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Research Note

The WSRT 1.4 GHz amalgamated source counts

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Summary. We present the extragalactic radio source count at 1.4 GHz, based on all high-latitude, high-declination (parts of) WSRT surveys published up to 1985. The main reason for our re-evaluation of the source counts from these surveys is the recently obtained result on the angular sizes of sources below ~10 mJy, which necessitates a rediscussion of so-called "resolution-corrections" that were applied in some of the earlier surveys.

We also combine the resulting WSRT source count with those obtained from recent 1.4 GHz WSRT surveys down to a limit of ~100 μJy, and with existing data at flux densities above ~140 mJy. This yields a total 1.4 GHz source count (based on observations of ~3000 sources, made with two instruments only) that spans about 5 decades of flux density. This combined count will serve as a very reliable (better than ~10% accuracy at $\Delta \log S = 0.3$-resolution) integral constraint for model extrapolations of the spatial density of radio galaxies beyond the redshifts out to which this density can be determined directly from observations. As such, it is an observational constraint relevant for discussions on redshift cut-offs in the spatial distribution of galaxies with active nuclei.

Key words: radio source surveys – radio source counts

1. Introduction

In the first fifteen years of operation of the Westerbork Synthesis Radiotelescope (WSRT), quite a few surveys of extragalactic radio sources were made in what are essentially random areas in the sky. The majority of these statistically-oriented surveys was conducted at frequencies between ~1400 and ~1415 MHz, with angular resolutions of ~22″ (prior to spring 1980) and ~12″ (from spring 1980 onwards) in right ascension – and the same values, multiplied by cosec δ, in declination. In this period, the sensitivity per unit integration-time improved by more than a factor of ten as a result of more sensitive receivers, larger continuum bandwidth, and increase in the number of interferometers. In all surveys, the effective field-of-view of an individual survey area is ~0.7 sq. degr., or ~2.0 10^{-4} steradian, out to a primary beam attenuation of −7 dB.

The statistics of the individual surveys (source count, angular sizes and, where appropriate, spectral indices) have been dealt with in the original papers. In general, new data were always found to be globally consistent with earlier results, but this is not surprising in view of the sample sizes of at most a few hundred sources per contiguous area (per ~1.5 decade of flux density), and in view of the median angular size of ~0.5 to ~1.0 beamwidths.

With the increase in resolution by a factor of ~2 in spring 1980, it appeared that a significant fraction of the fainter sources in a survey might be resolved-out, to the extent that they would *not* be included in the complete sample to which they belong. The basis for this was the *assumption*, that the angular sizes of the fainter sources (which had not been measured directly) were *not* systematically different from the sizes of the brighter sources (except the very brightest, which were known to be significantly larger!).

On this assumption, Windhorst et al. (1984) simulated the combined effects of resolution and noise near the survey-limit, and came up with correction factors that correct for the "loss" of sources from a complete sample due to resolution. It will be clear that the validity of these corrections depends directly on the validity of the assumption of a non-varying angular-size distribution below, in this case, ~10–20 mJy.

Recently, this assumption has been shown to be invalid. High-resolution Very Large Array (VLA) observations of faint sources found previously in WSRT surveys (Oort et al., 1987) show quite convincingly that the angular sizes of sources with fluxes below ~10 mJy are significantly smaller than was assumed before.

Apart from the significance of this result for our understanding of the evolution of the radio source population, it also implies that our corrections for resolution effects had been overestimated. These corrections are most important for the source counts (and derived quantities, e.g. space densities), but they also affect upper limits to angular sizes.

In this note, we concentrate on the first of these two aspects, viz. the overestimation of the surface density near the survey limit as a result of the *assumption* of too large angular sizes of the faint sources. We may note that our assumption was shared by the majority of the workers in the field, in the *absence* of evidence to the contrary.

Rather than update the relevant information for individual sources (primarily the weight-parameter) we summarize the effect of the reduction of the resolution corrections by rederiving the source counts for the individual surveys. As an extra, we derive a

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Table 1. The published 1.4 GHz WSRT samples, used in the combined source count

Nr.	Survey Name	No. of fields	$S_{\rm lim}$ (mJy)	Ref.
1	Deep Lynx	1	0.31	Oort and Windhorst (1985)
2	LBDS	3	0.69– 1.39	Windhorst et al. (1984)
3	WEDS	9	1.09– 1.50	Katgert-Merkelijn et al. (1985)
4	Background	51	2.5 – 7.5	Willis et al. (1976)
5	3rd Westerbork	24	6.25	Katgert (1975)
6	1st Westerbork	18	6.75–10.0	Katgert et al. (1973)
7	Background	21	65	Willis et al. (1976)

single source count from the published 1.4 GHz WSRT surveys, and combine the latter with the count from the most recent and sensitive WSRT surveys, and with published data from Green Bank 1400 MHz surveys at high flux densities.

