Imaging Capability of the LWA Phase II

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1 Introduction

The LWA Phase I will consist of a single LWA station near the center of the VLA and another station at a distance similar to that of the Pie Town station. Phase II will expand this system by adding another seven stations even farther out to create an array with a maximum baseline of between 150 to 200 km. These nine antennas can be used alone or, when observing at 74 MHz, they can be used in combination with the 27 VLA antennas. In this memo, I propose a possible LWA Phase II array design, explore the imaging capabilities of such an array using image simulations, and finally estimate the number of actual sources in the sky that could be successfully calibrated with such an instrument.

2 Array Design

The nine LWA stations which will comprise the LWA Phase II must be placed to provide the best possible *uv*-coverage with a maximum baseline length of roughly 150 to 200 km. I considered possible locations for stations only at places with existing roads, and only on state land, which is much easier to acquire. I also considered existing NRAO sites, such as near the VLA itself, or future NRAO sites such as the planned location of outlier antennas for the EVLA II, to be preferable. The sites chosen are listed in Table 1. These nine sites include the two LWA Phase I sites (the "VLA" and "Horsesprings" stations) and five sites which are already planned for the EVLA II. The remaining two sites, "West Arm" and "Datil", were added to provide more short baselines for sensitivity to larger-scale source structure. The longest baseline in this configuration is 174 km and the shortest is 16.6 km. Figure 1 shows a map of the configuration and its location relative the the VLA "Y", and Figure 2 shows the *uv*-coverage at several source declinations.

This nine station array can be used as a stand-alone instrument or, at 74 MHz, in combination with the 74 MHz system on the VLA. In this memo, I consider the imaging capabilities for both these

Table 1: List of LWA Phase II Station Sites.

Name	Longitude (W)	Latitude (N)	Notes
VLA	107.628°	34.071°	Near VLA: location of Phase I station
Horse Springs	108.294°	33.927°	Probable Phase I station
West Arm	107.788°	34.000°	Near End of VLA West Arm
Datil	107.940°	34.080°	8 miles South of Datil on Rt. 12
Dusty	107.607°	33.683°	Dusty EVLA site
Spurgeon Mesa	108.930°	33.477°	Spurgeon Mesa EVLA site
West US60	108.783°	34.263°	West US60 EVLA site
Mangas Valley	108.447°	32.726°	Mangas Valley EVLA site
Cuchillo	107.383°	33.233°	Cuchillo EVLA site

