RFI Memo No. 158

Satellite-Telescope Boresight Interaction Percentage
Sheldon Wasik, Aaron Lawson, Bang Nhan, Chris De Pree
December 6, 2024

1 BACKGROUND

Estimating the probability of a satellite passing close to a telescope's pointing is crucial in not only understanding interference impact on the receiver, but the impact on the transmitting network if they implement mitigation measures. The goal is to eventually use probability metrics to propose realistic exclusion zones to ensure protection of the receiver equipment, without heavily impacting the transmitting networks service.

The computational solution to this problem grows quickly as more satellites are launched into orbit and more time needs to be analyzed. For reference, if we want to divide the observable sky into 0.1 deg x 0.1 deg segments, and analyze the SpaceX's Starlink network as it exists on 8/20/2024, there are about 19 billion points that would need to be analyzed per real-world time in seconds. Given the Starlink satellite network operation algorithm can change rapidly in time, telescope observation sessions typically last from minutes to hours, a Starlink satellite takes around 15 minutes max to go across the sky above horizon in a worst-case scenario, and areas of Starlink service are constantly changing, re-running models with short notice at this time resolution becomes unfeasible.[1] To overcome this with the current code structure implemented in similar satellite interference memos, time-saving methods were considered. The goal of the methods described in this memo is to generate useful satellite-telescope pointing interaction percentages for both a wide range of parameters in a computationally inexpensive method, as well as targeted observations of known positions to quantify major interference levels. There are two methods and results described in this memo, the Entire Sky Probability, and the Single Observations. They both look to address related, though slightly different, questions regarding interaction percentages from a satellite network.

2 METHOD – ENTIRE SKY PROBABILITY

The current satellite script that is utilized for several NRAO analyses utilizes PyEphem[2], where we are able to generate an azimuth/elevation (Az/El) plot of satellite positions in the sky in reference to an observing point. We are able to generate this for a given time range with resolution of a second, based off of public satellite Two-Line Element (TLE) data from CELESTRAK[3]. However, as

[1] Utilizing parallelization with GPU to speed up runtime is being evaluated at the time of this memo
[2] https://rhodesmill.org/pyephem/
[3] https://celestrak.org/

noted in the Background section, the number of points grows rather large to run a full telescope pointing network to determine the probability of near boresight interaction across the entire sky. In experimenting with different output formats, it became clear that matplotlib's Portable Network Graphic (PNG) exports can be given a number of pixels to be saved with. The python image library (PIL) is a useful resource to interpret and edit images with python, as it is often used to edit photography. This led to determining if the PIL Image module would be useful in reading a high pixel count PNG of the Az/El positions in the sky, and provide a useful percentage of the sky that would result in a close to telescope boresight pass.

3 PROOF OF CONCEPT – ENTIRE SKY PROBABILITY

To ensure we get useful results with this method, we had to test if it accurately calculates the percentage of coverage on a given plot to a reasonable error. Initially, we used a simple circle in a box calculation, since its coverage can be calculated by hand. With this method, we can also fine tune the number of pixels to save an image at, giving us the run efficiency, while maintaining the accuracy. To do this, we set up an image for a 0-90 and 0-360 bounded image to be saved, with the figsize in respect to the height always being 10 inches to keep the correct Az/El dimensions. On that image we added a green box, covering the entire grid, then plotted three non-touching red circles with a known radius. We saved that image to a PNG and loaded it back in with the PIL Image module. We converted the image to RGB colors, counted the red pixels, and divided by the total pixels (red + green) to gather our percent. We then calculated, with some simple geometry, what that value should be (area of square - area of all circles). We experimented with a different base figsize height and radii (1 to 15 degrees), expecting different results. While generating larger size images would ideally yield more accurate results, after some brief analysis, it was determined a 10-inch height is efficient and accurate enough for the purpose of this project. At the 10-inch height figsize, we could generate the "circle on box" image and analyze it in a matter of seconds. Early results showed various radii to agree in area percentage within 0.1% or less.

