NGVLA Memo 84

The NGVLA Long Baseline Array: Configuration Suggestions

R. Craig Walker (NRAO)

October 4, 2020

ABSTRACT

This memo presents some configuration options for the Long Baseline Array (LBA) portion of the NGVLA. The first section considers the concept of station pairs for robust self calibration of isolated stations. The reference configuration has four such pairs at the outer sites. This is an area for more careful study, but my sense is that the separation of pair members should be a few hundred to roughly a thousand km so that the baseline is in the well-calibrated regime in stand-alone LBA observations. One consequence is that the VLBA_HN and Westford stations are too close to each other. But the separation of VLBA_HN and Green Bank is in the appropriate range. So I suggest moving the Westford station to Green Bank. This has a variety of other advantages which are mentioned. The next section deals with the concern that the number of stations in the LBA on longer baselines is no greater than the VLBA, for which imaging complex sources can be difficult. I suggest an enhanced array with one additional station in each of the United States, Canada, and Costa Rica and 2 additional stations in Mexico. With this array, the UV coverage is much improved and even the snapshot coverage is reasonable, including when all of the MID stations are left out. The final section presents a bold – perhaps too bold – suggestion for a configuration that provides a large improvement in resolution and a huge improvement in southern-source UV coverage at the cost of significant logistical complications. That suggestion is intended to plant the seeds of ideas for future NGVLA enhancements rather than being a serious suggestion for the initial project.

BACKGROUND

The main motivation for this study was a long standing worry on my part that the LBA configuration had not received much attention beyond what had gone into the original VLBA configuration design. I was also asked by project management to look at some specific configuration issues. The NGVLA plan involves a vast increase in the number of antennas over previous practice on the VLA and VLBA, but not much was being planned to enhance the long baseline coverage other than the huge improvement in the short baselines provided by the smaller parts of the NGVLA. The only real change was the addition of the pair partners for Mauna Kea (VLBA_MK; or where ever that station winds up), St. Croix (VLBA_SC), Hancock (VLBA_HN), and Brewster (VLBA_BR). Those partners greatly extend the range of spacings to each outer antenna to improve self calibration. They also provide a few short spacings when the LBA is used on its own. But they do not alter the UV coverage much. For more information about the current reference array configuration (RevC.01), see NGVLA Memo 82.

For this study, I used my usual tools as described in NGVLA Memo 49. The plots were made with SCHED and I used Google Earth to look for reasonable sites. The station locations suggested in this memo are far from the NGVLA core and thus are rather flexible from a UV perspective. Changes of 100 km or more would not change the UV coverage significantly. The first panel in the plots shows a map with the station positions shown as blue, red, or yellow dots. The tracks for baselines between a red station any other active station are plotted in red on the UV coverage plots. The tracks between blue stations are plotted in blue. Yellow stations are inactive – baselines to such stations are not plotted in this plot although they are in the station list and are used elsewhere in this memo. The second panel is a list of the stations used with their latitude and longitude. The rest of the panels show the UV coverage for four sample declinations, 44, 18, -6, and -30 degrees. The minimum elevation is set at 15 degrees. Note that, at -30 deg (galactic center), the more northerly stations cannot see the source. Long tracks are scheduled for 12 hours, centered on transit at the NGVLA core, but are cut off on the ends if less than 5 stations are above the elevation limit of 15 deg. The tracks are arbitrarily shown as a series of 12 minute scans with 8 minute gaps, so they show up as dashed lines.

On the scales of the NGVLA CORE, SPIRAL, and MID arrays, the station locations are constrained by access and infrastructure. There are some regions, such as cities and wilderness areas, that need to be avoided. On the scale of the LBA, there are some rather rigid constraints imposed by the oceans. There is nothing dry between Hawaii and the mainland, so long NE/SW baselines with any visibility to the south are hard to achieve. Also the Atlantic imposes restrictions on long E/W baselines to the CORE for equatorial sources. There are fuzzier constraints imposed by the desired observing conditions for the high frequencies which can be observed by the NGVLA. Low latitude, low elevation sites are likely to be a problem at the highest bands. Partly for this reason, the current VLBA_SC site is not outfitted with 86 GHz receivers and so cannot participate with the rest of the VLBA at that band (VLBA_HN also does not have 86 GHz but that is mainly because of unfixed antenna surface issues). Some of the suggested stations here will likely be poor at the highest frequencies. I don't know any way to deal with the UV issues they address with better observing sites. Note that even poor stations can be used when self-calibration is possible or if WVRs work well. It is mainly phase referencing (astrometry and weak sources) observations that are problematic. For reference, my M87 VLBA observations at 43 GHz worked acceptably well at VLBA_SC thanks to the ability to self-calibrate on time scales of a few seconds.

For this study, I have used a subset of the MID array to cover short spacings. For the plots, I show 10 inner antennas consisting of the four VLBA antennas, VLBA_KP, VLBA_PT, VLBA_LA, and VLBA_FD, that are included in the MID array, one antenna from the core (M130), and a selection of five drawn from the MID array design presented in VLBA Memo 49. Those five could just as easily been drawn from the reference design without significant effect on the topics of this memo. Using 10 MID antennas is enough to show the effects of the concentration of antennas toward the middle. Of course, the final array could be used with all of the MID stations for much denser coverage on the center to outer station baselines, or it could be used with only a few or even no MID antennas. The effects of leaving out all MID antennas is shown later in this memo.

REFERENCE PLOTS

Figures 1 and 2 show the UV coverage of the reference array on a 9300 km maximum scale. These

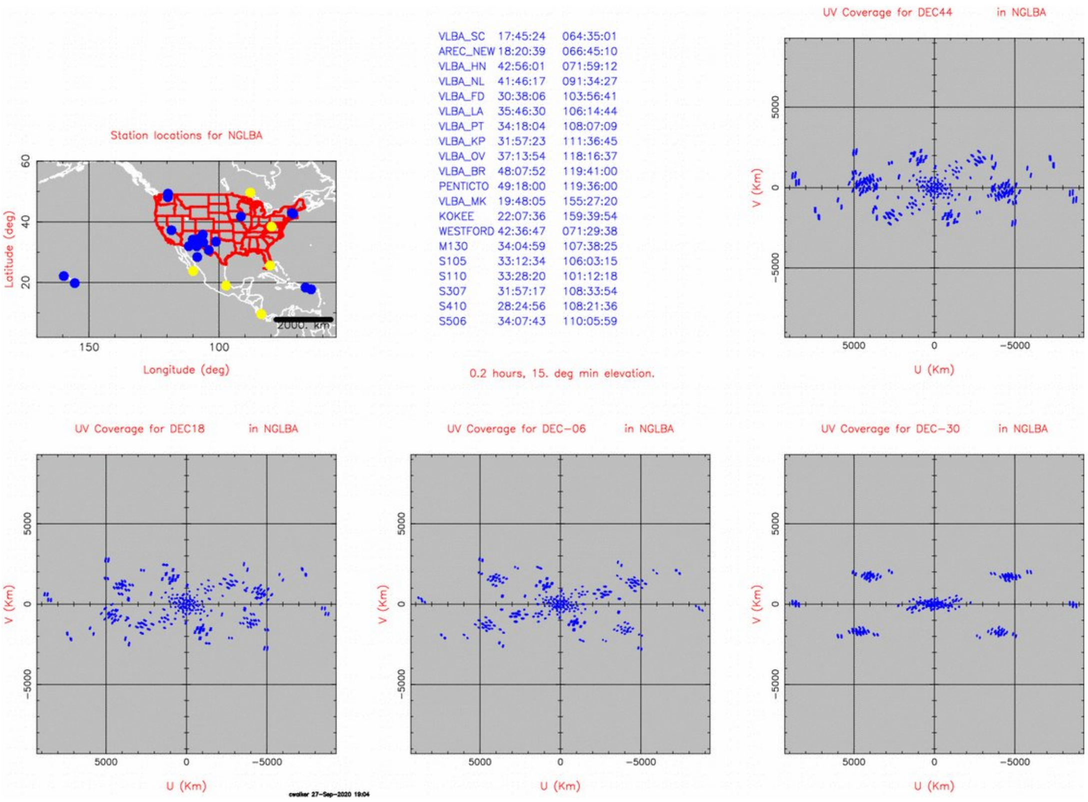

Figure 1: Snapshot coverage of the reference configuration of the NGVLA LBA. This is a single scan of 12 minutes centered at transit at the NGVLA center.

