VLA Sky Survey Community Review

Final report — 2015.05.13

I. Overview

On March 4–6, 2015, 13 panelists — 11 in person and 2 virtually — took part in a community review of the Very Large Array Sky Survey (VLASS) proposal. The review was held at the Pete V. Domenici Science Operations Center of the National Radio Astronomy Observatory (NRAO); it featured presentations from members of the VLASS Survey Science Group (SSG) and its associated working groups, VLASS Project Director Claire Chandler, and VLASS Survey Design Group lead Steven Myers. The panel also considered the results of NRAO's scientific and technical reviews of an earlier version of the VLASS proposal, community feedback on the final proposal submitted through an online forum, responses by the SSG and NRAO to seven pages of written questions submitted by the panel in advance of the review, and viewpoints expressed by members of the proposing team and of the NRAO scientific and technical staff during two days of very lively discussion. Panelists who might have been perceived as conflicted on issues related to field selection stepped out of the meeting room at all relevant junctures. As a final input, on April 13 the SSG provided a detailed written response to the panel's request for assessment of alternate scenarios for executing VLASS that relax the data rate limit of $25\,\mathrm{MB\,s^{-1}}$ originally given to the SSG as a boundary condition.

The review panel would like to salute the dedication of *all* of the parties involved in the development of the VLASS proposal. This list begins with SSG co-chairs Stefi Baum and Eric Murphy, extends to the other members of the SSG and their respective working groups, and includes the NRAO staff members who provided excellent management and technical support for the proposal and its review. It is also important to acknowledge the wisdom and foresight of the National Science Foundation (NSF) in supporting the VLA upgrade, without which VLASS would be entirely infeasible. The panel is positively impressed by many aspects of the proposal: it nicely highlights multiple exciting, timely science opportunities enabled by new VLA capabilities, and it demonstrates both the community's appetite for very large and ambitious programs and its ability to work cooperatively to make such programs a reality. The level of technical detail of the proposal's preliminary design studies is seen as especially impressive. The panel does note that the non-traditional process by which VLASS came into existence has given the proposal two unusual qualities relative to other large survey proposals at NRAO and elsewhere. First, the ambition to support many areas of science under one umbrella has resulted in a survey design that is not necessarily optimal for each area. Second, although the proposal was strongly community-driven, it does not include specific commitments of effort by community members going forward. These understandable, perhaps inevitable consequences of the VLASS design process have affected the panel's assessment of the survey's scientific motivation (§III.1, §III.2) and its promise for delivery of a full suite of data products (§III.6).

The panel has arrived at nine specific recommendations to NRAO, which are listed as **R1** through **R9** immediately below. The report continues with a narrative summary of the panel's assessment of the VLASS proposal (§II) and detailed responses to each of the questions comprising its charge (§III.1–9). Recommendations **R1** through **R9** are restated and explained in greater detail in §III.9 and at the end of a discussion of very large principal investigator (PI) science programs in §IV. References and panel members are listed in §V and §VI, respectively.

R1. The first two epochs of the All-Sky tier should be approved, provided that a clear plan for delivery of enhanced data products (EDPs) is presented at preliminary design review (PDR).

R2. Approval of the third epoch of the All-Sky tier should be deferred, contingent on results and timely delivery of basic data products (BDPs) and EDPs from the first two epochs.

R3. VLASS BDPs should include tapered versions of Stokes I maps.

R4. At PDR, NRAO should assess costs and benefits of mapping half of the All-Sky area twice per epoch at double the speed assumed in the VLASS proposal.

R5. At PDR, NRAO should report on whether observations of the All-Sky tier can be scheduled flexibly to mitigate impacts on PI science.

R6. At PDR, NRAO should evaluate a detailed plan for communication, education, and outreach activities.

R7. The NRAO Users Committee should be consulted about the possibility of reduced access to hybrid configurations by general VLA users during and/or after the execution of VLASS.

R8. The Deep tier should be declined as part of VLASS.

R9. NRAO should take immediate steps to facilitate the review, scheduling, and support of very large VLA programs — starting as soon as possible — to enable transformational PI-led investigations focused in (potentially) a wide range of science areas.

II. Narrative summary of response

The VLASS proposal describes a scientifically unified program featuring two observational tiers — "All-Sky" ($2.5''$ resolution, $69\,\mu$Jy beam^{-1} rms) and "Deep" ($0.8''$ resolution, $1.5\,\mu$Jy beam^{-1} rms) — that support six key science themes. As discussed in §III.1, the panel views three of these themes as highlighting especially exciting and qualitatively new science that a very large VLA program would enable: "Radio galaxies as cosmological probes" (hereafter, "cosmology"), "Hidden explosions" (hereafter, "transients"), and "Faraday tomography of the magnetic sky" (hereafter, "polarization"). Of these three, the transient and polarization science are very well matched to the design of the All-Sky tier, while the cosmology science is not as well matched to the design of the Deep tier or to other qualities that are desirable in a "community" survey. This distinction, together with the considerations discussed below, have led the panel to draw different conclusions about the attractiveness of the All-Sky and Deep tiers as part of VLASS.

The panel judges the All-Sky tier of VLASS to be

- well-matched to groundbreaking transient and polarization science, which will be within reach as soon as the first tranches of data products are released;
- well-matched to the desire for user-friendly data products; and
- a clear advance over the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-one centimeters (FIRST) survey in terms of area, frequency, and angular resolution, though somewhat less so in terms of faint source counts.

The All-Sky tier is also subject to somewhat less technical risk than the Deep tier (per the VLASS Technical Implementation Plan = TIP) and promises to have a gentler impact on PI science in terms of local sidereal time (LST). Given these attractive attributes, the panel recommends the approval of the All-Sky tier for scheduling, subject to development of a credible plan for the delivery of EDPs by the community to the community (§III.4, §III.6). As an incentive, the panel further recommends that the third epoch of All-Sky observations be scheduled contingent on the results and delivery of BDPs and EDPs from the first two epochs.

The panel views the design of the Deep tier of VLASS as most strongly motivated by the potential for cosmology and especially an intriguing effort to detect cosmic shear, which

- is challenging to harmonize with the proposal's galaxy evolution science (e.g., in terms of field selection);
- defers a key science result (5σ detection of shear) until the end of observing, more characteristic of an experiment than a survey; and
- requires processing (e.g., in the *uv* plane) that is beyond the capabilities of the general astronomical community.

