ngVLA Memo no. 137
ngVLA Long Baseline Station Layout

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Abstract

The ngVLA project will replace both the Very Large Array and the Very Long Baseline Array (VLBA) with a single instrument. The long baseline stations of the ngVLA will have multiple antennas in a single location to improve total collecting area and allow for improved phase calibration using new techniques and technologies like water vapor radiometers, fast switching, paired antenna calibration, and Multiview. This memo describes considerations for site layout. We find, based on VLBA data, that the orientation of the antennas at each site does not greatly impact the amount of shadowing incurred in total. At sites that generally have lower humidity, an antenna separation of 80 meters should be acceptable to minimize shadowing and allow for paired antenna calibration. At sites with higher humidity, placing the antennas between 40 and 60 meters apart will allow for paired antenna calibration and should not experience significant shadowing.

1. Introduction

The Very Long Baseline Array (VLBA) will eventually be replaced by the Next Generation Very Large Array (ngVLA). The long baselines of the ngVLA will be made up of stations comprising three antennas. The locations of the long baseline stations have been discussed in Memos 84 and 105. Since each station is expected to have 3 antennas, some thought needs to be put into layout for the stations. With three antennas, an equilateral triangle should be used minimize spacing for all antenna pairings, and to limit shadowing to a single antenna at any given time. Both physical and scientific constraints need to be considered when determining site layout, and we attempt to do that below.

2. Physical Constraints

Several physical constraints will limit the antenna layout at each site. Most of these constraints will be common to all sites, but local topography and available space will also need to be considered. Since nominal sites are selected, but no final sites are selected, we cannot address specific site-constrained issues.

Firstly, both the standard and low elevation variants of the ngVLA antenna must be a minimum of 38 meters apart to prevent collisions. This establishes a lower limit for baseline length within a site. Although it has not been formally investigated, it is also plausible that RFI emission from antennas can interact with each other. The RFI effects should be tested when the test antenna is installed at the VLA site in 2026. Since this effect is unknown, it will not be incorporated into this memo.

Second, ngVLA antenna design has a 12-degree elevation limit. These antennas will potentially shadow each other over a small range of azimuths when baselines are shorter than 85 meters. A long baseline antenna design is currently being generated and studied, with the primary added feature being an elevation limit of 7 degrees. These antennas will potentially be shadowed if they are closer than 147 meters. The tradeoff between calibration and shadowing will be discussed further below. One strategy to avoid the effects of shadowing would be to examine horizons at the site carefully. We should avoid high horizons as much as possible to avoid spillover from the horizon and blocking parts of the sky. If we cannot avoid higher horizons, we can strategically place antennas within the horizon to minimize shadowing.

We will also have to carefully consider how to lay out sites that currently have a VLBA antenna or will have a geodetic antenna that used the ngVLA low elevation antenna design. If the VLBA antennas still exist at the time of ngVLA LONG construction, we will have to work within the constraints of the existing site to find space for three new ngVLA antennas. If NRAO builds a geodetic array and those selected sites overlap with ngVLA sites, we will have the opportunity to create an overall site layout to optimize 4 antennas at a site.

3. Scientific considerations

The primary scientific consideration is the effect of antenna separation on the paired antenna calibration method. This calibration method is likely to be used for high frequency observations, and projects using fast switching or a proven water vapor radiometer systemare unlikely to be affected by different baseline lengths.

A higher RMS phase indicates larger changes in phase over short time periods, leading to loss of coherence and difficulties in imaging. Essentially, this measurement tells us how rapidly the phase is changing. Typically, this change is caused by the ionosphere at lower frequencies and the troposphere at higher frequencies. Using the total electron content along the line of sight has proven to be an effective strategy to remove systematic gradients in ionospheric activity at lower frequency, and studies are investigating the use of total electron content models to correct for the rapid fluctuations. Phase referencing can be used to remove tropospheric effects, but at higher frequencies the atmosphere changes more rapidly, and to avoid coherence loss, one needs to observe your calibrator more often. This is called fast switching. Another method, Paired antenna calibration, uses one or more antenna to observe phase calibrators while the other antenna(s) observes the target.

From Carilli and Holdaway, 1999, the phase noise from the troposphere scales with the baseline length to the nth degree. The exponent is dependent on the width of the turbulent layer of the atmosphere relative to the baseline length. In each high frequency calibration method mentioned above, the baseline

Case	Phase Referencing Method	Approximate Calibration Phase RMS error at 43 GHz (deg.)		
		Good Sites	SC – Obs. 1	SC – Obs. 2
0	Contribution from 2° calibrator-target offset	10	46	29
1	Fast switching, VLBA (50 sec). Includes calibrator interpolation error	15	80	49
2	Fast switching, ngVLA single antenna (30 sec.). Includes calibrator interpolation error and offset source error	13	64	40
3	Fast switching, ngVLA single antenna (30 sec.), single source interpolation only. Used for other calculations	9	44	28
4	Paired antennas 100m between antennas, no gradient used. Use 10 sec points from Memo 110	9	44	33
5	Paired antennas 50 m, no gradient used. Use 5 sec. points in from Memo 110	7	33	21
6	Four antennas. Weighted quadrature sum of 100m paired antenna RMSs (case 4) with 3 calibrator antennas. Weights 0.333 each. Results applied simultaneously to target observed with the fourth antenna	5	27	19
7	Four antennas. Same as Case 6, but with 50m spacing	4	19	12

8	Four antennas. 100m. Gradient interpolation. Alternate calculation for the same data as case 6	6	32	21
9	Four antennas. Like 8, but for 50m.	5	19	13
10	Three antennas. Weighted quadrature sum of 100m paired antenna RMS at 2 calibrator antennas. Weights 0.5 each	6	32	23
11	Three antennas. Same as 10 but 50m spacing	5	23	15
12	Three antennas, 100m. One each continuously observing the primary calibrator and target, and one fast switching between the other two calibrators. Determine gradient after interpolation. One antenna Case 3 and Case 6	6	30	21
13	Three antennas. Same as case 12, but with 50m spacing	5	24	15
14	Three antennas, switch between gradient and target scans.	Fluctuations similar to case 1-5, mainly for astrometry		

Table 1 -Table taken from ngVLA Memo 110, which estimates the RMS of the Phase from correlated data. The RMS was estimated from two separate calibrators in different observations. SC here denotes the Saint Croix VLBA site which has the highest phase RMS. The numbers after SC denote which observation the measurement was taken from. The rows highlighted in green indicate the rows that are relevant to this memo, namely fast switching, paired antennas, and two antennas on a calibrator and one on target.

can be replaced by an effective baseline. In the case of fast switching, the effective baseline is roughly $b_{eff} \approx d + \frac{v_a t_{cyc}}{2}$ where d is the physical distance in the troposphere between the calibrator and the source, v_a is the windspeed and t_{cyc} is the calibration cycle time. For paired antenna calibration, the effective baseline is $b_{eff} \approx d + \Delta b$ where d is again the physical distance in the Troposphere between the calibrator and source, and Δb the baseline between the main and calibration antennas. A quick analysis of the effective baseline, and therefore RMS of the phase, assuming the Troposphere height is 2 km, and source-calibrator separation of 2°, gives a d value of roughly 70 meters. At this point, the dominant source of phase error becomes the source-calibrator separation, and making antenna's closer provides only a marginal decrease in the RMS of the phase. I do note that ngVLA memo 98 states that current performance estimates for the ngVLA suggest a lower 3 sigma detection threshold of 10 mJy in 3 seconds at 93 GHz on a single baseline. This corresponds to roughly 19 degrees in phase RMS. With this threshold, the average distance between calibrators probably falls to 1 calibrator per square degree, meaning the average angle between source and calibrator falls to roughly 1 degree. This means d is cut in half, and the dominant effect in the RMS of the phase is the distance between the primary antenna and the calibrating antenna for baselines larger than 38 meters. This is the smallest possible distance between antennas within a station, and antennas must be further apart than 38 meters.

A deep investigation of the effect of antenna proximity can be found in ngVLA Memo 110 (Walker, 2023). In short, the study uses data from the VLBA, and assumptions about the height and windspeed of the troposphere, to make estimates for the RMS of the phase for different baseline lengths. Memo 110 assumes a Troposphere height of 1.4 km, and a windspeed of 10 m/s. It then looks at bright calibrator scans of real data after some initial calibrations are done to determine the RMS of the absolute phase difference every n seconds, where n is an integer from 1 to 60. It uses this data to infer the RMS phase at 43 GHz for various calibration techniques and scenarios. Table 1 is pulled directly from memo 110 and covers a number of calibration schemes, with the green highlighted cases specific to this site layout memo.

The suggestion from Memo 110 is that the antennas should be placed as close together as possible to optimize paired antenna calibration at high frequency for wet sites. Specifically looking at example 10 and 11 in the Table 1, the likely RMS phase at 100m separation would be 6 degrees at good sites, and up to 32 degrees at wet sites like St. Croix. For a separation of 50 meters, RMS phase at good sites is essentially the same, but at St. Croix it drops to ~23 degrees. This is calculated by equally weighting phase measurement of 2 antennas each observing calibrators near the target source, essentially reducing the phase in case 4/5 by the square root of two. The memo suggests this correction could likely be improved by better weighting and careful selection of calibrators allowing one to measure the phase difference between two points and properly interpolating based on rough tropospheric wind speed.

Alternatively, we do need to consider the scientific impact of shadowing. It is important to note that only one antenna will be shadowed at any given time, and it’s not immediately clear how often shadowing one antenna will be a problem. Placing the antennas approximately 40 meters apart causes shadowing to 24 degrees in elevation. This shadowing will cover roughly 50 degrees in azimuth and will severely limit access to the horizon. On 75-meter baselines shadowing occurs below 13 degrees elevation, which is roughly the limit for the standard ngVLA antenna. This will limit the total tracking time for at least one antenna. It will also limit the ability to carry out geodetic observations, which will be required to determine station positions.

These two tradeoffs are somewhat hard to reconcile. The United States Naval Observatory has paid for development of a low elevation antenna specifically to look at horizons to disentangle troposphere from station vertical. Though it’s not clear this is completely necessary, going on to limit antenna elevation to 20 degrees for parts of the sky would likely not meet requirements for USNO observations. USNO may be able to get around shadowing by utilizing subarrays and having all antennas observing the parts of the sky available to them. Then they could apply the information from a non-shadowed antenna to the shadowed antenna. Of course, there are no instruments in which this technique can currently be tested, so it's not clear this is a solution. It would also likely require software development from USNO, NASA Goddard, or some other group that has limited resource for that work.

On the other hand, the paired antenna calibration at high frequencies on ngVLA may be a well-used mode. The paired antenna calibration then becomes an important method, and a shorter baseline length will improve effectiveness of the paired antenna calibration method.

The paired antenna calibration will work at longer baselines at drier sites, so this conflict can likely be resolved at those sites. It seems then, that this needs to be resolved for the wet sites like Puerto Rico and Florida. Based on tables in Memo 110, Hancock, the next best site, should be capable of using the paired antenna calibration method at 93 GHz with two antennas observing calibrators and interpolating the measurement on the target on a 100 m baseline. To determine if there are other sites that would benefit from having closer baselines, further investigation into the weather at each site should be used to characterize current VLBA sites and planned ngVLA LONG sites.

Insight from the VLBA

Current VLBA stations do not have three antennas at each site, so the effects of shadowing cannot be directly measured. We can, however, use pointing data from the VLBA to study effects of antenna proximity on shadowing above 7 degrees elevation, the limit of the low elevation variant of the ngVLA antenna.

To study these effects, we gathered the last 5 years of pointing data for the VLBA sites. We note here that while observing below 5 degrees in elevation at any given site is not recommended, the VLBA can point to 2 degrees elevation. This can be seen in Figure 1. The data was separated into experiments focusing primarily on astronomy and experiments focusing primarily on absolute astrometry. Table 2 below shows the total number of telescope pointings at each site for astronomical and astrometric purposes.

Table 2- Total number of pointings at each site separated into astronomical and astrometric observations

VLBA Site	Astronomical Pointings (5 years)	Astrometric Pointings (5 years)
Brewster	12,248,784	4,196,492
Fort Davis	12,442,288	3,864,612
Hancock	11,455,403	5,169,622
Kitt Peak	10,774,657	3,397,629
Los Alamos	12,573,701	3,923,397
Mauna Kea	11,608,069	5,638,046
North Liberty	12,522,691	3,911,787
Owens Valley	12,327,150	4,276,305
Pie Town	12,235,842	4,080,571

St. Croix	10,939,628	4,336,465

Using this pointing information at each site, I simulated antennas being placed in an equilateral triangle at each site. For the first antenna, I simulated an antenna blocking the view at 0 degrees azimuth and an antenna blocking the view at 60 degrees azimuth. Antenna 2 would then have an antenna blocking it's view at 120 degrees azimuth and 180 degrees azimuth. The third antenna would have antennas blocking its field of view at 240 degrees and 300 degrees azimuth. For each of antennas 1, 2, and 3, I found the number of pointings blocked and then added them together to get the total number of pointings blocked for each antenna. Then I rotated so that antenna 1 had pointings blocked at 1 degree azimuth and 61 degrees azimuth and did the same thing. This was done through 120 degrees of rotation, as at that point the triangle would be in the same position as the initial setup.

The above process was repeated for antenna separations of 40, 80, and 120 meters. The percentage of pointings blocked was calculated by dividing the total number of blocked pointings by 3 times the total number of pointings for the given antenna shown in Table 2. The optimal layout is then selected as being the layout with the lowest percentage of blocked antennas, while the worst layout is the layout with the highest percentage of blocked pointings. These percentages for the optimal and worst antenna layouts are shown in Table 3.

Table 3 - Table showing the percentage of total VLBA pointings blocked assuming a triangular antenna layout separated by 40, 80, and 120 m.

Site	Separation	Astronomy (Percent Blocked)		Astrometry (Percent Blocked)	
		Best	Worst	Best	Worst
BR	40 m	1.1	2.2	1.7	3.5
	80 m	0.2	0.3	0.3	0.8
	120 m	0	0.1	0.3	0.9
FD	40 m	0.8	1.1	1.5	2.3
	80 m	0.1	0.2	0.2	0.4
	120 m	0	0.1	0.1	0.5
HN	40 m	2.0	2.7	2.6	3.9
	80 m	0.3	0.5	0.5	0.6
	120 m	0	0.1	0.2	0.3
KP	40 m	0.9	1.3	1.8	2.9
	80 m	0.1	0.1	0.2	0.4
	120 m	0	0	0.1	0.3
LA	40 m	0.9	1.5	1.8	3.0
	80 m	0.1	0.2	0.2	0.5
	120 m	0	0	0.1	0.4
MK	40 m	3.3	3.5	4.1	5.2
	80 m	0.6	0.8	0.7	1.2
	120 m	0.2	0.4	0.7	1.3
NL	40 m	1.1	2.0	1.8	3.4
	80 m	0.1	0.3	0.3	0.7
	120 m	0	0.1	0.2	0.8
OV	40 m	1.0	1.6	1.7	3.0
	80 m	0.1	0.2	0.2	0.6
	120 m	0	0	0.2	0.5
PT	40 m	0.9	1.4	1.9	3.0
	80 m	0.1	0.1	0.2	0.5
	120 m	0	0	0.1	0.4
SC	40 m	1.9	2.1	2.3	2.5
	80 m	0.3	0.4	0.4	0.5
	120 m	0.1	0.1	0.2	0.4

Table 3Table 1 demonstrates two things. First, for astrometric observations, having the antennas 40 meters apart blocks a significant amount of pointings on the critical longest baselines. Mauna Kea would have roughly 4-5% of pointings blocked. Hancock would have 2.5-4% of pointings blocked. This is more than the rate of pointings blocked during astronomical observations because astronomical observations don't get good quality data toward the horizon due to atmosphere, and the astrometric observations purposefully observe close to the horizon to disentangle added delay from the troposphere at zenith and errors in station vertical measurements from their observations (Sovers, Faneslow, and Jacobs, 1998). Second, the astronomical data shows that at 40 m separation, the difference in percentage of pointings blocked between the best and worst orientations is at most 1.8%. At 80 m that difference drops to at most 0.5%. The actual orientation of the antennas will most likely not make a significant difference in either case.

