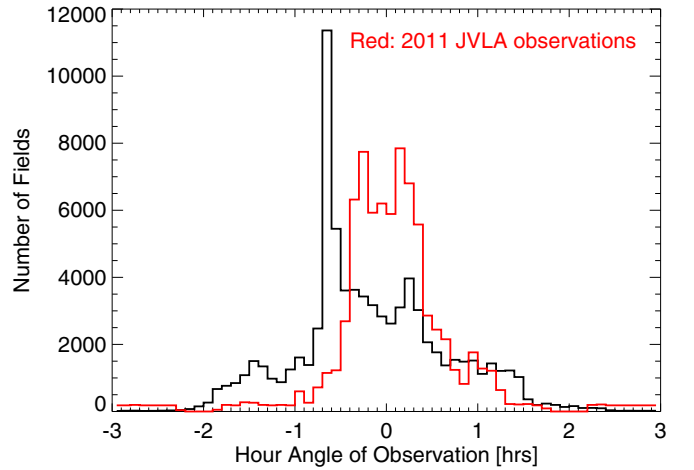
**Notes.** <sup>a</sup> These catalog versions have fewer sources and a slightly reduced sky area because the JVLA images are not co-added with older VLA images. See text for more details.

band centered at 1730 MHz, to be used in deriving source spectral indices, will be reported elsewhere. All the changes in 2011 were motivated by a combination of the changing requirements of the JVLA receiver/correlator system, plus the desire to reduce the observing time and to extract additional science using the new capabilities of the JVLA.

While the pilot observations used a 3 s integration time, we quickly adopted 5 s integrations as standard. For the 2011 JVLA observations, however, the wide bandwidth required a reduction of the integration time to 1 s. These changes affect the data analysis but do not lead to appreciable changes in the survey data products. The on-target dwell time was 165 s per field until 2011, at which time the wider bandwidth available allowed us to reach our 1 mJy sensitivity while reducing the observing time to 1 minute per field. The wider bandwidth and different frequency do have some effects on the data (discussed further below). The shorter integration time also required a change in the pointing pattern, since the time spent per field was then much less than the sidereal rate at which the sky passed overhead. A traveling-salesman algorithm using simulated annealing (Kirkpatrick et al. 1983) was developed to minimize slew time between fields.

During both 2009 and 2011, the Sun was located in the sky region to be observed, requiring us to schedule around a zone of avoidance centered on the apparent solar position. A 7° avoidance radius was used in 2009; the zone was expanded to 10° in 2011 owing to increased solar activity. This, coupled with non-optimal scheduling of our time allocations, led to many of the observations being taken farther from the zenith than was desirable. The scheduling challenges combined with the loss of a significant quantity of data to interference also resulted in some holes in the sky coverage and led to the disconnected island of coverage that is visible in Figure 1 near  $\delta = 15^\circ$  in the south Galactic cap.

Figure 2 shows how the observations were distributed with respect to the meridian. Ideally the fields would all have been observed as they passed the meridian (zero hour angle), but the real distribution is more complex. 90% of the observations for the entire survey were acquired within 1.4 hr of the meridian.



**Figure 2.** Distribution of hour angles for the *FIRST* observations. The hour angle is zero for fields observed as they pass the meridian. The black line shows the distribution for the entire survey. The red line shows the distribution for the 2011 JVLA observations, normalized to the same area as the overall distribution. The latter distribution differs owing to shorter 1 minute integrations and the need to avoid pointing toward the Sun.

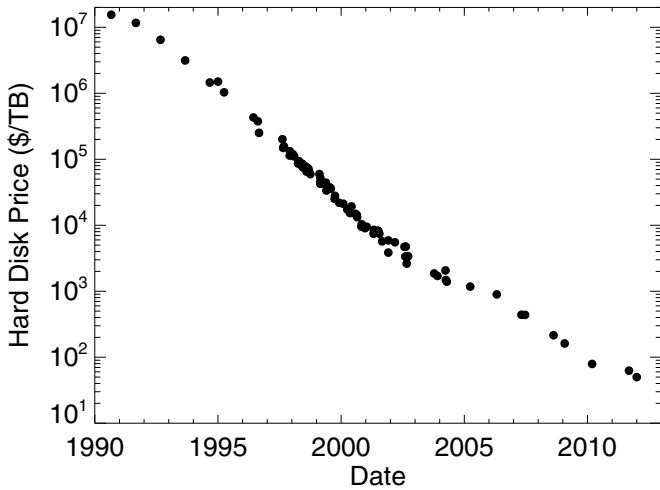
The distribution is noticeably spiky and asymmetrical because the observing time blocks allocated were often non-optimal, requiring that we observe fields off the meridian. The distribution for the short 1-minute JVLA observations, shown by the red line, is more symmetrical (the result of our traveling salesman algorithm) but also has a very extended tail at large hour angles (due to the need to avoid the Sun.) All these effects conspire to produce point-spread functions (PSFs) and sidelobe patterns that vary slightly from year-to-year. For most purposes, however, the PSF can be treated as if it were uniform. Over the northern sky the PSF is a circular Gaussian with FWHM 5''.4. South of declination +4°33'21" the beam becomes elliptical, 6''.4 × 5''.4, with the major axis running north-south. South of −2°30'25" the elliptical beam size increases further to 6''.8 × 5''.4.

In the final 2014 December 17 version of the catalog, the JVLA images are not co-added with older VLA images to avoid problems resulting from the different frequencies and noise properties of the two data sets. That leads to small gaps in sky coverage at the boundaries between the JVLA and VLA regions, but has the advantage that it cleanly separates sources from the old and new configurations. All sources in the final catalog that have field names ending with “W” come from the JVLA data.

## 2.2. VLA Anomalies

Unsurprisingly, with 4000 hr of observing time to reduce and a million sources to catalog, subtle and/or rare effects, not noticeable in ordinary VLA programs, can appear. We summarize several such anomalies here.

**Misassignment of data blocks:** searches of the *FIRST* database for source variability led to the discovery of a bug in the online VLA software that appends to the current observation a few integrations from the previous observation. This was revealed when investigating the (ultimately spurious) detection of variability in a bright source (Gal-Yam et al. 2006; Ofek et al. 2010). All *uv* data sets were subsequently checked for this error and 190 cases of discontinuities in *uvw* values within a single scan were identified (Thyagarajan et al. 2011). These data sets were edited and the images re-made. Note that all versions of the catalog prior to 2012 may contain a few spurious sources as a consequence of this error.



**Figure 3.** Price of disk storage (dollars per terabyte, using constant 2012 dollars) over the duration of the *FIRST* survey. Storage prices have dropped by a factor of roughly 300,000 since the *FIRST* survey proposal was submitted in 1990. Computer processing and memory have also become dramatically less expensive over the lifetime of the survey.

*Misassignment of array configuration:* In collecting the global observation records to include in this paper, we noticed that the VLA archive sometimes records incorrect array configuration labels for some observations. All observations for the *FIRST* survey were, in fact, taken in the B configuration. The VLA archive also is currently missing entries for  $\sim 1\%$  of the *FIRST* fields.

*Image stretch and rotation.* By comparing the positions of sources observed in multiple pointings, we discovered that there exist both a stretch and a rotation of VLA images, which we infer are related to small clock errors at the VLA and small changes in bandpass shape (see footnote 6 of White et al. 1997). The astrometric errors introduced are very small ( $< 0''.1$ ) for most sources, as the errors tend to cancel out in the co-added images. Only for sources at the very edge of the survey coverage area can the errors rise to  $\sim 0''.3$ . For the first four epochs of observation, we solved for the stretch and rotation corrections using multiply observed sources. Since the parameters were quite stable from epoch to epoch, we then fixed the correction and applied it to each epoch's images through 2003. The last two epochs have not had these small corrections applied. Thus, the positions of sources at the edge of the coverage in the south Galactic cap should be assigned slightly larger astrometric uncertainties.

### 2.3. Data Reduction Changes

Computing power and storage capacity have increased dramatically over the life of this project (Figure 3). In addition, the AIPS software package has evolved, as have the scripts we run to process the *FIRST* data. Finally, the recent upgrade to the JVLA hardware has required changes in the processing pipeline. We briefly note here all significant changes to the data processing.

*Data flagging.* Prior to 2011, the data were collected in two sets of seven 3 MHz channels, and if interference was strong in one channel, all seven channels of data for that integration period (5 s) were deleted. With the advent of the broad-bandwidth JVLA correlator, identified interference in one 2 MHz channel leads to the deletion of that channel and the two adjacent channels only.

*Self-calibration.* The self-calibration process (Högbom 1974) requires iteratively CLEANing images and using the flux models

from those images to improve the antenna phase (and sometimes amplitude) calibrations. During the initial years of the *FIRST* survey, the computing required to construct a map was daunting. To render the computing tractable, we adopted an approach of making an initial low-resolution map to find bright sources in the image and then using only a set of small maps centered on those source positions for the self-calibration iteration (Becker et al. 1995). Following the six-year hiatus in 2009, we simplified the process for new data by repeatedly making full-field images during the self-calibration iteration as well as for producing the final map.

*Wide-field bright-source mapping.* Owing to processing speed limitations, our original approach for the final map was to augment a  $2048 \times 2048$  map covering the central primary beam with small satellite maps placed at the positions of nearby bright sources (from single-dish catalogs) that lie within  $10^\circ$  of each field center (for details see Becker et al. 1995). Beginning in 2009, we simply made  $4096 \times 4096$  images and dispensed with special treatment for far off-axis sources. With 1.8 arcsec pixels, these images span  $2''.0$ , which is four times larger than the 20 cm FWHM primary beam diameter. Note that because these images are snapshot observations, there is no need for any special treatment of three-dimensional sky effects in the processing. The three-dimensional distortions are removed in post-processing by warping the map as described in Becker et al. (1995).

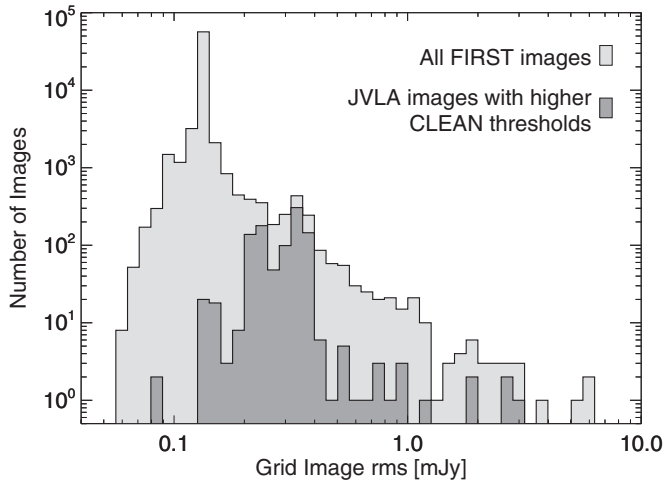
Also, in the first section of the survey, each field center was shifted by up to  $0''.9$  so that the brightest source in the field fell at the precise center of a pixel. We never found any evidence that this significantly affected image quality and, since it complicated the image processing and the final products (which otherwise had a predictable pixel grid), we abandoned this procedure in processing the final two epochs.

*Source extraction.* We used our AIPS source extraction program HAPPY (White et al. 1997) to identify and measure the properties of sources in the *FIRST* images. HAPPY evolved over the course of the project as a result of minor enhancements and bug fixes. To ensure a more uniform catalog, in 2007 we reprocessed all the data using the current version of HAPPY. That led to minor changes in the source lists.

*Flux calibration and CLEAN bias.* The flux density calibrators 3C286 and 3C48 were used for the North and South Galactic Caps, respectively. The co-adding procedure to create the final images from the individual grid images, as well as the source detection and parameterization procedures, remained unchanged throughout the survey period.

