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# Candidate Phase Calibrators at 93 GHz in the ngVLA Sky: Developments Since 2022

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## ABSTRACT

For fast switching at 93 GHz with ∼200 ngVLA antennas, Wrobel & Ho (2022) suggested that candidate phase calibrators be selected down to ∼10 mJy, leading to ∼1 per deg$^2$, and also be drawn from wide surveys from Chile of the Cosmic Microwave Background (CMB). Here, we discuss developments since 2022, including an imminent catalog of Atacama Cosmology Telescope sources (Naess 2024), a proposed CMB wide survey from the Northern Hemisphere (Desert et al. 2024), and the prospects for cross-matching Gaia-identified sources (Carnerero et al. 2023) with CMB-discovered sources.

*Keywords:* Interferometry (808)

## 1. MOTIVATION AND RECAP

The next-generation VLA (ngVLA) will be an interferometric array operating at frequencies between 1.2 and 116 GHz, with ten times the sensitivity and angular resolution of the VLA and ALMA (McKinnon et al. 2019). The calibration strategies for the ngVLA are being developed but already it is clear that these will be the most demanding for Band 6, the highest-frequency band centered at 93 GHz (Selina et al. 2022b).

Fast switching between a phase calibrator and a science target will be utilized at 93 GHz (Carilli 2015). A smaller switching angle is desirable for both the quality and the efficiency of the calibration. Regarding quality, the phase in the direction of the calibrator becomes a better estimate for the phase in the direction of the target. Regarding efficiency, less time is wasted slewing between the phase calibrator and the target.

The ngVLA will access all right ascensions and all declinations above −40 deg (Figure 1; Selina et al. 2022a). Ensuring a small switching angle to any target demands a high areal density of phase calibrators in the ngVLA sky. In Wrobel & Ho (2022) we suggested that for fast switching at 93 GHz with ∼200 ngVLA antennas, candidate phase calibrators be selected down to ∼10 mJy, leading to ∼1 per deg$^2$ (Figure 2), and also be drawn from forthcoming wide-area surveys of the Cosmic Microwave Background (CMB) conducted from Chile (Table 1).

Here, we discuss developments since 2022. Section 2 describes developments concerning CMB wide surveys from Chile (Naess 2024; Sierra et al. 2024; Cho 2024) and from the Northern Hemisphere (Desert et al. 2024). We focus on ngVLA Band 6 but occasionally draw on the surveys' traits at lower frequencies relevant to ngVLA Bands 4 and 5. We also consider the prospects for comparing catalogs of CMB-discovered sources with a catalog of Gaia-identified sources (Carnerero et al. 2023). We close in Section 3 with a summary of how the ngVLA might benefit from CMB wide surveys, both existing and proposed.

## 2. CMB WIDE AREA SURVEYS

### 2.1. *General Remarks*

We describe developments since 2022 relating to CMB wide area surveys from Chile and from the Northern Hemisphere (Table 1). Near 93 GHz, the point-source full depths at five times the RMS noise $\sigma$ are $\lesssim$10 mJy

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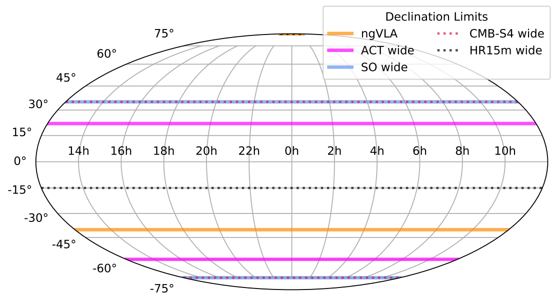


**Figure 1.** Solid lines convey declination limits for the ngVLA (Selina et al. 2022a), the wide survey with the Atacama Cosmology Telescope (ACT) in Chile (Naess et al. 2020; Naess 2024), and the wide survey with the Simons Observatory (SO) in Chile (Stevens et al. 2018). Dotted lines convey limits for proposed wide surveys, CMB-S4 from Chile (Abazajian et al. 2019; Carlstrom et al. 2019) and HR15m from the Northern Hemisphere (Desert et al. 2024).

and the Chilean-based surveys offer a typical angular resolution at FWHM of $\sim$2 arcmin.

