A Quick Look at the 3 GHz Radio Sky I. Source Statistics from the Very Large Array Sky Survey

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ABSTRACT

The Very Large Array Sky Survey (VLASS) is observing the entire sky north of −40° in the S-band (2 < ν < 4 GHz), with the highest angular resolution (2″.5) of any all-sky radio continuum survey to date. VLASS will cover its entire footprint over three distinct epochs, the first of which has now been observed in full. Based on Quick Look images from this first epoch, we have created a catalog of 1.19 × 10^6 reliably detected radio components. Due to the limitations of the Quick Look images, component flux densities are underestimated by ~ 15% at S_{peak} > 3 mJy/beam and are often unreliable for fainter components. We use this catalog to perform statistical analyses of the ν ∼ 3 GHz radio sky. Comparisons with the Faint Images of the Radio Sky at Twenty cm survey (FIRST) show the typical 1.4 − 3 GHz spectral index, α, to be ~ −0.71. The radio color-color distribution of point and extended components is explored by matching with FIRST and the LOFAR Two Meter Sky Survey. We present the VLASS source counts, dN/dS, which are found to be consistent with previous observations at 1.4 and 3 GHz. Resolution improvements over FIRST result in excess power in the VLASS two-point correlation function at angular scales ≲ 7″, and in 18% of active galactic nuclei associated with a single FIRST component being split into multi-component sources by VLASS.

Keywords: Radio Astronomy (1338), Radio Galaxies (1343), Radio Source Catalogs (1356), Sky Surveys (1464),

1. INTRODUCTION

The past two decades have seen the advent of wide-field continuum imaging surveys of the radio sky. The advantages of blind surveys over targeted observations include large numbers of objects for which observations are obtained, and the potential to discover new phenomena (Padovani 2016; Norris 2017). The National Radio Astronomy Observatory (NRAO) Very Large Array Sky Survey (NVSS, Condon et al. 1998) set the bar for wide-field radio continuum surveys by surveying 80% of the sky at 1.4 GHz. With an angular resolution of ~ 45″ and a typical rms noise of 450 μJy/beam, NVSS has catalogued ~ 2 × 10^6 radio detections. The Faint Images of the Radio Sky at Twenty cm survey (FIRST, Becker et al. 1995), also at 1.4 GHz, probes deeper than NVSS with an rms of 130 μJy/beam, and improved angular resolution of 5″.4 while covering 25% of the sky. Meanwhile, at low frequency the Tata Institute of Fundamental Research Giant Metre Radio Telescope Sky Survey (TGSS, Intema et al. 2017) has mapped 90% of the sky at 150 MHz with an rms of 5 mJy/beam and an angular resolution of ~ 25″.

Technological improvements over the past two decades have allowed upgrades to existing radio telescopes such as the Karl G. Jansky Very Large Array (VLA), and the
construction of new facilities such as the LOw Frequency ARray (LOFAR, van Haarlem et al. 2013), the Australian Square Kilometre Array Pathfinder (ASKAP, Johnston et al. 2007), and the MeerKAT telescope (Jonas 2009). These state-of-the-art facilities allow for sky surveys that probe deeper, with shorter observing times, and with higher resolution than were previously possible, allowing us to build upon the scientific output of the last generation of continuum sky surveys. For instance, ASKAP is being used to conduct the Rapid ASKAP Continuum Survey (RACS, McConnell et al. 2020) and Evolutionary Map of the Universe survey (EMU, Norris et al. 2011), providing $\nu \sim 1$ GHz coverage of the Southern Sky, the latter down to sensitivities ($\nu_{2020}$) and Evolutionary Map of the Universe survey (ASkAP Continuum Survey (RACS, McConnell et al. 2020) and Evolutionary Map of the Universe survey (EMU, Norris et al. 2011), providing $\nu \sim 1$ GHz coverage of the Southern Sky, the latter down to sensitivities of $\sim 10 \mu$Jy/beam. Meanwhile, the LOFAR Two-metre Sky Survey (LoTSS, Shimwell et al. 2017) will survey the entire Northern sky at $\sim 150$ MHz with a synthesised beam size of $6''$ and an rms of $\sim 70 \mu$Jy/beam, providing deep, low-frequency observations to complement existing high-frequency data.

Of the current generation of radio continuum imaging surveys, the highest angular resolution will be provided by the VLA Sky Survey (VLASS, Lacy et al. 2020). With an angular resolution of $\sim 2''$.5, VLASS is currently surveying the entire sky North of $-40^\circ$ in the S-band ($2 < \nu < 4$ GHz, hereafter referred to as $\nu \sim 3$ GHz). Such a small beam size has the advantage of revealing morphological structure on smaller angular scales than other surveys — e.g. many sources that appear compact in FIRST or LoTSS may be resolved by VLASS. Furthermore the resolution of VLASS allows improved study of the true sizes of radio sources in the sky (e.g., Allen et al. 1962; Cotton et al. 2018) as well as more reliable identifications of their optical or infrared hosts. Survey operations for VLASS began in 2017, and observing for the first of three planned epochs was completed in 2019.

In this paper we describe a catalog of radio components produced from the VLASS epoch 1 Quick Look imaging. Here, and throughout, we use the term radio component to refer to a single detection by the source finding algorithm rather than radio source as, especially at high resolution, a single physical radio source may be described by multiple components. For example, the two hot spots of a double-lobed radio galaxy may appear as two different components in the catalog while still belonging to the same physical source. Host galaxy identifications for detections in this catalog will be detailed in an upcoming work (Gordon et al., in prep).

The data used and the production of the VLASS epoch 1 Quick Look component catalog are described in Section 2. The rapid CLEANing of the Quick Look images leads to limitations of the scientific usefulness of this catalog, and these are described in Section 3. We match our catalog to $\nu \sim 1.4$ GHz and $\nu \sim 150$ MHz data from FIRST and LoTSS respectively in Section 4, and present the resultant spectral index and spectral curvature distributions in Section 5 we present the VLASS source counts. We use our catalog to explore the size distribution of VLASS components in Section 6. This is complemented by an analysis of the VLASS two-point correlation function, and by exploring the impact of a factor of $\sim 2$ improvement in angular resolution over FIRST. A summary of this paper is given in Section 7. Throughout this work we adopt the convention $S_\nu \propto \nu^\alpha$ for radio spectral index measurements, and assume a flat $\Lambda$CDM cosmology with $h = 0.7$, $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. CATALOG PRODUCTION

2.1. VLASS Quick Look Images

The first-epoch observations from VLASS are currently available as rapidly-processed Quick Look images. In this paper we describe a catalog of radio components produced using these images, the availability of which was first announced in Gordon et al. (2020). These Quick Look images are produced by NRAO and made available within weeks of the observations being conducted. However, the expedited nature of the image processing limits their quality, and hence constrains their scientific usability. Furthermore this rapid-CLEAN process employed by NRAO was updated between epoch 1.1 and 1.2 resulting in significant differences in image quality between the two sub-epochs 1.

1 The epoch 1 Quick Look images are described in full in Lacy et al. (2019), but we highlight here the key issues known in advance:

- **Flux calibration** - The flux density values in the Quick Look images are on average systematically low by $\sim 10\%$. Furthermore, Lacy et al. (2019) show that there is a substantial scatter, $\sim 15\%$, in the ratio of flux densities measured by VLASS and pointed observations of calibrator targets.

- **Astrometry** - The positional accuracy of the VLASS Quick Look imaging is limited to $\sim 1''$. This improves to $0''.5$ at declination, DEC, $\geq -20^\circ$.

- **Ghosts** - These appear offset by multiples of $\sim 3'$ in right ascension, RA, east of bright sources. The Quick Look image production pipeline is designed

1 49.9 and 50.1% of the imaging was performed in epoch 1.1 and 1.2 respectively.
to flag and remove these but some faint ghosts may still remain. Moreover the removal of ghosts was refined between epoch 1.1 and 1.2 meaning that the earlier images are more likely to contain residual faint ghosts.

The impact of these reliability issues on our component catalog are further detailed in Section 3.

The full epoch 1 Quick Look image set consists of 35,285 one square degree Quick Look images (henceforth referred to as subtiles) across 899 ~ 40 deg^2 VLASS observing tiles (Kimball 2017). The catalog based on these data and used in this paper has been made available to the community via https://cirada.ca/catalogues (Gordon et al. 2020), and its production is described below. An extensive User Guide is also available for download with the catalog, and we recommend reading this prior to accessing the data.

