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# The Impact of Satellite Constellations on Radio Telescopes: GBT

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## ABSTRACT

Managing radio frequency interference (RFI) is critical to the operation of a radio telescope and the success of its observations. Thus, as new sources of RFI develop, radio astronomers must investigate these sources and determine their impact on radio astronomical observations. One new source of RFI is SpaceX's Starlink Low Earth Orbit (LEO) satellite constellation, the largest active satellite constellations in operation. In this paper, we investigate the impact of the Starlink satellite constellation on Green Bank Telescope (GBT) observations, and chronicle the development of tools that help to quantify how satellite constellations such as Starlink impact radio astronomical observations at the GBT.

*Keywords:* RFI, Satellites, GBT.

## 1. INTRODUCTION

### 1.1. *Starlink Background*

Starlink is a satellite constellation developed and operated by SpaceX with the goal of providing broadband internet access across the globe. As of August 2022, there were over 2,800 Starlink satellites in orbit around the Earth. SpaceX ultimately intends to have 42,000 Starlink satellites in orbit Mann et al. (2022) Howell (2022). Each of these non-geostationary orbit (NGSO) satellites is in low Earth orbit (LEO) at around 550 kilometers SpaceX (2022). The internet downlink signals occur across 8 channels in the 10.7 to 12.7 GHz range, with each channel having a ∼240 MHz bandwidth DePree et al. (in prep). The signals transmitted by the Starlink satellite constellation are received by Starlink user terminals to provide internet service to users. The user terminals also send uplink signals to the satellite constellation in the 14.0 to 14.5 GHz range.

### 1.2. *Starlink RFI at GBO*

Downlink signals from satellites were expected to be a source of RFI at radio telescopes. To protect the data integrity of observations performed by the GBT, there exists an exclusion zone within which radio transmissions are restricted. Starlink satellites are subject to these restrictions, and do not transmit downlink signals when within this exclusion zone. During certain experimental periods of coordinated GBO/SpaceX testing, however, Starlink satellites were allowed to transmit downlink signals for the purpose of studying their impact on the GBT. Such experimentation is important in building the knowledge base of the GBO and NRAO, particularly regarding how current radio telescope instrumentation interacts with non-geostationary satellites.

## 2. EXPERIMENTAL DESIGN

As of August 2022, 3 separate experiments have been conducted at the GBO in coordination with SpaceX. The first was conducted in February 2022, the second in May 2022, and the third in July 2022. Each of these experiments had varying experimental designs, but all shared the goal of investigating the impact of the Starlink satellite array on GBT observations in the uplink and/or downlink bands.

### 2.1. *February Experiment*

The February experiment consisted of testing at various locations around the GBT, ranging from as close as the GBO parking lot to over in nearby towns such as Dunmore. Conducting tests at multiple locations served to provide data on any RFI produced by either the satellite downlink signals or user terminal uplink signals. Over a 1 to 2 hour period, an operator would power on a Starlink user terminal at the given location and connect to the Starlink satellite network. The Starlink satellites were permitted to transmit in the exclusion zone for the duration of each testing period. For a portion of the testing, a computer program known as iPerf was used to maximize the uplink and downlink data transmission. While testing was ongoing, the GBT was rotated to the azimuth direction of the UT, and pointed such that the receiver side lobes aligned with the horizon, since it is thought that RFI entering the receiver side lobes is more significant than RFI entering the main dish in this context. GBT observations were conducted using the Ku-band receiver so as to allow observation within both the uplink and downlink frequency ranges.

### 2.2. *May Experiment*

The May experiment consisted of a single 2 hour testing period. The goal of this experiment was to study the effect of downlink channel switching on the data collected by the GBT. The channels were divided into 2 active groups, the first consisting of channels 3-5 and the second consisting of channels 6-8. Channels 1 and 2 were inactive for the duration of the experiment. Over the 2 hour period, downlink signals were restricted to one of the active groups for a portion of the time, and were at other times not restricted. No user terminal was operated by GBO, and the satellites were instead directed to illuminate the GBO cell (and a few surrounding cells). The GBT maintained the same pointing as the February experiment, observed with the Ku-band receiver for the first hour and with the X-band receiver for the second hour. Due to the placement of the uplink and downlink channels, the only active channel visible in X-band yielded less reliable data due to band-edge effects. Thus, the majority of data analysis for the May experiment was from the Ku-band data, covering the 11.5-14.5 GHz range.

