Starlink's Supplemental Coverage from Space (SCS) Tests at S-Band and UWBR

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Abstract

As part of the ongoing tests to facilitate spectrum compatibility between satellite internet providers and the radio astronomy community, NRAO's Electromagnetic Spectrum Management (ESM) group, funded by the US National Science Foundation (NSF)'s Spectrum Innovation Initiative - National Radio Dynamic Zone (SII-NRDZ) grant, has been performing coordinated tests with SpaceX (Starlink). These tests have been performed with the Very Large Array (VLA) and Green Bank Telescope (GBT) at X-Band and S-Band. In this memo, we describe the second coordinated test (SCS-T02-GBT) investigating the effects of Starlink's Supplemental Coverage from Space (SCS) Direct to Cell (DtC) downlinks between 1990-1995 MHz in the S-Band and the under-development Ultra Wideband Receiver (UWBR) data on the GBT. For internal reference, this memo is for the SCS-T02-GBT and SCS-T03-GBT tests.

Contents

Changelog

317.0 Bautista et al. (2025-03-12) — Initial published version.

1 Introduction

In early 2024, the Federal Communications Commission (FCC) authorized SpaceX to engage in testing of 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. T-Mobile and SpaceX have reached an agreement on the use of this 5 MHz band for space to ground transmissions in such a way as to not impact normal use of this band on the ground (FCC, 2024a; FCC, 2024b). The US National Science Foundation and SpaceX have arranged tests to determine how SpaceX can operate the Direct to Cell (DtC) system without undue impact on sensitive receivers. The plan was to carry out testing of these transmissions as soon as enough capable satellites were in orbit to make testing useful. The first test (SCS-T01-VLA) was performed on the VLA with only three operational SpaceX-SCS satellites observed in March 2024. This first test observation was performed to assess the impact of the Starlink SCS transmissions in the VLA's L-Band receiver (which covers 1.0 - 2.0 GHz)[1].

A follow up test at the VLA was performed in July 2024 with two separate observation sessions (SCS-T02a-VLA and SCS-T02b-VLA). In both test sessions, the DtC transmissions are visible in the VLA L-Band data. These tests will be described in a separate RFI memo. In the case of the VLA, the downlink frequencies fall well within the sensitivity of the L-Band receiver. On the Green Bank Telescope, the receiver sensitivities are such that the SCS transmissions fall in range of the S-Band (1.73-2.60 GHz) and UWBR (0.7-4.0 GHz)[2] receivers. Coordinated tests were performed with both receivers to assess the presence of the SCS transmissions in GBT data.

2 Observing Setup

2.1 S-Band

At the GBT, the S-Band receiver has a nominal sensitivity range of 1.73 - 2.60 GHz, placing the SCS transmissions within the bandpass sensitivity. To check for spectral leakage outside of the SCS transmission band, three observing windows (subbands) were used. Their rest frequencies were set at 1943(1931.28 - 1954.72), 1992.5(1980.78 - 2004.22), and 2018(2006.28 - 2029.72) MHz, so as to sample the spectrum above and below the DtC transmission band, as well as fully covering the DtC range. The observations were configured in VEGAS Mode 24, giving a bandwidth of 23.44 MHz, and 65536 frequency channels, resulting in frequency resolution of 0.357 kHz. Circular polarization data was recorded, with an integration time of 500 ms. Due to the telescope being shut down for summer foundation maintenance, the telescope pointing was locked at an (Az, El) = (77.850°, 188.1°).

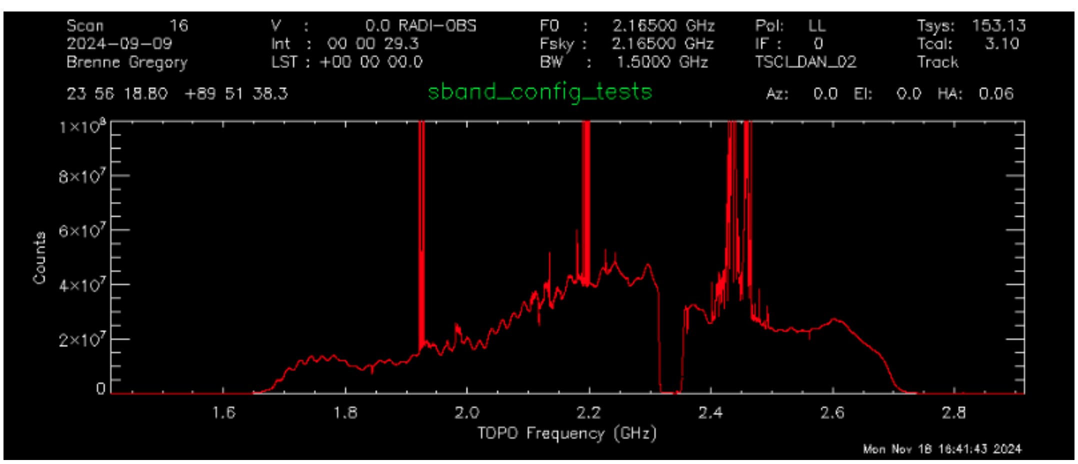


Figure 1: S-Band bandpass.