One of the systematic errors in VLA images that came to light from *FIRST* and NVSS was the so-called CLEAN bias. Sources extracted from CLEANed snapshot images invariably lost flux in the CLEANing process. Further analysis of the *FIRST* images for studies of sub-threshold sources through stacking (White et al. 2007) showed that the CLEAN bias effect is really a snapshot bias that reduces the flux densities of even faint undetected sources. This was quantified by Becker et al. (1995) and White et al. (2007) by adding artificial sources into the UV data and comparing the input and output flux densities for tens of thousands of point sources. We continue to add a CLEAN bias offset of 0.25 mJy to the peak flux densities of all sources (see Becker et al. 1995).

Since with the change of VLA hardware there was some concern that the CLEAN bias would be different, we repeated these CLEAN bias tests using artificial sources for each day of data taken in the final 2011 JVLA epoch. We found that the



**Figure 4.** Distribution of rms noise values in individual *FIRST* survey images. The dark shaded histogram shows the noise distribution for JVLA fields observed on three days with particularly bad interference; their mean noise levels are  $\sim 2.5$  times higher.

CLEAN bias was not stable and seemed to correlate with the amount of interference in the data. In particular, there were three days when the CLEAN bias was significantly higher than usual. The higher CLEAN bias on those days appeared to result from CLEANing too deeply, i.e., since there was more interference, the rms was higher and hence using the standard CLEAN limit was inappropriate. For those days the images were remade with a shallower CLEAN threshold, which brought the CLEAN bias back into line with the normal level.

The price of shallower CLEANing for those fields was an increase in the rms noise levels. Figure 4 shows the distribution of the rms noise levels in all *FIRST* “grid” images (single pointings, before co-adding), with the rms distribution for images on the three noisy JVLA days highlighted. The mode of the noise distribution is 0.132 mJy, but the distribution has a tail toward higher rms values (most often the result of bright sources in the field). The extension to lower rms values is the result of multiply observed fields that have been combined to reduce the

noise. The noise levels for JVLA fields observed on the three bad days are typically 2.5 times higher. Note that the *FIRST* catalog uses these noise measurements for all contributing grid images to compute the rms noise as a function of position in the co-added images (White et al. 1997); consequently, the final *FIRST* catalog has rms noise estimates that correctly reflect the elevated noise in these regions.

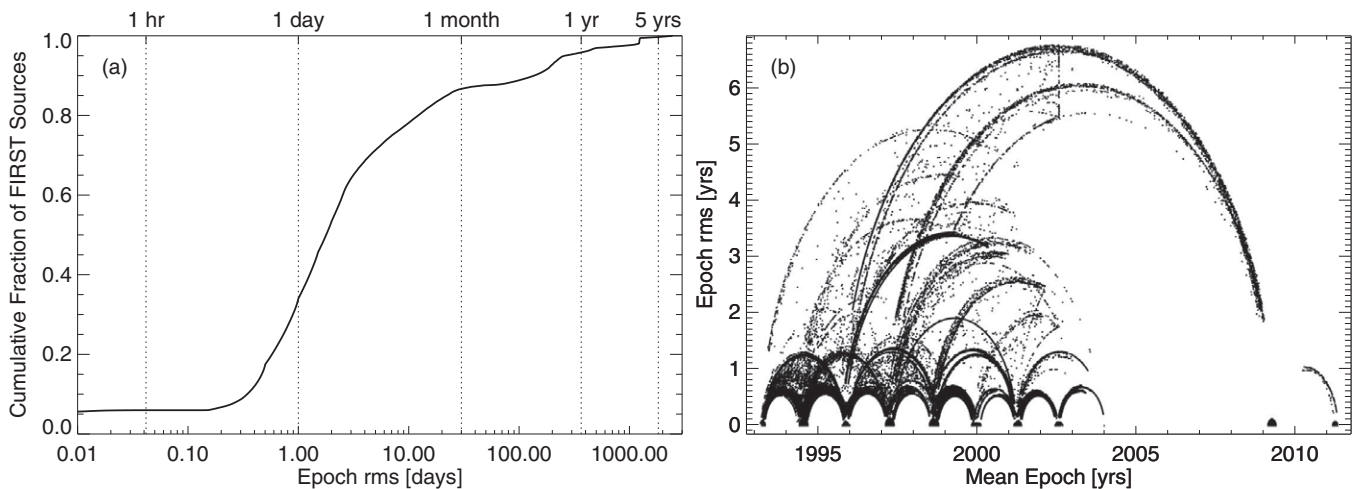
#### 2.4. Epochs of Observations

To enable the use of *FIRST* data for time-domain science, the 2014 December 17 release of the *FIRST* catalog includes observation epochs for the sources. Since the catalog is created from co-added images, each source may have contributions from many different pointings taken at different times. For some sources all the contributing observations come from a narrow time range of only a few minutes (when one or two consecutive grid images dominate the co-added source position), while others have significant contributions from pointings taken years apart (typically at the seams between observing seasons and near fields that were re-observed owing to problems with the original observations).

The catalog includes a mean weighted epoch  $\bar{t}$ , defined to be the average of the epochs of all the contributing pointings at the source position weighted by the same weights used to combine the overlapping maps. It also includes the weighted rms  $\sigma(t)$  of the scatter of the pointing epochs about that mean, which is a measure of the effective spread in the observing epoch. Figure 5(a) shows the cumulative distribution of  $\sigma(t)$ ; the median rms is 1.8 days, and 90% of the  $\sigma(t)$  values are less than four months, so most observations are well-localized in time. Plotting  $\sigma(t)$  versus  $\bar{t}$  (Figure 5(b)) shows the tail of much higher epoch rms values for sources in the overlap regions between observing sessions.

### 3. ASTROMETRY

In our initial description of the *FIRST* survey (Becker et al. 1995) we evaluated the astrometric precision of the source catalog by comparing the positions of 46 Multi-Element Radio-Linked Interferometer Network (MERLIN) calibrators lying



**Figure 5.** (a) Cumulative distribution of observation epoch ranges  $\sigma(t)$  in the *FIRST* catalog. Many sources have flux densities measured over an interval of an hour or less, but some come from combined observations that span years. (b) The distribution of epoch rms with the mean epochs of the individual pointings. The small arcs from year-to-year originate in the overlapping boundaries between sky areas covered in consecutive observing seasons, as individual pointings from different years are combined in the weighted, co-added images to produce a rapidly changing mean epoch with a large rms value. Larger epoch arcs and rms ranges come from overlaps between observing seasons that are several years to decades apart; the longest arcs connect to the 2009 observing season, which resumed observations of the south Galactic cap region after a long hiatus.

**Table 2**  
*FIRST* Matches with External Catalogs

FIRST	Subset	External	Match	Match	Position rms $\sigma^c$		Position Mean Offset <sup>d</sup>	
Subset	Percentage <sup>a</sup>	Catalog	Radius	Percentage <sup>b</sup>	$\Delta$ R.A.	$\Delta$ Decl.	$\Delta$ R.A.	$\Delta$ Decl.
(1)	(%)	(3)	(arcsec)	(%)	(arcsec)	(arcsec)	(arcsec)	(arcsec)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
All	100.0	NVSS	15	54.9	5.46	5.59	$-0.009 \pm 0.008$	$0.064 \pm 0.008$
Isolated <sup>e</sup>	73.0	NVSS	15	50.6	4.64	4.89	$-0.011 \pm 0.008$	$0.066 \pm 0.008$
All	100.0	2MASS	2	8.0	0.42	0.43	$0.021 \pm 0.002$	$0.007 \pm 0.002$
Pt <sup>f</sup>	37.1	2MASS	2	8.3	0.34	0.34	$0.020 \pm 0.002$	$0.006 \pm 0.002$
Pt, bright <sup>g</sup>	4.9	2MASS	2	6.8	0.23	0.23	$0.022 \pm 0.004$	$0.009 \pm 0.004$
All	93.0 <sup>h</sup>	SDSS all	2	32.9	0.36	0.37	$0.021 \pm 0.001$	$0.016 \pm 0.001$
all	93.0	SDSS galaxy <sup>i</sup>	2	26.5	0.38	0.39	$0.021 \pm 0.001$	$0.016 \pm 0.001$
All	93.0	SDSS star <sup>j</sup>	2	6.3	0.26	0.28	$0.023 \pm 0.001$	$0.014 \pm 0.001$
Pt	35.3	SDSS all	2	38.2	0.28	0.28	$0.020 \pm 0.001$	$0.014 \pm 0.001$
Pt	35.3	SDSS galaxy	2	29.6	0.30	0.30	$0.020 \pm 0.001$	$0.015 \pm 0.001$
Pt	35.3	SDSS star	2	8.6	0.21	0.22	$0.022 \pm 0.001$	$0.012 \pm 0.001$
Pt, bright	4.7	SDSS all	2	41.0	0.17	0.17	$0.022 \pm 0.001$	$0.012 \pm 0.001$
Pt, bright	4.7	SDSS galaxy	2	23.4	0.19	0.19	$0.020 \pm 0.002$	$0.013 \pm 0.002$
Pt, bright	4.7	SDSS star	2	17.7	0.15	0.16	$0.025 \pm 0.002$	$0.011 \pm 0.002$
JVLA <sup>k</sup> , isolated	4.5	NVSS	15	52.0	4.62	4.99	$0.005 \pm 0.030$	$0.179 \pm 0.031$
JVLA	6.4	2MASS	2	6.7	0.47	0.49	$0.000 \pm 0.007$	$-0.029 \pm 0.008$
JVLA	99.3	SDSS all	2	28.4	0.40	0.44	$0.002 \pm 0.003$	$-0.009 \pm 0.003$

**Notes.**

<sup>a</sup> Percentage of *FIRST* catalog sources included in the selected subset.

<sup>b</sup> Percentage of the *FIRST* subset that has matches in the external catalog.

<sup>c</sup> rms difference between *FIRST* and external catalog positions. For NVSS the 68.3% percentile width of the distribution is reported because the NVSS difference distribution is highly non-Gaussian (Figure 10).

<sup>d</sup> Mean value of *FIRST* position minus external catalog position.

<sup>e</sup> Isolated *FIRST* sources having no neighbors within 50".

<sup>f</sup> *FIRST* point sources having fitted FWHM major axes < 6".

<sup>g</sup> Bright *FIRST* sources having peak flux densities > 10 mJy.

<sup>h</sup> Includes only sources in sky area covered by SDSS DR10.

<sup>i</sup> SDSS sources classified as galaxies (type = 3).

<sup>j</sup> SDSS sources classified as stars (type = 6).

<sup>k</sup> Includes only sources from 2011 JVLA observations.

in the first survey strips and found the systematic errors to be  $< 0''.05$ . An additional comparison with 4100 optical counterparts from the Automatic Plate Measuring machine scans of the Palomar Optical Sky Survey plates (McMahon & Irwin 1992) found the same limit for the optical-radio frame offset (see McMahon et al. 2002 for further discussion). For a survey in which the individual catalog entries have typical positional uncertainties of  $0''.3$ , any systematic position offsets of this magnitude were insignificant for all envisioned initial usages of the catalog. In the *FIRST* catalog paper (White et al. 1997) we used a larger sample of radio calibrators and the increased size of the survey coverage area to conclude that any offset from the radio reference frame was  $< 0''.03$ .

With the survey now complete, large optical and infrared catalogs of the sky now available, and significant work over the intervening two decades invested in the creation of the International Celestial Reference Frame (ICRF2; Ma et al. 2013), we have the opportunity to investigate small astrometric effects in some detail. In subsequent sections, we provide definitive matches of the *FIRST* survey's final catalog to the NVSS, SDSS, and 2MASS catalogs; Table 2 summarizes the results of those matches, including the mean astrometric offsets between *FIRST* and other catalogs.