The Deep tier is also subject to somewhat greater technical risk than the All-Sky tier (§III.5) and will have greater impact on PI science due to its peakier LST distribution (§III.7). Given this combination of attributes, and following a vigorous and wide-ranging discussion, the panel recommends that the Deep tier be declined as part of VLASS per se. The panel nevertheless endorses the science potential of one or more Deep-like programs, and urges NRAO to take **immediate** steps to facilitate the competitive review, scheduling, and support of very large PI-led programs (§IV). Given its desire to leave space in the VLA science program for such very large programs and other groundbreaking PI science leading into the 2020 Decadal Survey, the panel does not support accelerating execution of the All-Sky tier of VLASS relative to its nominal timeline (§III.5).

III. Detailed response to charge

The panel's detailed responses to the nine questions comprising its charge are presented below. Assessment of the science motivation for the survey is made separately for each of the proposal's six science themes (§III.1.a through III.1.f), following the order in which they appear in the proposal.

1. *Is the science motivation for the proposal sufficiently compelling to justify the total time request of the survey?*

   (a) **Galaxy evolution**

   The panel has received the galaxy evolution science in the VLASS proposal with mixed enthusiasm: although all members agree that expanded radio samples of star-forming galaxies and active galactic nuclei (AGN) will be useful at some level, not all are convinced that radio-wavelength observations are uniquely capable of revealing the details of AGN feedback, or that mapping large areas with the VLA is preferable to mapping already known clusters and overdensities as a means of studying the effects of environment on star formation. There is also a sense that galaxy evolution science is disconnected from key survey design parameters: the requested depth of the Deep tier flows from the cosmology (weak lensing) science case, while the requested depth of the All-Sky tier flows from the upper limit on data rate that the SSG was asked to adopt as a boundary condition in its deliberations.

   Following energetic discussion, the panel ended up with greater sympathy for the science case for the All-Sky tier. The very wide sky coverage and high resolution of this tier will provide large samples of star-forming galaxies and AGN over wide ranges in luminosity. The lack of obscuration bias at radio wavelengths is key to studying the full populations of these source classes, in contrast to the bias that affects studies at near-infrared, visible, and soft X-ray wavelengths. Among star-forming systems, normal galaxies will be detected to $z = 0.15$ and ultraluminous infrared galaxies (ULIRGs) to $z \sim 0.5$; full radio characterization of these populations will be a major step forward in its own right. Among accreting systems, the All-Sky tier will provide a complete sample of radio-loud quasars (comprising $\sim 10\%$ of the AGN population), including significant numbers of the rarest sources, to $z \sim 4$. This epoch pushes well beyond the peak of the quasar population at $z \sim 2$ (current surveys reach to $z \sim 2.7$ with smaller samples) and into the regime where AGN are forming, with more luminous sources visible out to the highest redshifts. Radio emission from radio-intermediate and radio-quiet sources will be detected out to higher redshifts than before (e.g., $z \sim 4$ for the radio-intermediate population). The predicted surface density of radio AGN will be comparable to that of the Sloan Digital Sky Survey (SDSS) for the first time, with the majority of SDSS quasars detected. Comparison of radio and optically selected populations will probe the level of obscuration as a function of redshift and luminosity. At low redshift, the All-Sky tier will identify and characterize the full AGN population over a full range of radio loudness, which will shed light on the key questions of how much accretion power is present in the universe and why only some AGN are radio-loud.

Considering the design parameters of the All-Sky tier, the panel views $2.5''$ resolution as providing a good compromise between identifying sources and resolving radio structure vs. losing information on large scales. The comparison of FIRST and NVSS detections presented by the SSG in Socorro was reassuring on this last point (see also §III.4). The sensitivity requested for the All-Sky tier, which goes somewhat deeper than FIRST, pushes the normalized differential number counts well below the general flattening at all frequencies around 3 mJy, thus extending S-band counts below current limits and ensuring that new scientific ground is broken throughout the survey area. The panel very much appreciated the careful and detailed discussion of spectral index selection and surface brightness sensitivity presented by Condon (2015). After a lengthy discussion, the panel identified as key the results of previous VLA full-synthesis surveys from 1.4 to 8.4 GHz, which show that the median angular size of the radio source population declines steadily with decreasing flux density. At the sub-mJy level, the median angular size will remain at $\lesssim 1'' - 2''$, so that a $2.5'''$ FWHM beam is necessary and sufficient to (i) identify all sources relatively free of confusion, (ii) measure angular sizes for many sources, and (iii) reliably identify counterparts in deep optical/near-IR imaging from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS1), the Large Synoptic Survey Telescope (LSST), the Wide-Field Infrared Survey Telescope (WFIRST), etc. The panel realizes that $2.5''$ resolution will come at the cost of surface brightness sensitivity for the nearest star-forming galaxies, but since the median redshift at sub-mJy flux densities is likely $z \sim 0.5 - 0.8$, this was not considered a major limitation. Indeed, the panel recognizes that a future large VLA 3 GHz program mapping all known $z < 0.1$ star-forming galaxies in the All-Sky footprint at lower resolution could mitigate this situation.

For the Deep tier, extension of AGN and star-forming galaxy studies to much lower fluxes and higher redshifts is potentially powerful as a means of studying evolution in both populations. This tier will facilitate environmental and evolutionary studies of star-forming galaxies to $z \sim 4$, probe the radio-far-IR correlation out to $z \sim 2$, and resolve structures that *Herschel* (given the $6'' - 35''$ resolution of its cameras) is unable to see. AGN studies can be extended to radio-quiet objects, with nearly all SDSS active galaxies detected. However, the VLASS proposal does not justify the request for a large area in terms of a needed sample size, or explain why other radio survey samples are not already sufficient. As a result, the major insights on galaxy evolution that the Deep tier will provide relative to existing or approved radio surveys are unclear.