2.2. Component Extraction and Duplicate Finding

For each of the 35,285 subtiles in VLASS, the source extraction code Python Blob Detection and Source Finding (PyBDSF, Mohan & Rafferty 2015) was run in ‘srl’ mode - meaning that a list of components is provided rather than a list of individual Gaussian fits. The method adopted by PyBDSF is to detect flux islands at 3σ above the image mean (where σ is the local rms), and then to fit components composed of one or more Gaussians within those islands with a peak brightness at 5σ above the image mean. For the most part the default PyBDSF parameters are used, with two exceptions:

1. The sliding box used by PyBDSF to calculate the rms is set at a fixed size of 200 x 200px with a slide step of 50 px. Explicitly, the argument rms_box={200,50} is called when running PyBDSF. The pixels in the subtiles are 1", square.

2. For completeness PyBDSF is set to output detected islands of flux density to which it did not fit components in addition to the list of fitted components it finds. This is achieved by running PyBDSF with the argument inc_empty=True, and such detections are included and identified in the catalog by S_Code == 'E'. These 'empty islands' are generally faint, with 95% of such detections having a peak brightness of less than 2 mJy/beam.

The resultant 35,285 individual PyBDSF component tables for each subtitle are then merged into a single table. As there is a ~ 2" overlap region between the images the catalog contains duplicate entries that refer to the same component. Based on the beam size and the positional uncertainty associated with the images, we use a 2" search radius around each component to identify duplicates. Where component duplicates are identified, preference is given to the component with highest ratio of peak brightness to local rms. All duplicates are retained within the catalog but are flagged as such (0=unique component; 1=duplicate component that is the preferred version of this component; 2=duplicate component that is not the preferred version of this component). To select a duplicate free list of components only components with Duplicate_flag < 2 are used for the statistics presented in this work.

2.3. Reliability of Detections

In addition to the basic measurements provided by PyBDSF, we wish to determine which detected components are real, as opposed to false positive detections. A column, Quality_flag, is provided in our catalog to highlight our recommended components to use based on analysis of the raw output. This takes account of three different parameters which are combined into a single integer flag value. These are:

1. The ratio of the total flux density and peak brightness measurements. Given the reliability issues associated with the Quick Look images, any component where the total flux is less than the peak brightness should be considered to be a possibly dubious measurement. Thus, we flag component with Speak > Stotal by setting Quality_flag = Quality_flag+4.

2. The signal-to-noise (S/N) of the component. We flag components with a peak brightness lower than 5 times the local rms and set Quality_flag = Quality_flag+2. Nearly all components flagged here have 3 < S/N < 5, however we note that 1,600 components have S/N < 3. This is attributed to differences in the local rms from the rms image used to detect the islands, and the fitted island rms.

3. The ratio of peak brightness to the maximum flux density in a ring centred on the component position and with inner and outer radii of 5" and 10" respectively. This is specifically designed to identify potential sidelobe structures that have erroneously been fitted as components. Sidelobes should have a low value for this ratio compared to true components that are surrounded by just the background noise (see Figure 1). A caveat here is that close-double radio sources, the detection of which should be a forte of VLASS, will also provide low values to this ratio, and could thus be
Figure 1. The ‘peak-to-ring’ metric is specifically designed to catch false-positive components that have been fit to artefacts, and more specifically sidelobes. In these images the green ring shows the inner radius (5") and the yellow ring the outer radius (10") of the annulus in which flux density is compared to the component peak brightness. The left-hand panel shows two good component detections with high peak-to-ring values. The right hand plot shows a component erroneously fitted to a sidelobe. In this case the ratio of peak brightness to maximum flux in the annulus is only 1.33, demonstrating that lower peak-to-ring values have diagnostic value in flagging false detections.

Inadvertently be identified as sidelobe detections. In light of this, this metric is only used to flag components that are more than 20" from another component and with $\text{Peak_to_ring} < 2$. Here we apply $\text{Quality\_flag} = \text{Quality\_flag} + 1$.

The combination of these parameters gives a single flag with an integer value between 0 and 7. In Figure 2 we show examples of our quality flagging routine identifying spurious detections due to image artefacts around bright components.

In Figure 3 we compare the peak brightness distributions for all components with components that have $\text{Quality\_flag} = 0$. The distribution for components that have not been flagged shows a reduced number of faint detections. Although this demonstrates that suspect detections are generally faint, note that the distribution for unflagged components deviates from the flagged component peak brightness distribution up to $\sim 5 \text{mJy/beam}$. Therefore, to select only the most reliable measurements, we recommend using $\text{Quality\_flag} = 0$, indicating that the component has not been flagged for any of the above quality issues, in addition to just applying simple brightness cuts to the data.

Whilst not explicitly provided by PyBDSF when set to provide component lists, we recover the pixel coordinates of components based on the image header information and provide them as additional information. Further information on the VLASS tile and subtile to which a detection belongs, and angular separation from the nearest other component (given in the column $\text{NN\_dist}$ for components with $\text{Duplicate\_flag} < 2$ and $\text{Quality\_flag} = 0$), are included. Additionally, we provide the angular separations from the nearest detections in the two previous NRAO wide-field continuum surveys, NVSS and FIRST, as the columns $\text{NVSS\_distance}$ and $\text{FIRST\_distance}$ respectively. These latter two metrics may be useful to further assess the reliability of the detection (particularly for fainter sources), and for finding potential variable objects (in which case we urge caution on the part of the user and remind them of the systematic underestimation of fluxes in the VLASS Quick Look imaging). The resultant component catalog consists of 3,381,277 rows where each row corresponds to a detected component or empty flux island. Of these, 1,692,158 have $\text{Duplicate\_flag} < 2$ and $\text{Quality\_flag} = 0$.

3. DATA QUALITY

As FIRST only covers around 1/3 of the VLASS footprint, $\text{FIRST\_distance}$ should only be considered useful within the FIRST footprint.
Here we detail the issues with data both known about from Lacy et al. (2019) and discovered during our quality assurance testing. Whilst the major known issues are described here this list is unlikely to be comprehensive.

3.1. Noise Variation Between Images

Between epoch 1.1 and 1.2 the VLASS Quick Look image pipeline was upgraded to include automatic as opposed to manual flagging of science data. Whilst reducing the human workload, this automatic routine increased the amount of flagging, resulting in a reduced bandwidth and thus noisier data (Mark Lacy, private communication). It follows that these differences in the image processing between the two data sets will impact upon the sample homogeneity. The median rms for images from epoch 1.1 is 128 $\mu$Jy/beam compared to 145 $\mu$Jy/beam for epoch 1.2, indicating the impact of the change of image processing methods on the data. In Figure 4 we show an Aitoff projection of the local rms around components in our catalog. Inspecting this plot shows several curious features highlighting the lack of homogeneity of the VLASS Quick Look imaging. In particular, users of this catalog should be aware of the following:

1. At southern declinations a ‘checker-board’ pattern of rms is apparent. This clear patterning is indicative of variation between VLASS tiles, and moreover of the difference between the two sub-epochs (see also the VLASS tiling pattern described in Kimball 2017).

2. At Northern latitudes in particular, high noise levels are visible at the East-West boundaries of VLASS tiles. The increase in noise at specifically the East-West boundary is likely attributable to the fact that some tile edges were flagged to avoid unreliable fluxes associated with online software bugs related to the ghosts (Lacy et al. 2019).

3. There is a region of high noise that stands out at DEC $\sim +85^\circ$ and 12 hr $< RA < 24$ hr.

4. The Galactic plane is clearly visible as a region of enhanced noise, albeit only at very low Galactic latitudes ($|b| \lesssim 0.5^\circ$) and for a relatively narrow range of Galactic longitudes ($350^\circ \lesssim l \lesssim 50^\circ$).

5. There are several strips at $0^\circ <$ DEC $< +1^\circ$ which have lower noise ($\sim 100$ $\mu$Jy/beam). This is the result of accidentally observing these regions twice during survey operations and using both observations in the production of the Quick Look images. This deeper VLASS region has a total area of $\sim 160$ deg$^2$.