### 2.3. *July Experiment*

The July experiment was conducted in a very similar manner to the May experiment, with a 2 hour time block during which downlink channel switching was utilized. The primary change to experimental design was that the GBT observed with the Ku-band receiver for the duration of the experiment. This was done to avoid observing at the X-band band edge effects and instead collect Ku-band data throughout the experiment.

## 3. DATA ANALYSIS

Thus far, the experiments conducted in coordination with SpaceX have provided evidence regarding several aspects of the Starlink impact on the GBT. These aspects of the Starlink impact on the GBT are the uplink signal, downlink signal, downlink channel switching, and periodic narrowband signals.

### 3.1. *Uplink Signal*

The February experiment in which the impact of the user terminal uplink signals was studied evidenced a minimal impact of the user terminal uplink signals on the GBT.

The testing from Horse Ridge, as shown in Figure 1, revealed no significant RFI noise contribution to the spectrum in the uplink signal (14.0-14.5 GHz) frequency range. Similar results were observed across various other testing locations, including those relatively close to the GBT itself. The lack of noise observed in the user terminal uplink signal range indicates that the impact of the user terminal on the GBT is minimal enough such that it does not itself pose a threat to the integrity of data collected by the GBT. The Starlink downlink signal, on the other hand, is much more visible by the GBT.

### 3.2. *Downlink Signal*

The February experiment provided data regarding the satellite constellation downlink signal on the GBT and RFI was apparent as noise in the 12.2-12.7 GHz frequency range. The 12.2-12.7 GHz range corresponds to downlink channels 7 and 8, which were transmitting data during an "on" portion of the experiment and were not transmitting data during an "off" portion of the experiment. Figure 1 illustrates the difference between a scan taken by the GBT during an "on" portion compared to a scan taken during an "off" portion. With the baselines subtracted from each of these scans, it can be seen that the GBT did not observe any noise during the "off" portion, but observed significant noise during the "on" period. These observations indicate that the Starlink downlink signal could pose a risk to the

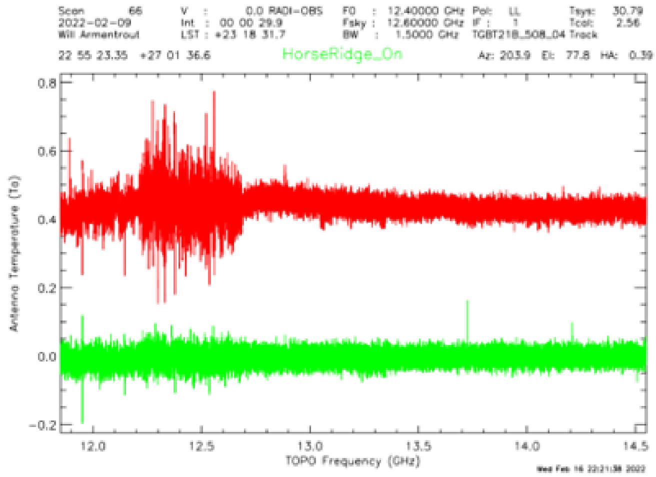


**Figure 1.** Plot of antenna temperature (Ta) vs. Frequency (GHz) of the GBT using the Ku-band receiver. Two baseline-subtracted scans are shown from the Horse Ridge testing of the February experiment. We refer to "on" as a time span when the UT was operational. We refer to "off" as a time span when the UT was unplugged/non-operational. The scan in red is an "on-off" scan and has been overplotted and offset in order to show the green "off-off" scan as well.

data integrity of radio data taken with the GBT during satellite downlinks. Thus, it is vital that Starlink continue to follow transmission restrictions within the GBO exclusion-zone.

