Next Generation Very Large Array Memo #124

Analysis of ngVLA Rev E Mid Sites Using GIS

Crystal Price (NRAO)

June 25, 2024

Abstract

Preliminary site assessment can save time and money by eliminating sites that are not feasible and replacing them with sites likely to be constructible. There are various reasons why a site may not make it to the construction phase, ranging from topography to land acquisition or permitting issues. Prior to ground truthing of sites it is possible to utilize resources such as ArcGIS and public databases to select sites with the greatest probability of success while also preserving the scientific integrity of the array. This document describes the selection criteria and process of preliminary site analysis for Rev E Mid sites, including future work that can be done to further define the feasibility of selected sites.

1 Introduction

The ngVLA is composed of individual sites which are grouped into Short Baseline Array (SBA), Core, Spiral, Mid, and Long sites (Figures 1 and 2). The Rev E configuration contains 19 SBA antennas, 114 Core antennas, 54 Spiral antennas, 46 Mid antennas, and 30 Long antennas (10 sites, three antennas per site). Other documentation may refer to the "plains array," which is a term used for sites on the San Agustin plains and includes the SBA, Core, and Spiral sites.

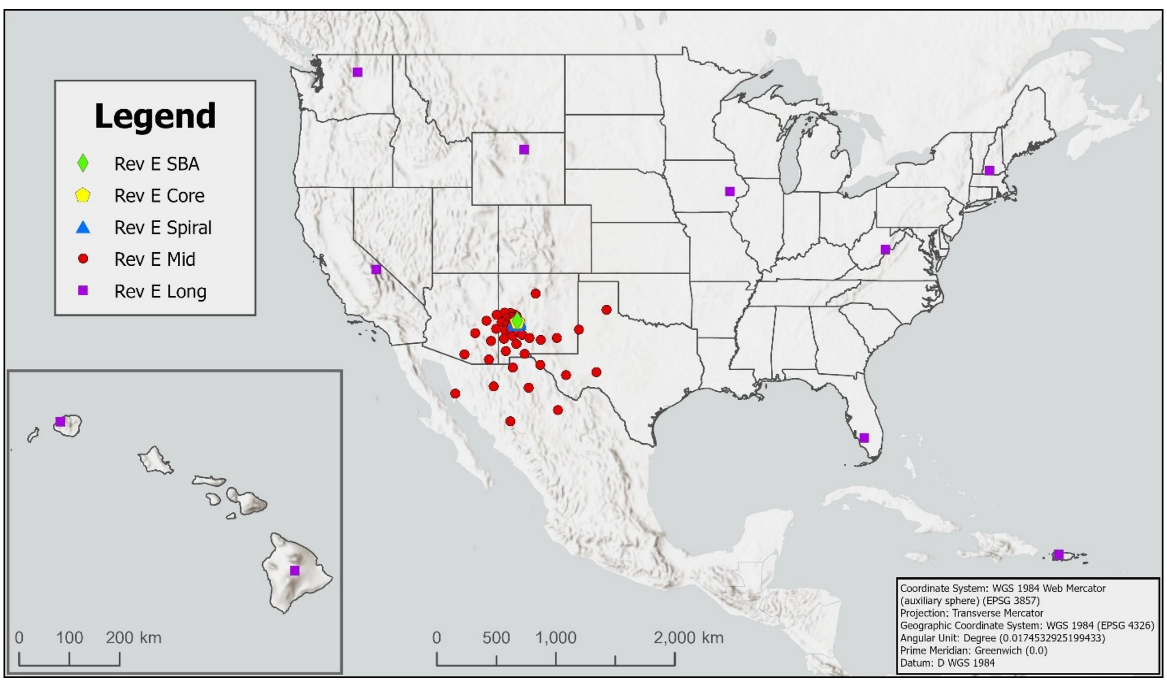

Figure 1: Overview of Rev E site locations.

Various iterations of site placement have been explored resulting in array versions from Rev A to Rev E. Work is currently beginning on Rev F. Site locations will ultimately be a balance between scientific value and available infrastructure. Each revision has attempted to improve the scientific value of the array while also ensuring the sites are not cost prohibitive to construct. Real world site

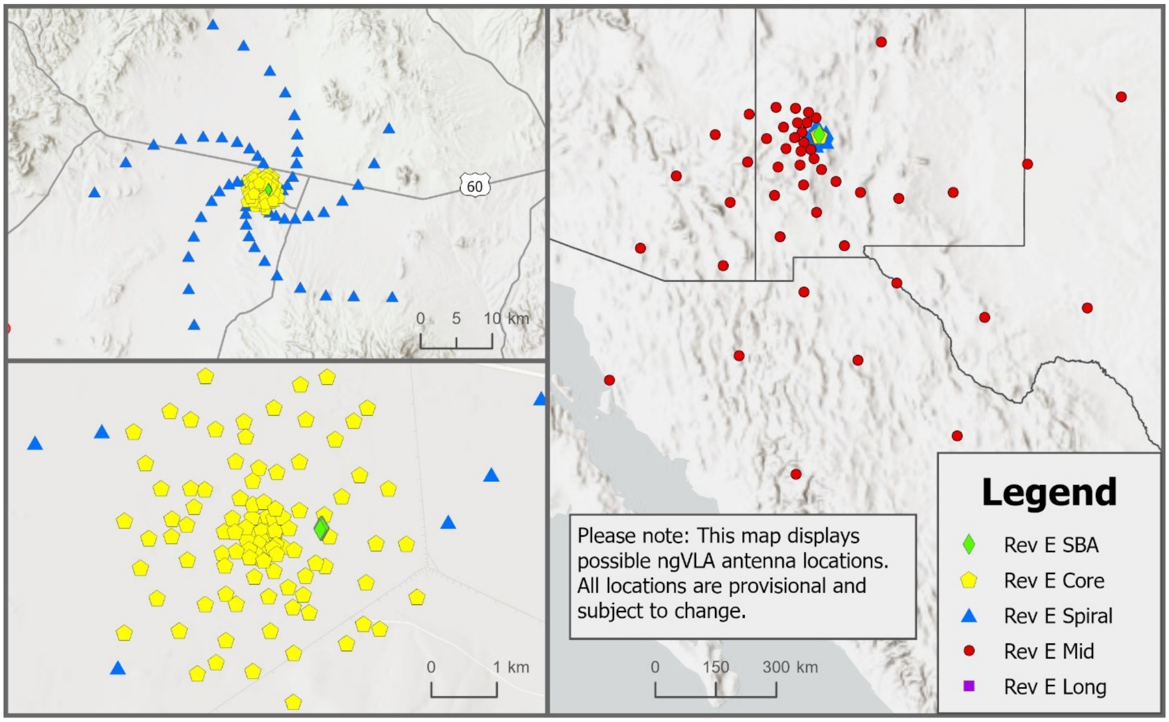

Figure 2: Detailed view of Rev E site locations.

placement was not examined in detail in Rev A through Rev C but Rev D site placement was highly controlled by available infrastructure corridors and initial criteria for site placement were identified (Carilli, 2021; Walker, 2022). The site distributions that would become Rev E were based purely on mathematical spirals and did not account for real world obstacles on the ground (Walker, 2022) or closely follow existing infrastructure corridors, as were done in Rev D. The current version of Rev F includes approximately half of the sites from Rev E but follows infrastructure corridors a bit more than Rev E, particularly in areas where Rev E sites were far from existing infrastructure. Rev E Mid sites are examined in this document as they have been the most thoroughly vetted with the process described herein.

The Mid sites, in general, will be the most problematic sites to construct. The SBA, Core, and Spiral are all within the plains of San Agustin, where the VLA is located. The VLA provides access to established infrastructure such as existing roads and power and while these may need to be modified or extended to accommodate the ngVLA telescopes, the basic infrastructure exists nearby. The Long sites, while also dispersed, have much more freedom of movement while preserving scientific value and so are not expected to be as difficult to place. The Mid sites represent 46 sites throughout New Mexico, Arizona, Texas, and Northern Mexico, each with different siting and permitting needs. The VLBA sites at Pie Town, Kitt Peak, and Fort Davis are included in the Mid sites and have existing infrastructure. Los Alamos is currently included in the Mid sites but may become a Long site or move to another location due to its distance from the Mid arms.