I do include the heat maps showing all pointing information for one antenna's view at Mauna Kea, Pie Town, and Hancock in Figure 1 below. The pointing information for the VLBA is offset in azimuth by 180 degrees, so the red lines in the figure below indicate the cardinal directions for clarity. The yellow rectangles roughly represent the amount of sky that would be shadowed by this orientation of the telescopes that causes the least amount of shadowing at each of the sites. The left plots show the shadowing of antennas separated by 40 meters, and the right plots show the shadowing of antennas separated by 80 meters. The yellow lines show the 5-degree elevation limit that USNO uses, the ngVLA Low Elevation antenna limit at 7 degrees, and the standard ngVLA antenna at 12 degrees. We note here that there are points below 5 degrees shown in our plot, and that the physical limit of the VLBA antenna is 2.5 degrees. The orange lines show the horizon at each site as documented in the VLBA scheduling program sched. Finally, while these three plots represent the distribution, the plots for the rest of the sites and antennas are added in the appendix for the curious.

Figure 1 highlights that mutual visibility is important for long baseline telescopes. The two antennas that are furthest from the center of the array, Mauna Kea in Hawaii and St. Croix in the Virgin Islands, have far fewer pointings away from the center of the array (i.e. Mauna Kea does not often point to the West and St. Croix does not often point to the East). The plots also show that the optimal array orientation does differ slightly between 40- and 80-meter antenna separations.

Though the specific layout doesn't likely matter much, I did plot the optimal layout for each site. Figure 2 shows the trend in the difference between the bearing of the geographical center and the bearing of the optimal layout. The bearing of the optimal layout is defined as the vector from the vertex to the opposite side that is closest to the bearing of the geographical center from the center of the triangle. The figures showing the optimal layout including the bearing of the optimal layout, and the bearing to the geographical center are included in the appendix. I then compared trends in optimal layout and latitude, longitude, and distance from the geographical center of the array. The trend plots are shown below. The best correlation is likely distance of the site from the geographical center, but it is not a strong correlation and for greenfield sites I do not think we could reasonably predict the optimal layout. Finally, I ranked the orientations based on percentage of pointings blocked, with 1 having the lowest percentage of pointings blocked and 120 having the highest percentage. Figure 3 shows the fraction of flagged pointings vs rank of the orientation. Again, it is not necessary to predict the optimal layout as the difference between the best and worst layouts typically amounts to less than 1% of total pointings.

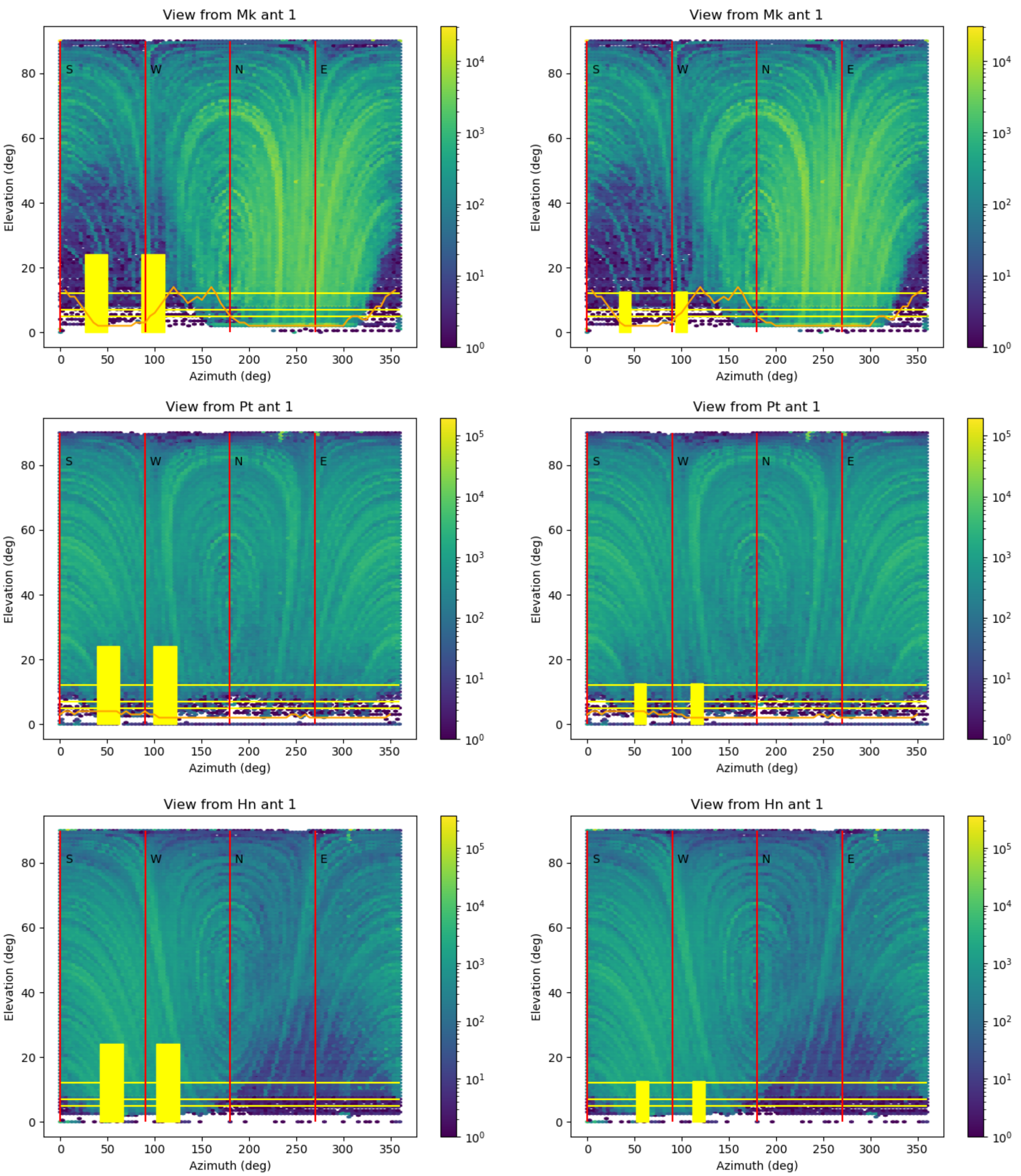


Figure 1 - Heatmap of astronomical pointing data from Mauna Kea, Pie Town, and Hancock VLBA antennas. The red lines show the cardinal directions, the yellow lines show the scientific elevation limits of 5 degrees for the VLBA, 7 degrees for the ngVLA low elevation antenna, and 12 degrees for the standard ngVLA antenna. The orange line represents the horizon at each of the sites. The yellow rectangles show the simulated placement of the other two LONG antennas at the site. Note that this shows a single, random orientation of the antennas. A similar plot could be made for all 120 antenna positions that constitute the full unique rotation. The left side shows antenna separation of 40m and the right side shows antenna separation of 80 m. While the listed elevation limit of the VLBA is 5 degrees, it can point to 2.5 degrees.

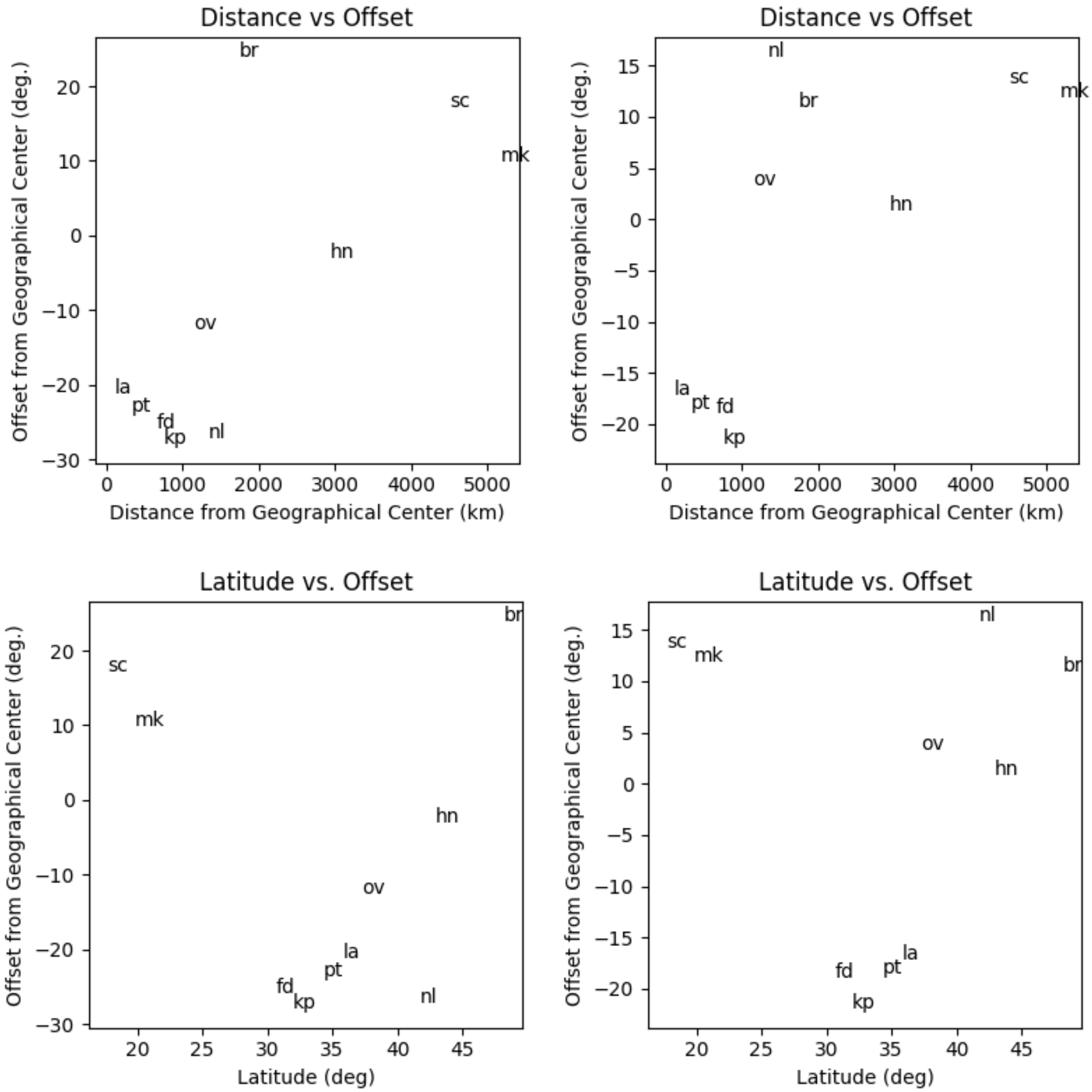
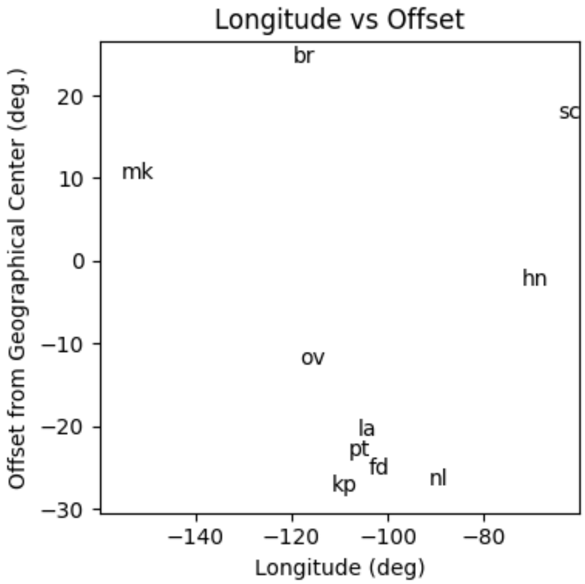
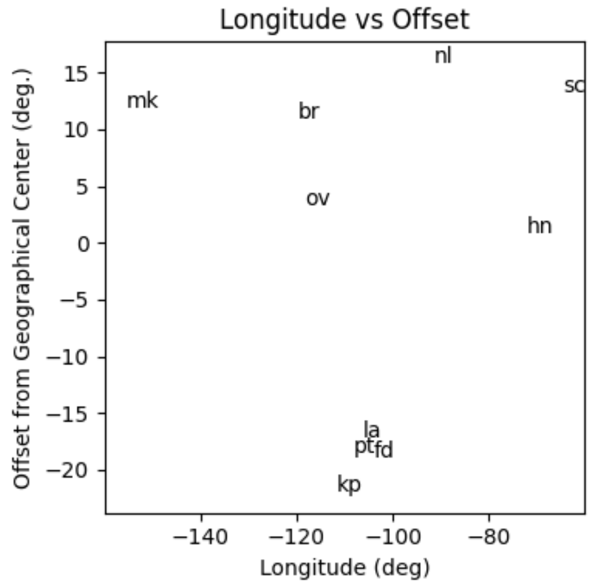


Figure 2 - Scatter plot of the bearing of the geographical center minus the bearing of the optimal layout. The left plots are for 40-meter separation, and the right plots are for 80 m separation.



