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The Breakthrough Listen Search for Intelligent Life: Technosignature Search of Transiting TESS Targets of Interest

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ABSTRACT

A practical method to perform a Search for Extraterrestrial Intelligence is to search the sky for extraterrestrial signals, also known as technosignatures. A technosignature search of many nearby systems is currently underway by the Breakthrough Listen Initiative. Additionally, Breakthrough Listen is collaborating with NASA's Transiting Exoplanet Survey Satellite (TESS), designed to search for nearby exoplanets, and observing TESS Targets of Interest (TOI). This study performs a radio technosignature search within a frequency range of 1-12 GHz of 61 TESS TOI that are in transit during their Breakthrough Listen observation at the Robert C. Byrd Green Bank Telescope. More specifically, we perform a narrowband Doppler drift search with a resolution of 3 Hz while simultaneously removing radio frequency interference across a cadence of target sources. We have not found any evidence of technosignature events that resemble an extraterrestrial signal. However, due to our lack of detection we find that at L, C, S, and X band fewer than 52%, 16%, 20%, and 15%, respectively, of transiting exoplanets possess a transmitter.

Keywords: technosignatures — search for extraterrestrial intelligence — radio astronomy — exoplanets

1. INTRODUCTION

The Search for Extraterrestrial Intelligence (SETI) seeks to answer to the age old question: Are we alone in the universe? The search to answer this question formally began in the 1960s with a search for technosignatures, or signs of intelligent extraterrestrial life. Due to the limited technology, this search was across a narrow band of radio frequencies Sheikh et al. (2020). However, as technology has developed, SETI methods have broadened into three primary categories: in situ observations, biosignature searches, and technosignature searches.

In situ observations focus primarily on nearby targets and directly observe the conditions of the planets. For example, an in situ observation of Mars search for signs of life by sending probes directly to the surface for observations Enriquez et al. (2017). While in situ observations are direct and reliable, they are currently not possible to perform on distant exoplanets. Instead, biosignature and technosignature searches are ideal to search for signs of life at a distance. Biosignature searches observe exoplanetary atmosphere spectra for molecules that either support or are a direct result of life. On the other hand, technosignature searches, the focus of this study, look for signs of intelligent life by observing star systems for extraterrestrial signals. Examples of technosignatures include, but are not limited to, extraterrestrial radio signals and irregular, transiting megastructures.

The Breakthrough Listen (BL) initiative is a large collaboration of scientists that began in 2015 and plans to search over 1 million targets for technosignatures. BL searches the sky for extraterrestrial signals across both optical and radio bands across a wide variety of telescopes including the Robert C. Byrd Green Bank Telescope (GBT), Automated Planet Finder (APF), and the Parkes Telescope. This study specifically focuses on a technosignature search of the frequency range from 1 to 11 GHz using the GBT in West Virginia.

NASA's Transiting Exoplanet Survey Satellite (TESS) has recently found many new exoplanets, some of which are reasonable hosts of life. For this reason, a technosignature search of these exoplanets provides a promising opportunity for discovering Extraterrestrial Intelligence (ETI). Traas et al. (2021) recently performed such a

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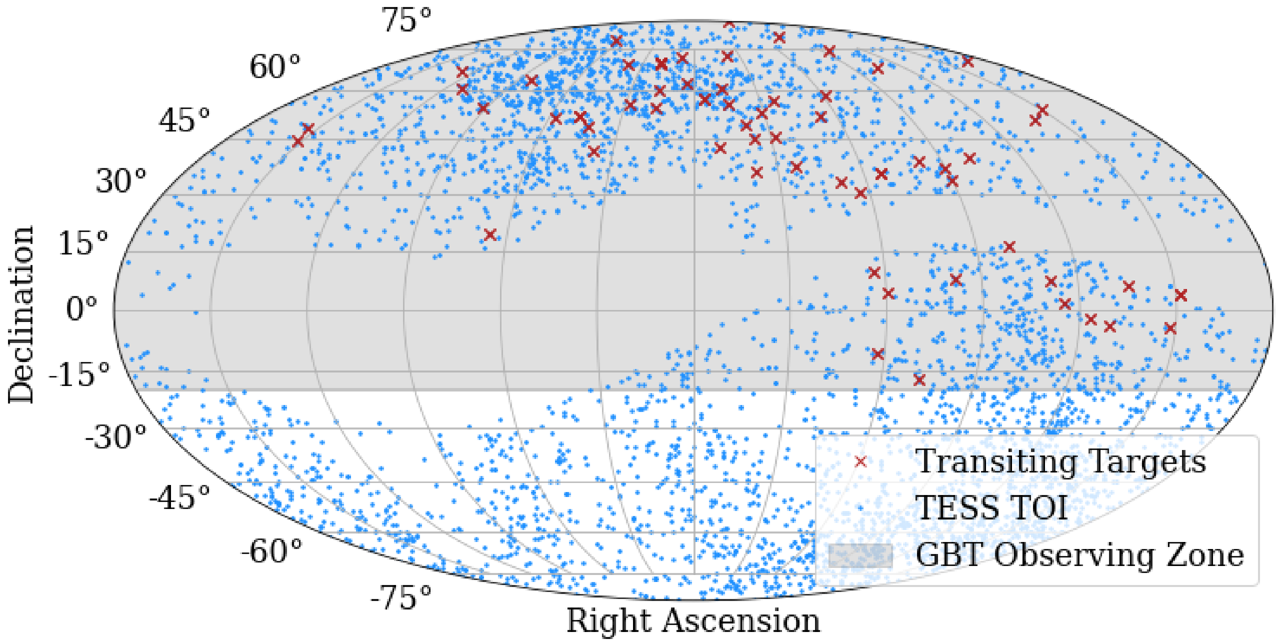