2. Combined 1.4 GHz WSRT source count above ~0.3 mJy

Because the North-South resolution of the WSRT deteriorates with decreasing declination we have imposed a lower limit of 30° in declination for individual survey fields. This ensures that the axial ratio of the synthesized beam never exceeds 2 to 1, and minimizes confusion effects. In addition, we have imposed a lower limit of 30° to galactic latitude (both north and south), which was relaxed to 10° for very bright ($S_{1.4} > 65$ mJy) sources, to improve the statistical weight at higher flux levels.

These limits do not affect the 1st Westerbork Survey (Katgert et al., 1973), the 3rd Westerbork Survey (Katgert, 1975) and the survey of a field in Lynx by Oort and Windhorst (1985). On the other hand, they eliminate the 2nd Westerbork Survey (Katgert and Spinrad, 1974) completely, as well as parts of the so-called Background Survey (Willis et al., 1976), the Leiden-Berkeley Deep Survey (Windhorst et al., 1984) and the Westerbork-Einstein Deep Survey (Katgert-Merkelijn et al., 1985). In addition, we excluded the two survey fields in Hercules from the Leiden-Berkeley Deep Survey because more sensitive observations have become available (Oort and van Langevelde, 1987), the results of which will be summarized later.

In total, about 35% of the available WSRT survey data at 1.4 GHz is not used for the reasons explained above.

However, this still leaves us with a total of ~1200 sources in a total survey area of ~83 sq. degr., in complete samples with completeness limits between ~0.3 and ~10.0 mJy. Some information about these samples is given in Table 1. Remember that surveys nr. 1 and nr. 2 were done with ~12″ E-W resolution, while all others were done with an E-W resolution of 22″.

Using the sources in the samples listed in Table 1, we have rederived the source counts for the individual survey, as well as a weighted average source count in the flux range 0.442 to 452.5 mJy, with a logarithmic resolution in flux density of $\Delta \log S = 0.3$.

As indicated in the introduction, we have applied *no* correction for resolution effects in *any* of the surveys. We now know – from high-resolution (~1″.4) VLA observations, carried out by Oort et al. (1987) at a frequency of 1.49 GHz – that the large majority of the sources in surveys nr. 1 and 2 (the surveys with the highest WSRT resolution) are (much) smaller than the WSRT beam. In addition, the median angular sizes of sources with $S_{1.4} \leqq 1$ Jy are at least a factor of two smaller than the WSRT beam of surveys nr. 3 to 7, so that resolution effects are small – if not negligible – over the entire flux density range covered by the published WSRT 1.4 GHz surveys.

In deriving the source counts we *did* apply the, by now well-known, correction for the flux-dependence of the completeness area of the surveys. Sources which, on the basis of their peak flux density, would only have been "visible" (i.e. included in the complete sample) over part of the survey area are taken to represent identical counterparts in the remaining part of the survey area. On average, each of the ~1100 "observed" sources contributing to the total source count represents a total of 1.5 "implied" sources. Near the completeness limits of the individual surveys this factor may become as high as ~3.5; for individual sources the factor is almost never larger than ~10.

The resulting source counts for the surveys in Table 1 are displayed in Fig. 1a, in which the surveys are indicated by their running numbers from Table 1. The dotted line represents the 3rd-order polynomial fit to the *combined* source count, which is:

$$\log(n(S)\,S^{5/2}) = \sum_{i=0}^{3} a_i (\log[S/\mathrm{mJy}])^i$$

with $a_0 = 0.908$, $a_1 = 0.619$, $a_2 = 0.190$, $a_3 = -0.075$. One may well ask whether in these three decades of flux a third-order polynomial does not over-interpret the data. However, in the next section we will extend the flux range to 5 decades, in which case a second-order polynomial does not represent the data adequately.

In general, the source counts from the various surveys agree very well, considering the statistical uncertainties, and can be considered random draws from the parent flux distribution described by the above polynomial expression. The low values at 20 and 40 mJy in survey 1 are almost certainly due to limited statistics. The high value at 320 mJy in survey 6 (an observed number of 11 sources, against 3.5 predicted from surveys 4, 5 and 7) was already noted in the paper describing the 1st Westerbork Survey. However, since the *average* source density at 320 mJy in surveys 4, 5, 7 *and* 6 agrees *very* well with that derived from single-dish surveys (see below) the high source density in survey 6 is probably only a statistical fluctuation.

The general, good agreement between source densities derived near the flux limits of individual surveys and those derived at the same flux from more sensitive surveys, provides an a posteriori confirmation of our assumption that resolution effects are very small in essentially all present surveys.