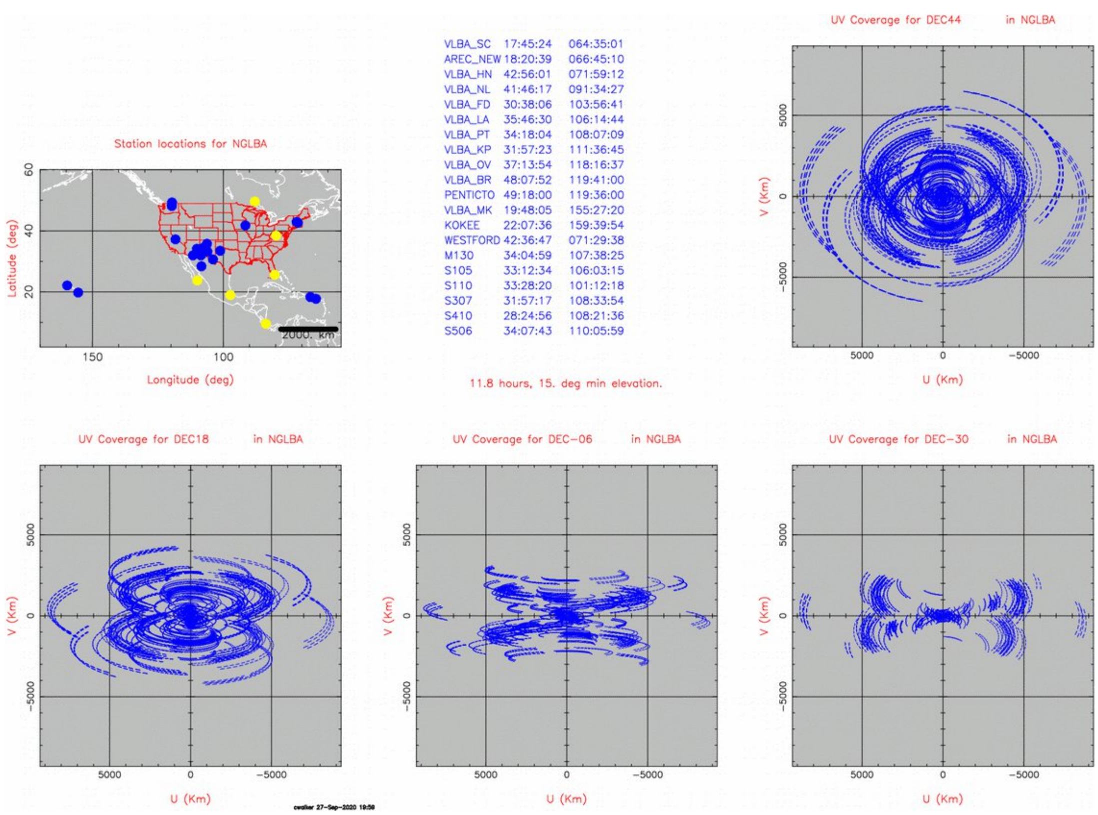

Figure 2: Full track coverage of reference configuration of the NGVLA LBA. This is up to 12 hours as long as 5 stations are above 15 deg elevation. There are 12 minute scans with 8 minute gaps.

plots are for comparison with those that come later. The short baselines are covered as described above with 10 antennas of the MID array, including 4 VLBA stations. Figure 1 shows the reference array used in a snapshot mode of one 12 minute scan. Figure 2 shows the reference array in a long track mode. The track is up to 12 hours long, limited at lower declinations by a requirement that at least 5 antennas are above a 15 degree elevation limit imposed for these plots. The actual antennas can go below that, but calibration gets difficult. Note that the use of several snapshots spread in time can provide coverage more like the long track, although not as dense. One obvious effect of the central concentration of antennas is the prominence of the clusters of baselines between the outer stations and the antennas from the MID array. This is even more pronounced if one uses all of the MID array or, in an extreme case, the whole NGVLA. To first order, the coverage of those dense clusters of UV tracks to the center is most of what matters. That is where the sensitivity is concentrated.

PAIRED STATIONS AND GREEN BANK

If you look at the UV coverage of the VLBA or the NGVLA LBA without the paired antennas, there is essentially no overlap between the VLBA_MK baselines or the VLBA_SC baselines and other baselines in the array. This is shown in Figure 3 which does not include Kokee or Arecibo, the pair partners for those two outer stations. The figure shows all of the baselines between either of those outer VLBA stations and any other station in red. All baselines not including either of the outer stations are shown in blue. The division between the groups of baselines is stark, with the separation at about 3000km. VLBA_MK and VLBA_SC don't have shorter baselines. The rest of the array doesn't have longer baselines. This means that the amplitude calibration for those two stations is pretty much free to float relative to the other stations, affecting the derived source sizes. This appears as the common effect in self calibration where the shortest baselines are lowered in amplitude and the longest are raised relative to where they probably should be (seen often in my M87 data). In the NGVLA LBA reference configuration, this issue is addressed by providing new stations (Kokee and Arecibo) near the outer VLBA stations so that there is at least one baseline to every station that falls in the lower end of the overall baseline range. The same issue applies to HN and BR to a somewhat lesser, but still significant, degree. So those antennas also have pairs in the LBA.

One question that has not been studied to my knowledge is the optimal spacing for a calibration pair. If it is too short, it will be seeing structures that are not well imaged by the array and therefore not so good for self calibration, unless similar baselines are provided by the MID or smaller parts of the NGVLA. If it is too long, the problem is not fixed. My educated guess is that the separation should be in the range of about 400 to 1200 km where the VLBA baselines are typically well calibrated. Without a proper study, these limits are very fuzzy.

Looking at the planned pairs, VLBA_MK to Kokee is 508 km so that is good. VLBA_SC to Arecibo is 239 km - short but probably ok and there aren't many options. VLBA_HN to Westford is 54 km, which I claim is too short. Besides, Westford still has the problems that drove us away when building the VLBA, namely proximity to Boston and the presence of powerful radars on other antennas at the site. BR to Penticton is 130 km, a bit uncomfortably short. BR to OV is 1215 km which is on the outer edge of my guessed range, but it is north-south where the coverage of the inner antennas is worse (shorter), so it tends to be outside the well covered region. So I am on the fence about whether the pair for BR is needed, and if so, if Pentiction is good. Of course an option might be to keep Penticton for partner relation reasons and to escape the low elevation plus the extensive satellite antenna farm on the hill

