NGVLA Memo 128

Going Big: Enhancing the Angular Resolution of ngVLA LONG

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ABSTRACT

The planned configuration for the VLBI portion of the ngVLA project, ngVLA_LONG, is based on the VLBA configuration, which was constrained to US territory. It does not fully utilize the maximum baselines available on the Earth, especially for southern sources. This memo presents three of the many possible options to significantly improve the angular resolution. The first is to network with existing VLBI stations. As an example, which would work with the highest frequencies and hence the highest resolution observations, the coverage obtained by adding the Global Millimeter VLBI Array (GMVA) is shown. The second option is to construct a few new stations at locations chosen to enhance the UV coverage. I propose a set of 6 such stations at seemingly viable sites that I call the ASPEN array (**A**tlantic, **S**outh America, **P**acific, **E**urope, **N**orth America). This option is complimented by the LEVERAGE project to add 4 ngVLA type stations in Germany. Finally the impact is shown of adding a few southern stations that are already under consideration by the geodetic/astrometric community. With those stations, the resolution is close to being Earth limited over most of the sky, representing a significant improvement over the ngVLA by itself and allowing the ngVLA to cover very nearly the full range of baselines available from the surface of the Earth.

BACKGROUND

An option for extending the resolution of ngVLA_LONG, somewhat similar to what will be shown in this memo, was presented as an “Extreme Array” in ngVLA MEMO 84. Revisiting the ideas presented there was provoked by a couple of developments. The first was a desire to limit proposed sites to ones that are not thought to present major issues either for permission to build or for fiber access. The second development was the interest being shown elsewhere in adding stations to the ngVLA or in building new instrumentation for VLBI. The most advanced cases are the LEVERAGE project and some of the developments in progress in the geodetic/astrometric community. Other projects may develop in the future. With this memo, I hope to provide guidance on where added stations would be most useful. While it would be great if the ngVLA project could add stations with its own resources, the ability to do so may be limited. So my main hope is that this memo will help motivate and guide potential partners.

