NRAO RFI MEMO Series No. 154

Coordinated GBT-Starlink Tests (April-July 2023)

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I. Background

In late spring and early summer 2023, SpaceX and NRAO/GBO carried out a series of short, controlled experiments on the following dates: April 26, 2023, July 13, 2023 and July 28, 2023. The details of these three experimental plans are contained in Appendix A (1,2,3) of this memo.

The basic process of each experiment was for SpaceX to use its Starlink satellites to illuminate all cells in the NRQZ as indicated in Fig. 1, with the exception of two or three cells[1]containing the GBO site and one cell containing the Sugar Grove Research Facility (SGRS).

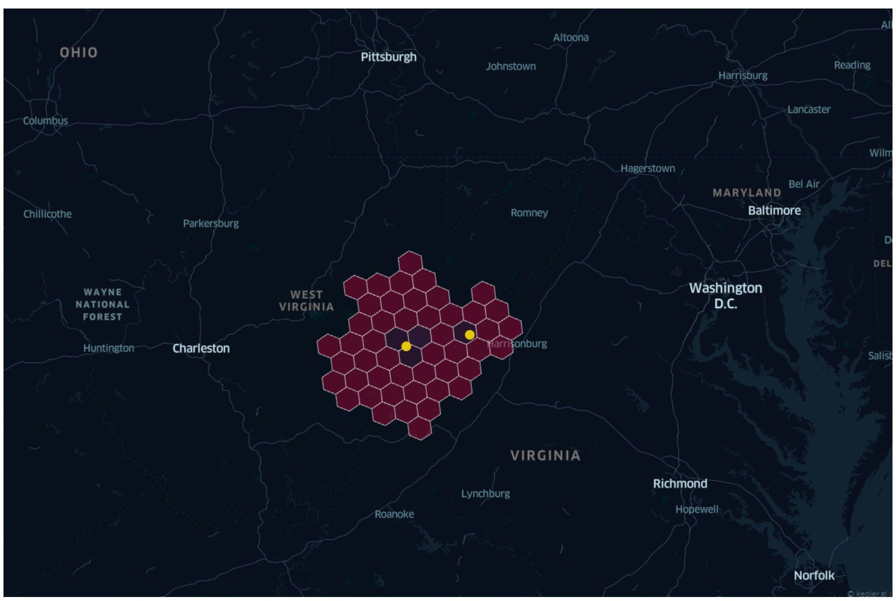

Fig. 1 Large angle view of illuminated Starlink cells during the experiment. For two of the 3 experiments, cells were illuminated in Channels 4/5 only. Darker cells (around GBT and SGRS indicated in yellow) were not directly illuminated in any downlink channel.

[1] Two cells bracketing the GBT to the NW and SE were excluded in the April 26 and July 13 tests. The three cells shown in Fig. 1 (including a new cell to the NE of the GBT) were excluded in the July 28 test.

For the April 26 and July 13 experiments, the satellite downlinks to these cells were in Channels 4 and 5 only[2], and during the experiment, each cell was served by Starlink. *The goal of these first two experiments was to gauge the impact of this full illumination of the NRQZ in these two channels, and to measure the strength of RFI as detected by the GBT during these periods.* Given that the illumination was in only Channels 4 and 5, and that the downlink signals of the Starlink system are right hand circularly polarized (RHCP) with known bandwidth and channel frequencies, the signals were relatively easy to identify. The results of these two experiments are described in Sections 2 and 3.

The goal for the July 28, 2023 experiment was slightly different: testing whether SpaceX could implement active avoidance to reduce the strength of the signal detected from satellites passing near boresight. The results of this experiment are described in Section 4.

For all three experiments, the GBT's new X-band receiver was set to receive signals in 4 overlapping Intermediate Frequencies (IFs) covering all downlink channels. Details of the GBT setup are given in Appendix A.

2. April 26, 2023 Experiment

For this first test, the GBT was rotated from South to North through West at the beginning of the experiment, and back to South at the end of the experiment (also through West). During the middle 30 minutes of the experiment (when the CH 4/5 downlinks into the NRQZ were being carried out by SpaceX), the telescope was pointed directly north, and took data at the following elevations (in degrees): 78, 65, 55, 45, 35, and 25 degrees. Each elevation produced thirty 1-s integrations. The telescope then took additional datasets from 25 back to 78 degrees in the same steps, also for thirty 1-s integrations at each elevation. In addition, the telescope took data in "on the fly" mode as it rotated from South to North and then back to South at the beginning and end of this experiment.

Sample Detections

The test proceeded as outlined in Appendix A-1, with the following detailed illumination timescale provided by SpaceX after the experiment (Table I). This time range for CH4/5 illumination was as expected, starting at 16:44:12 ET and ending at 17:14:12 ET. Note that between 4:44:12 and 5:14:12 PM ET, NRAO expected to only see Starlink signals between 11.45-11.95 GHz.

[2] Although cells outside the NRQZ could potentially be served by the same satellite in other channels (e.g. 3, 6, 7, 8).

	Before Test	Test Start	Test End	After test
Eastern Time (ET)	<Wed, 04/26/2023, 4:44:12 PM PT	>=Wed, 04/26/2023, 4:44:12 PM PT	<Wed, 04/26/2023, 5:14:12 PM PT	>=Wed, 04/26/2023, 5:14:12 PM PT
Pacific Time (PT)	<Wed, 04/26/2023, 1:44:12 PM PT	>=Wed, 04/26/2023, 1:44:12 PM PT	<Wed, 04/26/2023, 2:14:12 PM PT	>=Wed, 04/26/2023, 2:14:12 PM PT
Restricted Channels	1,2,3,4,5	1,2,3,6,7,8	1,2,3,6,7,8	1,2,3,4,5
Restricted Frequencies (GHz)	10.7-11.95	10.7-11.45 and 11.95-12.7	10.7-11.45 and 11.95-12.7	10.7-11.95
Transmit Channels	6,7,8	4,5	4,5	6,7,8
Transmit Frequencies	11.95-12.7	11.45-11.95	11.45-11.95	11.95-12.7

Table 1 Channel restrictions and timescales before, during and after the experiment.

Table 2 gives the expected signal strength at the GBT (in dB and Jy) from downlink transmissions of known strength (e.g. Starlink downlink between 10.7-12.7 GHz). These values are based on requirements of maximum signal strength from Starlink downlinks, and assume a forward gain of 80 dB for the GBT. Inner sidelobe values are taken from calculations similar to those shown in EVLA Memo 222.

We note that a GBT mainlobe to satellite mainlobe interaction (very rare, however not impossible in this experiment) would be expected to produce a very large detector response. A satellite sidelobe to GBT mainlobe interaction (rare but much more probable) would produce a signal in the thousands of Jys, and a satellite mainlobe to GBT sidelobe interaction (the most probable of the detectible interactions) should produce a signal that is on the order of Jys.

We note that throughout the April experiment, there is only one RFI signal attributable to Starlink (e.g. correct channels and polarizations) that is in the thousands of Jys, and several that are a few Jys.

GBT	**Satellite Mainlobe**	**Satellite Sidelobe**
Mainlobe	-192 dB [6.3e+6 Jy]	-230 dB [1e+3 Jy]
Sidelobe		
(inner)	-243 dB [41 Jy]	-282 dB [6e-3 Jy]
(outer)	-262 dB [0.63 Jy]	-300 dB [1e-4 Jy]

Table 2 Expected signal strength at the GBT resulting from Starlink downlink signals.

Table 3 shows the scans associated with each portion of the experiment described above. Scan 1 includes all data as the GBT rotated to the North, and Scan 14 contains all data as the telescope rotated back to the South. Scans 2-13 (inclusive) contain all the data from the thirty 1-s integrations at each telescope tip-elevation while pointed to the North.

Scan	Source	Vel	Proc	Seq	RestF	nIF	nInt	nFd	Az	El
1	rfiscan2	0.0	Track	1	9.750	4	720	1	180.3	77.8
2	sidelobe_horizon	0.0	Track	1	9.750	4	30	1	360.0	77.8
3	tip_65	0.0	Track	1	9.750	4	30	1	360.0	65.0
4	tip_55	0.0	Track	1	9.750	4	30	1	360.0	55.0
5	tip_45	0.0	Track	1	9.750	4	30	1	360.0	45.0
6	tip_35	0.0	Track	1	9.750	4	30	1	66.4	35.0
7	tip_25	0.0	Track	1	9.750	4	30	1	360.0	25.0
8	tip_25	0.0	Track	1	9.750	4	30	1	360.0	25.0
9	tip_35	0.0	Track	1	9.750	4	30	1	293.6	35.0
10	tip_45	0.0	Track	1	9.750	4	30	1	360.0	45.0
11	tip_55	0.0	Track	1	9.750	4	30	1	326.3	55.0
12	tip_65	0.0	Track	1	9.750	4	30	1	0.0	65.0
13	sidelobe_horizon	0.0	Track	1	9.750	4	30	1	360.0	77.8
14	rfiscan2	0.0	Track	1	9.750	4	189	1	180.3	77.8

Table 3 Scan numbers associated with the ~1 hour experiment. Scans 2-13 were all acquired during the CH4/5 restricted period.

