

A DESIGN CONCEPT FOR A VERY LARGE ARRAY SKY SURVEY

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ABSTRACT

We argue the merits of an extra-galactic survey of $\sim 10,000 \text{ deg}^2$ in the B-array of the Jansky Very Large Array to a 5σ depth of 0.2 mJy ($40 \mu\text{Jy rms}$) at 2–4 GHz (S-band). Such a survey would be roughly equidistant between FIRST and VLA-COSMOS in depth and would allow forced photometry to the VLA-COSMOS depth, but with $10,000\times$ the area—enabling radio photometry for of order 10 million sources. Time requirements are estimated at 7500 hrs (with overhead), which is less than twice the time required for the FIRST survey and less than 10% of the total lifetime of LSST. Such a survey would be the first wide-field look at the radio sky at 3 GHz and would provide crucial high-resolution radio support for next-generation optical/IR surveys such as Pan-STARRS, SkyMapper, DES, SuMIRe, VST/VISTA, and, of course, LSST by overlapping these areas as much as possible.

1. Introduction

While deep, pointed observations are crucial for understanding the details of our Universe, large-area sky surveys provide the laboratories in which these experiments are conducted. The Sloan Digital Sky Survey (SDSS) and the Faint Images of the Radio Sky (FIRST) surveys provide clear examples of how sky surveys can expand our existing knowledge and drive discovery in new directions. Each new generation of surveys has greatly increased our knowledge of the cosmos and has led to the discovery of heretofore unknown phenomena. Today we are on the edge of a new age in optical surveys with the genesis of Pan-STARRS, SkyMapper, DES, VST/VISTA, and SuMIRe. Ten years from now, LSST will begin constructing the definitive large, deep optical map of the Universe. These surveys will probe new realms by covering large areas of sky to depths as faint as 28th magnitude with multiple epochs allowing new time-domain discoveries. Yet without multi-wavelength support, these surveys will fail to live up to their full potential as observations that span the electromagnetic spectrum are crucial for completing the picture of most astronomical sources.

The FIRST survey (Becker et al. 1995), with an area matching that of SDSS and relatively high resolution, provided a long-wavelength bandpass to the nominal SDSS *ugriz* survey. It is in that vein that we outline a radio survey using the Jansky Very Large Array (JVLA) that is complementary to the next generation of optical surveys. The combined surveys will allow us to address fundamental questions in the evolution of galaxies, the star formation history of the universe, and the demographics and growth of supermassive black-holes. This project would provide a legacy database of ~ 10 million radio sources to sub-milliJansky flux densities and allow for measurements in the sub-microJansky regime (through image stacking).

Here we lay out some basic principles that are important desiderata for any large-scale survey with the JVLA in the era of ground-based synoptic surveys in the optical. The basic premise herein is that a VLASS would be of maximal utility to the broader astronomical community if it is optimally synergistic with existing and next generation ground-based imaging surveys in the optical and IR. We consider the issues of areal coverage, resolution/array, depth, and bandpass separately. However, these are not independent choices and will be considered together within the context of the total time a survey with optimal choices in each would need.

2. Resolution/Array

Arguably the most important question for any VLASS is that of what resolution such a survey should be performed at. Issues of source confusion between optical/IR surveys and any VLASS would be minimized by using a bandpass/array combination that achieves a resolution that is roughly comparable to ground-based optical surveys (which have sub-arcsecond resolution). In the optical, this criterion is, in part, to measure the shapes of galaxies for weak lensing experiments, so a VLASS perhaps need not have quite the same resolution. However, relatively high resolution is crucial for cross-band object matching to the depth of new optical surveys. For example the cumulative number counts of galaxies per square arcminute goes as $N = 46 * 10^{0.31*(i-25)}$ (LSST Science Book), which means that we would expect ~ 2 galaxies with $i < 24$ (LSST single-epoch depth) in the $10''$ beam of ASKAP (for example) and nearly 14 galaxies with $i < 26.8$ (LSST co-added depth). The density of stars varies considerably with position, but, averaged over the sky, is comparable to the density of galaxies. Thus it is clear that a VLASS must have a resolution much better than ASKAP to minimize radio-to-optical confusion issues in order to provide maximal utility with respect to LSST and other such ongoing surveys.

Of course, we must consider that high resolution leads to “over-resolving” of extended sources. However, this problem is mitigated in a number of ways. First is that Ivezić et al. (2002) find that the fraction of FIRST radio sources with complex morphology is only $\sim 10\%$. Second is that the NVSS survey (Condon et al. 1998) already provides a low-resolution survey (to a limit of $\sim 2.5\text{mJy}$) at 20cm (L band; 1.4 GHz). Similar back-up for over-resolution within a VLASS will come from EMU¹ (and WODAN) whose beam of $10''$ ($15''$) and an L-band rms of $10\ \mu\text{Jy}$ will provide crucial calibration for bright extended sources.

A resolution roughly double that of FIRST (which had $\sim 5''$ resolution) will provide an excellent match to the relative astrometric accuracy in the optical. FIRST had astrometric accuracy of $\sim 1''$ —better than the typical seeing of SDSS (and only a few times worse than the astrometric accuracy). Next-generation optical surveys will have seeing that is roughly twice as good and a VLASS should attempt to match that improvement. Further improvement in resolution beyond that is unnecessary and perhaps unwarranted given the reduction in photometric accuracy for extended objects that comes with higher resolution. However, it must be emphasized that good resolution is key. For example, Figure 1 from Hodge et al. (2011) shows that there is important morphological information to be gained from improvement in resolution over FIRST (see, e.g., Section 8.1.2).