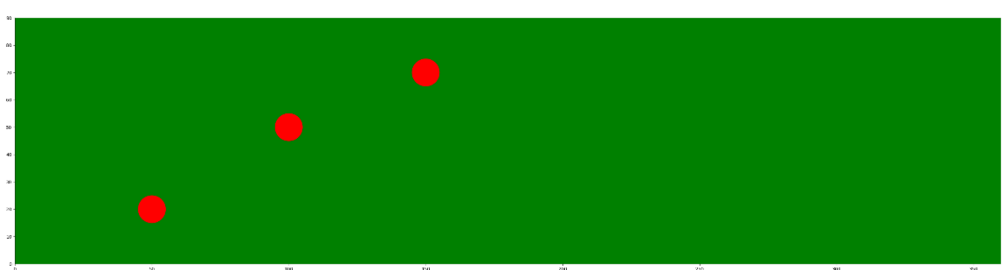

Figure 1: The "circle in box" plot for three 5-degree radius circles with a figzise height of 10 inches, and width of correct ratio based on the elevation to azimuth ratio.

We then used this circle in a box method at the 10-inch height figsize to test how the percentage differences varied for degrees (radii) less than 1.5 degree, to mimic near boresight passes. There was a very close agreement between the two methods. We saw a clumping of percentage differences that appeared to jump around, mostly dropping in agreement. We suspect this to be due to square pixels overlapping circle edges. We were able to confirm this by changing the PNG resolution and/or changing the position the circle is placed. However, the widespread results agreed to minimal error, and did increase again as the circle radius got larger confirming the suspicion and validating the method was appropriate to a given error.

This proved the method useful, leading us to pursue the proof of concept for a couple satellites in the Starlink network. Since the main problem with analyzing the entire Starlink network is the number of points and necessary computational time, we selected 4 satellites above the horizon at a given point in time. We ran the sky positions of the satellites for 60 seconds time, grabbing 4, 25, or 75