### 3.3. *Downlink Channel Switching*

In addition to studying the impact of the uplink and downlink signal themselves on the GBT, the GBO/SpaceX collaboration also aimed to study whether downlink channel switching might have an impact on the spectral noise in downlink channels observed by the GBT. The primary goal of the May experiment was to investigate this impact by segmenting the 2 hour experiment into periods of different downlink channel usage.

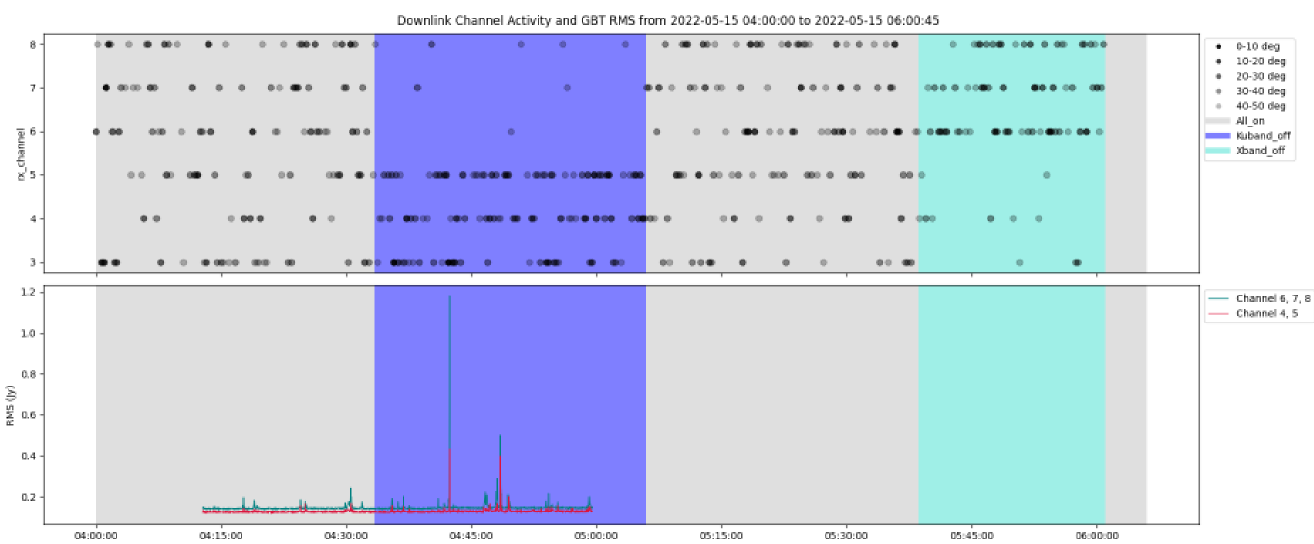


**Figure 2.** Upper plot depicts Starlink satellite transmissions to the GBO cell within the time block of the May experiment. Each dot represents an active satellite transmitting to the GBO cell in its respective channel, with transparency representing the satellite's angular offset from the GBT pointing. Lower plot depicts the noise seen in the upper vs. lower channel groups, quantified by the root mean square (RMS) of the noise in each channel. Only data from the Ku-band receiver is shown here due to unreliability of channel noise data from the X-band receiver.

As shown in Figure 2, the channel noise baseline as quantified by RMS for both the upper and lower channels is fairly constant throughout the Ku-band observations. Though there are intermittent spikes in RMS in both the upper and lower channels, these spikes only last for a short period of time. Outside of the spikes, both the upper and lower channel groups have RMS values that stay approximately around 0.1 Jy. The consistency of the noise over time indicates that the downlink channel switching that occurred during the experiment did not change the RFI picked up by the GBT. The time block in which all channels are unrestricted has the same noise baseline as the time block in which channels 6-8 are restricted. Thus, the channel restrictions that were imposed do not appear to have affected the impact of Starlink on the GBT. We note that with additional satellites in the constellation (with numbers increasing by a factor of 10), the aggregate impact could be much greater.