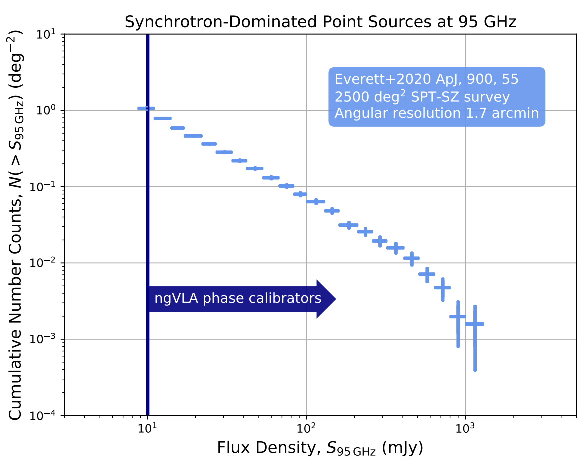


**Figure 2.** Counts of synchrotron-dominated sources at 95 GHz from the 10m South Pole Telescope (SPT) Sunyaev-Zeldovich survey at declinations below $-40$ deg (Everett et al. 2020). These are active galactic nuclei (AGNs) and are point sources at the survey's angular resolution. Cross-matches with multi-wavelength catalogs suggest these AGNs are primarily blazars, that is, relativistic jets directed toward us (Blandford et al. 2019). The overall point-source population at 95 GHz is only mildly contaminated by dust-dominated sources.

**Table 1.** CMB Wide Area Surveys

| (1) | (2) | (3) | (4) |
|---|---|---|---|
| ACT Survey from Chile | | | |
| Frequency (GHz) | ... | ... | 98 |
| Angular resolution (arcmin) | ... | ... | 2.0 |
| Full depth $\sigma$ (mJy) | ... | ... | 0.7-3 |
| SO Survey from Chile | | | |
| Frequency (GHz) | 27 | 39 | 93 |
| Angular resolution (arcmin) | 7.4 | 5.1 | 2.2 |
| Full depth $\sigma$ (mJy) | 4 | 2 | 1.4 |
| CMB-S4 Survey from Chile | | | |
| Frequency (GHz) | 30 | 40 | 95 |
| Angular resolution (arcmin) | 7.4 | 5.1 | 2.2 |
| Full depth $\sigma$ (mJy) | 0.8 | 0.6 | 0.2 |
| One week $\sigma$ (mJy) | 15 | 11 | 3 |
| HR15m Survey from Northern Hemisphere | | | |
| Frequency (GHz) | ... | ... | 90 |
| Angular resolution (arcmin) | ... | ... | 1.0 |
| Full depth $\sigma$ (mJy) | ... | ... | 2 |

Candidate phase calibrators found in CMB wide surveys will eventually be vetted interferometrically for compactness at 93 GHz (Wrobel & Ho 2022). In the interim, simultaneous spectral indices and time variability from CMB surveys can serve as proxies for compactness (e.g., Liodakis et al. 2017; Blandford et al. 2019; Hsu et al. 2023). We thus comment below on the prospects for extracting those diagnostics from each CMB wide survey. We also comment on the timelines for each survey, for comparison with plans for ngVLA construction (2028-2037) and for ngVLA Early Science (2031-2037)[1].

Other proxies for compactness can be leveraged from non-CMB surveys. For example, Carnerero et al. (2023) reported 33,706 photometrically variable sources from Gaia DR3 with counterparts at centimeter wavelengths (Figure 3). These sources have a sky density of $\sim$1 per deg$^2$ away from the Galactic plane. They are primarily blazars based on their multi-wavelength traits. Cross-matching such Gaia blazars with CMB-discovered sources could be a quick way to confirm the blazar nature of the sources and begin assembling a list of candidate phase calibrators. Also, their prior localizations at centimeter wavelengths and with Gaia could accelerate future interferometric vetting at 93 GHz.