2 Methods

A geodatabase structure was established in ArcGIS Pro to house geospatial data for the ngVLA project. Many geodatabase configurations and geographic coordinate systems were considered. The choice of coordinate system was very important as some are more accurate for local areas, while others are better representations of larger areas or the entire world. The coordinates were provided by the science group in WGS84 (EPSG: 4326). However, future measurements, such as road widths, area calculations, and other activities as the sites move towards construction would require precise local measurements. To focus in on local areas, a geodatabase was set up for each US state planned to contain an antenna site and the best zone for each in UTM NAD83 (2011) was chosen to represent that state. For maps which required displaying all Long sites, an overview geodatabase was created for visualization only in WGS84 Web Mercator (EPSG: 3857). An additional geodatabase was generated for Mexico using Mexico ITRF2008 (EPSG: 6372).

The shapefiles to populate the geodatabases were derived from a variety of reputable sources. All shapefiles had to be generated or obtained for each locality. The configuration files that represented sites and dither zones were made within the NRAO. The remaining shapefiles were collected from government organizations, public databases, and private businesses. Metadata were retained or added as needed and the date data were last updated was also added when available. While all geodatabases exist and the data structure is established, the most complete geodatabases are for states with Mid sites. Geodatabases for states with Long sites will be populated when the Long site review commences. All geodatabases continue to grow as new information comes to light or as the project's needs evolve.

3 Configuration

Rev D is currently the authoritative configuration for the ngVLA. The location of Rev D sites was based heavily on available infrastructure but the power law distribution used to generate Rev D provided too few short baselines (Walker, 2022) and necessitated a change in the array design. An exponential distribution was attempted to see if it would improve scientific performance (Walker, 2022). The exponential distribution yielded several possible configurations, of which one was chosen to become Rev E (Figure 3).

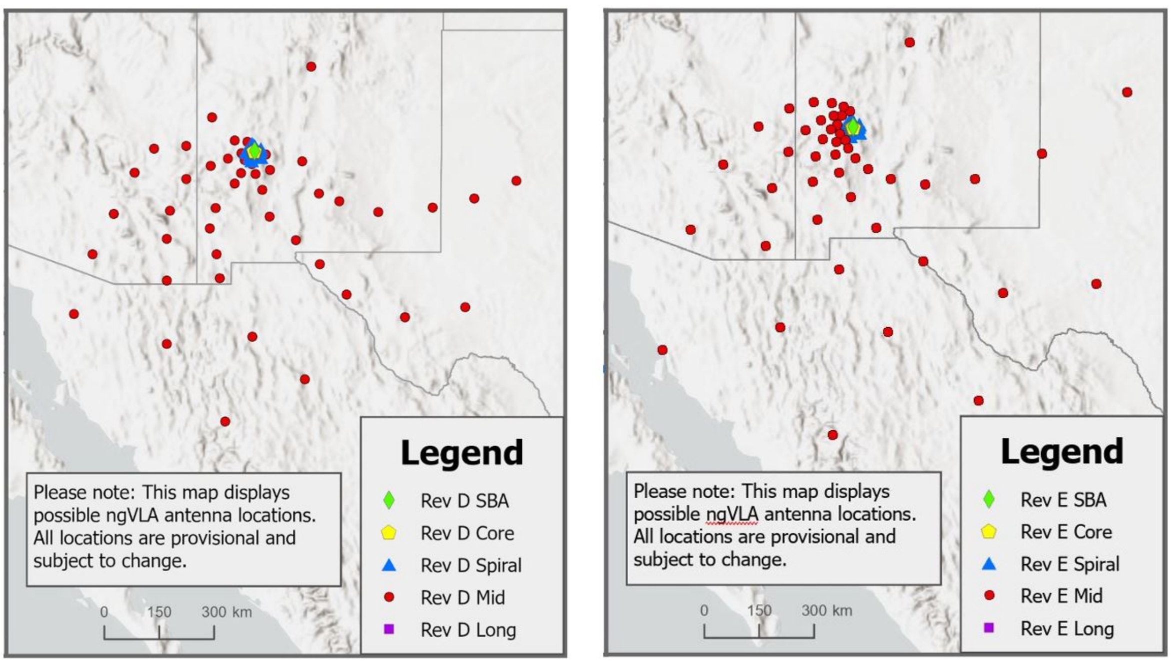

Figure 3: Comparison of Rev D (left) and Rev E (right).

Rev E locations were provided to Site Development to determine their constructability and to move to more favorable locations if issues were detected. The Rev E coordinates provided by the Science group are referred to as original sites. Several alternate site locations were identified by Site Development and are referred to as alternate sites. Alternate sites receive the same vetting for preferred attributes as the original sites. In cases where the original site has unmitigable issues the alternate sites provide potentially viable alternatives, allowing the project to pivot quickly to an alternate site if issues are present with the currently preferred site. Similar to the Science group, other departments throughout the project had preferred attributes for potential sites. The preferred site features were guided or defined by engineering requirements, probability of successful permitting, and the desire to keep costs at a minimum.

A site that meets specific criteria as set forth by project requirements has a greater chance of advancing to construction. There are characteristics, from science, engineering, and site development perspectives, that indicate whether or not a site will be successful. For a site to be successful scientifically it should have good baseline (uv) coverage over a range of scales, be located in Southern latitudes for good sky coverage, avoid line of sight to radio frequency interference (RFI) transmitters, have an elevation of greater than 1750 m if possible, PWV (precipitable water vapor) less than 6 mm, average wind speed of less than 5 m/s (for high frequency performance, opacity, phase stability), and avoid close terrain obstructions (within 10°) to the horizon (Carilli, 2023). In addition to the science criteria, a site must also meet a combination of engineering and site development criteria, described below, to become a successful site.

4 Site Development Selection Criteria

4.1 Relocation (Dither) Range

One of the first questions Site Development considered was how far sites could deviate from the original locations with minimal impact on scientific data obtained by the array. The initial solution provided by the Science group was a dither range of 2.5%, defined as 2.5% of the distance from a site to the array center. The dither range became the radius of a circle that defined the amount of movement each site was allowed. However, as site analysis proceeded, it was noted that Rev D allowed a dither range of up to 10% and this convention was adopted for Rev E as well. Circular dither ranges of 2.5%, 5%, and 10% were defined for each site to allow relative comparison of original, preferred, and alternate site locations (Figure 4). While sites within the 10% dither would maintain scientific integrity of the array, sites closer to or within the 2.5% dither range are desired as they are closer to the original site locations.