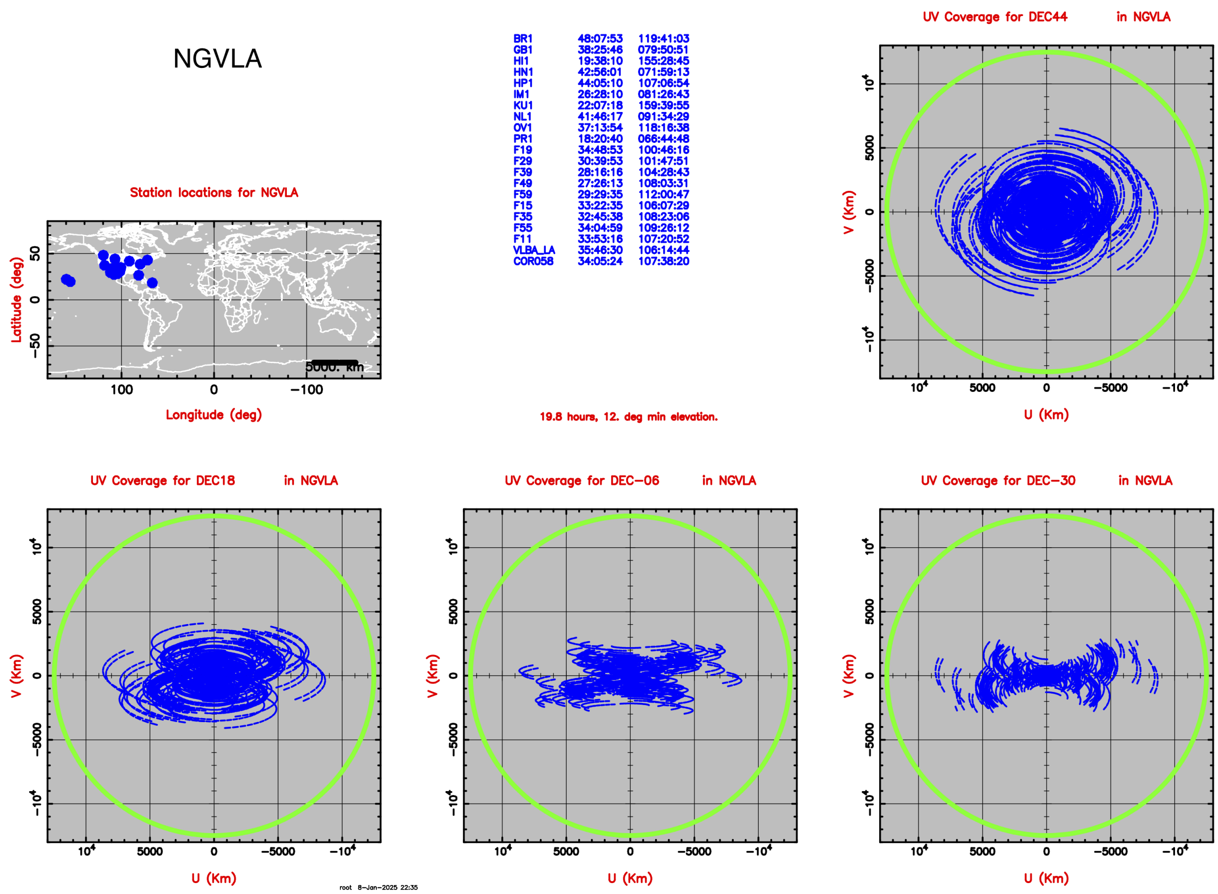

Figure 1: The UV coverage of the ngVLA_LONG plus 10 antennas of ngVLA_MID (including the outermost antenna on each arm) plus one CORE antenna. The scale is the same as is used in al the other UV figures. The declinations of the plots are 44°, 18°, -6° and -30° here and in Figures 3 and 4. The green circle represents the maximum possible baselines on the surface of the Earth using antennas with a 12° elevation limit. The tracks are based on a 24 hour schedule for which every antenna observes for as long as the source is up at at least 4 stations. In the map, the stations shown as blue dots. The map covers the full extent needed for later figures. An expanded version is shown in Figure 2.

The limitations of ngVLA_LONG are inherited from the VLBA which was subject to a US territory constraint. The ngVLA_LONG configuration is basically the VLBA configuration plus calibration partners for the outermost stations and the consignment of the shorter baselines to ngVLA_MID. US territory spans a significant fraction of the Earth's diameter in the east-west direction but is seriously constrained north-south. For an average Earth diameter of 12756 km and for antennas with a 12° elevation limit (the ngVLA design), the maximum baseline is 12477 km. The maximum ngVLA_LONG baseline is 8685 km or about 70% of the maximum. But that baseline, oriented east-west, along with the other one between Hawaii and Arecibo, is fairly isolated. In the north-south direction, the limited extent of US territory in that direction, compounded by projection for southern sources, makes the situation is much worse with the maximum baselines being around a quarter or less of the maximum possible.

Figure 1 shows a map of station locations and the UV coverage of ngVLA_LONG plus 11 stations of the inner ngVLA (MID and CORE) to fill in short spacings and spread out some of the long tracks.