Some of the scans show little to no RFI evident above system noise in the spectrum. Many (but not all) scans also show a known 10.7 GHz "birdie" that was coming from the GBT holography system[3]. Fig. 2 shows one of these typical scans, which is the spectrum from a 1-s scan, with the GBT tipped at 25 degrees (EL) from the horizon, differenced to a 1-s scan taken with the telescope at an elevation of 78 degrees (EL), which is the standard elevation for GBT RFI scans.

For the 1-s scan shown in Fig. 2, there is no Starlink signal evident in CH4 or CH5. However, at the same elevation (~9 seconds later) a 5-6 Jy signal is evident (see Fig. 3-Left). Fig. 3-Right shows the same frequency coverage and time, but in LHCP radiation. As expected, the RFI signal apparent in RHCP disappears in the LHCP scan at the same time.

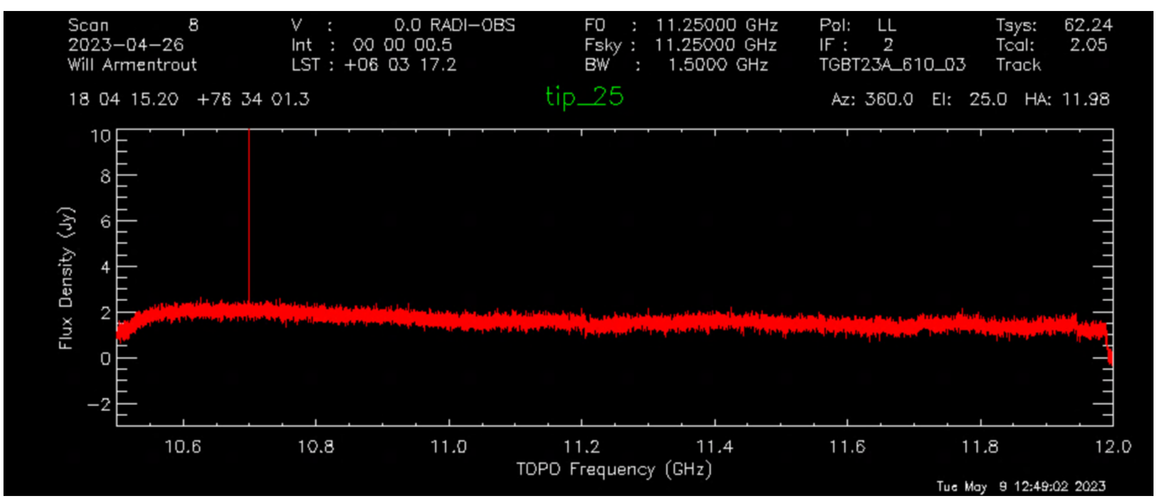

Fig. 2 A 1-s scan taken with the telescope at 25 degrees elevation. Many 1-s scans look like this with little to no RFI evident in the CH4-5 frequency range (11.45-11.95 GHz).

[3] This issue has been resolved. The holography system now has a software switch and can be turned off.

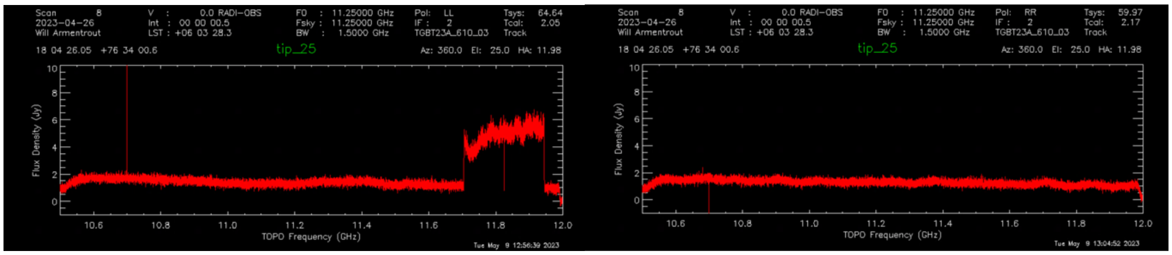

Fig. 3 Impact of timing and polarization. (Left) A 1-s scan taken with the telescope at 25 degrees elevation, about 9 seconds later than the scan in Fig. 2. (Left) shows the spectrum in LL (RHCP signal from SpaceX), and (Right) shows the spectrum in RR (LHCP from SpaceX). The characteristic Starlink downlink signal accupies channel 5 (11.7-11.95 GHz). This result is not surprising, since the downlink signal from SpaceX in 10.7-12.7 GHz is a RHCP signal. The RFI disappears at this same time in the RR plot, as expected. This signal strength is expected when a GBT sidelobe interacts with a satellite mainlobe.

Figure 4 shows a 1-s integration taken from scan 9 (when the telescope was at an elevation of 35 degrees). This RFI signal (RHCP) in Channel 4 is very large, between 3000-4000 Jy, and has the characteristic start and stop frequencies of a CH4 downlink signal. This signal strength most closely resembles when the GBT mainlobe overlaps with a satellite sidelobe (see Table 2). At this time, the GBT was apparently pointed (35 degrees above the horizon, pointing north) with its main beam coincident with a satellite sidelobe. The signal in Channel 5 in this same plot is not as strong, but still several 100s of Jy.

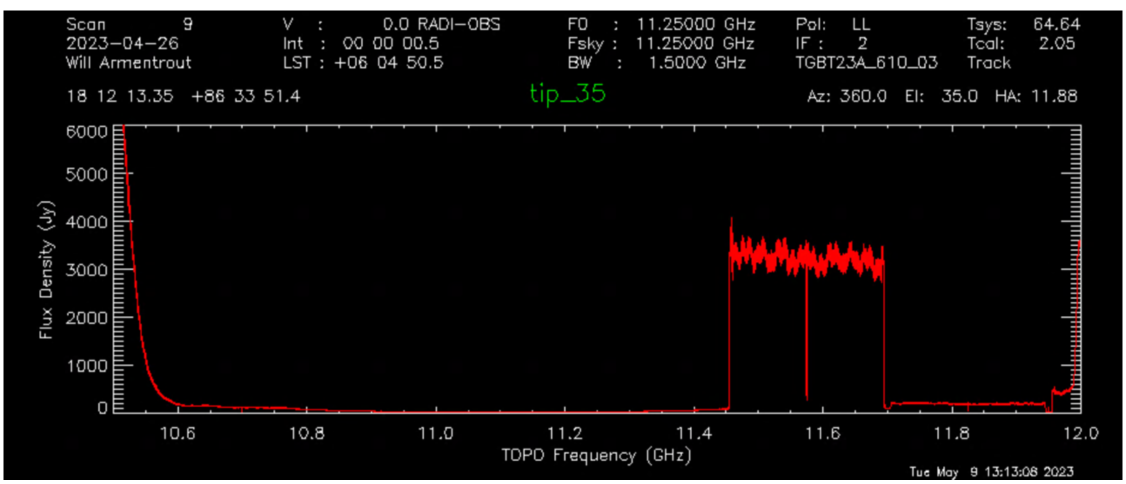

Fig. 4 A 1-s scan taken with the telescope at 35 degrees elevation. This RFI is likely the result of a CH4 interaction between the GBT-mainlobe and the satellite-sidelobe (see Table 2).

Results and Conclusions

We have examined the spectra in RR and LL polarizations in each of the tilts from the GBT. In general, we find that the signal strengths are at the level of a few Jys, RHCP, with ~250MHz bandwidth. Signals with these characteristics come and go over the 30-s of data (in 1-s integrations) taken at each inclination. Referring to scan numbers in Table 3, we note that no signals are detected at elevations of 78 degrees or 65 degrees at the start of the tilt. Scans 5-8 show small (few Jy) signals in channels 4 and/or 5. Scan 8 (at a 35 degree inclination) shows the largest signal that lasts for a few seconds and has the correct bandwidth and polarization. We expect that this signal (shown in Fig. 4) is the result of a GBT mainlobe to satellite sidelobe interaction (see Table 2). We note that during the detection of this large RFI signal, the LHCP signal is also large (though not at the level of 1000s of Jy). The second largest RFI signal detection is also at an elevation of 35 degrees (Scan 6), but only rises to a value of about 20 Jy.

The conclusions of this first experiment were:

1. We have detected signals with the correct frequencies and polarizations consistent with being SpaceX/Starlink downlink signals. The detected RFI signals occur in CH 4 and CH5, and possess RHCP.
2. The signal strengths detected are consistent with known interaction modes between the GBT and a downlinking satellite (see Table 2).
3. We see no signal strengths large enough to be satellite-mainlobe to GBT-mainlobe (~10^6 Jy), but given the very small beam size of the GBT and the cells containing the GBT not being served, we expect that this type of interaction would have low probability.
4. We do see evidence that a single satellite could be illuminating at one channel resulting in RFI at the ~1-10 Jy level (satellite-mainlobe to GBT-sidelobe) and in another channel resulting in RFI at the ~1000 Jy level (satellite-sidelobe to GBT-mainlobe). SpaceX has indicated that a single satellite could perform in this way. Further inquiry is needed to confirm that this effect is what we are detecting in the data.