3.2. Reliability of Flux Density Measurements

From Lacy et al. (2019) we know the flux densities in the VLASS Quick Look imaging are systematically underestimated. Based on comparisons with $> 50$ VLA calibrator sources, Lacy et al. (2019) estimate that the peak brightness in the VLASS Quick Look images are underestimated by $\sim 15\%$, and the total flux density of components is underestimated by $\sim 10\%$. Lacy et al. (2019) report a scatter of about 8% in these measurements. In this Section we compare the flux density measurements in our catalog to existing survey data so as to obtain our own estimate of the VLASS flux density reliability.

3.2.1. Direct comparisons with other 3 GHz data

One approach to measure the impact of the potential flux density underestimation of the VLASS Quick Look images on our catalog is to directly compare our measurements to existing 3GHz flux densities for components in our catalog. However, previous blind continuum

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3 We encourage users to report any additional issues they encounter with this data via the catalog feedback portal at https://cirada.ca/catalogues.
Figure 4. Aitoff projection in equatorial (J2000) coordinates of the rms values found around all VLASS components. For clarity only $100 < \text{Isl rms} < 200 \mu\text{Jy/beam}$ are shown and on a log$_{10}$ scale. Additionally this is limited to components with $\text{Quality flag} == 0$ and $\text{Duplicate flag} < 2$. From this plot it is clear that the depth of the Quick Look imaging is not homogeneous. Key features in this plot include the Galactic plane at low Galactic longitudes, the checker-board pattern at southern latitudes, high noise at the East-West boundaries of tiles, and a region of high noise at DEC $\sim +85^\circ$ in the Western hemisphere ($12 < \text{RA} < 24\text{hr}$).

Observations at this frequency have come from deep, narrow-field surveys (Vernstrom et al. 2016; Smolčić et al. 2017), limiting the overlap in detected components with VLASS. Of the available 3 GHz catalogs, the VLA-COSMOS 3 GHz Large project (hereafter referred to simply as VLA-COSMOS, Smolčić et al. 2017), covering the two square degrees of the COSMOS field, presents the largest overlap with VLASS in terms of sensitivity and sky coverage. Our VLASS catalog contains 131 components with a VLA-COSMOS detection within 2".5 (126 of these are separated by less than 1"").

The small number of overlapping components between VLASS and VLA-COSMOS limits our ability to perform a robust flux calibration of our catalog via a direct comparison of the independent flux density measurements at 3 GHz. Nonetheless, we report here our findings in comparing the measurements from both catalogs. Given the already small sample size, for this comparison we do not account for the difference in resolution between VLA-COSMOS (0".75) and VLASS. In Figure 5 we show the ratio of VLASS to VLA-COSMOS flux density measurements for the 131 matched components as a function of peak brightness in VLASS. This sample contains 33 components with a peak VLASS brightness greater than 3 mJy/beam, and for these the median value of $S_{\text{VLASS}}/S_{\text{VLA-COSMOS}}$ is 0.95 with a standard error of 0.07. Below about 3 mJy/beam there is substantial scatter in the ratio of measured flux densities between VLASS and VLA-COSMOS.

3.2.2. Comparisons with multi-band radio data

Given the limited available $\nu \sim 3\text{ GHz}$ data with which to compare our catalog, we adopt a method similar to that used by Sabater et al. (2021) in order to estimate
Table 1. Parameters used when matching comparison surveys with VLASS for flux calibration. The frequency ($\nu$) of the survey in MHz, the minimum angular distance to the nearest neighbor for the matched VLASS component in arcseconds, the minimum flux density of components from that survey used in mJy are listed below for each survey. The number of matched components for which the VLASS to comparison survey flux density ratios are used to calibrate the VLASS flux are given in the column $N$.

| Survey | $\nu$ [MHz] | Isolation radius $\Psi_{\text{max}}$ [arcsec] | $S_{\text{min}}$ [mJy] | $N$ |
|--------|-------------|-------------------------------|----------------|-----|
| TGSS   | 150         | 14                            | 30              | 60  | 806 |
| WENSS  | 330         | 54                            | 0               | 20  | 1,636 |
| SUMSS  | 843         | 43                            | 10              | 10  | 1,747 |
| FIRST  | 1,400       | –                             | 0.5             | 3   | 6,189 |
| VLASS  | 3,000       | –                             | –               | –   | –    |

Figure 5. Comparison of VLASS flux measurements to the 3GHz VLA-COSMOS measurements for the 131 matched components in the 2 square degrees of the COSMOS field.

the reliability of our flux density measurements. This approach determines the distribution of flux density ratios for matched components between the survey being calibrated and a reference survey at a number of different frequencies. A power law can then be fit to the average flux density ratio as a function of frequency, with the intercept at the frequency of the survey being calibrated used to determine the flux density accuracy. As the VLASS footprint covers $\sim 80\%$ of the sky there are a number of overlapping wide-field continuum surveys that can be used in this way.

We compare our data with TGSS at 150 MHz, the Westerbork Northern Sky Survey (WENSS, Rengelink et al. 1997) at 330 MHz, the Sydney University Molonglo Sky Survey (SUMSS, Bock et al. 1999; Mauch et al. 2003) at 840 MHz and FIRST at 1.4 GHz. As all these surveys have different angular resolutions and effective depths, care must be taken when matching components. For instance, WENSS has an angular resolution of $54'' \, \text{csc(DEC)}$ and a single WENSS component could easily be observed as multiple components in VLASS. Therefore, to qualify as a matched components we require the distance to the nearest neighboring VLASS component to be greater than half the angular resolution of the comparison survey, using the isolation radius given in Table 1. As the elliptical beam geometry varies with declination for TGSS, WENSS and SUMSS, the poorest possible resolution in the overlap with VLASS is assumed when defining this isolation limit for these surveys.

Only unresolved or barely resolved components are matched to one another in this calibration. For VLASS, we consider components with a deconvolved angular size, $\Psi$, of less than $0.5''$ to be suitable here. The maximum angular sizes of components we use from the comparison surveys are listed in Table 1, and for FIRST and SUMSS these are based on the cataloged deconvolved sizes. The WENSS catalog provides the Gaussian fitted sizes (i.e. including the beam size) for resolved components, and lists a ‘zero’ size where the ratio of peak and integrated flux density is indicative that the component is unresolved (Rengelink et al. 1997). It is these unresolved WENSS components we include in our analysis. TGSS only provides a fitted component size and does not highlight likely unresolved components, so we only consider TGSS components with a fitted angular size smaller than $30''$ in this analysis.

The appropriate samples of isolated VLASS components are then cross matched with their respective comparison surveys. As TGSS, WENSS and SUMSS have different angular resolutions and effective depths, higher (lower) effective noise levels imply shallower (deeper) surveys

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4 defined as the noise level when accounting for observing frequency assuming a typical spectral index of $-0.7$; higher (lower) effective noise levels imply shallower (deeper) surveys
substantially poorer angular resolutions than VLASS we use a search radius of 5′ when cross matching these surveys with VLASS. For FIRST, which has an angular resolution (5′.4) that is more comparable to that of VLASS, a search radius of 2′.5 is used.

All of the comparison surveys are at a lower frequency than VLASS; comparing to a survey with a greater effective depth (e.g., FIRST) will be biased by components with flat- or inverted-spectrum sources. Comparisons with lower effective depth surveys (e.g. WENSS) will be biased towards components with very steep negative spectral indices. This effect can be seen in the curvature at the low ends of the flux density comparisons for VLASS, WENSS and FIRST shown in Figure 6. To eliminate this bias, we select only components with a spectral index, \( \alpha \), in the range \(-1.5 < \alpha < +0.5\), that would be detectable in both VLASS and the comparison survey. Explicitly, this is achieved by satisfying:

\[
S_{\text{VLASS}} > \frac{S_{\text{min, comparison}}^2}{S_{\text{comparison}}} \times \left( \frac{3 \text{ GHz}}{\nu_{\text{comparison}}} \right)^{0.5}, \tag{1}
\]

when the comparison survey is effectively shallower (TGSS, WENSS and SUMSS), and by

\[
S_{\text{VLASS}} > \frac{(3 \text{ mJy})^2}{S_{\text{comparison}}} \times \left( \frac{\nu_{\text{comparison}}}{3 \text{ GHz}} \right)^{-1.5}, \tag{2}
\]

when the comparison survey is effectively deeper (FIRST). \( S_{\text{VLASS}} \) is the VLASS flux density of the component, \( S_{\text{comparison}} \) is the flux density of the component in the comparison survey, \( S_{\text{min, comparison}} \) is the completeness limit of the comparison survey (see Table 1), \( \nu_{\text{comparison}} \) is the comparison survey frequency, and the completeness limit of VLASS is taken to be 3 mJy. This selection is shown by the light blue shaded regions in Figure 6 for WENSS and FIRST.

