# Galactic kU-band Thermal Survey (GUTS)

**Loránt O. Sjouwerman & Elisabeth A.C. Mills**

National Radio Astronomy Observatory, Socorro, New Mexico, USA

email: `lsjouwer@nrao.edu, bmills@nrao.edu`

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**Abstract**

This White Paper proposes a unique milli-Jansky sensitive arcsecond resolution VLA 15 GHz (Ku band) continuum polarization imaging survey of the Galactic plane using C array configuration. The science driver is to fill the gap between previous lower frequency VLA Galactic plane surveys, mainly detecting synchrotron radio emission at 1.4 and 5 GHz, and the higher frequency (future ALMA and present *MSX, SPITZER, PLANCK, WISE*) 0.1-100 THz infrared surveys that detect thermal radiation. The 15 GHz band appears to be the highest frequency at which such a survey is both feasible and maximally unique from the synchrotron radio view and will facilitate new multi-waveband Galactic research and, for example, identify targets for ALMA. Depending on the final survey parameters, for example a 3 second integration time for a ($8\sigma$) 1 mJy 12-18 GHz detection limit over a 10 degree band along the VLA observable (280 degree) Galactic plane, this survey would consume up to 3200 VLA observing hours using on-the-fly mapping and still allow for, e.g., an additional sub-Jy sensitive 12.2 GHz methanol maser line survey. Furthermore this survey would reveal potential compact high-frequency VLA calibrators in the Galactic bulge and plane, a region where there is a severe lack of them.

## Motivation

Whether they simply cover large areas on the sky or only a very detailed view of a specific targeted region of high interest, the scientific yield of surveys is immensely large, with diverse applications, cross-waveband value and legacy importance.

To be outlined here, albeit also motivated by our own research area, is a survey feasible with the VLA and available data reduction techniques, that in our opinion would make the largest impact possible in a maximum number of astrophysical fields.

With a typical division of surveys into deep-field and/or large-sky extragalactic surveys and surveys of (select areas of) the Milky Way galaxy, we are most familiar with the latter and thus here we will concentrate on a radio survey of the Milky Way galaxy.

Given the impact of an instantaneous large field of view on survey speed, it is tempting to opt for surveys at the lower frequency bands for the VLA. Indeed some of these surveys have been done with the VLA prior to the upgrade, such as the NVSS, FIRST, CORNISH and VGPS surveys (Condon et al., 1998; Becker et al., 1995; Hoare et al., 2012; Stil et al., 2006). However, regardless of the scientific motivation for these previous surveys, the lower frequencies ($\nu \leq 5\,\mathrm{GHz}$) predominantly detect sources of non-thermal synchrotron radiation and are not very well suited to study thermal sources that radiate more of their energy at higher radio frequencies ($\nu \geq 10\,\mathrm{GHz}$).

Given the recent wealth of detailed large sky-area arcsecond-resolution observations with sophisticated spacecraft in the infrared (*IRAS, MSX, AKARI, SPITZER, HERSCHEL, WISE, PLANCK, ...*), at wavebands that are not hindered by interstellar extinction (just like in the radio regime), it seems obvious to, as a first step, match the (thermal) radiation from dust, star forming regions, planetary nebulae, etc., detected in these surveys with their radio counterparts. However, without disregarding the surveys done with other instruments at higher frequencies, and future surveys to be done at even higher radio frequencies ($\nu \geq 100\,\mathrm{GHz}$) with ALMA (when it becomes acceptive to large-area surveys), so far a milli-Jansky sensitive arcsecond resolution continuum polarization imaging survey of the Galactic plane at a higher frequency ($\nu > 5\,\mathrm{GHz}$) is lacking. The science drivers for this survey are nicely outlined, among others, e.g., in the CORNISH (Purcell et al., 2008; Hoare et al., 2012) and AMIGPS (Perrott et al., 2013) papers. Please also imagine inserting your own favorite Galactic science topic here. We are sure there are many that we have not thought of that may well matched to a survey like presented here, with or without slight modifications (to be discussed).