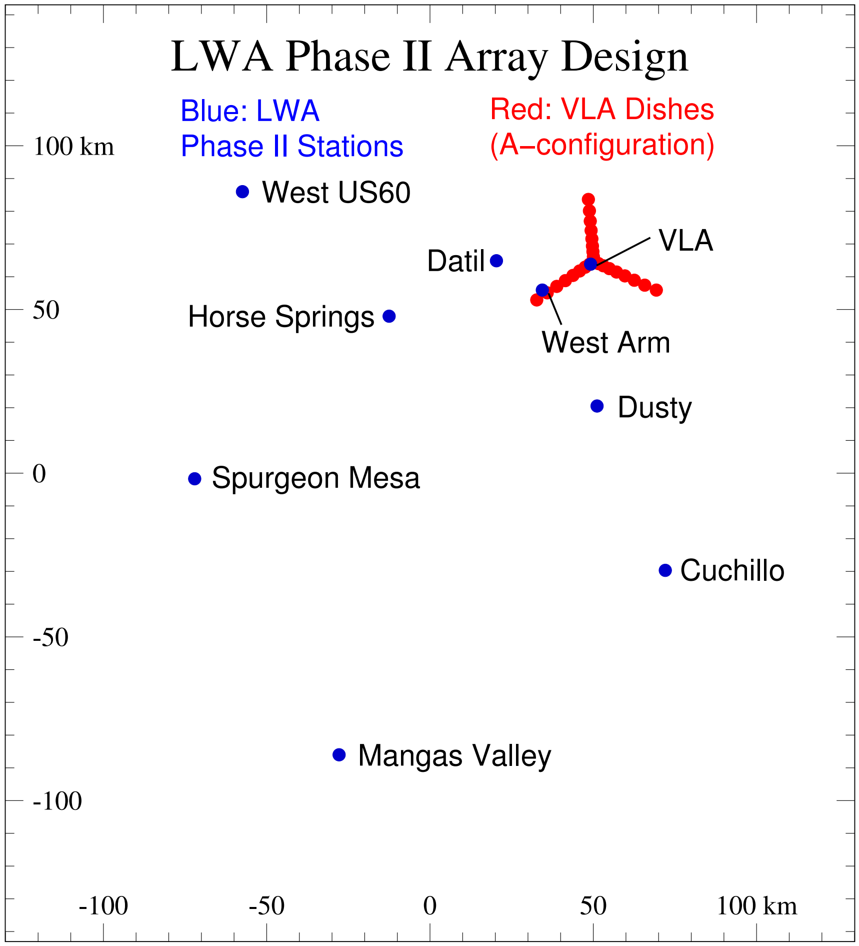

Figure 1: Proposed configuration for the LWA Phase II. The VLA antennas are in red, and the LWA stations are in blue.

cases. Practical considerations, such as land restrictions or the cost of optical cable, may require adjustments to the locations of some of these sites. However, simulations with the configuration described above should provide a reasonable estimate to the imaging capabilities of this or any similar array configuration.

3 Point Source Imaging Capability

I simulated the imaging capability of the given array of nine LWA stations by creating synthesized uv-data sets with the AIPS task UVCON. This task inputs the positions of the antennas, and projects a source model onto the corresponding visibilities in addition to thermal noise. To calculate the correct amount of thermal noise at 74 MHz, I assumed a collecting area equal to 256 times $\lambda^2/4$ (assuming 256 dipoles per station), a sky temperature of 2000 K, and a bandwidth of 1.5 MHz. The uv-data sets consist of full tracks, from when an object rises above an elevation of 30° to when it sets below 30° elevation. I simulated sensitivity and resolution for a variety of source declinations by using a blank model, producing an image with equal balance between full uniform and natural