Figure 1. This plot is the Declination vs. Right Ascension for of all TESS TOI as blue dots with the selected Transiting TESS Targets overlaid as red x's. In addition, the grey shaded region is the GBT observing zone and shows that the 61 transiting targets are inside the GBT observing zone.

technosignature over 28 TESS targets of interest (TOI) across all four receiver bands.

Additionally, for two reasons, observing these exoplanets while they are transit would further improve the chance of receiving an extraterrestrial signal. First, a transiting planet is not behind its host star, improving the chance that a transmitted signal would have more of a clear path to Earth. Second, as explained by Sheikh et al. (2020), Earth is in the ecliptic for a transiting system. Therefore, extraterrestrial life may know Earth is monitoring their system during a transit so their is a higher likelihood they would send transmit a signal. Thus, motivating a more specific technosignature search of exoplanets that transit during their BL observation.

2. OBSERVATION

2.1. *Target Selection*

Data for 66 cadences was selected from existing Green Bank Telescope (GBT) observations of exoplanets that transit during their Breakthrough Listen (BL) observation. To find these targets we queried the go_scans database, a list of all observed BL GBT targets, for all previously observed TESS targets. Then, we cross-matched that list of 985 unique GBT TESS target observations with the TESS TOI catalog[1] which includes 4190 total targets. Using the TESS TOI catalog, we determined that 61 GBT targets across 66 observations transit during their GBT observation, making them ideal targets for this study [2]. These 61 targets are shown in Figure 1. The 61 targets are across 66 observations because some targets are observed two or three times with different receivers at GBT. These are summarized in 1.

In addition, a histogram of the fraction of each transit observed is in Figure 2. The fraction of transit observed was calculated by dividing the observation time of the entire cadence divided by the total transit time of the exoplanet as shown in equation 1.

$$\mathrm{FTO} = \frac{t_{\text{obs, transit}}}{(t_{\text{egress}} - t_{\text{ingress}})} \tag{1}$$

Where FTO stands for the Fraction of Transit Observed, $t_{\text{obs, transit}}$ is the amount of time in the overlap of the transit time and observation time, and t_{egress} and t_{ingress} are the time of Egress and Ingress, respectively. We later are able to compare this fraction of transit observed parameter with the amount of signal detected during an observation. Additionally, targets that cross the midpoint of their transit, as shown by the hashed bins in Figure 2, are especially interesting. Assuming ETI has placed a constant radio emitter away from their

[1] https://exofop.ipac.caltech.edu/tess/view_toi.php

[2] Note that we are using versions of these databases from June 2021 when we first selected targets. Both catalogs are subject to updates.

host star, such as at the second Lagrange point, this signal would be strongest at the midpoint of transit.

2.2. *Observation Technique*

The targets identified in §2.1 were previously observed by the GBT with their output files stored on the GB computers. The GBT has four receivers at four different frequency bands: L, S, C, and X band. The bands are defined by the frequency ranges defined in Table 1. Like the rest of BL targets, these were observed with an on/off ABACAD cadence method. This means that the primary target, "A", is observed, then an off target, "B", is observed. This method is then repeated twice more with the same "on" target and two new "off" targets, "C" and "D". Each target in the cadence is observed for 5 minutes such that the ON target is observed for a total of 15 minutes and each OFF target is observed for 5 minutes. In addition, the OFF targets are close by to the on target which allows us to differentiate between Radio Frequency Interference (RFI) signals and an ETI signal.

Table 1. GBT Receiver Ranges

GBT Receiver	Frequency Range (GHz)	No. Cadences
L	1.10 - 1.90	5
S	1.80 - 2.80	17
C	4.00 - 7.80	21
X	7.80 - 11.20	23

3. DOPPLER SEARCH

GBT output files for BL are filterbank files that are fine-frequency resolution spectrum over their 5 minute observation time. For each target observation, depending on the GBT reciever used, different sections of data are stored on different compute nodes. Then, some of these files are spliced together and stored while others are left in their unspliced form on the compute nodes. As explained in §2.2, each of these files has a corresponding cadence of 6 files in an ABACAD pattern adding up to 30 minutes total of observation time. For this study, there is 21TB in total and are currently stored on the GBT BL compute nodes [3].