(b) **Cosmology**

The panel views the All-Sky tier as having some utility for future cosmological studies. VLASS source catalogs and image cut-outs should be heavily used for comparison with wide-area surveys at other wavelengths, while correlating VLASS catalogs with the cosmic microwave background (CMB) should enable an improved measurement of the integrated Sachs-Wolfe (ISW) effect. However, it is the Deep tier that clearly has greater potential for cosmology. Conclusively determining the bias of radio sources relative to the underlying dark matter distribution is a necessary prerequisite for robust tests of cosmological models, and a worthy goal. Even more exciting, but also more risky, is the possibility of using Deep tier observations (including polarization measurements) for a weak lensing analysis. The panel was impressed by the creative, lucid, and frank case for a 5σ detection of cosmic shear that was made by the SSG in the VLASS proposal (where the parameters of the Deep tier can be easily traced back to this science goal) and at the face-to-face review. Notwithstanding this positive impression, however, several concerns arose as a result of cosmology's being *so* dominant as a driver for the Deep tier. First, it is not clear how much legacy value for a wide range of science areas the Deep tier will actually have, and if a key result is only expected to emerge at the 5σ level after all observations are in hand, the ultimate legacy value for cosmologists will be uncertain for years as well. Second, it is not clear how much of the community can effectively engage with the cosmological analysis of the Deep tier data: it is likely to be extremely hard to achieve a robust and convincing detection of cosmic shear, requiring analysis (e.g., in the *uv* plane) that realistically can only be done by a combination of weak lensing and aperture synthesis experts. (As in the case of the EDPs, the panel is concerned by the VLASS proposal's lack of information on who exactly will be engaged in this challenging work.) Third, since cosmology is the most exciting driver for the Deep tier, it would seem advisable to *further* optimize the survey design in this direction. A VLA cosmic shear detection, for example, might be easiest to obtain for a single contiguous field at a northern declination (i.e., giving a better synthesized beam) that has already been targeted for a weak lensing study in the optical (i.e., allowing comparison of shear due to structures at different redshifts). Overall, the panel feels these concerns could be most naturally addressed if the Deep tier were reconceived as one or more PI-led proposals (with clear commitments of effort from named individuals) whose detailed design parameters might be tweaked to support specific cosmological goals.

(c) **Transients**

The panel views the transients science case as one of the most scientifically compelling aspects of VLASS, with potential for groundbreaking new discoveries, particularly in the followup of gravitational wave (GW) events. By providing a near-instantaneous snapshot of the entire northern sky, the All-Sky tier of VLASS will provide a reference map for all future transient searches, which will be a key step in locating the electromagnetic counterparts of GW events detected by facilities such as the Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) and Advanced Virgo (AdV). The paucity of radio transients relative to optical transients — LSST is expected to detect $\sim 10^5$ variable stars per night — implies a much lower rate of false positive GW counterparts in the radio band, which together with the isotropic nature of radio afterglows and the slower evolution timescale at lower frequencies makes radio followup extremely valuable in the search for an electromagnetic counterpart to a GW detection. The outstanding science potential here argues *against* tweaking the scheduling of All-Sky observations in any way that would delay the provision of a complete reference image (e.g., as in a scenario advanced by the SSG in its April 13 response that would leave the southern sky and the north celestial pole still incomplete after two configuration cycles).

While GW counterpart searches may offer the greatest science return, a sensitive, wide-field, relatively high-frequency transient survey such as the All-Sky tier of VLASS has the potential to address other fundamental scientific questions, including the true rates of tidal disruption events and gamma-ray bursts (GRBs). The VLASS proposal suggests that the rates of core collapse supernovae (Types Ib, Ic, and II) in the local universe can also be measured, since their radio emission would not be hidden by dust obscuration. However, recent modelling by Metzger et al. (2015) has suggested that the long evolution timescales of Type II supernovae and the low luminosities of Type Ib/Ic supernovae make the detection of such systems improbable in blind radio surveys prior to the advent of the Square Kilometre Array (SKA). Unless the fraction of obscured supernovae is high ($\gg 90\%$), these classes of supernova events will likely be undetectable by VLASS.

Although previous searches have yielded very few transient detections (see, e.g., Frail et al. 2012), these have typically been limited by a small accessible sky area, poor sensitivity, a low observing frequency, or some combination of the above. The choice of a higher observing frequency than any previous or planned all-sky survey (other than the Australia Telescope 20 GHz = AT20G survey, whose limiting depth of 40 mJy is almost three orders of magnitude higher) will give VLASS a significant advantage in detecting synchrotron transients, which evolve more slowly at lower frequencies. The multi-epoch survey design is well matched to the timescales of this class of transients at 2–4 GHz, with the 32-month separation between epochs ensuring that any transients will have had time to evolve significantly between observations, thereby maximizing the transient detection rate. The large sky area of VLASS combined with its sensitivity will make it approximately two orders of magnitude more sensitive to extragalactic transients than most previous transient surveys, allowing it to probe a region of parameter space that is theoretically expected to be populated by interesting classes of events.

Metzger et al. (2015) have simulated the likely numbers of transients that will be detected by several future surveys. Scaling from their numbers for a now-deprecated "VLASS-Wide" survey design suggests that the All-Sky tier of VLASS will likely detect a few tens of extragalactic transients (primarily long GRBs, magnetars, and tidal disruption events) over its three epochs. This number is relatively consistent with the observed transient rate in the Stripe 82 VLA survey of Mooley et al. (2015). Owing to its smaller area, the Deep tier of VLASS is unlikely to detect more than a few events, primarily long GRB afterglows. While the VLA will be capable of following up newly-detected transients across a wide range of frequencies, this followup should be focused on the most interesting events. The angular resolution and broad bandwidth of VLASS will provide important diagnostics to help target followup work, including the locations of the transients in their host galaxies and their spectral indices.

VLASS also has the potential for commensal transient searches that open up different volumes of parameter space. Should VLA Low-band Ionospheric and Transient Experiment (VLITE) commensal observations at 330 MHz be provided as an EDP, as the panel hopes, it would be possible to use the same transient detection algorithms applied to the All-Sky tier to search for low-frequency transients. Although the lower peak flux densities and longer synchrotron evolution timescales at low frequencies make the detection of incoherent transients unlikely at these frequencies, it would be possible to detect certain classes of coherent transients, similar to the Galactic Center Radio Transients (e.g., GCRT J1745$-$3009; Hyman et al. 2005), whose nature is still unknown. Finally, if the processing requirements can be met, it might be possible to carry out a commensal search for fast transients (e.g., Law et al. 2015), aiming to localize Fast Radio Bursts (FRBs) by detecting them in very short-timescale (tens of milliseconds) images. Localization of a number of FRBs would enable searches for their host galaxies, which if detected would yield redshifts, enabling their use as one of the few available probes of the intervening intergalactic medium. While both the low-frequency and fast transient searches are extremely exciting prospects, they are not envisaged as BDPs; realizing their potential will therefore require significant additional effort by members of the community.