Longitude vs Offset
Offset from Geographical Center (deg.)
Longitude (deg)
br
sc
mk
hn
ov
la
pt
fd
kp
nl



Longitude vs Offset
Offset from Geographical Center (deg.)
Longitude (deg)
nl
sc
mk
br
ov
hn
la
pt
fd
kp

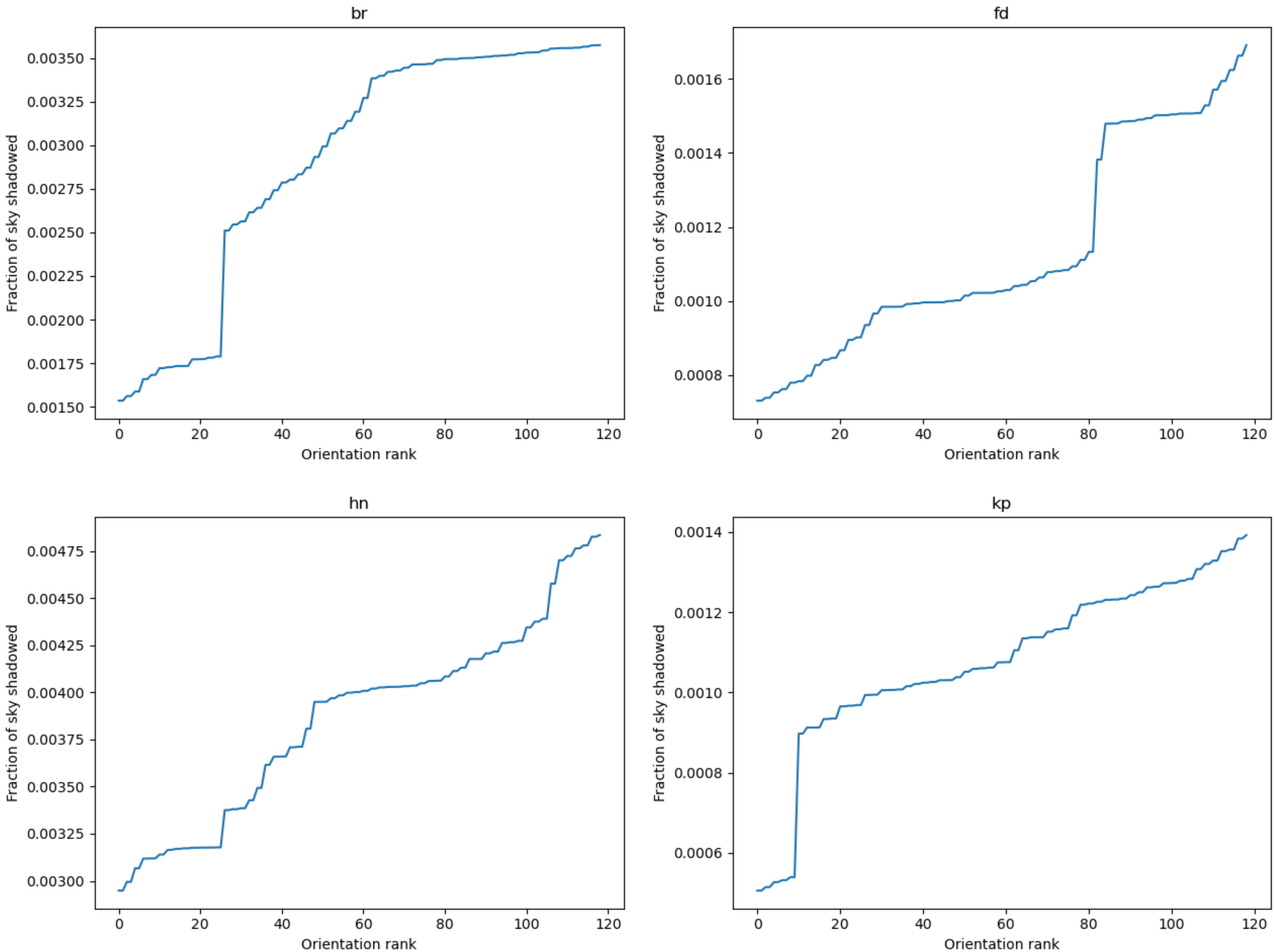
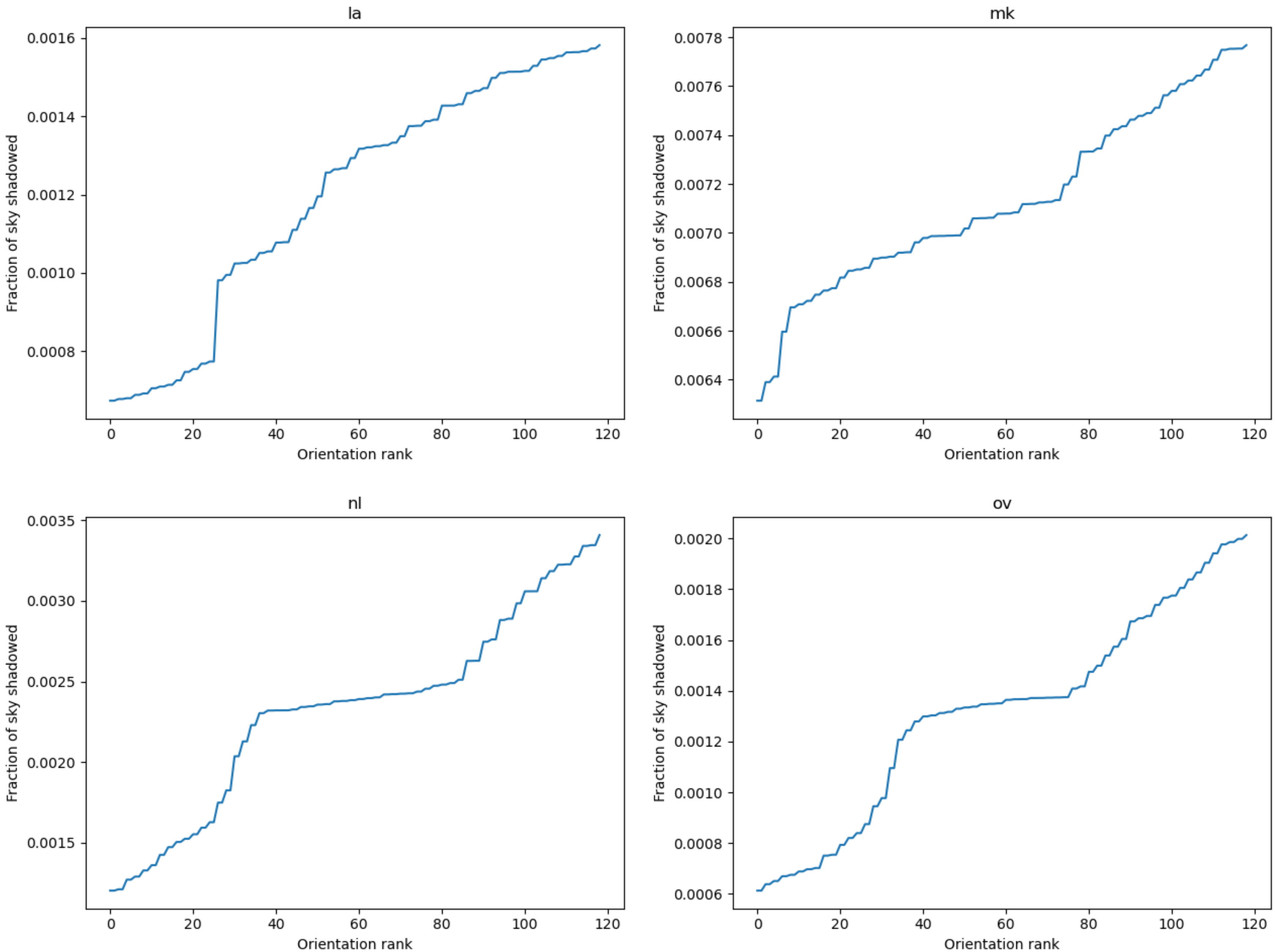
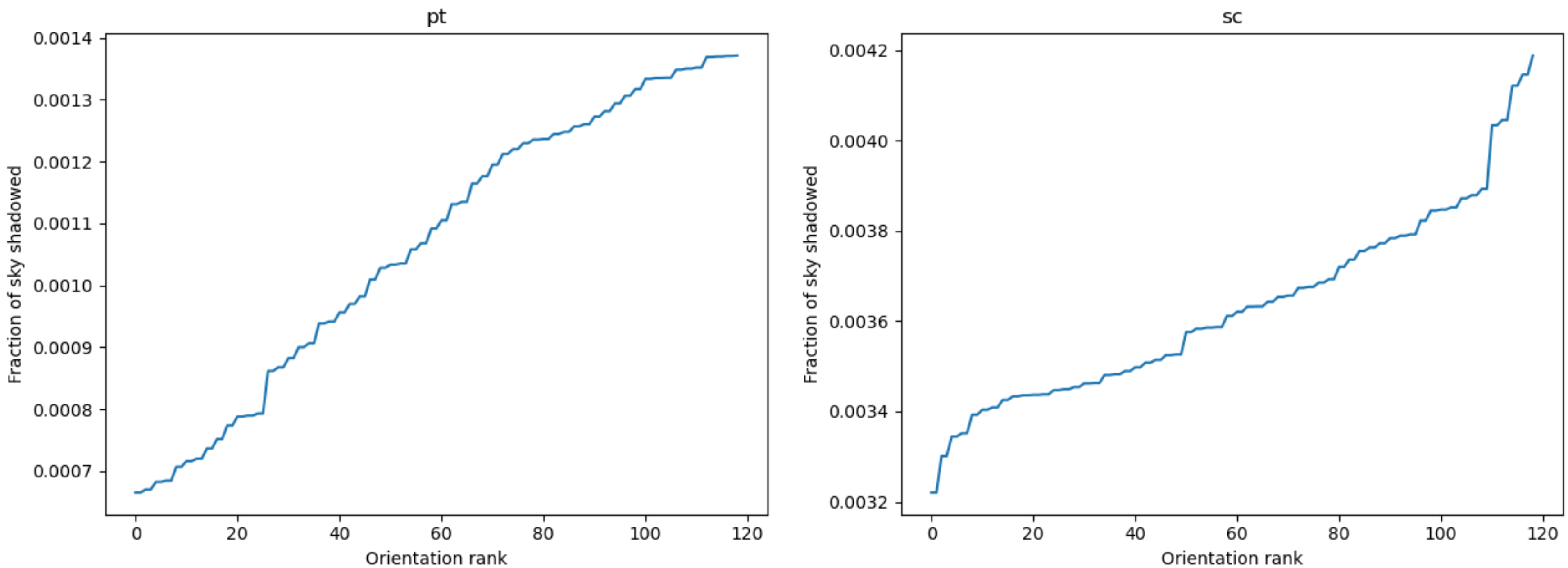


Figure 3 - How orientation changes the percentage of pointings blocked. The orientations were ranked from lowest fraction of pointings blocked to highest fraction of pointings blocked. The rest of the plots below are part of figure 3.



la
mk
nl
ov
Fraction of sky shadowed
Orientation rank
0.0016
0.0014
0.0012
0.0010
0.0008
0.0078
0.0076
0.0074
0.0072
0.0070
0.0068
0.0066
0.0064
0.0035
0.0030
0.0025
0.0020
0.0015
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0
20
40
60
80
100
120


pt
0.0014
0.0013
0.0012
0.0011
0.0010
0.0009
0.0008
0.0007
Fraction of sky shadowed
0
20
40
60
80
100
120
Orientation rank
sc
0.0042
0.0040
0.0038
0.0036
0.0034
0.0032
Fraction of sky shadowed
0
20
40
60
80
100
120
Orientation rank

Conclusion

This memo suggests that antennas be laid out in a roughly equilateral triangle shape. If there are any high horizons, antennas should be placed so that they hide within the already obscured view. Orientation of the triangle at a given site does not have a significant impact on the total number of points shadowed for astronomical observations.

Future work should be done to determine typical atmospheric conditions for each site to determine how close the antennas need to be. Green Bank uses weather predictions to determine when observing conditions will be good for high frequency, and the VLA is currently trying to do something similar using past weather data. This can be adapted to work for the ngVLA and ngVLA LONG site selection.

Acknowledgements

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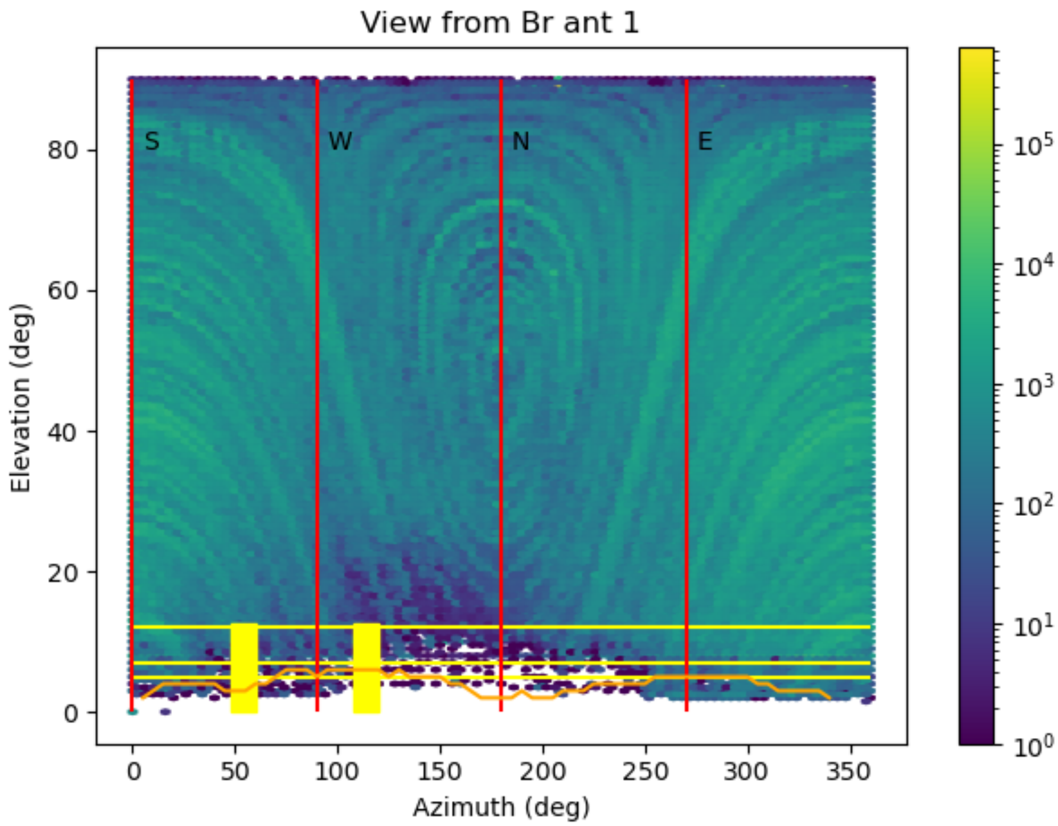
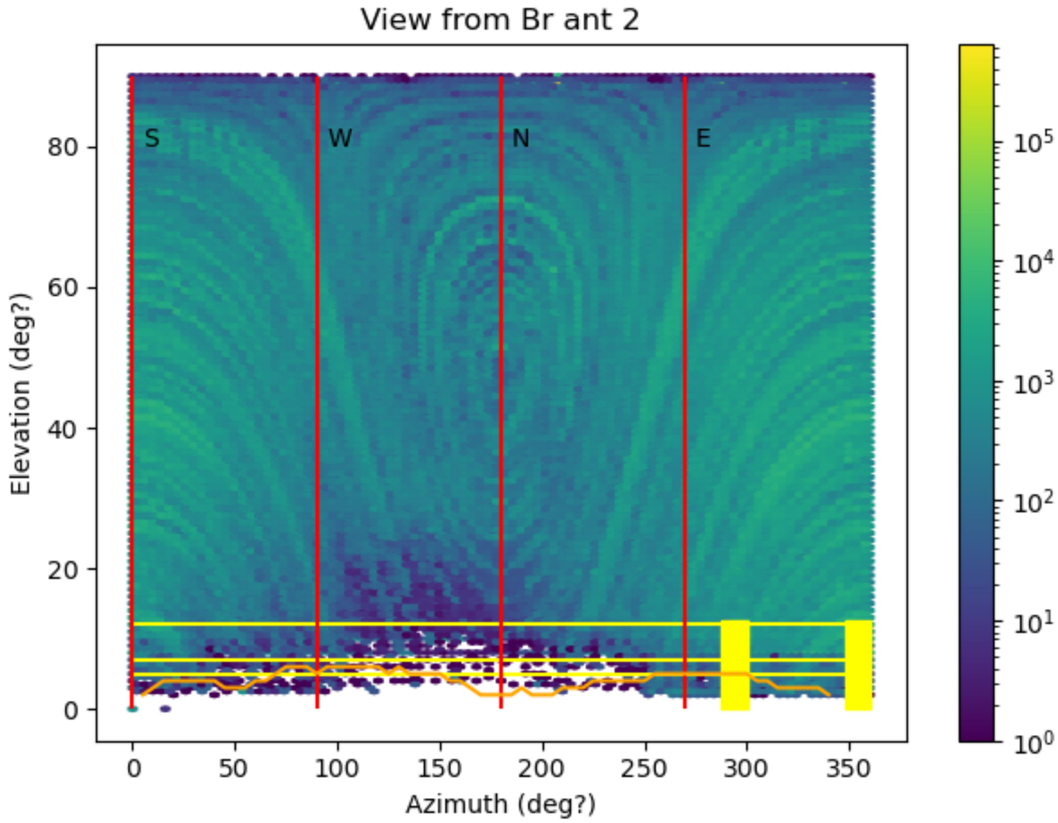
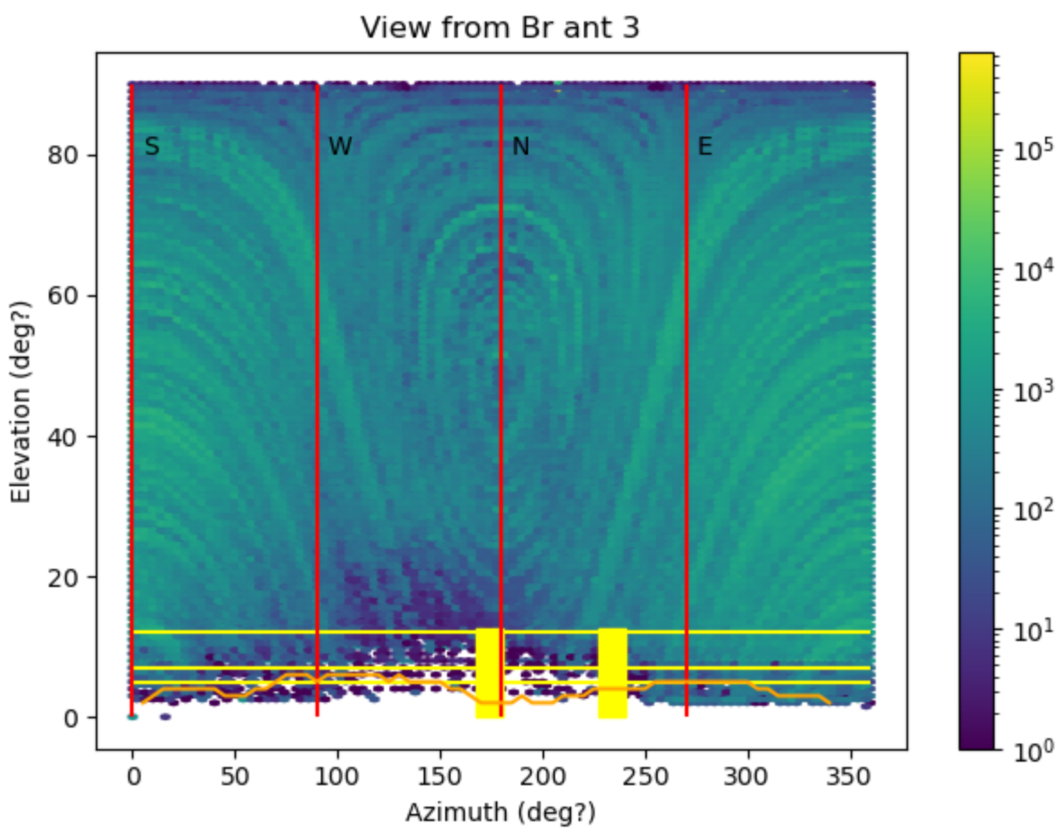
Appendix 1 – Pointing maps with 80m antenna separation