[3] It is important to note that during observations, a few compute nodes dropped out leaving some data missing. This data has been excluded for analysis.

Each cadence was analyzed using the BL turboSETI pipeline (Enriquez & Price (2019)) which includes 3 steps:

1. Run the turboSETI FindDoppler software to identify signals in each file
2. Run the turboSETI find_event software to compare the signals across each cadence and filter RFI
3. Run the turboSETI plot_event software to plot the find_event output and visually inspect

The first step, to run the turboSETI FindDoppler software, identifies every signal in the filterbank files. The software first converts any filterbank files to hdf5 files and then searches each frequency channel for signals. Each signal that FindDoppler finds, including RFI, are called hits and later compared across the cadence. FindDoppler takes a filterbank or hdf5 file as input as well as the minimum and maximum drift rate to search and the minimum signal to noise ratio (S/N) for a signal to be considered a hit. FindDoppler searches between the minimum and maximum drift rate for any signals and then if the S/N is above the specified minimum, the hit is documented for later. In this case, we searched up to a maximum Doppler drift of ± 4 Hz/s and above a S/N of 10. These parameters were chosen following the guidance of past studies, such as Traas et al. (2021).

To run turboSETI on all of the data as efficiently as possible, it was processed on all 64 compute nodes available to BL at GBT. This is part of a movement among the BL team to parallelize the turboSETI processing to reduce the total time it takes to run turboSETI on many files at once. The general flow of this parallelization is first to create a list of all the files that have not yet been run through turboSETI. Then, split that list up into smaller groups of files by cadence, and, third, send those files as inputs to turboSETI on each compute node. Once turboSETI is complete on each of those files, mark it as done running through turboSETI and it moves onto the next file in the cadence. This method to run turboSETI greatly reduces runtime on large datasets, which is ideal for this study. After using the FindDoppler software to identify hits in the data, the find_event pipeline compares the hits across each cadence. The find_event software takes in the FindDoppler output data files in a cadence as well as a filter threshold of 1, 2, or 3 which get increasingly strict with the definition of an event. For a filter threshold of 3, the option we used for this study, find_event checks for hits in the on observations that are not in any of the off observations. Therefore, for a filter threshold of 3, an event is defined as any hit that has a S/N greater than

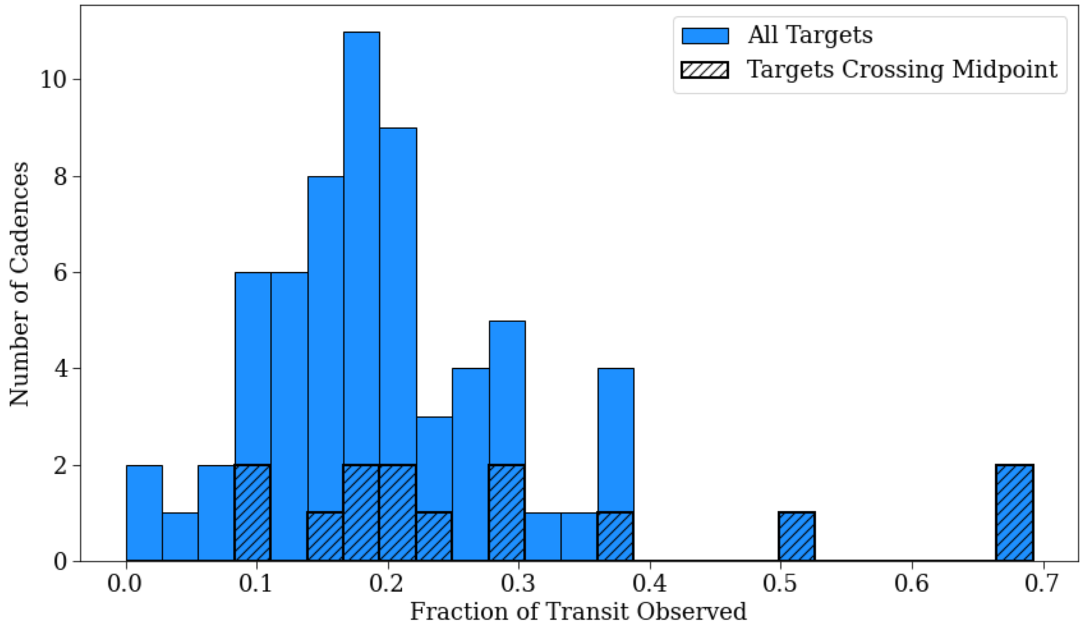

Figure 2. This histogram shows the number of cadences at each fraction of the transit that each GBT observation caught. The blue bins represent all 66 cadences while the hashed bins on top are any target that crosses the midpoint of its transit during the observation.