Publicly available data indicates that a Starlink satellite did pass very close to boresight at the time of the 4000-Jy detection shown in Fig. 4. This satellite trajectory is shown superimposed on the GBT beam in Fig. 5a. While the trajectory does not pass through the maximum of the GBT beam, it passes within a few arcminutes of boresight. The strength of this detected signal is consistent with simple modeling of a GBT-mainlobe to satellite-sidelobe interaction. Figure 5b shows the expected relative power below peak telescope response.

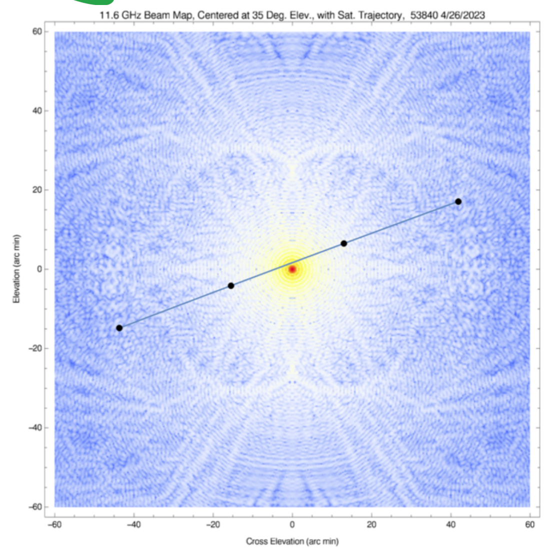

Fig. 5a GBT beam map at 11.6 GHz, centered at the appropriate azimuth and elevation at the appropriate time on April 26, 2023. X- and y-axes are distance (arcmin) from boresight. The black dots indicate the position of a Starlink satellite at one second intervals. Note that this image covers a 2x2 degrees square on the sky. The large signal shown in Fig. 4 is from the one second integration as the satellite passed closest to boresight.

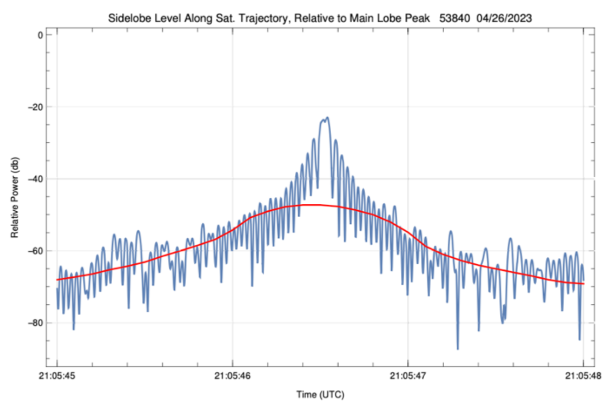

Fig. 5b This figure shows the sidelobe level along the trajectory of the close to boresight passage. Blue is the instantaneous sidelobe level, and the red line is a running 1-second average of the sidelobe level. Note that at the closest passage, the relative power is approximately 50 dB below the GBT gain (85 dB).

3. July 13, 2023 Experiment

The main goal of the July 13, 2023 experiment was to make observations of satellites passing at various (close) known distances to boresight and to examine the resulting RFI. The GBT was directed to point at AZ: 44.71 deg, EL: 37.735 deg. Given this telescope pointing at a specified time, SpaceX provided a listing of close-to-boresight passages, ranging from 0.05 degrees to 2.6 degrees away from the GBT beam. These passages are shown in Table 4. In this table, close-to-boresight passes are sorted by distance from boresight (degrees), and columns are (I) degrees from boresight, (II) passage time (UTC), and (III) Starlink satellite No.

Boresight Distance (deg)	**Passage Time (UTC)**	**Starlink Satellite No.**
0.053	22:06:11	5543
0.181	22:12:55.50	3667
0.187	22:23:16.50	1564
0.307	22:05:50.50	5837
0.387	22:00:57.50	1752
0.424	22:11:52.50	4531
0.485	22:02:33	30106
0.709	22:14:21.50	3539
1.491	22:05:26.50	2738
1.512	22:18:48	2098
1.619	22:08:43	5594
1.704	22:13:19	4544
1.995	22:24:19	2117
2.185	22:29:41	3886
2.607	22:08:27	5974

Table 4. Predicted close passages between 22:00:00 UTC – 22:45:00 UTC on 07-13-2023 arranged by distance to boresight of the GBT. Boresight distance is in degrees, and passage time is in UTC.

For these observations, there were 60 scans, each with sixty 1-s integrations (1 hr of data). Each scan was followed by 10-12 s of setup and telescope configuration for the next scan. The setup "gap" between successive GBT scans caused us to miss a few of the predicted close passages. For example, the closest pass (0.05 degrees) was missed by 1-s (it occurred between two successive scans consisting of sixty 1-s integrations). For the 0.05 degrees from boresight passage, UTC 22:06:10 was the end of the scan, and UTC 22:06:11 was the predicted passage within 0.05 degrees (see Fig. 6). In addition, the pass at 1.512 degrees was missed for the same reason.

As a result of this test, we understand the need to adjust observing protocols to avoid this type of data loss. In all of the predicted close-to-boresight passes, a strong downlink signal was detected at the expected time. We note that in Fig. 6, the expected downlink channel (CH5; 11.7-11.95 GHz) is apparent, but another channel (CH3; 11.2-11.45 GHz) is even stronger. This behavior is likely due to the fact that single satellites are simultaneously sending downlink signals to multiple cells in multiple channels. Starlink engineers have confirmed this capability.

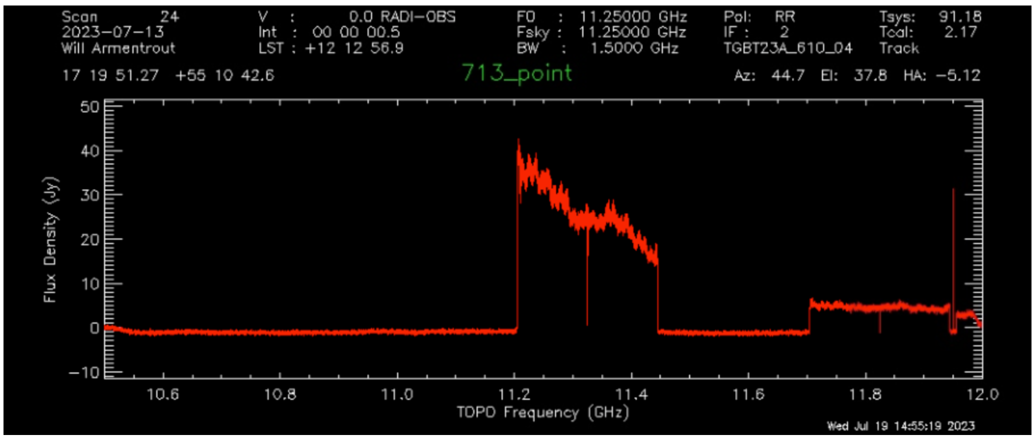

Fig. 6 Starlink downlink signal was detected, but before it would have peaked (likely in the next 1-s integration).

Sample Detections

Below are a sample of detections at varying distances from boresight, from 0.187 degrees to 2.607 degrees. Plots are made from a difference between the known close passage time and a baseline time, both consisting of 1-s of data. Because of the rapid movement of LEO satellites across the sky, averaging data for more than 1-s is less useful. Also, because the spectra result from the difference between two scans, the zero level in the plot may be offset from 0 Jy.

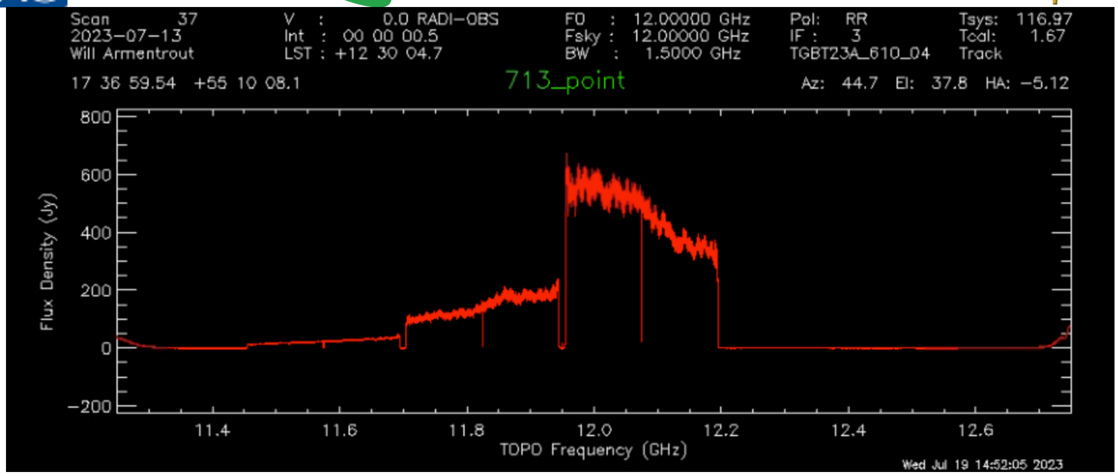

Fig. 7a Downlink signal from a 0.187 degrees from boresight passage.