Here we give some arguments why a group of select and similar previous continuum surveys are insufficient for the multi-wavelength comparison studies that we argue should be a driving motivation of the VLA Sky Survey (VLASS). Below we also discuss some line options, but line sensitivity has a large impact on the request for observing time (for a specific coverage on the sky) and are thus only realistically feasible for select areas of interest. While covering such specific target areas may be of high importance for some fields in astrophysics (insert your favorite target here), we choose to focus on the more general applications of larger scale continuum surveys.

- **AT20G** (Murphy et al., 2010; Massardi et al., 2011) This all-sky ATCA survey at 20 GHz is sensitive to non-synchrotron emission and covers the sky below Dec. 0°. Though the survey in principle covers the inner Galaxy and Southern plane, it unfortunately omits the Galactic plane itself (covering $|b| > 1.5°$) and lacks coverage in the well studied fringes of the Northern part of the plane ($0° <$ D*ec.* $< +40°$) also accessible with the ATCA. Furthermore, in comparison to infrared surveys like GLIMPSE the angular resolution is poor ($\sim$100″). At an RMS noise level of about 10 mJy/beam (detection limit just under 100 mJy/beam), AT20G is sufficiently sensitive to detect high-frequency calibrators for the pre-expanded VLA at the higher Galactic latitudes.

- **GPA** (Langston et al., 2000) This survey of almost the entire Northern sky Galactic plane ($-15° < l < 255°$) also covers a considerable range of Galactic latitude ($|b| < 5°$), and therefore almost completely covers the MSX infrared survey visible from the Northern Hemisphere. The observing frequencies of $\sim$8 and $\sim$14 GHz in principle would detect non-synchrotron sources, but the RMS sensitivity of $\sim$230 and $\sim$800 mJy/beam, respectively, is poor as well as the angular resolution ($\sim$580″ and $\sim$400″) of these single dish observations. However, these low resolution maps may help augment sensitivity to large scale structure not detectable in VLA snapshots or with on-the-fly (OTF) mapping in the VLASS.

- **AMIGPS** (Perrott et al., 2013) An interferometric survey at $\sim$16 GHz that has more than a factor of two better angular resolution, and almost a factor of 300 better noise ($\sim$3 mJy/beam) compared to the single dish GPA survey over the same Galactic latitude ($|b| < 5°$). Unfortunately this survey only covers regions of the Galactic plane that pass at high elevations ($76° < l < 170°$), which critically will still avoid the Galactic center and bulge even after the survey is extended to lower elevations in the future ($53° < l < 193°$).

- **VLA-L** (Zoonematkermani et al., 1990) To our knowledge this is the Galactic plane survey with the largest range in Galactic longitude ($-20° < l < 120°$) using the (pre-expanded) VLA at 1.4 GHz. The Galactic latitude is fairly limited to a single pointing on each side of the Galactic equator ($|b| < 0.8°$), but the angular resolution is matching ($\sim$5″) for comparison with most infrared catalogs and images. The RMS of $\sim$10 mJy/beam is reasonable, but the largest problem for the study of thermal or non-synchrotron radio sources is that this survey is performed at the low frequency of 1.4 GHz.

- **VLA-C** (Becker et al., 1994) This 5 GHz survey is similar to the VLA-L survey with a fairly limited Galactic latitude of a single pointing on each side of the Galactic equator ($|b| < 0.4°$) and also a 2/3 cut in longitude coverage ($-10° < l < 40°$). However, observing the Galactic plane at a three-times higher frequency (4.9 GHz) it also has an angular resolution ($\sim$4″) well matched to infrared surveys and generally a better RMS (2.5-10 mJy/beam). This makes the combination of the VLA-L and VLA-C surveys an excellent resource to obtain spectral indexes of radio sources in the 40 square-degree overlap region and determine whether sources are non-synchrotron emitters.

