A Preliminary Summary of The VLA Sky Survey

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(On behalf of the entire Science Survey Group)

1 Executive Summary

After months of critical deliberation, the Survey Science Group (SSG), along with its community working groups, have focused in on the following survey definition for the VLA Sky Survey (VLASS), culminating in a cohesive science program that has been identified to simultaneously provide the largest scientific impact, generate substantial involvement from all astronomical communities, and leave a lasting legacy value for decades. Like nearly all modern surveys, we have adopted a tiered ("wedding-cake") approach, combining comprehensive all sky coverage with sequentially deeper coverage in carefully identified parts of the sky. This approaches both enables unique scientific discovery and critical information to inform interpretation of the shallower, but more extensive, sky coverage components of the survey. In doing so, the combined sum of all tiers far outweighs that of the individual components, allowing detailed investigations for a broad range of astrophysical research topics such as: Galactic HII regions and supernova remnants, radio transients, the evolution of star-forming galaxies, AGN physics from the evolution of their radio properties, and their impact on galaxy formation. Such an approach provides astronomers information for every point of the radio sky, while simultaneously addressing fundamental questions about the nature and evolution of astrophysical objects. Multi-wavelength communities studying rare objects, the Galaxy, radio transients, or galaxy evolution out to the peak of the cosmic star formation rate density will equally benefit from the VLASS. Furthermore, the currently proposed tiered survey will undoubtedly help guide a number of PI led science projects that could not be properly conceived (e.g., due to not having enough statistics) without the time investment of the VLASS.

In addition to scientific and legacy considerations, the proposed VLASS definition pays close attention to what will soon be coming online via the various Square Kilometer Array (SKA) pathfinders (e.g., ASKAP/EMU, WODAN, LOFAR), and the SKA itself. In doing so, the VLASS showcases the strengths and unique capabilities of the VLA over these other facilities, namely high resolution imaging and exquisite point-source sensitivity for going deep, free from the effects of source confusion, which are critical for source identification. For the next $\gtrsim$10 yr (i.e., until an SKA_1; $>>$ 2020), the VLA will provide the combination of the highest resolution and point-source sensitivity of any GHz radio interferometer in the world. This has led to the choice of S-band ($2-4$ GHz) and a combination of A- and B-configurations as the frequency and resolution choices for the entire survey. Considerations for polarization studies also leads to the S-band as a natural choice, since depolarization will be lower than at L-band. Below, the current components of the comprehensive survey definition are summarized. Though the exact details may change (including the distribution of time, sensitivity, and coverage between the components outlined below), this provides a high level overview of the integrated program.

2 Survey Definition Components

2.1 ALL-SKY

The entire sky visible to the VLA (i.e., $\delta > -40^\circ$; 82% of the celestial sphere – same as the NVSS footprint) will be covered to a depth of at least $100\,\mu$Jy ($1\,\sigma$) in the S-band ($2-4$ GHz) with a resolution of $\lesssim 2''.1$. In doing this, the survey will achieve FIRST-like depth over the entire VLA-visible sky with better than a factor of two improvement in angular resolution (critical for source identification), providing sufficient bandwidth coverage for determination of spectral indices and Faraday rotation measures. This survey will provide an indispensable resource for the entire astronomical community to systematically study classes of objects as well as to identify and study radio counterparts to their own multi-wavelength observations.

The ALL-SKY component will enable the discovery of rare classes of objects in the radio, such as $z > 6$ radio-emitting quasars, that are bright enough for followup with existing telescopes. Coverage over the entire VLA-visible sky will also allow the broader astronomical community to determine the radio emitting properties of rare classes of objects that are identified at other wavelengths (e.g., brown dwarfs, supernova remnants, or objects from future surveys such as LSST). The radio flux densities from VLASS will be used, in combination with data from surveys at other wavelength to select rare classes of objects from their unique spectral properties (e.g., identifying AGN in Pan-STARRS).