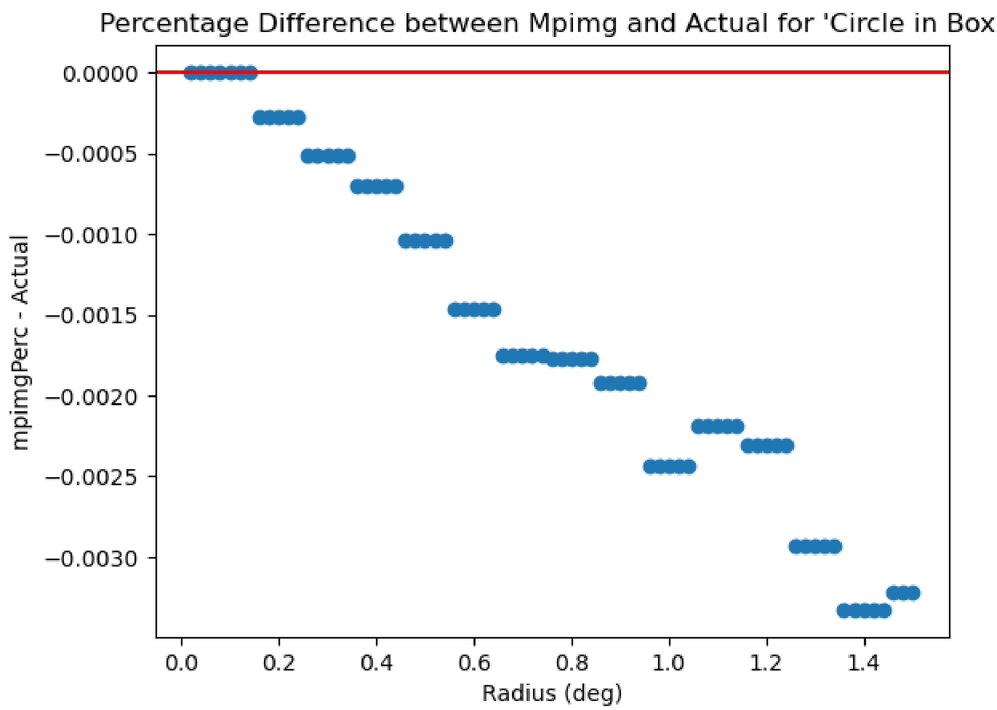

Figure 2: Comparing the percentage difference between the mpimg (PIL) method and calculating the "circle in box" percent by hand, across 0.01 to 1.5 deg radius. We suspect the step like features to be related to circles overlapping box grids.

points, depending on its elevation, between each second of satellite data to better encompass the entire trajectory. We recognize the satellite path will be slightly arced, however for simplicity this will give very similar probability results. We stepped over 0.1 deg chunks of [0,360] and [25, 90] in Az/El of the sky to determine the percentage of time a satellite would be close to boresight. We then compared that percentage to the method using the PIL Image module, finding the PIL PNG method resulted in 0.226% percent of interaction rate, and the "stepping over the sky" method resulting in 0.205%. We expected the PIL PNG method to be slightly greater due to only stepping by 0.1 deg, due to runtime constraints. On a smaller scale test, we did see decreasing the step size from 0.1 to 0.01 increases the percentage by 0.01 – 0.02 %, agreeing even closer with the results found by the PIL PNG method, and validating this method is useful to a small degree of error.

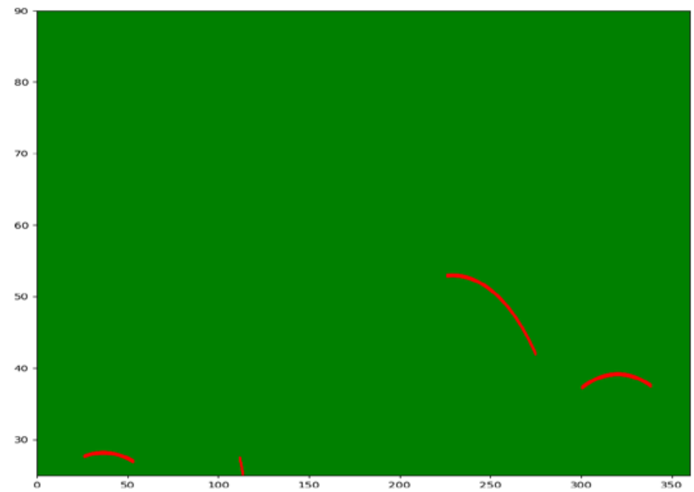

Figure 3: In respect to the VLA, sky positions of 4 satellites with 0.2-degree radius (red) for 60 seconds time that were found to be above the horizon, to compare the PIL method to the "stepping across 0.1 degree" method.

4 RESULTS – ENTIRE SKY PROBABILITY

With this method, we were able to produce results fairly quickly for a range of input parameters. Due to telescope beam size and Starlink satellite capabilities, we focused on a 0.2 deg interaction zone from the location of the Very Large Array (VLA), although both the interaction zone and receiver location could be changed for future analysis. For a random 1-hour time range across [0,360] [25, 90] Az/El, there is a 78.4 % chance of the telescope boresight coming within 0.2 degrees of at least one satellite during its observation. Since longer observing times likely results in larger interaction rates, we ran the same parameters for a 15-minute time range, as it is our understanding that is the longest time a Starlink satellite will be above the horizon at these latitudes. This resulted in a 31.1 % chance of an interaction, significantly lower than the 1-hour scan. The 1-hour satellite sky coverage plot (Figure 4)