- **CORNISH** (Hoare et al., 2012) To our knowledge this is the Galactic plane survey with the highest angular resolution ($\sim 1''$) and the best sensitivity (0.4 mJy/beam RMS). Observing at a frequency of 5 GHz, it was designed to match the *SPITZER* GLIMPSE infrared survey of part of the Galactic plane, North of the Galactic bulge, with a similar angular resolution ($|b| < 0.8°$, $10° < l < 65°$). The main science driver was to detect UCHII regions produced by B3 stars across the Galaxy, as well as detecting, among other sources, planetary nebulae, ionized winds from evolved massive stars, active stars, binaries, non-thermal emission from active stars, high energy sources, active galactic nuclei and radio galaxies. The investigators also point out the legacy applications beyond the original scope and drivers. Unfortunately, this survey omits the Galactic bulge and center, and higher Galactic latitudes where many of these sources will be found as well. Furthermore, as this survey was done at a low frequency (5 GHz), it is still primarily sensitive to synchrotron radiation.

- **MeerGAL** (Mark Thompson[1] & Sharmila Goedhart) is a planned sensitive (better than 0.1 mJy/beam) Southern Galactic plane survey ($|b| < 1°$, $280° < l < 350°$) with MeerKAT to start after 2018 in the 10-14 GHz frequency range. We note that this longitude range almost completely covers the longitude range unavailable to the VLA. Details about angular resolution ($\sim 0.2''$?) are not readily available, but we imagine that MeerGAL and the here proposed survey are completely complementary.

With the exception of MeerGAL, which has yet to be executed, the above surveys were designed to achieve specific science goals and have done just that very well. However, to characterize the emission from the majority of components in the Galactic plane, bulge and center, which involves stars in any stage of their evolution and warm and dusty cloud cores, these surveys are too biased toward synchrotron radiation, or toward extragalactic AGN. To address the shortcomings of the above surveys, a new VLA Sky Survey of the Milky Way should aim to cover as much of the Galactic plane, bulge and center (as large as currently pragmatic), at a frequency higher than previous surveys (as high as currently pragmatic), at the best possible sensitivity (as sensitive as currently pragmatic) and at an angular resolution that is well-matched to the best angular resolution ($\leq 1''$) of recent infrared surveys. Essentially a VLA survey, at a (high) frequency not used before, yielding a detailed view over a large area of general interest (the Galactic center, bulge and plane) for which data in other wavebands (on either side of the spectrum) is readily available for comparison and spectral index measurements. Such a new VLA Sky Survey would yield the least duplication of previous work and thus make the highest possible impact in astrophysics at this

[1]pysalt.salt.ac.za/meetings/talks_saao_meerkat/session3/SALT-MeerKAT%20%20MeerGAL.pptx www.herts.ac.uk/research/stri/research-areas/car/surveys/surveys-of-the-milky-way/radio-surveys

stage, and as a bonus, dramatically increase the density of high-frequency calibrator sources in a region in the sky where they are highly necessary but still lacking.

That is, we propose **a VLA survey that combines the superior sensitivity and angular resolution of the CORNISH survey, with the sky area covered by the low resolution GPA survey, while observing at a frequency comparable to the AT20G survey**, a survey that, given the capabilities of the VLA, is long overdue.

## Observing Parameters

To detect radio emission from non-synchrotron (thermal) sources the best choice is a radio frequency at the higher end of the receiver ranges. Unfortunately, the original VLA was not built with this in mind, meaning that observations at the highest end of the receiver range ($\nu > 20$ GHz) require significant extra overhead of antenna pointing. Furthermore, the antenna dishes are only sufficiently large to yield fields of view of the order of an arcminute or two, significantly affecting the survey speed. The highest frequency that may avoid the extra overhead of pointing seems to be the 12-18 GHz observing band (Ku, also known as U or 15 GHz, receivers). With 6 GHz continuum bandwidth this range is as sensitive as the 8-12 GHz band (X) and, due to the effect of the atmosphere, more sensitive than any of the higher frequency (K, Ka, Q) bands for which one can cover a full 8 GHz bandwidth. The center frequency of 15 GHz also is a natural "factor-3" extension of pre-expanded VLA surveys at 1.4 and 5 GHz. The next factor-3 frequency would be 45 GHz, also available at the VLA, but probably the topic of a next generation VLASS.