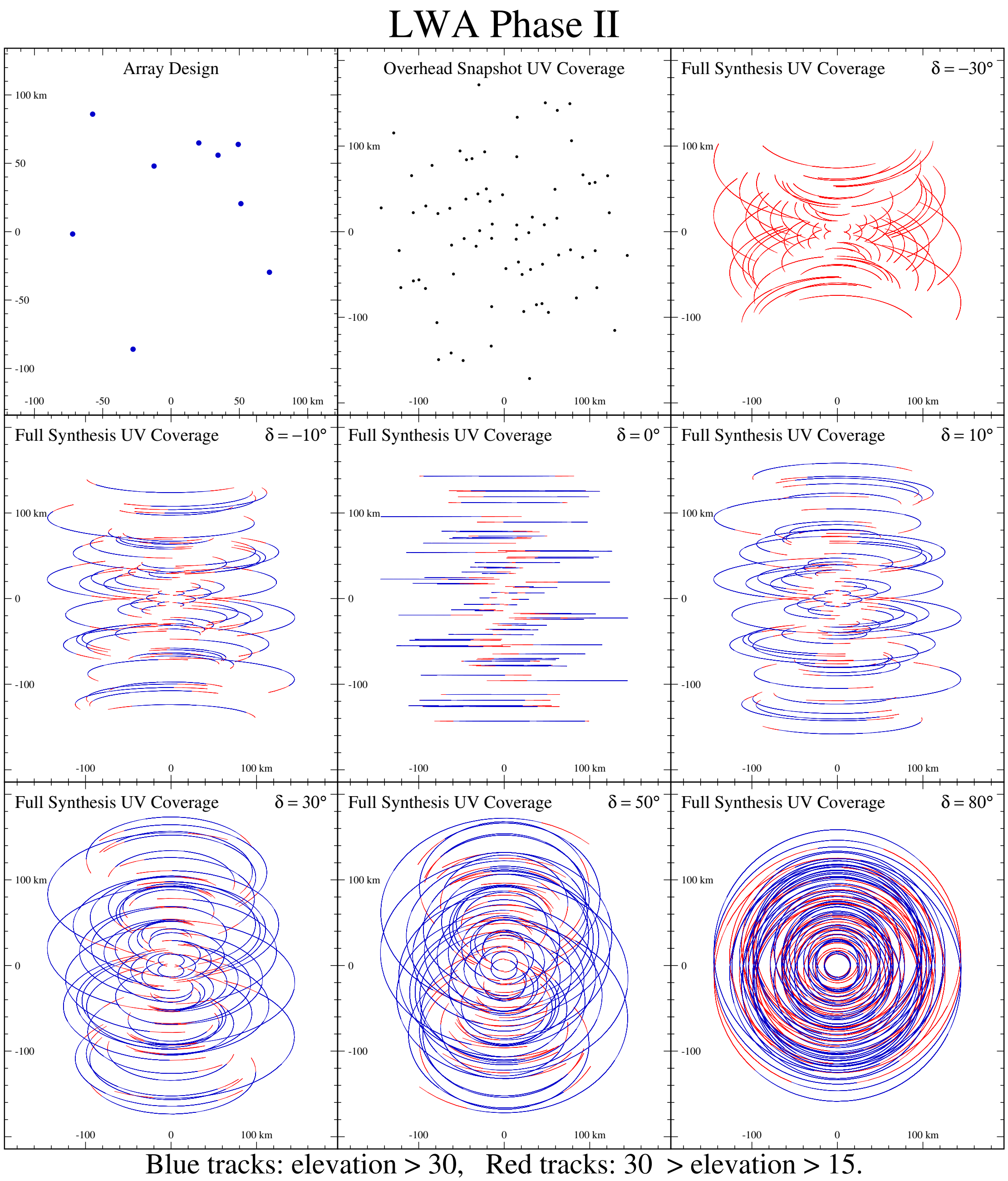

Figure 2: Top Left: Proposed LWA Phase II configuration showing LWA stations only. Top Middle: Overhead snapshot *uv*-coverage. Other 7 boxes: Synthesis *uv*-coverage for various source declinations.

Table 2: Basic imaging capability of the LWA Phase II at 74 MHz. Results are shown for 74 MHz with a sky noise of 2,000 K, a bandwidth of 1.5 MHz, and full track observations above an elevation 30°. Separate results are shown for both stand-alone mode (the 9 LWA stations only) as well as for the combined VLA-LWA mode (9 LWA stations and 27 VLA dishes in A-configuration). The uv data was weighted with a robust factor of 0.

	Phase II Stations Only		Phase II Stations + VLA	
Source Dec	rms noise (mJy/b)	Beam Size ($'' \times ''$, PA)	rms noise (mJy/b)	Beam Size ($'' \times ''$, PA)
+90	2.3	4.4×4.4, +89°	1.7	4.7×4.6, +90°
+80	2.9	4.6×4.0, +89°	2.3	4.9×4.2, +88°
+70	3.2	4.5×3.8, +90°	2.5	4.8×4.0, +83°
+60	3.2	4.3×3.7, +90°	2.6	4.7×3.8, +80°
+50	3.4	4.3×3.6, +89°	2.7	4.6×3.7, +77°
+40	3.5	4.4×3.5, +87°	2.8	4.6×3.7, +74°
+30	3.7	4.3×3.4, +83°	2.9	4.6×3.6, +70°
+20	3.7	4.3×3.4, +81°	3.0	4.6×3.7, +66°
+10	4.0	4.4×3.7, +77°	3.2	4.7×3.8, +59°
0	4.5	4.8×3.8, +83°	3.6	5.1×4.0, +63°
−10	4.9	4.6×4.2, +17°	3.9	5.3×4.1, +24°
−20	5.8	5.7×3.9, −6°	4.8	6.5×4.0, +13°

weighting (robust = 0), and measuring the beam size and rms noise level in the blank image. Table 2, shows the results for sources at various declinations for both the stand-alone instrument and the LWA Phase II combined with the VLA.

4 Complex Source Imaging Capability

In addition to the basic imaging qualities of sensitivity and resolution, it is also necessary to test the imaging capability of large, complicated sources, which could be dynamic-range limited. To do this, rather than use a blank model in UVCON, I instead used a model of the radio galaxy Cygnus A from a 325 MHz observation with the VLA in A-configuration plus the Pie Town antenna (Figure 3). This image has a resolution of 2.5″, which is safely below what the LWA phase II can achieve at 74 MHz. This a good model source because it is a radio galaxy, like most sources the LWA phase II will be able to see, and contains intricate features including both compact and diffuse emission.