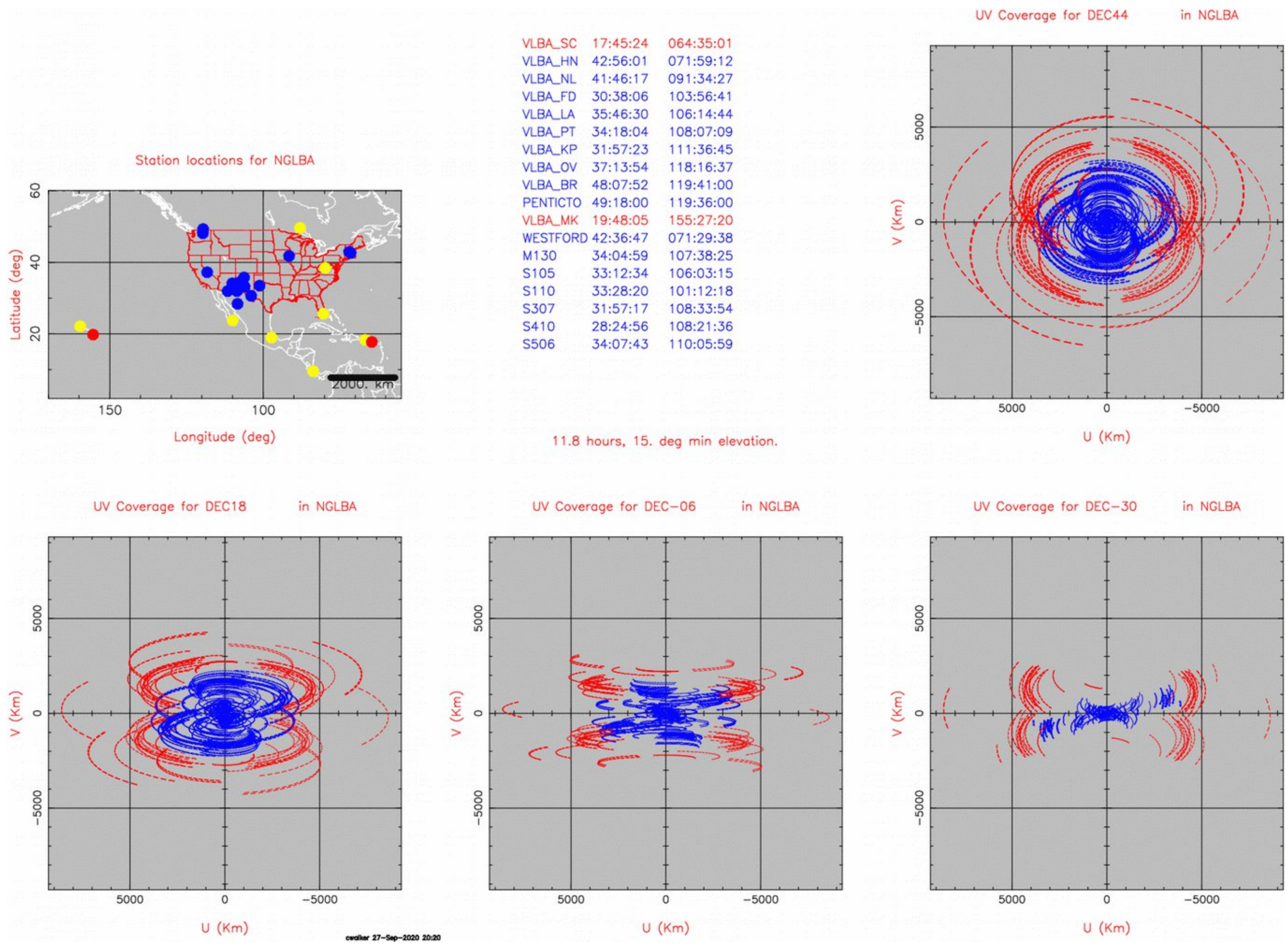

Figure 3: The full-track UV coverage for the NGVLA reference configuration but with Kokee and Arecibo, the antennas paired with VLBA_MK and VLBA_SC, removed. All baselines to VLBA_MK and VLBA_SC are shown in red. All others are in blue. Note the almost complete separation of the red and blue baselines. This is a problem for self-calibration, especially of amplitudes.

above VLBA_BR by moving that VLBA station.

VLBA_HN to Green Bank is 830 km which is nicely in my guessed optimal range. Plus a station in Green Bank would be easy to support, would aid with phase calibration of the GBT when that huge collecting area is used for VLBI, and perhaps provide other opportunities for use by the Green Bank staff and users. Also, GB to VLBA_NL is 1065, which is also in my guessed optimal range to assist self calibration. So Green Bank can serve as a self calibration pair for two other stations. For an added bonus, as is shown below, Green Bank enhances the UV coverage of the LBA. For these reasons, I recommend that Green Bank be used as the site of the self calibration partner antenna for VLBA_HN (and VLBA_NL) instead of Westford.

Note that I do not address the question of how many antennas should be in the Green Bank station. There should be at least as many as at the other outer stations to aid in paired antenna phase calibration, which uses antennas as close together as possible to have a shared atmosphere. They should also be close to the GBT, also for phase calibration. But whether there are more antennas for use for some sort of imaging with the GBT or perhaps for pulsar timing or other science, I will leave up to the GBO staff and the community.

CONFIGURATION ENHANCEMENT

The UV coverage of the reference design for the NGVLA only improves on the coverage of the 10 station VLBA because of the potential big improvement of short baseline coverage with the MID array and because of the paired antennas on the long spacings. Otherwise, on the larger scales, there are still significant holes. The coverage is not up to the standards of the rest of the NGVLA. Here I suggest some additional stations that can improve matters.

One issue with the current configuration is the missing baselines in an East/West direction in the equatorial region on the longer spacings. The oceans prevent a really good fix, but better can be done. Figure 4 shows the effect of adding stations at Green Bank and southern Florida. For the Florida station, I have used the location of the old geodetic station at Richmond. But that site is in a very urban environment and there is considerable flexibility to pick a site anywhere in Florida south of about the latitude of Orlando. Since there is no high ground in Florida, this station would likely have observing conditions comparable to VLBA_SC. Low frequencies should be ok, baring big RFI problems. At high frequencies, it may only contribute significantly when self calibration on short averages is possible or if WVRs work well. The Green Bank and Richmond baselines are shown in red. Note that all of the pair stations, including Kokee and Arecibo, are included in Figure 4.

The remaining new stations address the north-south coverage. These stations are all outside the United