At 15 GHz, to obtain the $\sim 1''$ angular resolution similar to that of the 5 GHz CORNISH survey, the natural choice for array configuration would be C, or CnB for the lower Declinations. Perhaps the D and DnC would better match the few-arcsecond angular resolution of the VLA-L and VLA-C surveys, but we would argue that one would want to match the best angular resolution available in the infrared while making use of an array configuration that is less oversubscribed. This is also a benefit for detecting the most compact sources that can be used for phase calibration at the higher frequencies. The largest angular scale in snapshot observations is just smaller than an arcminute for any of these arrays, which is sufficient for comparison with infrared maps. Detecting gas (apart from masers) is not an essential part for this survey and therefore does not impose the constraint to observe in the smallest (D, DnC) array configurations. Note that the same $\sim 1''$ angular resolution is obtained at 45 GHz with the D array configuration.

While the survey will be set up as a continuum polarization survey, which only has a minimal effect on total calibration overhead, correlator resources are available

Table 1: On-the-fly observations at 3 sec field integrations

| $\nu$ (GHz) | FOV ($'$) | BW (GHz) | RMS ($^a$) | slew ($''$/s) | 10° strip (min) | $\Delta l$=280° # strips | Time (hours) | Total (hours) |
|---|---|---|---|---|---|---|---|---|
| 18-26/K | 1.23 | 7.5 | 225 | 25 | 24+oh | 13650 | 5460+oh$^b$ | ~7000 |
| 12-18/Ku | 1.78 | 5.5 | 130 | 36 | 17+oh | 9450 | 2680+oh | ~3200 |
| 8-12/X | 2.67 | 3.5 | 130 | 53 | 11+oh | 6300 | 1155+oh | ~1400 |
| 2-4/S | 11.3 | 2.5 | 210 | 160 | 3.8+oh | 2100 | 133+oh | ~150 |

[a] RMS in $\mu$Jy/beam

[b] Includes extra overhead for pointing scans, next to standard calibration for flux density, bandpass, delay/phase and polarization

to include searches for narrower line emission other than with the default 2 MHz (~40 km·s$^{-1}$) channel separations, at the cost of a higher data rate and data volume and a slightly more complicated data reduction. The details will vary with the details of the line setup, but the point of this “almost for free” extra survey data is that it should be included.

The catalog compiled by Frank Lovas[2] lists about 80 lines detected previously in what can be considered the VLA Ku-band frequency range (11.9-18.1 GHz). Probably the most interesting categories are those of masers ($CH_3OH$, OH, maybe SiS), thermal cores ($H_2CO$, $CH_3OH$, maybe $NH_3$) and the vast amount of carbon molecules, such as variations of HCN, $HC_xN$ (with $x$ an odd positive integer <10). Easiest to observe are the (methanol) masers as they typically are compact (point-like in any array configuration) and bright, and can be detected in a minimum scan time over the entire Galaxy, but it won't hurt to include others if resources are remaining. The X band range (7.9-12.1) returns about 65 lines of mostly other transitions of the same species.

The intrinsic continuum sensitivity is impressive which means that for a very reasonable detection limit only a few seconds of integration are needed per field to achieve sub-mJy sensitivity (see Table 1). With only a few seconds per pointing, it will be impractical to use the individual field point-and-shoot approach as the slewing overhead will be larger than the total on-source observing time. Therefore for any such survey an on-the-fly (OTF) mapping mosaic is the way to go. In Table 1

