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To: VGOS Broadband Group

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Subject: Westford–SpaceX coordinated testing procedures for mitigation of adverse effects from Starlink direct-to-cell transmissions at S band

1 Introduction

In early 2024, the Federal Communications Commission (FCC) authorized SpaceX to engage in testing the use of the 1990-1995 MHz band for space-Earth transmissions in the continental US. This band is normally used for cellular transmissions by T-Mobile to user handsets. T-Mobile and SpaceX have reached an agreement on the use of this 5-MHz band for space-to-ground transmissions labeled Supplemental Coverage from Space (SCS), in such a way as to not impact normal use of this band on the ground.[1, 2].

Transmissions from Starlink's implementation of SCS on direct-to-cell (DTC) equipped satellites occur currently at 1990-1995 MHz and are quite bright compared to celestial sources, in a manner that is required to close the link budget for cellular communications applications. These transmissions can cause significant problems for ground-based radio telescopes. In particular, the frontend of the 18-m Westford telescope is sensitive enough that it can experience low-noise amplifier (LNA) / frontend compression, and potentially physical damage, in cases where DTC transmissions from the Starlink DTC phased-arrays occur too close to the telescope boresight direction. During normal operations, this boresight direction changes frequently as multiple celestial targets are observed for geodetic purposes.

To mitigate the possibility of receiver compression or damage at Westford, this memo documents a series of operational tests that were conducted between SpaceX DTC assets and Westford, coordinated through NSF's Electromagnetic Spectrum Management (ESM) unit. These tests were designed to gauge the brightness in the Westford analog system of the 1990-MHz DTC transmissions from orbit, with the goal of determining the appropriate keep-out angle around boresight that should be maintained by Starlink through position-dependent disabling of DTC beams.

The results of the testing have subsequently informed operational boresight avoidance algorithms within the Starlink DTC constellation using the Operational Data Sharing (ODS) system first set up at NRAO [3], and now operationally implemented at Westford.

2 Experiment Design

2.1 Philosophy

The testing procedure involved observing with the Westford telescope, which is equipped with a broadband Very Long Baseline Interferometry (VLBI) signal chain (also known as VLBI Geodetic Observing System, or VGOS) that includes the ultra-wideband, dual-polarization quadruple-ridged flared horn (QRFH) feed that is operationally used for geodesy as part of the international VLBI service (IVS). The Westford frontend has a 2.2-GHz high-pass filter post-LNA, which was kept in place during the testing. Data were collected at a gridded series of off-boresight angles during periods when DTC satellites were actively transmitting towards the telescope. To fill in the grid, the Westford operational team chose individual off-boresight angles during each active DTC satellite pass commanded by the SpaceX team.

2.2 DTC satellites used and Westford offset angle grid selections

After initial discussions on a coordinated NSF–SpaceX radio astronomy discussion group, Westford testing was arranged for a period in November 2024. At the time of the test, the DTC system on orbit was not fully operational. Accordingly, Jacob Donenfeld at SpaceX considered available orbital ephemerides and coordinated the activation of a select number of DTC satellite downlink beams at 1990 MHz when in view of Westford. These were distributed across a number of satellites.

Table 1 lists the DTC satellites chosen for the test transmissions toward Westford on 2024-11-05. The values of "Offset Az" and "Offset El" were chosen by the Westford operators to map the desired boresight relative angle offset grid. Due to practical considerations, the grid was not uniformly sampled and represents a best-effort basis.

2.3 Westford measurement procedure

For each satellite pass / offset az-el pair, Westford operators used an Agilent MXA Signal Analyzer and Keysight FieldFox spectrum analyzer on the feed's horizontal polarization (H-pol) channel and measured the following values:

- Peak-to-noise floor ratio in primary band: 1990-1995 MHz, dB
- Peak-to-noise floor ratio at 2nd harmonic: 3980-3990 MHz, dB

These were manually recorded and later aligned with Table 1's values. The background values of the power used in the calculation of the ratio were obtained from times before and after the center time of the pass, as indicated in Table 1.

Additionally, an Ettus USRP N310 software defined radio, connected to the same H-pol channel, was used for several direct boresight illumination passes from DTC to Westford, in order to gauge high-time resolution measurements of feed response during a full boresight pass. Measurements were sampled at 32 MHz complex I/Q and stored in DigitalRF format (cf. `https://github.com/MITHaystack/digital_rf`), to examine the fine details of Westford's feed response.