The positional offset for all *FIRST*-NVSS matches in right ascension is consistent with zero:  $\Delta$ R.A. =  $-0.009 \pm 0''.008$  (avoiding source confusion by selecting isolated sources only,

the value is  $\Delta$ R.A. =  $-0.011 \pm 0''.008$ ). This agreement is unsurprising given that both surveys were conducted for the most part with the same instrument, but it eliminates the possibility that any errors have been introduced by the data reduction procedures.

Comparisons with the optical and near-IR catalogs, however, reveal an apparent discrepancy. In Table 2, the mean offset in R.A. between *FIRST* and either SDSS or 2MASS is consistent with  $0''.021$ , and the offset is determined with a very small uncertainty ranging from 1 to 4 mas for the various subsets. We note that an A-configuration survey of the SDSS Stripe 82 region (Hodge et al. 2011) also finds  $\Delta$ R.A. =  $0''.020$ . Since the offset between the ICRF2 and optical reference frames has been established to be less than  $0''.003$  in R.A. (Orosz & Frey 2013; Assafin et al. 2013), it appears that VLA data suffer from a +20 mas offset.

However, using only *FIRST* data taken with the JVLA and matching to the SDSS catalog, we find  $\Delta$ R.A. =  $0''.002 \pm 0.003$ . The timing system, correlator, and data acquisition hardware and software are different between the VLA and the JVLA. Thus, we find strong evidence that positions derived from the old VLA system have a systematic offset in R.A. of  $\sim +20$  mas with respect to the radio and optical reference frames.

Note that this systematic error is very much smaller than the positional uncertainties on sources in the *FIRST* catalog; for even the brightest sources, the random position errors are

$\sim 100$  mas or larger. This error is small enough to be irrelevant except in large-scale cross-matches that compare astrometric systems.

The declination offsets also show some systematic variations in Table 2, although different external catalogs have different offsets. The SDSS matches have a typical declination offset of 15 mas, while the 2MASS offset is smaller,  $\sim 7$  mas. The NVSS-*FIRST* declination offset stands in stark contrast with a difference of 60 mas. As for Right Ascension, in the JVL region the remaining declination offsets compared with SDSS are consistent with zero. We discount the large discrepancies from the NVSS match, which we find in Section 5 to have highly non-Gaussian position difference distributions with long tails. With that caveat, we conclude from the SDSS and 2MASS matches that systematic errors in the *FIRST* declinations at all epochs are of order  $0''.02$  or less.

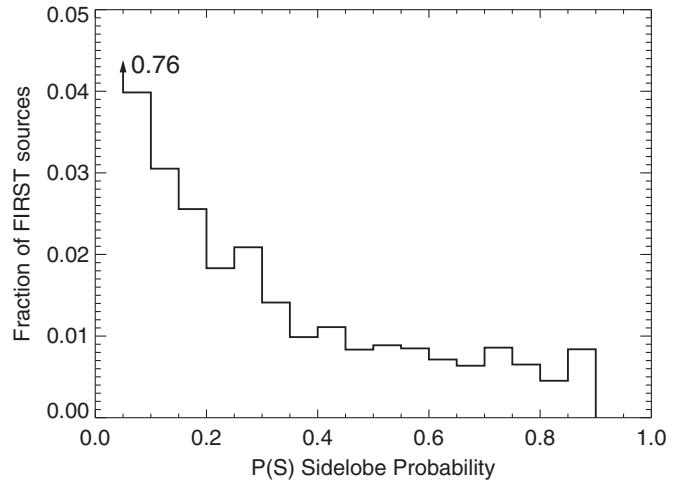
#### 4. THE SIDELOBE FLAGGING ALGORITHM

The original versions of the *FIRST* catalog (beginning with the 1995 October 16 release) included a sidelobe warning flag that indicated a likelihood that the source entry was actually a sidelobe of a bright nearby source rather than a real object (White et al. 1997). The algorithm for setting this flag used an oblique decision tree classifier<sup>9</sup> (Murthy, Kasif & Salzberg 1994) that was trained using a set of sidelobes identified by visual examination of some *FIRST* images.

While this approach had some value in identifying potentially spurious sources, it was not very accurate. It was easy to find cases where sidelobes were not flagged or real sources were incorrectly flagged. In addition, the use of a binary yes/no flag for sidelobe flagging did not provide much guidance as to the actual likelihood that a source was spurious. Consequently, this catalog entry was considered somewhat unreliable and saw relatively little use.

White et al. (2005) developed a more sophisticated and useful variation on this algorithm. We used deep observations of a portion of the Galactic plane from a different survey to determine objectively which sources in a catalog were spurious (not seen in the much deeper data) and which were real (confirmed in the deeper data). That produced a reliable training set for the decision tree classifier. We then created multiple independent decision trees whose output was combined to obtain a sidelobe probability estimate for each source rather than a simple binary classification. This voting decision tree approach is described in more detail by White et al. (2000) and White (2008).

For the 2008 and later releases of the *FIRST* catalog, we adopted a similar approach to computing sidelobe probabilities for the *FIRST* sources. We created a training set of 1905 sources (including 120 sidelobes). We matched *FIRST* with two deep radio surveys, the *Spitzer* First Look Survey (416 *FIRST* sources, 15 sidelobes; Condon et al. 2003) and the COSMOS deep survey pilot area (72 *FIRST* sources, 6 sidelobes; Schinnerer et al. 2004).<sup>10</sup> We also included a less reliable but larger sample from our own survey of the Deeprange area (1356 *FIRST* sources, 99 sidelobes; White et al. 2003). Finally we augmented the set with a sample of 61 bright sources ( $F > 2$  Jy), none of which are sidelobes; this improved the performance of the classifier for bright objects.



**Figure 6.** Distribution of sidelobe probability  $P(S)$  in the *FIRST* catalog. 76% of the sources are in the lowest bin,  $P(S) < 0.05$ .

The 15 parameters used for the classification include nine source properties (peak-to-integrated flux ratio, rms noise level, source major and minor axes compared with the synthesized beam, source position angle, ratio of source peak and integrated flux densities to the corresponding values in the “island” to which the source belongs<sup>11</sup>), and six properties of the nearest bright source that could be creating sidelobes (positional offsets, flux ratios, and directions). Ten independent oblique decision trees were created using this training set. Their outputs are combined as described in White et al. (2000) to estimate a sidelobe probability,  $P(S)$ , for every *FIRST* source.

A histogram of the resulting sidelobe probabilities is shown in Figure 6. The vast majority of the sources have low sidelobe probabilities; in fact, 70% of the objects have the minimum  $P(S)$  value of 0.014. The mean sidelobe probability for the catalog is 0.097, which is an estimate of the fraction of sidelobes in the catalog.

Figure 7 shows the spatial distribution of objects in the vicinity of bright radio sources, which frequently give rise to nearby sidelobes. Applying a probability cut  $P(S) < 0.1$  (Figure 7(b)) eliminates the vast majority of the obvious sidelobe pattern. The effect of the bright source can also be seen in the radial dependence of the mean  $P(S)$  (Figure 8). The probability is lower in the closest bins because of the tendency of bright radio sources to have multiple components (doubles, triples, etc.); away from the center the probability declines with radius and with the bright source flux density.

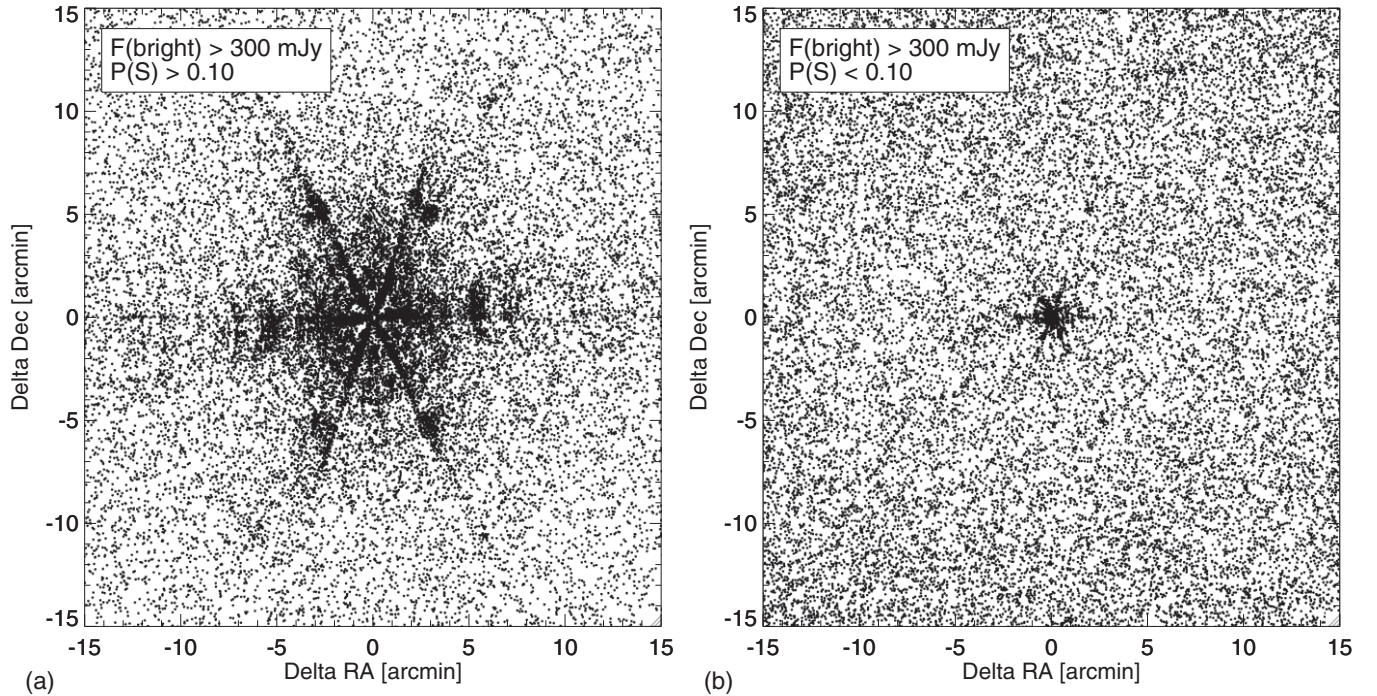
The sidelobes are heavily concentrated in the vicinity of bright sources. The 10% of *FIRST* catalog sources that fall within 10 arcmin of a bright object ( $F > 100$  mJy) have a mean sidelobe fraction  $P(S) = 0.24$  and account for 25% of all the sidelobes in the catalog. The remaining 90% of *FIRST* sources (not near a bright object) have a much lower sidelobe fraction,  $P(S) = 0.08$ . We conclude that the sidelobe probability behaves qualitatively as expected, and that the  $P(S)$  value does separate likely sidelobes from other sources in the vicinity of bright objects.

We rely on matches to external catalogs for quantitative assessments of the accuracy of the *FIRST* sidelobe probabilities. The NVSS-*FIRST* cross-match (Section 5) provides one obvious test of  $P(S)$ . It is not definitive, however, because the 2.5 mJy

<sup>9</sup> The OC1 oblique decision tree software is available for download at <http://www.cbcu.umd.edu/~salzberg/announce-oc1.html>.

<sup>10</sup> The deeper imaging from Schinnerer et al. (2007) was not available at the time.

<sup>11</sup> The islands are rectangular pixel regions surrounding sources as described in Section 3 of White et al. (1997).