Finally, a word or two about the amount of curvature – i.e. change of slope – of the source count, as implied by the data in Fig. 1a. A constant slope (or a linear fit of $\log(n(S)\,S^{5/2})$ in terms of $\log[S/\mathrm{mJy}]$) is not very plausible, as such a fit has a reduced-χ^2

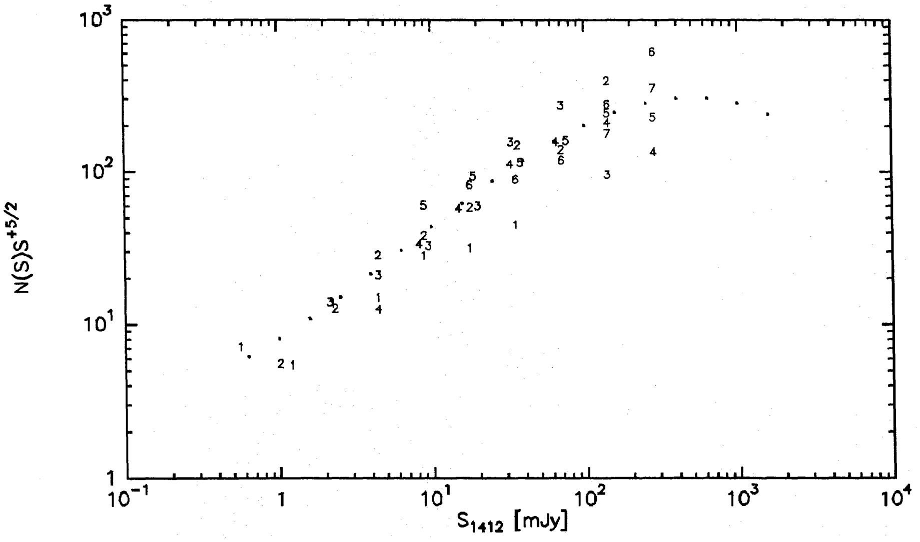

Fig. 1a. The differential source counts (expressed as $n(S)\,S^{5/2}$) of the high-declination, high-latitude parts of published 1.4 GHz WSRT surveys. The surveys are indicated by their running numbers from Table 1. The dotted line represents a third-order polynomial fit

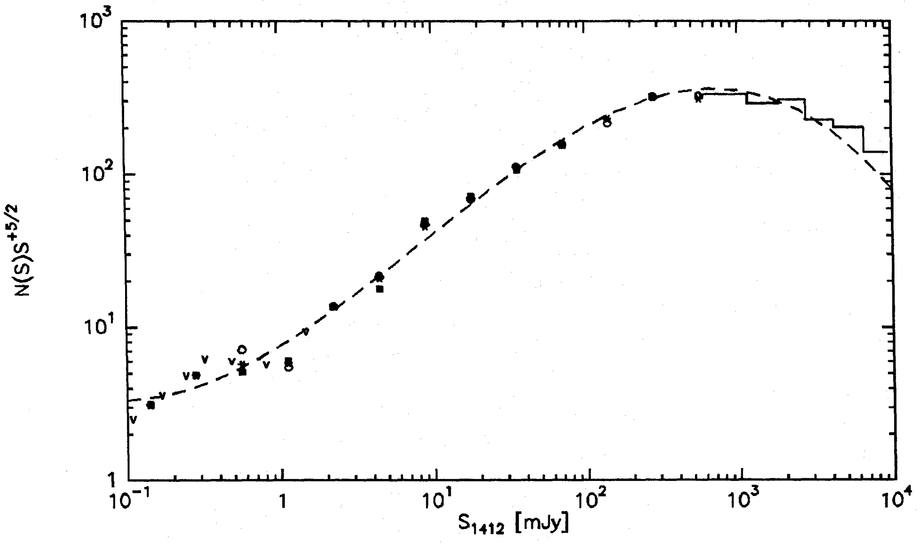

Fig. 1b. The total source count at 1.4 GHz, from WSRT and Green Bank surveys. The combined count from Fig. 1a is indicated by open circles. Filled squares represent results from recent, deep WSRT surveys (see text). The step-like line represents the count based on the 1.4 GHz Green Bank surveys, while the dashed line is again a third-order polynomial fit. The result from a deep VLA survey are represented by the letter "*v*"

value of 2.4. Limiting ourselves to polynomial fits of $\log(n(S)\,S^{5/2})$ versus $\log[S/\mathrm{mJy}]$, we find that a *second*-order polynomial has a reduced-χ^2 of 1.0 and the *third*-order polynomial quoted earlier a reduced-χ^2 of 0.8. Therefore, the present data by themselves are satifactorily represented by:

$$\log(n(S)\,S^{5/2}) = \sum_{i=0}^{2} (\log[S/\mathrm{mJy}])^i$$

with $a_0 = 0.855$, $a_1 = 0.905$ and $a_2 = 0.097$.