0.187 degrees (22:23:16.5 UTC)

- RHCP signal is stronger than LHCP
- Emission seen in CH 4/5 (11.45-11.95 GHz), but is stronger in CH 6 (11.95-12.2 GHz)
- Signal peaks at the correct time

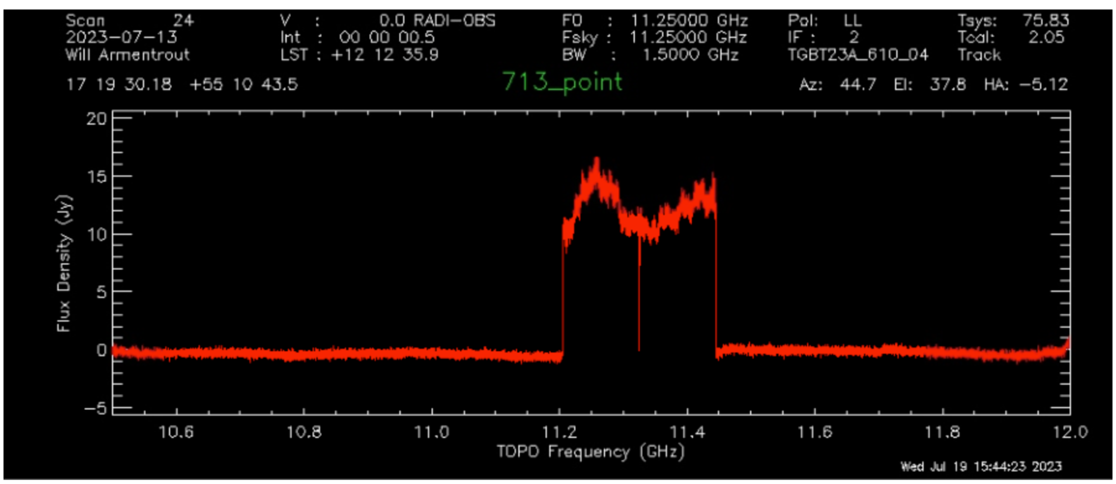

Fig. 7b Downlink signal from a 0.307 degrees from boresight passage.

0.307 degrees (22:05:50 UTC)

- RHCP signal is stronger than LHCP
- Emission seen in CH 3 (11.2-11.45 GHz)
- Signal peaks at the correct time

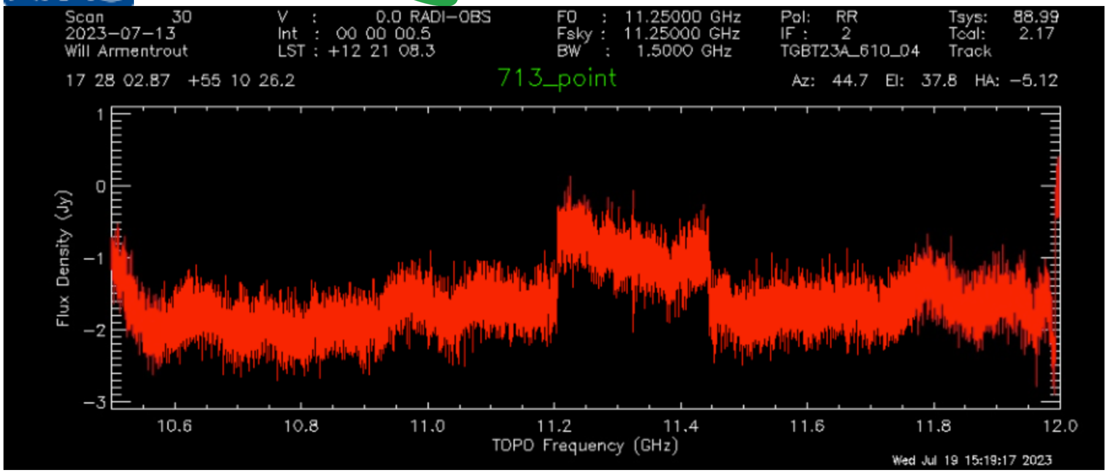

Fig. 7c Downlink signal from a 0.709 degrees from boresight passage.

0.709 degrees (22:14:21.5 UTC)

- RHCP signal is stronger than LHCP
- Emission seen in CH 3 (11.2-11.45 GHz)
- Signal peaks at the correct time

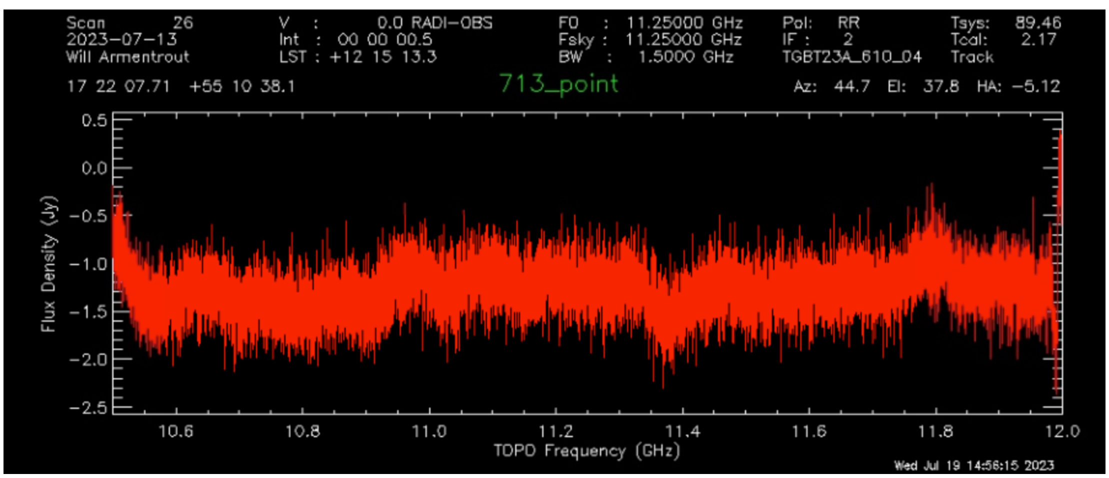

Fig. 7d Downlink signal from a 2.6 degrees from boresight passage.

2.6 degrees (22:08:27 UTC)

No RFI is apparent in the 1-s integration associated with this pass (or the adjacent 1-s integrations).

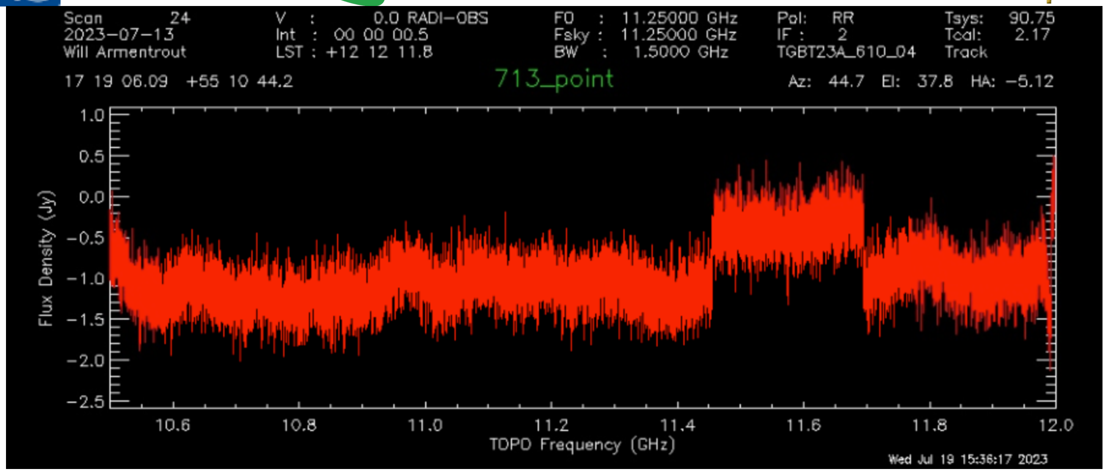

Fig. 8a Downlink signal from a 1.491 degrees from boresight passage, RHCP.

Polarization Data at 1.491 degrees from boresight (22:05:26 UTC)

To specifically highlight the difference detected in the RHCP and LHCP data, we look at the 1-s integration during a passage that is 1.491 degrees from boresight. These two 1-s integrations show that while a signal is detected in RHCP data (Fig. 8a) in CH4, there is no signal apparent in the LHCP data taken at the same time (Fig. 8b).