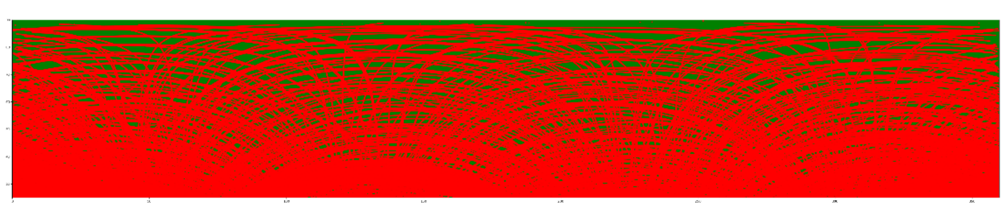

Figure 4: All Starlink satellite trajectories (red) with a 0.2-degree radius across [0,360] [25, 90] Az/El in respect to the VLA position across 1 hour of time. (May need to make the label fonts larger, hard to read currently)

also demonstrates that the lower in telescope elevation, the greater chance of an interaction. To quantify how the chance of at least one interaction occurring depends on telescope elevation, we ran this model for 15-minute time range across [0,360] [30, 40], [0,360] [60, 70], and [0,360] [80, 90] Az/El, attempting to meet the VLA observing recommendations of low frequency (< 15 GHz) observing avoid elevations of < 10°and > 85°. The set with the lower 10-degree elevation range resulted in an interaction chance of 43.6 %. The mid elevation range dropped the percentage to 29.7 %, and the highest elevation resulted in 10.8 %. In other words, if an observer was tracking an object across 15 minutes, resulting in an Az/El to fall between [0,360] [80, 90], there would be a 10.8 % chance there would be at least one satellite-boresight interaction within 0.2 degrees. We acknowledge this is a broad percentage due to input parameters, as observations don't scan large portions of the sky in a short time. However, this proves useful in understanding the chance of interference a telescope would receive in a portion of the sky that it wouldn't have before the Starlink network was launched.

To continue explanation of interactions, we set out to understand more realistic observations and how it compares to the results above. Specifically, we wanted to determine how many interactions could take place across an observation, as the above results do not indicate how much data would be impacted from the interference. We also set out to see if a random set of observations resulted in similar percentages seen in the results above, again confirming the PIL percentage chance of interaction method.

5 METHODS – SINGLE OBSERVATIONS

We set up the VLA to track a Right Ascension/Declination target across a given time range, and ran the entire Starlink network against the pointing trajectory of the telescope. We then logged a satellite if it came within 0.2 degrees of that telescopes pointing at that time step to understand the number of interactions across a more realistic observation. This method will be useful to identify what percentage of data in an observation would be impacted, not just whether any part of the observation is impacted.

To do our best to compare to the results of the entire sky probability, we ran several random pointings for the 15-minute time range, and compared the percentage of how many had an interaction. Due to the differing results between lower and higher telescope elevation pointings, we focused on analyzing a range to better encompass the average. However, we point out that the runtime of this method restricts how many results we can gather in a reasonable amount of time.

Again, we will be using the PyEphem python library public satellite Two-Line Element (TLE) data from CELESTRAK dating up to 8/20/2024. This will provide us with second resolution satellite position data we can then compare to the telescope pointing. We used astropy to convert the RA/DEC to Az/El to compare to the satellite position in the sky.

6 RESULTS – SINGLE OBSERVATIONS

We ran two 4-hour observations, one aiming in the lower sky elevations and one higher. The lower of the sources was an RA/DEC of 266.42/29.01 in the early morning in September. The telescope pointing trajectory, and satellite interactions within 0.2 degrees is seen in Figure 5. This realistic observation, ranging in the 20 to 27-degree elevation range, resulted in 17 seconds of