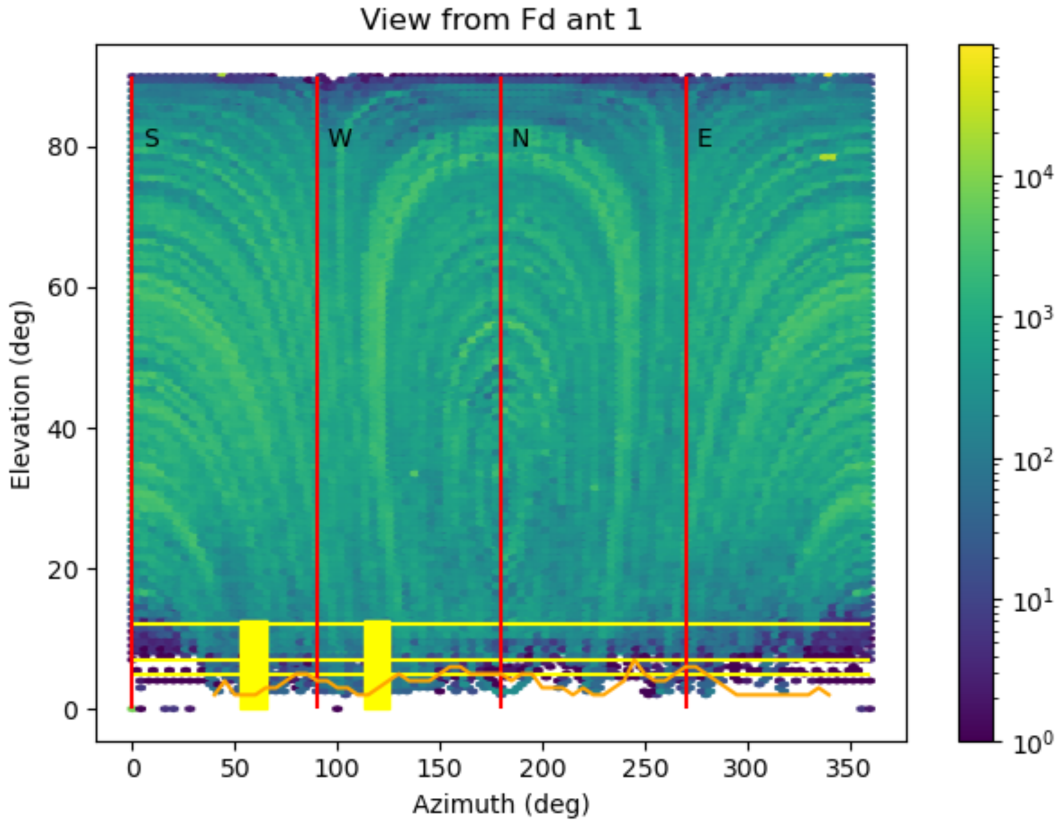


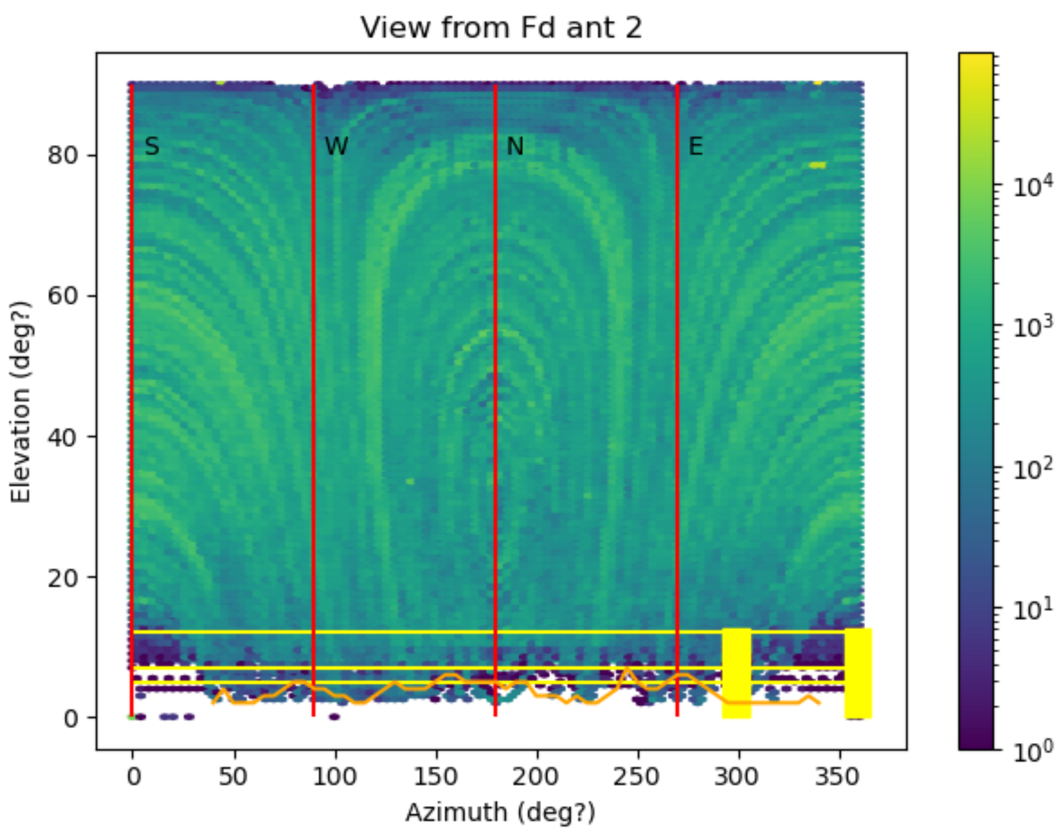


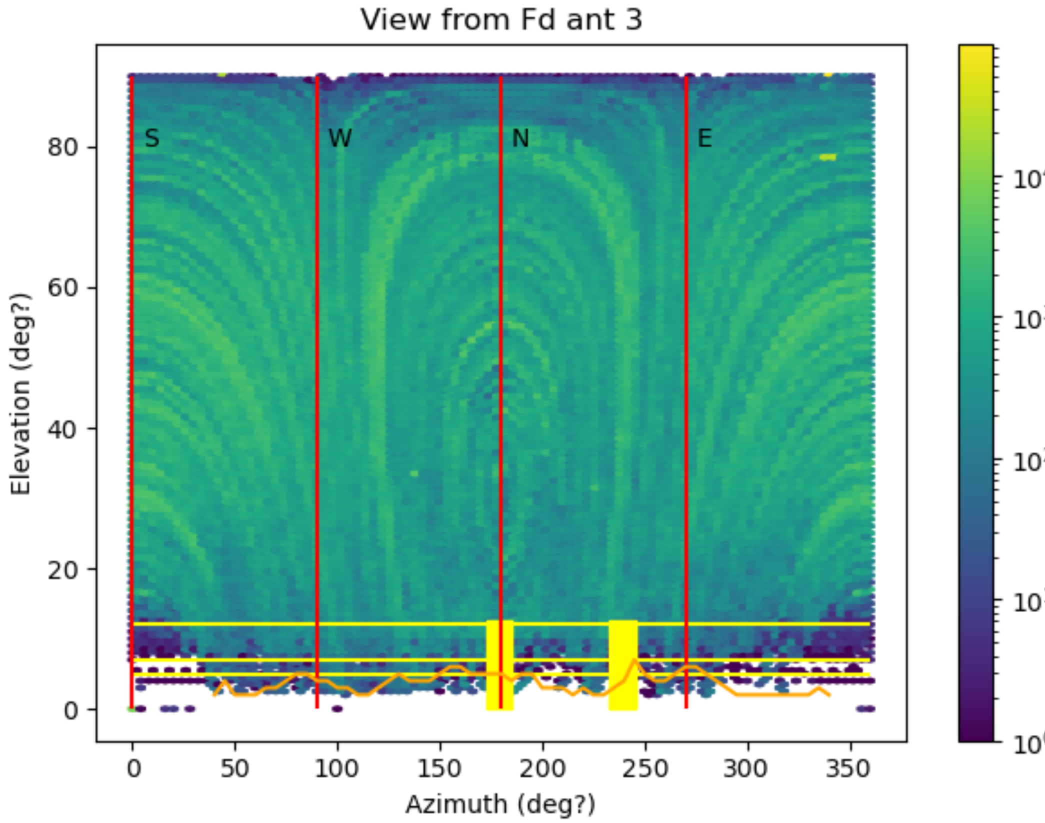
View from Br ant 2
S
W
N
E
Elevation (deg?)
Azimuth (deg?)
0
20
40
60
80
0
50
100
150
200
250
300
350
10^0
10^1
10^2
10^3
10^4
10^5



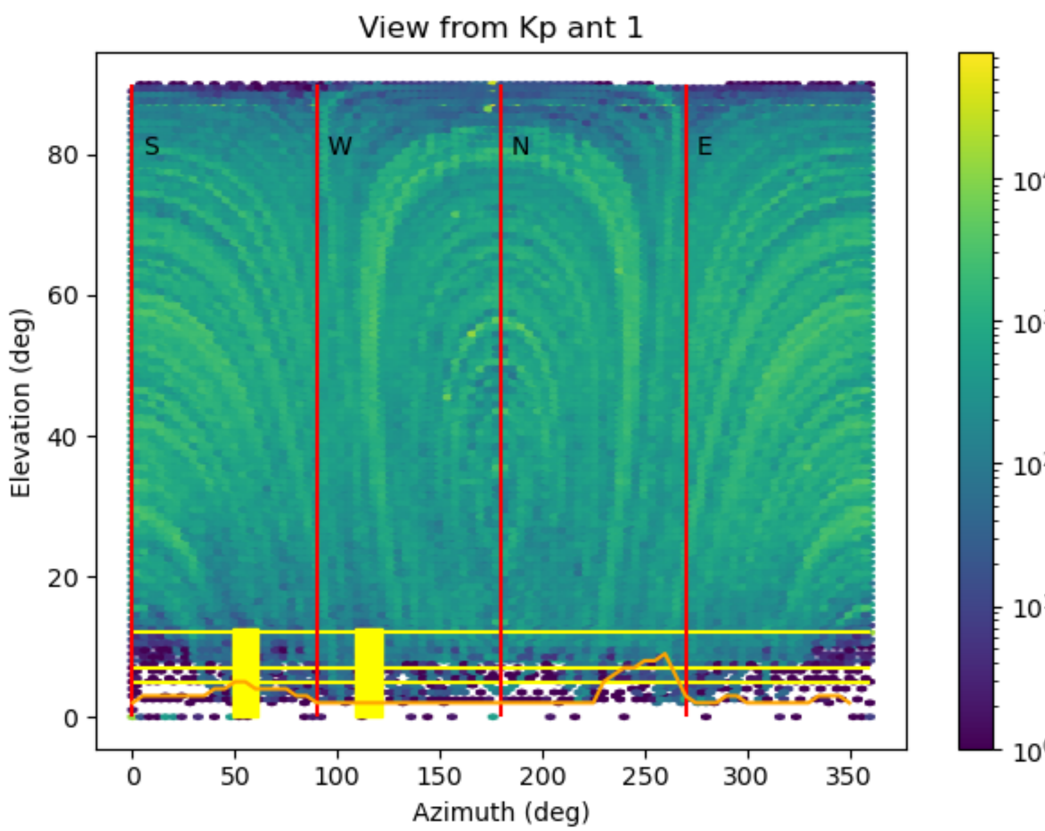
View from Br ant 3
S
W
N
E
Elevation (deg?)
Azimuth (deg?)
0
20
40
60
80
0
50
100
150
200
250
300
350
10^0
10^1
10^2
10^3
10^4
10^5


View from Fd ant 1
S
W
N
E
Elevation (deg)
Azimuth (deg)
0
20
40
60
80
0
50
100
150
200
250
300
350
10^0
10^1
10^2
10^3
10^4

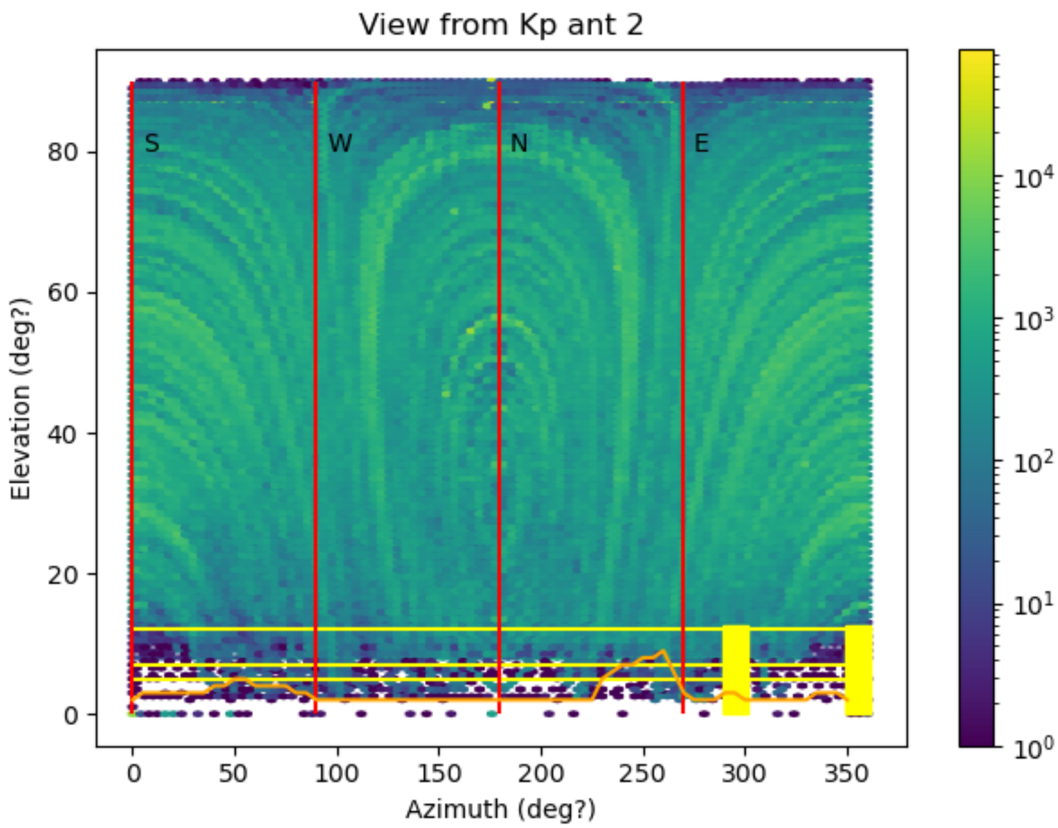

View from Fd ant 2
S
W
N
E
Elevation (deg?)
Azimuth (deg?)
0
20
40
60
80
0
50
100
150
200
250
300
350
10^0
10^1
10^2
10^3
10^4



View from Fd ant 3
S
W
N
E
Elevation (deg?)
Azimuth (deg?)