10, which comes from our minimum S/N defined while running turboSETI's FindDoppler software, in all three ON observations and less than 10 in all three OFF observations.

Finally, after identifying the events in each cadence, we visually inspected each event using turboSETI's plot_event pipeline. While the find_event pipeline should eliminate any RFI, sometimes some is still returned as events, so, to confidently remove this RFI we visually inspect each event. This visual inspection includes checks for hits in only the ON observations and searching for patterns across events in a single cadence. Any events left over after visual inspection are classified as potential candidates and then undergo further inspection.

4. RESULTS

4.1. *Technosignature Search*

After running the entire turboSETI pipeline, there were 2,442,347 hits and 634 events which were distributed across the receiver bands as shown in Figure 3. After visually inspecting all 634 events, we identified some interesting events which are shown in Figure 4. However, each of these events were discounted as candidates upon further inspection. It was concluded that each interesting event is simply RFI because the signal appears throughout the entire cadence, just with a S/N lower than the defined threshold of 10. Such S/N discrepancies makes it difficult for find_event to identify these as RFI rather than ETI.

Figures 4a and 4b are interesting because they have signals from the same target that seem to appear almost entirely in the ON observation. However, both waterfall plots seem to still have some signal in the OFF observations resulting in hesitation to classify them as candidates. In addition, each of these signals is not narrowband, which is what we would expect from a ET signal. Furthermore, we can the signal in Figure 4a is at the correct frequency for an air traffic control signal, a relatively common problem at GBT (see the candidates from Enriquez et al. (2017)), and is therefore excluded as a candidate. Likewise, Figure 4b is excluded as a candidate because it has a frequency similar to the Iridium Satellites (cite?).

Figure 4c shows a waterfall plot of TIC241076290 and is interesting because it is the only target whose transit is shorter than the 300 second observation. This means that we observe the beginning or end of the transit so it is important to check it for signals that appear or disappear, neither of which are seen in it. Therefore, since the signal is clearly present throughout the cadence, this signal is excluded as a candidate.

Third, Figure 4d is labelled as an interesting signal because it seems to split in the first observation. However, after reviewing similar waterfall plots, this split seems