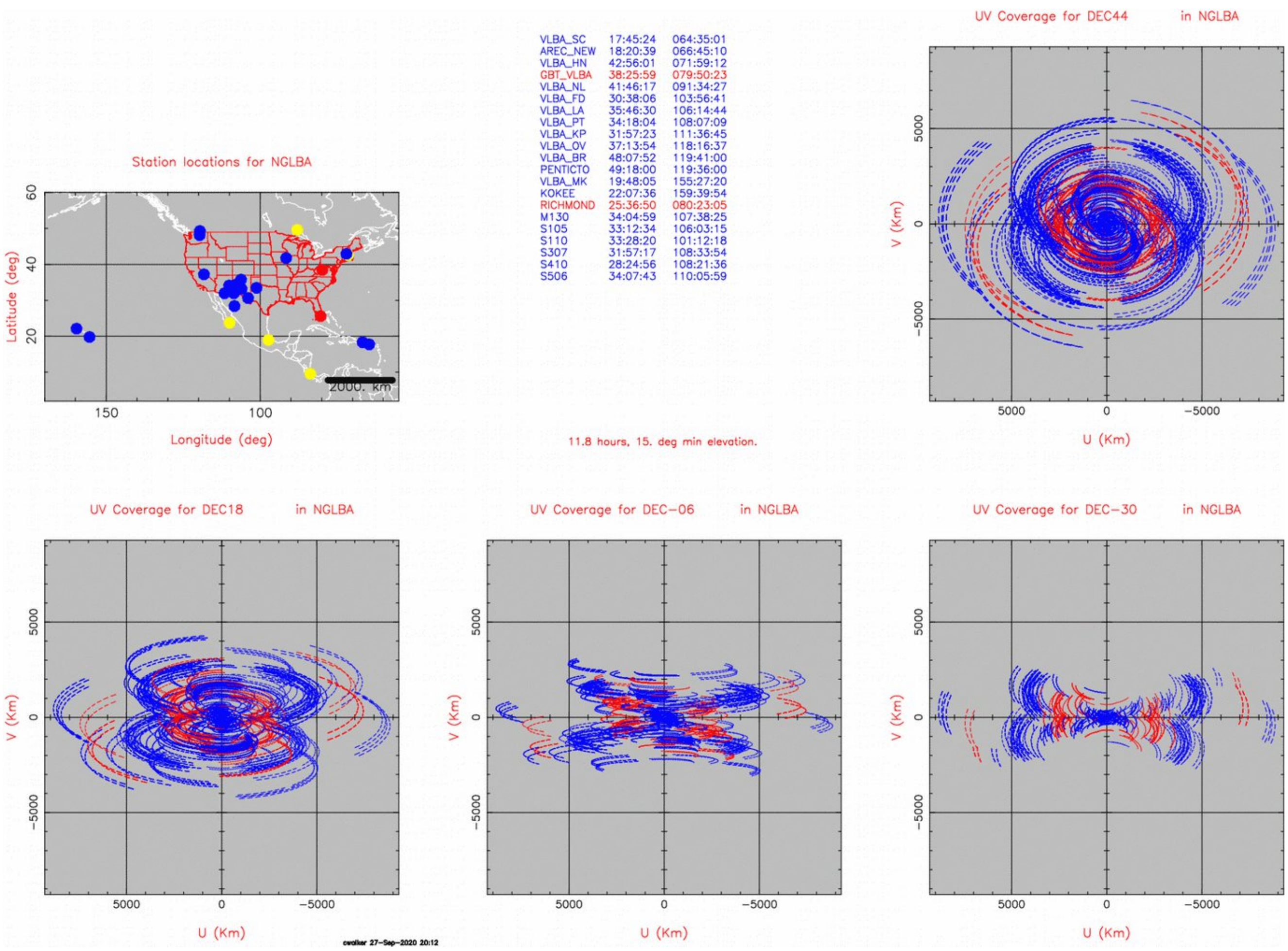

Figure 4: The UV coverage of the NGVLA LBA with new stations at Green Bank and Richmond, Florida. The red baselines are the new ones. They fill a number of holes in the east-west coverage.

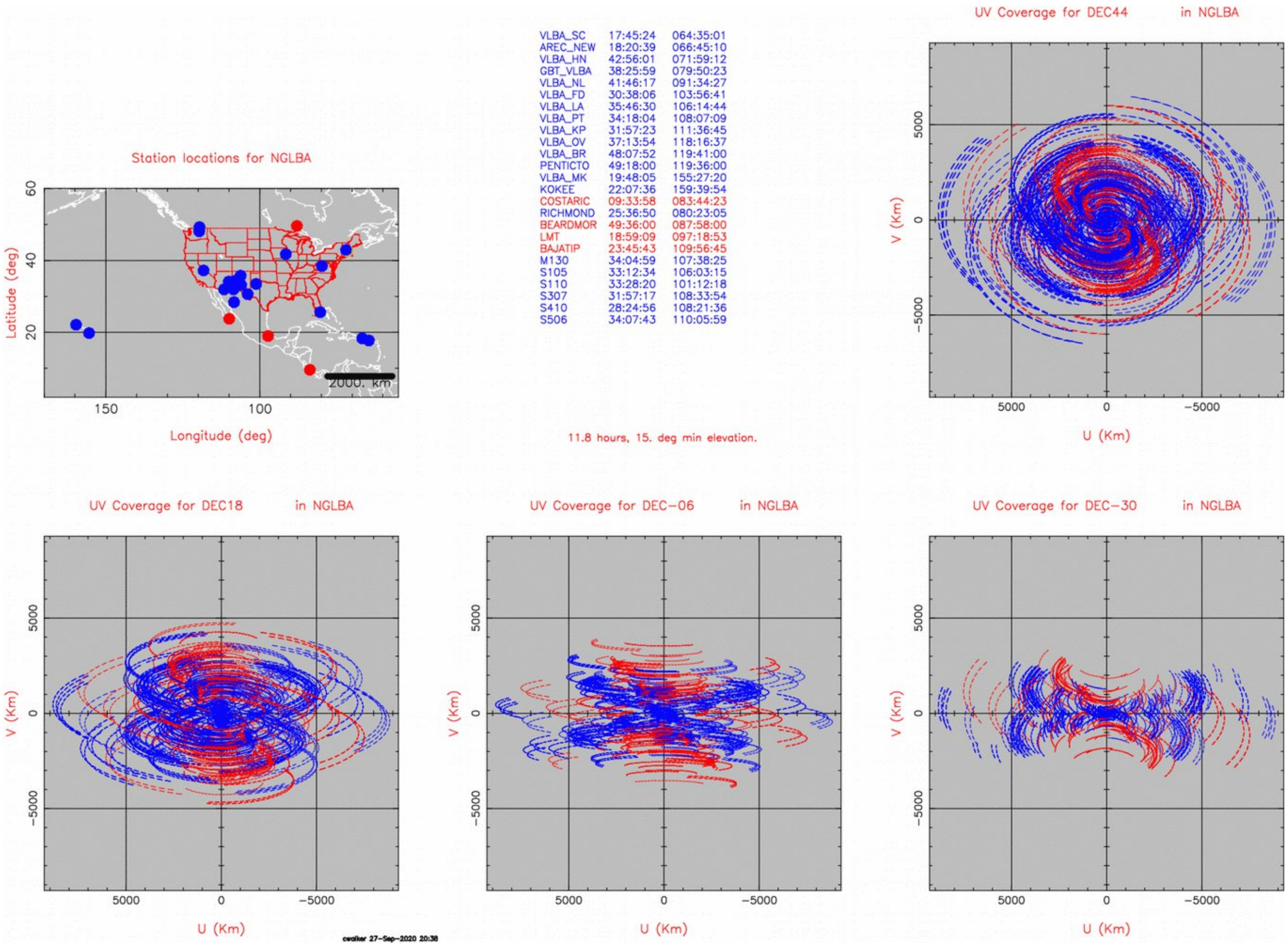

Figure 5: The UV coverage of the full suggested array. In this case the red stations are those being added in Canada, Mexico, and Costa Rica. These stations enhance the north-south UV coverage.

States. One is in Canada, two in Mexico, and one in Costa Rica. Figure 5 shows the effect of adding these stations to the reference configuration plus Green Bank and Richmond. The baselines to the 4 new N-S stations are shown in red. For improving the north-south coverage, stations to the south are preferred because they can see to lower declinations. For the VLBA, we had a restriction that we could not go outside of US territory. All of the stations I suggest here violate that restriction. The precedent has been set in both the current reference design and in the Memo 49 design of the MID array, both of which have stations in Mexico. Also the reference design has a station in Penticton.

One of the new stations is to the north at Breardmore, Ontario, Canada. The site is just east of Lake Nipigon along the Trans-Canada Highway. According to maps I've seen, there is a main fiber trunk along the highway. That station cannot see to the deep south, but it provides coverage at other declinations that cannot be provided by a southern station. The conjugate point for that station through the NGVLA center (the concentration of stations) is far out to sea, a problem shared by any southern locations with large separations from the center that are not significantly to the east. The site is a compromise between better UV coverage for long tracks somewhat farther east (eg. James Bay) and better coverage for snapshots to the west (eg Lake Winnipeg). In both cases, it would also be better to be a bit farther north if the the required infrastructure can be found, but that is remote territory.