[2] http://physics.nist.gov/cgi-bin/micro/table5/start.pl

the RMS and survey numbers are given for a 3 second field integration time for the 18-26, 12-18, 8-12 and 2-4 GHz ranges. The latter is included to show that indeed the large primary beam (FOV) of the lower frequencies is attractive in covering an area in the sky with minimum observing time, but that only holds if the observing frequency is more flexible and not a key parameter in the survey, as it must be to be most sensitive to thermal sources. The former is included for the opposite reason, as not only does the time per area become large at the higher frequencies, but for frequencies over about 20 GHz a significant amount of overhead needs to be included for antenna pointing scans. Also, it would impact the observing time available during high-frequency weather conditions considerably. The sweet spot in terms of sensitivity lies in the range 4-18 GHz, where we omitted to list the range 4-8 GHz (C band) as a partial Galactic survey in this range has already been done (VLA-C and CORNISH). The preference of the 12-18 GHz range over the 8-12 GHz range, which both are similar in RFI and other observing effects and constraints, then becomes a matter of potential return. Our preference for the higher frequencies is motivated by:
(-) the relative increase of non-synchrotron versus synchrotron radiation,
(-) the "factor-3" with respect to the previous VLA surveys,
(-) the higher resolution,
(-) the inclusion of the strong methanol maser at 12.2 GHz,
(-) a frequency that matches the missing Galactic plane data for the AT20G survey,
(-) a previously largely unused frequency range, and
(-) a new homogeneous survey that would not be sidetracked by re-observing or skipping the (non-homogeneous) areas from previous observations.

In Table 1 we have compiled the time it would take to survey the Galaxy for $|b| < 5°, -20° < l < 260°$ (2800 square degrees), i.e. the GPA and MSX survey area expanded to or overlapping with the maximum coverage at the VLA (that can reach slightly lower Declinations than the GBT). It also shows the time it takes for a 10° strip (i.e., sampling in $b$) and the number of such strips to cover the 280° of the entire visible Galactic plane (i.e. $l$) with the slew rate for 3 seconds per field. The raw and approximate (i.e., including overhead) total time for the whole survey is also listed for an integration time of 3 seconds per field. The integration time of 3 seconds is used as this would give an $8\sigma$ continuum detection limit of 1 mJy. This is comparable (but slightly better) to the sensitivity of the CORNISH survey and results, with 1 second dump times, in a data rate of 36 MB/s (128 GB/h) and a total data volume of 350 TB (excluding extra resources used for lines) when observing a 6 GHz bandwidth at 15 GHz. The numbers are a factor 1.5 smaller for the 4 GHz bandwidth at 10 GHz.

Note that with a detection limit of 1 mJy, continuum calibrators as faint as 25 mJy ($8\sigma$ on a single polarization baseline, both at 10 and 15 GHz) will be detected and greatly expand the list of calibrators available in and near the Galactic plane compared to the current cut-off of 100 mJy.

## Possible alternatives

The survey parameters described above are designed to yield the maximum scientific return for a Galactic VLASS. Although it is technically feasible (and indeed scientifically desirable) with the current observational status of the VLA to perform this survey, it is painful to think of alternatives for descoping if the survey would be considered *logistically* not feasible, even when spread out over many configuration cycles. There are however some alternatives, each with their trade-off consequences:

- **Slew rate/integration time/sensitivity:** Slew rate and integration time for a single epoch observation are both coupled such that changing either parameter impacts the overall sensitivity. We would point out that, e.g., doubling the slew rate or halving the observing time for a $\sqrt(2)$ cut in sensitivity, would mean increasing the dump rate by at least a factor two and thus increasing the data rate and data volumes by at least a factor of two. This may cause operational problems, but is certainly a point of consideration.

- **Survey area:** Cutting the survey area will cut the total observing time linearly with the coverage. One could argue that the outer Galaxy or the higher latitudes are less interesting. However, for legacy value and for coverage overlap with the MSX and GPA surveys, as well as for currently neglected studies in the outer Galaxy and higher latitudes, e.g., where the metallicity of the objects is much lower than for the inner Galaxy, it is important to maintain the goal of observing the fully overlapping accessible survey area.

- **Overhead:** The only luxury overhead included is the overhead for polarization calibration. However, the overhead is minimal and the extra scientific return of the availability of polarization measurements tremendously outweigh the small increase in observing time.

- **Frequency:** Observing at a lower frequency, like in the 4-8 GHz (C band) range, would speed up the survey speed due to the larger primary beam. However, observing at a lower frequency would severely impact the science goal of surveying non-synchrotron radiation.

- **Upscoping!** Perform this survey in the 40-48 GHz range (Q band) in D array configuration. The scientific return for thermal sources, a diversity of (maser) lines and high-frequency continuum calibrators would be much larger, but at a cost of a hugely increased demand on high-frequency weather observing time (and thus probably not feasible).

In summary: No GUTS, no glory!

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