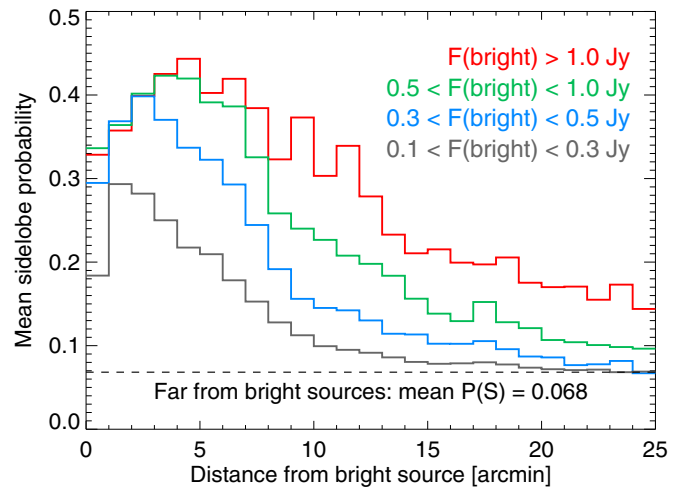


**Figure 7.** Distribution of sidelobes in the vicinity of bright sources. The offsets of all *FIRST* catalog entries in the vicinity of sources with  $F(\text{peak}) > 300$  mJy are shown. (a) The typical snapshot sidelobe pattern that results from the three arms of the VLA is clearly visible in sources with higher sidelobe probabilities,  $P(S) > 0.1$ . (b) The strong sidelobe pattern is almost absent for the sources with low sidelobe probabilities,  $P(S) < 0.1$ .

NVSS detection limit is significantly shallower than *FIRST*. The great majority of sources with high  $P(S)$  values are faint in the radio: the mean peak flux density for sources with  $P(S) > 0.1$  is only 1.35 mJy, and only  $\sim 4\%$  of those objects have flux densities above the NVSS detection threshold. That means that NVSS can only be used to confirm the accuracy of  $P(S)$  for bright sources; it does not provide any information about the much more common faint sidelobes. Nonetheless, the comparison is useful. Figure 9(a) shows the NVSS detection fraction for *FIRST* sources as a function of sidelobe probability. We include only *FIRST* sources that are bright enough that they ought to be detected by NVSS. The detection fraction declines as expected as  $P(S)$  increases. The general trend toward fewer detections at higher  $P(S)$  is clear and confirms that the sidelobe probabilities are reliable for brighter *FIRST* sources.

The cross-match between *FIRST* and SDSS (Section 7) provides a more powerful test of the sidelobe probabilities. That may be surprising since the optical counterparts of most *FIRST* sources are too faint to be detected by SDSS; the absence of an optical counterpart does not reveal much about the reality of an individual radio source. However, the SDSS match fraction provides an accurate *statistical* measurement of the sidelobe fraction down to the detection limit of the *FIRST* survey. The complication in this case is that the fraction of sources with optical counterparts depends on the radio flux density, but that variation is relatively smooth and can be easily modeled.

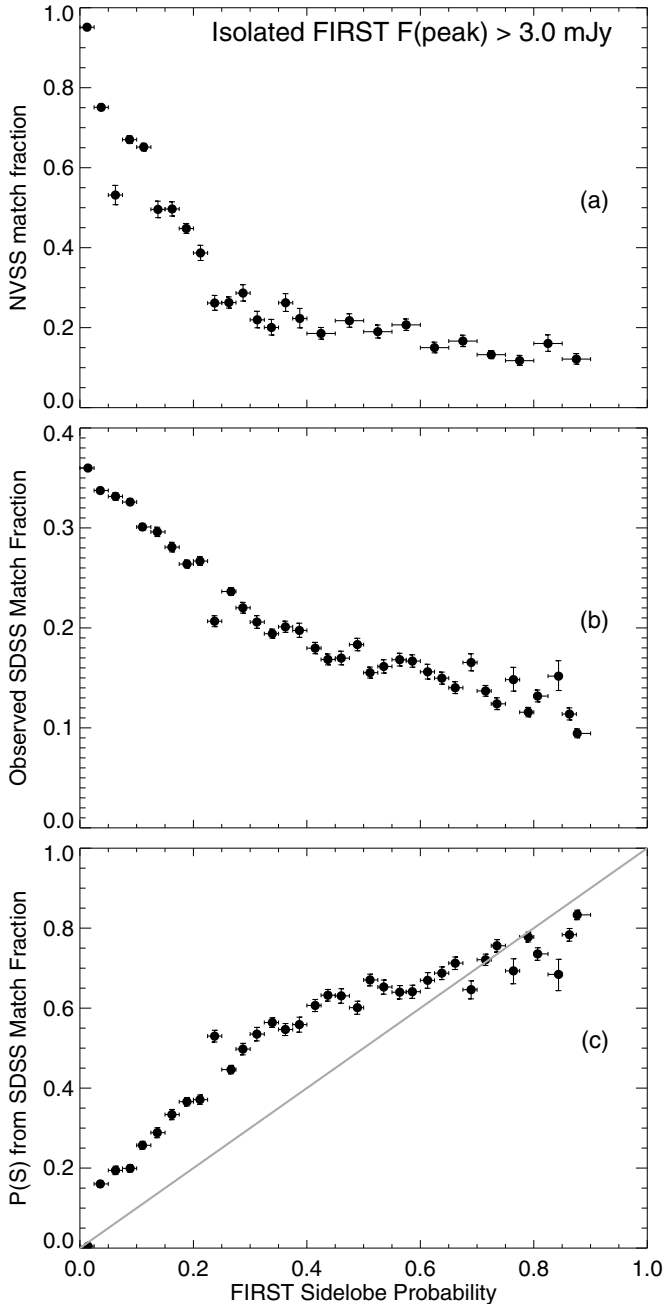
Figure 9(b) displays the fraction of *FIRST* sources with an SDSS counterpart as a function of the sidelobe probability. The distribution is well-behaved and clearly shows the expected decline with the increasing fraction of spurious sources (which naturally do not have SDSS counterparts). In this figure no corrections have been made for the dependence of the SDSS match fraction on radio flux density. For Figure 9(c), we have both corrected for that flux dependence and also have inverted the distribution, using the corrected SDSS match fraction as



**Figure 8.** Variation of mean sidelobe probability  $P(S)$  with distance from bright sources. The sidelobe likelihood generally declines with the flux density of the bright source and with distance from the bright source, as expected. The dashed line shows the mean  $P(S)$  for all the catalog sources that are not within 25 arcmin of a source brighter than 100 mJy.

a measurement of the sidelobe probability. This can then be compared directly with the catalog value for  $P(S)$ . The points would fall along the diagonal line if the catalog  $P(S)$  values were perfect predictors of the sidelobe fraction. The actual sidelobe probabilities appear to be slightly higher than the catalog estimates, but the catalog  $P(S)$  values do appear to be reasonably accurate.

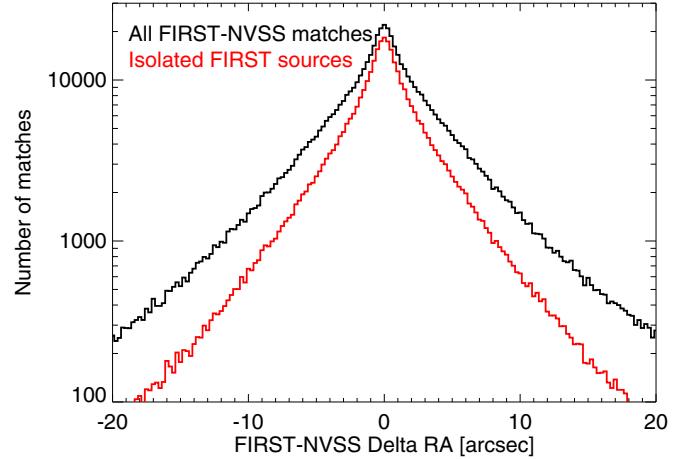
In summary, the sidelobe probabilities  $P(S)$  in the *FIRST* catalog give a useful measure of the likelihood that any source is spurious. The probabilities have been shown to be sufficiently accurate to be useful, and they do a good job of eliminating the spurious detections that tend to cluster around bright radio sources.



**Figure 9.** Tests of the accuracy of the sidelobe probability  $P(S)$ . (a) *FIRST*-NVSS match rate as a function of  $P(S)$ . Only isolated *FIRST* sources with integrated flux densities brighter than 3.0 mJy are included. For low  $P(S)$  values, 95% of the *FIRST* sources are detected in NVSS. (b) *FIRST*-SDSS match rate as a function of  $P(S)$ . The decline in the match rate with increasing sidelobe probability is roughly consistent with expectations assuming that the fraction of real sources in each bin is proportional to  $1 - P(S)$ . The distribution is not expected to be exactly linear since the radio flux density distribution varies with  $P(S)$ , and the observed SDSS match rate depends on radio flux (Figure 16). (c) Sidelobe probability estimated using the SDSS match rates in (b). The effect of variation of match rate with radio flux was corrected using a fit to the distribution in Figure 16. The points would lie along the diagonal line if the catalog  $P(S)$  values were perfect predictors of the sidelobe fraction. The sidelobe probability  $P(S)$  quoted in the catalog (x-axis) appears to be slightly underestimated for moderate probabilities ( $0.1 < P(S) < 0.6$ ).

## 5. COMPARISONS WITH NVSS: COMPLETENESS AND RELIABILITY

The NVSS (Condon et al. 1998), also conducted at 20 cm, covered over  $3\pi$  steradians of the sky north of  $\delta = -40^\circ$  to



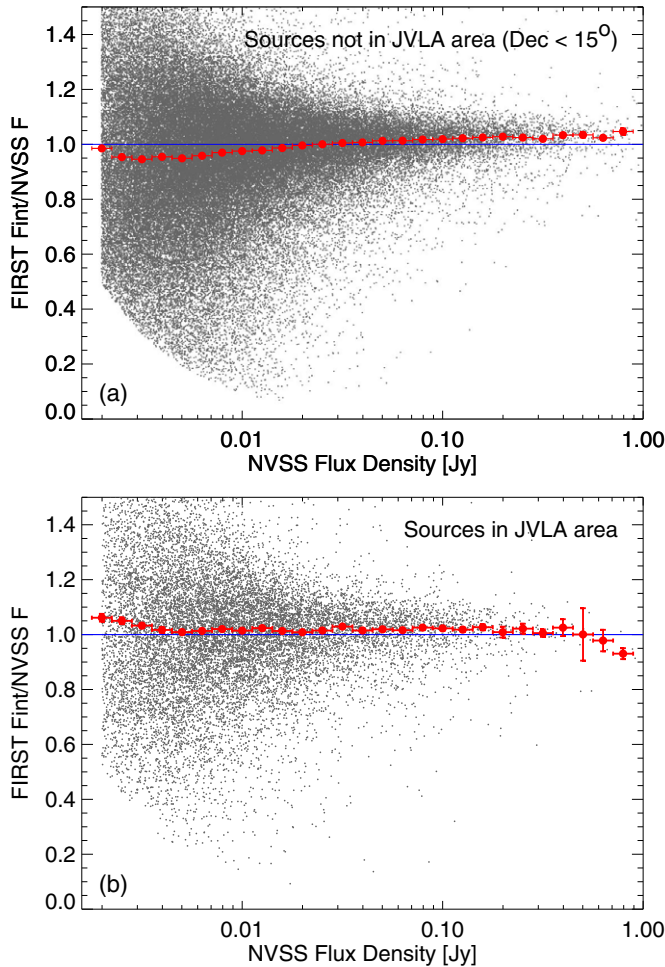
**Figure 10.** Positional offsets in R.A. for all *FIRST*-NVSS radio source matches (in black) and for isolated *FIRST* sources defined as there being only one such source within  $50''$  (the NVSS synthesized beam FWHM) of an NVSS source. The distribution is highly symmetrical and centered very close to zero (see Table 2 for quantitative details). The distribution for all sources is significantly wider as single NVSS sources are often resolved into multiple components by *FIRST*.

a completeness limit outside of the Galactic plane of roughly 2.5 mJy. The synthesized beam size was  $\sim 45''$  leading to rms positional uncertainties of  $7''$  for point sources at the catalog detection limit, with errors for brighter sources decreasing inversely with flux density to  $\sim 1''$  for the brightest sources.<sup>12</sup> The large beam size allowed the detection of extended, low-surface-brightness objects that can be resolved out by the high-resolution ( $5''$ ) *FIRST* beam; in addition, for sources with angular sizes between  $\sim 10''$  and  $60''$ , the *FIRST* flux densities underestimate the true integrated source intensity.