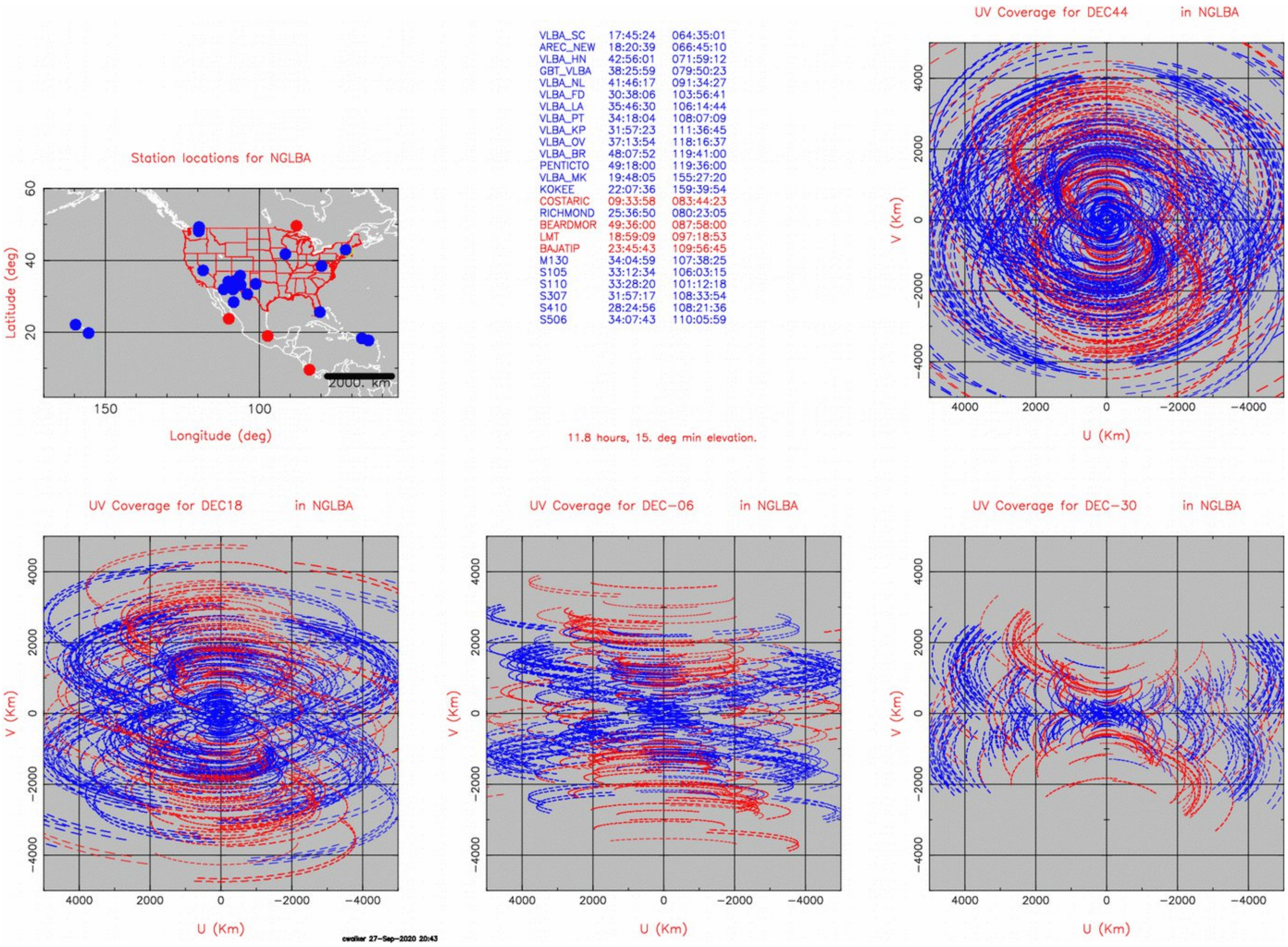

Figure 6: The same UV coverage and stations as Figure 5, but showing the inner 5000 km. This shows just how dense the coverage is over the main imaging portions of the array when using the new stations and a few stations of the MID array. It is a large improvement over the current VLBA.

Two new stations are in Mexico. One is at the Large Millimeter Telescope located on the summit of Volcán Sierra Negra at an elevation of 4640 m (15,220 ft). This site has astronomy infrastructure and access to high elevations. An NGVLA station would likely go somewhat lower than the actual LMT site at the summit. 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. One issue, hopefully temporary, is that threats of violence along the roads have resulted in reduced access to the mountain. The other Mexican station is near the southern tip of Baja California. It may be difficult to get very high at this station. There are 2000 m mountains nearby, but I don't see any sign on Google Earth that there is access high into those mountains. But Baja is very dry. I have chosen a site near the main road at about 560 m elevation, but a more detailed investigation of possibilities is needed.

The final suggested site is in Costa Rica. Costa Rica has significant mountains. The paved Inter American Highway is above 3000 m (10,000 ft) for a considerable distance. It might be possible to find a site along that highway with reasonable infrastructure. One issue is that there is a cluster of radio towers in the vicinity of the chosen site so we would need to hide from them. On the other hand, the probability that fiber is nearby is high with such facilities present. There is another possible area about

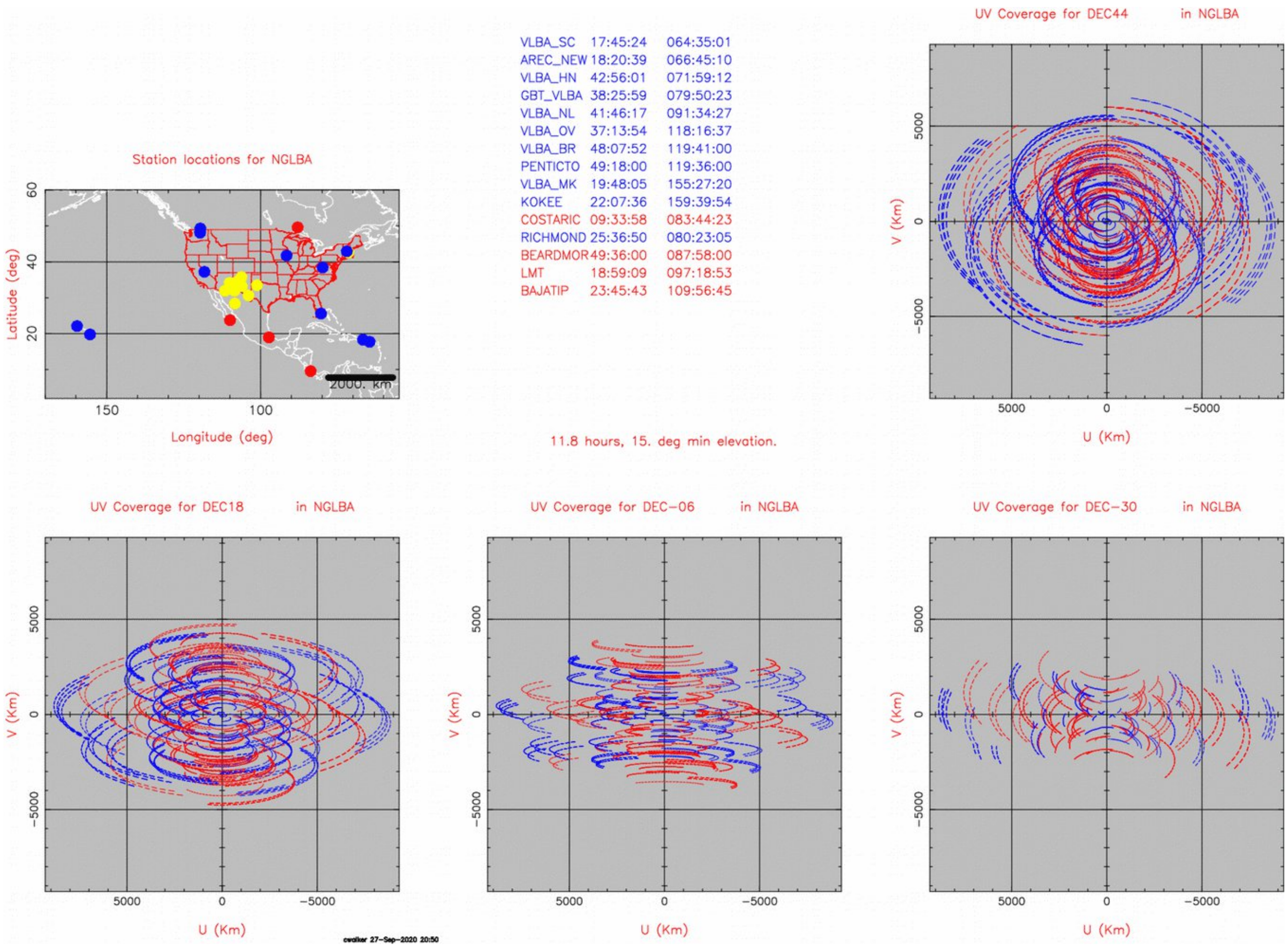

Figure 7: The UV coverage of the LBA without any MID stations, including none of the inner 4 VLBA stations that are part of the MID array. The red tracks are from baselines to the suggested new antennas, although Green Bank is treated as an original LBA station for this case as it replaces Westford. The coverage without the new antennas is shown by the blue tracks alone.