For the selected components we determine the median ratio of flux densities between VLASS and the comparison survey, and these are shown as a function of frequency in Figure 7. We fit a power law to these data points with a slope of 0.6 in order to extrapolate the expected flux density ratio between VLASS and benchmark 3 GHz measurements, and thus quantify the typical underestimate of flux density measurements in our catalog. From this we determine \( S_{\text{VLASS}} = 0.87 S_{3 \text{ GHz}} \). To compensate for this typical underestimate, we scale all the VLASS flux density measurements by \( 1/0.87 \) throughout the rest of this work. This correction is not applied to our catalog and anyone making use of this data is advised to apply the flux density correction themselves.

\[\text{Figure 6. Examples of VLASS flux densities compared to two of the comparison surveys. The upper panel shows the comparison with a shallower survey, WENSS (\( \nu \sim 330\) MHz), and the lower panel shows the comparison with the deeper survey, FIRST (\( \nu \sim 1,400\) MHz). The red/yellow density plots show the flux densities in VLASS and the comparison survey for all cross matched compact components. The black dashed lines show the minimum flux density used as a completeness limit for each survey, while the solid black line shows the cutoff we apply to prevent the different effective survey depths biasing our flux calibration. For WENSS this is based on Equation 1, and for FIRST this is based on Equation 2. The light blue shaded region above and to the right of the three black lines highlight the components selected for use in our VLASS flux calibration.}\]
Figure 7. The median ratio of VLASS to comparison survey flux density for cross matched components as a function of comparison survey frequency. Error bars represent the standard error. Four comparison surveys are used here: TGSS at 150 MHz, WENSS at 330 MHz, SUMSS at 840 MHz and FIRST at 1,400 MHz. The red dash-dotted line shows the best fit to the data, a power law with a slope of 0.6, from which we extrapolate $S_{\text{VLASS}}/S_{3\,\text{GHz}} = 0.87$. The black dotted line shows unity for the ratio of VLASS to comparison flux densities, and the black dashed line marks $\nu = 3\,\text{GHz}$.

3.3. Astrometry

Early investigations by NRAO into the epoch 1.1 Quick Look imaging showed issues with respect to the astrometric accuracy of the Quick Look images (Lacy et al. 2019). Comparisons with Gaia DR2 (Gaia Collaboration et al. 2016, 2018) showed the VLASS component positional accuracy to be limited to $\sim 1^\prime$, improving to $\sim 0^\prime.5$ at $\text{DEC} > -20$. These limitations to the VLASS astrometry are attributable to two factors. Firstly, the rapid processing technique employed fails to account for the $w$-term in the interferometer equation (Smirnov 2011a,b). The impact of this is to distort the VLASS point spread function away from the phase center, resulting in positional offsets in detections. Secondly, the pixels in the Quick Look images are $1^\prime$ compared to a typical VLASS beam size of $2^\prime.5$. Thus, the pixels in the Quick Look do not adequately sample the beam, and this may contribute to the positional uncertainty.

Comparing our catalog with Gaia DR2 we confirm NRAO’s findings in this regard. In Figure 8 we show the positional offset explicitly as $\Delta RA$ and $\Delta \text{Dec}$, where $\Delta x = x_{\text{Gaia}} - x_{\text{VLASS}}$ for $x = \text{RA, Dec}$. While the peak of $\Delta RA$ is close to 0, $\Delta \text{Dec}$ peaks at around $-0^\prime.25$ showing the VLASS Quick Look imaging astrometric errors to be dominated by offsets in declination. The lower panel shows the separation, $\sqrt{\Delta RA^2 + \Delta \text{Dec}^2}$, between VLASS and Gaia sources as a function of declination. At $\text{DEC} < -20^\circ$ the peak of the positional offset tends to higher separations indicating poorer astrometry at these declinations.

Figure 8. The positional offsets of Gaia and VLASS sources separated by less than $2^\prime$. The upper panel shows the offset in terms of RA and DEC. Here $\Delta x = x_{\text{Gaia}} - x_{\text{VLASS}}$, where $x = \text{RA, Dec}$. While the peak of $\Delta RA$ is close to 0, $\Delta \text{Dec}$ peaks at around $-0^\prime.25$ showing the VLASS Quick Look imaging astrometric errors to be dominated by offsets in declination. The lower panel shows the separation, $\sqrt{\Delta RA^2 + \Delta \text{Dec}^2}$, between VLASS and Gaia sources as a function of declination. At $\text{DEC} < -20^\circ$ the peak of the positional offset tends to higher separations indicating poorer astrometry at these declinations.
θ = 0′′, but we observe that the declination offset peaks at ΔDec ≈ −0′′.25. The offset in RA is minimal with a median of ΔRA ≈ 0. In agreement with the findings in Lacy et al. (2019), we also confirm that the positional offset is worse at DEC > +60° and DEC < 0°, with the separations between VLASS and Gaia sources mostly being < 0′′.5 at DEC > −20° (see Figure 8).

3.4. Data Selection

In Section 2.3 we detailed the efforts we have undertaken to identify the spurious detections that are present in our VLASS Quick Look catalog. While a selection based on Quality_flag == 0 provides a sample containing the most reliable measurements, this may not be a complete sample, and thus will hinder a statistical characterisation of the survey. In particular, the choice to exclude components where Peak_flux > Total_flux will remove a substantial number of real detections that are unresolved by VLASS, in addition to removing low signal-to-noise false positive detections.

To retain this population of unresolved components for the statistics presented in this paper, with the acceptance of source contamination by false positive detections at lower signal-to-noise, we select components from our catalog with Quality_flag == (0|4), Duplicate_flag < 2 and S_Code ≠ ‘E’. This sample of 1,880,195 components represents the ≈ 1.7 × 10^6 selected by the original, higher fidelity criteria outlined in Section 2.3 (Duplicate_flag < 2 and Quality_flag == 0), with the addition of fitted components (i.e. not ‘empty islands’) where Peak_flux > Total_flux. The distribution of the ratio of peak-to-total flux density as a function of peak brightness for these components is shown in Figure 9.

In order to quantify the impact of potential spurious detections arising from the population of Quality_flag == 4 components, i.e. those with S_peak > S_total but otherwise unflagged in our catalog, we visually inspect a random sample of 100 of these components. Here we find that 92±2%5 are clearly real detections. As the Quality_flag == 4 components account for 10% of the sample this suggests a contamination level of <1% spurious detections. Moreover, for components with S_peak > 3 mJy/beam used for most of the scientific analysis in this work (see Section 3.2.1) only 6% have Quality_flag == 4, suggesting a contamination level of <0.5% at this brightness level. Throughout the rest of this work we use these ~ 1.9 × 10^6 components with Quality_flag == (0|4), Duplicate_flag < 2 and S_Code ≠ ‘E’ as our primary sample. Many of the analyses presented are further restricted to the 615,045 components with S_peak > 3 mJy/beam where the reliability in the flux density measurements is best characterised (see Section 3.2).

4. SPECTRAL INDEX AND CURVATURE

4.1. The VLASS/FIRST Spectral Index Distribution

In the remainder of this work, we use the catalog of components from Quick Look images to explore the scientific potential of VLASS. The availability of wide field ν ~ 3 GHz observations at similar depths to previous surveys at 1.4 GHz lends itself to determining the distribution of spectral indices at these frequencies. For this we cross-match VLASS and FIRST components within 2.″5 of each other (85% are within 1″), where the cross match radius is based on the typical VLASS beam size. As in Section 3.2.2 we require the VLASS component to be isolated in order to prevent the flux from the poorer resolution FIRST observations being split across multiple VLASS components (see also Section 6.3). To enable further cross matching with LoTSS, that allows us to

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5 errors are assumed to be binomial based on Cameron (2011)
explore the spectral curvature of these objects in Section 4.2, we require the distance to the nearest neighbour in VLASS to be greater than 3′′ — half of the LoTSS beam size (6′′, Shimwell et al. 2019). So as to limit issues relating to VLASS missing flux from extended low-surface brightness regions, only relatively small FIRST components, those with deconvolved sizes of < 10′′, are included in this sample. We then determine the spectral index for > 500,000 VLASS components using their VLASS and FIRST total flux density measurements.