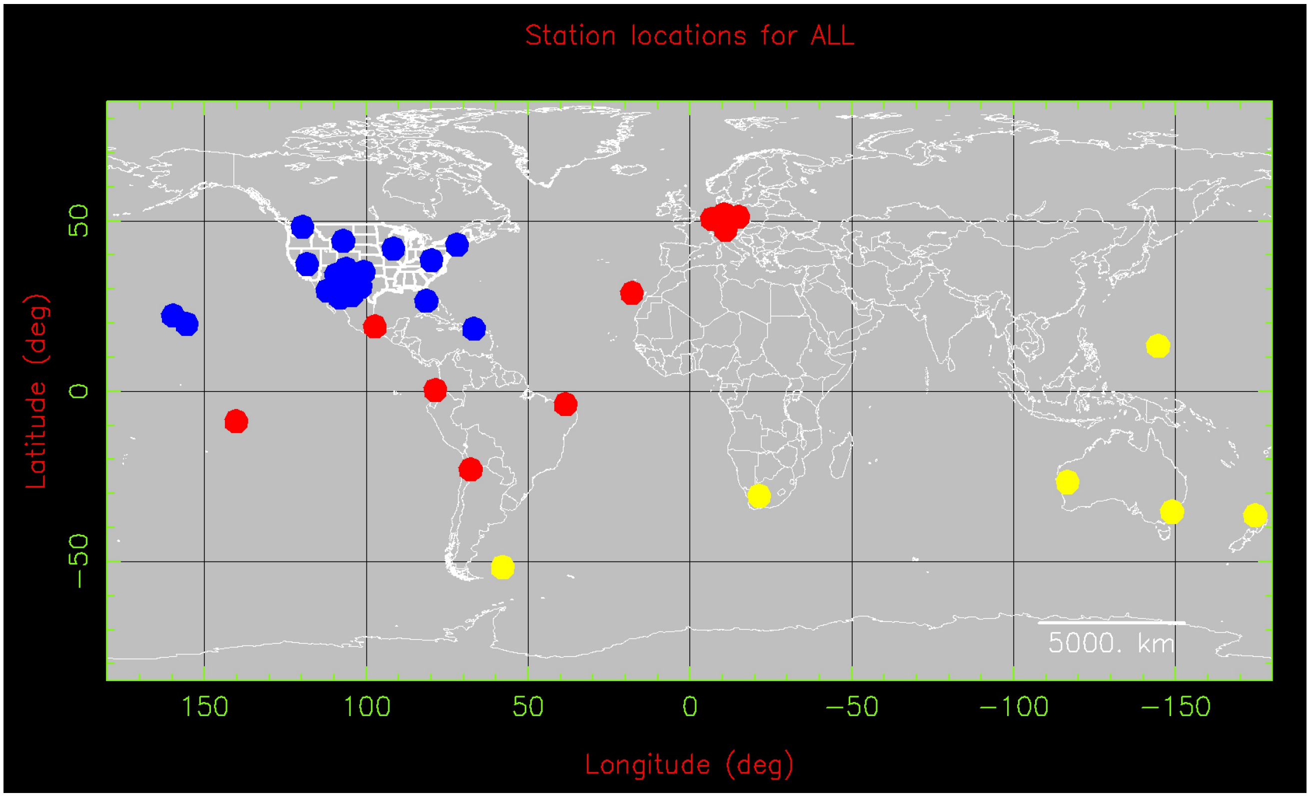

Figure 2: Large version of the map showing the station locations for the ngVLA_LONG (Blue), the ASPEN array and LEVERAGE (red) and the southern stations (yellow) discussed in this memo.

The map scale, which will be the same for all the figures in this memo, shows the whole Earth as will be more appropriate when other stations are included. For reference, Figure 2 shows an expanded version of the map with all the new stations (ie, not the GMVA) discussed in this memo marked. In Figure 1, there is a large green circle on each UV plot that, with a radius of 12477 km, represents the longest baselines possible with antennas with the 12° elevation limit of the ngVLA antennas. The tracks are for what is possible consistent with self-calibration. Each baseline is tracked for the entire time that at least 4 stations can see the source. All of the other plots in this memo are built in the same way and all have everything that is in Figure 1 plus what is added by adding stations.

There are many ways that one could try to improve the coverage of long baselines by adding stations. Only three will be shown in this memo, but they are three that should be meaningful and representative of what is possible. One is an example of working with existing observatories. Another involves new stations designed as ngVLA additions to significantly improve the long baseline coverage, but not attempt to pick up the far south or the very longest possible baselines. The final one takes that array, with the new stations, and adds to it stations in the south that others are considering building for their own reasons, but that could work well with the ngVLA. That is the one that comes close to providing the full range of baselines, in all azimuths and at all declinations, that is possible from the Earth.

All attempts to enhance the long baselines run into some troublesome geographic constraints. The main one is that ideally one could put stations more-or-less due south of the ngVLA center. But one quickly runs into a very large, empty region of the Pacific Ocean where the labels on globes are normally put. The Galapagos and Easter Island are the closest land to that region which is why they