47 km north near San Jose. It is also near radio towers and above 3000 m. A site in Costa Rica would have nearest neighbors that are 1800 - 2100 km away (Arecibo, Richmond, and LMT), which is not optimal for self-calibration. A site in northeastern Columbia would be about 1100 km from both Arecibo and Costa Rica, and might be usable as a pair for both those stations, perhaps instead of the high-corrosion VLBA_SC site. There is a very high mountain in the area (5700 m or 18700 ft), but I don't see much in the way of roads above about 1000 m on Google Earth.

Usually when designing an array, all of the stations work together to provide good coverage. Trying to change the configuration after some station locations are cast in concrete, literally, can do harm. We faced that when an effort to move the Hancock VLBA station to Green Bank arose during VLBA construction. But adding stations without making other changes is less problematic. This is especially true when the new antennas are in the outer parts of the array and are meant to address weaknesses in the long-baseline coverage of the original configuration. That is the case with all six of the stations discussed in this memo. In fact, each pretty much stands on its own so the decisions to add them can be made individually.

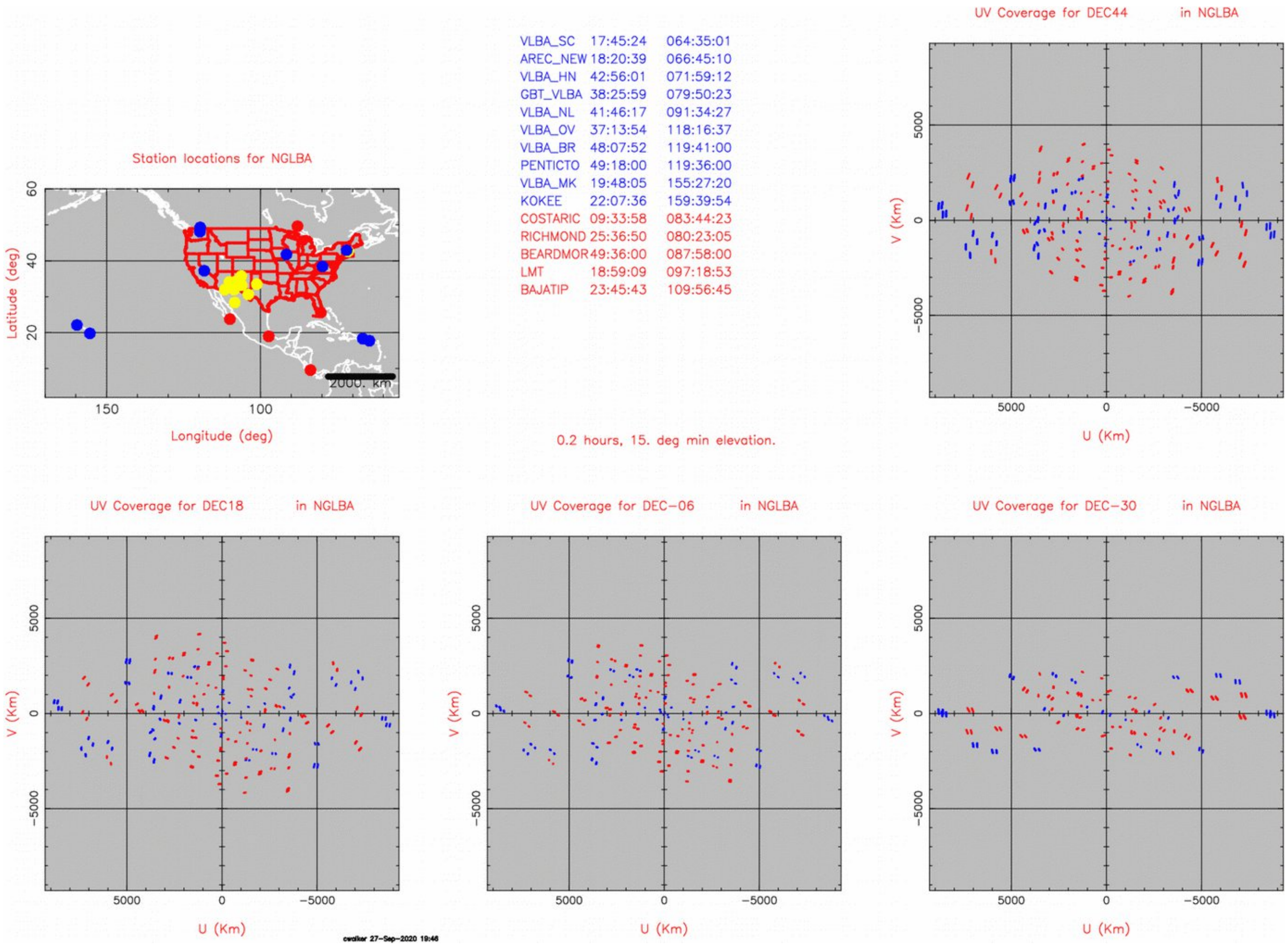

Figure 8: The snapshot UV coverage of the LBA with the suggested new stations but no MID stations. This is one 12 minute scan. The baselines provided by the new stations are shown in red. Green Bank is treated as an old station here. Note that the short spacings are from the self calibration pairs.

Figure 6 gives another impression of the enhanced UV coverage with the proposed new stations by zooming in to a 5000 km maximum scale. For those familiar with VLBA coverage, this is vastly better partly because of the new stations suggested here and partly because of the short baselines available from the MID array.

Figure 7 explores another extreme – the use of the outer stations only. This is the coverage of the LBA when all of the inner MID antennas, including the 4 inner VLBA antennas, are being used for mid scale observing. The new stations suggested in this memo are shown in red as are the baselines to those antennas. The coverage of just the current reference array, although with Westford moved to Green Bank, is shown in blue. If you ignore the red tracks, the distribution of the coverage is well spread out, but thin. This would work for astrometry and simple-source imaging. But the addition of the new stations makes a dramatic difference. This would actually be a fairly good imaging array. Note that it is not totally lacking in short baselines because of the baselines between the self calibration pairs.