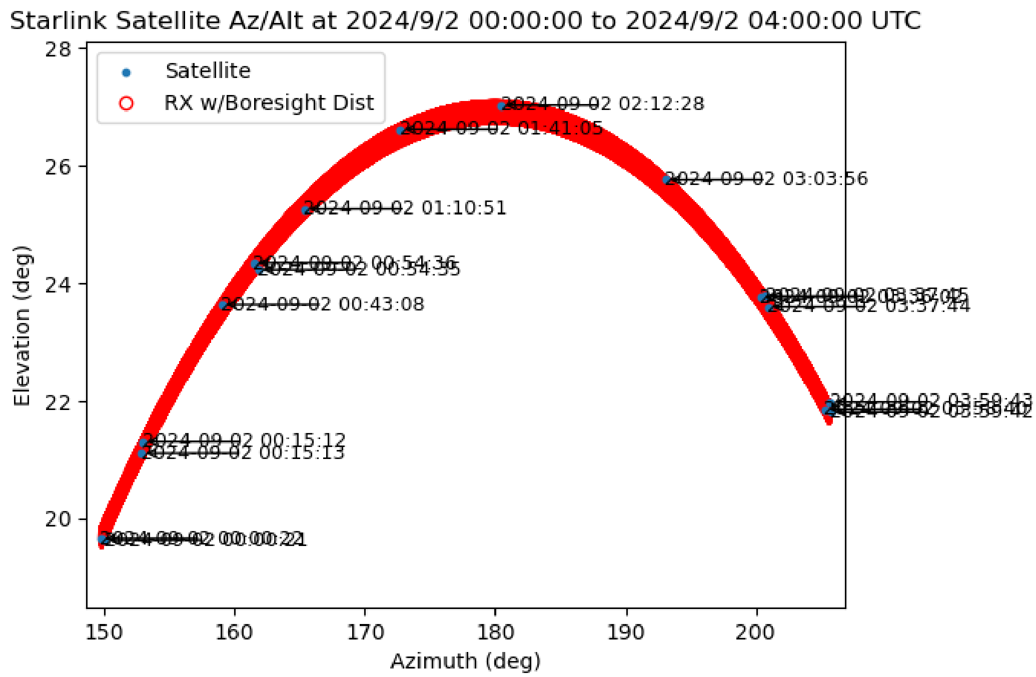

Figure 5: Telescope pointing with 0.2-degree radius (red) across 4 hours of pointing at RA/DEC 266.42/29.01 in the early morning in September. Each satellite that falls within 0.2 degrees of boresight is plotted (blue) with the given timestamp.

time a satellite is within 0.2 degrees (or 0.12 % of data to have major interference). This came from 12 individual satellites, showing there were several occasions a single satellite was within 0.2 degrees for longer than 1 second. We note this percent is not directly comparable to the percent in the entire sky probability for the 4-hour observation, since the single observation is concerned about the number of interactions across a time period, not if that time period will have any interaction at all. The second 4-hour observation was at RA/DEC 225.42/29.01 in the early morning in August to obtain an observation between 57 and 75-degree elevation range. This observation resulted in 2 seconds of time a satellite is within 0.2 degrees (or 0.014 % of data to have major interreference). This came from 2 individual satellites, showing there were not any occasions a single satellite was within 0.2 degrees for longer than 1 second. This trajectory can be seen in Figure 6. The differing number of interactions at different elevations was as expected based on results from the entire sky probability percentage.