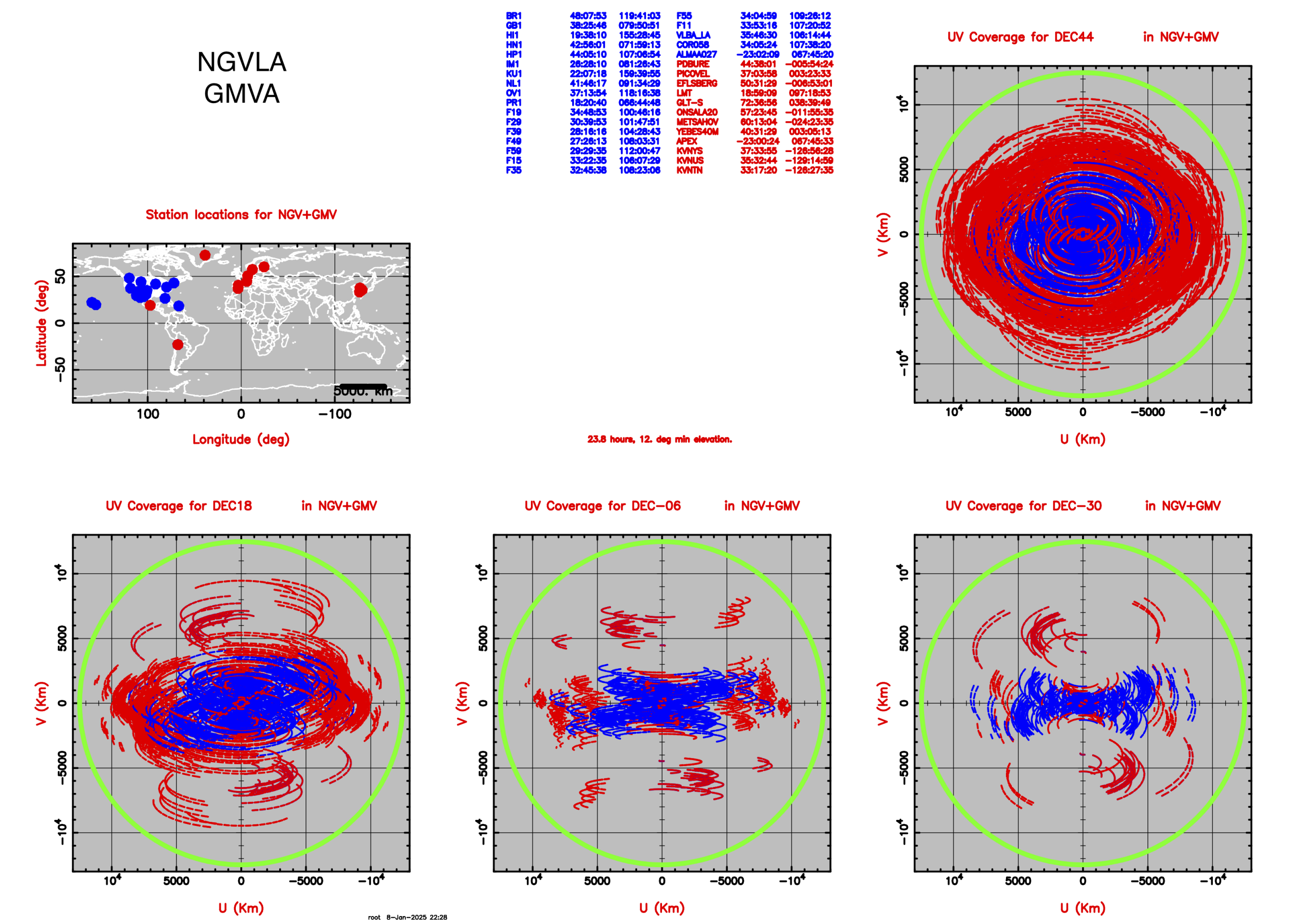

Figure 3: The UV coverage of the array shown in Figure 1 plus the stations that were in the July 31, 2024 GMVA Call for Proposals plus ALMA, LMT, and GLT, collectively referred to here as the GMVA. The GMVA antennas are in red and all baselines to them are in red while the ngVLA antennas and baselines in blue are the same as those in Figure 1. The coverage shown are for the full time that at least 4 stations can see the source.

were used in ngVLA Memo 84. But this memo shows what can be done without them.

NGVLA PLUS GMVA

One way to increase the resolution of the ngVLA would be to facilitate the use of existing radio observatories to complement the UV coverage. This is the network model that dates back to the beginnings of VLBI, well before any dedicated arrays were built, and is still in use for much of current VLBI. The advantage is that new antennas do not need to be funded and built. Also some of the existing antennas are larger and more sensitive than those at the dedicated array stations. The disadvantages are that every antenna is different and subject to a mix of scheduling constraints. Calibration can be difficult and dynamic scheduling to make sure that the observing programs are appropriate for the weather conditions can be problematic.

As an example of the impact of including existing antennas, the possibility of using the Global Millimeter VLBI Array (GMVA) with the ngVLA is considered. The highest angular resolution of the ngVLA will be achieved at the highest frequencies. That is in Band 6 which covers 70 to 116 GHz. It is possible to do VLBI observations today in that band using the GMVA. The most recent call for proposals was distributed on July 31, 2024. The telescopes prepared to participate are 8 antennas of the VLBA, the GBT, APEX, EFFELSBERG, PICO VELETA, NOEMA (Plateau de Bure), ONSALA, METSAEHOVI, YEBES, and the 3 antennas of the KVN. In addition, ALMA, the LMT, and the Greenland Telescope (GLT: currently at Thule, but to be moved to the icecap station used here) are used in current VLBI (eg. EHT) and could be used at 86 GHz. For the rest of this memo, “GMVA” will mean all of these telescopes except the GBT and VLBA stations, which are already at ngVLA sites and thus are included in Figure 1. Figure 3 shows the UV coverage provided by adding the GMVA to the ngVLA with the added stations and UV tracks shown in red. The GMVA telescopes increase the coverage in the empty parts of the UV plane in Figure 1 by a significant amount. But most of the stations are in Europe so the additions for southern sources are rather sparse. The benefit is mainly in the northern sky where the density of long baselines is much increased.

It might be useful to remember that the two sources in which a ring has been seen around a supermassive black hole, M87 and SGRA*, are at +12° and -29° declination respectively. Those are the sources where there will be great interest in observing the interaction of the jet and the inner disk/ring in the region where the jets are launched. Such observations require the highest possible resolution. For M87, the GMVA will help significantly. For SGRA* the added baselines will help to roughly define the structure, but will be marginal for very high resolution imaging of complex structures because of the big gaps at intermediate spacings. For declinations below about -60° only ALMA and APEX can observe and those two are at effectively the same location on VLBI scales, so there is no long baseline coverage.