In Figure 10 we show the two-point 1.4 – 3 GHz spectral index distribution, which peaks at $\alpha = -0.57$ and has a median of $\alpha = -0.39$, flatter than the typical value of $\alpha \sim -0.7$ one would expect based on previous works (e.g. Condon et al. 2002; Best et al. 2005; de Gasperin et al. 2018). We showed in Figure 5 that VLASS flux densities below $\sim 3\,\text{mJy}$ are unreliable, and we thus limit our sample of matched VLASS and FIRST components to those with a peak brightness higher than 3 mJy/beam. Doing this we find that the distribution peaks at $\alpha = -0.71$, in line with canonical values for the spectral indices of radio sources (see Figure 10). Setting an even higher limit on the minimum flux density of the sample of $S > 10\,\text{mJy}$, the peak of the distribution is located at $\alpha = -0.72$ (see Table 2).

Although our spectral index distribution is cleaner at $S_{3\,\text{GHz}} > 3\,\text{mJy}$, we note that the skew to flatter spectral indices when including components below the brightness threshold (see the upper panel of Figure 10) may be a real effect. If this observation were to hold up with higher quality data, it could support the observations of e.g., Prandoni et al. (2006), Owen & Morrison (2008), and Whittam et al. (2013) of a flattening of spectral indices at flux densities of $\sim 1\,\text{mJy}$, likely due to an increase in radio core dominance at low radio luminosities (Whittam et al. 2017). The future availability of cleaner VLASS Single Epoch images will allow reliable measurements of flux densities at this level, and the stacked three-epoch VLASS images will allow testing of this hypothesis using components with $\lesssim 1\,\text{mJy}$.

Notably, even when applying a cut on minimum flux density, the spectral index distributions for VLASS components have a skew toward flatter values. A potential explanation for this is the high resolution of VLASS results in radio lobes being resolved as separate components to their cores. To investigate the impact of resolved radio cores on the VLASS/FIRST spectral index distribution, we split our sample into likely compact and extended components with a peak brightness of $S_{3\,\text{GHz}} > 3\,\text{mJy/beam}$. We define compact as having $\Psi < 0.5′′$ and extended as having $2′′ < \Psi < 10′′$ (and thus larger than a typical VLASS beam). Here we find that the spectral index distribution for compact components peaks at $\alpha = -0.66$ with a median of $\alpha = -0.38$, compared to $-0.70$ and $-0.65$ respectively for extended components (see Figure 10).

![Figure 10. Normalised distributions of the spectral index, $\alpha$, for VLASS components associated with FIRST components with deconvolved sizes of less than 10′′. The upper panel compares the spectral index distributions for VLASS components over the full range of detected flux densities (blue solid line) to those with $S_{3\,\text{GHz}} > 3\,\text{mJy}$ (red dashed line). The lower panel compares components with deconvolved sizes greater than 2.5′′ (red solid line) to those smaller than 0.5′′ (blue/green dot-dashed line). We follow the convention that $S \propto \nu^\alpha$, and the spectral index is calculated using the total flux densities from the FIRST and VLASS catalogues.](image_url)
Furthermore, we can improve the identification of radio cores by requiring a compact component is spatially coincident with an infrared or optical source. To this end we cross match our sample with the AllWISE catalog (Cutri et al. 2013), based on observations from the Wide-field Infrared Survey Explorer telescope (WISE, Wright et al. 2010). If a component has an AllWISE detection in the W1 band (\(\lambda\) \(\sim\) 3.4\(\mu\)m) within 2.5\(\arcsec\) we associate the radio component and the infrared source with one another. Conversely, we consider a radio component to not have an AllWISE match if there is no W1-band detection within 10\(\arcsec\). For compact components with an AllWISE match, the spectral index distribution peaks at \(\alpha = -0.63\) and has a median of \(\alpha = -0.27\). Where a compact component is not associated with an AllWISE match the spectral index distribution peaks at \(\alpha = -0.81\), with a median of \(\alpha = -0.59\). Although this shows that radio cores contribute to the flatter spectrum bias of the VLASS/FIRST spectral index distribution, no account is taken in determining the spectral indices of potential for radio variability that may be present in a few percent of radio sources (e.g. Carilli et al. 2003; Mooley et al. 2016; Nyland et al. 2020). The availability of second-epoch VLASS observations will enable the impact of radio variability on this distribution to be quantified. The peak and median values of all the spectral index distributions analysed here, including those with and without an AllWISE counterpart, are listed in Table 2.

### 4.2. Spectral Curvature Between 150 MHz and 3 GHz

The availability of the first data release of LoTSS (DR1, Shimwell et al. 2019) allows for comparisons of our catalog with deep (rms \(\sim\) 70\(\mu\)Jy/beam), high resolution (\(\sim\) 6\(\arcsec\)), low-frequency (\(\nu\) \(\sim\) 150 MHz) observations over \(\sim\) 400\(\deg^2\). LoTSS DR1 lies within the FIRST footprint, allowing us to match our cross-matched VLASS/FIRST components with LoTSS, again using a 2.5\(\arcsec\) search radius, providing flux density measurements in three radio bands for these components. We find \(\sim\) 17,000 VLASS components with observations from both FIRST and LoTSS, and a FIRST deconvolved size smaller than 10\(\arcsec\), 5,497 of which have \(S_{3\,\text{GHz}} > 3\,\text{mJy/beam}\).

As in Section 4.1, we split our sample of radio components into compact (deconvolved size, \(\Psi < 0.5\,\text{arcsec}\), \(n = 1,205\)) and extended (\(\Psi > 2.5\,\text{arcsec}\), \(n = 645\)) using the deconvolved major axis size of the VLASS component. As in Section 4.1 the spectral indices are determined based on the cataloged total flux densities of the components. Comparing the low- (150 \(\lesssim\) \(\nu\) \(\lesssim\) 1,400 MHz) and high-frequency (1,400 \(\lesssim\) \(\nu\) \(\lesssim\) 3,000 MHz) spectral indices of these components demonstrates their spectral curvature and is shown on a radio ‘color-color’ plot in Figure 11. Most components possess normal radio spectra, with the highest density of both compact and extended components at \(-1 \lesssim \alpha_{1500}^{3000} \approx \alpha_{1400}^{1500} \lesssim -0.5\). A population of the extended components shows clear spectral curvature, a feature often being associated with older radio lobes (Kharb et al. 2008; Harwood et al. 2017).

The radio colors of compact components show substantial scatter, with radio colors displaying inverted spectra (positive spectral index at low- and high-frequency), flat spectra (spectral index \(\approx 0\) at low- and high-frequency), Gigahertz Peaked Spectra (GPS: positive low-frequency and negative high-frequency spectral indices, O’Dea 1998; O’Dea & Saikia 2020), and concave spectra (negative low- and positive high-frequency spectral indices). These distinct populations are highlighted in Figure 11. Some of the scatter in the radio color-color parameter space will be driven by radio variability, the impact of which will be quantifiable with the forthcoming availability of VLASS epoch 2 observations.

### 4.3. Infrared Colors of Compact Radio Sources With Differing Spectral Shapes

Considering point-like radio components as individual compact sources can have tangible scientific benefit,
allowing us to cross match with multiwavelength observations, and provide insights into the properties of their host galaxies. To this end we use the cross-match between VLASS and AllWISE described in Section 4.1 to obtain infrared magnitudes for the likely hosts of these compact sources. From this cross match we then select five samples of compact sources exhibiting different radio spectra:

- GPS sources with $\alpha_{150}^{400} > +0.5$ and $\alpha_{1400}^{3000} < -0.5$: 41 objects, 22 with AllWISE matches,

- inverted-spectrum sources having $\alpha_{150}^{400} > +0.5$ and $\alpha_{1400}^{3000} > +0.5$: 25 objects, 18 with AllWISE matches,

- flat-spectrum sources with $-0.3 < \alpha_{150}^{400} < +0.3$ and $-0.3 < \alpha_{1400}^{3000} < +0.3$: 129 objects, 94 with AllWISE matches,

- concave-spectrum sources with $\alpha_{150}^{400} < -0.5$ and $\alpha_{1400}^{3000} > +0.5$: 17 objects, 14 with AllWISE matches,

- and, for reference, normal-spectrum sources having $\alpha_{150}^{400} < -0.5$ and $\alpha_{1400}^{3000} < -0.5$: 246 objects, 147 with AllWISE matches.