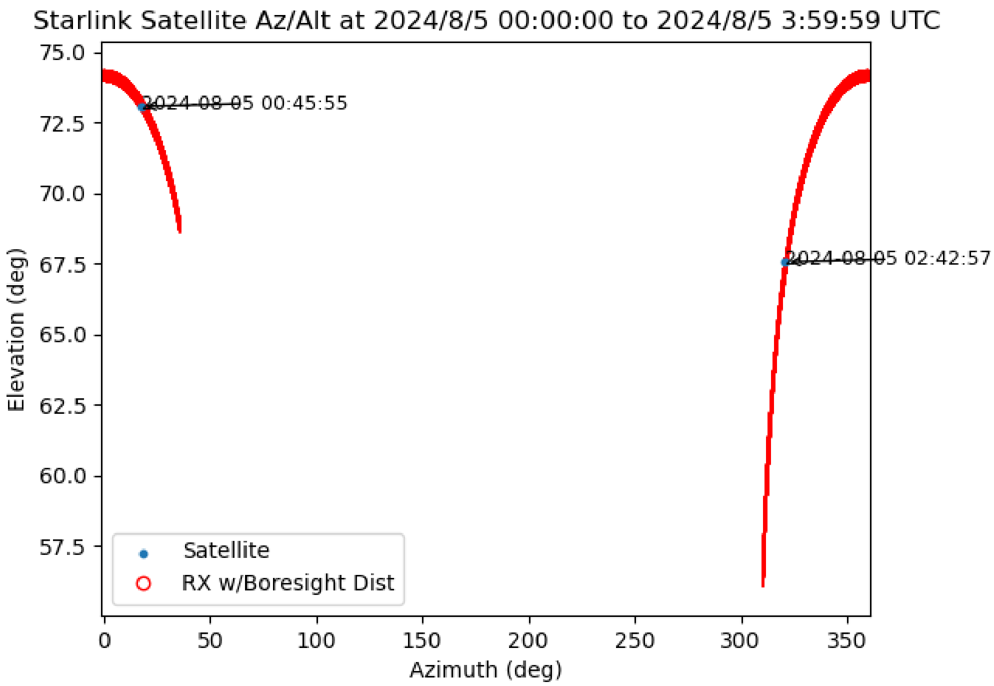

Figure 6: Telescope pointing with 0.2-degree radius (red) across 4 hours of pointing at RA/DEC 225.42/29.01 in the early morning in August. Each satellite that falls within 0.2 degrees of boresight is plotted (blue) with the given timestamp.

We ran 10 similar analyses for 15-minute observations, with the additional focus of comparing the percentage of a single interaction to the sky probability percentage seen previously in this memo, since the runtime is significantly less than the 4-hour analysis. Of the 10, around half had an elevation between 20 and 35 deg, with the rest being above 50 deg elevation. Three (30 %) had an interaction with a satellite at any given point, agreeing with the 31.1 % seen in the entire

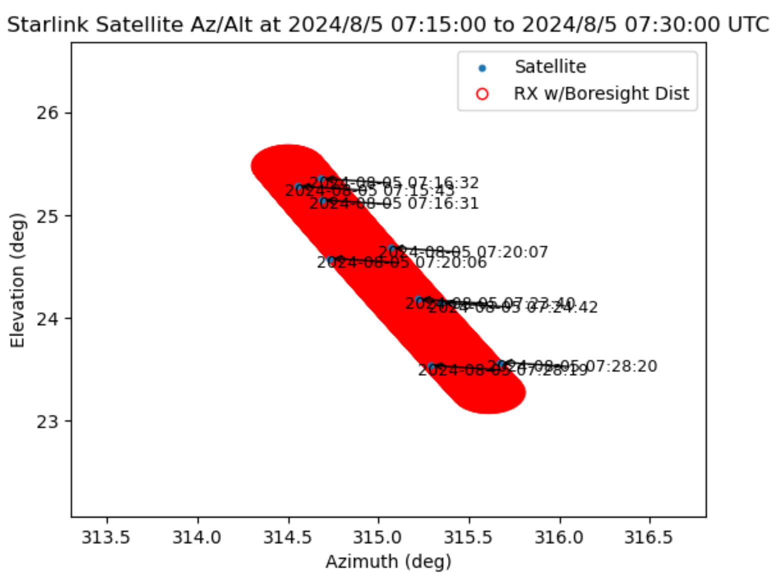

Figure 7: Telescope pointing with 0.2-degree radius (red) across 15 minutes of pointing at RA/DEC 225.42/50.01 in the morning in August. Each satellite that falls within 0.2 degrees of boresight is plotted (blue) with the given timestamp.

sky coverage for a 15-minute observation. However, this value should be explored with more 15-minute analysis, and wasn't in this project due to runtime and time allocation limitations. Of the 10 observations, the observation with the greatest number of interactions was at RA/DEC 225.42/50.01 during the morning in August, resulting in an elevation range of 23 – 26 deg. There were 9 seconds of time a satellite is within 0.2 degrees (or 1.0 % of data to have major interference). This came from 5 individual satellites, showing there were several occasions a single satellite was within 0.2 degrees for longer than 1 second.