As part of the data analysis process, the Starlink satellite telemetry data for the experiment was plotted alongside the channel group noise in order to investigate possible correlations. The number of active Starlink satellite transmissions to the GBO cell during time blocks in which certain channels were restricted was indeed reduced. For channels 6-8, for example, there were only 8 instances of transmission to the GBO cell when channels 6-8 were restricted by SpaceX. For equivalent time blocks outside of this restriction period, there were more than four times as many instances of transmission to the GBO in channels 6-8. The reduction in transmission in restricted channels indicates that the telemetry is consistent with the commands issued to the Starlink satellite constellation. The lack of a change on the RFI seen by the GBT, however, means that though the restrictions imposed by SpaceX resulted in change to number of instances of transmission to the GBT, the channel restrictions were not apparent in lower system noise.

### 3.4. *Periodic Narrowband RFI*

Much of the analysis of Starlink related RFI thus far has focused largely on broadband noise and how it changes over time as a method of quantifying the RFI produced by Starlink. In addition to data on the broadband noise profile, the GBO/SpaceX collaboration also yielded data on narrowband RFI observed by the GBT during the experiments.

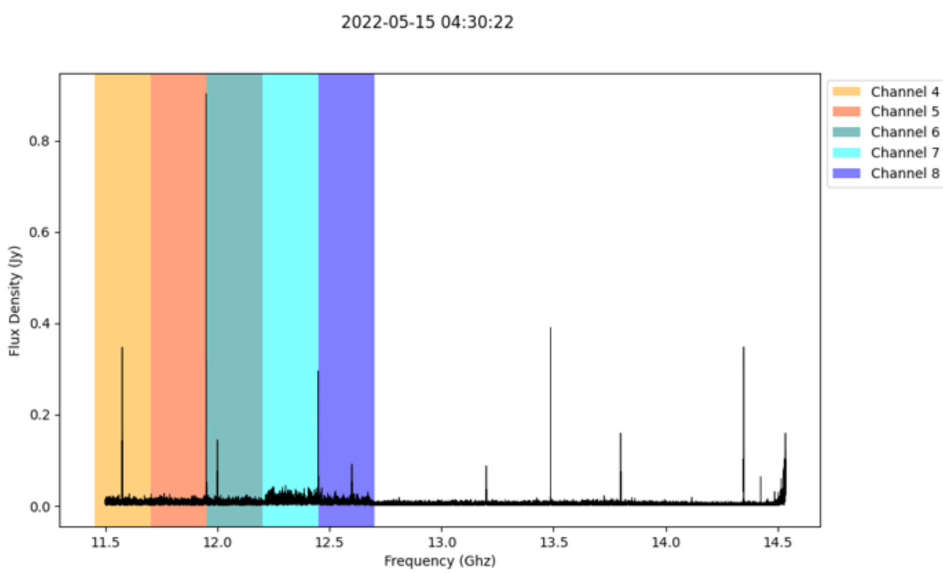


**Figure 3.** Plot of flux density (Jy) vs. frequency (GHz) of the GBT taken using the Ku-band receiver. The data is from a single one minute integration scan of the May experiment, and has the ranges of channels 4-8 overlaid for clarity.

In each of the experiments conducted by GBO in conjunction with SpaceX, a semi-periodic narrowband RFI signal was present. The RFI occurred at 3 different center frequencies, each with a bandwidth of 0.002 Ghz. The center frequencies are in line with 3 of the Starlink downlink channel edges and center frequencies. 11.575 Ghz is the center of channel 4, 11.950 GHz is the stop frequency of channel 5, and 12.450 GHz is the stop frequency of channel 7.