In Figure 12 we show the WISE colors (W1 [3.4 µm] − W2 [4.3 µm] and W2 − W3 [12 µm]) of the samples defined above. We then classify the host galaxies as either early- or late-type using the criteria of Jarrett et al. (2017), as AGN based on Jarrett et al. (2011).

Infrared colors associated with early-type galaxies are relatively uncommon amongst our sample — potentially the result of only including unresolved radio sources — accounting for $3.4_{-0.5}^{+2.2}$ % of normal-spectrum, $5.3_{-1.5}^{+3.3}$ % of flat-spectrum, and $7.1_{-2.3}^{+13.2}$ % of concave-spectrum sources. None of the 26 GPS sources in our sample have WISE colors expected of early-type galaxies. For inverted-spectrum sources however, $16.7_{-5.5}^{+12.1}$ % have WISE colors associated with early-type hosts. Unfortunately, the small size of our sample (17 objects) prevents any statistically significant conclusions being drawn here, but we note that where inverted-spectrum sources are associated with early-type colors, these colors are within half a magnitude of the Jarrett et al. (2017) early-/late-type segregation of the WISE color-space.

More generally, the WISE colors of our sample of compact radio sources are split between being consistent with late-type and AGN hosts. Late-type hosts account for $43 - 57$ % of compact radio sources (depending on spectral shape), whilst $35 - 45$ % of sources have AGN-like WISE colors. The fractions of normal-spectrum, GPS, inverted-, flat- and concave-spectrum sources having WISE colors associated with AGN, late- and early-type galaxies are explicitly given in Table 3. For comparison with the general galaxy population we also show the WISE colors of MPA/JHU sample from the seventh data release of the Sloan Digital Sky Survey (SDSS, York et al. 2000; Kauffmann et al. 2003; Abazajian et al. 2009) in Figure 12, and the fractions of each color classification (AGN, late- or early-type) are given in Table 3. It is worth noting however, that while the host of a radio source may have WISE colours associated with star-forming disk galaxies as defined by Jarrett et al. (2017), that in and of itself does not mean that star-formation is responsible for the radio emission as opposed to an AGN.
Figure 12. WISE color-color diagrams for compact radio sources with different spectral properties. We show five types of radio source here: normal-spectrum sources (blue circles, upper middle panel), GPS sources (blue triangles, upper right), inverted-spectrum sources (blue stars, lower left), flat-spectrum sources (blue square, lower middle), and concave-spectrum sources (inverted blue triangles, lower right). The WISE color-color distribution of galaxies in SDSS is shown in shown red for reference (and for clarity on its own in the upper-left panel). The x-axis shows the W1 - W2 color, and W2 - W3 is shown on the y-axis. The black-dashed line shows the quasar/AGN region defined by Jarrett et al. (2011), and the black dashed line marks out the regions of color-color space occupied by early- (left) and late-type galaxies (right, Jarrett et al. 2017).

Table 3. Percentage and binomial errors of fractions of compact sources with IR counterpart classifications as defined by Jarrett et al. (2011, 2017) based on their WISE colors (see also Figure 12).

| Sample           | AGN  | late-type | early-type |
|------------------|------|-----------|------------|
|                  | [%]  | [%]       | [%]        |
| SDSS             | 0.9±0.01 | 75.4±0.06 | 23.6±0.05 |
| normal-spectrum  | 35.4±4.1 | 57.1±4.9 | 3.4±2.2 |
| GPS              | 45.5±10.6 | 54.5±9.8 | 0.0±7.7 |
| inverted-spectrum| 38.9±12.1 | 44.4±11.7 | 16.7±12.4 |
| flat-spectrum    | 41.5±5.2 | 48.9±5.1 | 5.3±3.3 |
| concave-spectrum | 42.9±13.3 | 42.9±13.3 | 7.1±13.2 |

Despite the clear advantages of matching the VLASS, FIRST and LoTSS catalogs, the observations were not made simultaneously. Thus, there will exist contamination from sources exhibiting radio variability. Tackling this is beyond the scope of the work presented here which acts as a small-scale proof of concept. However, the future advent of multi-epoch observations from VLASS will be invaluable in identifying such detections. Additionally as more data is released by LoTSS the footprint over which such radio color-color data is available will increase beyond the ~ 400 deg$^2$ of the first LoTSS data release utilised here. Eventually such a VLASS/FIRST/LoTSS color-color map will be limited only by the ~ 10,000 deg$^2$ of the FIRST footprint.

5. EUCLIDEAN NORMALISED SOURCE COUNTS

For the first time wide-field coverage of the sky at 3GHz down to mJy sensitivities is made available
through this data. Thus this presents a prime opportunity to quantify the Euclidean normalised (i.e. normalised to the assumption of a geometrically flat and steady state Universe) 3 GHz source counts, \(dN/dS\), at this depth. In order to do this we must account for several complicating factors.

Firstly, in Figure 4 we demonstrate that the depth of the Quick Look imaging is distinctly non-homogeneous. This will impact upon the effective survey footprint over which faint sources can be detected. That is to say, that whilst a 1 mJy component may be readily detected in a relatively deep part of the survey, in one of the more shallow regions (e.g. the Galactic plane which is shown in Figure 4 to be particularly noisy) that component may not be detected. The dominant source of noise variance in the Quick Look images is due to observing tile edge effects — the distinctly higher noise at the edge of a VLASS tile. To estimate the impact of this we compare the peak brightness distributions of components more than 0.2" from a tile edge (and therefore not impacted by tile edge effects) with the full VLASS component peak brightness distribution. Bin-wise dividing the not-edge peak brightness distribution by the full sample peak brightness distribution provides the average completeness (and thus incompleteness) as a function of peak brightness due to tile edge-effects, \(p_{\text{edges}}(S)\). Additionally, the average noise in a particular image can be impacted by the presence of bright radio components. By taking 5× the mean image rms as the limiting flux density for a component to be detected in an image, we can estimate the sensitivity distribution of the Quick Look images. We can combine the distribution of image rms with the completeness due to tile edge effects to give a probability distribution, \(P(S)\), of a component of flux density \(S\) being detected across the survey footprint, i.e., \(P(S) = p_{\text{edges}}(S) \times p_{\text{imdepth}}(S)\), where \(p_{\text{edges}}(S)\) is the contribution from tile edge effects, and \(p_{\text{imdepth}}(S)\) is the contribution from varying image effective depth. At \(S_{\text{peak}} = 3\) mJy/beam the sample completeness is 99.8%, whereas at the 1 mJy/beam level the completeness of the catalog is 67%. The effective survey footprint as a function of component brightness is then estimated by \(P(S) \times A_{\text{VLASS}}\), where \(A_{\text{VLASS}}\) is the total observed footprint of the survey.

The second complication in deriving the VLASS Quick Look \(dN/dS\) is due to the fact that individually detected radio components are often resolved parts of larger structures that make up a distinct source. To counter this, and for consistency with previous works, we adopt the approach that most radio components within 50" are related (Oosterbaan 1978; Windhorst et al. 1985; White et al. 1997). Hence, for all components within 50"

**Figure 13.** The Euclidean normalised differential source counts, \(dN/dS\), for VLASS. The upper panel shows VLASS converted to 1.4 GHz for comparison with FIRST (blue circles). The red squares show the VLASS source counts after scaling the cataloged flux density by 15% as derived in Section 3.2.2. The grey empty circles show the VLASS \(dN/dS\) without correcting for the VLASS flux underestimate. For reference the black dotted line shows the sixth-order polynomial fit derived by Hopkins et al. (2003). In the lower panel we show the VLASS \(dN/dS\) at 3 GHz (red squares) alongside the VLA-COSMOS source counts (blue circles).
of one another their integrated flux densities are summed and they are treated as a single source.