Furthermore, the comparison to the FIRST resolution is only relevant for $10,000\ \text{deg}^2$ of sky. For the rest of the sky visible to the VLA, the appropriate comparison is to the NVSS (Condon et al. 1998), which has a resolution $10\times$ lower. This is important as up to 30% of NVSS sources are resolved into multiple components by FIRST. In terms of matching to catalogs at other wavelengths, this is an important consideration as the weighted mean position of multiple sources renders the nominal astrometric accuracy meaningless for these blended sources.

Given the desire for higher resolution than FIRST, we are driven to either L-band observations

¹EMU, the Evolutionary Map of the Universe (Norris 2011), is a planned 1.3GHz radio survey that will image the entire Southern sky to $\text{dec} = +40^\circ$ using the Australian SKA Pathfinder (ASKAP; Johnston, S., et al. 2008).

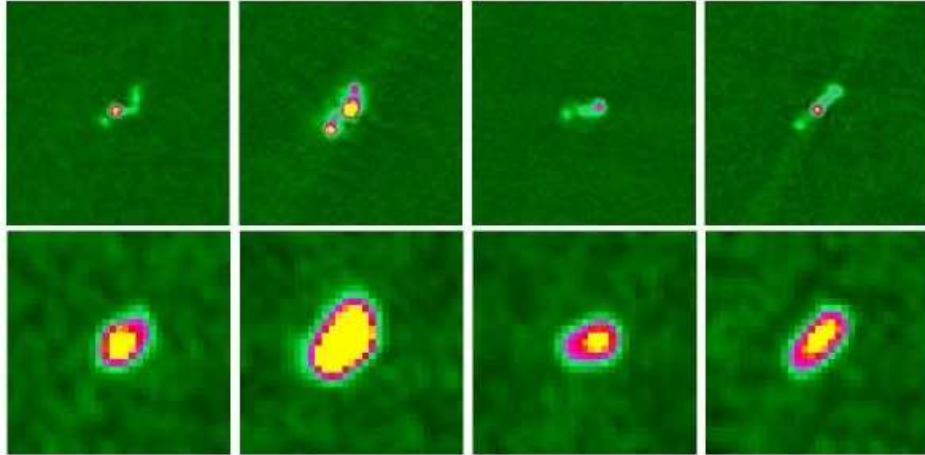


Fig. 1.— VLA A-array observations (*top*) of SDSS quasars observed with FIRST in the B array (*bottom*). in the A-array ($1''.3$), S-band observations in either the A or B arrays ($0''.65$, $2''.1$, respectively) or C-band observations in either the A or B array ($0''.33$, and $1''.0$, respectively). As A-array resolution in any of the L-, S-, or C-bands is perhaps higher than is needed (and indeed prudent given the problem of over-resolution), we consider the B-array a better choice.

3. Bandwidth

NVSS and FIRST both observed in the L-band (1.4GHz; at low- and high-resolution, respectively). A new, deeper L-band survey could be conducted much faster since the JVLA has a bandwidth (in L) of 1 GHz instead of 50MHz— $20\times$ wider. Thus naively redoing the FIRST survey today would take just 1/20th of the time (about 10 days!). In practice the full bandwidth is not available due to radio frequency interference (RFI) and may be more like 600 MHz; however that is still more than an order of magnitude improvement over FIRST and NVSS.

L-band provides relatively low spatial resolution in the B-array, so it is important to consider higher frequency bandwidths (we do not consider lower frequency as the resolution is worse). At 3GHz, S-band provides $2\times$ the resolution (with a nominal bandwidth of 2GHz) of L-band and C-band (GHz) provides $4\times$ the resolution (with a nominal bandwidth of 4GHz). Arguments regarding total survey time (below) lead us to suggest that S-band is an optimal choice for a VLASS. RFI in the S-band should be no worse than in the L-band and perhaps somewhat better, giving an effective JVLA S bandwidth of 1.5GHz—roughly $30\times$ that of the effective VLA L bandwidth.

Lastly it is crucial to realize that the size of the JVLA bandwidths mean that any new survey will yield radio “color” information that was not available in prior single-band observations with the VLA. We illustrate this (relative to mean quasar spectral energy distributions) in Figure 2 where we show that the S bandwidth is roughly as wide as the combined g and r bandwidths of SDSS. As a result S-band observations will allow for the determination of radio colors from a single observation (for sufficiently bright sources), providing crucial information on the shape of the radio spectrum (see Section 8.1.2).