[1] https://science.nrao.edu/facilities/vla/docs/manuals/oss2016A/performance/bands
[2] The Ultra Wideband Receiver is still under development and this is the current nominal sensitivity range.

Center Frequency [MHz]	Frequency Range [MHz]	Band
1409	1397.28 - 1420.72	HI protected band
1418	1406.28 - 1429.72	HI protected band
1665	1653.28 - 1676.72	OH protected band
1978	1966.28 - 1989.72	SCS
1992.5	1980.78 - 2004.22	SCS
2007	1995.28 - 2018.72	SCS
2695	2683.28 - 2706.72	Continuum protected band
3985	3973.28 - 3996.72	SCS 2nd Harmonic

Table 1: UWBR observing window (subband) coverage.

2.2 UWBR

At the GBT, UWBR has a nominal sensitivity range of 0.70 - 4.0 GHz, placing the SCS transmissions and their second harmonic within the bandpass sensitivity. To check for spectral leakage and other transmissions outside of the SCS band eight observing windows (subbands) were used. Their rest frequencies are summarized in Table 1. The observations were configured in VEGAS Mode 11, giving a bandwidth of 23.44 MHz, and 65536 frequency channels, resulting in a frequency resolution of 0.357 kHz. The UWBR receiver is only capable of recording data in linear polarization, so data was taken with full stokes parameters. To mirror the setup of the S-Band test, an integration time of 500 ms was used. At the time of the test, telescope motion was enabled, and the pointing was chosen to be (Az, El) = (-7.172°, 42.168°).

3 Data

3.1 Starlink Data

In advance of the GBT S-Band test on September 9th, 2024, the close-to-boresight passes were derived ahead of time from publicly available TLE data, and confirmed by SpaceX after the test, shown in Table 2. The satellites were scheduled to be placing the main beam of their transmission at estimated distances of 150, 210, and 500 km from the telescope, thus, none of the transmitting satellites were directly illuminating the telescope. SCS transmission downlink frequencies are 1990-1995 MHz.

In advance of the GBT-UWBR test on November 18th, 2024, SpaceX engineers shared the positions of the DtC satellites that would be transmitting during the test window. The positions of the satellites are shown in Table 3. The satellites were scheduled to be transmitting to three positions with estimated distances of 150, 210, and 500 km from the telescope, thus none of the transmitting satellites were directly illuminating the GBT.

3.2 S-Band Data

On September 9th 2024, 20:30 - 23:00 UTC, test observations were performed using the S-Band receiver. The first submission failed to balance properly, causing VEGAS power levels of scan 1 to be 5 dB lower than the ideal power levels. A failure to balance to the ideal power levels is known to occasionally happen to receivers with high RFI in band. The script was aborted and resubmitted to rebalance the IF path attenuation and the resulting calibrations were used for the remaining observing time.

3.3 UWBR Data

On November 19th 2024, 1:30-3:30 UTC (November 18th, 20:30-22:30 EST) test observations were performed using the UWBR receiver. Telescope motion was enabled for this test but due to problems with the IF manager,

Boresight Distance [degrees]	Timestamp (UTC)	Satellite ID	Downlink beam placement distance
16.431	2024-09-09T20:40:56	11135	210 km
63.460	2024-09-09T20:45:23	11124	N/A[a]
0.715	2024-09-09T20:48:15	11137	500 km
16.467	2024-09-09T20:55:35	11151	210 km
68.700	2024-09-09T21:00:11	11130	150 km
29.374	2024-09-09T21:02:57	11163	500 km
39.365	2024-09-09T21:10:18	11155	150 km
46.916	2024-09-09T21:17:40	11116	210 km
48.097	2024-09-09T21:24:34	11079	150 km
52.805	2024-09-09T21:25:03	11148	500 km
57.485	2024-09-09T21:32:27	11086	500 km
32.799	2024-09-09T21:33:30	11077	150 km
61.221	2024-09-09T21:39:49	11120	500 km
64.412	2024-09-09T21:47:15	11149	500 km
54.712	2024-09-09T22:24:33	11076	210 km
48.097	2024-09-09T21:24:34	11079	150 km
56.935	2024-09-09T22:28:14	11078	500 km
59.498	2024-09-09T22:32:55	11072	500 km
62.173	2024-09-09T22:42:38	11075	150 km

Table 2: S-Band boresight passes, computed from publicly available TLE data.

