The NRAO has announced the Jansky VLA Sky Survey (VLASS) initiative\(^1\) to conduct a new wide-area centimeter wavelength sky survey in support of multi-wavelength synoptic surveys using existing and future facilities. Community input is critical to the success of the VLASS. This document is a summary of the VLASS initiative and the capabilities of the VLA for surveys, for use in interpreting the requirements from White Papers in response to the recent call, and for use in writing follow-up White Papers. The initial set of White Paper submissions should be received by us on or before 15 December 2013 (or very shortly thereafter) in order to get full consideration in incorporating into the agenda for the January 5, 2014 AAS Workshop. However, we will be accepting submissions throughout the VLASS definition process and I anticipate that a second generation of White Papers building on and refining requirements for cases presented in the first generation of papers will be useful for the Survey Science Group (SSG) to get detailed input to their process which will commence after the AAS meeting.

Overview

It has been nearly 20 years since the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-cm (FIRST) surveys commenced, providing the first large community-accessible sky surveys and catalogs from the Very Large Array. With construction of the upgraded Karl G. Jansky VLA complete and science operations well underway, the undertaking of a new generation of large VLA surveys is now possible. A number of large optical synoptic surveys such as Pan-STARRS and the Palomar Transient Factory (PTF) are now underway. Looking ahead to the era of LSST starting at the end of the decade, a next-generation Jansky VLA Sky Survey (VLASS) would be a key addition to the suite of large radio astronomical datasets available to the general community, and open new spatial and temporal windows on the radio Universe.

The parameters of the VLASS have not been pre-defined – selecting the science goals and survey implementation is what the VLASS initiative is about. Community input to this process through White Papers, at the AAS Workshop in January 2014, and through participation in the Survey Science Group are all key to building the VLASS. It is important that possible avenues for new survey science not be closed prematurely, and thus we urge you to explore a wide range of science goals and technical approaches in generating White Papers.

\(^1\) For more information, go to [https://science.nrao.edu/science/surveys/vlass](https://science.nrao.edu/science/surveys/vlass)
Performance of the VLA for large mosaics

The following table summarizes the performance of the VLA for large surveys. We have chosen the reference level of 100 µJy rms for continuum images using the specified bandwidth for the sensitivity calculations at all bands.

<table>
<thead>
<tr>
<th>Band (freq)</th>
<th>Bandwidth</th>
<th>$t_{\text{int}}$ sec</th>
<th>$\theta_{\text{PB}}$</th>
<th>$\theta_{\text{res}}$ (B)</th>
<th>SS deg$^2$/hr</th>
<th>$\dot{\theta}$ arcm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (230-470 MHz)</td>
<td>200MHz</td>
<td>8553</td>
<td>122'</td>
<td>24.0''</td>
<td>0.98</td>
<td>0.01</td>
</tr>
<tr>
<td>L (1-2 GHz)</td>
<td>600MHz</td>
<td>37</td>
<td>30.00'</td>
<td>5.6''</td>
<td>13.90</td>
<td>0.65</td>
</tr>
<tr>
<td>S (2-4 GHz)</td>
<td>1500MHz</td>
<td>7.7</td>
<td>15.00'</td>
<td>2.7''</td>
<td>16.53</td>
<td>1.56</td>
</tr>
<tr>
<td>C (4-8 GHz)</td>
<td>3.03GHz</td>
<td>4.4</td>
<td>7.50'</td>
<td>1.3''</td>
<td>7.21</td>
<td>1.36</td>
</tr>
<tr>
<td>X (8-12 GHz)</td>
<td>3.50GHz</td>
<td>3.9</td>
<td>4.50'</td>
<td>0.78''</td>
<td>2.96</td>
<td>0.93</td>
</tr>
<tr>
<td>K$_u$ (12-18 GHz)</td>
<td>5.25GHz</td>
<td>3.5</td>
<td>3.00'</td>
<td>0.55''</td>
<td>1.45</td>
<td>0.68</td>
</tr>
<tr>
<td>K (18-26.5 GHz)</td>
<td>7.20GHz</td>
<td>7.0</td>
<td>2.05'</td>
<td>0.36''</td>
<td>0.34</td>
<td>0.23</td>
</tr>
<tr>
<td>K$_a$ (26.5-40 GHz)</td>
<td>7.20GHz</td>
<td>9.5</td>
<td>1.45'</td>
<td>0.25''</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Q (40-50 GHz)</td>
<td>7.20GHz</td>
<td>50</td>
<td>1.00'</td>
<td>0.18''</td>
<td>0.011</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The “Band” column gives the VLA band designations and their accessible RF span (“freq”). The “Bandwidth” column is the effective correlator bandwidth (RFI free) within that band used for sensitivity calculations – the intrinsic maximum bandwidths are 2 GHz (8bit mode, below 4 GHz) and 8 GHz (3bit mode, 4 GHz and above). Natural weighting is assumed for the calculation of integration times $t_{\text{int}}$ needed to reach 100 µJy image rms (these numbers were obtained using the VLA Sensitivity Calculator). The primary beam FWHM $\theta_{\text{PB}}$ and the image resolution $\theta_{\text{res}}$ are at calculated at band center. Synthesized resolutions $\theta_{\text{res}}$ are given for the B-configuration. Depending on science goals you can achieve higher resolution with 3.2 times smaller $\theta_{\text{res}}$ in A-configuration, or more sensitivity to larger scales at 3.3 times larger $\theta_{\text{res}}$ in C-configuration, and 11 times larger in D-configuration. The SS column gives the survey speed (SS) in deg$^2$/hour at 100 µJy image rms. The final column gives the estimated on-the-fly scanning rate $\dot{\theta}$ in arcmin/sec required to attain that survey speed in an optimally sampled mosaic. Note that scanning rates in excess of 6 arcmin/sec have not been verified for successful use on the VLA at this time. We plan to carry out extensive tests to define the actual scanning limits over the next 6 months.