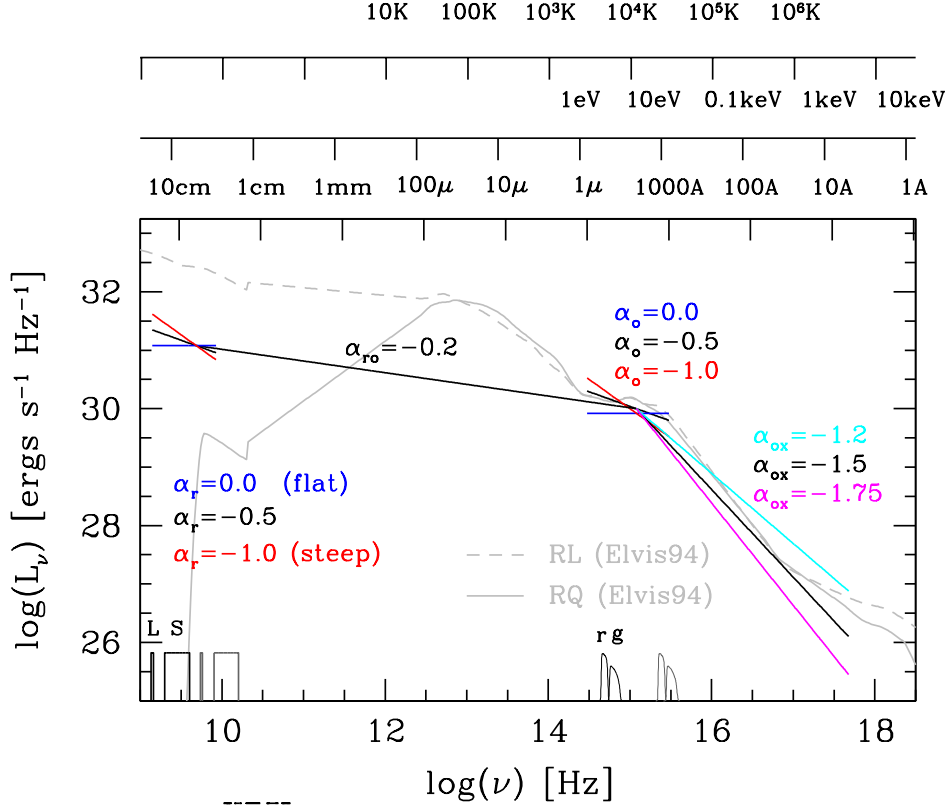


Fig. 2.— Quasar spectral energy distributions (SEDs) from the radio to X-ray. Light gray lines show the mean radio-quiet (solid) and radio-loud (dashed) quasar SEDs from Elvis et al. (1994). A radio-to-optical spectral index of $\alpha_{ro} = -0.2$ is the approximate dividing line between objects traditionally classified as radio loud and radio quiet ($\log R = 1$). We also show the range of spectral indices in the radio and optical bandpasses and between the optical and X-ray bandpasses. At the bottom of the figure, the VLA L, JVLA S, SDSS r , and SDSS g bandpasses are depicted at $z = 0$ (black) and $z = 3$ (gray). Note that the JVLA S-band is as wide as SDSS g and r combined, allowing determination of radio colors from a single observation.

4. Depth

The depth for a VLASS should be decided, based on the depth of existing radio surveys, the science that they cannot do, and the desired science to be done. For example at the FIRST survey’s approximate flux limit of $\sim 1\text{mJy}$, White et al. (2007) find that only 10% of SDSS quasars are detected by FIRST. Further justification for depth will be discussed in Section 8; however, it is typical for new surveys attempt to reach an order of magnitude deeper than the previous generation. Thus an obvious goal would be $\sim 15\mu\text{Jy}$ rms, which is approximately the depth of the VLA-COSMOS survey ($10\text{--}15\mu\text{Jy}$; Schinnerer et al. 2007). Even with the JVLA, that depth would require an unreasonable amount of time (for areal coverage equal to FIRST). However, when paired with an existing survey, it is possible to effectively reach that depth using forced photometry at the location of known sources with roughly a factor of $2.5\times$ less exposure. As such, we can use the density of sources from VLA-COSMOS to estimate the number of sources. For flat-spectrum ($\alpha = 0$) sources, the S- and L-bands achieve the same relative depths. For steep-spectrum sources ($\alpha = -1$), S-band is a factor of 2 shallower. For the typical star-forming galaxy with $\alpha = -0.7$, the S-band is about 40% shallower than L, thus we might expect of order 10 million total radio sources

to a 2σ depth of $\sim 0.15\text{mJy}$ in the S-band over an area of $10,000\text{ deg}^2$.

5. Areal Coverage

Finally, a VLASS will have maximal public utility if it overlaps existing and future large-area sky surveys in the optical/IR. Ideally it would cover as much area as is observable from Socorro, NM that is within the fields of SDSS, Pan-STARRS, SkyMapper, DES, SuMIRe, VISTA/VST, and LSST. Figure 3 (*left*) shows a comparison of the depth and area covered for major existing and future optical/IR sky surveys, including the HSC-wide area (SuMIRe), DES, PS1, and LSST. In the right panel we show a similar comparison for a sampling of high-frequency radio surveys. For example, FIRST covered over $10,000\text{ deg}^2$ within the SDSS footprint, while NVSS covered the full sky north of $\delta = -40^\circ$. With a southern bias in the next-generation optical/IR surveys, probing as far south as possible is crucial. While it would not be possible to cover the full LSST area ($\delta > \sim -60$) given the differences in hemispheres of the observatories, a survey covering $-30^\circ < \delta < 30^\circ$ is 50% of the sky or approximately $20,000\text{ deg}^2$. One possibility for areal coverage would be to avoid the Galactic plane and concentrate on the $10,000\text{ deg}^2$ in this declination band with the most overlap of existing/future optical/IR surveys (e.g., areas shared by both DES and LSST).