NEW STATIONS: ASPEN ARRAY AND LEVERAGE

The UV coverage for an array that is the array of Figure 1 (ngvla_LONG plus 11 inner ngVLA antennas) plus 6 stations chosen for their UV coverage plus the 4 stations of LEVERAGE is shown in Figure 4. I am calling the 6 stations the ASPEN array[1]. For the combined array of Figure 4, the coverage is close to round at all declinations and the longest baselines are between about 64% and 95% of the maximum possible. There is a region north and south of the center at lower declinations that is not as well covered as one might like. That is the result of the big empty area of the Pacific Ocean south of the center of the ngVLA. The stations of the ASPEN array are:

Marquesas, French Polynesia: The site used for the UV plots is on the island of Nuku Hiva. There is a cross-island road that gets to over 1100 m (3800 ft). There appears to be a submarine cable to Tahiti and another directly from Tahiti to the big island of Hawaii. The Marquesas are about 1400 km NE of Tahiti, which is the white dot on the maps in the figures SW of the Marquesas. Using the site closer to the array center, rather than Tahiti itself, works better from a UV point of view, but Tahiti would be a viable option and likely has better infrastructure. NASA is cooperating with France to install a 12-m VGOS antenna in Tahiti (https://science.gsfc.nasa.gov/earth/geodesy/projects/521). French Polynesia is a semi-autonomous French territory. If France were interested in providing an ngVLA station, this would be a much more useful location than adding another to the tight cluster already in Europe.

Ecuador or Columbia: A site near Quito is used as a place holder for this site. Both Quito and

1: When trying to come up with a name for this array, I tried for an acronym of Pacific, South America, North America, Atlantic, and Europe. I fed the letters to a web site that makes words out of groups of letters. When it came up with ASPEN, I jumped on it having, only days before, made reservations at Aspen, Colorado, for a ski week this winter.

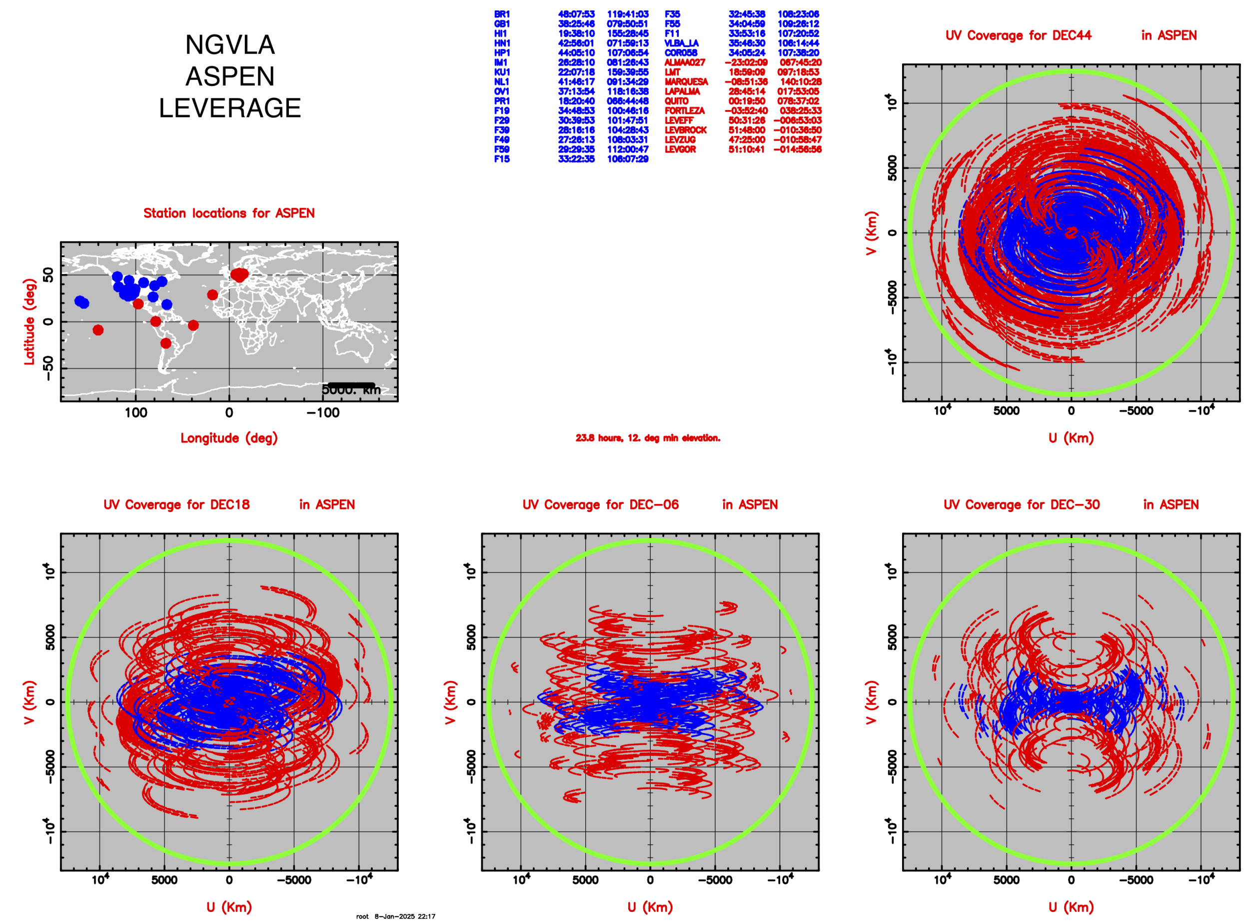

Figure 4: The UV coverage for the ngVLA_LONG plus the stations of the ASPEN Array and of LEVERAGE. The stations added to the array of Figure 1 are described in the text. As before, the green circle shows the maximum possible baselines. The red dots on the map show the locations of the added stations while the tracks added by those stations are also shown in red on the UV plots. The UV coverage is rather better, especially at low declinations, than when the GMVA stations are used which is not surprising given that these station locations were chosen to enhance that coverage. The UV tracks shown are for the full times that 4 or more stations could see the source.