View from Kp ant 1
S
W
N
E
Elevation (deg)
Azimuth (deg)


View from Kp ant 2
S
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Elevation (deg?)
Azimuth (deg?)
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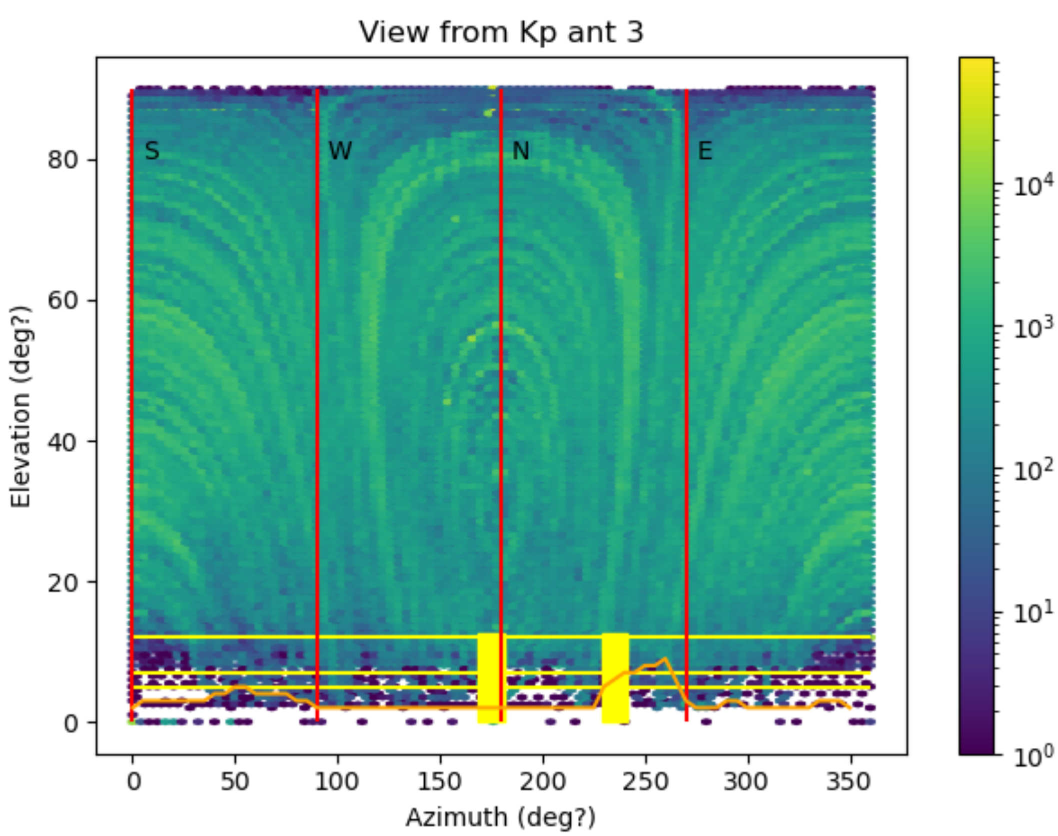
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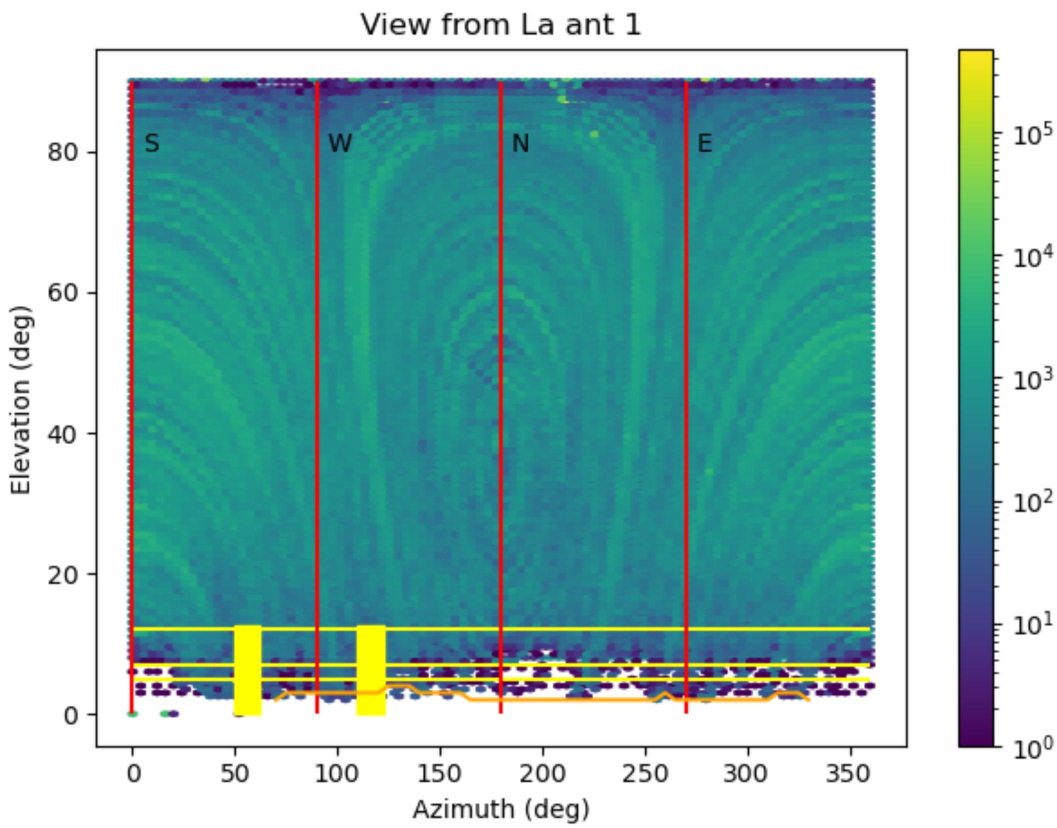
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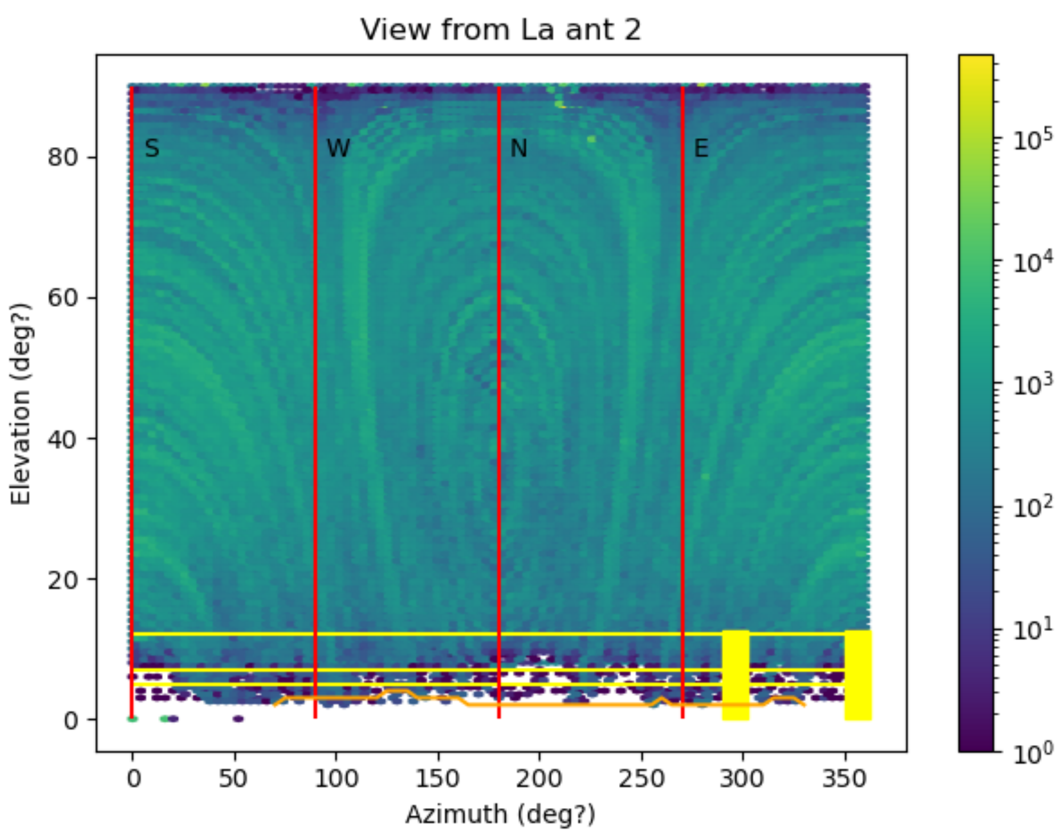
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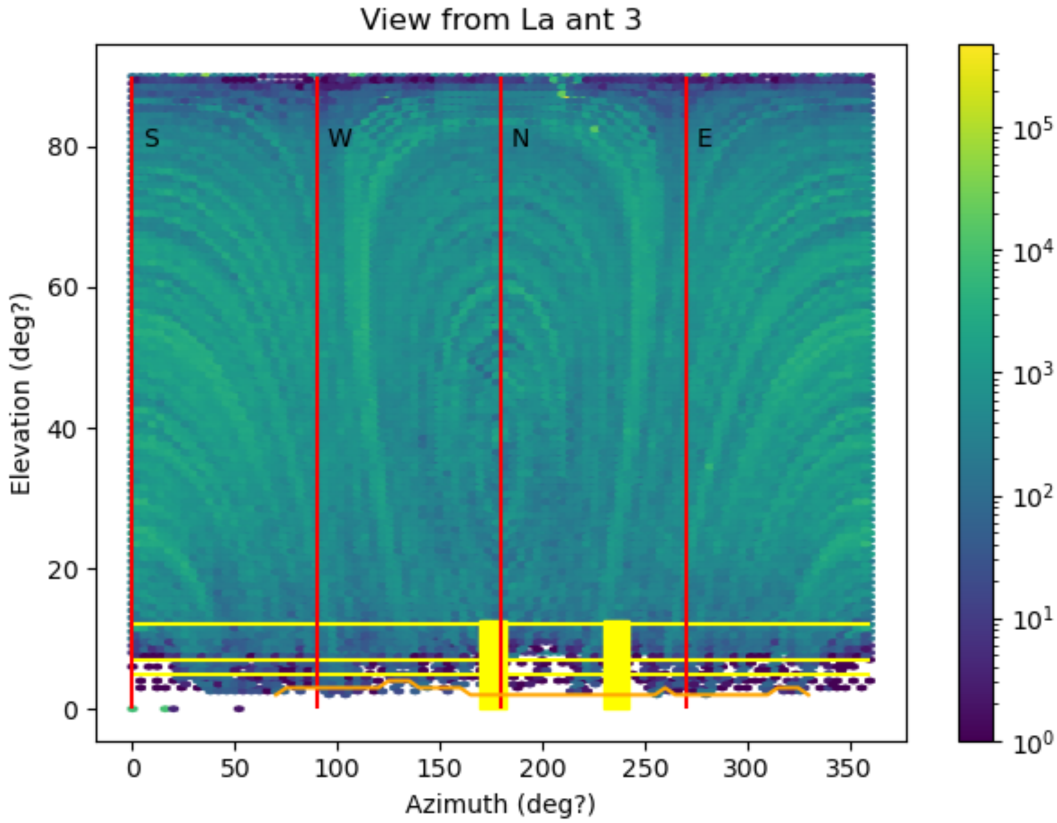