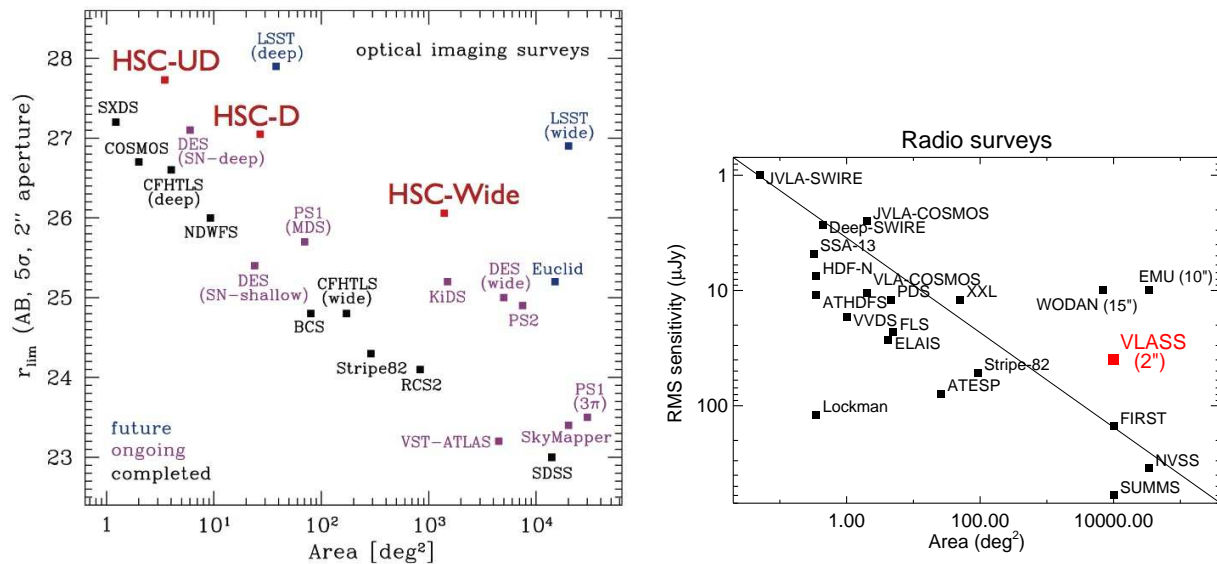


Fig. 3.— The limiting magnitudes (in r) and solid angles of existing, on-going, and planned optical imaging (*left*) and some examples of high-frequency radio (*right*) surveys.

6. Total Time

There is a tradeoff between the choice of bandwidth, areal coverage, and the total survey duration. In all, the FIRST survey took 4000 hours (≈ 5.5 months). Thus a VLASS would certainly be feasible if it took as much time as FIRST and was able to cover more area and/or to a greater depth than FIRST. Indeed an investment of 4000 hours represents only 5% of the LSST's 10 year lifetime.

If we wished to double the resolution from the FIRST survey (which was $4.5''$ —much worse than

the resolution of LSST), both the S-band (in A or B array at $0''.65$ and $2''.1$ resolution, respectively) or the C-band (in B array at $1''$ resolution) would be acceptable choices.

An S-band survey would need $4\times$ as many pointings as FIRST, as the angular extent of the VLA beam scales inversely with frequency. However, the wider bandwidth, in principle, will achieve the same depth $30\times$ faster, making the survey take $\sim 1/8$ th of the time as FIRST. Thus a depth of $150\ \mu\text{Jy}/\sqrt{8}$ over $10,000\ \text{deg}^2$ is potentially achievable in the same amount of time as FIRST.

A C-band survey in the B array would provide $1''$ resolution—intermediate between the two S-band options. Moreover, the C-band has double the bandwidth of the S-band – allowing the same survey in $1/2$ of the time and with twice the lever arm for determining spectral indices (between 4 and 8 GHz). The number of pointings to cover the FIRST area, would, however, also be larger—roughly $20\times$ as compared to $4\times$. As the increase in bandwidth (double) over the S-band is more than offset by the larger number of pointings needed ($5\times$), we consider an S-band survey in the B array to be more efficient than a C-band survey in the B array. Thus we are led to a natural choice of a S-band survey in the B array. Figure 4 shows a sample pointing configuration for such a survey following the pattern that worked so well for FIRST and NVSS.

Taking B-array and S-band as fixed parameters, we now consider the trade-offs between areal coverage, depth, and total survey time. While the VLASS web site² gives a nice breakdown of the survey times for each passband, the assumed depth of $100\ \mu\text{Jy}$ in each passband does not make for a realistic comparison to FIRST, being only $1/3$ deeper. Thus we provide a table with some possible scenarios with area between $10,000$ and $20,000\ \text{deg}^2$, depth between 15 and $50\ \mu\text{Jy}$, and survey times spanning 4000 to 8000 hours of clock time. The exposure times are based on scaling from the VLASS web page, but the total time is calculated by scaling the efficiency from the FIRST survey where an exposure time of 165s gave an efficiency of 88% (accounting for 10s for slewing and 6% for calibration and time lost). The first entry shows that our pipe dream survey of $10,000\ \text{deg}^2$ at $15\ \mu\text{Jy}$ is unrealistic. To achieve that depth, we would need to reduce the area to about $2200\ \text{deg}^2$ as shown in Row 2. Dropping the depth to $50\ \mu\text{Jy}$ as in the third row provides a more realistic survey for $10,000\ \text{deg}^2$ or even for $20,000\ \text{deg}^2$ (Row 4).