Not all 15-minute observations in the lower sky resulted in an interaction. Although all the observations above 50-degree elevation did not result in any interaction, we would expect these numbers to start to trend similarly to the entire sky probability as more use cases are analyzed. I.e. there will be more interactions in the lower part of the sky than the upper, but there should be interactions everywhere across an infinite timeline.

We compared these results, specifically the 4-hour observations, with the real-world data we have from initial Operational Data Sharing (ODS) results. Of the first data points extracted from ODS, between 2024/08/15 03:54:57 and 2024/08/17 19:48:12 UTC the VLA was in X-band for 99,322 seconds, and there were 190 satellite passes within 0.2 degrees of boresight, resulting in 0.19 % of time if the assumed pass only takes 1 second. At the time of this memo, we do not have the telescope pointing information, confirmation a pass was only 1 second long, and are still working through validating the results of this initial ODS log file, but do believe it agrees fairly well with the results from these models.

7 CONCLUSION

Satellite-telescope boresight interaction percentages are dependent on several parameters. There is not a "one size fits all" answer, since telescope pointing, time range of observations, and satellite telemetry all play a crucial role. We have identified two methods to answer slightly different interaction questions, though related closely:

1. If an observer is concerned about the entire observable sky over a normal observation timescale, using the PIL module method, we have demonstrated there is a significant chance of a single interaction given a random telescope pointing. The lower elevations dominate this percentage, and the percentage grows as the time increases.
2. For well defined, realistic observations with a known RA/DEC, we have shown several examples of multiple satellite-telescope boresight interactions taking place over a given time range and compared them to our first logfile from ODS. Again, the lower in telescope elevation the greater number of possible interactions.

For a 1-hour observation on the VLA, the chance of having at least one satellite-telescope boresight (0.2 degree) interaction for 1 second of time in a random pointing between [0,360] [25, 90] Az/El falls around 78 %. For realistic observations, we have shown several examples of multiple interactions taking place over a given time frame. It is difficult to estimate the upper limit of interaction time in a given time frame, however we have shown a few examples ranging from 0.014 to 1.0 %, with a real-world use case from both of our Operational Data Sharing (ODS) and proprietary SpaceX tasking log files being around 0.19 %. We estimate the average to be around this 0.19 %, however it will be skewed greatly by telescope pointing positions and hard to accurately define this early in the project. In future projects, we will take greater emphasis on elevation observing recommendations, especially as other satellite networks with different transmitting frequencies are analyzed. For example, the VLA validation process recommends:

1. High frequency (> 15 GHz) observing: avoid elevations < 30° (if possible) and > 80° (required)
2. Low frequency (< 15 GHz) observing: avoid elevations < 10° (recommended) and > 85°

In future tests, we also plan to analyze the Green Bank Telescope (GBT), common pointings in X-band for both the VLA and GBT, continue to compare ODS log files, analyze different satellite networks, and better define a distribution of interaction percentage across the entire sky and the number of interactions on a single observation. To help achieve greater reliability and real-time understanding, we hope to explore other, more accurate approaches to this method, such as using parallel computing to speed up the satellite telemetry computation time. We note the satellite data used for this analysis is from 8/20/2024, resulting in 6,322 satellites. It is likely more Starlink satellites have been launched since then, increasing the interaction percentages of both results slightly. These results are important for observers to understand, to both plan observations accordingly and understand the interference impact at different telescope pointings, especially as the number of satellites increase over time.

We give acknowledgements to Daniel Bautista and all who have worked on ODS. Without Daniel and the ODS team, important conversations regarding techniques wouldn't have occurred and we wouldn't have ODS log files to compare results.