[a] The downlink beam placement distance of this satellite was not provided to us. The angular separation from boresight is >63 degrees, so it might have been excluded.

Boresight Distance [degrees]	Timestamp (UTC)	Satellite ID	Downlink beam placement distance
5.92	2024-11-19T02:10:30	11224	150 km
2.34	2024-11-19T02:18:00	11227	210 km
1.20	2024-11-19T02:25:30	11128	500 km
92.42	2024-11-19T02:29:00	11175	150 km
1.89	2024-11-19T02:31:00	11318	210 km
79.12	2024-11-19T02:36:30	11179	500 km
0.67	2024-11-19T02:38:30	11319	150 km
70.32	2024-11-19T02:43:45	11183	210 km
5.860	2024-11-19T02:46:00	11334	210 km
57.96	2024-11-19T02:51:15	11189	150 km
14.20	2024-11-19T02:53:45	11293	150 km
3.41	2024-11-19T02:57:30	11194	210 km
45.09	2024-11-19T03:00:00	11317	210 km
1.85	2024-11-19T03:05:00	11197	500 km
57.84	2024-11-19T03:07:30	11305	500 km
2.580	2024-11-19T03:12:30	11180	500 km
3.94	2024-11-19T03:20:00	11187	150 km
80.44	2024-11-19T03:22:15	11308	500 km
15.45	2024-11-19T03:27:00	11168	210 km

Table 3: UWBR boresight passes, provided by SpaceX.

pointing and focus corrections were not able to be performed. Efforts to find pointing and focus corrections were halted and observations began at the planned pointing at 2:08:09 UTC.

4 Analysis

4.1 S-Band

In Figure 2, the spectral windows of scan 1 are plotted. Despite the low power levels, the DtC transmission band was visible in the left circular polarization. Strong emission outside of the DtC band was present in both polarizations, and was much stronger in the left circular polarization. This emission begins below the lower bound of the spectral window and goes up to 1984 MHz. The spectral windows in the subsequent observations with UWBR were chosen such that they cover the full extent of the emission, which was determined to cover 1976-1984 MHz.

Figure 3 shows the waterfall plots of the three spectral windows during scan 2. In this time, satellites 11124 and 11137 had closest approaches to boresight of $63.24°$ and $0.72°$ respectively. Satellite 11124 was not detected. Satellite 11137's DtC transmissions are detected twice as it passed through one of the beam sidelobes. A strong signal below the DtC band was also detected, with an upper frequency of 1984 MHz and extending below the sensitivity rolloff of the spectral window[3]. The subintegration capturing satellite 11137's closest approach shows signs of spectral leakage saturating the bandpass of spectral windows 1 and 2, and covering the lower 20% of spectral window 3.

In Figure 4, a single subintegration of scan 2 was calibrated using scan 9, which had no DtC transmissions, as the reference scan, and the noise diodes to set the scale. Here we can see the out-of-band emissions are stronger than the emissions in the DtC band— out of band emissions peaked at ~ 450 Jy and the DtC transmissions peaked at ~ 200 Jy. This strong emission was coincident with several close to boresight passes from satellites 11137, 11151, 11163, 11155, and 11077 and can be seen in the waterfall plots in Figure 5.

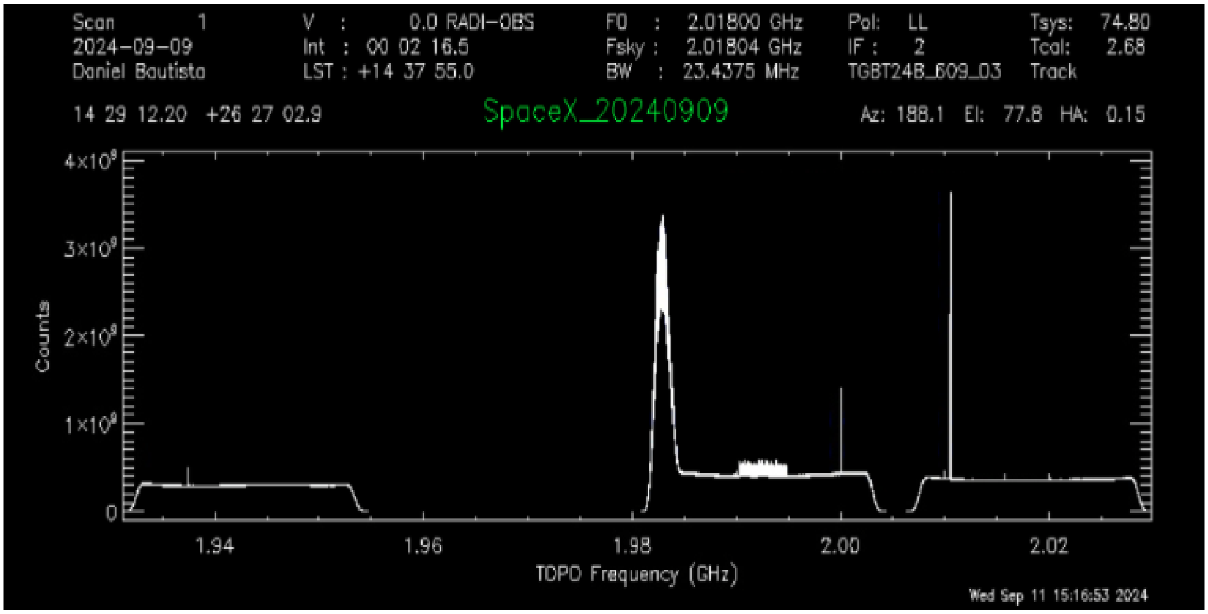
The waterfall plots in Figure 5 were produced by subtracting the median spectrum of the entire observation from each subintegration and plotting them increasing in time from bottom to top. Figure 5 is annotated with known transmission times (and boresight distances) for particular satellites.