Since the transient detection rate of the Deep tier is likely to be small, the science yield in the area of transients will be driven by the All-Sky tier. The time request for the All-Sky tier (as proposed) is currently driven by data rate considerations, but the minimum survey depth provides sufficient sensitivity to detect several tens of extragalactic transients over the duration of the survey, guaranteeing a minimum science yield (in addition to the enormous legacy value gained by providing a high-sensitivity, high-resolution reference image for the sky). While two epochs is the minimum required to detect transient events, a third epoch will increase the number of transient detections (effectively doubling the sky area that can be compared with the reference image from the first epoch), improve the ability to discriminate between competing predictions for transient event rates, and probe slightly longer-timescale events. Although improving the detection statistics in this way is a desirable goal, the third epoch is less essential than the second for delivering a basic level of transient science.

(d) **Polarization**

The panel was very impressed by the compelling and responsive case for polarization science made in the VLASS proposal and at the face-to-face review. By observing in full polarization mode, VLASS promises to break exciting new ground relative to other surveys in explicating the detailed physics of the magneto-ionic medium in galaxies and AGN. For this science theme, survey design and science goals are extremely well matched. Use of the full S band (minus excisions due to radio frequency interference), which is sensitive to greater Faraday depths than lower-frequency bands and therefore less vulnerable to depolarization, means that VLASS can provide more complete information about Faraday screen structure in individual sources and potentially uncover entirely new source populations. The combination of VLASS S-band observations with L-band continuum surveys at other facilities will further tighten constraints on detected source properties. The choice of configuration is also well-matched to the science: while the $3'' - 4''$ resolution in Faraday maps is determined by the low-frequency end of the S band, it will still deliver multiple beams per source for the typical $\sim 20''$ size of the polarized source population (Rudnick & Owen 2014), allowing probes of internal structure. VLASS observations will make it possible to investigate the evolution of magnetic fields in star-forming disk galaxies and the degree of mixing between thermal and synchrotron-emitting material in AGN-driven radio lobes. The Deep tier offers the possibility of studying evolution in the properties of polarized sources, but the panel is more impressed by the potential of the All-Sky tier, which offers better synergies with wide-area L-band surveys and better prospects for the physical insights that come from detailed source dissections. Moving Faraday mapping from "one-at-a-time" mode into mass production mode — as will be possible *if and only if* the VLASS EDPs are delivered by the community (see §III.6) — will be an extremely exciting development.

In addition to studies of intrinsic galaxy and AGN properties, VLASS data will enable the use of such systems as background probes of Faraday foregrounds associated with absorption-line systems and structures inside the Milky Way. The key advantage here is the factor-of-six higher surface density of polarized sources that the All-Sky tier is expected to detect relative to NVSS. Separating the contributions of electron density and magnetic field strength to Faraday depth will still require additional information or assumptions, but the better statistics will significantly strengthen constraints on large-scale magnetic field properties. The panel agrees with the SSG that this component of polarization science is appealing, but is second in priority to the intrinsic source studies discussed in the preceding paragraph.

(e) **Galactic**

Given the VLASS proposal's goal of supporting many science areas, its final design (in particular, its use of B rather than A configuration for the All-Sky tier) is not optimal for Galactic science. Nevertheless, with 20 times the angular resolution and twice the frequency of the NVSS, VLASS will allow a major advance in our understanding of the populations of compact (arcsecond-sized) sources in the Milky Way. These populations include non-thermal sources such as pulsars, radio binaries, and young supernova remnants, as well as thermal objects such as ultracompact H II regions, novae, and planetary nebulae. Even more interestingly, in combination with other radio studies of significant solid angles of the Galactic plane, including the Co-Ordinated Radio 'N' Infrared Survey for High-mass star formation (CORNISH), the Global View of Star Formation in the Milky Way (GLOSTAR) survey, and The H I/OH/Recombination line (THOR) survey, the VLASS may discover a new population or populations of Galactic sources.

(f) **Missing physics**

The theme of "missing physics" refers to the scientific opportunities that arise when a survey makes it possible to match radio sources (or upper limits) to multi-wavelength counterparts, and to find rare populations of radio sources. The panel views the All-Sky tier as very attractive from this point of view: there is unanimous support for the value of being able to characterize a source selected in some other waveband at a (radio) wavelength that provides unique insights into important physical properties. Thanks to its insensitivity to reddening, radio emission gives valuable information about bolometric luminosities, allows astronomers to identify otherwise hidden objects, and provides an important, isotropic probe of the rates and luminosities of transient events. NVSS and FIRST offer instructive precedents here: large fractions of the citations of both surveys come from this mode of survey science, and NVSS (despite its lower resolution) continues to be cited because FIRST does not cover as large a sky area. The All-Sky tier of VLASS will offer new opportunities relative to the earlier surveys, with polarization measurements that probe cosmic rays and magnetic fields, and contemporaneously operating gravitational wave observatories aiming to detect signals that may have radio-wavelength counterparts. The panel views the angular resolution and sensitivity proposed for the All-Sky tier as appropriate for source matching at the depths that will be reached in the optical by Pan-STARRS1. The proposal is less convincing in drawing an analogy between the combinations of VLASS+Pan-STARRS1 and FIRST+SDSS as equally potent sources of "legacy [data] products": Pan-STARRS1 lacks the spectroscopic component that was so crucial to the success of SDSS, e.g., in the identification of high-redshift quasar samples. Without a clear path to spectroscopy, at least until the advent of the Dark Energy Spectroscopic Instrument (DESI), the impact of VLASS may not be as great as portrayed. The "missing physics" section of the proposal also does not offer a clear forecast as to what types of VLASS sources (e.g., among star-forming galaxies, only LIRGs and ULIRGs will be detected?) are to be the prime targets for followup at the volume and depth provided by the All-Sky tier.