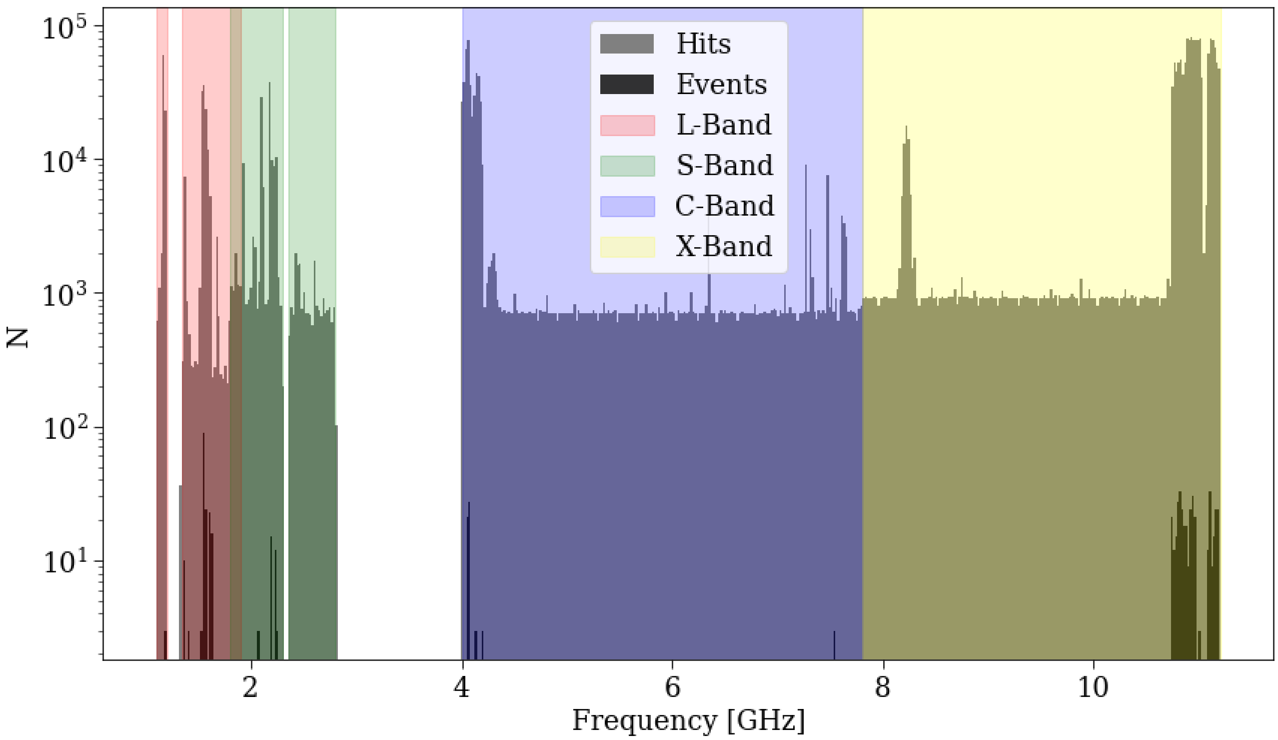

Figure 3. This histogram represents the number of hits or events versus the Frequency in GHz. Hits are shown in grey while Events are in black. In addition, the frequency range (band) for each Green Bank Telescope receiver has a different color overlayed on top of the histogram. The numerical values for each band are shown in Table 1 as well as the breakdown of the number of cadences observed at each band. This is important because there are a different number of cadences at each band making it difficult to directly compare the number of hits and events across bands.

more likely to be two signals crossing. Additionally, it can be easily ruled out as a candidate because of the signals strong presence in the OFF observations.

Finally, 4e is very interesting because it has a changing doppler shift, which is evidence of a moving signal, and satellites are usually just in only one or two observations. Instead, 4e has a signal present throughout the entire cadence as well as a changing doppler shift. While this is highly irregular, the signal can be ruled out as a candidate since it is present throughout the entire cadence. In addition, the signal can most likely be explained as a satellite around the apogee of a highly irregular orbit, resulting in a long period of time close to one place on the sky.

4.2. *Hit and Event Distribution*

The hit and event frequency distributions are shown in Figure 3. In addition, the S/N and Drift Rate distributions are both shown in Figure 5. Each of these plots shows the dispersion of hits and events across a different metric. It is important to note that, as shown in 1, the number of cadences analyzed at each GBT receiver is different which impacts the amount of hits and events for each receiver. Therefore, it is not appropriate to analyze the number of hits or events across receivers. However, it is still reasonable, and interesting, to compare the number of hits and events as a function of Drift Rate and S/N.

As expected, Figure 5 shows that there are significantly more hits and events at low drift rates. This makes sense because many of the hits are from near-Earth sources, resulting in a low Drift Rate. Additionally, it makes sense that most of the hits are at lower S/N since there are simply more Earth-based signals with a low S/N. This results in a higher population of hits at low S/N ratio which in turn results in more events at a lower S/N.

4.3. *Figures of Merit*

To further constrain the likelihood of detecting ETI through a technosignature search, we can compare SETI figures-of-merit to past SETI studies. One important figure-of-merit is the Drake Figure of Merit (DFM) (Gajjar et al. (2021), Enriquez et al. (2017), and Margot et al. (2021)). DFM has been used throughout SETI studies. While it does have some limitations as discussed in Enriquez et al. (2017) and Margot et al. (2021), it is still a viable figure-of-merit, especially for surveys across multiple receivers, such as this one. DFM is useful to compare because it takes into account both the bandwidth