The VLASS Quick Look $dN/dS$, corrected for $P(S)$, is shown in Figure 13 alongside VLA-COSMOS — the previously largest available 3 GHz dataset. Whilst VLA COSMOS probes deeper than VLASS, there is overlap in the flux density range covered by these surveys between $1 \lesssim S \lesssim 10$ mJy, and above $\sim 3$ mJy the VLASS $dN/dS$ is shown to be consistent with the $dN/dS$ from VLA-COSMOS. To compare with a radio survey covering a similar flux density range we additionally compare the VLASS $dN/dS$ to the FIRST $dN/dS$ (also shown in Figure 13) by extrapolating the VLASS flux measurements to 1.4 GHz assuming a spectral index of $\alpha = -0.71$. An additional benefit to comparing to the FIRST $dN/dS$ is that the radio source counts at 1.4 GHz have been well quantified and modelled by numerous observations from Jy level down to sub-mJy depths (e.g., Windhorst et al. 1985; White et al. 1997; Hopkins et al. 2003). Here we find that at $S_{1.4\, \text{GHz}} \geq 5$ mJy the VLASS Quick Look $dN/dS$ is consistent with both the FIRST differential source counts and the 6th-order polynomial fit to the 1.4 GHz $dN/dS$ obtained by Hopkins et al. (2003). Assuming $\alpha = -0.71$, 5 mJy at 1.4 GHz is equivalent to 2.9 mJy at 3 GHz. The agreement with the 1.4 GHz source counts is also indicative that the VLASS flux calibration derived in Section 3.2.2 is accurate, and we show the 1.4 GHz $dN/dS$ for VLASS using uncorrected flux measurements on this same plot for reference. The comparison with the $dN/dS$ at both 3 and 1.4 GHz as established by previous works is consistent with the VLASS Quick Look catalog being incomplete at flux densities below $S_{3\, \text{GHz}} \sim 3$ mJy.

6. THE SIZES OF RADIO SOURCES

6.1. Angular Size distribution of VLASS Components

With a median uncertainty of $\sim 0''.1$, the distribution of deconvolved component sizes, $\Psi$, in VLASS probes down to a scale of $\sim 0''.3 - 0''.4$. Below this, components are listed as having a zero size as observed in VLASS, and higher resolution observations are required to measure their sizes. The distribution of the full-width half maximum of deconvolved major axis, $\Psi_{\text{maj}}$, of VLASS components with $S_{\text{peak}} > 3$ mJy/beam is shown in Figure 14. Here we denote the population of components where $\Psi_{\text{maj}}$ is listed as zero in the bin at $\Psi_{\text{maj}} = 0''.03$.

For those components with a measured, rather than zero, deconvolved angular size we can exploit the availability of this large high-resolution data set to investigate the relation between radio source size and total flux density (Windhorst et al. 1990) at $\nu \sim 3$ GHz. In the lower panel of Figure 14 we show the distribution of non-zero deconvolved VLASS component sizes as a function of total component flux. Our sample shows substantial scatter, but with a trend for increasing size with flux density. For $S_{\text{total}} \lesssim 50$ mJy the median component
size follows a trend of $\Psi(S) \propto S^{0.3\pm0.01}$, consistent with $\Psi = 2\Psi_{1.4\text{GHz}}^{0.3}$ reported by Windhorst et al. (1990). For VLASS components brighter $S \gtrsim 50\text{mJy}$ the slope of this trend flattens somewhat to $\sim 0.2$. However, this may be attributable to the VLASS survey design. VLASS is run in the VLA’s B and BnA configurations. One of the impacts of this observing mode is that sensitivity to large angular scale structure is reduced by a lack of short baselines used in the array configuration. In the case of VLASS this results in larger ($\Psi \gtrsim 30''$) objects being resolved into multiple components or lost altogether (Lacy et al. 2020). As a consequence, VLASS will only sample components with small angular sizes at higher flux densities. A further effect is that the relationship between linear size and flux density is dependent on a source not being split into multiple components. Consequently, components detected in a high angular resolution such as VLASS are only suitable for testing this relation at small angular scales, and testing at large angular scales necessitates a sample of verified multi-component sources.

6.2. The VLASS Two-Point Correlation Function

The high resolution of VLASS lends itself to exploring small scale clustering of radio detections. To this end we determine the angular two-point correlation function for VLASS using the Landy & Szalay (1993) estimator:

$$\xi_{LS} = \frac{DD - 2DR + RR}{RR},$$

where $DD$ is the real data autocorrelation, $RR$ is the autocorrelation of random data, and $DR$ is the cross correlation of real and random data. Given the angular resolution of VLASS is about twice that of FIRST one might expect the two-point correlation functions of these surveys to diverge at angular scales below the FIRST beam size. To that end we additionally determine the FIRST two-point correlation function for comparison.

In Figure 15 we show both the VLASS and FIRST two-point correlation functions over the range $0.0003^{\circ} (1.1'') < \theta < 10^{\circ}$. To compensate for incompleteness at low flux densities only VLASS components with $S_{3\text{GHz}} > 3\text{mJy}$ are used in this analysis. To ensure a fair comparison with FIRST, we limit our two-point correlation for FIRST to components with $S_{1.4\text{GHz}} > 5\text{mJy}$. We fit the VLASS two-point correlation with two power laws, such that:

$$\xi(\theta) = A\theta^\alpha + B\theta^\beta$$

where $A\theta^\alpha$ and $B\theta^\beta$ are power law fits at angular scales larger and smaller than 0.05$^{\circ}$ respectively. For the VLASS Quick Look data: $A = 2.6\pm0.3 \times 10^{-3}$, $B = 1.9\pm0.3 \times 10^{-5}$, $\alpha = -1.03\pm0.03$, and $\beta = -2.83\pm0.10$. These parameters, as well as our determined values for the FIRST two-point correlation, are shown in Table 4 alongside the $\chi^2$ values for the two power law fits.

The VLASS two-point correlation function shows a slope of $-1.03$ at angular scales greater than 0.05$^{\circ}$. As expected, the gradient of the VLASS two-point correlation function steepens at $\theta \lesssim 0.05^{\circ}$ to $-2.83$. This break is the result of radio sources being split into multiple components at smaller angular scales resulting in excess observed clustering (Cress et al. 1996; Blake & Wall 2002). Notably, the VLASS two point correlation

|     | VLASS     | FIRST    |
|-----|-----------|----------|
| $A [\times 10^{-3}]$ | 2.6 ± 0.3 | 2.0 ± 0.3 |
| $\alpha$ | $-1.03 \pm 0.03$ | $-0.87 \pm 0.18$ |
| $B [\times 10^{-5}]$ | 1.9 ± 0.3 | 2.3 ± 0.4 |
| $\beta$ | $-2.83 \pm 0.10$ | $-2.77 \pm 0.11$ |
| $\chi^2$ | 2.82 | 1.59 |

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6 see https://science.nrao.edu/facilities/vla/docs/manuals/propvla/array_configs for more detail on VLA observing configurations.
function shows excess power relative to FIRST at angular scales smaller than $\theta \sim 0.002^\circ (\sim 7''$), the result of VLASS having twice the angular resolution of FIRST — multi-component sources at this scale split by VLASS are usually observed as a single component by FIRST (see also Section 6.3). The excess power at small angular scales in the VLASS two-point correlation function demonstrates the potential to probe the angular size distribution of double radio sources down to the order of a few arcseconds with VLASS.

6.3. Splitting Close Doubles With VLASS

Given that VLASS has a similar sensitivity to FIRST but with twice as good an angular resolution, it stands to reason that some fraction of double radio galaxies that are observed as a single component in FIRST will be split into double or triple sources by VLASS. To test this we take the AGN from the Best & Heckman (2012) catalog of radio galaxies that are associated with a single FIRST component. Using this data has the double advantage that a) the radio observations have been associated with a host galaxy already, and b) that the radio emission has been identified as being due to an AGN, rather than star formation and thus is potentially an unresolved double or triple radio source. To test this we search a radius of $10''$ around each of the 11,556 single-FIRST-component AGN in the Best & Heckman (2012) catalog counting the number of matches within our catalog for each Best & Heckman (2012) source - those with multiple VLASS matches are likely to be sources that have been split into multiple components by VLASS. In Figure 16 we show six examples of single-FIRST-component AGN that are split into multiple components by VLASS (five doubles and one triple).