4.2 UWBR

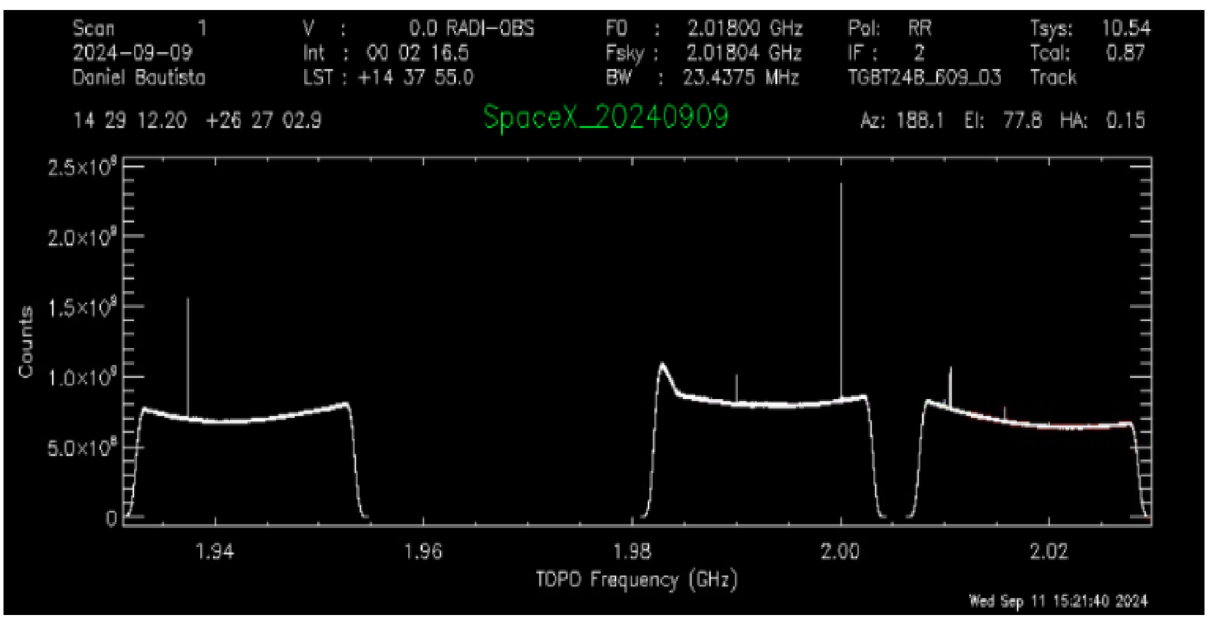
In Figure 6, a single 500 ms subintegration: scan 18, integration 1003, ifnums 3,4 in the XX polarization, is plotted. In it, the out of band emissions from some other part of the satellite are visible and with the added subbands, the extent of this out of band emission can be determined to cover 1976-1984 MHz. The intensity of this emission is lower than in the S-Band test, but its intensity is still the same strength as the DtC transmissions— the out of band emissions in the XX polarization peak at ~ 250 Jy and the DtC transmisions peak at ~ 200 Jy.

The waterfall plots in Figure 7 were produced by subtracting the median spectrum of the entire observation from each subintegration and plotting them increasing in time from bottom to top. Figure 7 is annotated with known transmission times (and boresight distances) for particular satellites.

[3] Additional spectral windows were used in the subsequent UWBR test to fully capture its frequency range.