2. *Is the proposed structure of the survey appropriate? Are all elements of the survey scientifically compelling and transformational?*
The panel views the SSG's definition of two complementary tiers as a reasonable approach to structuring a scientifically unified survey, but only supports the All-Sky tier as part of VLASS per se. The new-and-improved wide-area survey that the All-Sky tier represents will be transformational, particularly in its impact on novel transient and polarization science. The panel also expects the All-Sky tier to have great legacy value (as NVSS and FIRST have had) in providing fluxes and upper limits for a wide range of projects. The complementarity of the All-Sky tier relative to NVSS (in terms of angular resolution and frequency) will make the combination of the two even more powerful as a reference dataset going forward. The Deep tier, although potentially transformational in its impact on cosmology, is felt to be less compelling in terms of its broad interest and usefulness to the entire astronomical community. The panel also feels that the detailed design of the Deep tier reflects some tension between the needs of the galaxy evolution and the (more compelling) cosmology science cases, suggesting that a superior route to the same science might be for one or more focused, very large PI-led programs to be proposed at future deadlines.

3. *Is the requested sensitivity of the different elements of the survey appropriate?*
The sensitivity requested for the Deep tier is clearly traceable to the cosmology goals that provide its strongest science motivation: only by achieving the requested depth will the surface density of radio sources be high enough to enable the detection of a cosmic shear signal at the 5σ level. Tracing the sensitivity of the Deep tier to a quantitative science goal related to galaxy evolution is more difficult, as noted in §III.1.a. The sensitivity requested for the All-Sky tier is largely traceable to the limiting data rate of $25\,\mathrm{MB\,s^{-1}}$ that the SSG was encouraged to use as a boundary condition on survey design. Mapping the area of the All-Sky tier at the limiting slew rate that corresponds to this limiting data rate implies a sensitivity of $120\,\mu\mathrm{Jy\,beam^{-1}}$ per epoch and $69\,\mu\mathrm{Jy\,beam^{-1}}$ in the coadded map. The panel spent a great deal of time discussing the detailed design of the All-Sky tier, particularly the number of passes (for the benefit of transient science), the choice of configuration, and the possibility of relaxing the data rate limit of $25\,\mathrm{MB\,s^{-1}}$. This discussion led to a request that the SSG compare the All-Sky tier as proposed with three alternate designs featuring a data rate of $50\,\mathrm{MB\,s^{-1}}$, in terms of the impacts on science and resource needs:

   - A survey with the same three epochs and the same total depth of $69\,\mu\mathrm{Jy\,beam^{-1}}$ obtained in the same 5436 hours, but with *two* passes over the same sky area per epoch delivering better *uv* coverage and imaging quality.
   - A survey with three epochs and a total depth of $98\,\mu\mathrm{Jy\,beam^{-1}}$ obtained in 2718 hours, with only a single pass over the same sky area per epoch.
   - A survey with *four* epochs and a total depth of $85\,\mu\mathrm{Jy\,beam^{-1}}$ obtained in 3624 hours, with only a single pass over the same sky area per epoch.

   The SSG's very detailed and helpful response has convinced the panel that the latter two scenarios (compromising survey depth) would cause serious harm to VLASS transient science, and to the ability of the survey to probe the faint star-forming population for galaxy evolution studies. On the latter front, recognizing that mJy/sub-mJy radio source populations undergo an interesting transition from AGN/spheroid-dominated to star-formation-dominated in the flux regime that the All-Sky tier will be probing, and that the normalized differential source counts undergo a marked flattening below a few mJy, even a small loss in sensitivity would yield a far smaller sampling of star-forming systems. The costs to polarization science of reduced sensitivity appear more modest — "Faraday Survey" science is not compromised by a $\sim 22\%$ drop in the number of sources, while "Faraday Imaging" science is more vulnerable but can still move forward with samples of fewer than 22,000 galaxies. On balance, the panel views the proposed depth of the All-Sky tier as appropriate, and recommends that PDR consider only the "two passes per epoch, same sensitivity" option as a possible alternative to the baseline survey design.

4. *To what extent will the proposed survey result in a unique set of data products and science opportunities relative to both existing radio surveys and other surveys planned to take place over the next five to ten years?*
   The proposed survey takes full advantage of the unique capabilities of the VLA to provide a set of data products that will be unmatched until the advent of the SKA. In particular, the use of an extended configuration and the relatively high observing frequency (compared to both previous and future surveys) will provide imaging whose resolution will be unsurpassed by any planned instrument prior to SKA1-Mid. While the raw point-source sensitivity of the All-Sky tier will surpass those of NVSS and FIRST by a small factor (over the entire northern sky), the field of view of the VLA limits the survey speed as compared to several near-future surveys[1] that will ultimately provide deeper all-sky images if performance specifications are met. However, the unmatched spatial resolution of VLASS will allow confident cross-matching of radio samples with surveys at other wavelengths, in particular optical surveys with Pan-STARRS1 and LSST (median seeing-limited resolution $0.7''$) — provided care is taken to match radio sources rather than components of sources.

   Since VLASS will define a key community resource for use by astronomers of all backgrounds, the panel has carefully considered the survey's completeness. The extended array configuration that provides such excellent spatial resolution will limit sensitivity to emission on large spatial scales, a key characteristic of VLASS images that may not be appreciated by non-radio astronomers. A comparison of NVSS and FIRST sources shows that after correction for Malmquist bias, 19% of NVSS sources are not detected by FIRST. To go some way towards mitigating this issue, the panel recommends that *uv*-tapered images also be produced as a BDP (at least in Stokes I), to help highlight fields where missing large-scale structure could be a concern.

   While the high-resolution images will be unique in themselves, many other past and future surveys will produce similar sets of BDPs — e.g., NVSS and the ASKAP Polarisation Sky Survey of the Universe's Magnetism (POSSUM), which provide continuum images in Stokes I, Q, and U. The EDPs will thus add significantly to the legacy value of VLASS, particularly the transient catalogs, rotation measure images, and full spectral resolution image cubes. It is therefore of concern to the panel that due to the community-driven process by which VLASS was conceived, no project leads have been as yet identified to take responsibility for delivering these key elements of the survey. Provision for EDPs is crucial enough for the success of the

[1] These include the Evolutionary Map of the Universe (EMU) survey with the Australian SKA Pathfinder (ASKAP), the Westerbork Observations of the Deep Apertif Northern-Sky (WODAN) survey, the MeerKAT International GigaHertz Tiered Extragalactic Exploration (MIGHTEE) survey, and the tier 1 Low Frequency Array (LOFAR) survey.

project that the panel feels a plan should be in place for the survey to pass preliminary design review (see also §III.6).