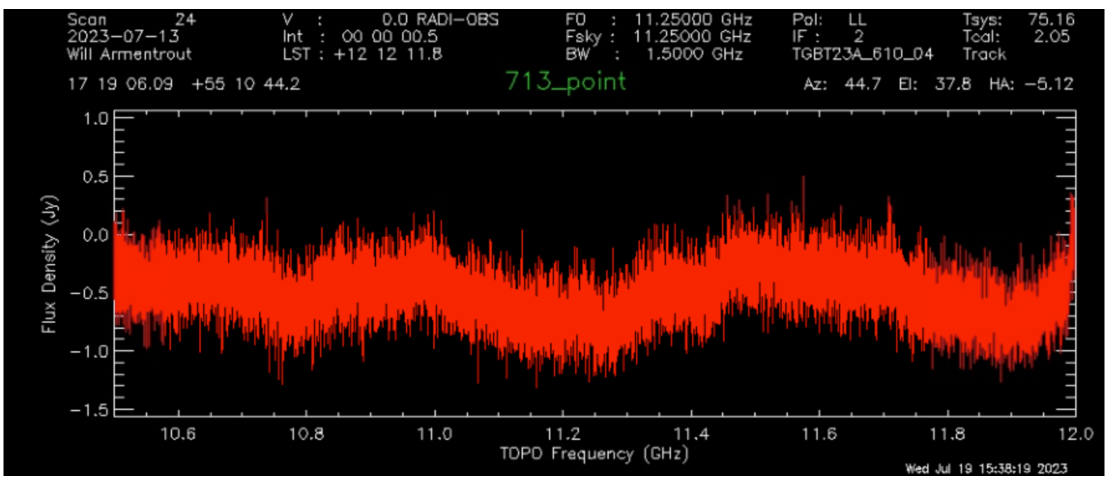

Fig. 8b Downlink signal from a 1.491 degrees from boresight passage, LHCP.

Finally, we plot the detected signal strength (maximum channel detected in a particular distance-from-boresight passage) as a function of distance from boresight. Here we see the not-surprising result that the detected signal drops rapidly with distance from boresight, falling below the 1-Jy level between 0.75 degrees and 1.5 degrees from boresight.

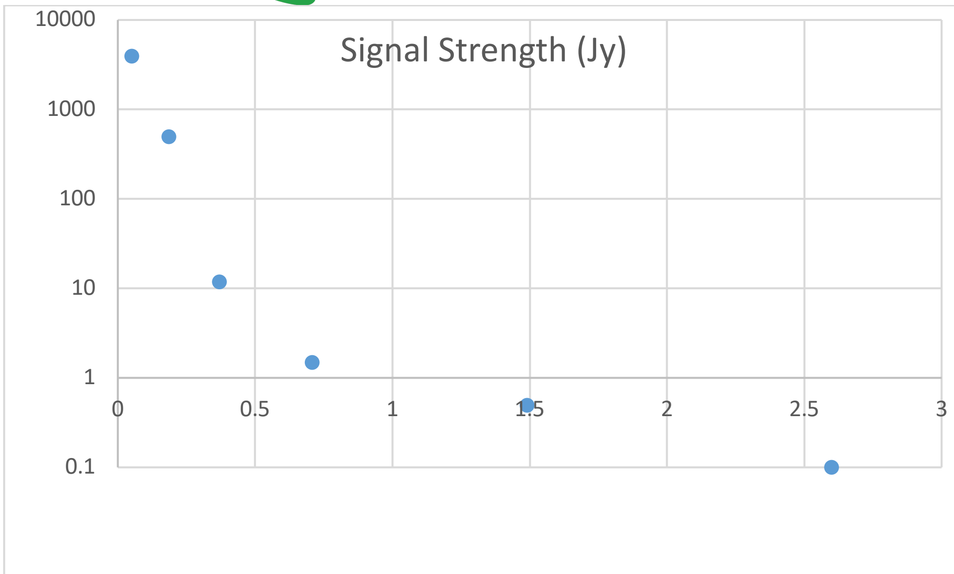

Fig. 9 Downlink signal strength plotted as a function of distance from boresight to the GBT (in degrees). Data above includes April 26, 2023 event discussed in Section 2.

Results and Conclusions

The results of this second GBT-Starlink test were as follows:

1. Signals are detected at predicted times. That is, close to boresight passages produced detectible RFI in expected channels. As shown in Fig. 9, signal strength decreases with distance from boresight. The variation in signal strength is the result of a combination of (1) distance from boresight and (2) the exact cell being served by the satellite.
2. As described above, some close passages (e.g. 0.05 degrees, 1.512 degrees) were not detected because of a normal timing gap between scans. This issue will be corrected in subsequent experiments.
3. At the time of the experiment, we wanted to resolve why some RFI was detected at predicted times, but in channels other than 4/5. This has been resolved in discussions with SpaceX: individual satellites can form multiple beams. So, while downlink beams into the NRQZ were in the expected channels (4/5), beams serving other cells – outside the NRQZ – could have been in other channels from the same satellite (close-to-boresight).

4. July 28, 2023 Experiment

The purpose of the July 28 experiment was to determine if active avoidance on the part of SpaceX could reduce the strength of detected RFI, particularly for satellites passing close-to-boresight.

The GBT, outfitted with the X-band receiver made spectral line observations in four overlapping 1.5 GHz windows centered at : 9.75, 10.5, 11.25, and 12 GHz. The GBT took the first 30 minutes of observing time to move to the requested pointing position (AZ: 42.752 deg, EL: 40.748 deg). GBT observations in X-band planned to begin at 1800 EDT and end at 1900 EDT. High winds changed this observing plan, and the GBT did not start taking data at the proposed AZEL position until 22:44:35 UTC (18:44:35 ET).

As a result, the telescope was unable to acquire data until 22:44:35 UTC on July 28, 2023. Fortunately, there were still 5 passes (of the 11 planned – see below) that fell within the final 20 minutes of data acquisition, and the closest passage to boresight in this experiment (0.2 degrees at 22:49:28.75) also fell within this time range.

At the requested pointing, SpaceX predicted the following close encounters at the UTC times listed in Table 5. In this table, close-to-boresight passes are sorted by time, and columns are (I) UTC passage time, (III) degrees from boresight, (IV) Starlink satellite ID.

Time (UTC)	Boresight Dist. (deg)	Starlink Satellite No.
22:03:51.75	*0.88*	*5141*
22:06:06.75	*1.0*	*4147*
22:09:09	*0.22*	*5955*
22:16:12	*0.69*	*2225*
22:18:25.50	*0.93*	*5705*
22:25:21.50	*0.52*	*3812*
22:48:21.75	0.27	3761
22:49:28.75	0.2	5741
22:51:09.75	0.24	5698
22:56:18.25	0.65	1060
22:57:24	0.8	2615

Table 5. Satellites with close passages to boresight during 07-28-2023 experiment. Italicized entries in the Table (first 6 time-ordered passages) were not observed due to high winds at the site.

Sample Detections

The July 28 experiment had a particular goal, which was to determine whether SpaceX could perform real time active avoidance to reduce the RFI impact on the GBT at the times associated with close passages. Only Channels 4 and 5 were part of the "active avoidance" experiment from the SpaceX side.

The following observations are 1-s integration time total power spectrum plots scaled to Jy at the listed time. For each close to boresight passage, the figure caption gives the time of closest passage, the distance to boresight in degrees and the Starlink satellite number.

To the right of each GBT total power spectrum is a plot of the satellite trajectory at this time, gleaned from public data (space-track.org via the SpaceTrackClient python module). Since all data were taken in a single 915-s long scan, these scans show the difference between the close-to-boresight passage integration (1-s) and a 1-s integration with no detected downlink signal. Y-axis is labeled as Counts, but we note that these signal levels are approximately in Jy.

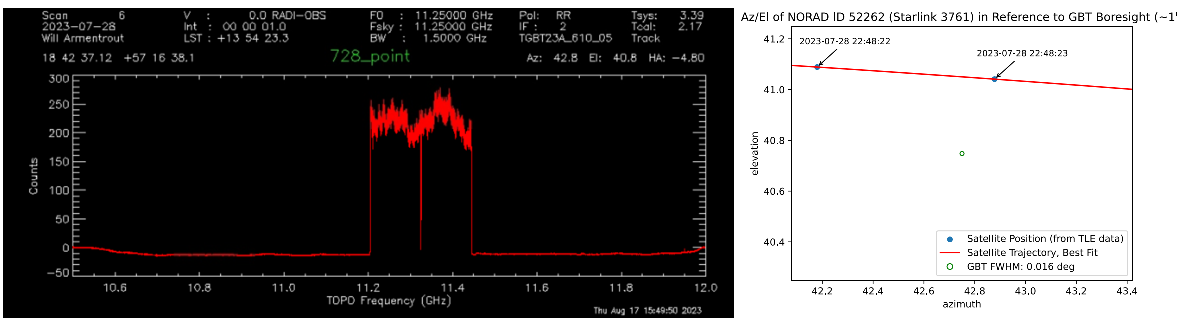

Fig. 10a (Left) Downlink signal detected in Channel 3 (~225 Jy). Time: 2023-07-28 22:48:21.75, Distance to Boresight: 0.27 degrees, Starlink Satellite Number: 3761. (Right) Starlink-3761 trajectory at this time, showing GBT FWHM at 12 GHz. Only Channels 4 and 5 were part of the "active avoidance" experiment from the SpaceX side.