Given the WIDE and DEEP tiers (see below) the necessary additional integration time to map the remaining VLA-visible sky is ≈1441 hr, or ≈1802 hr with 25% overhead.

2.2 WIDE

The WIDE survey component will cover ≈10,000 deg^2 down to $50\,\mu$Jy ($1\,\sigma$) in the S-band with a resolution of $2''.1$ (B-configuration). WIDE imaging will focus on portions of the sky for which major investments are already in place to gather optical/NIR spectroscopy, thus allowing meaningful astrophysical investigations of sources. Accordingly, WIDE will focus on covering a major portion of the 14,000 deg^2 area being targeted by the Dark Energy Spectroscopic Instrument (DESI), which obtain optical spectra for tens of millions of galaxies and quasars, constructing a 3-dimensional map spanning the nearby universe to 10 billion light years.

At the proposed depth, the WIDE tier will be able to detect ($5\,\sigma$) luminous star-forming galaxies (i.e., Luminous Infrared Galaxies; LIRGs) out to $z \sim 0.15$ and rarer ultra-luminous infrared galaxies (ULIRGs) out to $z \sim 0.5$, while additionally providing a good baseline sample of relatively nearby star-forming galaxies. For AGN studies, WIDE will increase the FIRST detection rate of SDSS quasars from 5 to $\gtrsim$20%. As the spectra already exist (with many more coming from DESI), the radio data from WIDE will immediately provide information as to whether there is strong evolution in both redshift and luminosity in the radio-loud quasar population. This is fundamental for understanding the physics of quasars and the nature of their relationship to galaxy evolution, as today it remains unclear as to whether the radio-loudness of quasars is linked to redshift or bolometric luminosity.

The necessary integration time for WIDE is ≈2420 hr, or ≈3025 hr with 25% overhead.

2.3 DEEP

The DEEP survey component will cover a total of 10 deg^2 down to 1.5 μJy (1 σ) in the S-band with a resolution of 0.″65 (i.e., A-configuration). The DEEP imaging will be divided up into 3 separate fields, tentatively 4.5 (XMM-LSS or ECDFS), 3.5 (ELAIS-N1), and 2 deg^2 (COSMOS), the latter of which will leverage the existing deep imaging. Having these three separate fields allows potential issues from cosmic variance to be critically assessed. Furthermore, to accurately measure the two-point correlation function and conduct halo occupation distribution analyses, which in turn provides information on the underlying dark matter distribution in these regimes, structures on $> 2 - 3$ Mpc scales must be fully sampled in angular space. It is on these scales that one moves from the non-linear to linear regime. Consequently, this equates to a linear dimension of the survey of $\sim$ 2 deg, or a contiguous area of ∼4 deg^2 (we plan to map rectangles 1.5 deg by 3 deg = 4.5 deg^2 in XMM-LSS or ECDFS and 2 deg by 1.75 deg = 3.5 deg^2 in EN1), which is not achieved even by COSMOS. By observing three separate fields we can average over any field-to-field variations on the largest scales that are still present.

A 7.5 μJy (the 5 σ detection threshold) corresponds to a star-formation rate of ∼50 solar masses per year at $z = 1.5$ (i.e., L* galaxies at the peak of the cosmic star formation rate density). Using the joint information between the WIDE and DEEP tiers allows extragalactic objects of similar luminosity to be observed over a much wider range of distances, out to larger look-back times, and allows similar volumes of the Universe to be studied at high and low redshifts. Consequently, the VLASS provides an essential lever arm to disentangle the effects of differing luminosity from the effects of cosmic evolution of the source population being studied. Furthermore, the DEEP component provides a reference truth image for the both the WIDE and DEEP tiers where they overlap, allowing accurate assessment of completeness and reliability in the shallower survey tiers.

The necessary integration time for DEEP is ≈2386 hr, or ≈2983 hr with 25% overhead.