In Figure 10 we show the positional offsets in R.A. for all *FIRST*-NVSS radio source matches (in black) and for all isolated *FIRST* sources defined such that there is only one such source within  $50''$  of the NVSS source position (roughly equal to the NVSS synthesized beam FWHM). The distribution is highly symmetrical and centered very close to zero (see Table 2 for quantitative details); the distribution of offsets in declination is indistinguishable from the R.A. distribution. The distribution for all sources is significantly wider as single NVSS sources are often resolved into multiple components by *FIRST*. Both distributions are distinctly non-Gaussian. Thus, rather than quote an rms in Table 2, we record the 68.3% percentile of the absolute value distribution, which is the equivalent of the rms for a Gaussian distribution.

In Figure 11(a) we plot the ratio of *FIRST* source flux density to NVSS flux density for all matching sources at declinations  $< 15^\circ$  (imposed for comparison with Figure 11(b)) as a function of NVSS flux density. The brighter of the peak or integrated *FIRST* flux density is used. The blue bar shows a ratio of unity, while the red dots show the median values for the bins indicated by the horizontal error bars (vertical error bars are smaller than the points). The 2.0 mJy cutoff on the left is the NVSS threshold; the curving cutoff in the lower left represents the *FIRST* threshold of 1.0 mJy. The  $\sim 1\%$ – $5\%$  deficit in *FIRST* flux density between 2.0 and 20 mJy is likely the result of diffuse flux from extended sources resolved out by the *FIRST* beam; the turn-up for the lowest two flux density points arises from

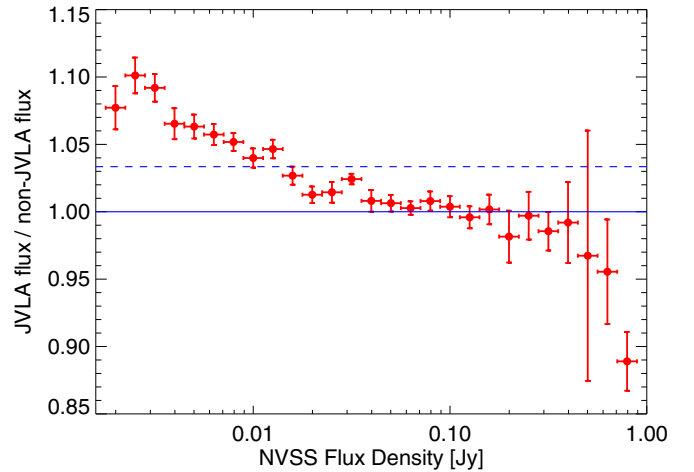
<sup>12</sup> But see Section 8.3 for a discussion of more realistic positional uncertainties for optical matching.



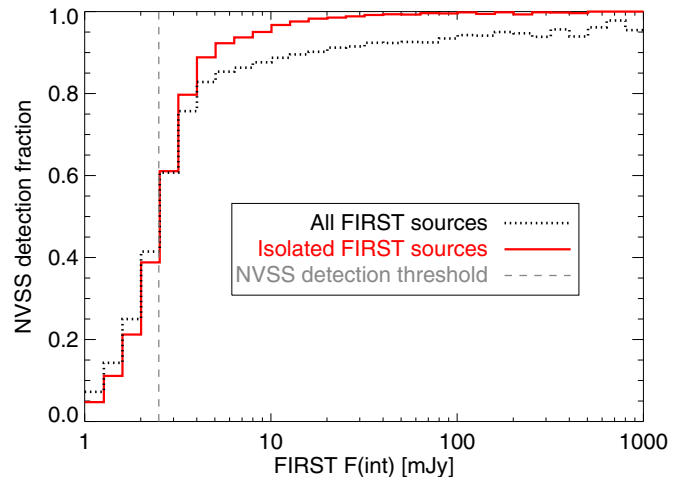
**Figure 11.** Ratio of *FIRST* source flux density to NVSS flux density as a function of NVSS flux density (a) for all matching sources at declinations  $< 15^\circ$  and (b) for sources observed in 2011 exclusively with the JVLA. The brighter of the peak or integrated *FIRST* flux density is used. The blue bar shows a ratio of unity, while the red dots show the median values for the bins indicated by the horizontal error bars (vertical error bars are mainly smaller than the points). The 2.0 mJy cutoff on the left is the NVSS threshold; the curving cutoff in the lower left represents the *FIRST* threshold of 1.0 mJy.

the imposition of the 1 mJy *FIRST* threshold that biases the distribution upward. The rise above unity at NVSS flux densities  $> 50$  mJy could arise from a calibration offset of  $\sim 2\%$  plus a (possibly dominant) contribution from the different bandwidths used in the two surveys convolved with the source spectral index distribution.

Figure 11(b) displays the same plot as Figure 11(a) for sources observed with the JVLA in 2011. For the JVLA data, the agreement with NVSS fluxes is actually somewhat better for flux densities greater than 4 mJy. In Figure 12, we plot the ratio of the flux density offsets (*FIRST* divided by NVSS) between *FIRST* data taken with the VLA and with the JVLA. All data are for sources with  $\delta < 15^\circ$  to eliminate any declination-dependent effects such as changes in the PSF. We believe there are several competing effects that produce the variations seen here. First, sources with typical spectral indices should be slightly brighter in the lower-frequency JVLA observations (1.335 versus 1.400 GHz—see Section 2.1). The horizontal dashed line at  $+3.3\%$  represents the expected offset for sources with a mean spectral index of  $\alpha = -0.7$ . That effect changes with flux, however, since the spectral indices become flatter for compact bright sources. A second effect is



**Figure 12.** Ratio of the flux density offsets (*FIRST* divided by NVSS) between *FIRST* data taken with the VLA and the JVLA. All data are for sources with  $\delta < 15^\circ$  to eliminate declination effects. The horizontal dashed line at  $+3.3\%$  represents the expected offset for sources with a mean spectral index of  $\alpha = -0.7$ , given the difference in effective frequency for the two sets of observations.

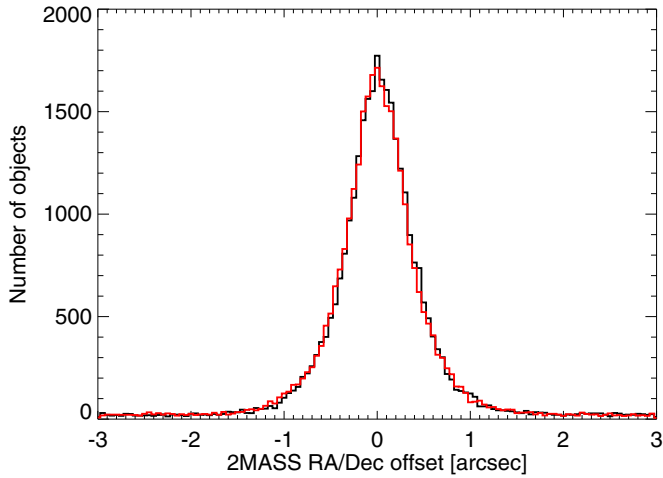


**Figure 13.** Fraction of *FIRST* sources that are detected by NVSS as a function of the *FIRST* integrated flux density using a  $15''$  matching radius. The vertical dashed line shows the NVSS 2.5 mJy detection limit. The black dotted line shows the distribution for all *FIRST* sources. The small fraction of bright unmatched sources are extended objects that are resolved into multiple components by *FIRST*. That is demonstrated clearly by the solid red line, which shows the distribution for isolated *FIRST* sources (having no neighbors within  $50''$ ).

that the lower-frequency JVLA observations are also of slightly lower resolution, which increases their sensitivity to extended emission. That is likely the reason why the dip seen from 3–10 mJy in Figure 11(a) is not seen in Figure 11(b).

This effect illustrates the sensitivity of large surveys to small changes in observing parameters. Subtle changes can lead to noticeable differences in large statistical samples of sources, so flux differences between the JVLA and VLA data at the level of 5–10% (Figure 12) should be treated with caution. Correcting for these effects would require knowledge of the spectral indices and sizes of the sources, which are usually not available. Note, however, that these systematic effects are small compared with the noise for faint sources, so most studies can treat the JVLA and VLA data as having equivalent flux scales.

Figure 13 shows the fraction of *FIRST* sources detected by NVSS as a function of the *FIRST* integrated flux density.



**Figure 14.** Positional offsets in R.A. (black), and decl. (red) between *FIRST* radio sources and 2MASS objects. The distribution is highly symmetrical and centered very close to zero (see Table 2 for quantitative details).

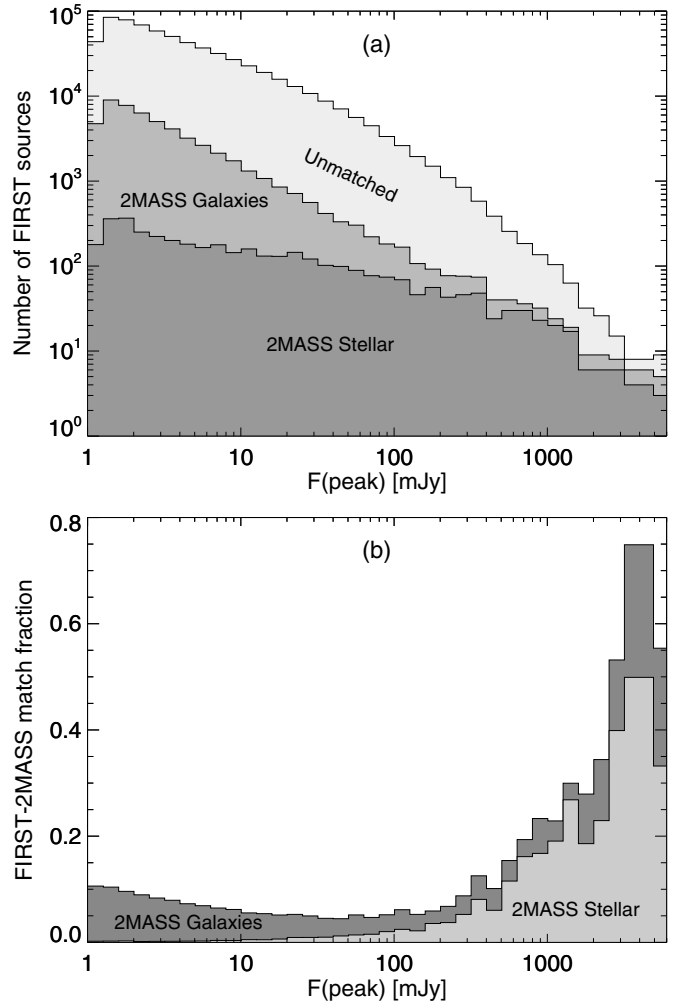
The factor of 10 difference between the resolutions of the two surveys complicates the interpretation of this figure. Many NVSS sources are resolved by *FIRST* into multiple components. Those sources will appear as lower flux *FIRST* sources detected by NVSS, when in fact NVSS only detects the sum of the components; that accounts for most of the tail of detections at fainter fluxes. Moreover, such sources will often have large positional differences so that they do not match within the  $15''$  matching radius we are using here; that accounts for the small fraction of bright *FIRST* sources that are undetected by NVSS. The detection fraction for isolated *FIRST* sources is also shown in Figure 13; essentially all bright isolated *FIRST* sources are detected by NVSS.

## 6. MATCH TO THE 2MASS CATALOG

The first deep image of the entire sky at  $2\ \mu\text{m}$  was produced by the 2MASS Survey between 1997 and 2001 (Skrutskie et al. 2006). The primary data products from the survey are an image atlas, and point and extended source catalogs containing over 470 million objects.