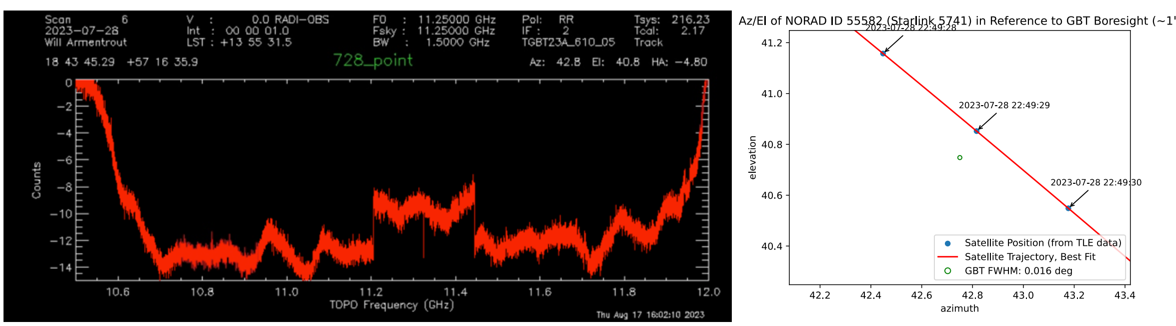

Fig. 10b (Left) Downlink signal detected in Channel 3 (~4 Jy). Zero level is negative because these values are taken from a difference between two 1-s scans. Time: 2023-07-28 22:49:28.75, Distance to boresight: 0.2 degrees, Starlink Satellite Number 5741. (Right) Starlink-5741 trajectory at this time, showing GBT FWHM at 12 GHz. Only Channels 4 and 5 were part of the "active avoidance" experiment from the SpaceX side.

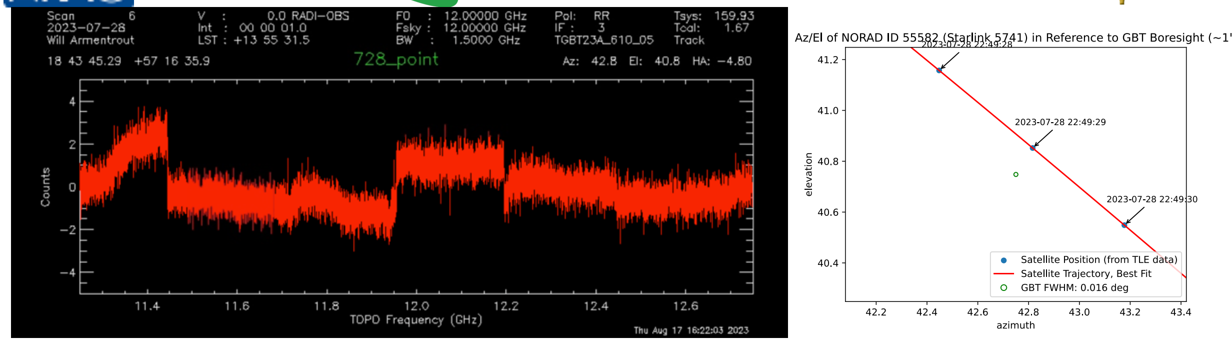

Fig. 10c (Left) Downlink signal detected in Channel 6 (~2 Jy). Time: 2023-07-28 22:49:28.75, Distance to boresight: 0.2 degrees, Starlink Satellite Number 5741. (Right) Starlink-3761 trajectory at this time, showing GBT FWHM at 12 GHz. Only Channels 4 and 5 were part of the "active avoidance" experiment from the SpaceX side. Only Channels 4 and 5 were part of the "active avoidance" experiment from the SpaceX side.

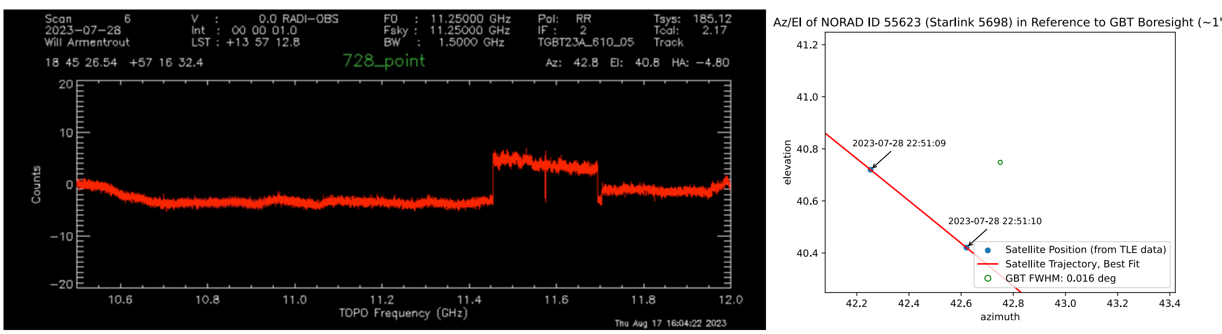

Fig. 10d (Left) Downlink signal detected in Channel 4 (~4-5 Jy). Time: 2023-07-28 22:51:09.75, Distance to boresight: 0.24 degrees, Starlink Satellite Number: 5698. (Right) Starlink-5698 trajectory at this time, showing GBT FWHM at 12 GHz. Channels 4 and 5 were part of the "active avoidance" experiment from the SpaceX side.

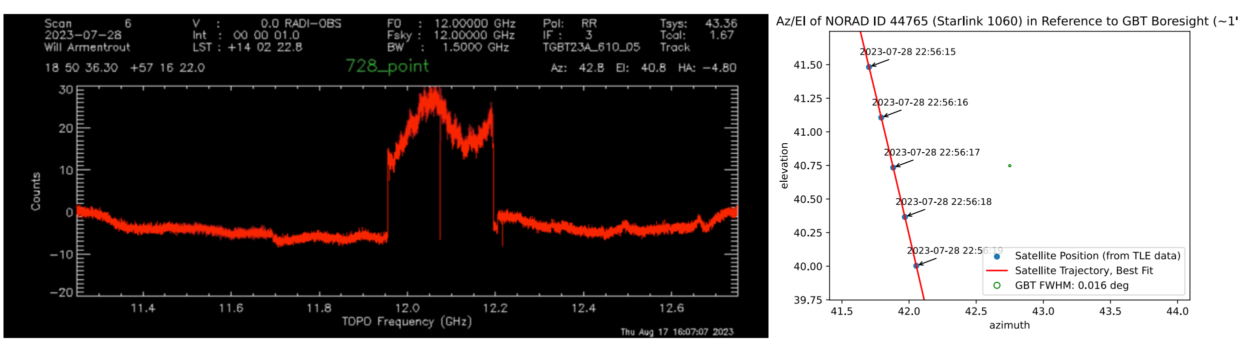

Fig. 10e (Left) Downlink signal detected in Channel 6 (~25 Jy). Time: 2023-07-28 22:56:18.25, Distance to boresight: 0.65, Starlink Satellite Number: 1060. (Right) Starlink-1060 trajectory at this time, showing GBT FWHM at 12 GHz. Only Channels 4 and 5 were part of the "active avoidance" experiment from the SpaceX side.

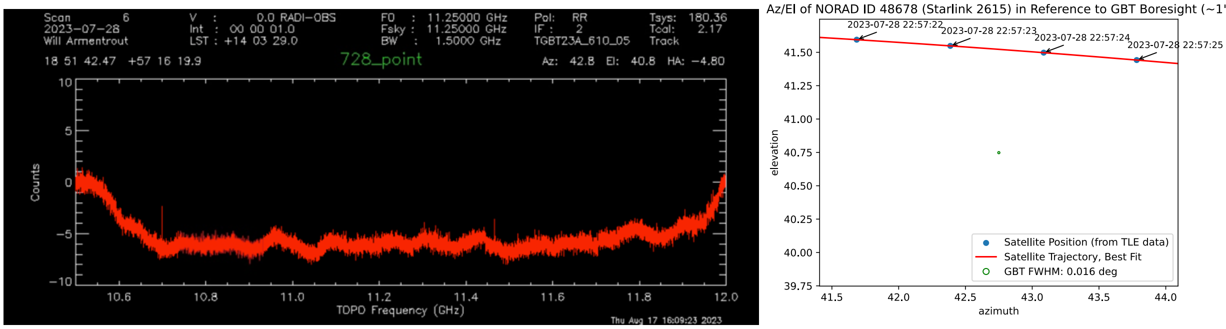

Fig. 10f (Left) No downlink detected at this time (largest distance to boresight in this group. Time: 2023-07-28 22:57:24, Distance to boresight: 0.8 degrees, Starlink Satellite Number: 2615. (Right) Starlink-2615 trajectory at this time, showing GBT FWHM at 12 GHz.