Most often, a spike was seen at each of these frequencies at the same time. This was not always the case, however, making it difficult to draw conclusions as to any precise timing pattern of the signal. From analysis of time-animated movies of the experiments and noise vs. time plots such as Figure 2, though, it is possible to estimate a periodicity of approximately every 5-7 minutes. When the signal was seen, however, the time period was fairly consistent on the

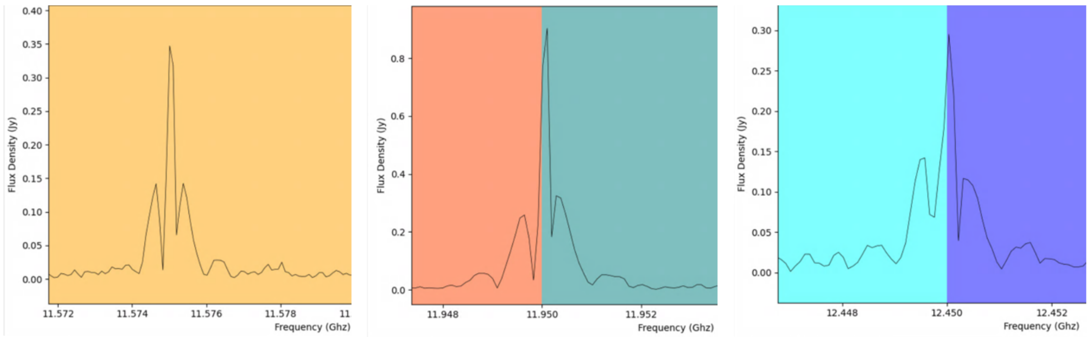


**Figure 4.** Zoomed in sections of the plot of Figure 3. Each of the 3 sections shows a narrowband RFI spike which occurred in simultaneity during the May experiment.

order of several seconds. Notably, this signal contrasts from the other narrowband RFI in the Ku-band spectrum due to its periodicity. No other signal peaks and drops back down to the baseline on the order of seconds, staying quiet until 5-7 minutes later. Nearly all other narrowband RFI in the Ku-band spectrum stays at a fairly constant flux density over time.

The uniquely periodic nature of this narrowband RFI signal, in combination with its alignment with Starlink's downlink channel frequencies suggests a connection between the signal and the Starlink satellite constellation. The exact source of the signal is still under active investigation, though, and its connection to SpaceX or lack thereof cannot yet be determined.

## 4. SOFTWARE DESIGN

A large portion the data analysis done on the GBO/SpaceX experiments was aided by software we designed provide better data visualization for RFI data. The software tool is available as a python package, RFI-Visualization, on GitHub. The primary data products of the software tool are interactive spectral plots, spectral movies, and noise quantification plots. The software tool also has visualization features adapted specifically to satellite RFI, such as the ability to display channel ranges in the background of a plot, process channel groups, and plot satellite telemetry data.