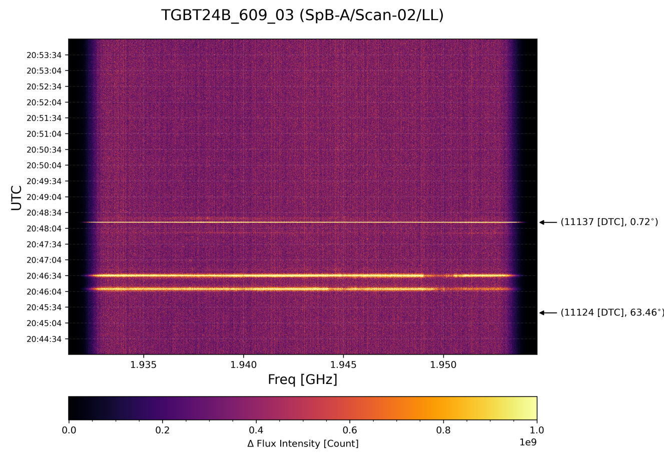


(a) S-Band scan 1, left circular polarization

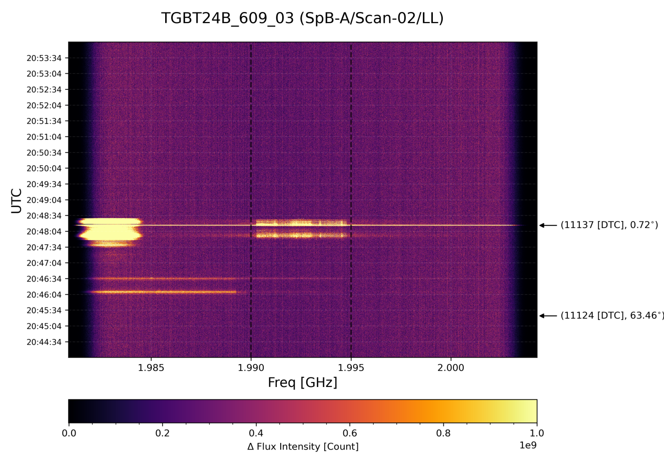


(b) S-Band scan 1, right circular polarization

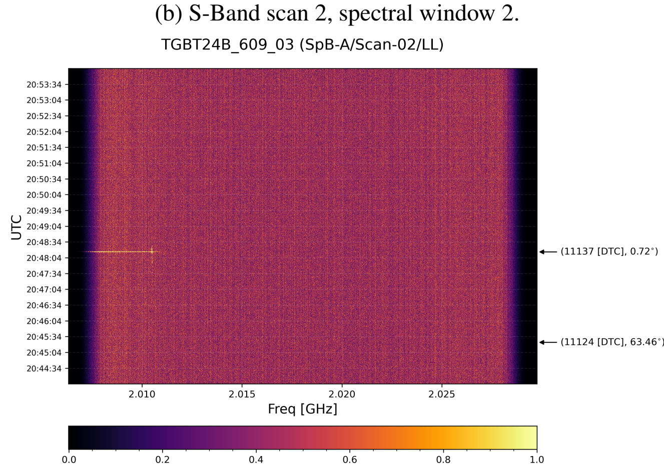
Figure 2: Average spectrum of 169.5 seconds (339 subintegrations) from Scan 1. The center subband contains the DtC allocated transmission band (1990-1995 MHz), and has visible emission in the left circular polarization plot (top). Also visible are strong emission starting at 1984 MHz and extending below the subband rolloff.



(a) S-Band scan 2, spectral window 1.



(b) S-Band scan 2, spectral window 2.



(c) S-Band scan 2, spectral window 3.

Figure 3: Excerpt of the S-Band waterfall plot of relative raw flux level (in the unit of counts) showing Scan 2. In plot (b), there is evidence of satellite 11137 additionally passing through one of the sidelobes from 20:47:34 through 20:48:34 UTC. At the subintegration of satellite 11137's closest approach, there was elevated bandpass spanning the entirety of the first two spectral windows, and 20% of the third spectral window. These instances of spectral leakage are known to happen when a strong, non-periodic signal is sampled. The strong emissions ending just below the DtC band at 20:46:04 and 20:46:34 UTC are unrelated to the SpaceX satellites.