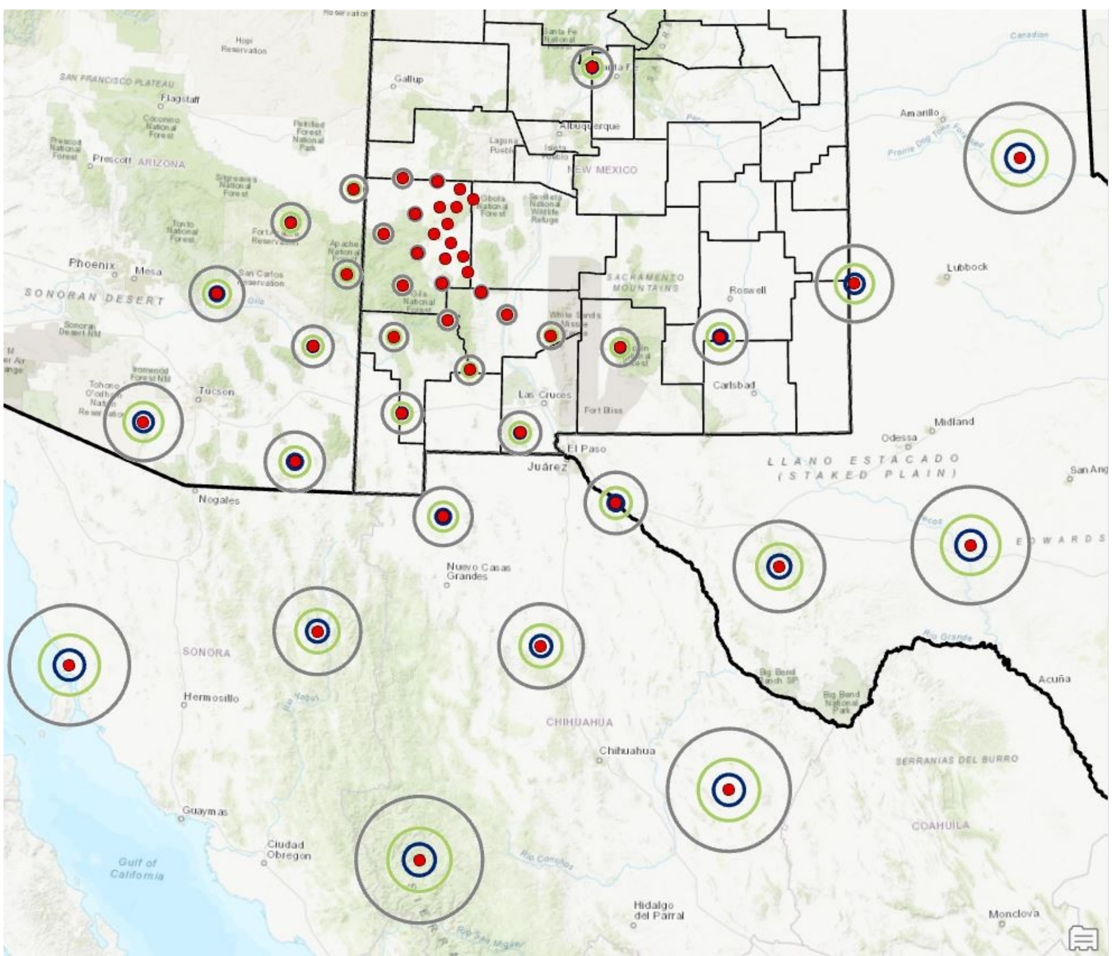

Figure 4: Dither ranges for original sites (blue: 2.5%, light green 5%, grey 10%).

4.2 Topography, Slope, and Line of Sight

Topography and slopes exercise significant control on site placement, specifically for site area, road and power access, and terrain shielding. Terrain shielding can work for or against a site: it can protect sites from RFI but it can also obstruct the horizon and interfere with line of sight. Elevation also factors into site placement as an elevation of greater than 1750 m is desirable but an HVAC restriction suggests the elevation should not exceed 2500 m (Selina and Dunbar, 2022; Walker, 2022) as it will increase the cost of the HVAC system. In addition, the paths of roads, power, and drainages are dictated by topography to varying extents. While no specific documented requirement existed for slopes, less than 3° for site slopes and less than 6° for roads was suggested (Carilli, 2023). Internal documentation for the Long sites proposed 6° or less for site slopes (to avoid shadowing issues between three antennas) and 10° or less for roads (Selina, 2023). For Rev E, 3° slopes are preferred for sites, with up to 6° allowed. Slope maps (Figure 5) can be generated in ArcGIS to illustrate the slopes within an area and are useful in determining which areas are amenable to development.

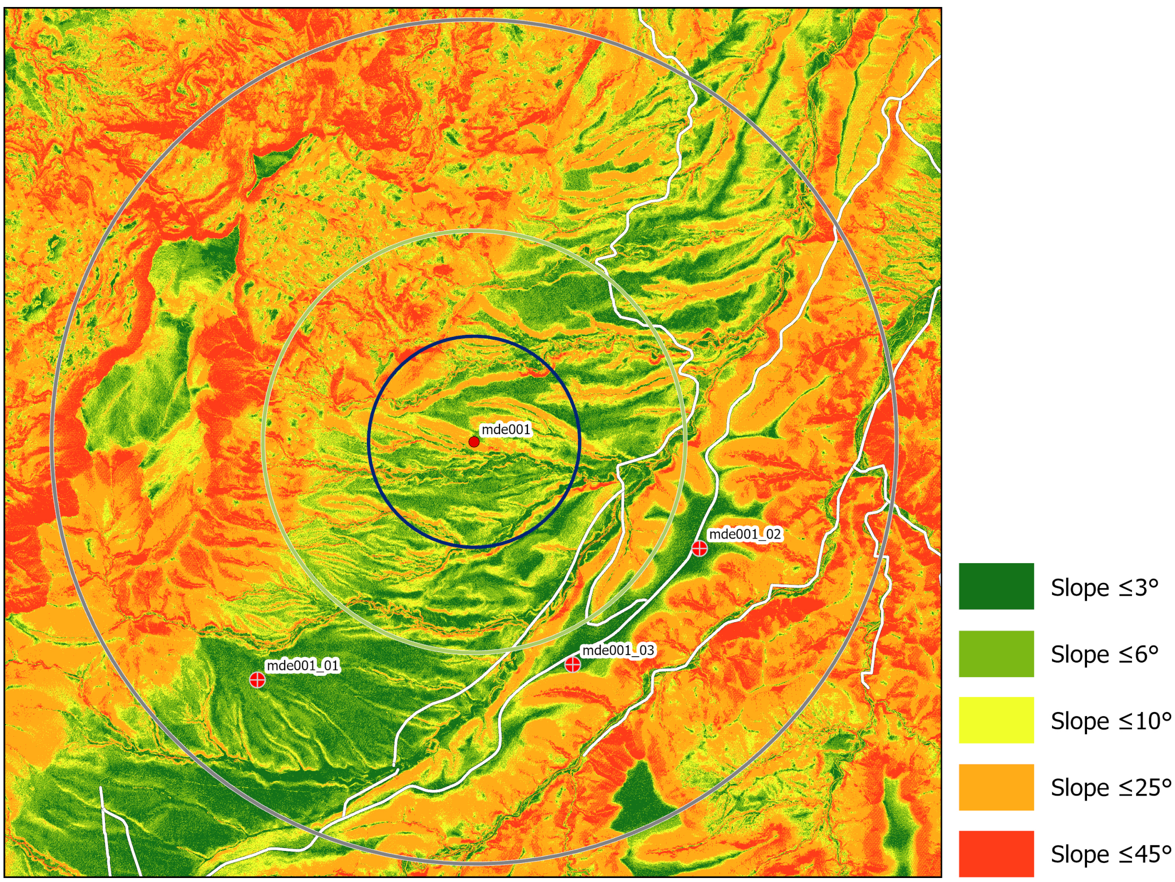

Figure 5: Dither ranges for original sites. (blue: 2.5%, light green 5%, grey 10%).

The size of the site area was not specified. For Mid sites, the site area was chosen to be large enough to place a telescope and possibly an associated shed or outbuilding, if needed, similar to the current VLBA sites. For example, Pie Town is approximately 75 m by 50 m but most Rev E sites have an area of acceptable slopes approximately 100 m by 200 m. A minimum site area of 100 m by 100 m is desired for Rev E Mid sites. Sites should also not be located in or at the terminus of drainages. Details of site roads will be provided in the appropriate section but accepted slopes for roads in Rev E are less than 6° (∼10.5% grade) with local exceptions possible on a site by site basis.

Trees present a unique issue for some sites. In areas where tree growth is thick and/or the trees are particularly tall, it can be a challenge to ascertain appropriate line of sight. The trees can block the field of view and additional land may need to be acquired in order to clear any trees obstructing line of sight to the horizon. This is of particular concern for sites located in heavily forested areas or in forested areas where land acquisition or logging may be problematic. Trees are difficult to assess with

ArcGIS alone as the height of trees changes with time. While the general height of trees in an area may be approximated in ArcGIS through tree cover datasets (where available), assessment of tree cover will likely be accomplished by site visits in conjunction with ArcGIS. ArcGIS can also analyze the topography to verify the site achieves sufficient sky visibility but site visits will confirm if additional obstructions are present.

4.3 Site Acquisition, Land Use, and Regulatory Compliance

Land acquisition and permitting are likely to be ongoing considerations that are revisited repeatedly until construction begins. Many issues can be mitigated by carefully selecting sites that appear obtainable and have a low probability of being held up by regulatory (permitting), environmental, or other issues. Also, different jurisdictions (and countries) will have differing requirements and priorities for permitting and land use or access. If the land is obtainable, suitable right of ways (ROWs) must be established to provide corridors for roads, power, and fiber.