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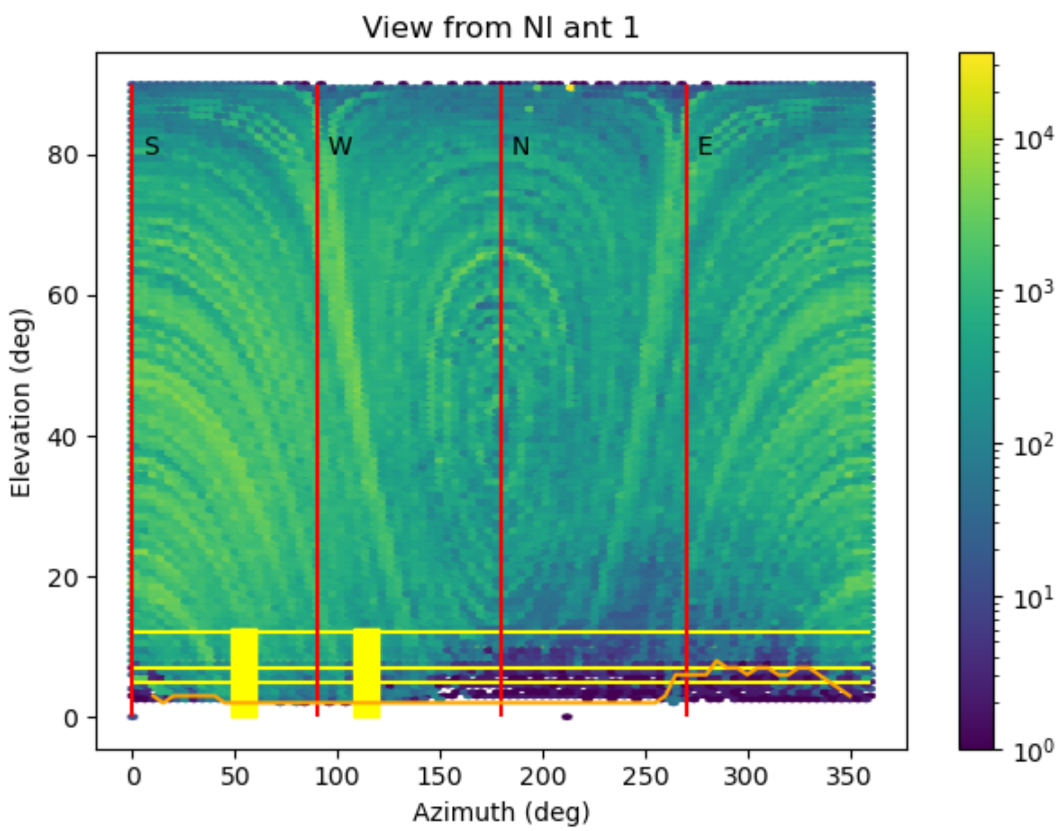
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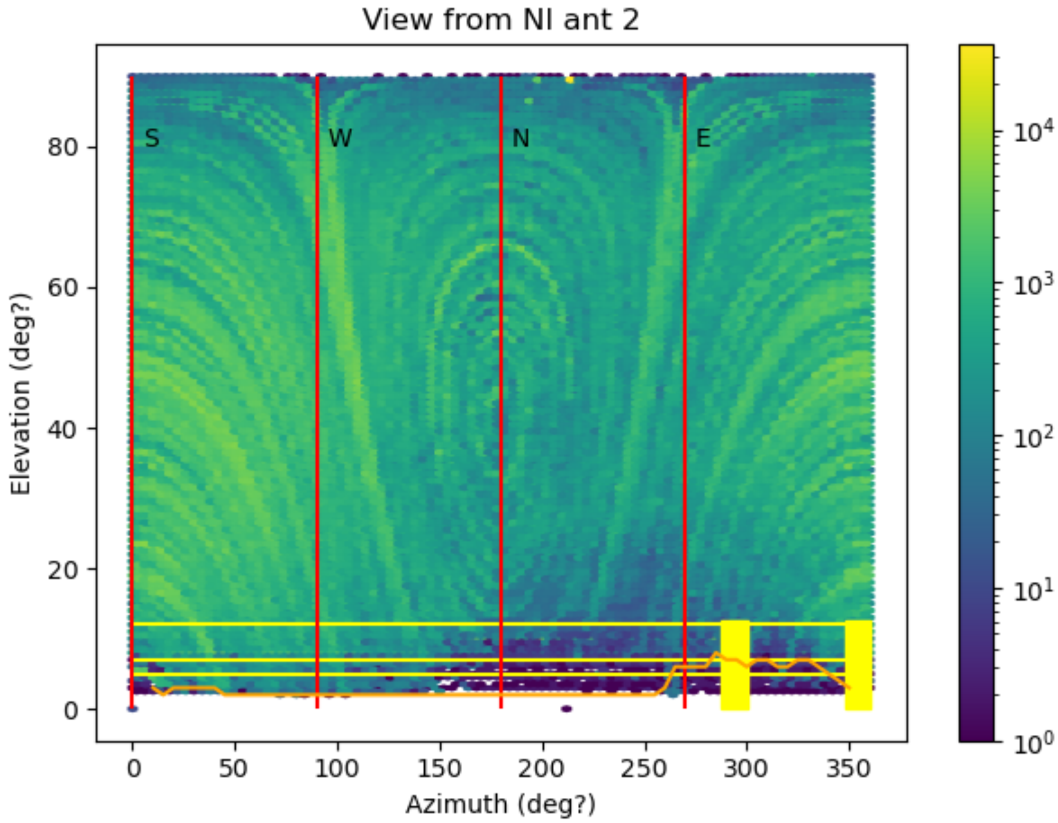
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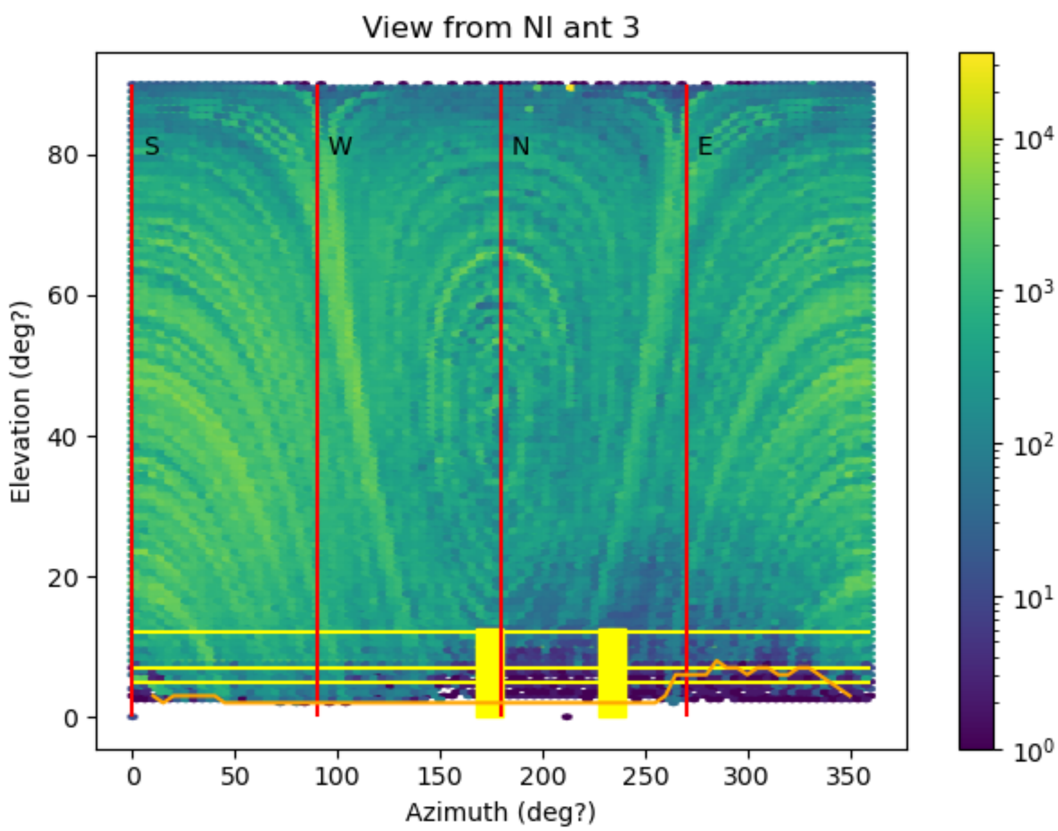
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Elevation (deg?)
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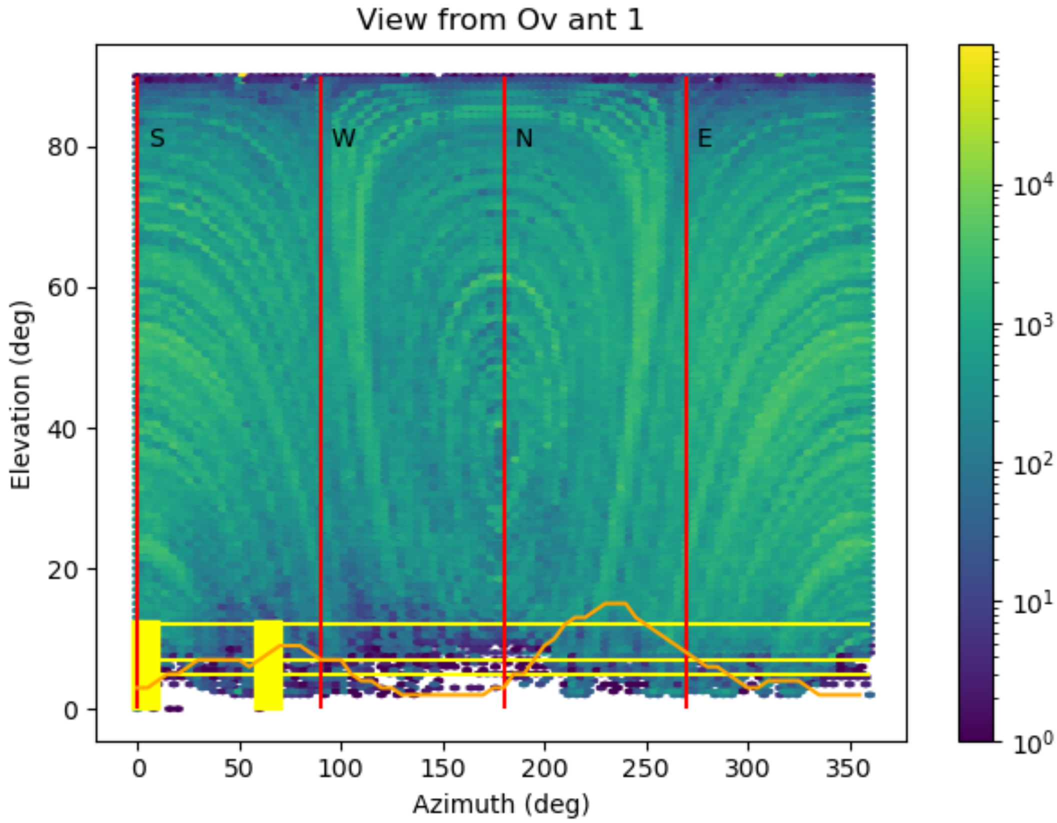
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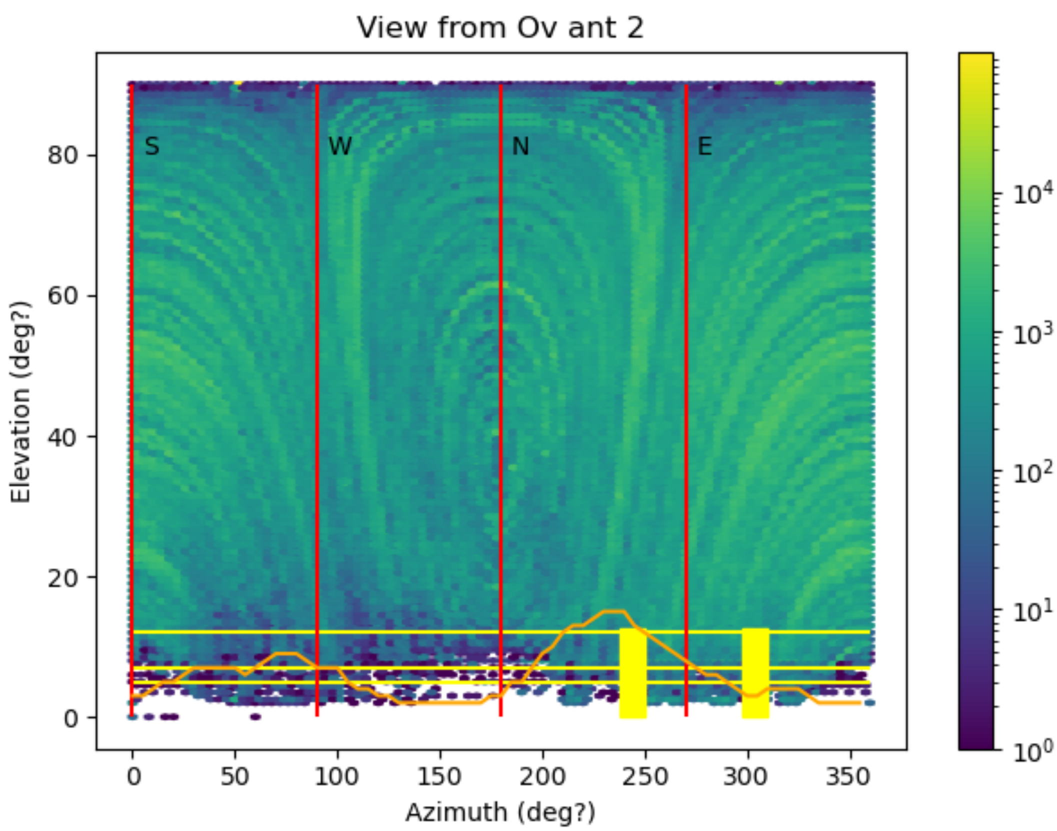
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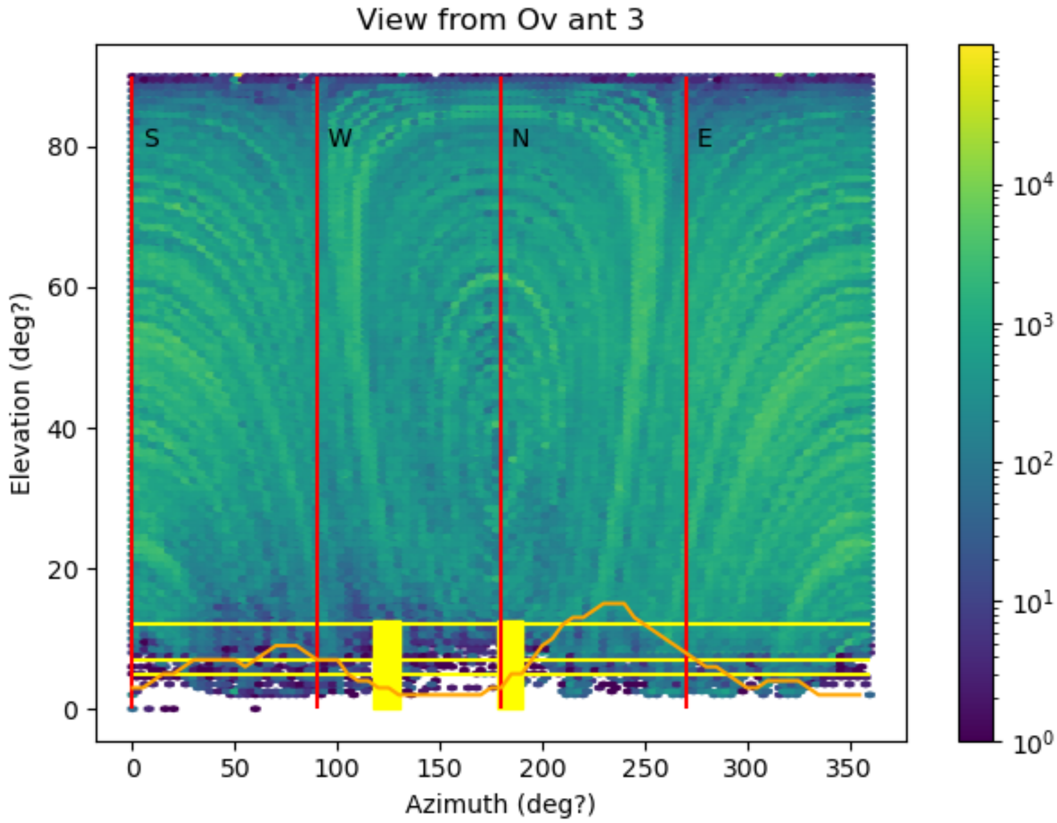