The snapshot coverage of the proposed array without any MID stations is shown in Figure 8. Figure 9 shows the same thing, but with the subset of MID stations included. The coverage is sufficiently good that this may be a popular mode . Remember that the coverage can be improved significantly through

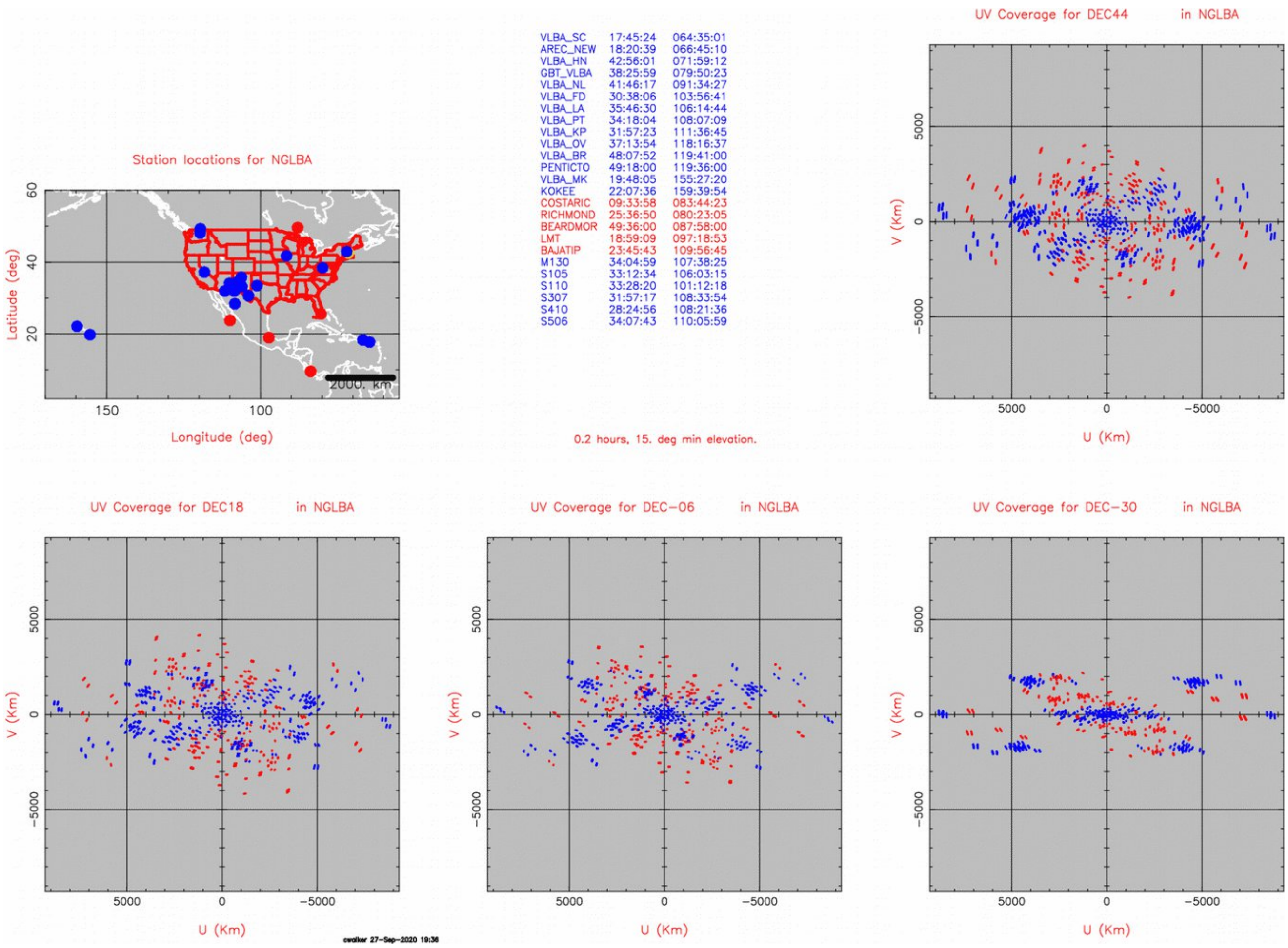

Figure 9: The snapshot coverage of the LBA, similar to Figure 8, but including the MID stations used in earlier figures.

the use of multiple snapshots, which is a common observing style on the VLBA when observing surveys or multiple source projects. The quality of the snapshot coverage, and the full track coverage shown in Figure 7, make the use of the remaining LBA antennas, when the full MID array is in use for something else, much more attractive than I had expected.

AN EXTREME ARRAY

I will now show an extreme array, with higher resolution and much better north-south coverage than anything shown so far. The logistics of building such an array and operating it are likely to be prohibitive, at least for now. But it might be something to consider for a future enhancement so I would like put it out as a teaser. The array has antennas on three Pacific islands besides Hawaii, two in South America, and one near Africa. I first encountered the concept of a Pacific Island array when Galen Gisler produced one during the VLBA configuration studies. His was exclusively in the Pacific, farther to the west. It had amazing coverage, but probable poor observing conditions at most sites and difficult logistics. We did not pursue it then and probably won't now. But there are, or soon will be, fiber cables all over the Pacific so it might become feasible before long.

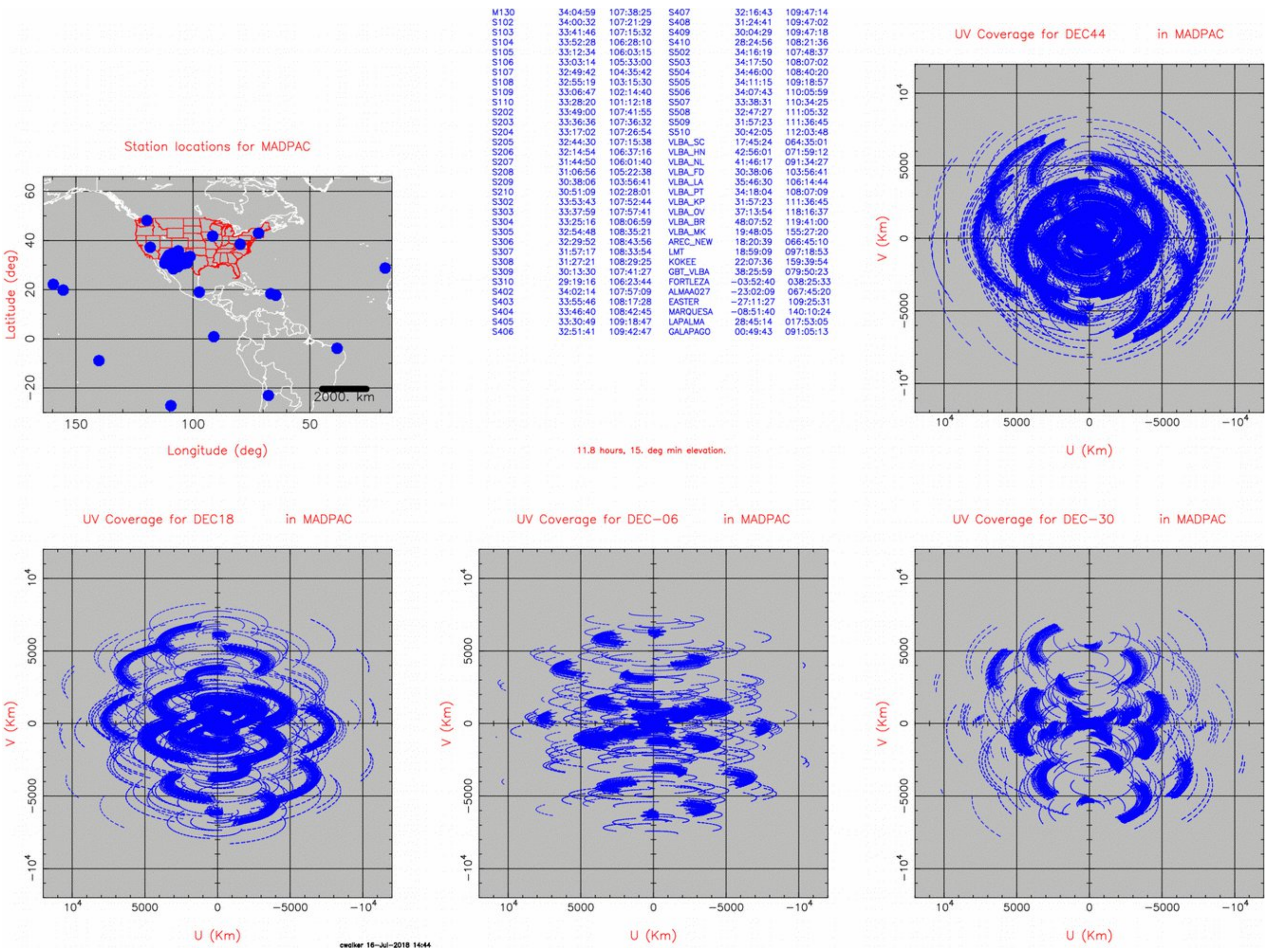

Figure 10: The coverage of the extreme array. Note that the scale has a maximum of 12,000 km compared to the 9,300 km of the other figures. This array has higher resolution and much better north-south coverage than the proposed NGVLA LBA. But it also comes with fairly extreme logistical difficulties so may not yet be practical.