4.3.1 Land Acquisition

Leasing or purchasing land from a private owner versus leasing through a state or federal entity can have a large impact on the permitting and development process and timeline. As a result, the controlling person or agency, as well as any matters that affect permitting, must be considered in site selection. Regulatory requirement AAC0601 for Rev D states "It is desired that sites on private and BLM land be prioritized. USFS and Tribal properties shall be avoided when possible" (Carilli, C., et al., 2022; Mason, B., et al., 2022). Given the many site requirements and the issues that may arise during acquisition, permitting, and up to construction, it is best to have site options on multiple ownerships/jurisdictions that are selected according to the unique aspects (environmental, regulatory, social, etc.) of each area.

If it is not possible to acquire the land for a selected site or if the process to build on the land is too onerous, an alternate site can be explored. For Rev E, alternate sites (generally three to five) were chosen on a variety of land options based on the types of land ownership within or near the dither range. Ownership options vary for each site but may include BLM, state, private, USFS, and Tribal lands. The current preferred arrangement of Mid sites includes 46 sites, of which two are on Tribal lands (one of which is the VLBA site on Kitt Peak), eight are on USFS lands, nine are on BLM lands, nine are on private lands, eleven are on state land, and six are in Mexico. The variety in land ownership allows the project to choose the most convenient site once land acquisition begins. Even with several options, as the project progresses to construction it may be necessary for a few sites to explore slightly outside the dither range to find land that can be acquired.

4.3.2 Land Use

Frequently, land within dither ranges is currently being used for other purposes. Grazing allotments and mining claims are two common uses. Either may be found within dither ranges and each has a unique effect on siting antenna locations. State and BLM land may be leased to ranchers for grazing purposes and these leases are called grazing allotments. Locating an antenna within a grazing allotment would require correlating with the landowner agency and potentially the lessee. BLM, state, and USFS lands are open to locating mining claims which may be surface or subsurface claims. For Rev E, areas with known mining claims, either surface or subsurface, were avoided.

Another potential use of land includes solar arrays. Many BLM lands in the Southwest are currently being evaluated by the BLM for solar development. While the evaluation is still in progress, much of the BLM land in Arizona and New Mexico that would be useful as antenna sites may be affected as solar companies are frequently looking for land with good sky exposure, road, and power access. The BLM solar plan is still under review and contains several alternatives but until an option is selected, there is much uncertainty as to which BLM lands will be available for site selection.

In Mexico, land in both Sonora and Chihuahua is commonly divided up into Ejidos. Ejidos are socially owned land granted to the local communities by the Mexican government expressly for agricultural purposes. While it could be possible to build on an Ejido, there would be additional legal and social requirements that are not present with private or government lands. Due the additional requirements, Ejidos were avoided at this time when designating alternate sites in Mexico. Any Rev

E Mid sites located on Ejidos were moved to areas without Ejidos. Outside of the Ejido boundaries, the land status of the sites in Mexico is currently unknown but they are likely held by the government or in private ownership. Obtaining shapefiles from the appropriate Mexican government agencies with more specific land information is in process.

4.3.3 Permitting, Environmental, and Regulatory Compliance

There are several requirements in the documentation for Rev D that address environmental concerns. AAC0602 states that "Sites shall be screened for environmental impact, such as overlap with identified endangered species habitat" (Carilli et al., 2022; Mason, B., et al., 2022). The Protected Areas Database (PAD) shapefiles show habitat and protected areas for various species, conservation areas, areas of critical environmental concern (AOCEC), and many other protected designations (USGS GAP, 2022). In addition, ArcGIS online layers exist for critical and known habitat zones for the Mexican Spotted Owl and the Desert Tortoise, two protected species native to the Southwest US. There are also shapefiles available from various databases showing wild and scenic rivers, Inventoried Roadless Areas (IRA), wild horse herds, Wilderness areas, and other protected regions. As in Rev D, Rev E sites will be screened for environmental concerns and any problematic areas will be avoided if possible to reduce risk during the site development process.

While some historic/cultural areas are included in the PAD, on site surveys will likely be needed to ascertain if any cultural artifacts are present. Historic mining towns (also called ghost towns) are often considered cultural preservation sites in the Southwest. There are GIS layers for New Mexico and Arizona showing historic mining towns and wherever possible these areas have been avoided. Geospatial databases of archeological areas exist for both Arizona and New Mexico but access is restricted due to the sensitive nature of the preservation sites. The following requirements for Rev D are focused on minimizing the project's impact on nearby ecosystems and communities:

> INF4000: The design and construction of utility corridors and roads shall minimize the impact on grasslands and water within the Plains of San Agustin (Selina et al., 2022).
>
> INF4003: Any fences shall not impede the flow of cattle and wildlife within and between neighboring ranches, or significantly increase the travel distance to water sources (Selina et al., 2022).
>
> INF4004: The project shall aim to reduce the environmental impact to cattle ranching as well as hunting/outfitting, which are both mainstays of local ranches (Selina et al., 2022).

Rev E sites are also being planned with the goal of minimizing impact on the environment and communities. Existing roads and infrastructure will be used whenever feasible, not just to reduce cost but also to minimize any additional disturbance. The site area needed for antennas is relatively small so fencing should not impede cattle or wildlife movement. Although sensitive areas will be avoided, any sites where nesting or other activities by a protected species occurs will follow all legal requirements to ensure the species is protected.

5 Roads

All sites will require access roads, either by using existing roads, through new construction, or a combination of both. Site roads will need to be sufficient for construction activities, including heavy machinery and equipment unable to navigate tight turns. Roads should be constructed with minimal impact and disturbance to the environment. Over time, site roads should be sustainable and reliable, providing safe operational access with (preferably) minimal maintenance requirements. The design of site roads will have substantial impact on constructability, cost, and overall maintenance.

Documentation for Rev D provides general road requirements but as the project shifts to Rev E, additional clarifications and specifics are necessary. For Rev E, the road design criteria will incorporate Rev D requirements and information from established road standards, such as the USDA Access

Roads 560 CP guidelines or BLM 9113-1 Road Design handbook for guidance. Utilizing established standards is advantageous as it offers years of data driven experience on best design practices tied to current engineering standards. Some flexibility will be allowed to account for local variations, substrate availability, and permitting conditions.

Rev D requirement AAC0701 states "It is desired that all sites be within 2 km of an existing road or access point" (Carilli et al., 2022; Mason, B., et al., 2022). This directive does not specify the type of road (dirt, gravel, paved) and current documentation does not directly address grade requirements. For the current iteration of Rev E, the term road has been applied to mean any access shown on a map or visible on an aerial. Existing roads will need to be verified with site visits as aerial photos can be several years old and may not reflect current road conditions. Sites closer to paved roads have been given preference to minimize cost when all other criteria are equal. Road grades were not measured during initial site selection for Mid sites but sites were chosen with access in mind and grades that appeared very steep on a topographic map were avoided. Future sites (beginning with Rev F) will undergo a more rigorous review that includes measuring exact distances to paved roads and calculating road grades. As a result of this review, some sites may move to more favorable locations.

Site access can be impeded in various ways and it is the goal of Site Development to choose locations that reduce or eliminate any access issues. Severe weather, seasonal closures, and military or other restricted areas all adversely affect site access. According to AAC0702 for Rev D, "Sites shall have clear access for maintenance at all times. i.e. no predicted access restrictions or seasonal roads" (Carilli et al., 2022; Mason, B., et al., 2022) and INF0008 states "The Array Infrastructure sub-system shall provide service roads suitable for year-round access to each antenna site by a two-wheel drive service truck" (Selina et al., 2022). Rev E sites and roads will be located to best avoid any hindrances to site access such as restrictions and road closures. Local exceptions to the two-wheel drive requirement may occur due to the remote nature of many of the Mid sites.

Rev E sites will be situated as close to existing roads as possible to minimize disturbance to the landscape. This requirement was documented for Rev D in INF4001 which states "Road widths and lengths shall be minimized to reduce the destruction of top soil. The road design shall aim to avoid the collection of water into new ditches or arroyos that will exacerbate soil erosion" (Selina et al., 2022) and in INF4002: "Existing ranch roads shall be assessed for suitability in both construction and operations. It is a goal to reuse existing roads where possible" (Selina et al., 2022). Any existing ranch roads, if not public access, will only be considered for use if a ROW agreement can be established with the landowner. When sites cannot be located immediately next to an existing road, every attempt will be made to locate the site as close to an existing road as possible.