Astrometric data from the match of the *FIRST* catalog to the 2MASS point source catalog are reported in Table 2 and displayed in Figure 14. We calculate the offsets between all *FIRST* source positions and any 2MASS object within  $\pm 3''$  in each coordinate; this large box includes some chance coincidences but is highly complete even for extended objects. The astrometric offsets and rms widths are determined from Gaussian fits to the distribution in each coordinate. There is a statistically significant  $+20\ \text{mas}$  offset in Right Ascension and a  $+10\ \text{mas}$  offset in declination that persists even when only bright ( $> 10\ \text{mJy}$ ) radio sources are used in the matching; as noted in Section 3, we believe that the R.A. offset, at least, arises from a systematic error in the VLA data acquisition system which the JVLA has corrected.

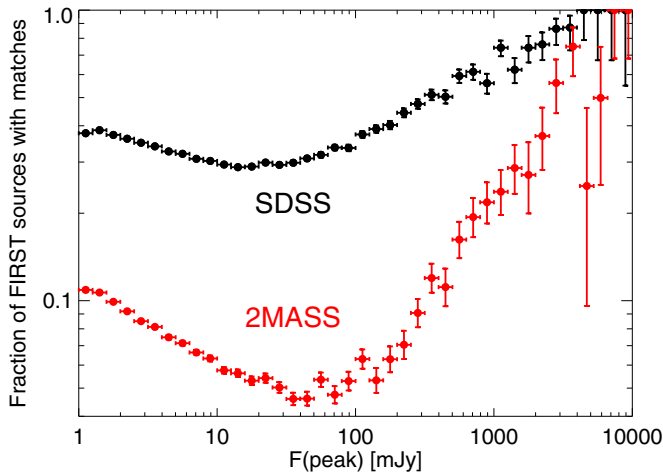
The rms uncertainties are the same in both coordinates. For the *FIRST* convolving beam size of  $5''.4$ , even bright point sources ( $> 5\sigma$ ) will have an inherent rms positional uncertainty of  $\sim 0''.1$  (White et al. 1997); the 2MASS  $2''.0$  pixel size convolved with variable seeing led to an astrometric accuracy of  $\lesssim 0''.10$  relative to the *Hipparcos* reference frame for objects with  $K_s < 14$  (Skrutskie et al. 2006). The fact that the large majority of the 2MASS matches are extended galaxies (see Figure 15)



**Figure 15.** *FIRST*–2MASS matches as a function of *FIRST* flux density. The 2MASS sources have been divided into stellar objects (mainly AGNs) and galaxies using the SDSS classification. (a) The raw counts of *FIRST* sources and 2MASS matches as a function of flux. Only sources with low sidelobe probabilities,  $P(S) \leq 0.02$ , are included, which is why the number of sources drops near the detection limit. (b) The fraction of 2MASS matches as a function of flux. The bulk of 2MASS sources detected by *FIRST* are galaxies.

plausibly makes up the remainder of the  $0''.23$  value reported in Table 2.

In Figures 15 and 16, we show the fraction of *FIRST* radio sources with 2MASS counterparts as a function of radio flux density. The match fractions have been corrected for the effects of false matches using the density of 2MASS objects that fall between  $7''.5$  and  $8''$  from the *FIRST* source. The *FIRST*–2MASS match fraction falls from 100% at the brightest flux densities ( $> 5\ \text{Jy}$ ) to less than 5% at  $40\ \text{mJy}$  and then begins a steady rise to 10% near the survey threshold of  $1\ \text{mJy}$ . This is a consequence of the two population components that comprise the radio log  $N - \log S$  curve in the  $1\text{--}1000\ \text{mJy}$  range: “monsters” (radio-loud active galactic nuclei) and “normal” galaxies (Condon 1992); see the end of Section 7 for further discussion of the effects of the transition between populations. This plot includes only *FIRST* objects with low sidelobe probabilities,  $P(S) \leq 0.02$  (Section 4); that avoids contaminating the counts in the lowest flux bins with spurious sources. The fact that the 2MASS points all lie below the SDSS fraction of detections (Figure 16) is simply a consequence of the shallower depth of the 2MASS images.



**Figure 16.** Fraction of *FIRST* radio sources with counterparts in the SDSS and 2MASS catalogs (using a 2 arcsec matching radius) as a function of peak radio flux density. Horizontal error bars represent the flux density ranges, while vertical error bars represent statistical uncertainties. Values are corrected for the false match rate. Only sources with low sidelobe probabilities,  $P(S) \leq 0.02$ , are included. Both curves show a minimum where the radio source counts change from being dominated by AGN at high flux densities to being dominated by normal galaxies.

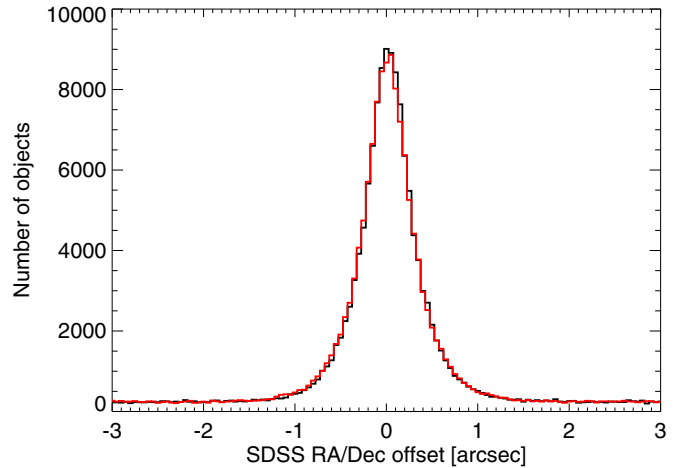
## 7. MATCH TO THE SDSS CATALOG

In recognition of the high scientific value to a radio survey of having complementary optical data from which to derive radio source identifications, the original *FIRST* survey footprint was designed to largely overlap the (then-planned) SDSS. In the end, 93% of the *FIRST* sky coverage is also covered by SDSS. The extension to the original *FIRST* footprint, approved in 2008, was added in order to provide complementary data to a portion of the SDSS III survey.

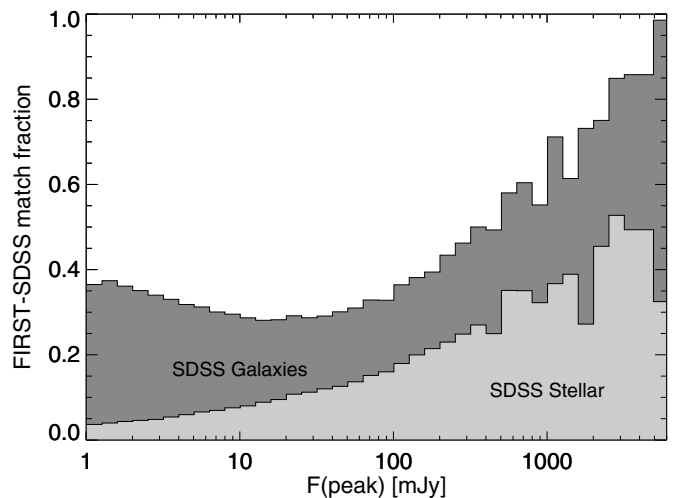
The SDSS I and II projects collected imaging data between 2000 and 2008 over more than 10,000 deg<sup>2</sup> of the northern and southern Galactic caps in five colors, as well as obtaining spectra of over one million objects within the survey area. The images and catalogs resulting from this effort are summarized in Data Release 7 (Abazajian et al. 2009). Data Release 10 in 2013 July increased the total sky coverage to over 14,500 deg<sup>2</sup> and brought the catalog to over one billion objects of which over 1.6 million have spectra (Ahn et al. 2014). The *FIRST* survey covers 68% of the SDSS DR10 sky area.

The first attempt at large-scale matching of SDSS and *FIRST* sources was published by Ivezić et al. (2002). The  $\sim 0''.1$  astrometric offset in declination they found was subsequently corrected in the SDSS astrometry pipeline. Figure 17 and Table 2 show the results of the final match presented here for various optical and radio source properties. As with the 2MASS matches, we determine the astrometric offsets and rms widths by fitting a Gaussian to the distribution of SDSS sources found within  $\pm 3''$  of a *FIRST* source in each coordinate. We report the match properties between all *FIRST* and SDSS objects as well as for subsets of the radio sources (point sources, bright  $> 10$  mJy sources) matched with optical objects separated into stellar and galaxy counterparts. As with 2MASS, we see a small but statistically significant +20 mas offset in Right Ascension and a +10 to +15 mas offset in declination (Section 3).

The uncertainties in R.A. and declination are essentially identical. For the brighter ( $S/N \gtrsim 50$ ) radio sources matched to point-like optical counterparts, the rms of  $\sim 0''.15$  is consistent



**Figure 17.** Positional offsets in R.A. (black) and decl. (red) between *FIRST* radio sources and SDSS objects. As for the 2MASS matches, the distribution is highly symmetrical and centered close to zero (see Table 2 for quantitative details).



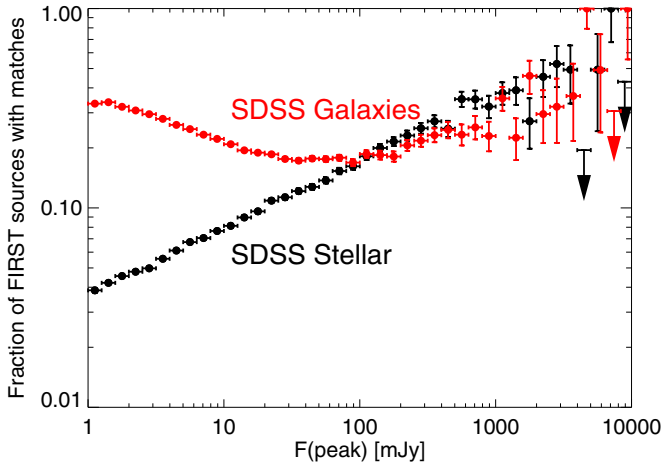
**Figure 18.** Fraction of SDSS matches to *FIRST* sources as a function of *FIRST* flux density using a matching radius of 2 arcsec. The SDSS sources have been divided into stellar objects (AGNs) and galaxies. Only sources with low sidelobe probabilities,  $P(S) \leq 0.02$ , are included.

with the reported rms positional uncertainty for SDSS ( $\sim 0''.1$ ), coupled with a similar uncertainty for *FIRST* sources.

Ivezić et al. (2002) reported that roughly 30% of the initial batch of  $10^5$  *FIRST* sources had optical counterparts in SDSS, the large majority of which (83%) were resolved optical objects (i.e., galaxies); galaxies accounted for  $\sim 50\%$  of the counterparts at the brightest radio flux densities, rising to 90% at the survey threshold of  $\sim 1$  mJy. The total fraction of SDSS matches in the completed catalogs, shown in Figure 18, is roughly consistent with this overall match rate.

Figures 18 and 19 show the SDSS match to the completed *FIRST* survey over a radio flux density range of a factor of  $10^4$ . At the bright end, the majority of radio sources have SDSS counterparts.<sup>13</sup> Stellar counterparts (all but a handful of which are quasars) fall monotonically to  $\sim 4\%$  of all *FIRST* sources

<sup>13</sup> In fact, just 6 of the 34 sources brighter than 3 Jy fail to match an SDSS object within  $1''$ . Three of these are components of M87 which, of course, does have a match; one falls outside the SDSS coverage; and the other two are 3C280 and PKS 2127+04, both radio galaxies at  $z = 1$  that do fall below the SDSS threshold.