At just over 2′ in size, it is somwhat larger than the largest angular scale visible to the LWA Phase II at 74 MHz. Therefore, I also use a model of Cygnus A which is scaled to be half it's actual size, or just over one 1′. For both the full and half-size models, I created simulated LWA Phase II data sets both with and without the VLA antennas. At declinations at every 10° from $\delta = -20°$ to $\delta = +90°$ I simulated full track observations above a source elevation of 30°. For each simulation, I measured the dynamic range of the image, defined as the peak flux density of the image divided by the rms noise away from the source. No noise was added to these images, and as only flux ratios matter here, it was not necessary to scale the overall flux density by a spectral index. As before, a robust = 0 weighting of the *uv* data was used. The results are shown in Figure 2. I also show simulated images for $\delta = +40°$ with and without the VLA for both the full-sized (Figure 4) and

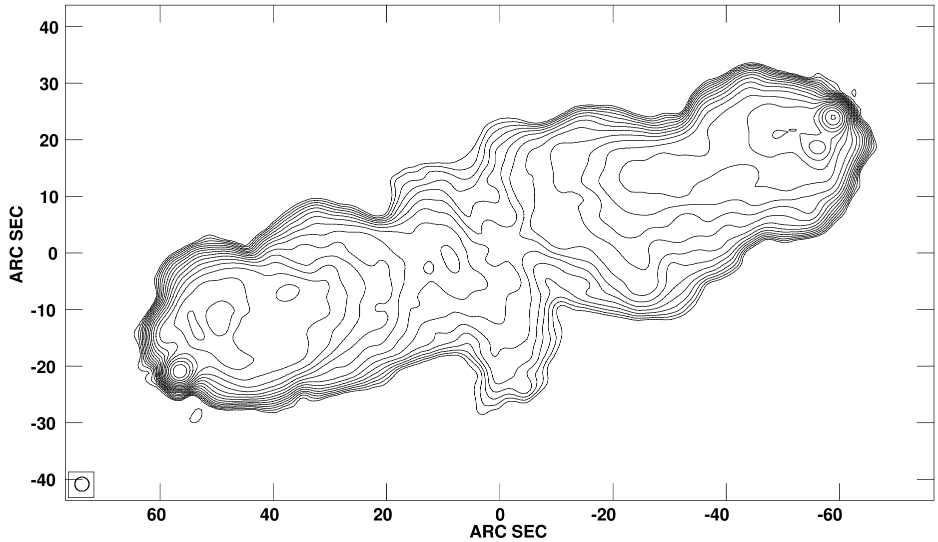

Figure 3: Cygnus A at 325 MHz

half-sized models (Figure 5).

For the full-sized model, the LWA Phase II in combination with the VLA can achieve very high dynamic range ($\sim$ 2,000) for a large and complex source structure. However without the shorter baselines of the VLA, the large scale source structure is poorly constrained resulting in a negative well surrounding the source. Though much of the source structure is retained, the dynamic range is significantly lower, and it seems clear that for sources larger that $2'$ the LWA Phase II in stand-alone mode begins to resolve out flux-density, and therefore such objects will require either observations with the VLA, or combination with previously obtained VLA data. For the half-sized model, at just over $1'$, the stand-alone instrument performs very well, achieving roughly the same very high dynamic range ($\sim$ 4,000) as it does combined with the VLA for all but the most southern declinations.

5 Observing at other Frequencies

All the above discussion centered on 74 MHz imaging. In this section I briefly describe imaging at other frequencies within the official frequency range specification of 23 - 80 MHz.

First let's consider lower frequencies than 74 MHz. One advantage of lower frequencies is larger collecting area due to the effective area being proportional to λ^2. Although the sky temperature increases somewhat faster, roughly in proportion to $\lambda^{2.6}$, the overall sensitivity is therefore proportional to $\lambda^{0.6}$, which is actually flatter than many spectral indices. Lower frequencies are also an advantage for large sources which are resolved out at 74 MHz, because the baselines measured in wavelengths are shorter. Therfore, as LWA Phase II can only image objects as big as roughly $1'$ at 74 MHz with the stand-alone instrument, it could image $2'$ and $3'$ objects at 37 and 25 MHz respectively. The main disadvantages are 1) more severe ionospheric phase delays (proportional to λ), 2) larger field of view with confusing sources, and 3) lower resolution. On balance lower frequencies are likely to be more challenging than at 74 MHz for most objects. However, if one can successfully calibrate at 74 MHz, it may be possible to "transfer" those phase solutions to lower