[1] https://ngvla.nrao.edu

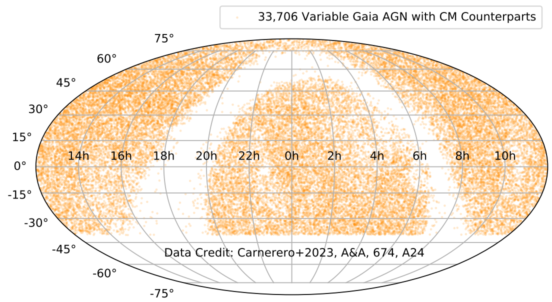


**Figure 3.** Positions of photometrically variable Gaia sources from DR3 with counterparts at centimeter wavelengths (Carnerero et al. 2023). These Gaia-identified AGNs span the full declination range of the ngVLA (Figure 1).

It is crucial that the aforementioned proxies for compactness at 93 GHz be examined as early as possible. Vetting thousands of candidate phase calibrators interferometrically will be a substantial ngVLA commissioning effort. This effort should start soon after ngVLA construction begins in 2028 and deliver a catalog of vetted phase calibrators by 2031, when ngVLA Early Science begins.

### 2.2. *ACT Wide Survey*

Table 1 gives the traits of a wide survey with the Atacama Cosmology Telescope (ACT) in Chile (Naess et al. 2020; Naess 2024). The survey spanned 2017-2022 and covered declinations from $-60$ deg to $+22$ deg (Figure 1).

Naess et al. (2020) applied a matched filter point-source finder to maps combining ACT DR5 and *Planck* data over $\sim$18,000 deg$^2$. This effort yielded a preliminary catalog of 18,507 ACT DR5 sources at 98 GHz detected above $5\sigma$, suggesting a sky density of $\sim$1 per deg$^2$. The detection thresholds of 3.5 mJy in deep regions and 15 mJy in shallow regions reach levels of interest for candidate phase calibrators for the ngVLA. Figure 4 shows an example ACT+*Planck* map cut out from an interactive atlas[2].

This year should see the release of the ACT DR6 catalog at 98 GHz (Naess 2024). Cross-matches with other catalogs are pending but the SPT results (Figure 2; Everett et al. 2020) suggest that blazars will dominate the ACT DR6 catalog. These blazars could serve as candidate phase calibrators at 93 GHz with declinations from $-40$ deg to $+22$ deg.

[2] https://phy-act1.princeton.edu/public/snaess/actpol/dr5/atlas/

### 2.3. *SO Wide Survey*

Table 1 gives the traits a wide survey with one 6m telescope at the Simons Observatory (SO) in Chile (Ade et al. 2019). Telescope deployment will occur this year (Sierra et al. 2024). The footprint of this wide survey is still under discussion. In the interim, we adopt the declination band from $-75$ deg to $+35$ deg that was shown to be feasible with an opportunistic survey strategy (Figure 1; Stevens et al. 2018).

The SO wide survey will start soon and span 5 yr. At 93 GHz the full SO survey is projected to reach a $5\sigma$ detection threshold of 7 mJy, a regime of interest to the ngVLA. An SO catalog would identify candidate phase calibrators with declinations from $+22$ deg to $+35$ deg, a swath not covered by the ACT wide survey.

For declinations from $-40$ deg to $+35$ deg, an SO catalog would offer simultaneous information at lower frequencies (Table 1). This can help screen for the flat spectra expected from blazars and help find candidate phase calibrators for ngVLA Bands 4 and 5.

For declinations from $-40$ deg to $+22$ deg, an SO catalog would help characterize the long-term variability of candidates at 93 GHz by leveraging on earlier ACT data.

It may be that an SO catalog is available this decade. But to facilitate ngVLA Commissioning and Science Validation at 93 GHz when construction starts in 2028, it would be desirable to have earlier access to an SO catalog. A possible solution would be to gain access to an SO mid-survey catalog, with its still-suitable detection threshold of $\sqrt{2} \times 7\,\mathrm{mJy} = 10\,\mathrm{mJy}$. Accessing an SO mid-survey catalog would also improve preparations for ngVLA Early Science, slated to start in 2031.