3 Results

3.1 Westford signal chain response in DTC primary band transmission

Figure 1 shows the peak-to-noise floor power ratio in dB observed during each DTC pass in the primary transmission frequency band of 1990-1995 MHz, as a function of azimuth and elevation offset in degrees. White "X" marks indicate the actual measured points while the background heat map is done using interpolation; see the figure caption for details. We note that the offset from center (i.e., boresight angle of 0/0 deg) is likely due to detailed orbit timing vs. that predicted in planning, causing a slight difference in actual passage of the satellite at the given boresight offset compared to what was predicted. Maximum response of the primary 1990-1995 DTC signal through the VGOS high-pass filter (which begins to cut off at -30 dB down at 2000 MHz) is still $\sim$22 dB above background levels despite the significant attenuation of that filter, with the caveat that some time averaging is unavoidable with the peak hold feature of the spectrum analyzer used (cf. section 3.3).

3.2 Westford signal chain response at 2nd harmonic of DTC primary band transmission

Similarly, Figure 2 shows the peak-to-noise floor power ratio in dB during each DTC pass, but in the 2nd harmonic band of 3980-3990 MHz, as a function of azimuth and elevation offset in degrees. Compared to Figure 1, the maximum response here is more severe, reaching $\sim$45 dB over the background. Since DTC satellite transmissions do not occur in this band, we consider any signature to be an indication of the onset of severe non-linearity in the Westford frontend caused by the bright DTC primary band transmission. The results clearly show the need to avoid the case of near-boresight transmissions from DTC to Westford.

3.3 High time resolution Westford signal chain response in DTC primary band during boresight passes

Figure 3 plots a representative spectral response vs. time and frequency for the high-resolution Westford H-pol feed measurements from the Ettus USRP N310 digital sampling system over a 32-MHz bandwidth centered at the primary DTC transmission frequency of 1990 MHz. Satellite ID 11288 is plotted here, occurring at 21:37:45 UTC on 2024-11-05 (cf. Table 1). The 5-MHz occupancy of the DTC signal is clearly visible. The high-resolution time measurements indicate that, compared to the spectrum analyzer response, which involved some unavoidable averaging, peak response during boresight passage reached over 30 dB at some frequencies compared to background values before and after the pass.

3.4 Keep-out boresight avoidance angle from DTC to Westford

After review of Figures 1 and 2, the Westford team chose 5 degrees as a conservative keep-out angle for DTC boresight avoidance. This was based on the following reasoning:

Table 1: Starlink DTC satellites used during the 2024-11-05 Westford tests, and Westford pointing offset grid values chosen for each satellite pass.