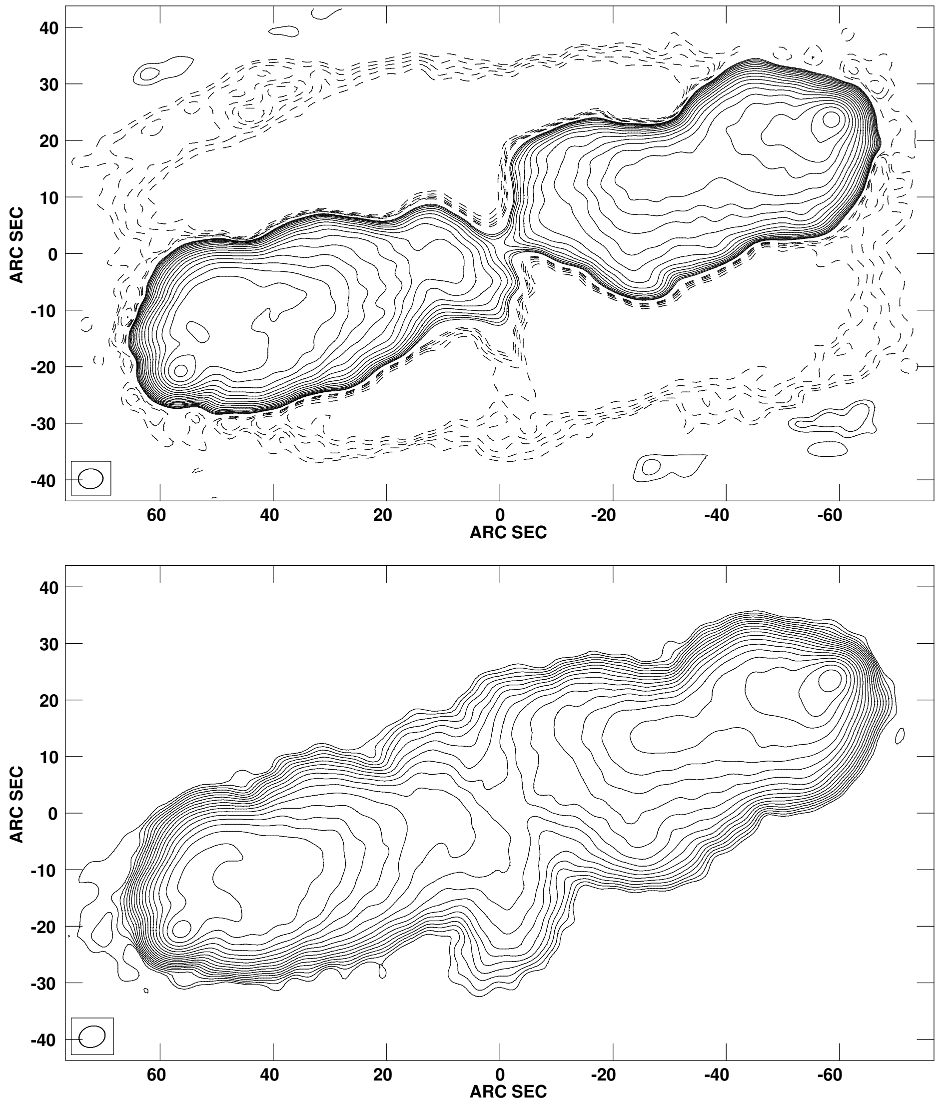

Figure 4: Simulated images of full-sized Cygnus A model with full track observations of the LWA Phase II for the source located at a declination of 40°. Above is the image for the LWA Phase II alone, and below is the image for the LWA Phase II combined with the VLA.