To calculate the survey speed, we use the formula

$$SS = 0.5665 \frac{\theta_{\text{PB}}^2}{t_{\text{int}}} \text{deg}^2\text{hr}^{-1}$$

which assumes a fully-filled large mosaic, with integration time $t_{\text{int}}$ in seconds and primary beam FWHM $\theta_{\text{PB}}$ in arcminutes. See the VLA Mosaicking guide\(^2\) for details.

\(^2\) See [https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/mosaicking](https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/mosaicking)
The scan rates in the final column are calculated assuming an “optimally” packed mosaic (with a scan separation of $\theta_{PB}/\sqrt{2}$) with

$$\dot{\theta} \approx 0.8 \frac{\theta_{PB}}{t_{int}} \text{arcmin sec}^{-1}$$

using the integration times $t_{int}$ (in seconds) and primary beam size $\theta_{PB}$ (in arcmin). The rate peaks at S-band at 1.56 arcmin/sec (6.2 times the sidereal rate of 0.25 arcmin/sec at the equator). We will further investigate the maximum allowed tracking rates to better determine the limits that should be applied for potential survey designs.

Another practical limit is that the integration (“dump”) time out of the correlator backend (currently limited to 1 sec or longer in normal observing) should be significantly smaller than the required time to cross the primary beam (ideally less than 0.1 $\theta_{PB}$). The scan rates for a depth of 100 $\mu$Jy are $\sim 0.2 \theta_{PB}$/s for C through Ku bands and so 0.5s integrations are desirable at these bands. For even shallower surveys, using shorter correlator dump times will help, at the cost of higher data rates into the archive.

These survey speed calculations assume a continuum image rms level of 100 $\mu$Jy using the full bandwidth available (width in 2$^\text{nd}$ column of table). This number is not intended to define the survey, but is chosen for reference purposes in the Table, and is scalable to other depths and assumed bandwidths. For bands at 2 GHz and above, the data will be taken using 2 MHz channel width (for L-band 1-2GHz these will be 1 MHz channels, and the standard setup uses 125 kHz channels at P-band). If you need sensitivity numbers in a given averaging bandwidth for line work, then adjust the speed numbers accordingly (e.g. by the ratio of the new bandwidth to the assumed bandwidth). When calculating for a reduced bandwidth, you may wish to also adjust the desired image rms levels so that the survey speed is multiplied by the square of the ratio of new imaging rms to 100 $\mu$Jy. For example, at 1.2 GHz a 1 MHz channel has a velocity width of 250km/s for HI at $z=0.18$, but the survey speed at 100 $\mu$Jy in this single channel is 600 times slower than that given for the 600 MHz continuum bandwidth given in the table, or 0.023 deg$^2$/hour, so at an image rms of 1 mJy, the survey speed is 2.32 deg$^2$/hour.

Further information on VLA performance can be found at https://science.nrao.edu/facilities/vla/docs/manuals/oss2014a/performance

**Effective Survey Speed for Object Detection Yield**

If your goal is to image and catalog objects like galaxies, AGN, stars, or exotica, which are from a defined population with known number-flux counts and a measured average spectral energy distribution (SED) then a relevant figure of merit might be the effective survey speed (ESS) for number of objects found per unit time.