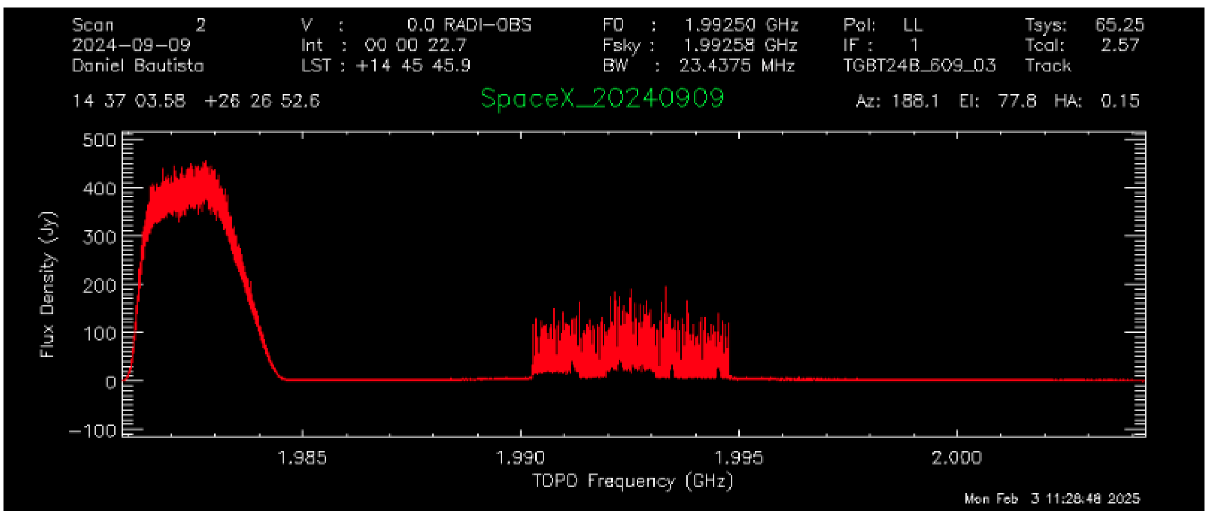


Figure 4: A calibrated subintegration of Scan 2. This spectrum corresponds to the close to boresight encounter of satellite 11137, which passed $0.72°$ from boresight. There is evidence of strong emission starting at 1984 MHz and extending below the sensitivity rolloff of the subband.