Bogota are at high elevations. It should be possible to be over 3000 m near these capital cities or at many other locations in the general vicinity. There is a local project in Quito to refurbish an old 32m tracking antenna for radio astronomy use (https://oaq.epn.edu.ec/index.php?option=com_content&view=article&id=376&catid=2). This, along with an IAU Symposium on Jets held in 2014 in the Galapagos, shows that there is interest in radio astronomy in the area. Slightly better UV coverage could be obtained by placing this station in the Galapagos, but the elevation would be much lower and there might be problems obtaining permission to build.

ALMA: High, dry site hosting the premier mm astronomy instrument in the world today in which NRAO is a major partner. ALMA (https://public.nrao.edu/telescopes/alma/) participates in the Event Horizon Telescope (EHT) observations and, even without new antennas, could be used with the ngVLA in the overlapping frequency bands between 35 and 116 GHz. Given the that highest ngVLA observing frequency is much lower than that of most of the ALMA bands, it might be worth considering locating an ngVLA station near the Operations Support Facility to ease the logistics. The

ALMA vicinity could be a natural location for an ngVLA station provided by any of the ALMA partners.

LMT: This is the Large Millimeter Telescope (http://lmtgtm.org/) located on the summit of Volcán Sierra Negra at an elevation of 4640 m (15,220 ft) in Mexico. This site has astronomy infrastructure and access to high elevations. It currently participates in EHT observations. Ideally an ngVLA station would be located close to the LMT to enable paired antenna calibration. If that is not feasible, it could go somewhat lower. There is considerable area above 4000 m (13,000 ft) in the vicinity including the location of the HAWC gamma ray and cosmic ray observation facility.

Fortaleza, Brazil: This is the site of an existing geodetic VLBI station. The station is slated to receive a new, modern geodetic VLBI antenna as part of the NASA Space Geodesy Project (https://space-geodesy.nasa.gov/). Haystack is building the signal chain. This station is close to the equator (latitude -4°), at low elevation (about 23m), and in a semi-urban environment. There are some hills of up to around 700-800 m height a few km to the south that could have better observing conditions and some protection from RFI. They should be investigated. In any case, using a station in the area at high frequencies will require special care, much like Arecibo, VLBA_SC, and Florida. It is likely that paired antenna calibration along with very small spacings between antennas would be required.

La Palma in the Canary Islands: There are extensive optical astronomy facilities at the site. The elevation is around 2400 m (7700 ft). A new geodetic VLBI antenna that is part of the RAEGE project (https://raege.eu/granc/) of Spain and the Azores is scheduled to start construction on Gran Canaria at around the time this memo was written. The 4 antennas of that project will operate in conjunction with GGOS. The Canary Islands are are an autonomous community of Spain. If Spain were to develop an interest in adding an ngVLA station, perhaps associated with LEVERAGE, this would be a good place to do it.

LEVERAGE is a German project to build 2 to 4 stations, each with 4 ngVLA antennas, across Germany. It is meant to be used with the ngVLA and SKA to enhance UV coverage. It could be used with the EVN and the GMVA. It is also meant to be used as a stand-alone array for transient studies and monitoring. The LEVERAGE station locations used here are those used by the proponents for simulations and were kindly provided by Florian Eppel of the University of Würzburg. The first antenna/prototype for LEVERAGE will be the Wetterstein Millimeter Telescope, announced recently (https://www.uni-wuerzburg.de/en/news-and-events/news/detail/news/ein-teleskop-der-weltspitze/). Matthias Kadler, also of JMU Würzburg is a good contact concerning LEVERAGE. For more about LEVERAGE, see Kadler et al. 2025, Proceedings of the 16th European VLBI Network Symposium, Ros, E., Benke, P., Dzib, S., Rottmann, I., & Zensus, J.A. (eds.), September 2nd-6th 2024, Bonn, Germany (to be published soon).