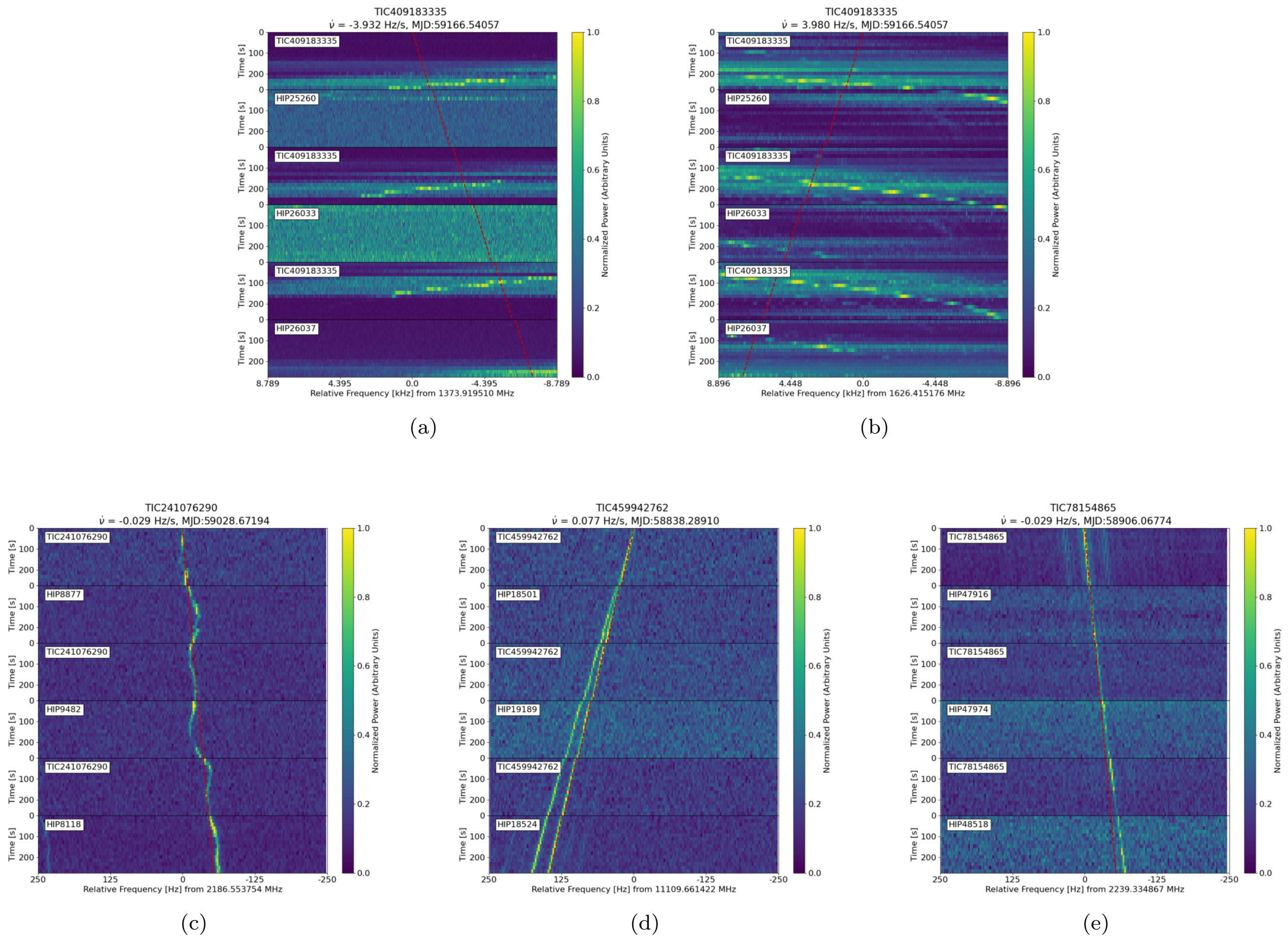

Figure 4. These five dynamic spectra (waterfall) plots are of different events of interest. Each plot has the 6 observations in a cadence stacked on top of each other with the y-axis being the time since the start of the observation and the x-axis the frequency offset from the event's central frequency.

surveyed as well as the minimum detectable power. Table 2 shows the DFM for this study as well as other recent studies for comparison.

Table 2. Drake Figure of Merit

Study	DFM [GHz m^3 W$^{3/2}$]
This Study	2.1×10^{32}
Margot et al. (2021)	1.11×10^{32}
Gajjar et al. (2021)	4×10^{28}

Since the DFM has some limitations, a second useful figure-of-merit is the Continuous Waveform Transmitter Rate (CWTFM) Enriquez et al. (2017). The CWTFM is a SETI figure-of-merit to describe the likeliness to find an ET signal at a specific and minimum Equivalent Isotropic Radiated Power ($EIRP_{min}$). $EIRP_{min}$ is a measure of the necessary power of a fictional antenna in the most distant star system for each Green Bank receiver. We plot the CWFTM vs. $EIRP_{min}$ for our study as well as many past SETI studies in Figure 6. As can be seen in Figure 6, there tends to be a general trend in SETI studies to be at either higher transmitter rate and lower EIRP or lower transmitter rate and higher EIRP. However, the most sensitive EIRP region, which is also the most difficult to acquire, is the lower left region of this plot. In this region, Extraterrestrial signals are more rare and there is both high sensitivity to ET signals.

Finally, due to our lack of signal detections, we can calculate the transmitter limit, or maximum percentage of observed stars at each band that possess a transmitter. In Traas et al. (2021), Price et al. (2020), as well as other SETI studies, this transmitter limit has been calculated using a one sided 95% Poisson confidence interval with a 50% probability of actually observing a signal if the transmitter is present Gehrels (1986). For consistency the poisson transmitter limit at each band for this study are listed in Table 3.