Results and Conclusions

For this final experiment of the series, SpaceX enabled active avoidance on channels 4 and 5 with a configuration that should limit signal received by the telescope to 10 Jy or less. The two close passes that exercised the method using these channels resulted in ~4 Jy and ~8 Jy signals respectively. While more data is necessary to fully ascertain the efficacy of this method, there is a stark difference in the signal strength associated with channels that have active avoidance enabled (e.g. CH 4, 5) versus those without. The GBT observed up to ~225 Jy of signal in channels 3 and 6 during the close-to-boresight passages. Further experiments of this nature are required to both gather more samples and test satellite passages that are even closer to antenna boresight (perhaps 0.1 degrees).

We note that automated signal processing could remove data at the times of known close-to-boresight passages, as close satellite passages typically take less than a second. In all, these tests provide valuable data with which to plan successive tests that we hope will begin on the GBT as it begins observations again in Fall 2023.

4. Future Work

NRAO and SpaceX plan to continue to carry out coordinated testing of spectrum use between radio telescopes and satellite networks. We are currently processing the next round of testing that involved performing a similar test (active avoidance for satellites passing close-to-boresight) with the Jansky Very Large Array in NM, carried out in early September 2023.

Acknowledgements

The authors acknowledge the planning and coordination made possible by many people working at NRAO, GBO and SpaceX.

Appendix A – Experimental Plans

(1. April 26, 2023; 2. July 13, 2023; 3. July 28, 2023)

1. **April 26, 2023: Test No. 6: Coordinated Channel 4/5 Test**

NRAO/GBT Satellite Constellation Coordination Test Series

Date and Time: March 29, 2023; 4:30-6:30 PM EDT

Satellite Network: SpaceX/Starlink

Telescope: Green Bank Telescope

Frequency Coverage Required: Starlink downlink channels 4 and 5 (11.45-11.95 GHz)

Other coordinated observations: xxx

Relevant NRAO/GBT Staff: Chris De Pree, Will Armentrout, Sheldon Wasik

Relevant SpaceX Staff: xxx

Experimental Plan: The SpaceX Starlink system will illuminate all cells contained within the National Radio Quiet Zone with 1-2 beams/cell from its satellite network, with the exception of the cells that contain the location of the Green Bank Telescope and the Sugar Grove Research Station (below). The illumination will use only downlink channels 4 and 5 (located between 11.45-11.95 GHz). The illumination will start at 5:00 PM EDT and end at 6:00 PM EDT. Before and after the period of this experiment, the Starlink network will illuminate only previously agreed upon cells, and only utilizing Channels 6, 7, and 8 (e.g. current operating mode).

Observations (GBT): The GBT, outfitted with the X-band receiver will make spectral observations in four overlapping 1.5 GHz windows centered at : 9.75, 10.5, 11.25, and 12 GHz. GBT observations will begin at 4:30 PM and end at 6:30 PM EDT, so that there are "off" times within the same dataset, before and after the "on" time. Will Armentrout (GBO) will be in control of the telescope during the experiment (remote).

Observations (SGRS): xxx

GBT Location:

38° 25' 59.24" -79° 50' 23.41"

SGRS Location:

38° 30' 53.82", -79° 16' 48.07"

2. **July 13, 2023: Test 2023_07_13: Coordinated Channel 4/5 Test**

NRAO/GBT Satellite Constellation Coordination Test Series

Date and Time: July 13 (Thursday), 2023; 21:30-23:00 UTC (17:30-19:00 EDT)

Satellite Network: SpaceX/Starlink

Telescope: Green Bank Telescope

Frequency Coverage Required: Starlink downlink channels 4 and 5 (11.45-11.95 GHz)

Other coordinated observations: xxx

Relevant NRAO/GBT Staff: Chris De Pree, Will Armentrout, Sheldon Wasik

Relevant SpaceX Staff: xxx

Experimental Plan: The SpaceX Starlink system will illuminate all cells contained within the National Radio Quiet Zone with 1-2 beams/cell from its satellite network, with the exception of the (3) cells that contain the location of the Green Bank Telescope and the (1) cell containing the Sugar Grove Research Station (see Fig 1a and 1b, shared by SpaceX). The illumination will use only downlink channels 4 and 5 (located between 11.45-11.95 GHz). The illumination will start at 18:00 EDT (22:00 UTC) and end at 18:45 EDT (22:45 UTC). Before and after the period of this experiment, the Starlink network will illuminate only previously agreed upon cells, and only utilizing Channels 6, 7, and 8 (e.g. return to current operating mode).

Observations (GBT): The GBT, outfitted with the X-band receiver will make spectral observations in four overlapping 1.5 GHz windows centered at : 9.75, 10.5, 11.25, and 12 GHz. The GBT will take the first 30 minutes of observing time to move to the requested pointing position (AZ: 44.71 deg, EL:37.735 deg). GBT observations in X-band will begin at 1800 EDT and end at 1900 EDT, so that there will be 15 minutes of data acquisition after the end of the Starlink coordination. Will Armentrout (GBO) will be in control of the telescope during the experiment.

At the requested pointing, we expect the following close encounters at the following UTC times:

[Angular separation [deg], satellite id, UTC time of closest pass]

```
[(0.053, 5543, '2023-07-13 22:06:11'),
 (0.181, 3667, '2023-07-13 22:12:55.500000'),
 (0.187, 1564, '2023-07-13 22:23:16.500000'),
 (0.307, 5837, '2023-07-13 22:05:50.500000'),
 (0.387, 1752, '2023-07-13 22:00:57.500000'),
 (0.424, 4531, '2023-07-13 22:11:52.500000'),
```

(0.485, 30106, '2023-07-13 22:02:33'),
(0.709, 3539, '2023-07-13 22:14:21.500000'),
(1.491, 2738, '2023-07-13 22:05:26.500000'),
(1.512, 2098, '2023-07-13 22:18:48'),
(1.619, 5594, '2023-07-13 22:08:43'),
(1.704, 4544, '2023-07-13 22:13:19'),
(1.995, 2117, '2023-07-13 22:24:19'),
(2.185, 3886, '2023-07-13 22:29:41'),
(2.607, 5974, '2023-07-13 22:08:27'),]

Observations (SGRS): N/A

GBT Location:

38° 25' 59.24" -79° 50' 23.41"

SGRS Location:

38° 30' 53.82", -79° 16' 48.07"

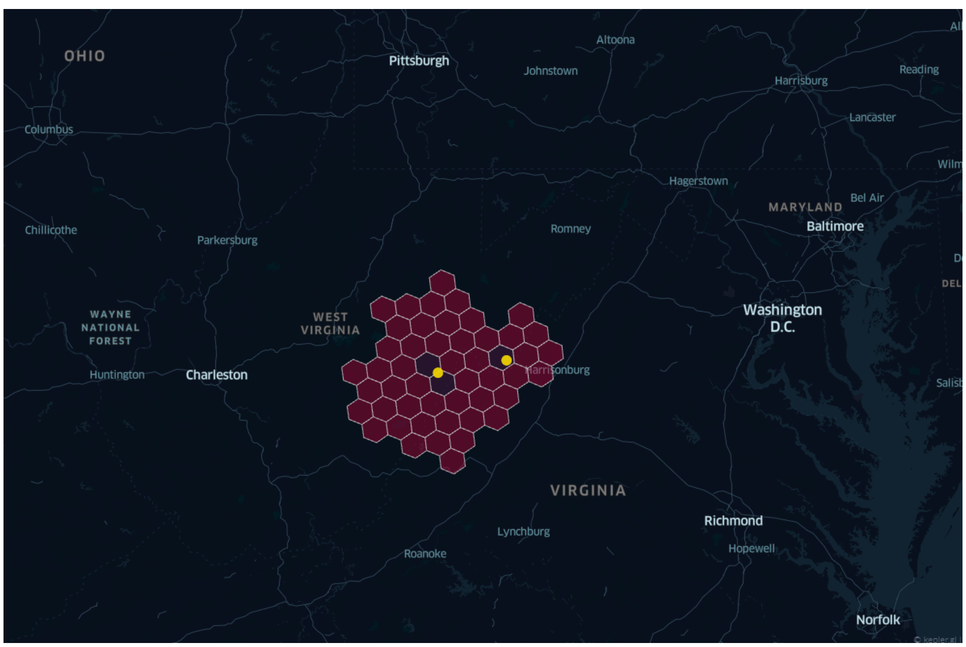

Fig 1a Large angle view of illuminated cells during experiment. **NB SpaceX will additionally exclude the cell to the ENE of the GBT location.**