ADDING SOUTHERN STATIONS

The UV coverage obtained by adding some more southern stations to the ASPEN array is shown in Figure 5. Note that the sources used in this figure are biased farther south than in the other figures. The stations used are approximately ones being considered for an enhanced geodetic/astrometric array to deal with the relative sparsity of good data for that science both in the geographic and the celestial south. The general locations used for this plot are New Zealand, Eastern Australia, Western Australia, South Africa the Falkland Islands (Islas Malvinas) and Guam (north of the equator but useful here). As place holders, the existing radio facilities Warkwort (NZ), Canberra, ASKAP, and SKA are used for their regions. In Figure 5, the blue sites on the map and the blue baselines are for the ngVLA, ASPEN,

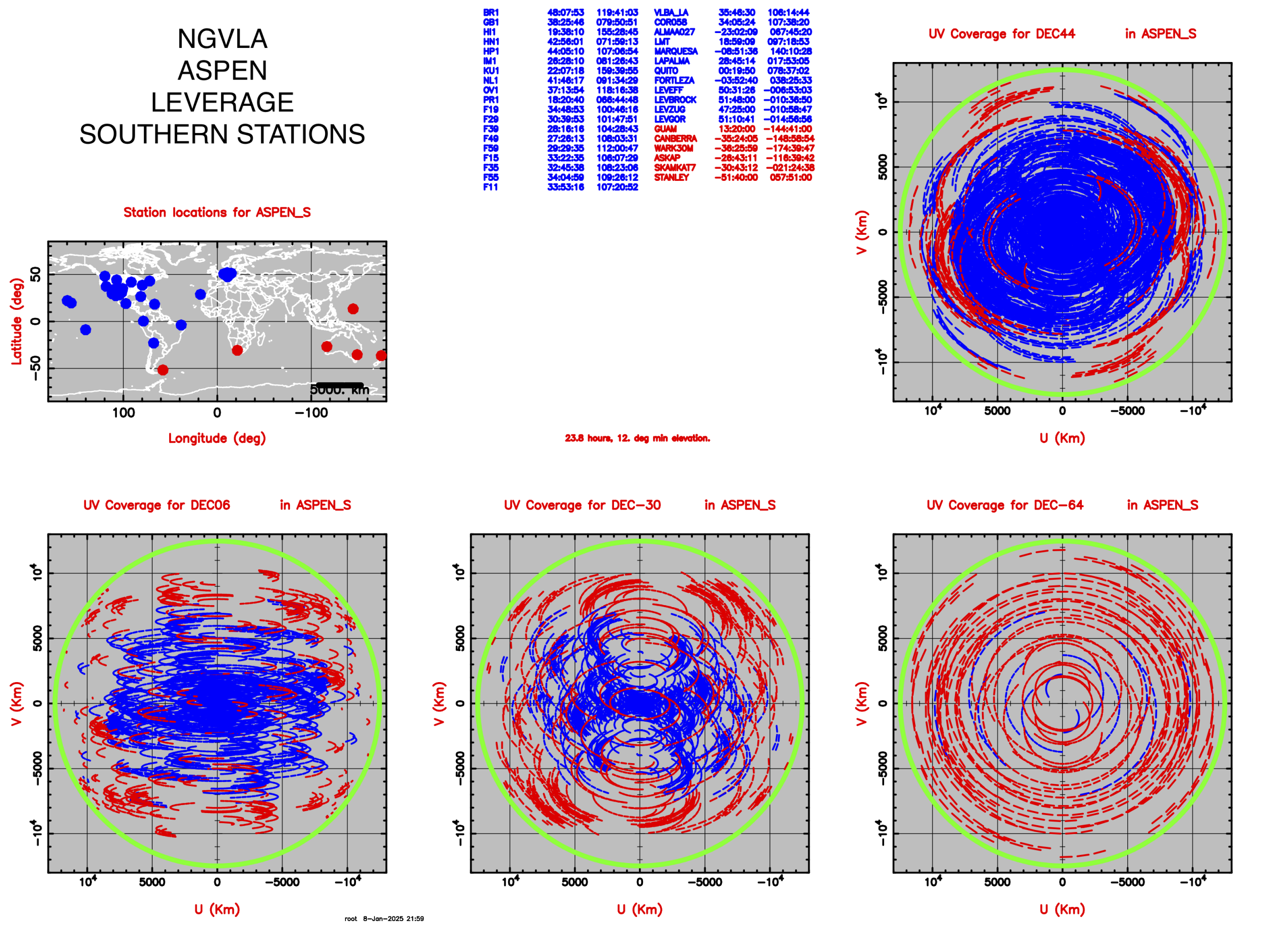

Figure 5: The UV coverage of ngVLA_LONG with the ASPEN Array and LEVERAGE, all in blue on the map and the UV tracks, and six additional stations in red that are in the south. The southern stations, except Guam and Stanley (Falklands), are at the sites of currently-active VLBI stations. All of these locations, or somewhere nearby, are under consideration for a geodetic/astrometric array with good coverage in the south. Again the green circle denotes the maximum baselines available from the surface of the Earth with a 12° elevation pointing limit. Note that the source declinations for this plot (44°, 6°, -30° and -64°) are not the same as in the previous figures in order to place more emphasis on the southern declinations. If this option becomes available, the resolution in all directions and at all declinations would be close to the limit for a ground array. Note the reasonably good coverage, except of very short baselines, for the source that is too far south to be seen by any of the planned ngVLA stations. Usable UV coverage should extend all the way to the celestial south pole.

and LEVERAGE stations. The red dots and tracks show what is added by the southern stations. The geodesy/astrometry community has a requirement for better sky coverage in the south so there is a good chance that stations such as these will be built. The maximum baselines with these additions are now close to the best that can be obtained from the Earth's surface in all directions and at all declinations.