If the observing time is fixed, and one wants to maximize the number of detected sources, then

²<https://science.nrao.edu/science/surveys/vlass/documents/VLASSurveyCapabilities.v1.pdf>

Table 1. FIRST-like S-band VLASS Survey Parameters

Area (deg^2)	Depth (μJy) [rms]	Time (hours)	Exposure (s)	Efficiency (%)
10000	15	37000	342	92
2200	15	8000	342	92
10000	50	3970	31	71
20000	50	7940	31	71
10000	35	7500	60	81

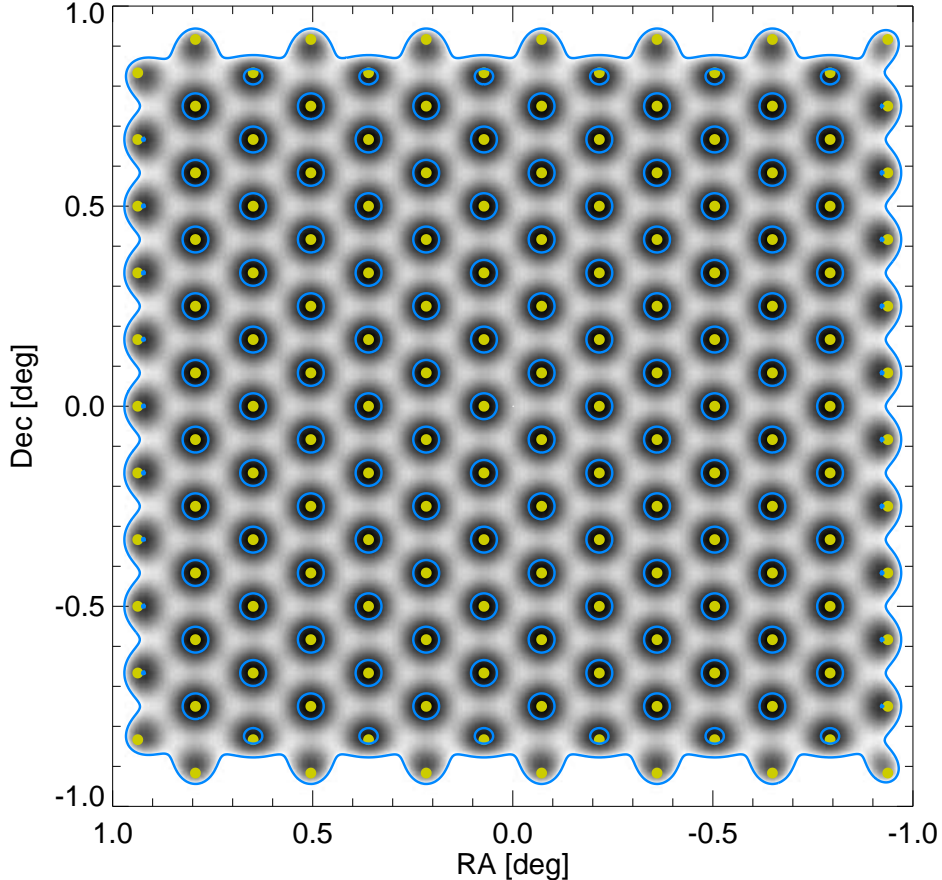


Fig. 4.— RMS noise resulting from a possible pointing grid. Pointing centers (yellow) are on a hexagonal grid with 10 arcmin spacing. The grayscale image and contours show the noise in coadded maps after summing across the 2 GHz bandwidth (assuming 0.5 GHz is lost to interference). The grid spacing is chosen to give good uniformity of coverage even at the highest frequency (4 GHz) and so has considerable overlap between fields at the lowest frequency (2 GHz). The contours represent roughly $\sim 35 \mu\text{Jy}$ at the center and $\sim 40 \mu\text{Jy}$ at the beam edges.

the tradeoff between area and depth depends on the slope of the source counts. For radio counts, the slope is shallower than Euclidean and a VLASS should prioritize area in order to produce the greatest number of source counts. As such, our baseline plan is shown in Row 5, with an area of $10,000 \text{ deg}^2$ to a depth of $\sim 35 \mu\text{Jy}$, taking 7500 hours—slightly less than twice the FIRST survey length. Such a survey would cover the same total area of sky as FIRST, which could be 1/2 the LSST area and would reach a depth of over $4\times$ the FIRST survey (for flat-spectrum sources and 2.5 times deeper for sources with $\alpha = -0.7$).

While such a large time block would necessarily take away from other observations, it is worth noting that survey observations come with an impressive level of efficiency ($> 70\%$). Such a large legacy proposal will take a lot of time, but it will be minimally wasteful in its drive to create a legacy radio survey comparable to the next-generation of optical/IR surveys.

Moreover, considering large sky surveys as a sort of a “virtual” VLA, the efficiency of such

observations are even higher. For example, the the FIRST cutout server (<http://third.ucllnl.org>) delivers on average more than 12,000 image cutouts every day to users around the world. Each image served is equivalent to a three-minute VLA observation; thus, the virtual VLA issues the equivalent of a 3-minute VLA observation every 7 seconds! The FIRST catalog is also heavily utilized. It is accessed through many online systems, and over the past year, complete versions of the FIRST catalog have been downloaded more than 1000 times. The latest FIRST catalog has been downloaded 200 times since June 2013; this number provides a first-order estimate of the number of serious users in the community. The time spent on surveys with widely usable data products is clearly repaid manyfold.

7. Considerations for the VLASS Survey Science Group

Within the context of the outlined program there are a number of issues that merit consideration of the VLASS Science Survey Group (SSG). Three specific areas that we identify here are related to the choice of array configuration, dealing with wide bandwidths, and the impact to JVLA scheduling.

While the VLA configurations are well thought out and long established, before embarking on an endeavor as significant as a VLASS it doesn't hurt to take a moment to reconsider them. The standard VLA configurations are A, B, C, and D with hybrid BnA, etc. configurations during transitions. Each configuration is used for approximately 4 months before the next change. Developing a new array design for a survey would be inefficient if it were not going to be used for at least this much time. However, as any VLASS is likely to require more time than is available in any one configuration per cycle, it may worth reconsidering the array design and perhaps establishing a special hybrid "survey" configuration.