6 Power

All Mid sites will require access to three-phase power and current estimates suggest Mid sites will need approximately 75 kVA service lines (Rob Selina, email communication). Rev D directive AAC0703 states "It is desired that all sites be within 2 km of an existing three-phase power line." (Carilli et al., 2022; Mason, B., et al., 2022). Three-phase power is not readily available in all locations, particularly for very remote sites. While it may be possible to convert to three-phase power on site, significant shielding would be required to prevent RFI interference. Any power conversion would also reduce efficiency and increase cost, making locating sites near existing three-phase power a better option. Power line distribution shapefiles are considered proprietary information by power companies and to date attempts to obtain current shapefiles for distribution lines have not been successful. Power poles are commonly visible on aerial photography but since such images vary in accuracy and may not be current, the information, while valuable, would need to be confirmed prior to construction.

Since power is a major cost factor, locating sites near power is exceedingly important. Rev E siting has attempted to place sites near power lines visible on aerial photography and by using the few (several years old) electric company shapefiles available. Another strategy employed when no power poles are visible on aerials is to locate sites near (but not too close) to existing structures such as houses or buildings. Remote homes may run on propane instead of electricity but for very remote sites the chance of power being available is better near structures than in areas with no development. Some electric servicers also offer credits for line extensions or additions based on how many customers are served so if a nearby ranch or populated area would gain electric access through the process of bringing power to a site, it could be beneficial to the area and to the project.

It is quite possible that some sites will be farther than 2 km from existing power lines simply because data are not available to confirm the current infrastructure or due to local or remote conditions. Future work will involve reaching out to power companies, either for shapefiles or by submitting a request for service inquiry, to obtain more information about power availability near sites.

7 Fiber

The current fiber plan for Rev E will require 14 strands of fiber for the SBA, Core, and Spiral sites on the plains of San Agustin. The Mid sites have five arms with nine sites on each arm. The last site on each arm will utilize three fiber strands, with each preceding site adding two strands. This allows each antenna to have two "home run" fiber strands that run back to the correlator for the digitized data. The LO signal sent out from the central electronics building is daisy chained down a fiber run, so it goes in and out of each antenna on a fiber trunk (Email Communication, Rob Selina). The Long sites will use two fibers and dense wavelength-division multiplexing (DWDM) (Email Communication, Sanford George). Sites more than 80 km from another Mid site will require special equipment to relay data.

Rev D directive AAC0705 states "Sites shall be selected assuming 'home run' fibers are required from the site to the correlator. Total fiber transmission distances shall be minimized through shared right-of-way and trenches" (Carilli et al., 2022; Mason, B., et al., 2022) and AAC0704 states "It is desired that all sites be within 2 km of an existing fiber optic network" (Carilli et al., 2022; Mason, B., et al., 2022). The current design links all Mid sites within 300 km of the control building through dark fiber (Figure 6). Having each site within 2 km of an existing commercial fiber network is more vital for sites outside the 300 km range as they will connect to local providers. Situating sites as close as possible to existing fiber will reduce construction costs and be especially beneficial if utility trenches and ROWs can be shared.

Unfortunately, fiber route shapefiles and maps in the US and Mexico are proprietary and not accessible in the public domain. Without information on existing fiber routes, it is difficult to ascertain the distance from sites to fiber access. There are organizations that offer fiber maps (at substantial cost) but with the disclaimer that the information may not be complete or is limited to certain providers. It may be possible to request route or quote information from individual companies but such requests would require sharing site coordinates, which could be problematic until exact site locations are ascertained.

The state of New Mexico maintains the New Mexico Broadband Map, which displays information on internet access in New Mexico. Of note is the information on projects that have applied for funding in various areas, including the project area. While this information may indicate future expansion in the project area, it does include other types of internet besides fiber and so may only have limited use. However, it does provide information on what providers are expanding where and suggests which companies could be contacted for specific areas. Similarly, a map is available online from one of the largest fiber providers in Mexico (Email Communication, Alfonso Trejo). While it does not show fiber routes, it does show towns that have fiber access and will be useful in siting Mid sites in Mexico.

For the current selection of Rev E Mid sites, it was presumed that fiber lines, if they exist in a given area, would likely run along major thoroughfares such as interstates and highways. Most cities and larger towns could presumably have fiber access as well. Without more detail on fiber route locations it is not possible to situate the sites closer to fiber lines with any great accuracy. However, if the Mid sites are connected as the Rev E design indicates, ROW access and topographic boundaries will likely be the dominant control on fiber distances.

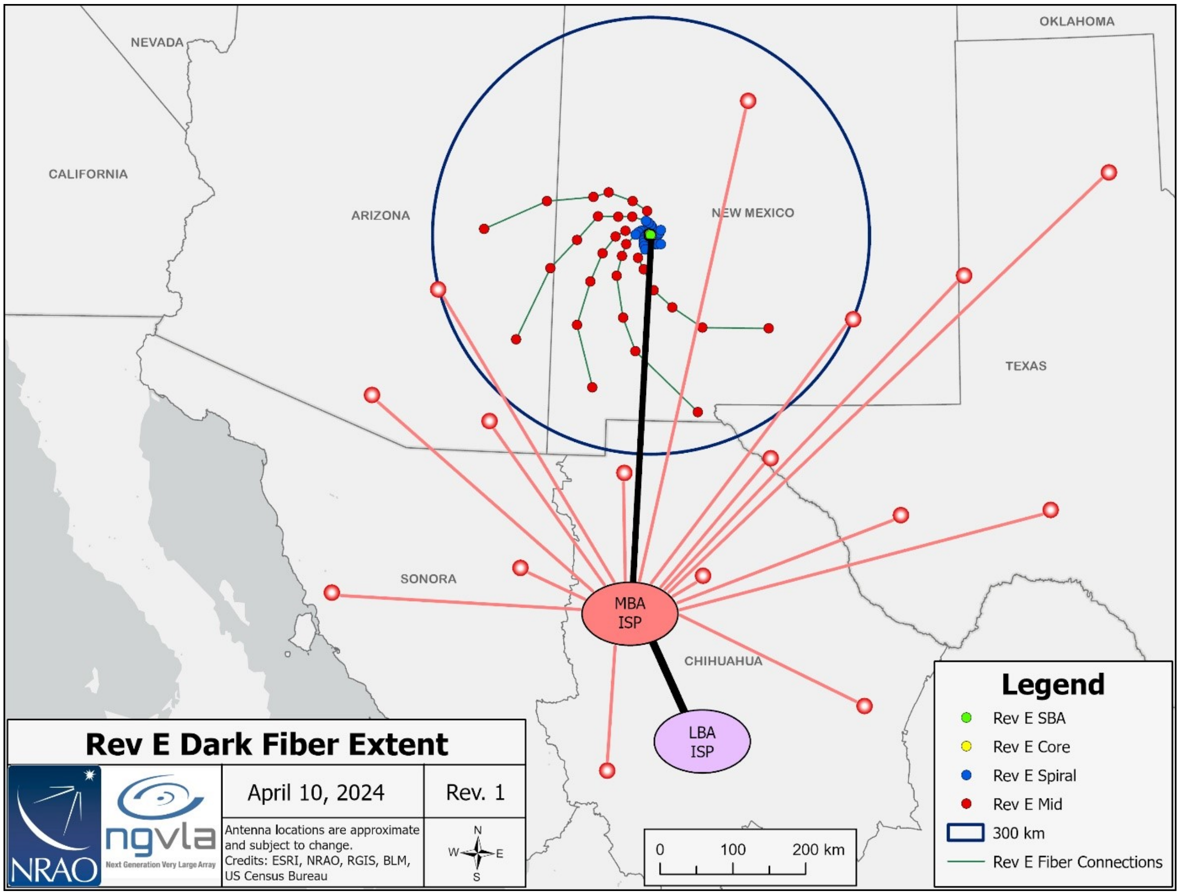

Figure 6: Map showing dark fiber plan for the ngVLA Mid sites.(blue: 2.5%, light green 5%, grey 10%).