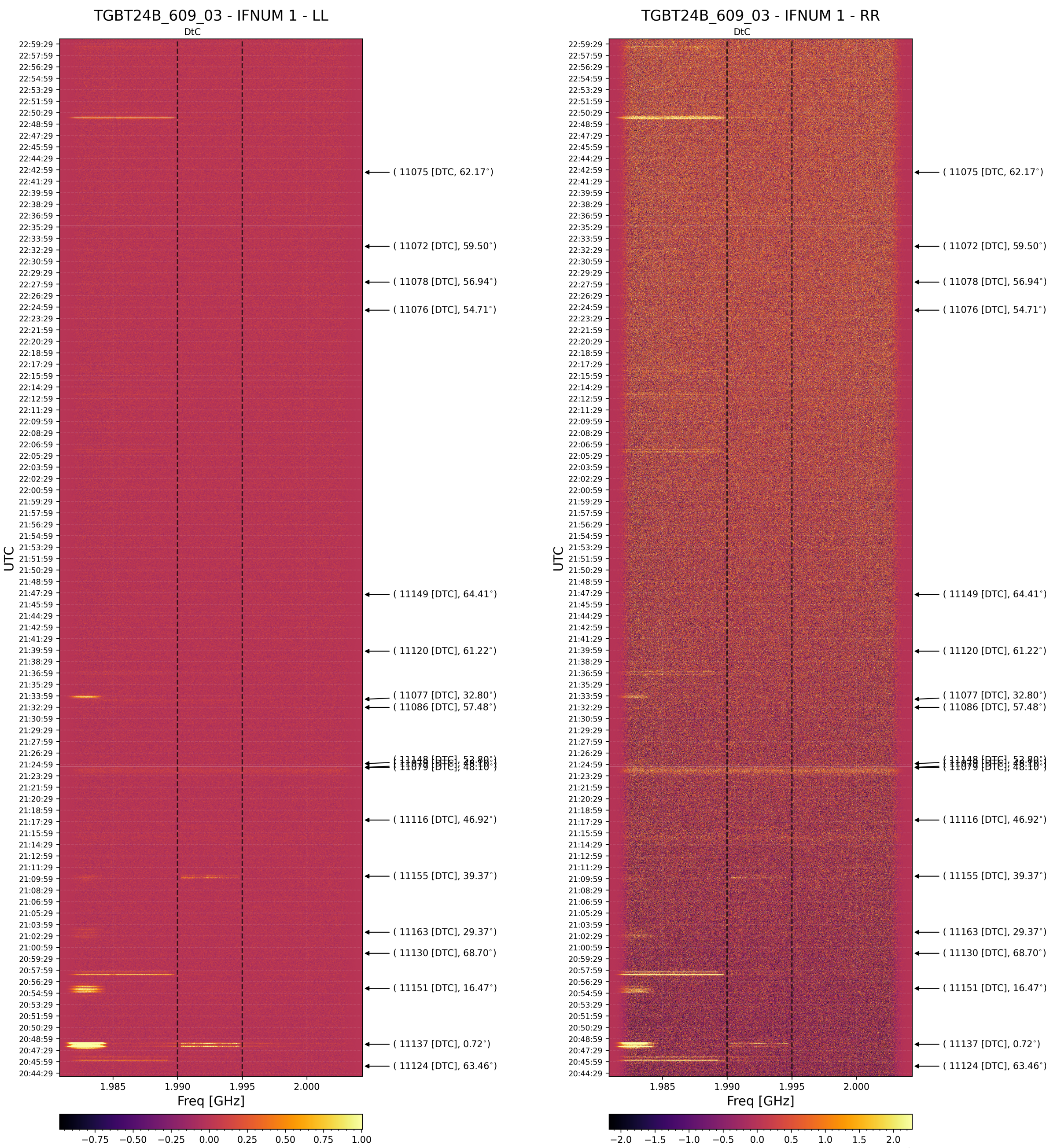


Figure 5: S-Band waterfall plot of relative raw flux level (in the unit of counts) for the entire observation session in both left (LL) and right (RR) circular polarization are shown. The bandpass with the SCS transmission range (1990-1995 MHz) is indicated with vertical dashed lines. The arrows to the right margin of each panel mark the expected timestamps, Starlink ID, and angular distance from the GBT's boresight, which was derived from TLE data, and verified by data provided by SpaceX engineers.

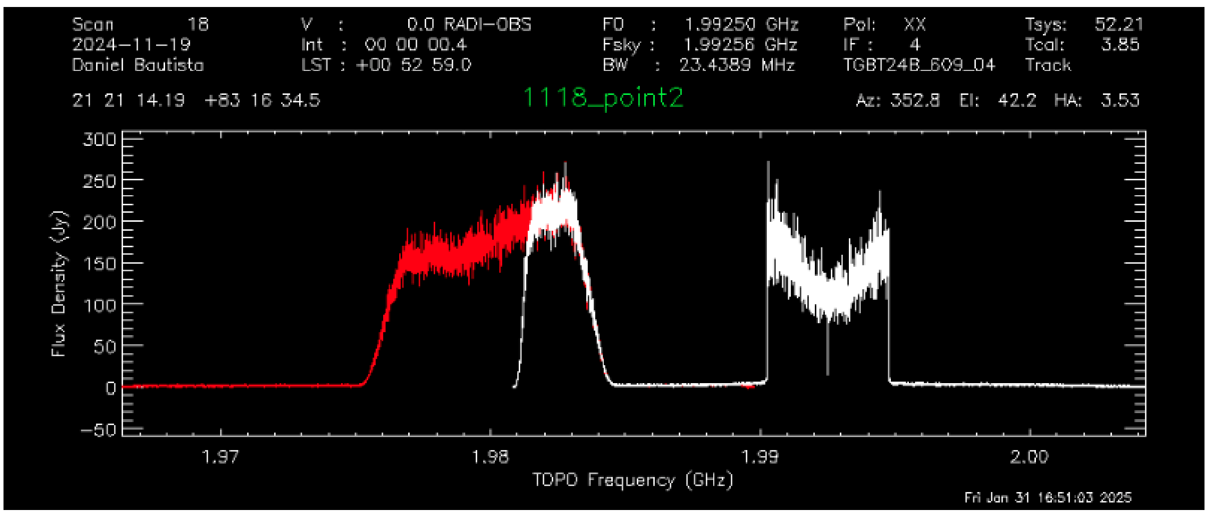


Figure 6: A calibrated 500 ms subintegration of Scan 18. This spectrum corresponds to the close to boresight encounter of satellite 11227, which passed 2.31° from boresight. Visible in the spectrum are the DtC transmissions from 1990-1995 MHz, with sharp cutoffs above and below the band, as well as the out of band emission seen in the S-Band test. With the additional subbands neighboring the DtC band, the full extent of these emissions were able to be measured. This emission covers 1976-1984 MHz. These emissions are reduced from the previous test, but are still strongly visible in the data. The white and red coloring of the spectra is to allow for differentiation between the two spectral windows.