Although they are not officially part of the VLASS data products, the commensal 330 MHz VLITE data arising from the survey could automatically provide a large lever arm in frequency to better characterize bright sources, and provide an important link with the numerous low-frequency radio surveys either underway, e.g., LOFAR tier 1 and the Galactic and Extragalactic Murchison Widefield Array (GLEAM) survey, or planned, as with SKA1-Low. VLITE data represent a possible EDP that the panel views as highly appealing based on its lasting legacy value.

In terms of science opportunities, the design of the All-Sky tier provides a timely and unparalleled opportunity for groundbreaking transient science (modulo timely delivery of EDPs, as noted above). The multiple passes provide opportunities for transient detection that were unavailable in previous surveys such as NVSS and FIRST, and the relatively high frequency and 32-month cadence of the observations ensure that each epoch will be independent — less likely to be the case for higher-cadence, lower-frequency transient surveys such as the Variables And Slow Transients (VAST) survey with ASKAP. Furthermore, the completion of the first epoch by early 2017 will provide a reference image for the sky on a similar timescale to the full implementation of aLIGO and AdV, allowing an effective search for the electromagnetic counterpart to any newly-detected GW signal.

The high resolution and polarization information afforded by the Deep tier are required for detection of a cosmic shear signal in the radio band prior to the advent of SKA. While this is an extremely difficult measurement with an expected detection significance of just 5σ, it provides an important check on systematics of similar measurements in other wavebands and will be a truly unique experiment that cannot be performed with previous or near-future surveys at lower resolution.

The high resolution and relatively high frequency of the All-Sky tier will provide unique science opportunities in studies of cosmic magnetism (again, assuming EDPs are delivered in a timely fashion). Although the higher-sensitivity SKA precursor surveys (e.g., ASKAP/POSSUM) will provide a higher density of polarized background sources, the higher frequency of VLASS will provide complementary information, accessing source populations with large Faraday depths, as well as those that are depolarized at low frequencies. The combination of VLASS data with data from future L-band surveys will provide extremely high-precision information on complex structures with a mix of Faraday depths. Finally, the high resolution of VLASS will allow this survey to resolve more distant galaxies, investigating the alignment of the magnetic field with galaxy disks, and probing the interaction between AGN radio lobes and their environments.

5. *Are the implementation plans for the survey well defined? If the capabilities required need testing before the survey can be started, is a test plan in place? Do the resource estimates required to execute the survey seem adequate?*
   The panel is very impressed by the level of care and detail reflected in the TIP, which was informed by the practical experience that several members of the SSG have gained in working with wide-area VLA mapping (e.g., Mooley et al. 2015). The TIP lays out a comprehensive and well-thought-out test plan with a credible risk register; in particular, the panel concurs with its assessment that the All-Sky tier of VLASS has a lower level of technical risk than the Deep tier, and has factored that distinction into its different recommendations for the two. Realistic resource estimates will require close attention at PDR: the panel's experience

is that software development efforts *always* take longer to complete than initially expected, and the fact that critical functionality and performance targets for the Common Astronomy Software Applications (CASA) package have not yet been met (e.g., release of a spectral line calibration pipeline) suggests that NRAO is no exception to this rule. The panel feels strongly that support for VLASS should not entirely crowd out support of other highly ranked science programs on the VLA, perhaps including a new category of very large programs (see §IV) that will inform development of 2020 Decadal Survey priorities every bit as much as VLASS itself.[2] Declining the Deep tier as part of VLASS per se will reduce the immediate pressure on NRAO, but the overall balance of support still needs to be monitored carefully.

6. *Are the data products of the survey well defined? Is the plan for their production, archiving, quality assurance and release to the community sound?*
   The VLASS proposal presents a well-thought-out plan for delivering BDPs that will serve the needs of most of the astronomical community. The panel's only recommended addition (noted in §III.4) is a tapered version of Stokes I maps, which should dramatically improve the community's use of the BDPs for only an incremental increase in data management costs. The schedule for release of BDPs appears reasonable. As noted in §III.5, the panel is concerned that software development needs for VLASS will overwhelm support for other worthy observing programs, and therefore encourages NRAO to carefully (i) assess resource needs at PDR, (ii) monitor progress in reaching milestones towards the start of VLASS observations, and (iii) ensure that some staff effort is still available to support other, PI-led programs.

   In contrast to the clear path to provision of BDPs, the panel sees rather murkier prospects for the development and delivery of the EDPs, some of which are critical for the achievement of key VLASS science. Alarmingly, the risk here is most salient for precisely those science themes (i.e., transients and polarization) where VLASS has the greatest potential to deliver truly transformational results. The transient object catalog and alert mechanism, for example, are essential for full exploitation of transient science: quick-look images will be available after 48 hours, but there needs to be software ready to analyze them and promptly generate a transient object catalog. (During the first epoch of observations for the All-Sky tier, this can be via comparison with NVSS, FIRST, and/or previous observations of particular fields available in the archive, since spectral indices at 1.4 GHz and the low-frequency half of the 2–4 GHz band are very similar.) Likewise, rotation measure images and catalogs are crucial if the potential of VLASS observations for polarization studies is to be realized. The panel understands that there are non-NRAO scientists who are interested in applying for funding to provide the various EDPs described in the proposal, but with no articulated plan, commitments from named individuals, or secure funding stream (in the U.S. or elsewhere), EDPs remain an area of substantial risk to the overall success of VLASS. To incentivize the community to work towards delivery of EDPs, the panel recommends that allocation of the third epoch of observations be made contingent on successful delivery of BDPs *and* EDPs for the first two. Moreover, if a clear plan for provision of EDPs is not in place as of PDR (see §III.9), the panel recommends that the start of VLASS observations be postponed.