### 2.4. *CMB-S4 Wide Survey*

Table 1 gives the traits of a proposed CMB-S4 wide survey with two 6m telescopes at the SO site in Chile (Abazajian et al. 2019; Carlstrom et al. 2019).

As proposed, the CMB-S4 wide survey would start in the 2030s and span 7 yr. But this timeline is uncertain because the U.S. National Science Foundation (NSF) declined to advance, at this time, the portion of the CMB-S4 proposal that requests resources at the South Pole Station (Cho 2024). Here, we assume only that a CMB-S4 wide survey from Chile might occur. Also, that survey's footprint has not yet been set, so we tentatively adopt the declination band from $-75$ deg to $+35$ deg that was shown to be feasible with an opportunistic survey strategy (Figure 1; Stevens et al. 2018).

Stacks of a CMB-S4 wide survey could be released to examine the week-to-week variability of point sources.

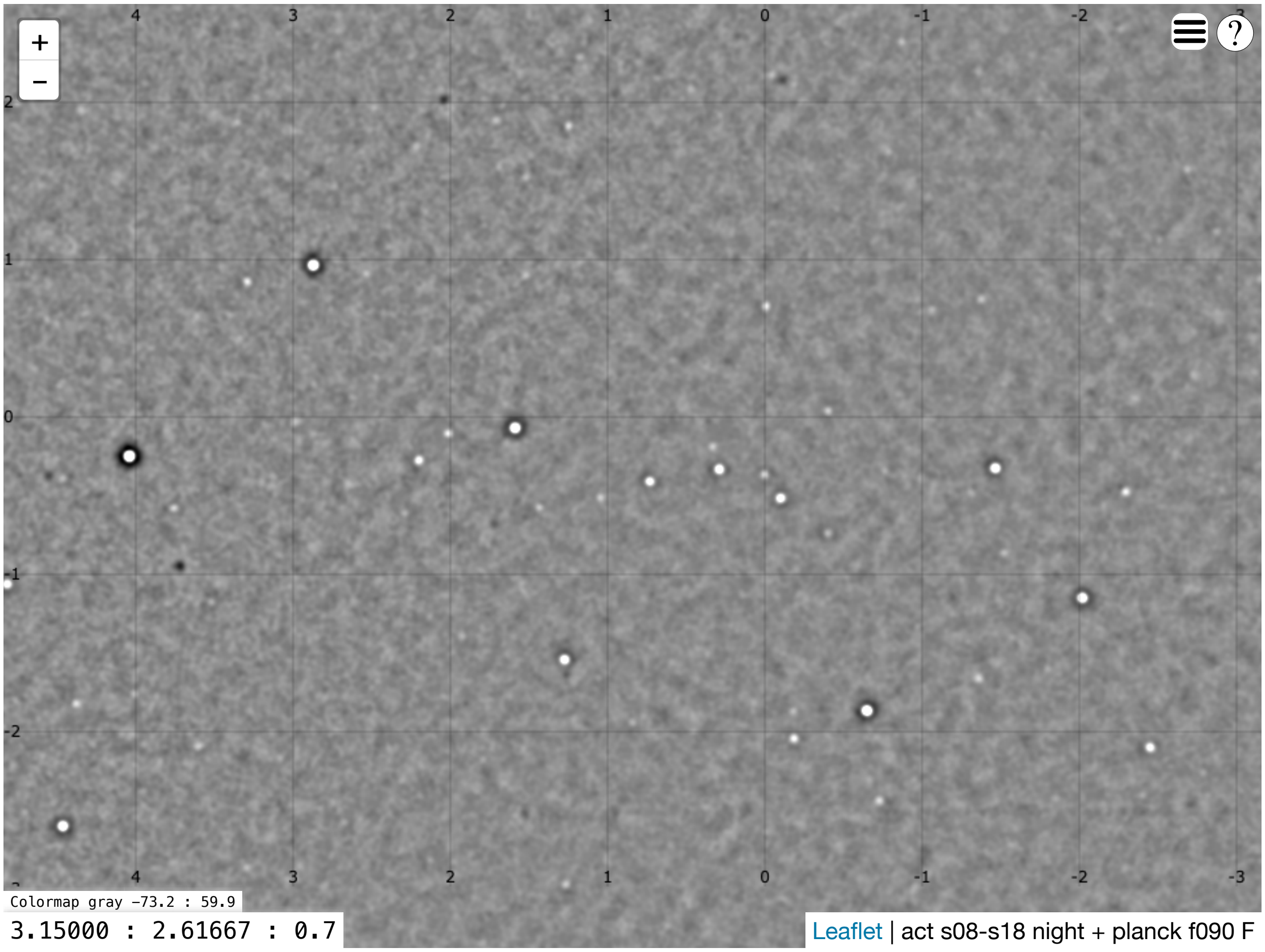


**Figure 4.** Example ACT+*Planck* map at 98 GHz filtered to enhance point sources and galaxy clusters. Right ascensions and declinations are labelled in degrees. Grid lines are spaced by 1 deg. Galaxy clusters have temperature decrements (dark). Point sources have temperature increments (light) and mark candidate phase calibrators for the ngVLA at 93 GHz.

At 95 GHz the weekly stacks could reach a $\sigma$ of 3 mJy. A $5\sigma$ detection threshold in the weekly stacks could serve to monitor candidate phase calibrators at 95 GHz down to $\sim$15 mJy. Such monitoring could characterize the week-to-week variability of the candidate phase calibrators with declinations from $-40$ deg to $+35$ deg.

Crucially, the weekly CMB-S4 stacks could help meet another ngVLA need: identifying secondary amplitude calibrators at 93 GHz. For the ngVLA, absolute amplitude calibration will be aided by observing a grid of secondary amplitude calibrators with known flux densities and suitable compactness (Selina et al. 2022b). The flux densities of this grid of amplitude calibrators will need to be monitored at appropriate intervals. To optimize the efficacy of this approach, it is desirable to populate the grid with the steadiest blazars. The weekly CMB-S4 stacks could be mined to identify the steadiest blazars.