The frequency spectrum of a class of objects must be considered when computing the relative speed between observing bands. For example, for a population with an SED given by a power-law with an average spectral index $<\alpha>$ with flux density $S$

$$S(\nu) \propto \nu^{<\alpha>}$$
(where \( \nu \) is the observing frequency) then

\[
\text{ESS}(\nu) \propto SS(\nu) \cdot \nu^{2<\alpha>}
\]

translates the raw imaging survey speed \( SS \) given above into ESS taking into account spectral shape. For example, the mJy population of galaxies at 1.5GHz has \( <\alpha> \approx -0.7 \) so

\[
\text{ESS}_{gal}(\nu) \propto SS(\nu) \cdot \nu^{-1.4}
\]

and thus all other things being equal a survey at 3GHz would yield an ESS of 38% compared to a survey at 1.5GHz and using the SS given in the table above the ESS at L-band is a factor 2.2 times higher than that using S-band.

The other factor to be considered when calculating the effective survey speed for choices of survey depth (image rms) and area covered is the number-flux density counts of the source population. The ESS is the yield in objects per unit time, so assumptions about the areal density of objects as a function of depth must be made. We assume over a range of flux densities of relevance the integral number-flux counts versus flux density \( S \) can be approximated by a power-law

\[
N(> S) \propto S^\gamma
\]

where \( \gamma = -1.5 \) for uniformly distributed objects in a Euclidean Universe (e.g. where corrections for cosmology are unimportant). Since the ESS is number per unit time \( t \), while \( SS \propto A/t \), where the survey depth \( S \propto t^{-0.5} \) and survey area \( A \propto t \), then

\[
\text{ESS}_{gal}(S) \propto SS(S) \cdot S^{\gamma+2}
\]

and thus for Euclidean counts

\[
\text{ESS}_{gal}(S) \propto SS(S) \cdot S^{0.5}
\]

meaning a shallower survey (higher limiting \( S \)) wins. Note that for galaxies observed at 1.5GHz the counts are Euclidean for flux densities between 50 \( \mu \)Jy and 1 mJy, and shallower (\( \gamma > -1.5 \)) outside this range so the total yield is higher for a wider/shallower survey at all depths.

### Possible VLA Sky Surveys

At this stage, we have no pre-defined overall target survey duration and span limitations to work from. We might use the NVSS and FIRST as data points in how VLA surveys were carried out in the past. For reference, these surveys were:

- The D-configuration (resolution 45") NVSS covered \( \approx 30000 \) square degrees in two 42 MHz bandwidth IF channels centered around 1.4 GHz to an image rms level of around 0.45 mJy/beam in Stokes I. The source catalog completeness limit was stated as 2.5 mJy and contained around \( 2 \times 10^6 \) discrete sources (Condon et al. 1998, AJ, 115, 1693). A total of 2932 hours was allocated to this project.

- The B-configuration (resolution 5") FIRST covered 10635 square degrees in two 42 MHz bandwidth IF channels centered around 1.4 GHz to an image rms level of around 0.15 mJy/beam in Stokes I. The source catalog completeness limit was stated as 1 mJy and the 2012Feb16 version of the catalog contained around
950,000 discrete sources. (Becker et al. 1995, ApJ, 450, 559; 2012yCat.8090). A total of 3200 hours was allocated to this project.

These two programs were allocated a total of around 6000 hours over the course of a decade. Thus, as a guess, we might reasonably expect to be able to get something on this order (3000-6000 hours), possibly somewhat more if the extent of the survey is indeed a full decade or more. Note that extremely strong justification will be required if a VLASS is proposed for 5000 hours or more!

The survey speeds given above can be used to calculate integration times required for different survey strategies. Example strategies for continuum surveys include:

- A large NVSS-style 30000 deg² survey at 2-4 GHz would require 1815 hours of integration time to reach an imaging rms of 100 µJy. This could be split into two configurations, e.g. A and C spaced by about 8 months. The A-configuration resolution of 1″ allows for identification in optical/infrared surveys, while the addition of C-configuration gives sensitivity to larger scale emission.
- A large FIRST-style 10000 deg² survey at 4-8 GHz would take 1387 hours of integration time per epoch to reach a single epoch rms of 100 µJy.
- A medium-area 1000 deg² synoptic survey from 8-12 GHz at 100 µJy rms would take 337 hours of integration per epoch. This could be repeated every 16 months when the configuration recurs in the cycle, and would build up a much deeper image of the static sky over multiple epochs. These could cover the Galactic Cap and/or Galactic Plane for extragalactic and galactic science respectively.

The choice of observing band(s), array configurations, sky coverage, and cadences to be chosen for the VLASS depends on the science goals. A multi-tier survey, with a succession of areas and cadences, is also a possible strategy. See the example provided below for how a multi-tier survey might be constructed.

The above examples are for continuum survey sensitivities – spectral surveys, targeting HI, OH, and redshifted CO, for example, could be carried out in parallel with the continuum studies, with a possible cost of increasing data rates and volumes if higher spectral resolution modes are needed. Obvious examples include the HI and OH lines in L-band, and the 6.7 GHz Methanol maser line in C-band. The science cases and required parameters for key spectral lines to be targeted in VLASS are good topics for White Papers.