7. *What does the Review Panel see as the relative pros and cons of the survey in terms of the*

[2] Although considering impact on the next Decadal Survey is not among the panel's charges, the SSG in its April 13 response cites "significant programmatic concerns" with the timing of VLASS relative to the Decadal Survey as a justification for accelerated execution of the former. The panel is not convinced by this argument, given the priority it places on scientific balance.

science return and impact on VLA PI science?
Both the All-Sky and Deep tiers will have impacts on PI science that must be balanced against their potential science returns. Each tier will potentially serve a large number of scientists — perhaps reducing the number of PI proposals with overlapping science goals, perhaps also seeding additional PI science interest in the community as data become available and astronomers seek detailed followup observations of specific targets. It will remain important to be sensitive to science areas that are not well represented in VLASS and thus will be disproportionately impacted by the reduced availability of PI time. In addition, care should be taken to protect time-sensitive Ph.D. thesis observations, which cannot wait to be completed until the end of VLASS observations. Besides agreeing on these general principles, the panel has considered the impact of VLASS on scheduling of VLA projects in three different areas:

- **Impact on dynamic scheduling.**
While VLASS observations will be most efficient if they are carried out in a "fixed date" mode, i.e., carefully scheduled and planned in advance, this mode of operation will disproportionately impact PI-led high-frequency science and time-critical transient science, which strongly benefit from dynamic scheduling. The panel recommends that PDR include a detailed investigation of how the impact on high-frequency science and time-critical transient science might be mitigated without unduly compromising the efficiency of survey observations. Taking a more nuanced approach than simply assigning the whole program a scheduling priority of A might be worth considering: although VLASS certainly belongs in the "must be completed" category, execution of the All-Sky tier does not have particularly tight scheduling constraints, so flexibility might minimize undue impacts on other programs in certain LST ranges.
- **Impact on specific LST ranges.**
The LST-specific scheduling of the Deep tier will have a strong impact on PI science near the LSTs of the survey fields, while the burden of the All-Sky tier will be more evenly shared with a less severe impact overall. This distinction has been factored into the panel's different recommendations for the two tiers.
- **Impact on configuration demand.**
The Deep tier is proposed for A configuration, which typically has the highest proposal pressure of all VLA configurations. The All-Sky tier is proposed for B configuration, which typically has a demand somewhat lower than that of the A configuration. If the 16-month VLA configuration schedule were to remain unchanged, the survey observations would have a disproportionate impact on PI science seeking to use these configurations. The panel endorses the idea of modifying the length of time spent in each configuration (within the same 16-month cycle) in order to better balance proposal pressure. A related issue is that the All-Sky tier would benefit from use of the BnA configuration for its southernmost pointings. The possibility of restricting the use of this hybrid configuration to *only* the VLASS while the survey is ongoing, if not eliminating hybrid configurations altogether (both scenarios discussed at the face-to-face review), is likely to be controversial in the community, particularly as observations with the Atacama Large Millimeter/submillimeter Array (ALMA) ramp up and complementary VLA studies of southern sources increase in popularity. The panel recommends that the NRAO Users Committee be consulted to determine whether and how to roll out a plan for reduced access to hybrid configurations by the general community of VLA users.

8. *Will the plans for communication, education, and outreach be effective at engaging both the*

astronomy community and the general public in the survey?
The panel feels that the various options presented for engaging the general public are very appealing and offer great potential for success. The possibility of integrating citizen science into the characterization and analysis of VLASS data — in particular, determining correct optical counterparts in Pan-STARRS1 and LSST imaging for hundreds of thousands of resolved, double, and/or extended sources, a process that must at some point involve human intervention — is seen as exciting if not essential. It is also clear, however, that deep engagement by the non-astronomical community will require a dedicated effort with specific individuals and/or institutions clearly identified as responsible for the different activities, as well as a detailed (management) plan describing how these activities will be coordinated. The panel recommends that a detailed plan for efficient communication, education, and outreach should be considered at PDR. Such a plan should lay out which resources (personnel, computing, etc.) are required, who will be responsible for coordinating and overseeing activities, and how the proposed activities will be prioritized in the event that less than full funding is available at the outset of the survey.

There are several levels at which the astronomical community can be engaged in VLASS, ranging from deep personal involvement in generating EDPs, to mining of BDPs and EDPs that are generated by others, to securing complementary or followup observations. These modes of engagement will require access to different sets of data products. The VLASS proposal does discuss a range of ideas and plans in this regard; however, the panel feels that a more clearly articulated match of VLASS data products to potential categories of professional users should be reviewed (as part of the education and public outreach plan) at PDR.

9. *Please recommend at what level NRAO should proceed with the VLASS at this time. Possible recommendations include, but are not limited to:*

   a) Approve the survey in full as proposed

   b) Approve one or more components of the survey for implementation, declining or deferring others

   c) Approve in full or in part, with modifications in specific areas

   d) Approve an initial pilot study (in this case, please recommend number of hours and specific instructions of what the pilot should do, and specify how a decision would be made about proceeding with the full survey following the pilot)

   e) Delay the start of the survey (in this case, please specify when the survey should begin, or technical or operational milestone[s] that must be reached before proceeding)

   f) Shelve the survey for the time being, and reconsider at a later date

   The panel makes the following recommendations to NRAO:

   R1. The first two epochs of the All-Sky tier should be approved, provided that a clear plan for delivery of EDPs is presented at PDR.
   This recommendation corresponds to an allocation of 3624 hours spread over four configuration cycles, as specified in the final version of the VLASS proposal. A "clear plan" at PDR should include a list of named individuals from the community who commit to leading efforts to provide EDPs; it is not expected that funding will be in place (or even applied for) as of PDR. If a clear plan is not in place at PDR, NRAO should delay the start of VLASS observations. This condition reflects the panel's view that much of the science potential of the All-Sky tier depends critically on the delivery of EDPs (§III.4, §III.6).

R2. Approval of the third epoch of the All-Sky tier should be deferred, contingent on results and timely delivery of BDPs and EDPs from the first two epochs.
This recommendation enables a future allocation of an additional 1812 hours spread over a further two configuration cycles, as specified in the final version of the VLASS proposal. The panel expects that with a third epoch of observations at stake, the community will be strongly motivated to rise to the challenge of delivering EDPs, thereby ensuring that the full scientific payoff of a full 5436 hours of observations is realized (§III.6).

R3. VLASS BDPs should include tapered versions of Stokes I maps.
The panel feels that inclusion of tapered maps as an additional BDP will reduce the risk of misinterpretation of VLASS data by astronomers who have little feel for how *uv* sampling influences flux recovery, and will thereby enhance the survey's overall legacy value (§III.4).

R4. At PDR, NRAO should assess costs and benefits of mapping half of the All-Sky area twice per epoch at double the speed assumed in the VLASS proposal.
By mapping at a rate of $48\,\mathrm{deg}^2\,\mathrm{hr}^{-1}$ (at the cost of driving the data rate to $50\,\mathrm{MB\,s}^{-1}$), it may be possible in principle to improve image quality (relative to the design presented in the VLASS proposal) without affecting the sensitivity or the data volume of the final maps. Based on the SSG's response of April 13, this change would benefit the polarization and galaxy evolution science that can be done with VLASS data products, as well as their long-term legacy value, although these gains must be balanced against detailed resource costs. Scenarios in which execution of the All-Sky tier is accelerated are disfavored for reasons related to balance with PI science (§III.7, §IV) and the timely provision of a complete reference image for GW counterpart searches (§III.1.c).