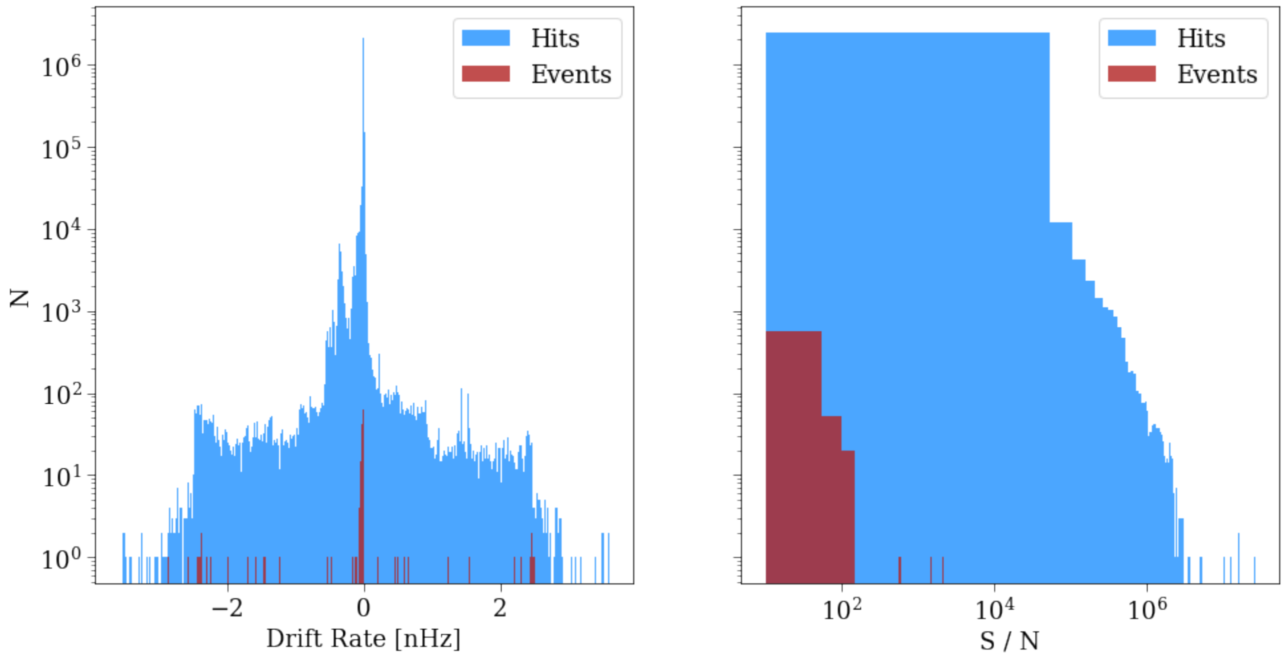

Figure 5. Both of these plots show the signal distribution compared to different measures of ET signals. The plot on the left shows the number of hits or events at each drift rate and the plot on the right shows the number of hits or events at each S/N. For both plots, the Hits are represented by the blue histogram bins while the events are represented by the red histogram bins.

Table 3. Transmitter Limit

Receiver	Poisson Transmitter Limit [%]	Binomial Transmitter Limit [%]
L	74	52
C	18	16
S	22	20
X	16	15

However, the poisson transmitter limit calculation has limitations, especially with low numbers of targets. For SETI studies, each target either has a detection or does not have a detection meaning that a binomial distribution is better for the transmitter limit calculations. In addition, the binomial distribution tranmistter limit calculation is much friendlier to low numbers of targets, such as the 5 cadences this study has at L-Band. Therefore, for this study, we also calculated the binomial distribution transmitter limit using the same confidence interval of 95% with a 50% probability of observing a signal if the transmitter exists. These transmitter limit values are also listed in 3.

5. CONCLUSION

In general, we performed a technosignature search of 61 TESS TOI over 66 cadences that are in transit during their Breakthrough Listen observation at the Green Bank Telescope. This is an important time to search for ET signals because Earth is in the ecliptic of these exoplanets as they transit and other intelligent civilizations may know that we are watching and try to communicate. Additionally, for obvious reasons, it is better to look for signals from an exoplanet while it is not behind its host star. This makes studying transiting exoplanets an interesting time to search for technosignatures from ETI.

The observations for this study were performed with the Green Bank Telescope using the typical Breakthrough Listen ON/OFF cadence of ABACAD. This means that each ON target ("A") is observed for 5 minutes, then an OFF target ("B", "C", and "D") are each observed for 5 minutes in the pattern ABACAD resulting in a total observation time of 30 minutes for each target. The target files were then analyzed using the turboSETI pipeline with the search parameters of S/N minimum of 10 and Maximum Drift Rate of ± 4 Hz/s. This allowed us to search for any signals with doppler drifts that are in the ON observations and not in the OFF observations. Each signal that was determined to be an event was visually inspected to check if it is actually an ET signal. Finally, any signal of interest (see Figure 4) was checked further to determine if it was a potential candidate.