The times calculated above are the total on-sky integration time. Calibration and slewing overheads must be added to these to arrive at the total duration required to schedule the survey. We estimate that 25% overheads are achievable for a carefully constructed large survey (multiply the integration times by 1.25 to get total duration).

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3 From https://science.nrao.edu/observing/largeproposals/largeproposals
An Example Survey

As a concrete example, I have devised a 3-tier survey taking a total of 5614 hours of integration time, broken down into:

- **Tier 1**: $30000\,\text{deg}^2$ in 2 configurations (A/C, 8mos. apart) to $100\,\mu\text{Jy}$ ($1815\,\text{h}$)
  - S1 – 2-4GHz in 2 configurations (A/C, 8mos. apart) to $100\,\mu\text{Jy}$ ($1815\,\text{h}$)

- **Tier 2**: $10000\,\text{deg}^2$ in SDSS/FIRST footprint
  - S2 – 2-4GHz in 2 epochs each at $100\,\mu\text{Jy}$ ($1210\,\text{h}$) $[58\,\mu\text{Jy} \, S2+S1]$
  - C2 – 4-8GHz in 2 configurations (B/D, 8mos. apart) at $100\,\mu\text{Jy}$ ($1400\,\text{h}$)

- **Tier 3**: $1000\,\text{deg}^2$ total, split into galactic plane, galactic cap, equatorial stripe, and possibly a prime target like the Virgo cluster or M31
  - S3 – 2-4GHz in 6 epochs each at $100\,\mu\text{Jy}$ ($363\,\text{h}$) $[33\,\mu\text{Jy} \, S3+S2+S1]$
  - C3 – 4-8GHz in 3 epochs each at $100\,\mu\text{Jy}$ ($416\,\text{h}$) $[50\,\mu\text{Jy} \, C3+C2]$
  - X3 – 8-12GHz in 1 epoch at $100\,\mu\text{Jy}$ ($338\,\text{h}$)
  - L3 – 1-2GHz in 2 configurations (A/C or B/D) at $100\,\mu\text{Jy}$ ($72\,\text{h}$)

All data would be taken with full polarimetry. The science goals for the parts of the survey using the above tier definitions might include:

- All-sky rotation measure studies with the S1 observations
- A baseline all-sky image in preparation for LIGO follow-up with S1
- A 3-epoch long-duration transient study with S1+S2
- Medium-deep rotation measure study with S1+S2 and C2; the Faraday depth limit is set by S-band, with C-band to provide extra range in high-Faraday rotation regions
- A 9-epoch transient and variability study with S1+S2+S2 and 4-epochs with C2+C3 to characterize the light-curves from 2-8 GHz
- Deep rotation measure study with all Tier 3 bands (L3+S3+C3+X3); the Faraday depth limit is set by L3. Galactic and extragalactic regions would be included in the Tier 3 regions totaling $1000\,\text{deg}^2$
- A 6-epoch galactic plane transient and variability survey in all Tier 3 bands (with possible commensal line studies)
- Transients would be identified in “real-time” (processed within hours of the observations) and alerts generated for the community. Some of the key epochs for transient studies (in S2 and S3) might be co-observed (simultaneously or with a time-lead) by optical/infrared survey telescopes such as Pan-STARRS and PTF.
- Some tiers (S1, C2, L3) have dual configurations for imaging quality and sensitivity to lower surface brightness extended emission. Alternatively, it might be possible to devise a special hybrid configuration incorporating baselines from B, C, and D-configurations that would provide single-epoch coverage of a better range of angular scales with reasonable uv-coverage when multi-frequency synthesis is used over the 2:1 bandwidths available with the Jansky VLA. Studies should be done to study this possibility!
Where I have not specified the configurations for the various multi-epoch tiers, they should have resolution of around 1-2 arc-seconds, or better, for optical identification of transients, so they would be A configuration at L-band, A or B at S-band, B or C configuration at C-band, and C or D configuration at X-band. Tier 3 might be carried out in different configurations for the galactic plane and out-of-plane regions.

This type of survey is not focused on a single science case, but provides a broad multi-use legacy dataset for a wide range of studies. Again, this is meant only as an example from my own science interests, not what NRAO plans for the VLASS! See the White Papers submitted on each of these science areas for more concrete goals and survey parameters than the simple ones presented here.

Closing Thoughts

I hope that this prospectus gave a useful overview of what the VLA is capable of in sensitivity, and the trade-off with survey and scanning speeds, in order to calculate the survey parameters for given choices for a VLASS. It will be the task of the Survey Science Group to define the VLASS based on science goals input from the community, so none of the examples given above should be taken as pre-determined. We look forward to receiving a wide range of White Papers covering the possibilities in more detail.

For help regarding VLASS and White Paper submission, contact us at vlass@nrao.edu or through the NRAO helpdesk at https://help.nrao.edu