2.4 GALACTIC

The VLASS will additionally map the Galactic plane and bulge regions down to 50 μJy (1 σ) in the S-band to achieve a resolution of 0.″9 (i.e., by combining A-configuration data with the ALL-SKY B-configuration data). The time request considers elevation-dependent $T_{\rm sys}$ (primarily spillover) effects to ensure a true sensitivity of 50 μJy is achieved. The coverage will include a Galactic longitude range spanning −20 to 260 deg, along with a latitude range of ±5 deg. This latitude range provides exceptional coverage of sources in the Galactic plane, overlapping with many infrared surveys of this region and providing significantly more survey area than many radio surveys of the Galactic plane. The Galactic bulge will be mapped between longitudes of ± 14 deg, with latitude coverage extending to ± 10 deg.

The key advantage of the VLASS for Galactic science, over other existing and planned radio surveys, lies in its high spatial resolution capability, which motivates a broad range of Galactic science investigations. Thus, the Galactic survey component will address fundamental questions laid out in the previous Decadal Survey of Astronomy & Astrophysics including the mass-energy-chemical cycle in galaxies, star formation, the influence of rotation and magnetic fields on non-degenerate stars, nailing down the progenitors of type Ia supernovae, the end lives of massive stars, and what controls the parameters of compact stellar remnants.

The necessary additionally integration time for the Galactic component is $\approx$713 hr, or $\approx$891 hr with 25% overhead.

2.5 TRANSIENT SCIENCE

The VLASS will initiate a new generation of transient science by being the deepest (i.e., by two orders of magnitude) radio transient survey yet attempted. Consequently, the VLASS will yield the detection of tens of radio supernovae, thereby determining the rate of obscured supernovae in the local universe. The VLASS will additionally provide an observational measure of the rate and inverse beaming fraction of detectable radio orphan GRB afterglows, in turn providing a measure of the true rate of these events. The prediction for detections is poorly constrained, but VLASS will likely produce a small but extremely significant number of detections. From the Galactic component, the VLASS will detect NS-NS mergers in the gravitational wave era. Rates are, once again, poorly constrained, hence uncertainty in the predictions for a-LIGO and Adv-Virgo. Any detection would be transformational. And, of course, the VLASS will probe extreme AGN activity across many epochs.

The comprehensive approach of the VLASS will additionally provide complementary information for the study of transients and variable sources through the WIDE and DEEP tiers. The DEEP tier will be observed with a more rapid cadence than the shallower WIDE tier, with depth being built up using many visits to the target fields, allowing studies of variability and transient phenomena on shorter timescales than in the WIDE tier. The WIDE tier, however, is better suited to finding rare, bright transient events. The combination of the DEEP and WIDE tiers enables the study of populations of the same objects at widely varying flux density levels, as well as the ability to find fainter populations that are completely missed in the shallower WIDE tier alone.

3 Conclusion

The proposed VLASS survey definition comprises a cohesive and aggressive science program that will benefit the entire astronomical community, deliver unique forefront scientific discovery, and keep its legacy value well into the SKA-era. The total time request for the entire survey is $\approx$8701 hr, to be executed over 5 yr, leading to a $15-20\%$ impact on PI science. The scientific legacy, impact, and efficiency of deep and all sky surveys are clearly established -

from the Hubble Deep Fields to GALEX to NVSS/FIRST to Sloan and the next US optical/NIR ground-based priority LSST. The proposed VLASS finds its place within this tried and true tradition of modern astronomy. Analysis of the statistics from NVSS and FIRST (as with the Hubble Deep Fields) clearly indicate that the impact on PI science from these kinds of community surveys is positive, as might seem counterintuitive. This is true not only in terms of the extensive usage of these data by wide swatches of the community, resulting in startlingly high publication rates, but also due to the new inquiry driven PI science they enable, that could not otherwise have been conceived or survived the proposal process without the critical enabling data and demonstration science from the surveys. The proposed VLASS will continue the integration of radio astronomical data into the multi-wavelength astronomical community, putting the U.S. broad astronomical community in an optimum position to make substantial use of the SKA when it comes online.