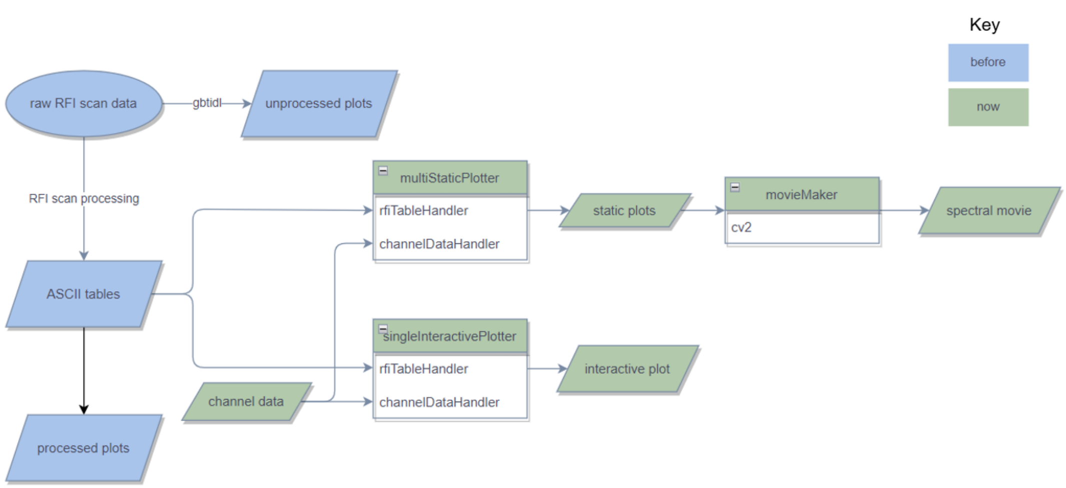


**Figure 5.** Pipeline of the production of spectral plots.

Figures 5 and 6 depict the pipelines used to produce many of the visuals used in data analysis of the experiments. Blue sections indicate software and data that existed before the start of our work on the project, and green sections indicate software and data that was created as part of our research. Though not every module used is shown, many of the significant ones are shown within the subsection of each software component. One of the primary focuses of the software design for the RFI-Visualization package was modularity. To improve the modularity and adaptability

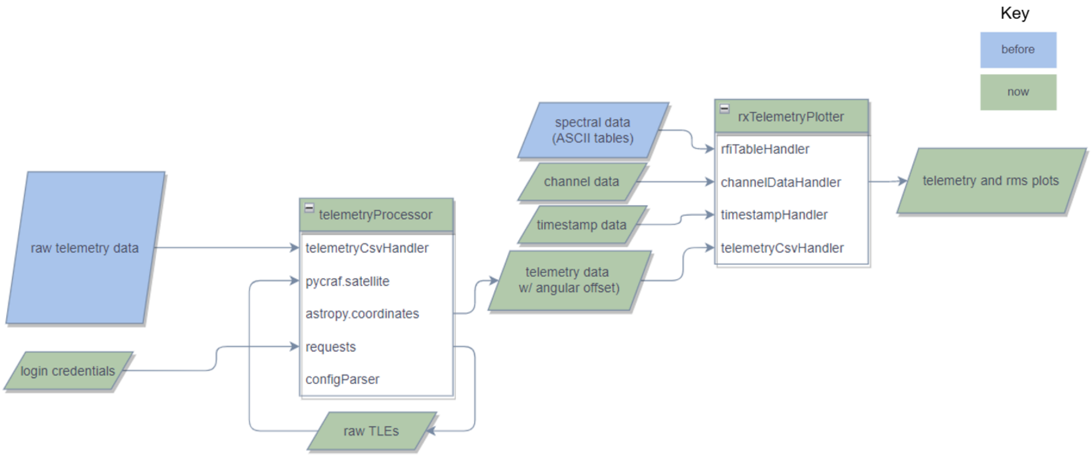


**Figure 6.** Pipeline of the production of telemetry and RMS noise quantification plots.

of the software, we designed several data handlers to handle RFI data, channel data, telemetry data, and timestamp data. Several of the handlers are shared between multiple software components, making it such that if a modification is made to the functioning of a handler, each component using the handler will adapt to the modification. The use of the handlers within the software components also helps encapsulate the data parsing and processing such that the software components themselves do not need to know how the data is parsed.

## 5. RESULTS

The GBO/SpaceX collaborative experiments have provided 4 main results regarding the impact of the Starlink satellite constellation on the GBT. The first conclusion is that the Starlink user terminal uplink signal is minimally visible by the GBT, and does not seem to be a significant source of RFI. The second conclusion is that the Starlink satellite constellation downlink signal is a significant source of RFI and should remain restricted by the GBT exclusion zone. The third result is data showing that partial downlink channel restrictions do not appear to have an effect on the RFI detected by the GBT. The fourth and final result is the discovery of periodic narrowband RFI within the Starlink channel ranges. Overall, the impact of the Starlink satellite constellation on the GBT can be deemed significant, and further investigation is needed to fully characterize the impact of downlink channel switching and the nature of the periodic narrowband RFI.

Put your acknowledgments in here.

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*Software:* matplotlib, astropy, cv2, pycraf, GBTIDL

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