Related to this is the need for the VLASS SSG to determine how to best schedule any large block of time. One possibility would be to devote an extra ~ 1.5 months to the JVLA cycle in each of the appropriate array configurations for the next decade, enabling the survey to finish before LSST gets fully under way. An option that may be potentially less disruptive in the long run would be to get it all over with at once, providing an immediate legacy survey that could be used for follow-up targeting of next-generation imaging surveys should spectroscopic capabilities come to fruition. Clearly a new hybrid array design would be efficient in this case.

Lastly we note that the large bandwidth presents challenges in addition to the benefits noted above as it is not as straightforward to process data in a 2GHz bandwidth as for 50MHz. While tools exist in CASA to do so, the VLASS SSG may want to consider the matter as, in practice, the 2GHz bandpass is broken into 16 IFs of 125 MHz each and the resolution from one end to the other changes by a factor of two. The data can be reduced in each IF separately, but some care is needed to combine them together in order to treat them as a single observation. This is particularly true near the limiting flux of the survey where the source spectral indices are not well determined.

8. Science Topics

Our proposal emphasizes AGN science; however, we recognize that a large fraction of sources detected will be star-forming galaxies, so we also consider that population.

8.1. Radio-Loud Quasars

8.1.1. Demographics

The primary demand that quasar science—at high redshifts in particular—places on a radio survey is for a wide area. Quasars are rare, and the radio-loud sources account for only $\sim 5\%$ of the population as a whole. To SDSS depth, the surface density of optically selected quasars is $\sim 43 \text{ deg}^{-2}$ at $0 < z < 5$ (Richards et al. 2006; Ross et al. 2013); of which only $\sim 1.4 \text{ deg}^{-2}$ are at $z > 3$. Thus only one high-redshift, radio-loud quasar is detected per $\sim 7 \text{ deg}^2$ of survey area. Building a large statistical sample of radio sources for demographical studies of, for example, the evolution of radio loudness with redshift (Jiang et al. 2007) requires significant sky coverage.

Not only is a large area required, so is significant depth. For example, while the physics that leads to the generation of huge radio lobes in radio-loud quasars still eludes us, it seems clear that black hole mass (e.g., Lacy et al. 2001) and spin (e.g., Blandford & Znajek 1977; Blandford & Payne 1982) play key roles in this question. Better coupling could be made to the detailed physics of black hole accretion if we had a deeper census of the demographics of radio-loud quasars. Jiang et al. (2007) have argued that the radio-loud fraction (RLF) goes down with increasing redshift and with decreasing luminosity. We show these trends using an updated sample of quasars in Figure 5. However, the robustness of these L and z trends is sensitively dependent on the completeness of the FIRST survey near its flux limit. While models of quasar evolution can explain these trends (major mergers both feeding and spinning up BHs with lower redshift; e.g., Volonteri et al. 2013), testing these results with much deeper data is crucial for our understanding of not only radio-jets, but black hole physics in general.

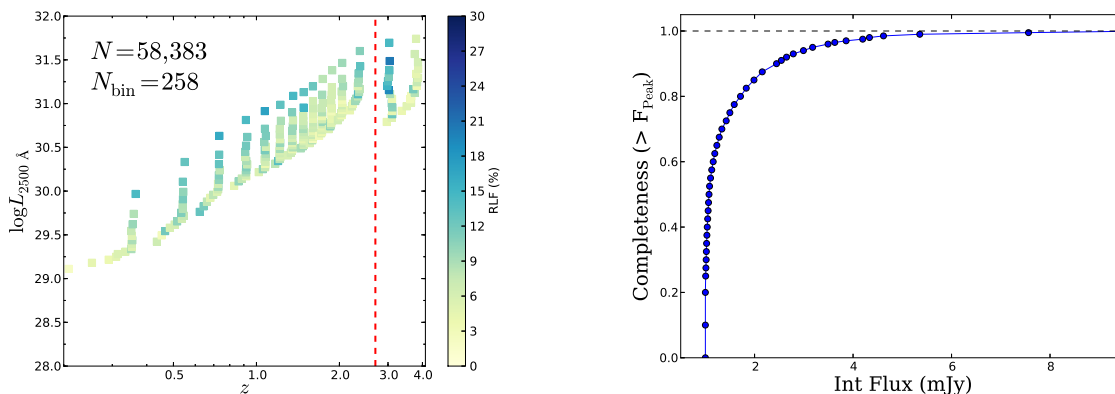


Fig. 5.— (*Left:*) Radio-loud fraction as a function of optical luminosity and redshift (Kratzer et al. 2014). The RLF is apparently a function of both L and z . However, this depends sensitively on the completeness of the FIRST survey near the flux limit (*right;* courtesy R. White).

High-resolution is also important for understanding of radio-loud quasars. The typical spectral index for a radio quasar is $\alpha_\nu \sim -0.5$. Although this is relatively flat, it still argues for lower frequencies in order to achieve higher sensitivity for a given flux limit. In addition, there are hints that compact, steep-spectrum radio emission may be more prevalent at high redshifts (e.g., Frey et al. 2011). Such sources will be easily detected by planned low frequency ($< 1 \text{ GHz}$) surveys with excellent sensitivity; however, these surveys will invariably have poor resolution. Efficient matching

of radio sources to surveys at other wavelengths (particularly in the optical) requires \sim arcsecond resolution. In this way, a higher frequency VLA survey can provide an essential complement to the low frequency surveys, providing localization of radio sources at a much greater depth than FIRST. This is prerequisite to identifying candidates for spectroscopic campaigns to obtain redshifts, either in the optical/near-IR, or with ALMA.