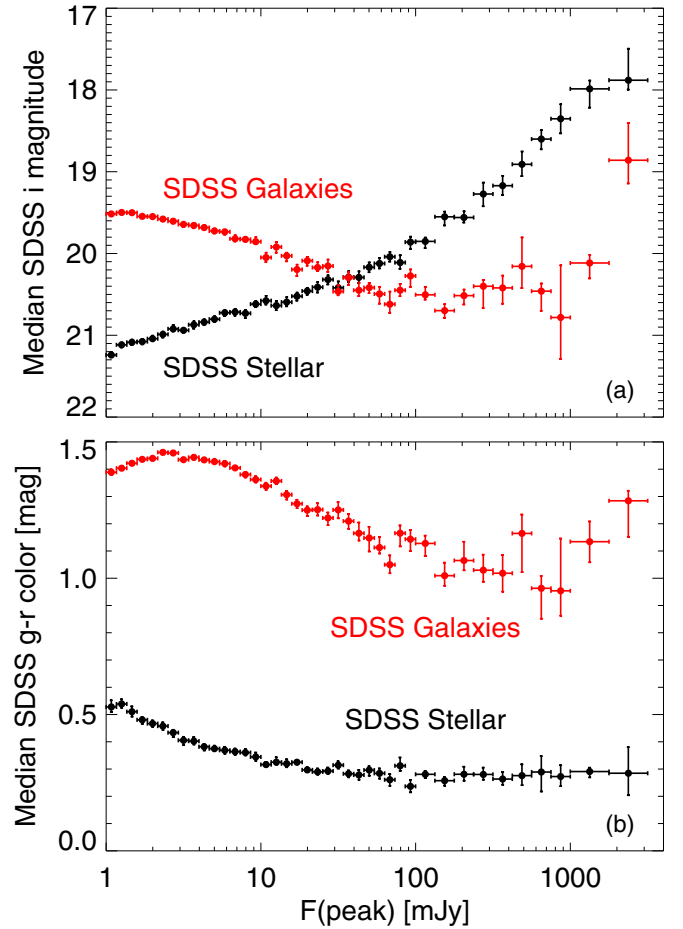
**Figure 19.** Fraction of *FIRST* radio sources with counterparts in the SDSS divided by counterpart classification: stellar objects which, with the exception of a handful of radio stars, are quasars or other AGNs, and galaxies. Only sources with low sidelobe probabilities,  $P(S) \leq 0.02$ , are included. The fraction of sources with stellar counterparts declines monotonically from 100% to 3%, while those with galaxy counterparts transition from AGN-dominated systems at high flux densities to radio emission dominated by star formation near the survey threshold.

at the survey threshold, while galaxy counterparts fall to a minimum of a 10% identification rate at 100 mJy and then rise again to  $>30\%$  of all *FIRST* sources at 1 mJy; this reflects the long-established change in the radio source population mix as a function of flux density (Condon 1992).

The magnitudes and colors of the SDSS counterparts to *FIRST* sources also vary systematically with radio flux density (Figures 20(a) and (b)). Changes in both of these quantities result from the transition from active galactic nucleus (AGN)-powered radio emission for the brightest radio sources to star-formation-powered radio emission for milliJansky radio sources. Around 1 Jy, the supermassive black hole “monsters” dominate the counterparts for both stellar objects and galaxies; objects appear as blue, point-like quasars when nuclear emission also dominates the optical, while radio galaxies have similar radio fluxes but are 10 times fainter in the optical. As the radio flux declines from 1 Jy to 1 mJy, quasars become both fainter and redder, mainly because the population is shifting to higher redshift. The magnitudes and colors of galaxies change little from 1 Jy to 100 mJy because the radio galaxy counterparts to bright radio sources are already close to the SDSS detection limit. However, below 100 mJy the median magnitudes of *FIRST*-selected galaxies actually get brighter as the radio flux decreases. This somewhat unexpected result is caused by the *FIRST* detection of nearby ( $z < 0.5$ ) star-forming galaxies. These objects are low-luminosity radio sources but are bright optical sources. As star-forming galaxies take over the sample compared with low-luminosity radio galaxies, the median galaxy brightness increases. The galaxy colors initially get redder because of the declining contribution of blue nuclear emission, and then around 4 mJy the galaxy colors begin to become bluer as nearby galaxies with high star-formation rates are detected.

## 8. CONCLUSIONS: LESSONS FOR FUTURE RADIO SKY SURVEYS

Rather than reiterate our results in a summary, we draw conclusions from the two-decade experience of the *FIRST*



**Figure 20.** Magnitudes and colors of SDSS stars (black) and galaxies (red) as a function of *FIRST* peak flux density. (a) Median *i*-band magnitudes. Stellar objects (mainly AGN) have radio and optical fluxes that decline in concert; the flattening around  $i = 21$  occurs as the SDSS detection limit is approached. Galaxies, on the other hand, optically brighten with decreasing radio flux density as the population shifts from high-redshift AGN in radio-bright galaxies to low-redshift star formation associated with mJy sources. (b) Median  $g-r$  colors. Stellar objects (quasars) are typically more than 1 mag bluer than galaxies. Both quasars and galaxies get redder as the radio flux density decreases, presumably due to the increasing redshift of fainter radio sources. Galaxies begin to get bluer for  $F < 3$  mJy as the nearby star-forming galaxies come into view.

survey that may be of use for the next-generation projects to map the radio sky. We include remarks on scheduling, the continuing usefulness of uniform sky surveys, and the all-important matter of angular resolution in radio source identification, concluding with brief remarks on the value of a JVLA sky survey.

### 8.1. Scheduling

A priority for any sky survey is uniformity. This is best achieved when the hardware, software, and researchers change little over the course of the project. Our original proposal to survey the radio sky with the VLA suggested arranging for a special, hybrid array to yield both high-resolution (and thus, high astrometric accuracy) and high surface brightness sensitivity (to detect nearby galaxies), and devoting six months to the project, after which normal VLA operations would resume. In the event, two separate surveys were conducted, consuming approximately nine months of observing time; in the case of the *FIRST* survey, this was spread over eighteen years. As noted earlier, the allocated observing windows were not optimally matched to the sky area to be covered, meaning the observations

often had to be carried out off the meridian (which would have been optimal). Queue scheduling, the antithesis of careful planned and optimized observing windows, should be avoided at all costs for survey observations.

Hardware and software changes accumulate the longer a survey takes. Examples from the *FIRST* experience are briefly summarized in Section 2; the changes to the researchers over two decades are best left to the reader’s imagination.

### 8.2. The Legacy Value of Uniform Sky Surveys

The papers of record describing the two VLA surveys—Becker et al. (1995) and Condon et al. (1998)—have received over 4000 citations; both papers recorded their highest annual citation rates in 2014, 19 and 16 years after their publication, respectively. Over six million snapshot images have been downloaded from the *FIRST* survey Web site alone. If those queries replaced three-minute snapshot observations, the observing time saved amounts to 75 times the total time invested in the survey by the VLA. And the number of images accessed continues to increase with time. Over the past two years (2012 June through 2014 June), more than 2.5 million image cutouts were extracted from our image server by 2500 different users around the world. Every 20 s our server delivers a cutout that is the equivalent of a 1 minute snapshot observation with the current JVLA receivers; in 3 weeks our server distributes snapshots with a combined exposure time equivalent to the entire 4000 hr of VLA time that was allocated for the *FIRST* survey. The investment of observing time in the *FIRST* survey continues to pay dividends to the astronomical community.

### 8.3. Angular Resolution and Source Identification

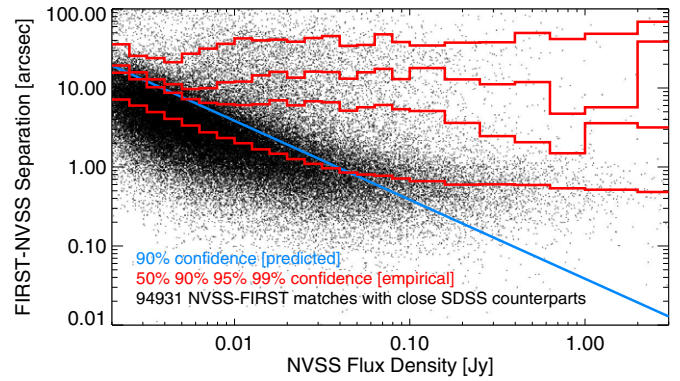
Radio surveys require high angular resolution in order to have positions sufficiently accurate to obtain source identifications with objects at other wavelengths. Optical and infrared counterparts of even relatively bright radio sources are faint: e.g., only 33% of *FIRST* radio sources have an optical counterpart bright enough to be detected in SDSS. An important corollary to the fact that radio source identifications are faint is that potential counterparts are dense on the sky, and accurate radio positions are required to confidently associate the radio and optical objects.

#### 8.3.1. Signal-to-noise Ratios and Source Positions

Can deeper radio observations at low resolution be a substitute for higher resolution observations? A common argument of advocates for lower resolution surveys is that as the signal-to-noise ratio (S/N) increases, the positions of catalog sources improve. Consequently one does not really need high resolution to do optical identifications. The prediction of this S/N model is that as the flux density increases, the positional error will decrease as  $1/S/N$ , allowing the optical counterpart to be confidently matched. Specifically, the NVSS description (Condon et al. 1998) gives this formula for the noise in R.A. or decl. for point sources:

$$\sigma_{1D} = \theta / (S/N \sqrt{2 \ln 2}). \quad (1)$$

Here  $\theta$  is the resolution FWHM (45'' for NVSS) and S/N is the signal-to-noise ratio. The median NVSS rms noise for objects that match *FIRST* sources is 0.47 mJy. Note that this noise equation already has been increased by an empirical factor of  $\sqrt{2}$  compared with the theoretical equation “to adjust the errors into agreement with the more accurate *FIRST* positions” (quoting



**Figure 21.** Position difference between NVSS and *FIRST* positions as a function of NVSS flux density. The sample includes only objects that have a close SDSS counterpart to the *FIRST* source position (within 0''.7). Blue line: theoretical 90% confidence separation limit computed using the S/N as in Equation (2). Red histograms: (from bottom to top) the 50%, 90%, 95%, and 99% confidence limits, computed by determining the actual separations in each bin. While the 50% curve behaves approximately as expected, the tail of the distribution is clearly non-Gaussian and has many more distant outliers than expected based on the predicted 90% curve.

the NVSS catalog description<sup>14</sup>) This predicts  $\sigma_{1D} \sim 7.6$  arcsec at the catalog detection limit ( $S/N = 5$ ) and  $\sigma_{1D} \sim 1$  arcsec at a flux density of 18 mJy.

The positional scatter in Equation (1) is a one-dimensional uncertainty, giving the error in either R.A. or decl. In a two-dimensional distribution, many values will scatter outside the  $1\sigma$  circle. The 90% confidence separation limit  $\sigma_{90}$ , which is typically more appropriate for catalog matching, is a constant factor  $\sqrt{2 \ln 10}$  times larger than  $\sigma_{1D}$ :

$$\sigma_{90} = \frac{\theta}{S/N} \sqrt{\frac{\ln 10}{\ln 2}}. \quad (2)$$

With this increase it is necessary for the NVSS flux density to exceed 40 mJy ( $S/N = 85$ ) to reduce the predicted separation error to 1 arcsec.