One problem with the array of Figure 5 is that there is very poor coverage of short spacings at declinations too far south for the ngVLA to see. That will inhibit good imaging. Fixing it should be possible with either additional existing or new antennas or with the SKA in the overlapping frequency bands. A single station about half way across Australia, for example, would help considerably. This issue will not be explored farther in this memo.

GENERAL CONCERNS AND COMMENTS

One criticism I've heard about ngVLA LONG is that it does not represent much of an improvement over the VLBA. The number of stations is the same, and the UV coverage is similar. The answer I usually give is that, when you add a number of ngVLA MID stations, the coverage and sensitivity is much better. But if the additions suggested in the memo could be added, the answer would be clear. The UV coverage at the longest baselines, and hence, the resolution, would be greatly improved, especially at low declinations.

All of the stations of the ASPEN array are either near significant population centers that presumably have fiber access (Quito, Fortaleza), are in places where I have specifically read that there is fiber (Marquesas and Tahiti) or are near observatories that probably have, or will have, fiber access (ALMA, LMT, La Palma). But whether adequate and affordable bandwidth could be obtained would need to be investigated. In principle there is the time honored VLBI method of using recordings, either with shipping or with buffering and spooling back at lower rates. But that gets very complicated with a system like the ngVLA, so I don't propose to explore it farther in this memo.

Any study of the UV coverage of arrays is faced with a more-or-less infinite number of options. For VLBI arrays, there are also serious geographic constraints. To keep this memo manageable, there are many options that I have not considered including:

Joint observations with the EVN: The European VLBI Network has many participating stations concentrated in European nations but including South Africa and stations extending across Russia to China, Japan, and Korea. But, other than those stations also in the GMVA, it does not cover the high frequencies of the ngVLA. At lower frequencies and high declinations, impressive coverage could be obtained with joint observations. As each antenna has a different suite of receivers, the coverage would be frequency dependent.

SKA: In the era of the ngVLA, the SKA will also be in operation and could in principle be used along with the ngVLA at the overlapping bands. The geography is such that there is poor mutual visibility between the SKA and the ngVLA so, except that it is included in Figure 5, I have not included SKA in the extended ngVLA_LONG options. The SKA project does intend to include VLBI capabilities. An option might be for the ngVLA and SKA to share some outer stations. It would be best if such stations were designed from the start to be compatible with both instruments.

Other VLBI arrays: There are other groupings, some overlapping, of antennas used for VLBI, such as the AVN (African VLBI Network), the LBA (Long Baseline Array in Australia), the EAVN (East Asia VLBI Network), the KVN (Korean VLBI Network), and VERA (VLBI Exploration of Radio Astronomy in Japan). Plus there are a number of geodetic/astrometric stations active in VLBI. I have not attempted to explore the joint use of these networks with the ngVLA but such joint use would certainly be possible at many observing bands.

All of the UV plots in this memo are for long tracks to show the maximum that could be obtained with the constraint that at least four stations can see the source at any given time to facilitate self calibration. The single-scan snapshot coverage with ngVLA + ASPEN + LEVERAGE was checked and is fairly good. But that is probably not how observations would be done. With multiple scans, even only 3 at about 4 hour intervals, the coverage is rather good. With the southern stations, a single scan snapshot is not so good because of the wide longitude spread of the antennas. Several of the southern antennas cannot see the sources in a snapshot centered over the ngVLA CORE.

SUMMARY

This memo[2] presents the UV coverage for collections of extra antennas meant to extend the angular resolution of ngVLA_LONG. Adding the existing GMVA antennas, plus ALMA, LMT, and GLT, can do a reasonable job in the north, but leaves large UV holes at medium baselines for southern sources. As an alternative, a set of six possible station locations has been identified that, with the ngVLA, provide good, nearly-round coverage for resolutions of about 70% of what is possible from the Earth's surface. These stations are collectively referred to as the ASPEN array. All of these locations appear to have reasonable infrastructure and half have telescopes in the area that already do VLBI. These are complemented, especially in the northeast/southwest direction, by the LEVERAGE project to add 4 ngVLA stations in Germany. That project seems to have significant support and appears to stand a reasonable chance of being built. Finally, the geodetic/astrometric community is considering building antennas to provide good coverage for the geographic and celestial south. With six of the sites that are under consideration, four located near existing facilities currently capable of VLBI observations, the longest baselines are rather close to the maximum allowed by the size of our planet. If those stations are built, and have the capability to operate with the ngVLA, the ngVLA will be capable of good quality observations over nearly the full range of resolutions possible from the Earth's surface.

2 The originally submitted memo had figures which, due to an oversight, showed UV tracks based on a 15° elevation limit. The revised version (Jan 8) shows UV tracks based on the 12° elevation limit of the ngVLA antennas. The text was not changed except one typo and the UV plots show only very minor differences.