3. Recent WSRT extension towards lower flux densities

In order to allow a study of intermediate- and low-luminosity radio galaxies at redshifts larger than a few tenths, a very deep 1.4 GHz Westerbork survey was recently carried out by Oort: One single field (in Lynx) was observed for 16 × 12 h, yielding a complete sample of sources down to 80–100 μJy (Oort, 1987a). In addition, Oort and van Langevelde (1987) also studied two fields (in Hercules) to a limit of approximately 0.4 mJy. Finally, a survey was carried out to a limit of 0.15 mJy in Triangulum by Oort and Geuze, of which a preliminary reduction has yielded a complete sample down to 0.25 mJy (see Oort, 1987b). We refer to their articles for details, and discuss here only the source count data from these surveys *in combination* with those presented in Sect. 2.

In Fig. 1b we have summarized the data in Fig. 1a by open circles, and added to those the new data from the three recent surveys mentioned above (filled squares) in the flux range 0.11 to 3.83 mJy. As before, no resolution correction was applied. In the flux range of overlap the new and older surveys agree quite well, although two of the three new surveys seem to be slightly low (by about 25%) compared with the older surveys. However, in view of the difference between the counts of the various older WSRT surveys (see Fig. 1a), we consider this to be a statistical fluctuation.

In Fig. 1b, we show the count obtained by Mitchell and Condon (1985) who used the VLA as well, indicated by the letter "*v*". The agreement between the two counts is quite satisfactory (note that the VLA count was transformed to 1.40 GHz by Mitchell and Condon).

4. The total 1.4 GHz source count between 0.1 mJy and 10 Jy

At flux densities above ~100 mJy, the combined high-declination, high-latitude WSRT surveys contain just over a hundred sources. At these flux densities we therefore complement our data with the single-dish, large solid-angle data furnished by the Green Bank 1.40 GHz surveys (Fomalont et al., 1974; Machalski, 1978).

From Fig. 1 b it can be seen that between ~0.11 and ~0.45 Jy the Green Bank and WSRT counts are in very good agreement. We have only used the Green Bank data below 10 Jy; the 34 sources with fluxes larger than 10 Jy indicate a constant value of $n(S)\,S^{5/2}$ around 150 (i.e. the same as the value between ~6.5 and 10 Jy).

The total source count displayed in Fig. 1 b is based on about 3000 sources, contributed almost equally by the WSRT and the Green Bank 300-foot telescope. A third-order polynomial representation of $\log(n(S)\,S^{5/2})$ versus $\log[S/\mathrm{mJy}]$ yields: $a_0 = 0.878$, $a_1 = 0.614$, $a_2 = 0.191$ and $a_3 = -0.70$. Clearly, this representation should not be extrapolated outside the flux range in which it was derived, viz. 0.1 mJy to 10 Jy. For example, extrapolation beyond 10 Jy is in conflict with the existing data that we did not include. Also, extrapolation below 0.1 mJy implies an upward curvature, which we would be rather surprised to find confirmed in future observations (and which, in fact, is not indicated by the deepest VLA-data available (see Condon, 1984).

It is interesting to note that the polynomial obtained now using five decades in flux) is very similar to the one found in Sect. 2, based on data in three decades only. Although the latter (3rd order polynomial) overinterpreted the data, it already sensed the high-order curvature quite well.

Comparing the present count with the earlier ones by Windhorst et al. (1984) and by Oort and Windhorst (1985), one finds that below ~10 mJy the latter ones were higher by 15 to 25%. This difference is clearly due to the overestimation of the resolution correction, as discussed in Sect. 1. Nevertheless, the character of the source count, and in particular the "upturn" below ~10 mJy, is changed only marginally. The presence of an upturn has now been established more firmly than was possible before, although it makes itself felt at slightly lower flux densities than previously thought.

This change will influence the conclusions of a discussion of the space distribution of the radio source population, like the one given by Windhorst (1984). A comprehensive discussion of the space distribution of faint radiogalaxies will be given by Oort (1987b).

5. Conclusions

We have rediscussed the radio source counts from published WSRT 1.4 GHz surveys at high-declinations and high-latitudes. We have applied no correction for resolution effects, as the median angular size is now known to be significantly smaller than the beamwidth at all flux levels.

The counts from the various surveys can be regarded as random draws from the total flux distribution of these surveys.

The total count so obtained is extended towards lower flux levels using results from recent WSRT surveys down to ~0.1 mJy. Below ~5 mJy the differential count shows an "upturn".

When complemented at high fluxes with single-dish data we obtain a source count that spans 5 decades at ~10% accuracy for $\Delta \log S = 0.3$ resolution.

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