The combination of FIRST and SDSS provides an example of a radio survey well-matched to an optical imaging/spectroscopic survey in depth and resolution. FIRST detections matched to counterparts in the SDSS imaging received spectroscopic fibers during the survey, and the number of radio quasars with redshifts increased dramatically (Schneider et al. 2010), particularly at high redshift. However, even though the SDSS was relatively shallow, FIRST was not complete in terms of radio-loudness for typical SDSS quasars. Using a definition of radio loudness as $\log(f_{5\text{GHz}}/f_{2500}) > 1$ (Stocke et al. 1992), FIRST was only sensitive to radio-loud SDSS quasars with $i < 19.0$, predominantly the bright, low redshift ($z < 2$) sample.

Obviously a deeper survey with the JVLA would significantly improve this situation, but trade-offs with frequency must be considered. For a typical quasar with a spectral index of -0.5 , the flux at 3 GHz will be roughly two-thirds of that at 1.4 GHz. Nonetheless, at a depth of 0.2 mJy, a higher frequency survey would reach quasars roughly five times fainter in the radio than those in FIRST. In terms of radio loudness, the proposed S-band survey would be sensitive to all radio-loud quasars in the SDSS spectroscopic catalog ($i < 20.2$). Utilizing forced photometry, radio fluxes could also be measured for a large number of radio-intermediate sources, and many of the new spectroscopic quasars in the BOSS catalog ($2.2 < z < 3.5$, $r < 22$) and the upcoming eBOSS ($0.9 < z < 2.2$, $r < 22$). It is worth noting that although BOSS extended the depth of FIRST source targeting by nearly 3 magnitudes relative to the SDSS, a paltry 4% of BOSS quasars appear in the FIRST catalog (Pâris et al. 2013). Clearly, a next-generation survey is needed to explore the radio properties of these large quasar samples.

8.1.2. Orientation

Quasars are thought to have many axisymmetric structures (e.g., accretion disks, dusty torii, etc.) with associated observed properties that vary with viewing angle. Both continuum emission and broad emission line velocity widths depend on orientation and, critically, bias black hole mass measurements (e.g., Wills & Browne 1986; Runnoe et al. 2013). As such, in order to enable corrections to quasar black hole mass estimates and to conduct other orientation studies, it is desirable to have orientation estimates.

The jets of radio-loud quasars display their axisymmetry and provide the only reliable ways of determining quasar orientation. When the jet structures are clearly spatially resolved, the radio core flux relative to either the optical or extended radio emission can provide an estimate of orientation (e.g., Wills & Brotherton 1995). At higher redshifts, with young radio sources, or when dealing with lower resolution imaging, the jet morphology is not always clear and the radio spectral index is a more dependable orientation indicator (Orr & Browne 1982; Richards et al. 2001; DiPompeo et al. 2012). Jet-on sources close to the line of sight are dominated by a relativistically boosted flat

core spectrum, while more inclined sources are dominated by the steep optically thin synchrotron emission from the radio lobes.

Currently, while FIRST is well matched to the SDSS, there is no equivalent survey of similar depth but a different frequency with which to obtain spectral indices. The best match is the Westerbork Northern Sky Survey (WENSS) at 92 cm which covers about a third of the SDSS area (2955 square degrees), but only reaches to 18 mJy, not particularly well matched to the depth of FIRST. The currently proposed survey would dramatically improve the situation: at 1 mJy S-band spectral indices can be determined to $\Delta\alpha = \pm 0.24$ given the proposed $40 \mu\text{Jy}$ rms flux limit. This improves to $\Delta\alpha = \pm 0.08$ for sources brighter than 3 mJy.

8.2. Radio-Quiet Quasars

While only about 5% of SDSS quasars meet a formal definition of being radio-loud, it is increasingly clear that even radio-quiet quasars are not radio-*silent*. Stacking analysis (White et al. 2007) of formally radio undetected objects can be used to explore the radio properties of the other 95% of quasars. The baseline proposed survey would increase the fraction of SDSS quasars detected (not just radio-loud) to 25% at 5σ and possibly as high as 50% using forced photometry techniques. Stacking analysis would enable the exploration of the remaining 50% of SDSS quasars.

Achieving this greater depth is important as an open question is whether this radio flux is intrinsic to the AGN or is due to star formation. Results from Kimball et al. (2011) based on just 179 quasars suggests both: those radio-quiet quasars well below the established “radio loud” dividing line are likely to be dominated by star formation. However, it is also likely that the radio-loud division is excluding objects that, while not displaying classical properties of radio-loud sources, are still dominated in the radio by AGN-related processes.

Better radio catalogs that complement next-generation optical surveys will be crucial to developing a full understanding of the radio contributions within AGN populations.

8.3. High- z Quasars

Today over 60 quasars have been discovered at $z > 6$, and the first quasars at $z \gtrsim 7$ have been found in near-IR surveys (Mortlock et al. 2011; Venemans et al. 2013). Although FIRST is relatively shallow, two of these quasars were selected from FIRST (McGreer et al. 2006; Zeimann et al. 2011), while two more have FIRST counterparts. At face value, this indicates that the radio-loud fraction remains high enough at $z \gtrsim 6$ for radio surveys to provide an effective probe of the Epoch of Reionization (EoR). Indeed, it has been argued by Volonteri et al. (2011) that *Swift* detections of high-redshift blazars demand a substantially larger population of high- z radio quasars than currently known, unless there is significant evolution in the physical properties of jetted sources. A larger population may indeed exist if the fraction of optically obscured sources increases with redshift, an area where radio surveys have been particularly successful at complementing optical surveys (e.g., Glikman et al. 2013).