NORAD ID	Satellite ID	PT Start Time	PT End Time	UTC Mid Time	Center Lat Geod. Deg	Center Lon Geod. Deg	Center Az Deg	Center El Deg	Offset Az Deg	Offset El Deg
11104	59763	9:04:12	9:06:27	17:05:26	44.04828468944880	-71.31503301	35.818	68.054	0	0
11268	61055	9:24:42	9:25:27	17:24:57	39.28578480107850	-67.6803843	136.174	33.539	0	0
11098	59760	9:26:12	9:28:27	17:27:28	42.22946897320630	-73.17526493	219.909	70.623	1	-1
11294	61054	9:31:27	9:32:57	17:32:18	39.75455670031350	-68.72197672	137.136	40.278	2	-1
11177	60118	9:37:12	9:38:27	17:37:38	46.24490622116970	-69.2847301	29.552	36.921	2	1
11230	61053	9:38:42	9:40:27	17:39:35	40.20638419289930	-69.77340494	138.776	48.624	2	2
11105	59758	9:41:12	9:42:57	17:42:05	40.77551831247030	-74.22072883	222.101	47.970	1	2
11203	60117	9:44:27	9:45:57	17:45:12	45.36322270327810	-69.0300207	31.452	42.596	0	2
11284	61052	9:45:57	9:47:57	17:47:01	41.263220355210600	-69.83358011	140.720	59.371	-1	2
11252	61051	9:53:12	9:55:27	17:54:10	41.70314813065030	-70.84281217	142.705	71.700	-2	2
11112	60115	9:58:57	10:00:57	17:59:49	44.04034126006570	-69.7732045	34.925	58.269	-2	1
11198	60114	10:06:12	10:08:27	18:07:11	43.63070944788050	-70.71902207	33.789	69.403	-2	0
11233	61061	10:15:12	10:17:27	18:16:18	43.553730679152300	-72.76363698	324.932	66.910	-2	-1
11297	61060	10:22:27	10:24:42	18:23:38	43.96104730799070	-73.71955964	326.356	56.374	-2	-2
11095	59720	10:26:12	10:27:27	18:26:39	39.38503541509340	-68.22020653	136.919	35.918	-1	-2
11162	60123	10:28:12	10:30:12	18:28:54	41.43390532067060	-72.74233281	220.380	64.341	0	-2
11154	61059	10:29:57	10:31:57	18:31:00	44.89706825146690	-73.56555706	327.694	47.941	1	-2
11103	59718	10:33:12	10:34:57	18:34:06	39.843731297217000	-69.2731312	137.731	43.370	2	-2
11119	60121	10:35:27	10:37:27	18:36:23	40.99126959083040	-73.75810451	220.746	52.673	3	-2
11299	61058	10:37:27	10:38:57	18:38:26	45.29186815538220	-74.46201106	329.176	41.278	3	-1
11157	60122	10:42:57	10:44:42	18:43:46	40.54276666162940	-74.78400371	222.468	43.381	3	1
11231	61057	10:45:12	10:46:12	18:45:40	46.17485340753330	-74.21466081	330.245	36.044	3	2
11101	59715	10:47:42	10:49:42	18:48:46	41.35125417067680	-70.37295641	139.599	63.987	3	3
11160	60125	10:50:42	10:51:42	18:51:07	39.47847690593150	-74.90182912	223.551	36.018	2	3
11082	59711	11:24:27	11:26:27	19:25:32	44.58618815400730	-73.14820277	326.151	52.741	1	3
11241	60936	11:27:57	11:29:12	19:28:27	39.23747479315890	-68.65099993	136.475	36.655	-1	3
11092	59710	11:31:57	11:33:42	19:32:51	44.974120839679100	-74.08176802	327.589	45.087	-2	3
11142	59957	11:33:27	11:34:42	19:34:07	46.341169686554000	-69.40718826	29.660	36.776	-3	3
11088	59709	11:39:27	11:40:57	19:40:02	45.87334958201890	-73.85163481	329.447	39.152	-3	2
11133	59954	11:55:12	11:57:12	19:56:17	44.14826436578320	-69.88118332	33.453	57.963	-3	-2
11143	59953	12:02:27	12:04:42	20:03:34	43.74282671674620	-70.82941906	35.034	68.823	-3	-3
11204	60931	12:11:27	12:13:42	20:12:34	43.42203369971870	-72.86356052	326.051	67.945	-2	-3
11251	60930	12:18:57	12:20:57	20:19:53	44.37655375125120	-72.74743884	325.392	57.240	-1	-3
11240	60929	12:26:12	12:28:12	20:27:20	44.77666907	-73.66859375	327.099	48.439	0	-3
11151	60049	12:28:12	12:28:57	20:28:39	46.67899898615280	-69.03492287	29.430	33.719	1	-3
11130	59950	12:31:42	12:33:57	20:32:48	41.462870155732000	-73.72214965	220.542	57.577	2	-3
11238	60928	12:33:42	12:35:27	20:34:30	45.16359253726630	-74.59130439	328.869	41.870	3	-3
11163	60047	12:35:12	12:36:42	20:35:57	45.817723444958100	-68.74536395	30.528	38.357	0	10
11123	59948	12:39:12	12:41:12	20:40:12	40.41873497225930	-73.78402699	32.448	51.694	0	5
11244	60926	12:41:27	12:42:27	20:41:49	46.05053579321080	-74.35765954	330.407	36.505	0	-5
11155	60046	12:42:27	12:44:12	20:43:20	45.43891624677050	-69.64115369	31.788	44.233	0	-10
11116	60045	12:49:42	12:51:42	20:50:36	44.52058394587380	-69.44117227	32.682	51.580	-5	0
11145	59945	12:54:27	12:55:12	20:54:42	39.502799736937200	-75.86773281	220.022	65.947	5	0
11086	60043	13:04:12	13:06:27	21:05:21	43.71160703768140	-71.3209934	34.283	72.694	0	0
11122	60040	13:26:12	13:28:27	21:27:02	41.86922684284110	-73.21646728	219.247	66.250	0	0
11289	60991	13:29:57	13:30:57	21:30:23	46.11959789102870	-68.35485753	29.474	35.280	0	0
11140	60039	13:33:42	13:35:42	21:34:40	40.83675808	-73.25607121	220.120	54.048	0	0
11288	61002	13:36:57	13:38:27	21:37:46	45.74599128299630	-69.24571394	30.549	40.409	0	0
11129	60038	13:41:12	13:42:57	21:41:55	40.385138463044200	-74.28273491	222.059	44.604	0	0
11274	61001	13:44:12	13:45:57	21:45:06	45.366133130343800	-70.14621976	32.752	46.778	0	0
11135	60048	13:48:42	13:49:42	21:49:22	39.57303442706430	-75.47016068	223.182	34.358	0	0
11282	60992	13:51:27	13:53:27	21:52:30	44.44510713537890	-69.94742309	34.147	54.959	0	0
11290	61000	13:58:42	14:00:57	21:59:49	44.04219938296000	-70.88742312	34.314	65.212	0	0