### 2.5. *HR15m Wide Survey*

Table 1 gives the traits of a proposed wide, high-resolution (HR) survey with a 15m telescope located in the Northern Hemisphere (Desert et al. 2024).

As proposed, this so-called HR15m survey could access all declinations above $-15$ deg (Figure 1), start in the 2030s, span 4 yr, and achieve a $5\sigma$ detection threshold of 10 mJy at 90 GHz. No lower frequencies have been proposed. Crucially, the HR15m wide survey could find candidate phase calibrators at declinations, above $+35$ deg, that are not viable from Chile.

The pacing of an HR15m wide survey could reach $\sim$6,000 deg$^2$ per year. The survey's timeframe is uncertain but could overlap Commissioning and Science Validation during ngVLA construction (2028-2037) as well as ngVLA Early Science observing (2031-2037). To optimally aid those efforts at 93 GHz, it would be desirable to prioritize declinations above +35 deg early in the HR15m wide survey.

## 3. SUMMARY OF NGVLA BENEFITS

Section 2 leads to this summary of how the ngVLA might benefit from existing or proposed CMB wide surveys near 93 GHz:

- The timely release of the ACT DR6 catalog (Section 2.2) would allow a cross-match with Gaia blazars (Section 2.1), quickly testing a path for finding candidate phase calibrators.
- If the SO and CMB-S4 wide surveys from Chile were to adopt an upper declination limit of +35 deg (Sections 2.3 and 2.4), it would enhance their overlap with the ngVLA sky.
- If an SO mid-survey catalog was made available (Section 2.3), it would accelerate delivery of a catalog of vetted phase calibrators before 2031, the start of ngVLA Early Science.
- If the CMB-S4 wide survey occurs (Section 2.4), its weekly stacks could be mined to help identify secondary amplitude calibrators for the ngVLA.
- If the HR15m wide survey occurs (Section 2.5), its declinations above +35 deg could be mined to find candidate phase calibrators in the ngVLA sky inaccessible from Chile.

## 4. ACKNOWLEDGMENTS

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