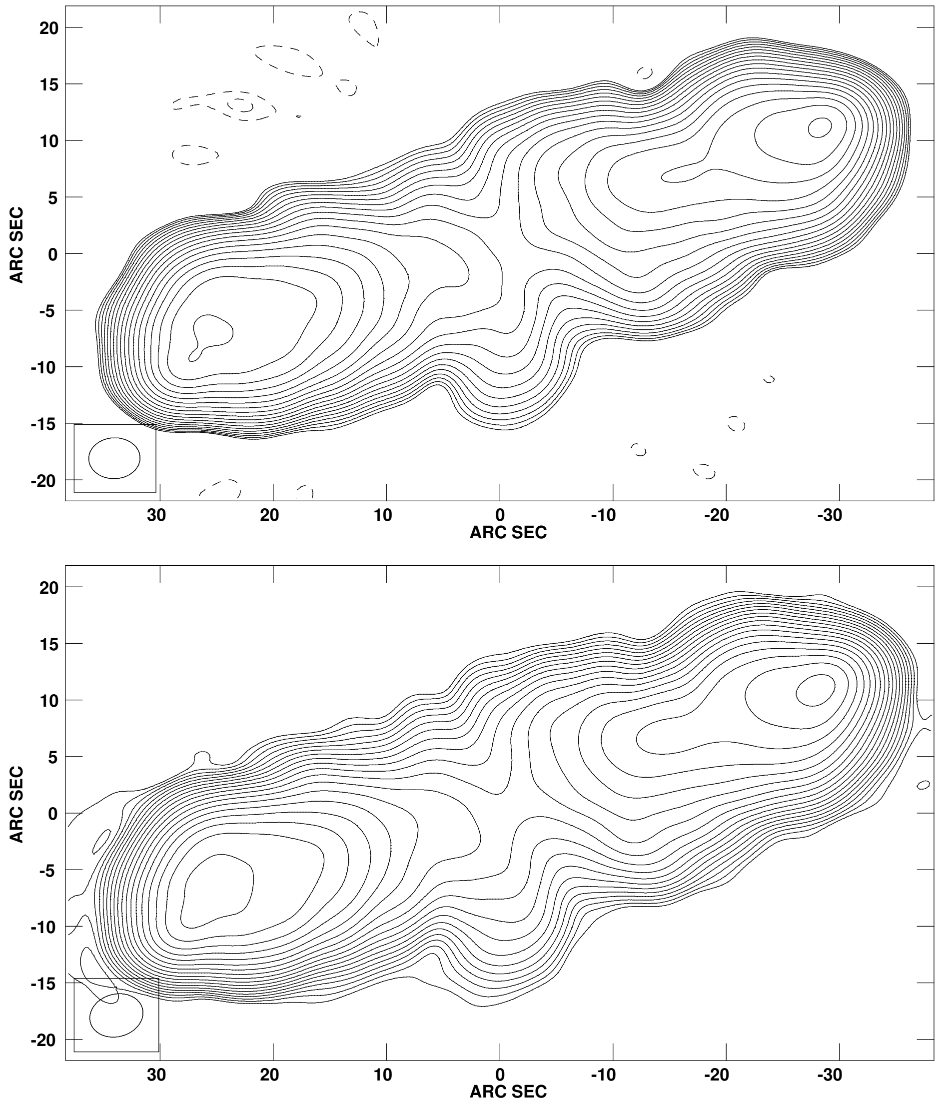

Figure 5: Simulated images of half-sized Cygnus A model with full track observations of the LWA Phase II for the source located at a declination of 40°. Above is the image for the LWA Phase II alone, and below is the image for the LWA Phase II combined with the VLA.

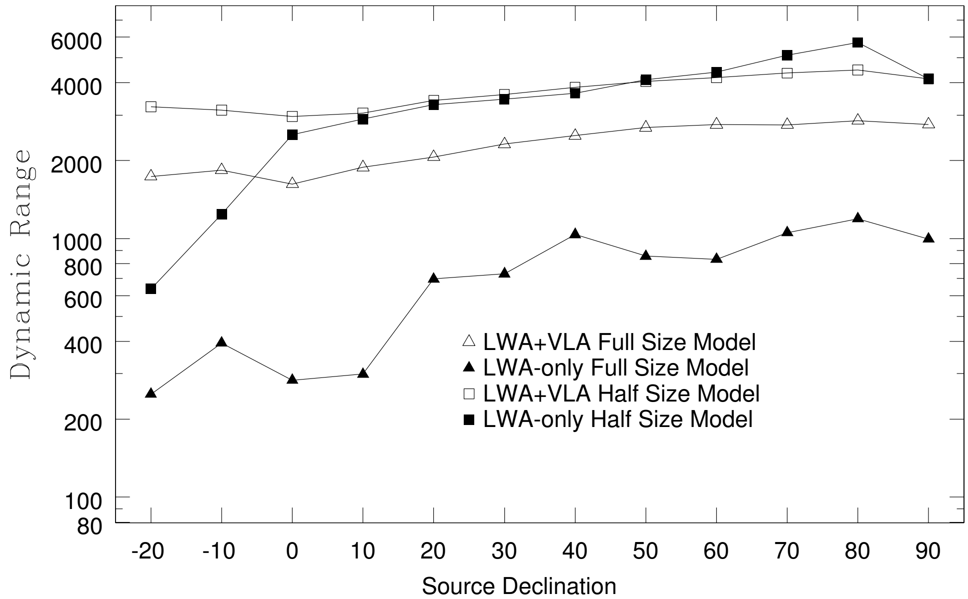

Figure 6: LWA Phase II 74 MHz dynamic range simulations for both the full and half size Cygnus A model both with and without the VLA.

frequencies. The greater challenge will likely be well worth the effort, as the scientific potential could be even greater with lower frequencies, as no one has ever observed at any frequency below 74 MHz with resolution less than several arcminutes, and LWA Phase II will achieve a resolution of roughly $12''$ at 23 MHz.