View from Ov ant 3
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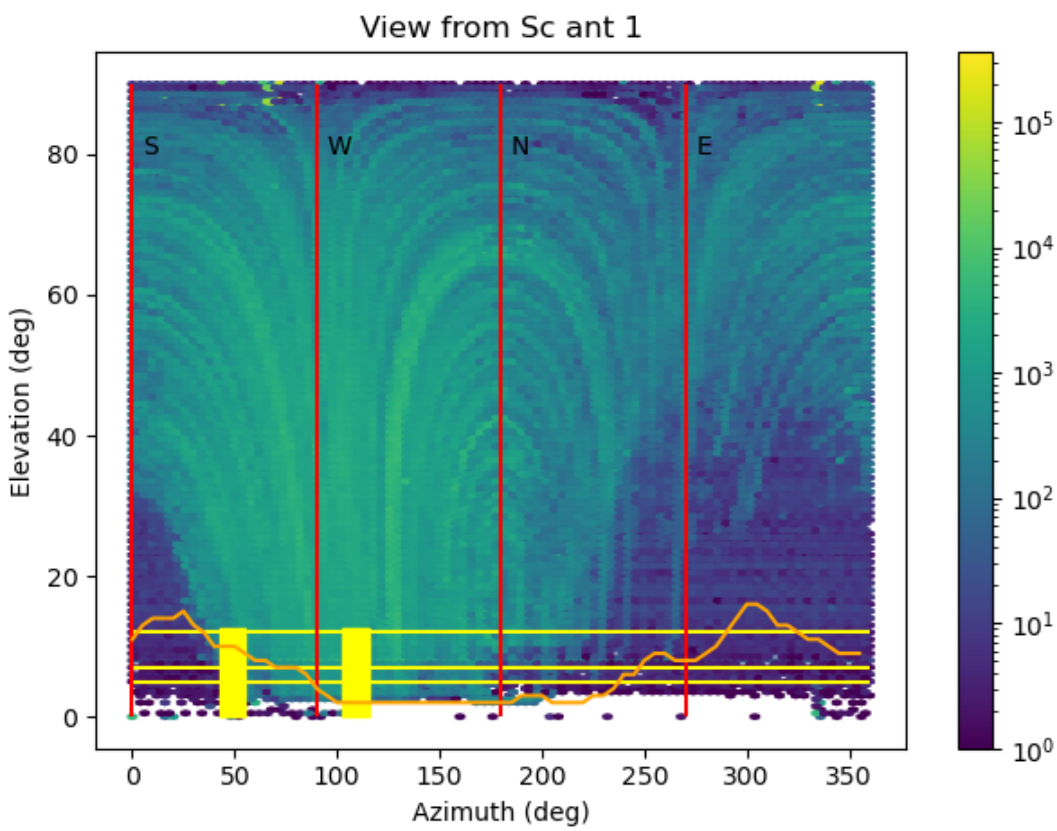
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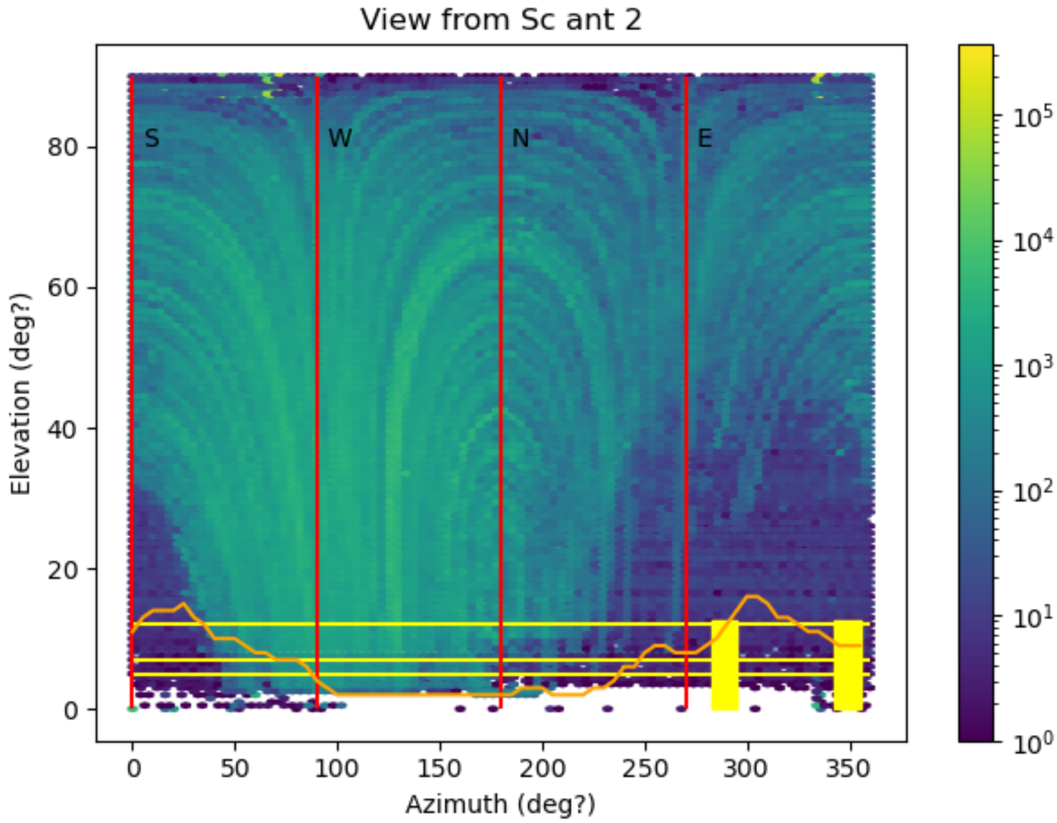
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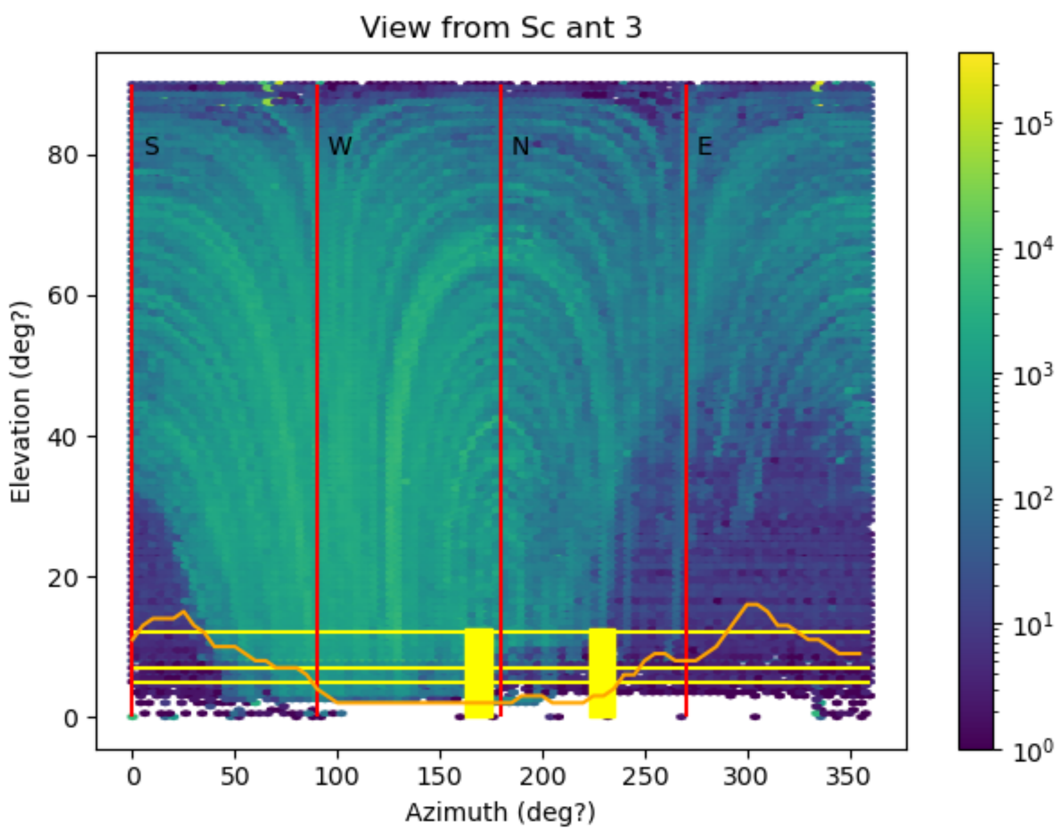
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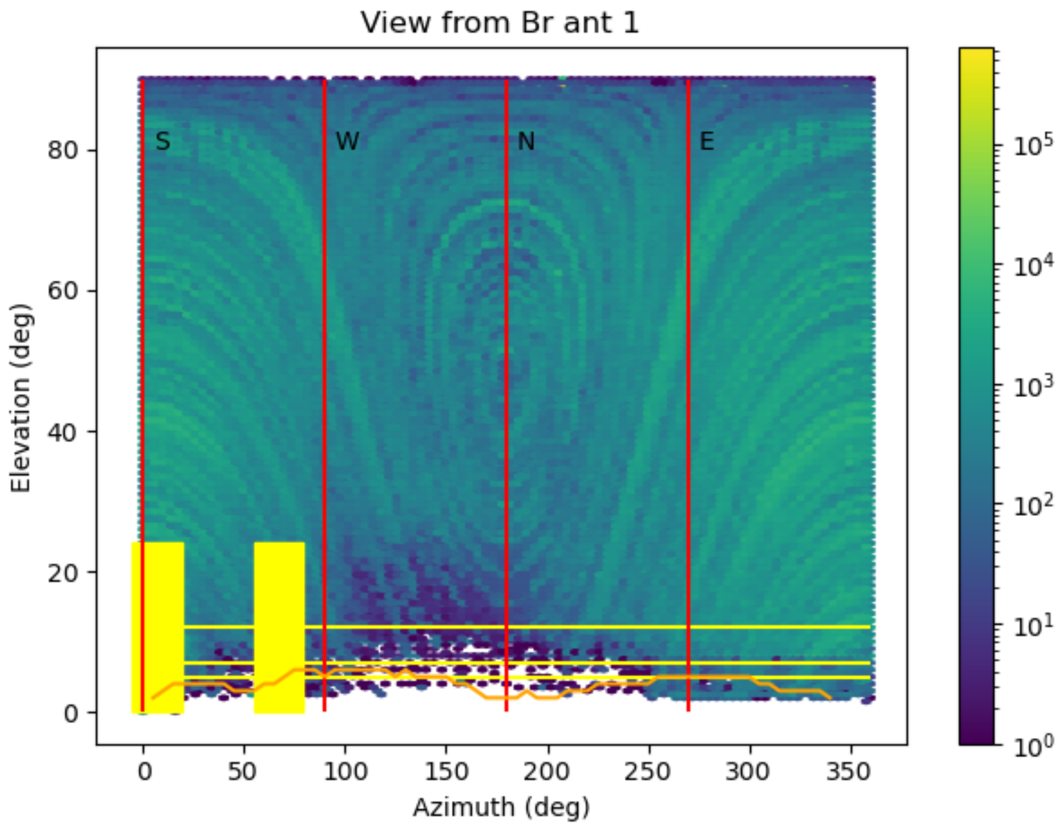
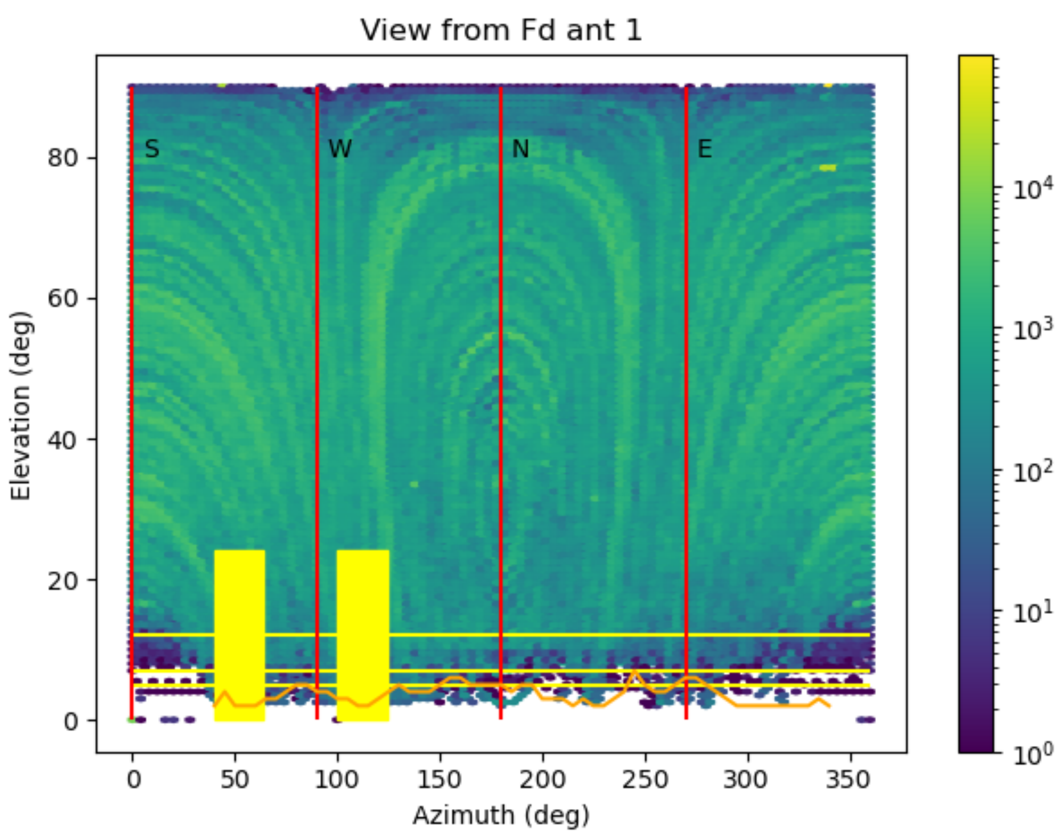
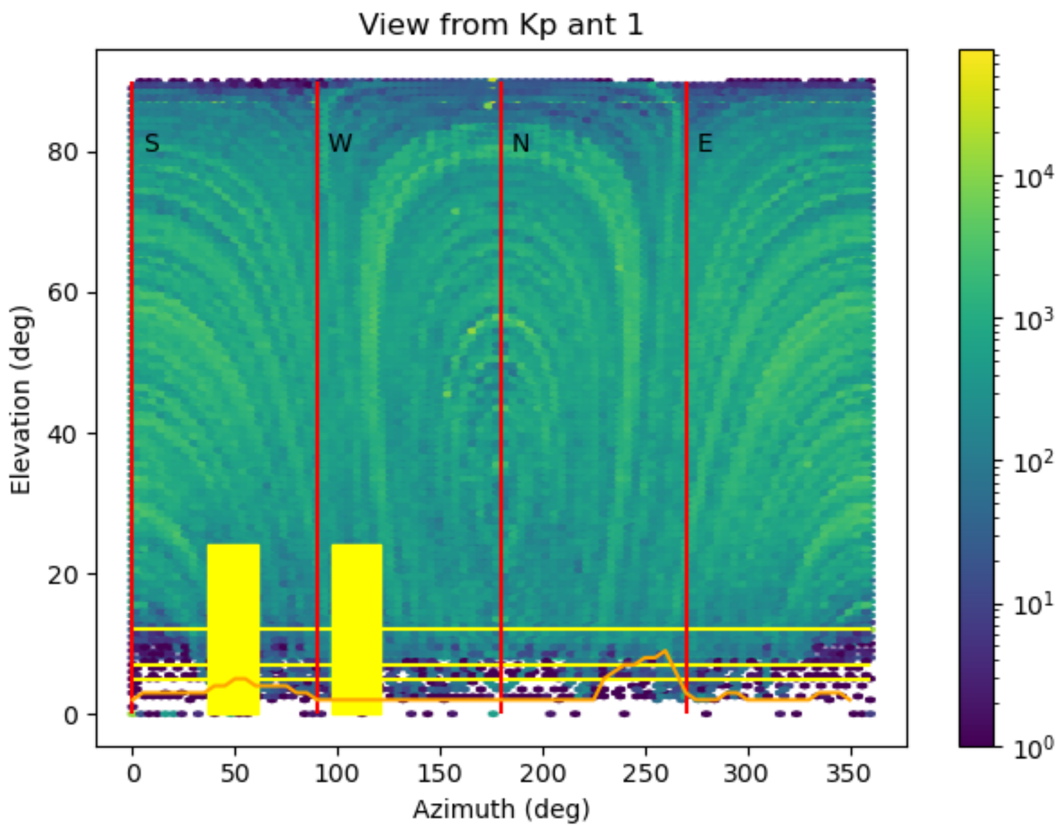
Appendix 2 – Pointing maps with 40m antenna separation