After searching the 66 cadences of exoplanets that transit during their BL observation for technosignatures, we did not find any evidence of extraterrestrial signals. Every signal identified as an interesting event was later dismissed as RFI from satellites or other Earth-based

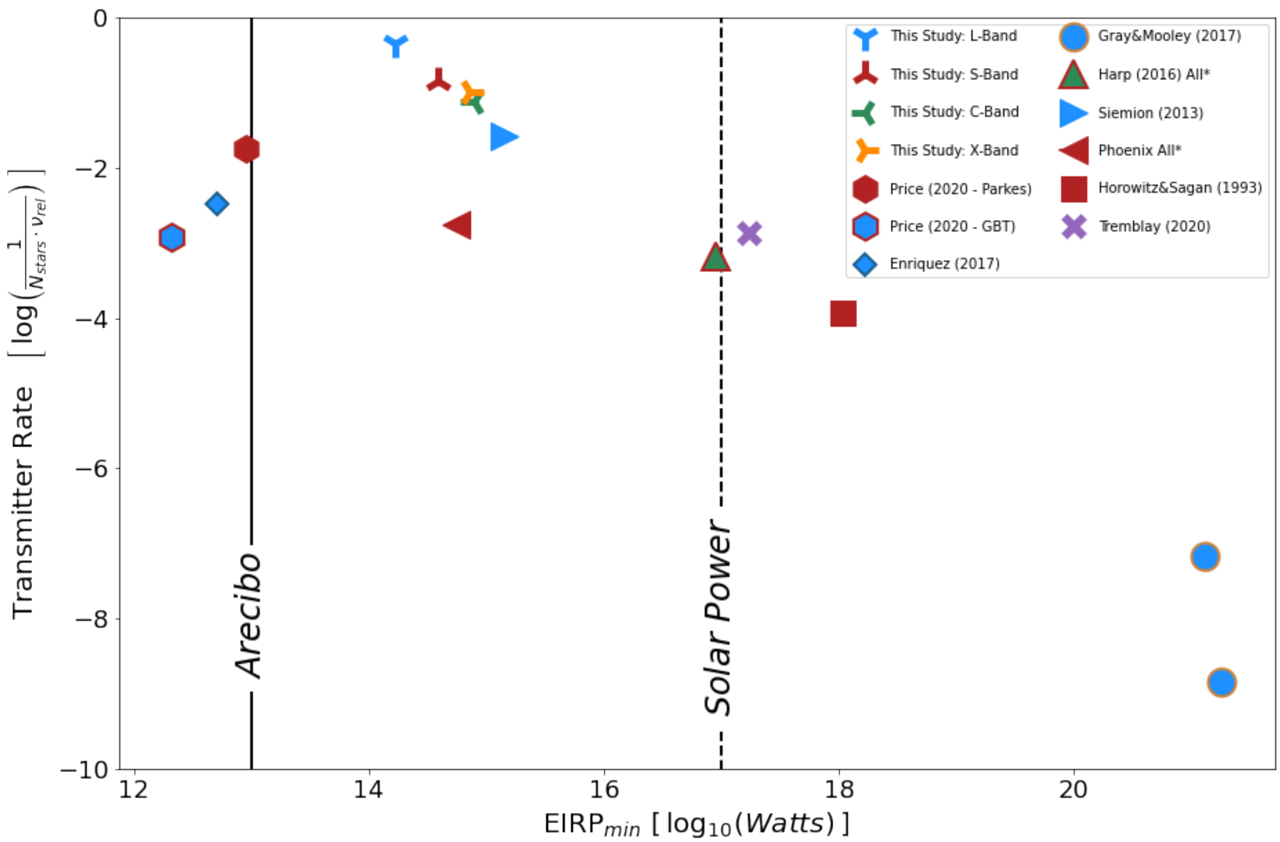

Figure 6. This plot shows the CWFTM, labelled the Transmitter Rate here for consistency, versus the $EIRP_{min}$. The four Y-shaped points are for this study while the rest of the shapes represent past studies. The two vertical lines represent the EIRP values of Arecibo and the Solar Power incident on Earth, as labelled, for comparison.

signals. Even though we did not discover an extraterrestrial signal, we found the transmitter limit for each receiver to help further constrain the existence of narrowband transmitters on transiting exoplanets.

6. FUTURE STUDIES

There are three future studies that would be interesting to follow this study. The first is analyzing targets that are entering or exiting their secondary transit during their observation. This way, an observer could see if a signal appears or disappears as the exoplanet enters or exits it's secondary transit. While there are probably few observations already done where this is the case, it would be interesting to study.

Second, studying exoplanets that enter or exit their transit during their Breakthrough Listen observation may present signals that appear or disappear as the star enters the transit. Using similar logic to this study, since ETI may know that Earth is watching the exoplanet during it's transit, ETI may point a beacon to Earth only during the transit to get our attention.

Third, and finally, it would be interesting to focus solely on planets that enter their peak transit with respect to Earth during their observation. In other words, the planet transits the center of the star from Earth's perspective during it's observation. This would be an interesting SETI study since ETI may be more likely to direct a narrowbeam signal to space directly outward from their host star in the ecliptic. Therefore, searching this region may improve the probability of discovering such a technosignature.

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