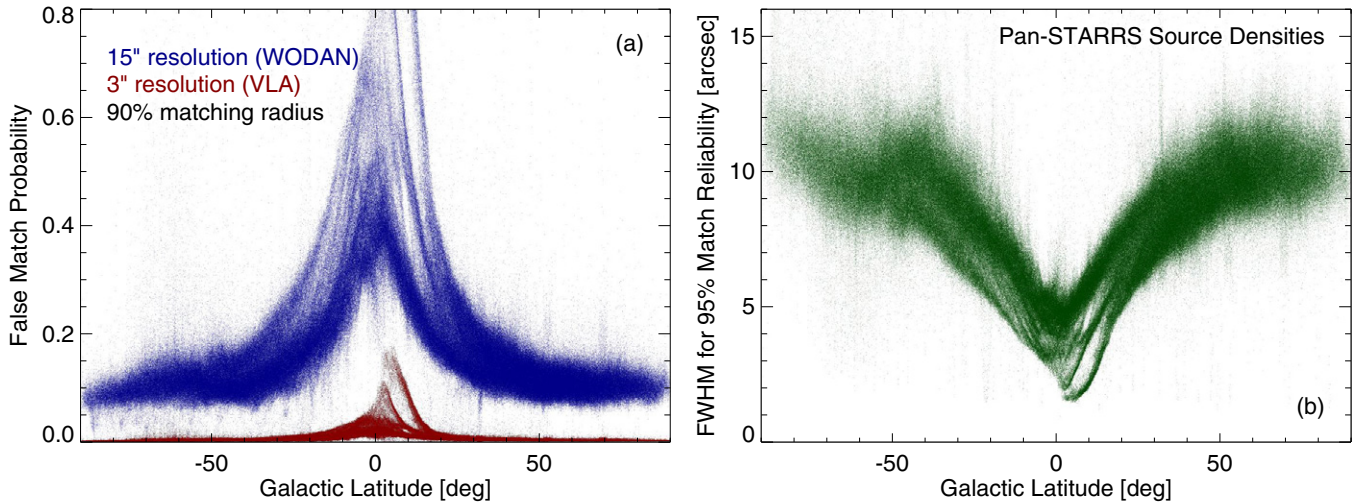
#### 8.3.2. Does the S/N Model Work for NVSS?

The above positional accuracy applies to perfect point sources (and perfect data). But how well does it work for real data? We can assess the accuracy of Equation (2) using a comparison of the *FIRST* and NVSS data.

We selected a sample of all the *FIRST* sources that have an SDSS match within 0.7 arcsec and that have an NVSS match within 100 arcsec. We restricted the sample to sources with *FIRST* peak flux densities greater than the 2.5 mJy NVSS detection limit. For all these  $\sim 95,000$  sources, we computed the distance to the nearest NVSS source. The important thing about this sample is that the *FIRST* source matches the optical source position. That means that if NVSS is to identify the same counterpart, it needs to have a position close to the *FIRST* source position. There may be several *FIRST* source components associated with a single NVSS source, but only the *FIRST* sources that match optical counterparts are included.

How do the positional errors in Equation (2) compare with reality? Figure 21 shows the position distance between the NVSS and *FIRST* positions as a function of the NVSS flux density. The positional differences decrease as expected as the flux densities increase. The blue line shows the 90% confidence

<sup>14</sup> <http://www.cv.nrao.edu/nvss/catalog.ps>



**Figure 22.** Left: probability of a false match in Pan-STARRS as a function of Galactic latitude. Right: FWHM resolution required to achieve 95% cross-match reliability. The actual density of PS1 objects was used to calculate the likelihood of a false counterpart within the 95% confidence radius. The bands come from filamentary structure in the dust absorption, which leads to regions of low and high object density in the Pan-STARRS catalog. The left panel shows probabilities both for the WODAN 15'' resolution (blue) and the VLA S-band 3'' resolution (red). Over most of the extragalactic sky  $\sim 10\%$  of WODAN-PS1 cross-matches will be chance coincidences, compared with  $<1\%$  of the VLA-PS1 matches. The VLA positions are sufficient for identifications even close to the Galactic plane. The right panel shows that in the extragalactic sky ( $|b| > 30^\circ$ ) a resolution better than 11'' is required. WODAN does not have the required resolution; ASKAP-EMU just reaches this limit but will not cover most of the northern sky. The VLASS S-band survey easily meets this requirement.

separation limit  $\sigma_{90}$  from Equation (2), simply assuming that all objects are point sources with the median NVSS rms value. Between 1 and 100 mJy, this line generally tracks the decline in positional differences as the flux density increases; however, there are still many points above the line.

The red histogram shows the empirical 50%, 90%, 95%, and 99% confidence separation limits as a function of flux density, computed by determining the relevant percentile of the actual separations in each bin. The computed separation has been corrected for the effects of chance nearby NVSS associations. *The actual 90% confidence radius shows no improvement in the positions for flux densities greater than 4 mJy, and it is much larger than the predicted 90% curve.*

This empirical distribution does not look like the theoretical distribution. Remember that there is an optical counterpart near zero separation in these plots for every source. To find 90% of those counterparts using the NVSS positions, it is necessary to use a matching radius of approximately 7 arcsec ( $\sim 0.15\theta$ ) even for sources that are 100 times the rms noise level. The theoretical S/N model predicts that the positions for such bright sources ought to be much more accurate than that ( $\sigma_{90} = 0.8''$ ). To include 95% of the counterparts requires a matching radius of 15'' ( $\sim 0.3\theta$ ), while finding 99% of the counterparts requires matching out to 39'' ( $\sim \theta$ ).

### 8.3.3. Why are the Low-resolution Positions so Inaccurate?

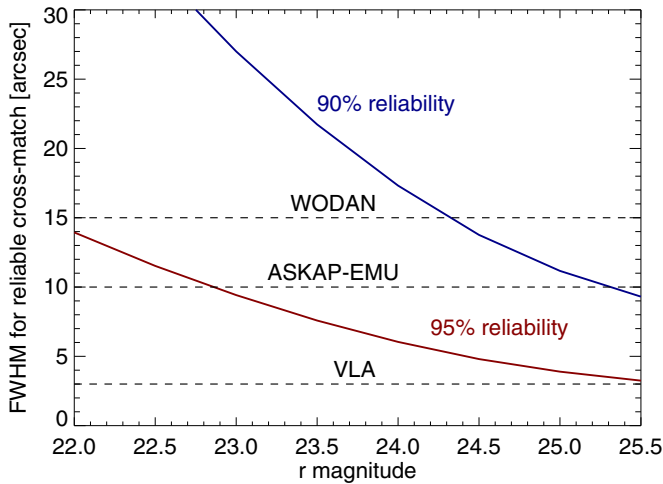
Why are the inaccuracies in the positions so much greater than the S/N model predictions? Real radio sources are not symmetrical objects. They have lobes, jets, and cores; star-forming galaxies have spiral arms. And there can be confusion when multiple radio sources get mixed together in a low-resolution beam. A low-resolution survey does indeed give a very accurate measurement of the mean flux-weighted position as the S/N increases. *However, the flux-weighted centroid is often not where the optical counterpart lies.* In many cases the counterpart is associated with some sharp structure within the radio source, and that structure may be far from the flux-weighted center.

### 8.3.4. Effect on Optical Identifications

This analysis demonstrates that matching at the 45'' resolution of NVSS requires a matching radius of 15'' = 30% of the NVSS FWHM resolution to achieve 95% completeness. Our experience with the FIRST survey is similar: to get a reasonably complete list of optical identifications we had to use a matching radius of 2''  $\sim 40\%$  of the FIRST FWHM resolution. We argue this is a universal requirement for radio sources, at least for sources down to the sub-mJy regime: the matching radius that is required for realistic radio source morphologies is at least 30% of the FWHM resolution for 95% completeness.

The planned Square Kilometer Array (SKA) precursor surveys have relatively low resolution. The resolution for WODAN (Röttgering et al. 2011) is of order  $15 \times 17$  arcsec, while the resolution for ASKAP-EMU (Norris et al. 2011) is 10 arcsec. For 95% completeness, WODAN will therefore require an optical matching radius of 4.8 arcsec and ASKAP-EMU will require 3 arcsec. Such large matching radii are a serious problem for optical matching. The cross-match between SDSS and FIRST shows that 19% of FIRST sources have a false (chance) SDSS counterpart within 4''.8. For comparison, 33% of FIRST sources have a true match within 2''. So one-third of the optical counterparts at SDSS depth will be false matches when using a 4''.8 matching radius. Of course the false rate can be reduced somewhat by doing a careful analysis of the likelihood of association as a function of separation, but when the starting point is a sample that is contaminated by 33% false matches, the final list of identifications is going to be neither complete nor reliable.

The false matching problem will only get worse for deeper optical/IR data. For example, Pan-STARRS (PS1; Kaiser et al. 2002) goes more than 1 mag deeper than SDSS in the red and also goes into the Galactic plane where the source density is much higher, demanding better resolution. We have used the sky density of objects in a preliminary PS1 catalog to compute the likelihood of false identifications in PS1 as a function of Galactic latitude. The left panel of Figure 22 compares WODAN to a VLA S-band (2–4 GHz) B-configuration survey



**Figure 23.** FWHM resolution required to achieve reliable cross-matches at fainter magnitudes using  $r$ -band galaxy counts. The curves define the limits for 90% and 95% reliable identifications, and the resolutions of ASKAP-EMU, WODAN, and a VLA 3'' resolution survey are shown. The depths of various  $r$ -band surveys are also shown by the vertical lines (Pan-STARRS, DESI, LSST, HSC). The SKA pathfinders are at best marginally sufficient for identifications at SDSS/Pan-STARRS depths, while a VLA  $S$ -band survey is usable with the much deeper surveys.

having 3'' resolution. For WODAN, 10% of sources even in the extragalactic sky ( $|b| > 30^\circ$ ) will have a spurious counterpart in PS1. For most purposes that is an unacceptable level of contamination. In contrast, a VLA survey has only a  $<1\%$  contamination rate in the extragalactic sky, and is usable even quite close to the Galactic plane.

The right panel of Figure 22 turns this around and asks what FWHM resolution is required to achieve a 95% reliability ( $\sim 2\sigma$ ) in matches to the PS1 catalog. At  $|b| > 30^\circ$  a FWHM resolution of 11'' is required. That is significantly higher resolution than WODAN and just at the resolution reached by ASKAP-EMU, but one easily satisfied by VLA surveys. In fact, a VLA survey with a resolution of 3'' has 95% confident PS1 matches over 99% of the current PS1 catalog area, with only the most crowded areas of the Galactic plane requiring higher resolution.

The next generation of optical/IR surveys will be considerably deeper than Pan-STARRS. Figure 23 shows the resolution required as a function of magnitude using the  $r$ -band galaxy counts from the CFHTLS-D1 1 deg<sup>2</sup> survey (McCracken et al. 2003). Since this does not include stars or redder galaxies, it is more optimistic (and less realistic) at the PS1 limit, but it shows the resolution required for deeper identifications. For 90% reliable identifications, a 3'' resolution VLA survey can be used to  $r = 27.2$ , ASKAP-EMU to  $r = 25.3$ , and WODAN to  $r = 24.3$ . For 95% reliable identifications, the magnitude limits are 24.9 (VLA), 22.1 (ASKAP-EMU), and 20.7 (WODAN). The SKA-precursor surveys are usable at the depth of SDSS and Pan-STARRS in the extragalactic sky, but fall well short of the required resolution at fainter magnitudes. The higher resolution VLA survey, by contrast, is useful at least to  $r = 26$ .

The inescapable conclusion is that we need high resolution to get the accurate positions required for optical identifications. Deeper radio imaging is not a substitute for the requisite angular resolution.

#### 8.4. A JVLA Sky Survey

A new generation of radio sky surveys will soon be conducted by survey arrays such as LOFAR (de Vos et al. 2009),

ASKAP (Johnston et al. 2008), MEERKAT (Booth et al. 2009) and, ultimately, perhaps, the SKA (Schilizzi et al. 2010). But the analysis above shows that none of the three SKA precursors provide the angular resolution necessary for unambiguous radio source identification or to resolve complex source regions. In addition, they operate at wavelengths of 20 cm or longer (initially, at least). It is thus worth considering whether the substantially enhanced JVLA might again be used for a sky survey.

The use of the JVLA for  $\sim 7$  months could produce a  $3 \times 10^4$  deg<sup>2</sup> survey at 2–4 GHz with an angular resolution two times that of *FIRST* and a sensitivity two times greater. This would produce over three times as many sources (taking into account the flux density falloff of most sources with frequency), one-quarter of which would have accurate spectral indices and all of which would have full Stokes parameters available. The positional accuracy for the three million sources would be better than 1''.

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