High redshift studies favor higher resolutions, as extended sources would be difficult to detect anyway due to surface-brightness dimming. The rarity of objects argues for maximal areal coverage. Indeed, another argument for maximizing the area is that large area surveys can find the rarer bright objects that are suitable for followup observations (e.g., spectroscopy). For example, if two surveys produce equal numbers of high- z quasar candidates, but the wide-shallow survey has candidates with $m < 23$ while the narrow-deep survey has candidates with $m < 25$, the brighter candidates are much easier to follow up.

In terms of depth, to test the predictions of Volonteri et al. (2011), one could attempt to identify all sources with a radio loudness $R > 100$ at $z > 5$ to a given optical flux limit. FIRST would only be complete to these highly radio-loud sources to a depth of $m \sim 21.4$, already above the SDSS imaging depth. On the other hand, a 0.2 mJy radio survey would be sensitive to $R > 100$ quasars to an optical flux limit of $m \sim 23.1$, closer to the single-epoch LSST imaging depth, and also the limit for obtaining usable spectroscopy with an 8-10m telescope in ~ 1 – 2 hours.

Our picture of the evolution of radio AGN at high redshift is very much limited by poor statistics at this time. Using a simple model connecting dark matter halos to the active black hole population, Haiman et al. (2004) predict that a GHz radio survey to a depth of 0.2 mJy would detect $z \sim 10$ quasars at a rate of $\sim 3 \text{ deg}^{-2}$, and $\gtrsim 70 \text{ deg}^{-2}$ at $z \sim 6$. Extrapolating from recent evolutionary models for the optical quasar luminosity function at high redshift (Willott et al. 2010; McGreer et al. 2013) and folding in the empirical radio loudness distribution that Baloković et al. (2012) derived from FIRST and SDSS, results in ~ 130 quasars at $5 < z < 10$ with $S_{3 \text{ GHz}} > 0.2 \text{ mJy}$ and $m < 23$ in a $10,000 \text{ deg}^2$ survey, compared to ~ 60 using FIRST survey parameters. If one goes to LSST-like depth with $m = 25$ then a 0.2 mJy survey would detect nearly 500 $z > 5$ radio quasars. While this remains much smaller than the theoretical predictions, it is nonetheless a further demonstration that radio surveys must keep up with their optical counterparts if we are to understand the role of radio emission from AGN in the first Gyr after the Big Bang. Finally, even just a few bright radio sources within the EoR would enable direct studies of the neutral hydrogen content on large scales through 21cm absorption studies (e.g. Carilli et al. 2002).

8.4. Star-Forming Galaxies

At the depth of the FIRST survey, essentially all of the sources detected belong to the AGN and quasar populations. A sky survey like that outlined here, on the other hand, would begin to detect star forming galaxies. In particular, the well-known correlation between star formation and radio emission means that such a survey would be a highly sensitive tracer of the dust-unbiased star formation in these galaxies. This is significant, as the effects of dust on the traditional optical and UV measurements of the star formation rate are still debated (e.g., Carilli et al. 2008), and those shorter wavelengths may miss the IR bright population entirely (e.g., Walter et al. 2012). The result is that the behavior of the cosmic star formation rate density at redshifts above $z \sim 1$ is still uncertain.

The proposed depth would allow the direct detection of LIRGs out to a redshift of $z \sim 0.15$, ULIRGs out to $z \sim 0.5$, and HyLIRGs out to $z \sim 1.3$. By stacking the ~ 4 billion photometric redshifts

expected in the area in the LSST gold sample ($i < 25.3$, $S/N > 20$), we could push out to even higher redshifts. The feasibility of such a stacking project has already been demonstrated by Karim et al. (2011), where they were able to probe out to $z \sim 3$ by stacking star forming galaxies in the 2 square degree VLA-COSMOS field. By stacking in bins of only ~ 15 galaxies, a VLASS like that outlined here would already reach the depth of the unstacked VLA-COSMOS survey, where Smolčić et al. (2009) were able to confirm the steep rise in the cosmic star formation history out to $z \sim 1$. With a 5000 times larger area, stacking in larger bins would allow us to put tight constraints on the dust-unbiased cosmic star formation rate density out to redshifts of at least $z \sim 1-2$, when galaxies were undergoing their final assembly, and beyond.

9. Conclusions

If the JVLA were to carry out another large sky survey, a number of important decisions will need to be made as the capabilities of the facility to perform vastly different types of sky surveys greatly exceeds the time available. The basic tenet that we set forth in this whitepaper is that such a survey will have maximum value to the astronomical community if it is designed in a way that best supports the next-generation of imaging surveys in the optical/IR. We would argue that this also allows for great science to be done using the radio data alone. Given the science goals of these surveys (quasars, supernovae, baryon acoustic oscillations, galaxy clusters—all at high-redshift) we have argued that relatively high resolution in the radio is important. We have further argued that the S-band is the logical new survey band for the JVLA with an optimal trade off of bandwidth and beam size. The wide bandwidth of the new S-band means that, in a single observation, a new survey could effectively reproduce previous VLA surveys in *both* the L-band and C-band (instead of just L-band), doubling the efficiency of such observations and allowing key science using radio spectral indices. Reaching a depth of ~ 0.2 mJy at relatively high resolution would enable the survey to effectively act as an additional long-wavelength bandpass for next-generation optical/IR imaging surveys, providing an important legacy data product for both the radio and optical/IR communities.

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