We find that 1,011 single-FIRST-component AGN from Best & Heckman (2012) are split into multiple components by VLASS. Of these, 890 objects are split into two components, 110 sources are split into three components, 9 are split into four components, and two sources are split into five VLASS components. In Figure 17 we show the fraction of Best & Heckman (2012) single-FIRST-component AGN split into multiple components by VLASS as function of the total flux density of that source in the FIRST catalog. At lower

Figure 16. Six examples of single-FIRST-component AGN from Best & Heckman (2012) that are split into multiple components by VLASS. The postage stamp images are $1' \times 1'$, and are arranged into two rows and three columns of paired images. The top panel in a pair shows the FIRST image and the bottom panel shows the VLASS image. Five of the six examples show VLASS doubles, and the lower-right image pair shows an example of single-FIRST-component AGN split into a triple source by VLASS.

Figure 17. The percentage of AGN in the radio galaxy catalog of Best & Heckman (2012) associated with a single FIRST component that have been split into multiple components by VLASS plotted as a function of 1.4 GHz flux density. The grey shaded region to the left of both black dashed lines represents $S_{1.4 \text{GHz}} < 10 \text{mJy}$, where the combination of spectral index and spreading the emission across multiple components is expected to result in missed VLASS detections. The yellow shaded region to the right of both black dashed lines shows $S_{1.4 \text{GHz}} > 100 \text{mJy}$, where the high flux density of VLASS components may result in sidelobes contaminating the fraction of multi-VLASS-single-FIRST-component sources.
flux densities \(1 \lesssim S_{1.4\,\text{GHz}} \lesssim 10\,\text{mJy}\) the fraction of resolved sources increases from 8\% to \(\sim 20\%\) with increasing flux density. This trend of increasing resolved fraction is probably due to sensitivity and frequency differences between the surveys. For instance, a typical spectrum radio source with \(\alpha = -0.7\) and a 1.4 GHz flux density of 1 mJy would be expected to have a 3 GHz flux density of 0.59 mJy. If that source is then split into multiple components the flux density of each component is naturally lower than the sum of the total source flux density — e.g. a 0.6 mJy source could be resolved into two components of 0.3 mJy each. At \(10 \lesssim S_{1.4\,\text{GHz}} \lesssim 100\,\text{mJy}\), around 20\% of single-FIRST-component AGN are split into multiple components by VLASS. For sources brighter than this, the resolved fraction tends to increase with flux density again. This is likely biased by false-positive detections near bright components that were not removed by our quality flagging. For example sidelobes around sources brighter than \(S_{1.4\,\text{GHz}} > 100\,\text{mJy}\) are themselves bright enough that they may not be flagged by the catalog quality flagging algorithm. Such cases will contribute to a fraction of single-FIRST-component AGN that may appear to have multiple components in the VLASS Quick Look images and artificially inflate the resolved fraction. Taking sources with \(10 < S_{1.4\,\text{GHz}} < 100\,\text{mJy}\) \(17.7 \pm 0.6\%\) of single-FIRST-component AGN are split into multiple components by VLASS.

As the Best & Heckman (2012) catalog includes spectroscopic data about the host galaxies, we can report on the properties of those radio galaxies split into multiple components by VLASS. The spectroscopic properties of these sources are of interest as the AGN in Low- and High-Excitation Radio Galaxies (HERGs and LERGs respectively) are expected to powered by different accretion modes (e.g., Hardcastle et al. 2006, 2007; Buttiglione et al. 2010; Evans et al. 2011). However, the splitting of single-FIRST-component AGN into multiple VLASS components is the combined result of the physical extent of the radio emission and the distance to the source. Spectroscopic incompleteness resulting from the latter of these factors could bias the spectroscopic classification in such a comparison. Indeed, considering only those sources with \(10 < S_{1.4\,\text{GHz}} < 100\,\text{mJy}\), the redshift distribution of single-FIRST-component AGN split by VLASS differs from that of the general single-FIRST-component AGN (see Figure 18). Consequently, we focus on radio AGN at \(z < 0.15\) and \(10 < S_{1.4\,\text{GHz}} < 100\,\text{mJy}\) when comparing those single-FIRST-component sources split by VLASS \((n = 94\), hereafter referred to as the ‘split’ sample\) to the wider single-FIRST-component AGN population \((n = 927\), referred to as the ‘full’ sample\). Moreover, taking the minimum possible separation between split components to be the VLASS beam size of 23.5 corresponds to a linear size of 7.5 kpc at a redshift of \(z = 0.15\). Thus VLASS can resolve radio lobes down to galactic scales, ostensibly FR0s (Baldi et al. 2018), in local universe.

For the split sample, 96.8\(^{+1.0}_{-2.9}\)% are hosted by LERGs and \(1.1^{+2.4}_{-0.3}\)% by HERGs (with the remainder unclassified). Comparably LERGs and HERGs account for \(95.7^{+0.6}_{-0.8}\)% and \(3.2^{+0.7}_{-0.5}\)% respectively of the full sample. Additionally, the availability of redshift data for these objects allows us to report their radio luminosity. In Figure 18 we show the 1.4 GHz luminosity distributions of the split and full sample, calculated using the flux density of the FIRST component. The radio luminosity distributions of the two samples are statistically consistent.
with a Kolmogorov-Smirnoff test returning a \( p \)–value of 0.06. The similarity in both spectroscopic classifications and radio luminosity distributions of these two samples suggests that these two populations are hosted by physically alike AGN. This is consistent with previous studies showing radio extent alone cannot distinguish between fundamentally different populations of AGN (e.g. Baldi et al. 2018; Capetti et al. 2020).

7. SUMMARY

Using the VLASS epoch 1 \textit{Quick Look} images we have produced a catalog of radio components and characterized their quality. Using this we have investigated the number counts and size distributions of radio components and sources at \( \nu \sim 3 \text{GHz} \). The key points of this work are as follows:

- A catalog of \( 1.9 \times 10^6 \) reliable and unique detections from VLASS epoch 1 \textit{Quick Look} imaging is available at https://cirada.ca/catalogues. Flux density measurements are underestimated by \( \sim 15\% \) above 3 mJy/beam and may be less reliable below this. For the statistical analyses presented in this work we compensate for this by scaling our flux densities accordingly, but this correction \textit{is not} applied to the catalog data. Additionally, the astrometric accuracy of this catalog is limited to \( \sim 0.5'' \) at Dec > \( -20^\circ \), and \( \sim 1'' \) at more southerly declinations.
- Combining our catalog with FIRST shows VLASS components at \( S_{3 \text{GHz}} > 3 \text{mJy/beam} \) have a typical spectral index of \( \alpha \sim -0.71 \) between 1.4 GHz and 3 GHz. Further combining with LoTSS DR1 demonstrates the potential for finding large numbers of radio sources with non-normal spectral curvature by utilizing upcoming survey data.
- At \( S_{3 \text{GHz}} \gtrsim 3 \text{mJy} \) the VLASS \( dN/dS \) distribution is consistent with VLA-COSMOS, FIRST, and the 6th order polynomial fit to 1.4 GHz observations from Hopkins et al. (2003). Our VLASS catalog is shown to suffer from incompleteness at \( S_{3 \text{GHz}} < 3 \text{mJy} \).
- The advantage of having higher angular resolution than FIRST is demonstrated via excess power in the VLASS two-point correlation function relative to FIRST at angular scales below \( \sim 1'' \). Moreover, \( \sim 20\% \) of AGN associated with a single FIRST component are split into multiple components using VLASS. At \( z < 0.15 \), single-FIRST-component AGN that are split into multiple components by VLASS have the same radio luminosities and spectral excitation state as those that are observed as a single component by VLASS.

\textit{(Author note: After the public release of our VLASS Quick Look catalog, Gordon et al. 2020, and the completion of this manuscript based on that data, the authors have become aware of a second, independent, VLASS catalog that has recently been made available to the community by Bruzewski et al. 2021.)}

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Software: The following software packages were used in the production of this work: astropy (Astropy Collaboration et al. 2013, 2018), matplotlib (Hunter 2007), TOPCAT (Taylor 2005)

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