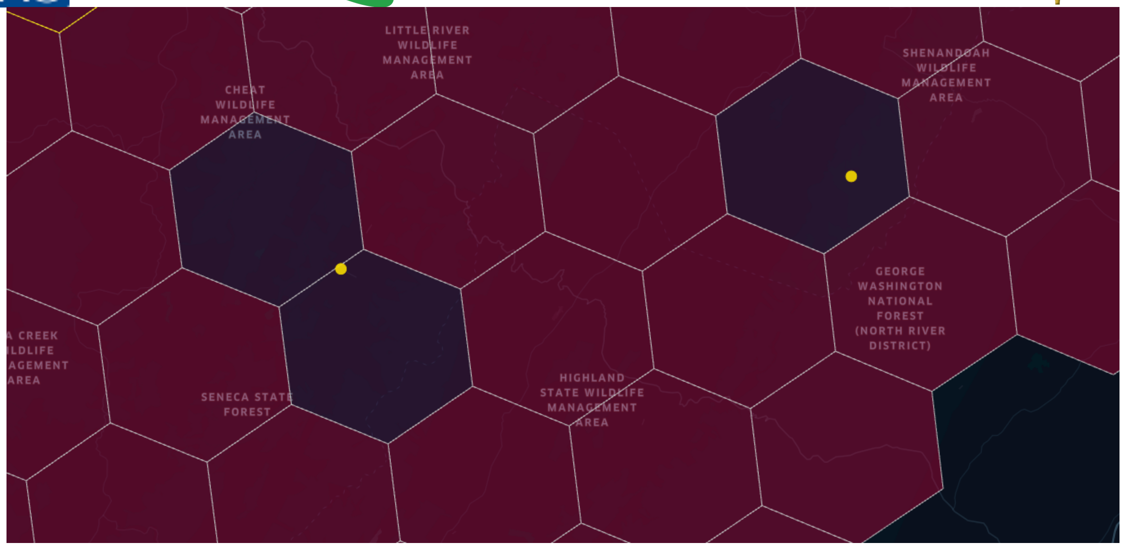

Fig 1b Detailed view of excluded cells near GBT (left) and SGRS (right) **NB SpaceX will additionally exclude the cell to the ENE of the GBT location.**

3. **July 28, 2023: Test 2023_07_28: Starlink Beam Forming**

NRAO/GBT Satellite Constellation Coordination Test Series

Date and Time: July 28 (Thursday), 2023; 21:30-23:00 UTC (17:30-19:00 EDT)

Satellite Network: SpaceX/Starlink

Telescope: Green Bank Telescope (X-band receiver)

Frequency Coverage Required: Starlink downlink channels 1 through 6 (10.7 GHz – 12.4 GHz), RR and LL polarizations

GBT Pointing Direction:
Azimuth: 42.752 degrees
Elevation: 40.748 degrees

Other coordinated observations: xxx

Relevant NRAO/GBT Staff: Chris De Pree, Will Armentrout, Sheldon Wasik

Relevant SpaceX Staff: xxx

Experimental Plan: As in previous experiments, the SpaceX Starlink system will illuminate all cells contained within the National Radio Quiet Zone with beams from its satellite network, with the exception of the (3) cells that contain the location of the Green Bank Telescope and the (1) cell containing the Sugar Grove Research Station (see Fig 1, shared by SpaceX). Illumination of cells within the NRQZ will use only downlink channels 4 and 5 (located between 11.45-11.95 GHz). The illumination will start at 18:00 EDT (22:00 UTC) and end at 19:00 EDT (23:00 UTC). Before and after the period of this experiment, the Starlink network will illuminate only previously agreed upon cells, and only utilizing Channels 7 and 8 (e.g. return to current operating mode). ***The change in this experiment is that satellites that pass within 1 degree of boresight (times below) will utilize new beam planning technology to mostly reduce the received signal at the GBT to a few Jy in all downlink channels, regardless of the cells the satellite is serving (inside or outside the NRQZ).***

Observations (GBT): The GBT, outfitted with the X-band receiver will make spectral observations in four overlapping 1.5 GHz windows centered at : 9.75, 10.5, 11.25, and 12 GHz. The GBT will take the first 30 minutes of observing time to move to the requested pointing position (AZ: 42.752 degrees
deg, EL: 40.748 degrees deg). GBT observations in X-band will begin at 1800 EDT and end at 1900 EDT. Will Armentrout (GBO) will be in control of the GBT during the experiment.

At the requested pointing, SpaceX predicts expect the following close encounters at the following UTC times:

List entries sorted by time (pass time, degrees from boresight, satellite ID)
[('2023-07-28 22:03:51.750000', 0.88, 5141),
('2023-07-28 22:06:06.750000', 1.0, 4147),
('2023-07-28 22:09:09', 0.22, 5955),
('2023-07-28 22:16:12', 0.69, 2225),
('2023-07-28 22:18:25.500000', 0.93, 5705),
('2023-07-28 22:25:21.500000', 0.52, 3812),
('2023-07-28 22:48:21.750000', 0.27, 3761),
('2023-07-28 22:49:28.750000', 0.2, 5741),
('2023-07-28 22:51:09.750000', 0.24, 5698),
('2023-07-28 22:56:18.250000', 0.65, 1060),
('2023-07-28 22:57:24', 0.8, 2615)]

List entries sorted by distance from boresight (degrees from boresight, pass time, satellite ID)
[(0.203, '2023-07-28 22:49:28.750000', 5741),
(0.215, '2023-07-28 22:09:09', 5955),
(0.24, '2023-07-28 22:51:09.750000', 5698),
(0.273, '2023-07-28 22:48:21.750000', 3761),
(0.52, '2023-07-28 22:25:21.500000', 3812),
(0.647, '2023-07-28 22:56:18.250000', 1060),
(0.689, '2023-07-28 22:16:12', 2225),
(0.795, '2023-07-28 22:57:24', 2615),
(0.881, '2023-07-28 22:03:51.750000', 5141),
(0.928, '2023-07-28 22:18:25.500000', 5705),
(1.0, '2023-07-28 22:06:06.750000', 4147)]

Observations (SGRS): N/A

GBT Location:

38° 25' 59.24"	-79° 50' 23.41"

SGRS Location:

38° 30' 53.82", -79° 16' 48.07"

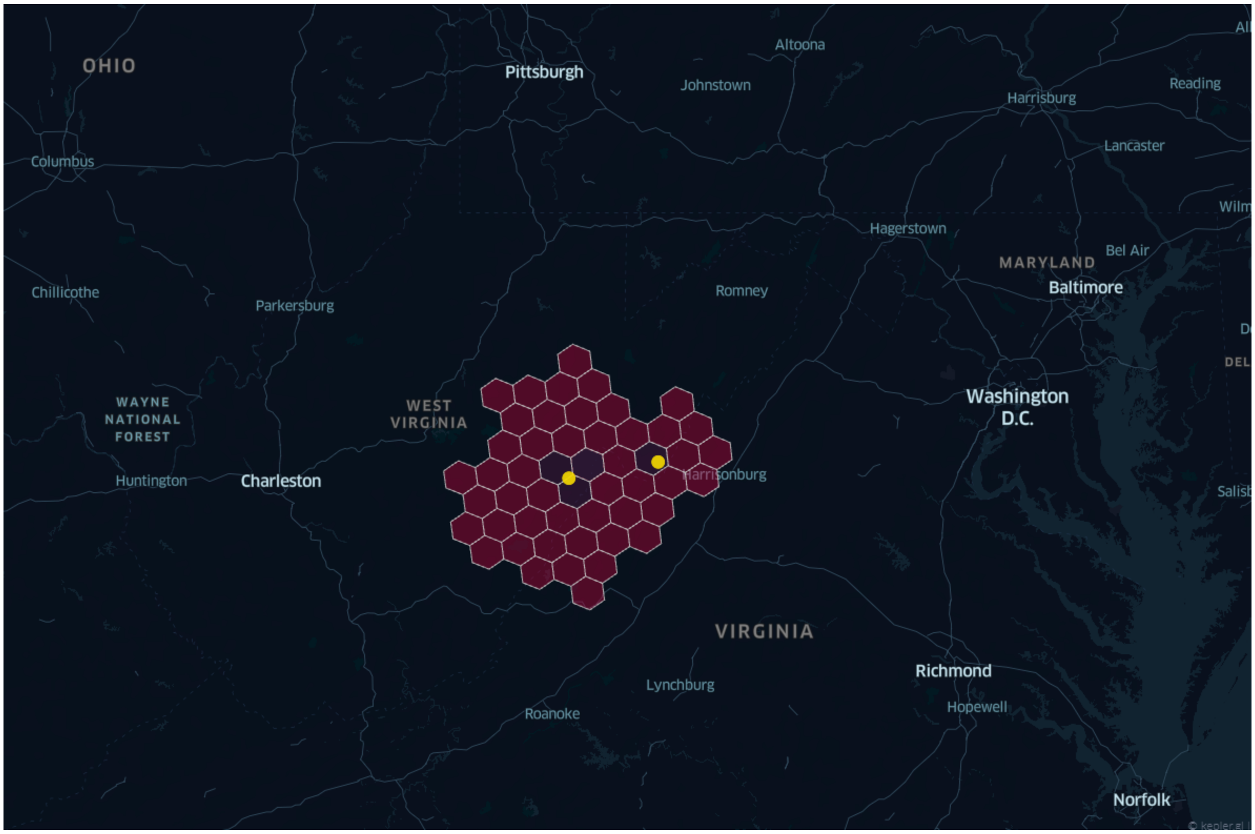

Fig 1 Large angle view of illuminated Starlink cells during the experiment. Red cells will be illuminated in Channels 4/5 only. Darker cells (around GBT and SGRS) will not be directly illuminated in any downlink channel.