8 Radio Frequency Interference (RFI)

There are numerous sources of licensed and unlicensed RFI, some of which would interfere with antenna observations. These sources include (but are not limited to) transmission towers, high voltage lines, populated areas, airports, and roads. Rev D requirement AAC0706 states "It is desirable that sites limit line of sight to public roads, transmitters, and other known sources of RFI" (Carilli et al., 2022; Mason, B., et al., 2022). All sites should avoid detrimental RFI but it is especially important for sites closer to the center of the array. To the greatest extent possible, Rev E Mid sites were placed to avoid sources of RFI.

Initial RFI mitigation is possible in ArcGIS, though the degree of mitigation is dependent upon the recency and accuracy of the shapefiles. A shapefile can only provide information up to the date of publication. For example, the file used for cell communication towers was published June 1, 2022 and would not include any towers built since that time. However, since infrastructure is generally added, not removed, it is unlikely that there would be less RFI sources than what are shown in the shapefile, even years after publication.

An attempt was made in ArcGIS to locate Rev E Mid sites in places that did not have line of sight to known RFI sources. However, there are very few locations without any line of sight to RFI sources so the focus shifted to mitigating the effect by choosing sites with the least RFI exposure. This included using topographic maps to determine if terrain shielding could reduce RFI. A more detailed analysis is upcoming which will use the Skyline tool and barrier polar plots in ArcGIS to identify any line of sight issues. Choosing sites to reduce RFI was easy in some areas and difficult in others, particularly dependent upon the amount of land suitable for site placement within a dither range and the source of RFI. The RFI source must also be considered to evaluate the extent of the RFI. Communication towers can be a source of RFI as long as they are within line of sight, whereas RFI from other sources,

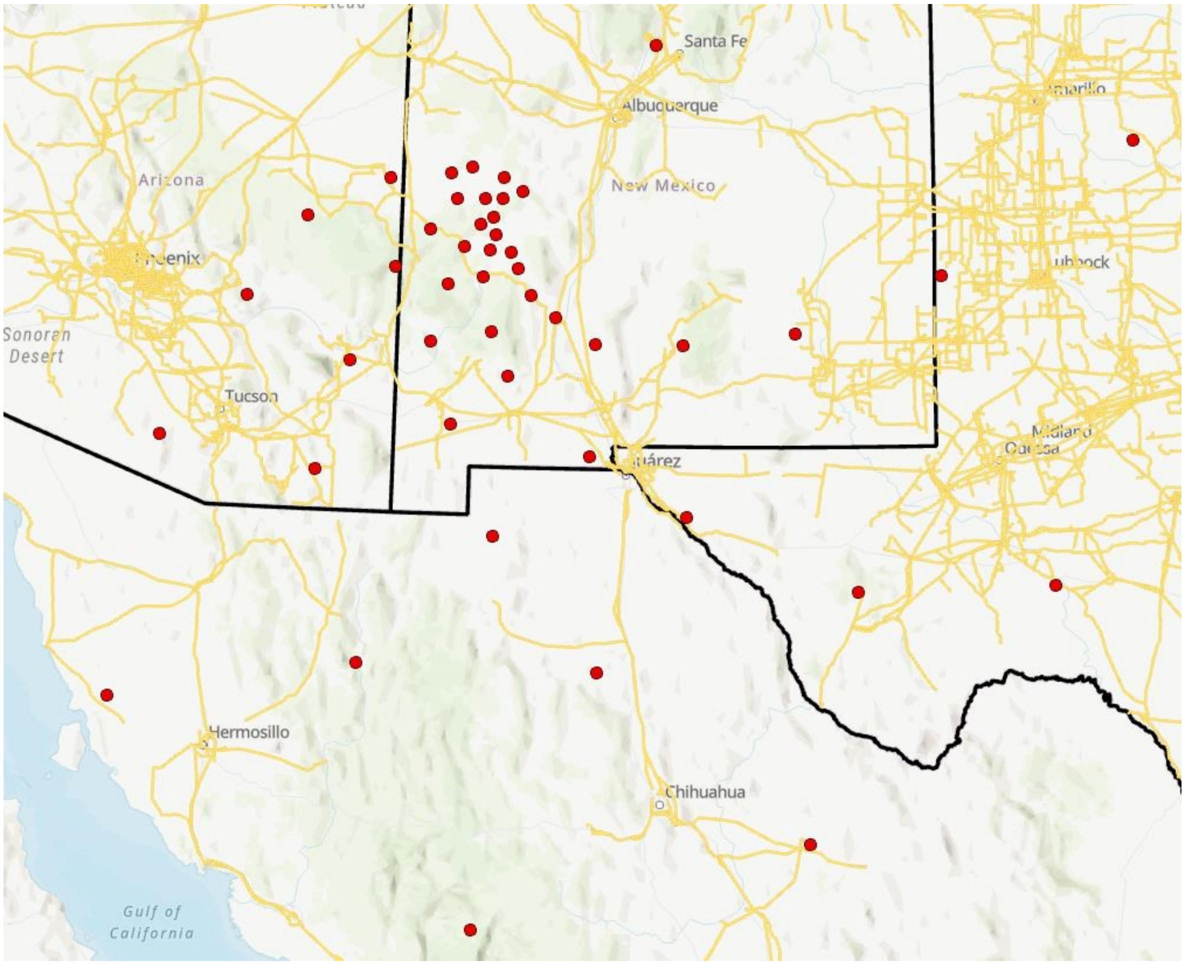

Figure 7: High voltage lines in the Southwest US and Northern Mexico in relation to Rev E Mid sites (red dots).

such as high voltage transmission lines, decreases with distance.

The plains of San Agustin are mostly devoid of high voltage lines (45KV to 510KV; Figure 7) that would interfere with the SBA, Core, or Spiral sites but high voltage lines are a significant concern when siting Mid sites. For high voltage transmission lines, a distance of 6 km or greater is considered to be acceptable, resulting in negligible RFI interference (Email Communication, Rob Selina). Site-specific assessments (from Crane, 2010) can be made for situations where the candidate site is closer than 6 km or if the voltage of the line exceeds 510KV. Terrain shielding can also be an acceptable method of high voltage RFI mitigation. Sites may be placed so that topographic rises interrupt line of sight or can be placed on ridges above high voltage lines with enough setback from the slope break so that the ridgeline shields the site.

There are frequency/spectrum monitoring firms that can establish probable RFI levels for a particular location by reviewing FCC licensed transmitters. While unlicensed transmitters would not be included, such a study may prove beneficial for early RFI exploration as it can help rule out any sites with unexpectedly high RFI levels or levels that exceed scientific tolerance. The main benefit of an RFI study would be to eliminate any sites with exorbitant RFI early in the site selection process before significant time is spent on their analysis in other areas. Once site visits begin, an RFI survey at each site would establish actual RFI levels, including any unlicensed transmitters. Given the time before construction is expected to start, it is quite possible that the RFI landscape will change for many sites prior to construction. RFI will almost certainly increase over time because communication towers will be constructed and development will continue as the years pass.

9 Hazards

Hazard analysis is crucial for site selection in order to avoid costly damages and reduce antenna down time. Locating in areas prone to damage from floods, landslides, fires, sinkholes, subsidence, or any number of various hazards can be detrimental to the antenna. Other hazards, such as site security issues, may be less obvious but are equally important to consider. Directive AAC0707 for Rev D states "It is desirable that sites have rural neighbors who may provide indirect site security checks" (Carilli et al., 2022; Mason, B., et al., 2022). While it is not possible to mitigate all hazards completely, it is possible to choose sites least likely to be affected by known issues.

The Federal Emergency Management Agency (FEMA) publishes the National Risk Index as a shapefile. Primarily used by insurance companies, the National Risk Index provides scores and ratings for the expected annual loss from each risk in a given geographic area. The 18 natural hazards contained in the National Risk Index are Avalanche, Coastal Flooding, Cold Wave, Drought, Earthquake, Hail, Heat Wave, Hurricane, Ice Storm, Landslide, Lightning, Riverine Flooding, Strong Wind, Tornado, Tsunami, Volcanic Activity, Wildfire, and Winter Weather. Information from this shapefile was used to check Rev E Mid sites for any significant hazard exposure.