Figure 10 shows the UV coverage of the extreme array used with the NGVLA MID array. Figure 11 is the same antennas, but without the MID array and emphasizing southern declinations (30, 00, -30 and -50 degrees). Note that these plots do not assume any of the stations proposed earlier in this memo are built, although it does assume that Green Bank and LMT are used. If the other new antennas were added, the coverage near the center would improve in the manner indicated in the earlier figures. Note that the plot scale in Figures 10 and 11 have a maximum of 12,000 km rather than to the 9,300 km maximum used above in the other figures.

Below I give some very limited details about the stations that are not in the NGVLA, going clockwise:

La Palma in the Canary Islands: There are extensive optical astronomy facilities at the site. The elevation is around 2400 m (7700 ft).

Fortaleza, Brazil: This is the site of a geodetic VLBI station. This station will be at very low latitude (-3 deg) and low elevation (<1000 ft) so it will be somewhat limited at high frequencies, much like VLBA_SC and Florida.

ALMA: High, dry, existing NRAO site.

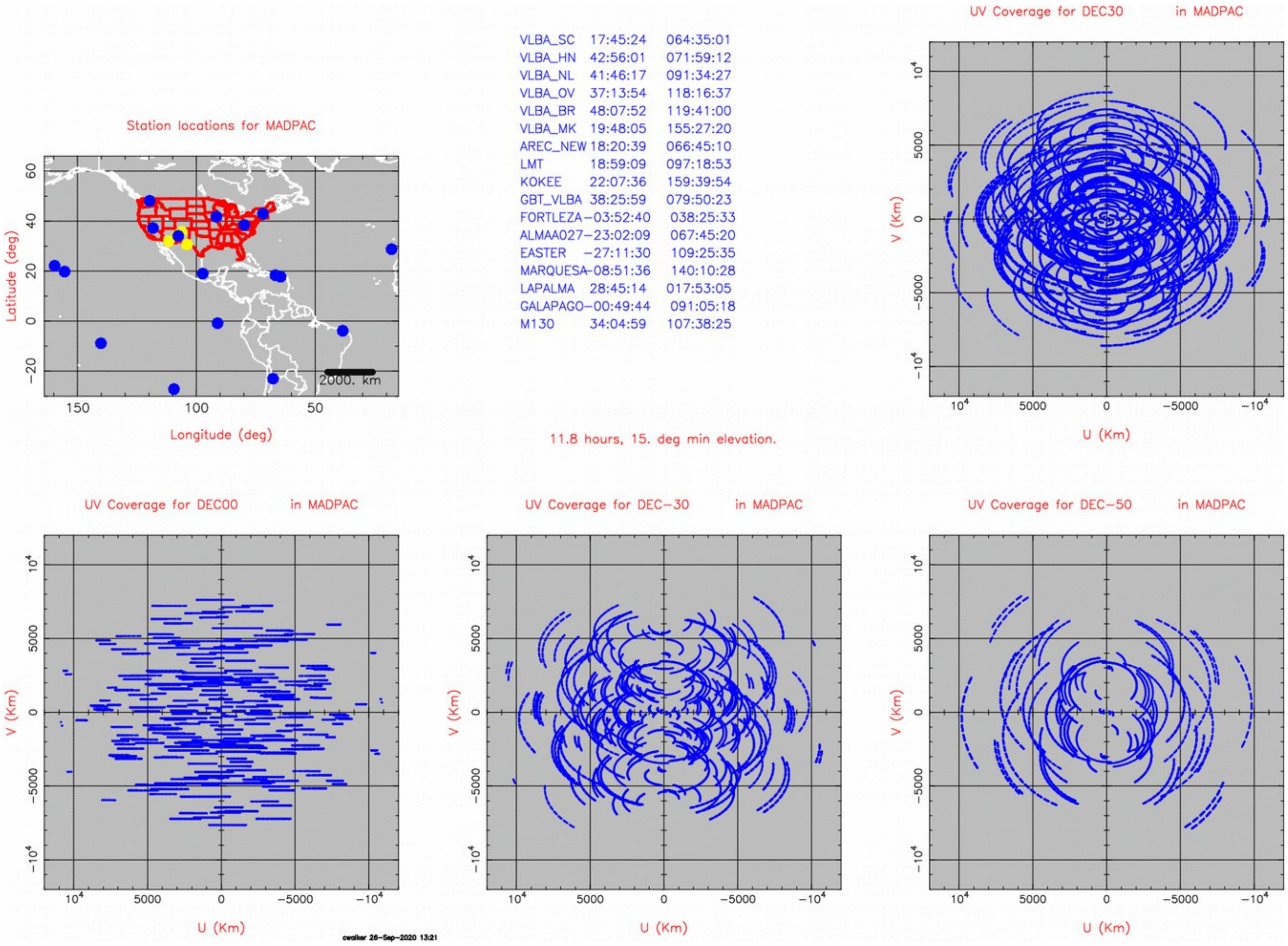

Figure 11: The UV coverage of the extreme array, without all the antennas of the MID array included, is shown for declinations of 30, 0, -30 and -50 deg. Only one antenna from the NGVLA CORE array is included to enhance shorter spacings. No MID antennas, including none of the inner four VLBA stations, are included. The coverage of short baselines, especially in the deep south, is a bit thin on short baselines but otherwise rather good. The short baselines can easily be improved by using some MID antennas.

LMT: This station is included in the enhanced array described earlier so see the discussion there.

Galapagos Islands, Equador: There are farms and roads above 760 m (2500 ft) on Sierra Negra on Isla Isabela near Puerto Villamil. I'm guessing that environmental issues, that are likely to be extreme in much of the Galapagos, would not be so bad near farms. There are claims that a submarine cable will begin operating in 2021.

Easter Island, Chile: There is a project to place a fiber cable from Chile to Australia, with a connection at Easter Island. Originally, it was meant to go directly to Asia, but Australia is connected to Asia and is closer. A site on the island would probably be at around 200 m (600 ft). The latitude is -27 deg which is comparable to Florida.

Marquesas, French Polynesia.: The site I am using 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. These islands are about 1400 km NE of Tahiti. Using the site slightly closer to the array center, rather than Tahiti itself, seems to work a bit better, but other options could be explored.

SUMMARY

The principle results of this memo are:

Green Bank should replace Westford in the NGVLA LBA. Green Bank is a better option for the self-calibration pair for VLBA_HN than Westford because of the larger separation. It will have less exposure to urban RFI and local radars. Also it provides interesting UV coverage for the LBA in it's own right, can aid in calibration of the GBT when that telescope is used in VLBI observations for its huge collecting area. Finally, it can can do double duty as the self calibration pair for VLBA_NL.

The capability of the LBA can be improved with the addition of a few new stations. The extra stations suggested here include one in the United States, one in Canada, two in Mexico, and one in Costa Rica. Each is somewhat independent of the others so they could be considered individually. One possibility to cushion the spec and cost change would be to consider funding by the host countries, especially Canada and Mexico, which are already partners in the NGVLA.

The coverage of the LBA without any MID antennas, including without the four inner VLBA antennas, is still rather good, especially if the new antennas are added. There are still some short spacings, which are required for imaging, thanks to the self calibration pairs. Even the snapshot coverage is quite useable.

Finally I presented an extreme array, that probably cannot be considered now because of logistical difficulties, but that shows what is possible and maybe even feasible in the not-too-distant future.