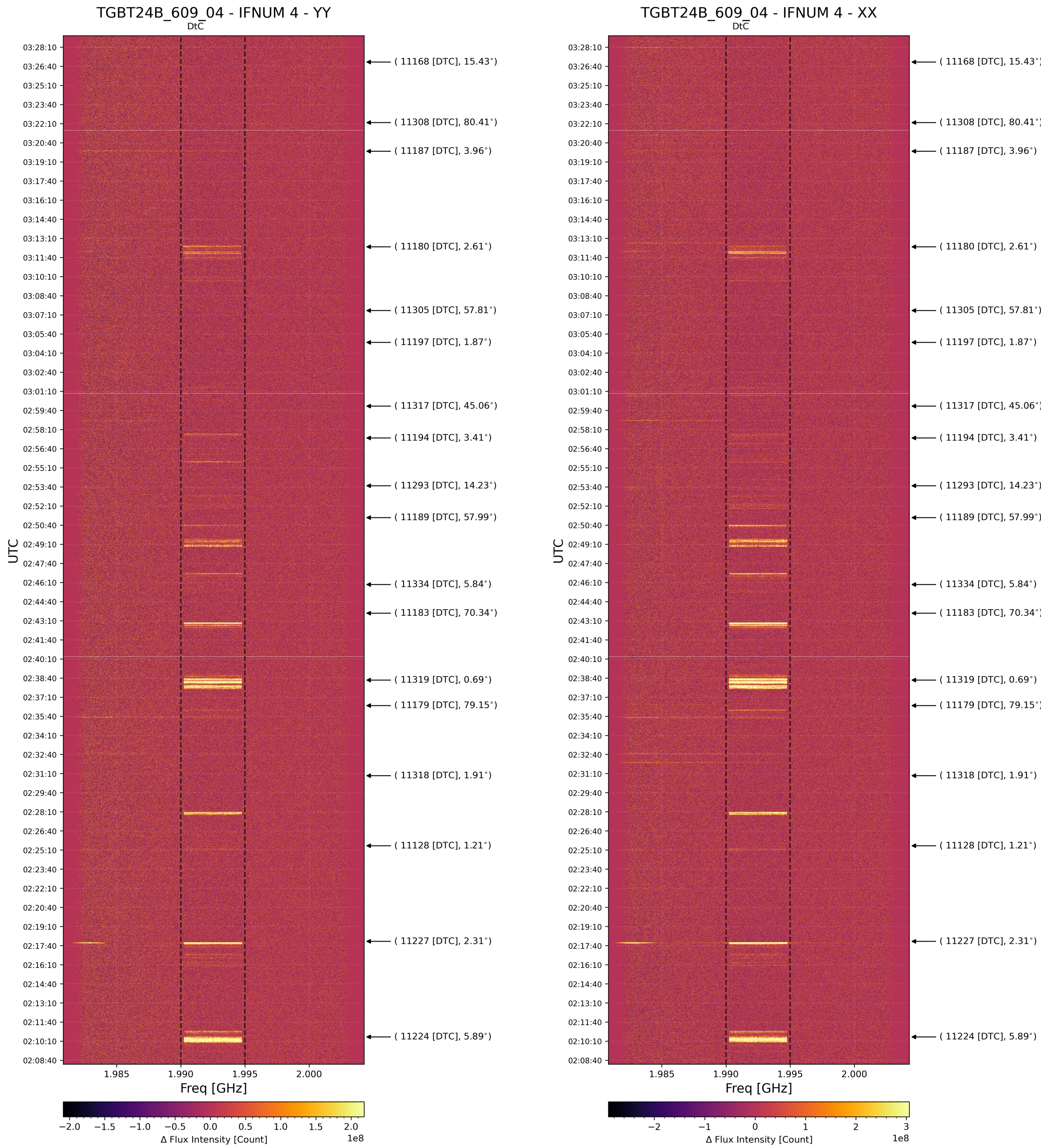


Figure 7: Waterfall plot of UWBR spectral window containing the DTC transmission. The intensity shows relative raw flux level (in the unit of counts) for the entire observation session in linear YY and XX polarizations circular polarization. The bandpass with the SCS transmission range (1990-1995 MHz) is indicated with vertical dashed lines. The arrows to the right margin of each panel mark the expected timestamps, Starlink ID, and angular distance from the GBT's boresight, which were computed from the data provided by SpaceX engineers.

5 Conclusions

These tests revealed that both the S-Band and UWBR receivers are affected by the DtC transmissions from the Starlink satellites at 1990-1995 MHz, especially when close to boresight. The GBT detected strong out-of-band emissions (OOBE) between 1976-1984 MHz that coincided with close to boresight passages of the satellites. Calibrated signal strengths were similar between the S-Band and UWBR results. **While there were a number of close to boresight passages in these tests, none of these satellites illuminated any closer than 150 km from the site.** NRAO plans to redo a similar test within the next 12 months when the S-band and UWBR receivers are again on the GBT. It will be important to gauge the impact of site illumination and a larger number of operational SCS satellites. By then, we expect the Operational Data Sharing (ODS) boresight avoidance will be in place for the GBT to provide additional protection if needed.

6 Acknowledgements

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