Sinkholes, faulting, and subsidence were checked through other means. Sinkholes and faults or fractures are not explicitly addressed in the National Risk Index and can cause extensive damage to foundations. Mid sites in southeastern New Mexico and western Texas are most at risk for sinkhole and subsidence damage, while fault damage can occur near any active fault zone. To mitigate this risk, sinkhole and faulting information were analyzed in ArcGIS. Aerial photography was examined near site locations in southeastern New Mexico and western Texas to search for probable sinkhole scars within dither zones. A search for shapefiles related to sinkholes produced few options. The sinkhole shapefiles located for the project area were both incomplete and on a very localized scale. A USGS publication, "Karst in the United States of America: A digital map compilation and database Quaternary faulting" included shapefiles showing areas with potential for karst and pseudokarst development. This information was also used to exclude potentially unstable areas from site consideration.

Quaternary faults are faults that have moved in the last 2.58 million years. For the purposes of the project, these faults with recent movement would be the most likely contributors to fault or fracture damages. The USGS "Quaternary fault and fold database for the United States" provides shapefiles for Quaternary faults. These shapefiles were used to exclude any faulted areas and fracture zones from site consideration. Soil subsidence can also cause foundation issues and may even contribute to tilt of the antenna over time. The USDA maintains a Web Soil Survey which includes information on mapped soil types. Information can include data on properties such as subsidence, compaction, and potential to corrode concrete or steel. Soil properties for Rev E Mid sites, if available, will be checked against the USDA database. Since the soils mapped may be incomplete or the survey may have generalized over a wide area, site specific soil analysis is still recommended.

Wildfires are a significant hazard and are unpredictable. However, the burn scars from fires, especially on steep slopes, can leave land susceptible to landslides and mudflows after intense rainfall. New Mexico has a shapefile for wildfire burn scars and similar information presumably exists for other states. This analysis is somewhat limited by time as there may be additional wildfires in the future, prior to construction, or once the antenna is in place, that could leave burn scars with potential to damage equipment.

Site security will be extremely important from the construction phase onward. In both the US and Mexico there are areas where the local population may be amenable to the project and willing to check in on or watch over the site and equipment. In other areas, it may not be safe to leave equipment unattended due to high incidences in the area of vandalism or theft. ArcGIS has many shapefiles that could assist with assessing crime in areas near planned antenna sites. As site selection progresses, these layers may be employed to determine which alternate sites would have the best security. In addition, site visits, combined with talking to local residents, could provide a plethora of information on current conditions.

Safety hazards, such as exclusion zones, can also be assessed through ArcGIS. The safety exclusion zone is the area around that antenna that needs to remain clear for safety purposes. It also restricts how close antennas can be placed near each other and the minimum distance any roads or equipment need to be from the antenna. Safety exclusion zones affect placement of SBA and Core antennas most but are also relevant for Mid sites with regards to site size, as well as road and equipment placement.

10 Site Selection Process

The process of selecting a suitable site requires applying the criteria stated above but it also involves understanding the interplay between all requirements. Each potential site is evaluated based on examination of the unique characteristics of the area. With so much information to be considered, it is not helpful to analyze all layers at once in GIS when selecting a site. Rather, individual layers are turned on and off to examine their relationship to the topography and each other until all suitable site candidates are identified and other sites excluded. The suitable site candidates are then examined to see which would be the most cost effective and to discover any other qualities that might be exceptionally beneficial. The site that would require the least cost expenditure is chosen (unless there are other mitigating factors, as mentioned below) and all other suitable sites become alternate sites.

Not all sites will perfectly fit the desired guidelines but if a site excels in one area, it may be worth allowing leniency in other criteria. For example, if a site has a significant topographic advantage which produces an excellent line of sight, it may be worth having an access road that is a bit longer drive to a main road. In areas where there are limited potential sites within the dither range, the best site may not perfectly fit all criteria or might be slightly outside the dither range. The dither range is a significant constraint because if too many sites fall outside the dither range, there may be a need to rework or rotate the array. Every attempt is made to locate sites within the 10% dither range when possible to avoid the need to move the entire array.

Within the dither range, topography is the next criteria evaluated. Many site locations are just not possible due to steep terrain or impassible road grades that would be required for access. Suitable sites should be relatively flat and not on slopes, not in drainages, preferred on ridges or higher terrain, and without topographic obstruction that obviously hinders line of sight. Any areas that pass these checks are then examined to see if they fall in environmentally sensitive areas or regions that restrict development such as protected species habitats, conservation areas, AOCEC, inventoried roadless areas, wilderness areas, wilderness study areas, national parks, historic/cultural area (where data are available), wild horse herds, wildlife refuge, conservation easements, and others. Land ownership is determined and sites are selected to represent as many ownership varieties as possible. These sites are then examined to see if they are located on or near mining claims, grazing allotments, or other special ownership status that may need consideration.

Site proximity to road and power access is measured and priority is given to sites closest to existing well-traveled roads and power. If power shapefiles are available, the distance to three-phase power and the nearest single-phase power are calculated. Where power data are not available, the area is examined to see if there are visible powerlines on an aerial or nearby towns, ranches, or houses that may have power. Obvious impediments to site access, such as restricted areas or seasonal road closures, are noted. Sites are then examined for RFI, faulting, and obvious subsidence concerns.

RFI analysis in GIS involves checking for cellular or other transmitters, nearby cities or busy roads, solar farms, and airstrips. If other sources of significant RFI are identified, such as military bases, sites are moved or excluded as necessary. Examination of Quaternary faults, ground motion potential, and aerial photography (looking for pock marked areas that may represent sink holes or subsidence) allows identification of any sites that could be impacted by ground movement or subsidence. Soil subsidence and compaction data, where available, are considered and noted as well. Finally, sites are evaluated for potential hazards. The FEMA hazard layer is overlain with additional layers representing strong winds, significant weather events, and wildfire scars. Any sites with significant hazards are noted and if the hazard is unmitigable, the site is removed from consideration.

11 Summary

Site selection is a multifaceted process that includes input from multiple divisions. ArcGIS is a useful tool to explore potential site locations but criteria and guidelines must be clearly identified to ensure chosen sites have the best chance of proceeding to the construction phase. The following table (Table 1) lists current site criteria used to evaluate Rev E Mid sites (some criteria may differ from Rev D criteria). All items listed are guidelines and not absolutes. An ideal site would meet all criteria, while some sites that are in particularly challenging areas may require leniency in one or more criteria.

Table 1: Summary of Mid Siting Criteria

Criteria	**Directive**	**Source**
Sites should be within 10% dither range.		Carilli, 2023
Good baseline (uv) coverage over a range of scales		Carilli, 2023
Southern latitudes for good sky coverage		Carilli, 2023
Avoid line of sight to radio frequency interference (RFI) transmitters.		Carilli, 2023
Elevation of greater than 1750 m if possible.		Carilli, 2023
Elevation less than 2500 m (HVAC restriction)		Walker, 2022
PWV (precipitable water vapor) less than 6 mm		Carilli, 2023
Average wind speed of less than 5 m/s (for high frequency performance, opacity, phase stability)		Carilli, 2023
Avoid close terrain obstructions (within 10°) to the horizon		Carilli, 2023
Site slopes of 3° or less preferred, up to 6° allowed.		Carilli, 2023; Selina, 2023, Established in this document
Minimum site size of 100 m by 100 m desired.		Established in this document
Sites and alternate sites shall be chosen on a variety of land ownership to provide options at the land acquisition and permitting stages.	Modified from AAC0601	Established in this document; modified from Carilli, C., et al., 2022; Mason, B., et al., 2022
Ejidos in Mexico will be avoided if possible.		Established in this document
Active and identified mining areas (including surface and subsurface) will be avoided if possible.		Established in this document
Alternate sites are to be identified on a variety of land options based on the types of land ownership within or near the dither range.		Established in this document