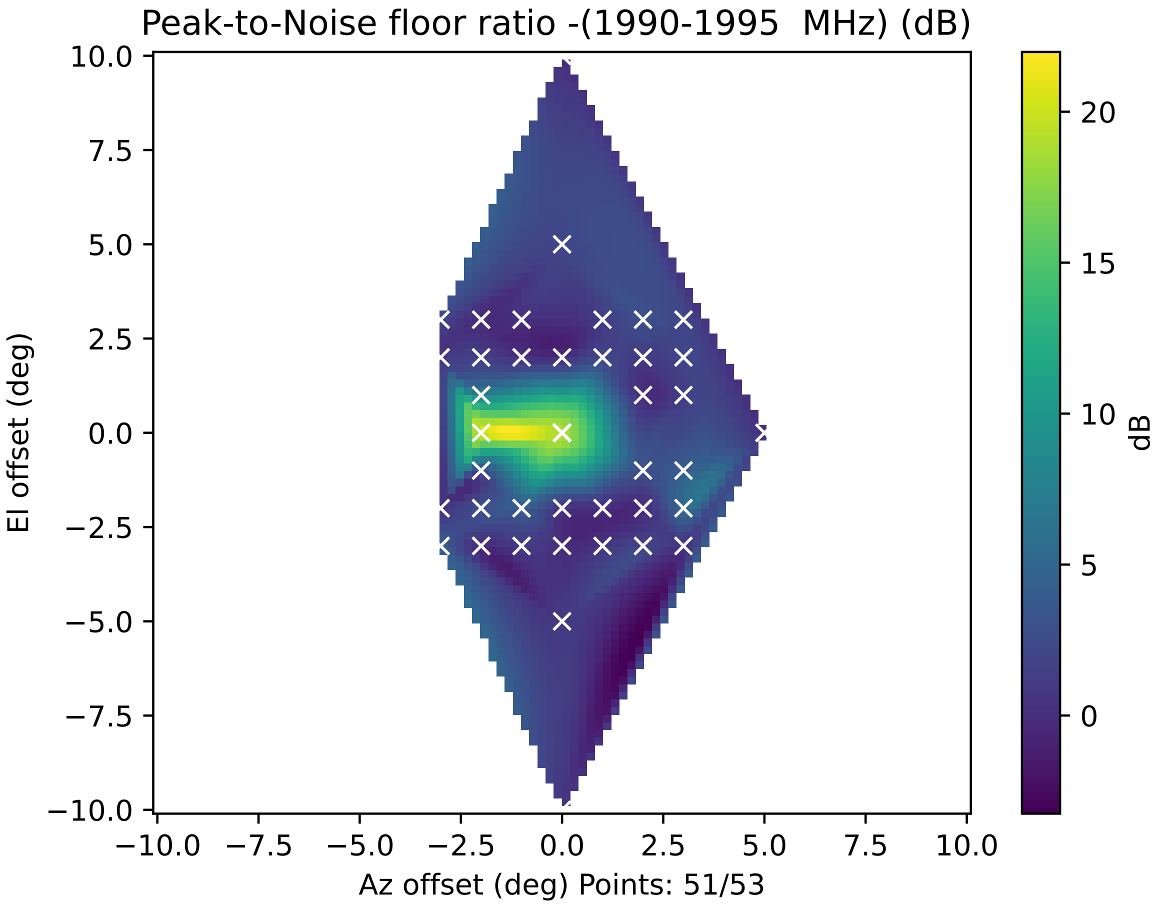

Figure 1: Peak-to-noise floor power ratio in dB measured in the primary DTC band of 1990-1995 MHz at Westford (H pol channel) as a function of azimuth and elevation offset in degrees during 2024-11-05 SpaceX DTC test. White X symbols mark the measurement locations with data. Python's `scipy.interpolate.griddata` package was used for the background color map, using `cubic` interpolation –i.e., the value determined from a piecewise cubic, continuously differentiable (C1), and approximately curvature-minimizing polynomial surface. Maximum response value is estimated at ∼22 dB over the background. "Points: 51/53" label in the X axis indicates that 2 points were rejected due to measurement problems prior to plotting.