For frequencies above 74 MHz, but below the upper LWA limit of 80 MHz, there will not be much change. The resolution will be slightly better, and the field of view slightly smaller.

6 How Many Sources Can Be Imaged?

With so few baselines, calibrating the ionosphere across the entire field of view will be very difficult. In the early stages, it will likely only be possible to observe sources which are much brighter than anything else in their field of view so that simple self-calibration can be applied. To determine how many such sources there are at 74 MHz, we can use the nearly half-completed VLSS survey (`http://lwa.nrl.navy.mil/VLSS`). Using the catalog from that survey, we consider each source in comparison to all its surrounding sources. Assuming a station diameter of 100m, we calculate the field of view to have a FWHM = $2.34°$, and multiply the flux density of all sources within a 5 degree radius by a Gaussian with this half power diameter.

We set two criteria for a source which we can expect to be able to self-calibrate successfully: 1) it must have a peak flux density at least 3 times greater than any other single source in the field of view and 2) it must have an integrated flux density equal to at least half the sum of all other sources in the field of view. These criteria are based mainly on our experience with the 74 MHz VLA, and are on the conservative side of what has generally been possible with that system. Still, a total of 272 sources (out of 32,000) met this criteria in the VLSS region, which is only half the visible sky. Therefore we estimate that over ~ 540 sources will be observable to the LWA Phase II at 74 MHz with calibration algorithms available today. As the VLSS will be complete in less than a year, we can expect to have a full list of observable sources ready by the time the LWA Phase II is ready for observations.

One potential problem with this analysis is that the VLSS flux densities are measured with an $80''$ beam, while the LWA phase II will have a resolution of roughly $4''$. Therefore, one might wonder if many of the sources we intend to image through self-calibration could be resolved out at this higher resolution, and therefore not have enough flux density (or not have the dominant flux density in the field of view) for self-calibration to be successful. To help shed light on this issue, we look at the 21 out of the 272 suitable VLSS sources which are also in the 1.4 GHz FIRST survey. The FIRST survey has a resolution of $5''$ and if we compare the total flux density in the FIRST images to that in the 1.4 GHz NVSS images at resolution $45''$, we can get an estimate as to how much of the flux density the LWA Phase II will see as compared to the VLSS. Our results showed that for 15 out of the 21 sources, over 90% of the flux density in the NVSS image was retained in the FIRST image. For another 4, between 60% to 90% was retained. Only one source was truly resolved out, with only a few percent of the flux density remaining. From this analysis, we conclude that about 70% of all the sources should retain nearly all the flux density of the VLSS image, while about 95% should retain a high fraction of the total VLSS flux density. Therefore we should expect roughly 380 to 510 sources to be imaged using the LWA Phase II.

The above arguments are very conservative. Our own experience with self-calibration indicates that in some cases, one can successfully self-calibrate to sources with only 1/5 to 1/3 of the total flux density in the field of view, and with only 2-3 times the peak flux density of the next highest peak in the field of view. In addition, it may be possible to use the technique of "peeling", where 1 or 2 problematic sources elsewhere in the field can be calibrated and subtracted from the *uv*-data set. Finally, even with only eight stations, it may still be possible to do some crude field-based calibration. This would probably not be sufficient for full field imaging, but may be enough to expand somewhat the parameter space of sources we could image. Therefore, the 380-510 source estimate we give above should be taken as a conservative lower limit, which estimates the number of sources we are virtually certain we can image.

7 Conclusions

We conclude that with a nine-station configuration with maximum baseline of 174 km, the LWA Phase II is a very capable instrument. At 74 MHz, it will achieve a resolution of about $4''$ and a sensitivity of about 3 mJy/beam for full track observations. It is capable of imaging typical radio galaxy morphologies with sizes up to about $1'$ at high dynamic range, and even larger objects when combined with VLA data. Using the existing 74 MHz survey data (VLSS) we conclude that we are highly likely to be able to image at least 380-510 objects and possibly many times more than that.