Table 1: Summary of Mid Siting Criteria Continued

Criteria	Directive	Source
Sites shall be screened for environmental impact, such as overlap with identified endangered species habitat.	AAC0602	Carilli et al., 2022; Mason, B., et al., 2022
The design and construction of utility corridors and roads shall minimize the impact on grasslands and water within the Plains of San Agustin.	INF4000	Selina et al., 2022
Any fences shall not impede the flow of cattle and wildlife within and between neighboring ranches, or significantly increase the travel distance to water sources.	INF4003	Selina et al., 2022
The project shall aim to reduce the environmental impact to cattle ranching as well as hunting/outfitting, which are both mainstays of local ranches.	INF4004	Selina et al., 2022
Existing roads and infrastructure will be used whenever feasible to minimize disturbance.		Established in this document
Sites will be located as close as possible to a well-maintained road, with 2 km or less preferred.	Modified from AAC0701	Established in this paper; Modified from Carilli et al., 2022; Mason, B., et al., 2022
Site roads should have slopes less than 6° ($\sim$10.5% grade) with local exceptions possible on a site by site basis.		Established in this document
Sites shall have clear access for maintenance at all times. i.e. no predicted access restrictions or seasonal roads.	AAC0702	Carilli et al., 2022; Mason, B., et al., 2022
Road widths and lengths shall be minimized to reduce the destruction of top soil. The road design shall aim to avoid the collection of water into new ditches or arroyos that will exacerbate soil erosion.	INF4001	Selina et al., 2022
Existing ranch roads shall be assessed for suitability in both construction and operations. It is a goal to reuse existing roads where possible.	INF4002	Selina et al., 2022

Table 1: Summary of Mid Siting Criteria Continued

Criteria	Directive	Source
Sites will be located as close as possible to power (three-phase if available), with 2 km or less preferred.	Modified from AAC0703	Established in this paper; Modified from Carilli et al., 2022; Mason, B., et al., 2022
Sites shall be selected assuming "home run" fibers are required from the site to the correlator. Total fiber transmission distances shall be minimized through shared right-of-way and trenches.	AAC0705	Carilli et al., 2022; Mason, B., et al., 2022
Sites not connected by dark fiber will be located as close as possible to an existing fiber network, with 2 km or less preferred.	Modified from AAC0704	Established in this document; Modified from Carilli et al., 2022; Mason, B., et al., 2022
It is desirable that sites limit line of sight to public roads, transmitters, and other known sources of RFI.	AAC0706	Carilli et al., 2022; Mason, B., et al., 2022
Sites will be located at least 6 km away from high voltage lines. If a 6 km distance is not advantageous, the RFI will be calculated and the site evaluated based on the result.		Established in this document
It is desirable that sites have rural neighbors who may provide indirect site security checks.	AAC0707	Carilli et al., 2022; Mason, B., et al., 2022
Sites will be evaluated for hazards and any significant potential hazards will be noted.		Established in this document
Safety exclusion zones will be defined for each antenna.		Established in this document

12 Future Refinements

A list of Mid site candidates and alternate sites was circulated for review in mid-January. Though the arrangement of the sites was acceptable in preliminary scientific reviews, additional information was gathered afterward that further refined site criteria. As a result, it became apparent that documenting the criteria (in this memo) used to assess Rev E Mid sites would be beneficial not only for the current analysis but also to establish what has been reviewed, the extent of the review, and any limitations. The review of Rev E was planned to conclude on or about October 1st 2024 and any changes thereafter would be included in the next revision. However, in the process of preparing this manuscript items were identified that necessitated a reworking of the array, moving the configuration into Rev F.

The main issue was that the mathematical design of Rev E did not closely follow infrastructure corridors, particularly in the AZ-NM region. While all sites were located as close as possible to power and roads, every attempt was made to keep the sites within the dither ranges. Unfortunately, for some sites the only power available in dither ranges was single-phase power and the only roads available were poorly maintained dirt roads. Providing three-phase power and adequate road access to these sites would greatly increase the cost of construction so it was determined that the best way to address the lack of infrastructure was to rework the array with the science group identifying sites closer to infrastructure corridors that would still provide good scientific results. The science group is still examining what will become Rev F but the current revision relocates about half of the Mid sites from Rev E in the AZ-NM region. At this time, the sites in Mexico and Texas are unchanged from the January release of Rev E sites. However, this is subject to change as Rev F evolves.

Once the science review of Rev F sites is complete, the Rev F sites will be analyzed according to the criteria set forth in this memo for Rev E sites. The Rev F sites will also undergo additional analyses focusing on distances from high voltage lines, line of sight obstructions, and exact road grades. HV line proximity is important because HV lines produce significant RFI. The distance at which the RFI from HV lines becomes negligible is quantifiable and for most cases a distance of 6 km or more away from HV lines results in insignificant RFI. Sites were initially placed to take advantage of the best line of sight possible but ArcGIS can quantify any obstructed line of sight by percent obscured and direction, which provides much more detail on percent of sky available. Tree cover will also be included in these analyses where information is available. Road grades were estimated based on topography when choosing Rev E Mid site locations with obviously steep grades avoided. However, a more rigorous review of road placement will be part of the Rev F analysis. As more information is obtained, other site review criteria may be required. The land acquisition and the permitting process will also certainly result in additional site reviews.

Future revisions will involve reaching out to power companies, either for shapefiles or by submitting a request for service inquiry, to obtain more information about power availability near sites. Detailed examination of soil properties and hazard assessments will be addressed in subsequent revisions. Site visits to verify and/or quantify tree coverage, line of sight, and other issues will be required. RFI studies, either remotely or on site, will provide a wealth of information beyond what can be supplied through GIS. As the project moves towards construction, land acquisition and regulatory compliance will dictate additional site adjustments. Preliminary site analysis allows only the most viable sites to become candidates for additional evaluation, saving time and reducing costs. While there is still much to do, the preliminary site analyses completed with GIS provides a solid foundation on which to make refinements in future revisions.

13 Acknowledgements

The author would like to thank the following persons for their review of the manuscript, helpful discussions, and thoughtful input: Jon Cooper, Alfonso Trejo, Craig Walker, William Howjnowski, Rob Selina, Brian Mason, Chris Carilli, Eric Murphy, Sanford George, and others who worked on project documentation that helped define site selection criteria. This manuscript would not have been as complete without their contributions.

14 References

Carilli, C., (2023). Site Selection Criteria. [Unpublished Document]. NRAO.

Carilli, C., et al., (2022). Array Configuration: Design Description, Ver. C. NRAO Document No. 020.23.00.00.00-002-DSN.

Carilli, C., et al., (2021). Configuration: Reference Design Rev D Description. NRAO. ngVLA Memo Series 92.

Crane, P. C., (2010). Radio-Frequency Interference (RFI) From Extra-High-Voltage (EHV) Transmission Lines. Long Wavelength Array (LWA) Memo Series 168. March 22, 2010. https://leo.phys.unm.edu/~lwa/memos/

George, S., and Selina, R., (2024). Email Communication.

Mason, B., et al., (2022). ngVLA Array Configuration: Technical Requirements. NRAO Document No. 020.23.00.00.00-0001-REQ.

Selina, R. and Bryant, C., (2023). ngVLA Remote Site Concept Site Plan. NRAO Project No. 020.60.00.00.00, DWG No. 020.60.00.00.00-0005.

Selina, R. and Dunbar, D. (2022). Antenna Technical Requirements. NRAO Document No. 020.25.00.00.00-0001-REQ.

Selina, R., et al. (2022). ngVLA Civil and Infrastructure Subsystems Requirements Specification. NRAO Document No. 020.60.00.00.00-0003-REQ.

Trejo, A. and Watson, L. (2023). First characterization of MID locations in Northern Mexico. IRyA, NRAO. ngVLA Memo Series 111.

U.S. Geological Survey (USGS) Gap Analysis Project (GAP) (2022). Protected Areas Database of the United States (PAD-US) 3.0. U.S. Geological Survey data release. https://doi.org/10.5066/P9Q9LQ4B.

U.S. Geological Survey and New Mexico Bureau of Mines and Mineral Resources, Quaternary fault and fold database for the United States. https://www.usgs.gov/programs/earthquake-hazards/faults

U.S. Department of Agriculture (USDA) Web Soil Survey. Soil Survey Geographic Database (SSURGO). https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

Walker, Craig R. (2022). Enhanced Central Condensation Options for the Configuration of ngVLA MID. NRAO. ngVLA Memo Series 102.

Walker, Craig R. (2018). Snapshot UV Coverage of the ngVLA: An Alternate Configuration. NRAO. ngVLA Memo Series 49.

Weary, D. J., and Doctor, D. H., (2014). Karst in the United States of America: A digital map compilation and database Quaternary faulting. USGS Open-File Report 2014-1156. https://doi.org/10.3133/ofr20141156