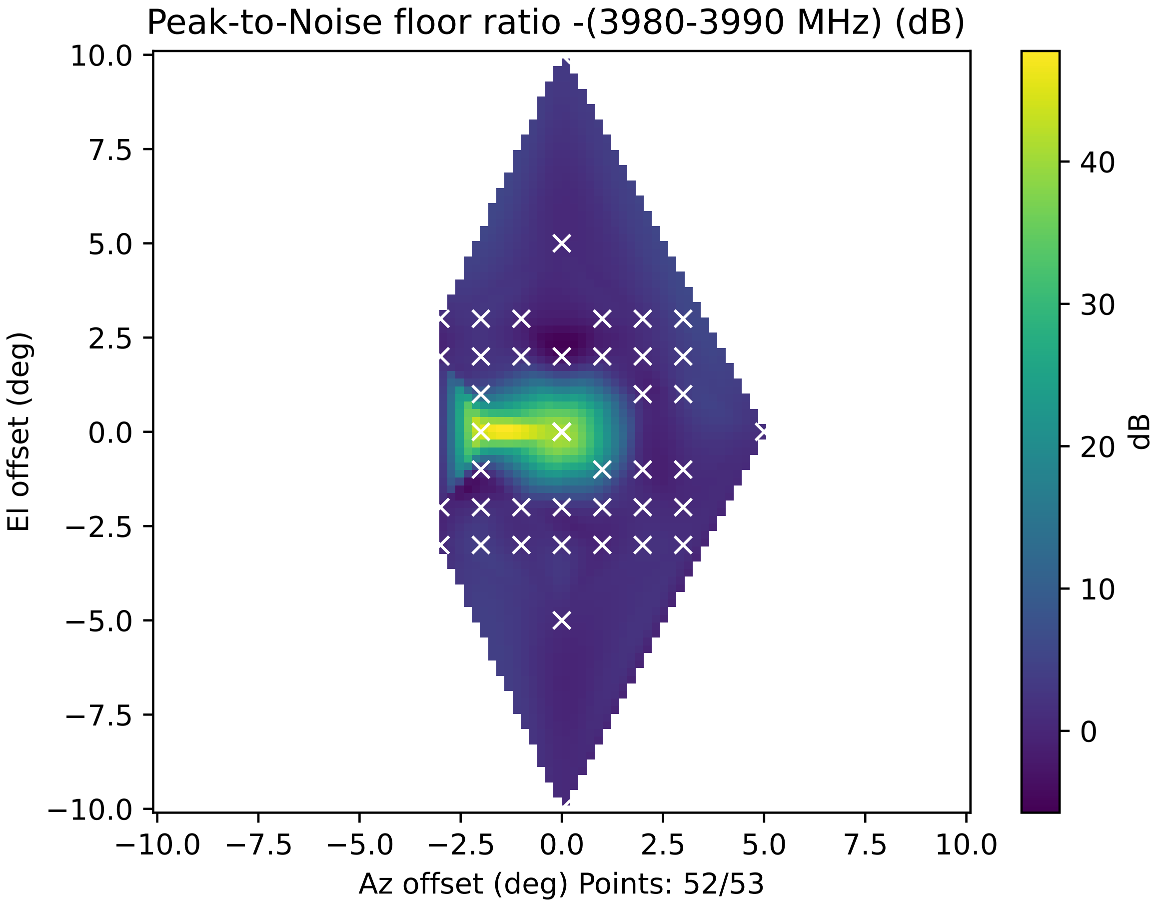

Figure 2: Same as Figure 1 but here in the 2nd harmonic DTC band of 3980-3990 MHz. Any observed response at these frequencies is a strong indicator of frontend / LNA overload. Maximum response value was estimated at ∼45 dB over the background. "Points: 52/53" label in the X axis indicates that 1 point was rejected due to measurement problems prior to plotting.

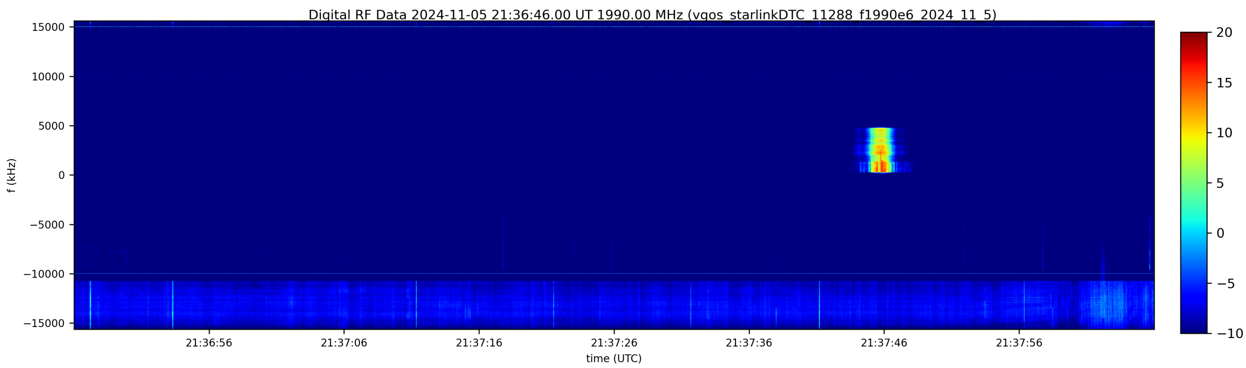

Figure 3: High time resolution spectral response of Westford H-pol feed during direct boresight DTC pass from satellite ID 11288 with nominal predicted passage at 2024-11-05T21:37:45 UTC (cf. Table 1). Boresight pass occurs near 21:37:46 UTC, slightly later than predicted, due to real vs. predicted orbital position for ID 11288. The high time resolution and bright response compared to the pre and post-pass background indicates that maximum response occurred at nearly 30 dB over background even through the sharp cutoff high-pass filter integrated into the signal chain, with this value likely being averaged over in the spectrum analyzer peak-to-noise floor observations near boresight shown in Figure 1.

- Peak response occurred at about -1.75 degrees from the azimuth center.
- Response dropped to the noise floor at about +1.5 degrees.
- Therefore, an avoidance cone of 3.5 degrees away from boresight is workable.
- Implementing an additional safety factor leads to a choice of 5 degrees, in a symmetric cone in azimuth/elevation around boresight.

This choice is also congruent with Rec. ITU-R RA. 769-2's suggestion of using 15 dBi for spaceborne interferers as an average gain for covering sidelobe reception up to 5° off the main telescope beam.

4 Conclusion

Based on the active DTC testing conducted at Westford on 2024-11-05 and described in this memorandum, a practical implementation of a keep-out avoidance angle of 5 degrees, symmetric around telescope boresight direction, is optimal for protection of the VGOS signal chain frontend of the Westford antenna from DTC transmissions at 1990-1995 MHz emitted from Starlink satellites.

5 Acknowledgments

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[3] Bang D. Nhan, Christopher G. De Pree, Matt Iverson, Brenne Gregory, Daniel Dueri, Anthony Beasley, and Brian Schepis. Toward Spectrum Coexistence: First Demonstration of the Effectiveness of Boresight Avoidance between the NRAO Green Bank Telescope and Starlink Satellites. *The Astrophysical Journal Letters*, 971(2):L49, August 2024. `doi:10.3847/2041-8213/ad6b24`.