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Azimuth (deg)
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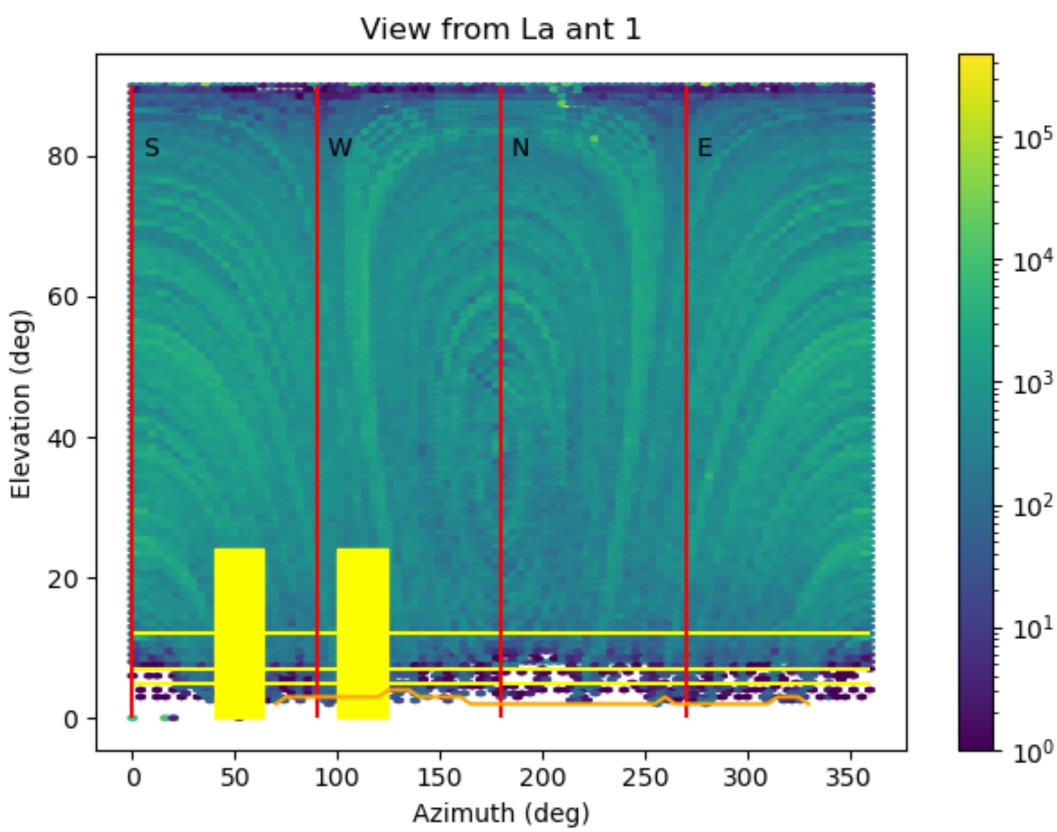
View from La ant 1
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Azimuth (deg)
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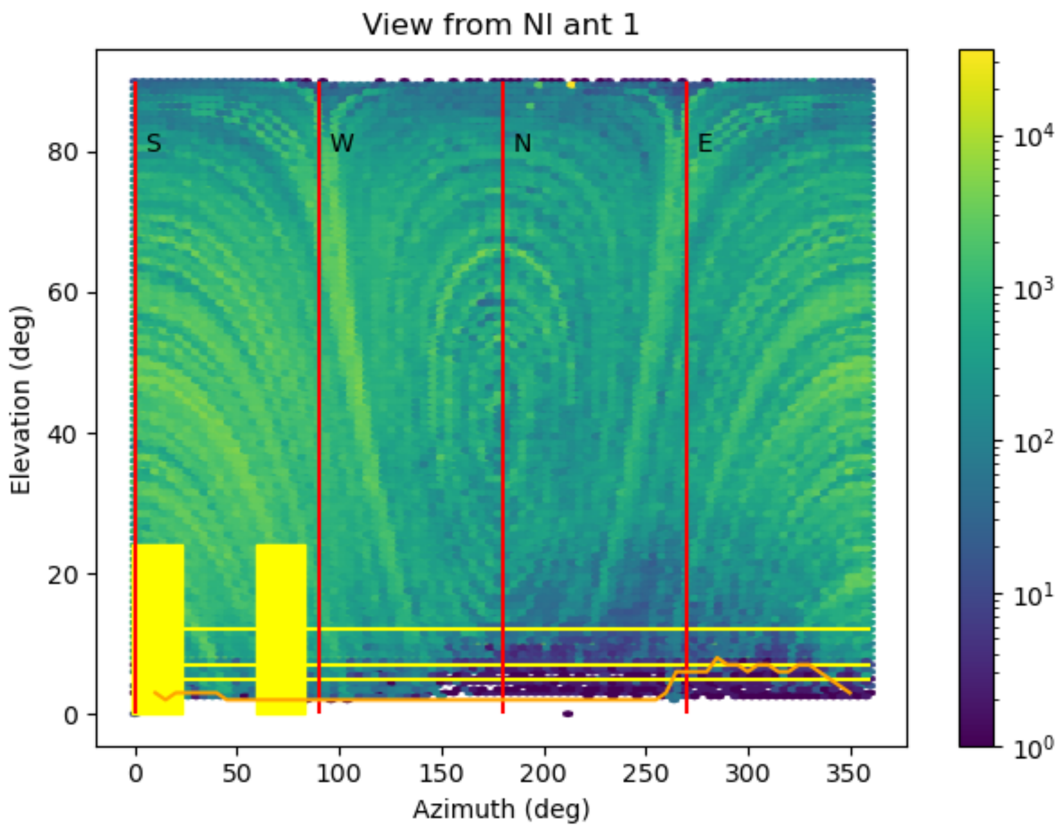
View from NI ant 1
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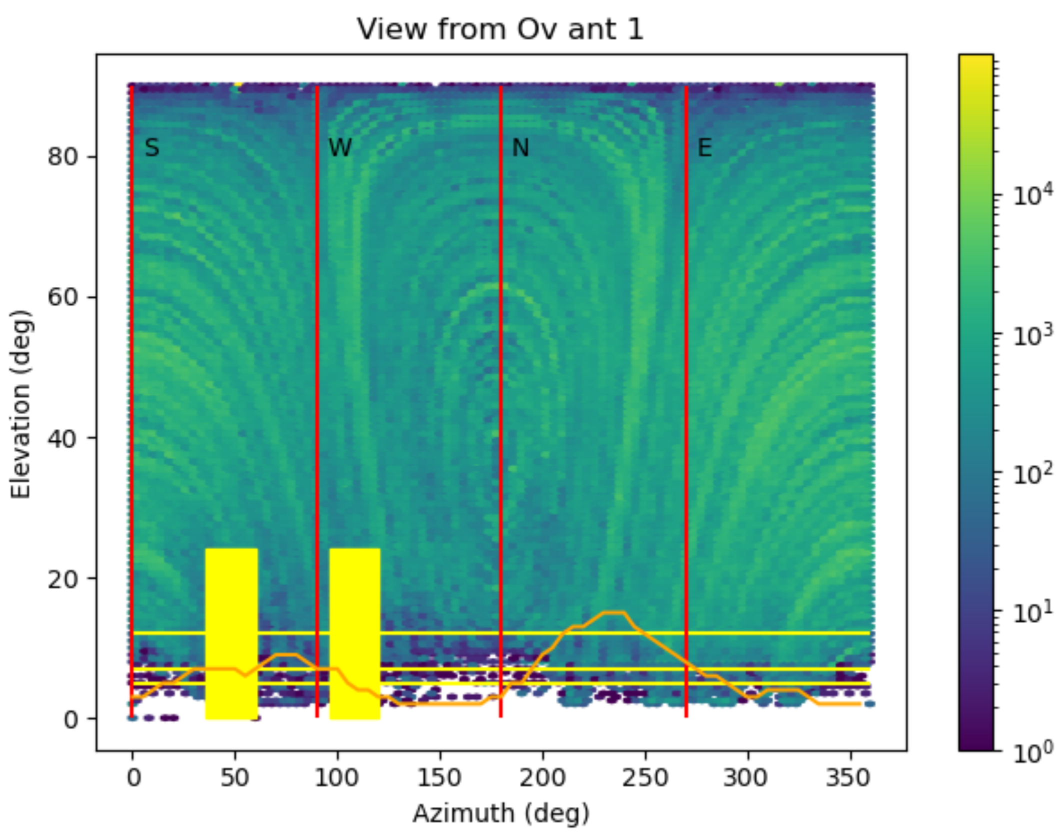
View from Ov ant 1
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Azimuth (deg)
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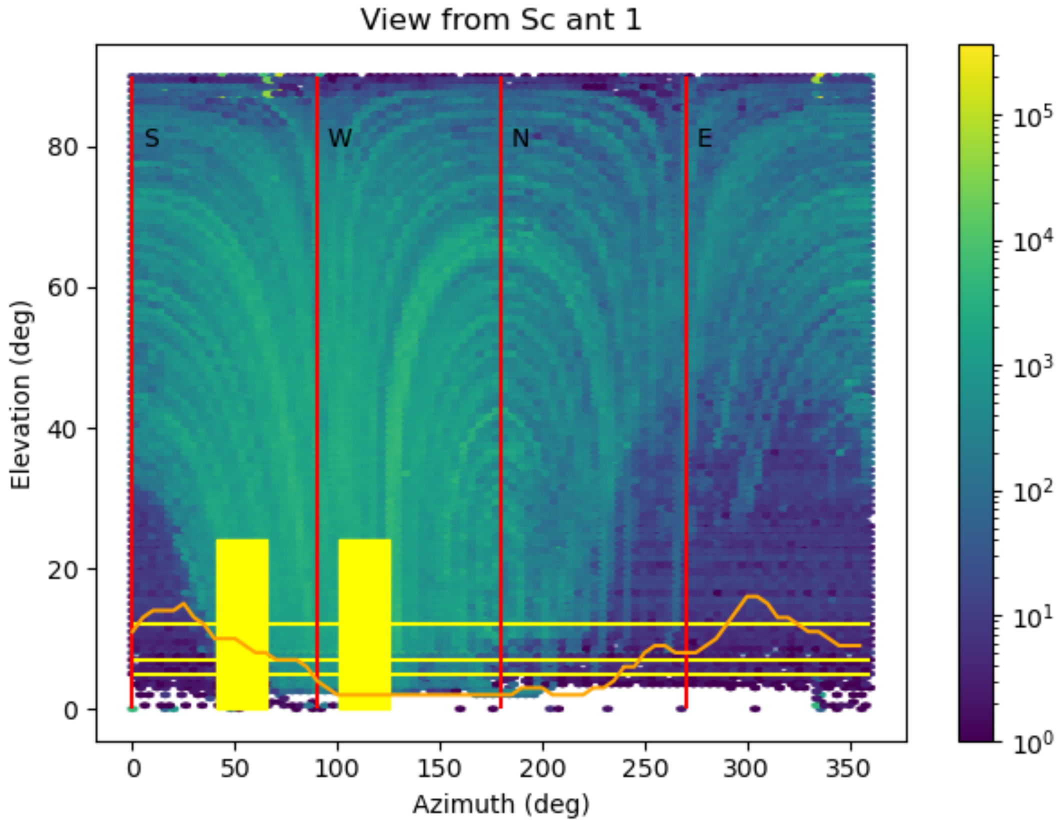
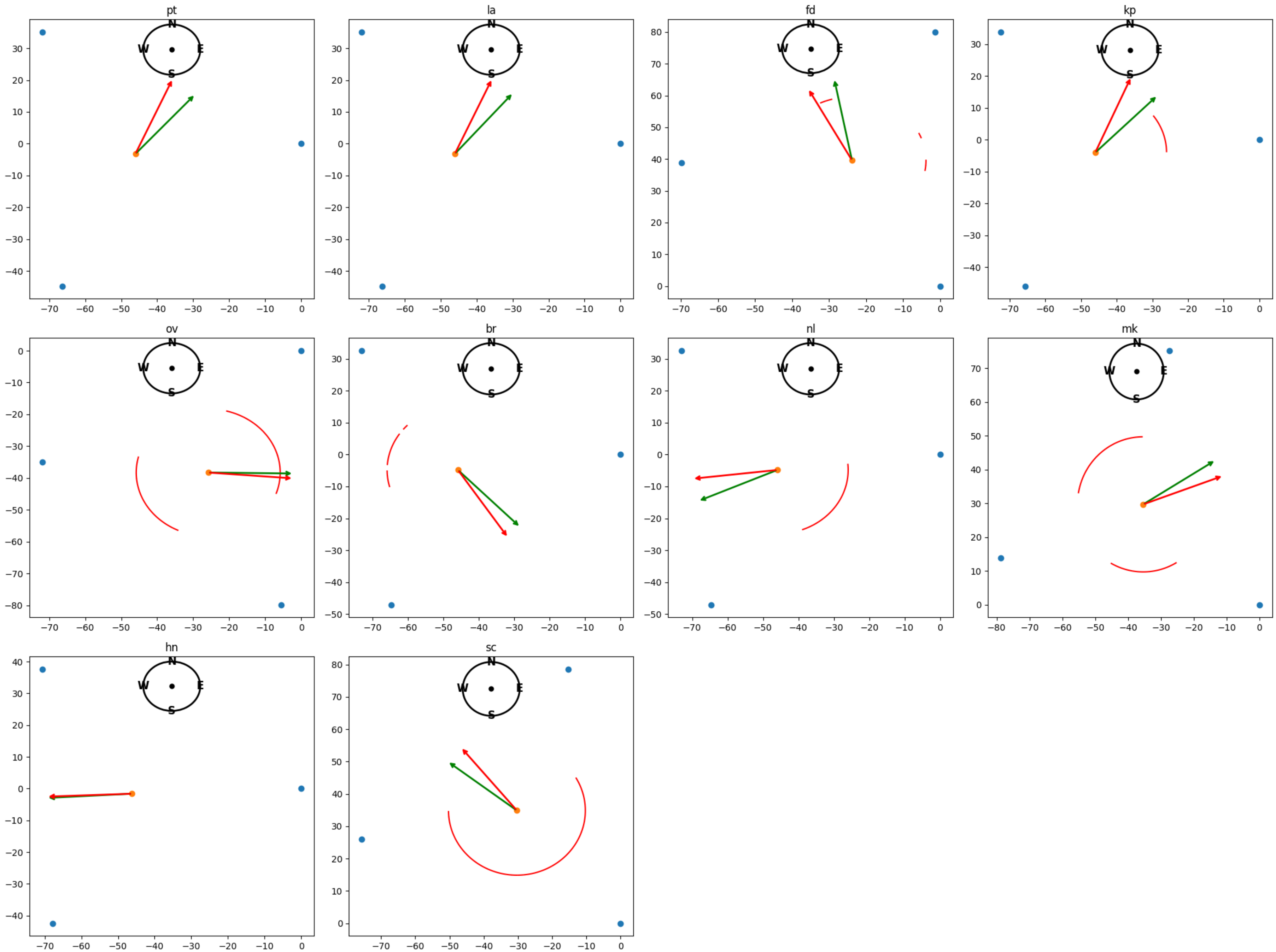


Appendix 3 – Optimal Antenna Orientation plots

The plots below show the optimal antenna layout. The blue points are show antenna positions. The red lines, if they exist, show horizons blockage above 7 degrees. The red arrow shows the bearing perpendicular to a triangle edge, and the green line shows the bearing to the array geographical center. A compass rose is also included

80 Meter antenna separations, Line indicates horizon above 5 degrees elevation, the limit used by USNO



40 Meter antenna separations, Line indicates horizon above 5 degrees elevation, the limit used by USNO