R5. At PDR, NRAO should report on whether observations of the All-Sky tier can be scheduled flexibly to mitigate impacts on PI science.
The panel views such an outcome as desirable for reasons of balance (§III.7), especially in view of the exciting high-frequency science and time-critical transient science that can be done through PI programs.

R6. At PDR, NRAO should evaluate a detailed plan for communication, education, and outreach activities.
A "detailed plan" at PDR should include a list of named individuals and/or institutions who are responsible for different activities, an outline of how these activities will be coordinated, and contingencies if sufficient funding for all activities is not available. A better delineated match of VLASS data products to prospective users in the professional astronomy community should also be provided (§III.8).

R7. The NRAO Users Committee should be consulted about the possibility of reduced access to hybrid configurations by general VLA users during and/or after the execution of VLASS.
This recommendation reflects the increasing pressure for VLA observations of southern sources expected as ALMA samples continue to expand (§III.7).

R8. The Deep tier should be declined as part of VLASS.
The panel expects that exciting Deep-tier science can still be achieved through one or more very large PI-led programs proposed at future deadlines, provided that NRAO takes steps to make such proposals welcome (as recommended in §IV below).

IV. Very large PI-led programs

As discussed above, the panel has concluded that the Deep tier of VLASS, although addressing exciting science goals that are uniquely enabled by the VLA's new capabilities, does not have the ideal design for achieving all of those goals and lacks the broad appeal and accessibility that would be preferred in a "community" survey. Although these concerns have led to a "decline" recommendation for the Deep tier, the panel emphasizes that the scientific and technical case(s) made in this part of the VLASS proposal are well-positioned to be revived and strengthened in the context of one or more proposals for very large PI-led programs at future NRAO deadlines. For a revived proposal to have a reasonable chance of success, it will be necessary for NRAO to do a better job of reviewing, scheduling, and supporting very large (loosely, requiring $\gtrsim 1000$ hr for execution) programs — particularly those extending across multiple configuration cycles — than has been the case in the recent past. Other observatories have been successful in soliciting and executing very large programs, whether through a separate call or via special instructions in a normal call. Examples include *Spitzer* Legacy programs, *Chandra* X-ray Visionary Projects (XVPs), *Hubble* Multi-Cycle Treasury (MCT) programs, and National Optical Astronomy Observatory (NOAO) survey programs — with the caveat that the urgency of executing very large programs may be different for space missions with limited lifetimes and for ground-based facilities that will be operational for decades. These efforts have produced some of the most highly-cited scientific results, and in many cases data sets that have been used widely outside of the original proposing teams. In some cases, the programs have been explicitly spread across several years. This approach mitigates the impact on smaller programs, while at the same time allowing individual PIs to propose game-changing rather than incremental observations.

For NRAO, the panel's sense is that the current risk/reward perception in the community strongly discourages astronomers from submitting ambitious long-term VLA proposals. The enthusiastic reception of a community-led VLASS initiative and the range of science that was squeezed (not always easily) under its single umbrella are evidence that there is a desire for such VLA proposals, and perhaps a level of frustration that it is simply too risky to be so ambitious when competing in the normal proposal process as currently designed. Allocating a nominal fraction of the observatory time to very large programs (perhaps 20–30%, subject of course to proposal quality) would be one way to encourage the community to be ambitious, while at the same time allaying concerns that these programs will crowd out other science. Assessing very large proposals within the normal review process (i.e., as recommended by Bridle et al. 1997) but allowing multiple Science Review Panels (SRPs) with relevant expertise to weigh in on their merits would be another way to give confidence that such proposals would be evaluated according to their full scientific scopes. The panel sees the Deep tier of VLASS as excellent source material for one or more ambitious, multi-year, PI-led programs. However, any plausible pathway to proposing very large programs can be expected to elicit competing proposals in other science areas, and perhaps competing observing strategies for studies of faint galaxies and AGN.

A major inhibitor to submission of very large VLA proposals at present is uncertainty about how the resulting programs are to be scheduled. Due to scheduling constraints, current regular and large programs are not always completed in a timely fashion, with scheduled but unobserved time left in limbo at the end of a configuration and the definition of survey "completion" consequently blurred. There is also a perception in some quarters that the VLA scheduling algorithm offers unfair advantages to those who know how to "game the system" in constructing observing sessions. For programs extending beyond one configuration cycle, a given linear rank score can translate to very different outcomes from one cycle to the next, depriving a program of the high, stable scheduling priority needed for completion on a reasonably predictable timescale. While realities inside the scheduling office may look different from perceptions outside, it would be prudent for NRAO to consider these concerns, explore ways to make VLA scheduling more efficient and transparent, and ensure that the structure of the scheduling process does not represent an insurmountable barrier to the execution of very large PI-led projects.

A final area of concern that colored some of the discussions at the face-to-face review is NRAO's level of technical support for very large programs. Some of the largest programs on the telescope at present are producing results more slowly than desired because of difficulties in going from raw data to science-grade images. Much of the expertise for bridging this gap resides at NRAO, but NRAO resources are spread thin, and there is a community perception that the urgency of getting the most out of current data is sometimes not recognized as a high priority (for software development in particular). Indeed, as §III.5 notes, the panel sees some tension between NRAO's support of VLASS and its support of other programs. From this point of view, the panel finds it helpful and appropriate to see resource estimates for VLASS presented in the TIP. For future very large programs, whether competed in a proposal review or developed via a community-led initiative, it will be appropriate for NRAO to consider the technical needs and explicitly include them in the observatory's overall resource planning, to ensure that technical delays don't slow down the science.

The above considerations lead the panel to offer a final recommendation, addressed at NRAO management in dialogue with the NRAO Users Committee:

R9. NRAO should take immediate steps to facilitate the review, scheduling, and support of very large VLA programs — starting as soon as possible — to enable transformational PI-led investigations focused in (potentially) a wide range of science areas.

The panel views the Deep tier described in the VLASS proposal as a strong candidate for development into one or more proposals of this type.

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