

THE BREAKTHROUGH LISTEN SEARCH FOR INTELLIGENT LIFE: PUBLIC DATA, FORMATS, REDUCTION AND ARCHIVING

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ABSTRACT

Breakthrough Listen is the most comprehensive and sensitive search for extraterrestrial intelligence (SETI) to date, employing a collection of international observational facilities including both radio and optical telescopes. During the first three years of the *Listen* program, thousands of targets have been observed with the Green Bank Telescope (GBT), Parkes Telescope and Automated Planet Finder. At GBT and Parkes, observations have been performed ranging from 700 MHz to 26 GHz, with raw data volumes averaging over 1 PB / day. A pseudo-real time software spectroscopy suite is used to produce multi-resolution spectrograms amounting to approximately 400 GB h⁻¹ GHz⁻¹ beam⁻¹. For certain targets, raw baseband voltage data is also preserved. Observations with the Automated Planet Finder produce both 2-dimensional and 1-dimensional high resolution ($R \sim 10^5$) echelle spectral data.

Although the primary purpose of *Listen* data acquisition is for SETI, a range of secondary science has also been performed with these data, including studies of fast radio bursts. Other current and potential research topics include spectral line studies, searches for certain kinds of dark matter, probes of interstellar scattering, pulsar searches, radio transient searches and investigations of stellar activity. *Listen* data are also being used in the development of algorithms, including machine learning approaches to modulation scheme classification and outlier detection, that have wide applicability not just for astronomical research but for a broad range of science and engineering.

In this paper, we describe the hardware and software pipeline used for collection, reduction, archival, and public dissemination of *Listen* data. We describe the data formats and tools, and present Breakthrough Listen Data Release 1.0 (BLDR 1.0), a defined set of publicly-available raw and reduced data totalling 1 PB.

1. INTRODUCTION

The Breakthrough Listen (hereafter BL) project (Worden et al. 2018), announced at the Royal Society in London in 2015 July, is currently undertaking searches for extraterrestrial intelligence (SETI) at telescope facilities across the globe. Motivated by the idea that some human technologies used for communication, propulsion, or other purposes, generate signatures that could be detected by a sufficiently sensitive telescope at interstellar distances, BL conducts observational astronomy programs targeting such “technosignatures” that may betray the presence of technology, and hence advanced life, on worlds other than our own.

Currently, BL undertakes the search for technosignatures at both radio and optical wavelengths. The radio search currently employs two large single-dish telescopes, the Robert C. Byrd Green Bank Telescope (GBT; MacMahon et al. 2018) in West Virginia, USA, and the CSIRO Parkes Radio Telescope (Price et al. 2018) in New South Wales, Australia. The optical search currently employs the Automated Planet Finder (APF) at Lick Observatory in California, USA. The program will soon expand to include radio observations using the MeerKAT telescope in South Africa and the VERITAS Cherenkov Telescope at the Whipple Observatory in Arizona, USA. Pilot programs and collaboration agreements are also in place for additional facilities, including the FAST 500m telescope in Guizhou Province, China (Ini 2016), the Murchison Widefield Array in Western Australia (Tingay et al. 2018), and the Jodrell Bank Observatory in Manchester, UK.

Core observational goals for the BL program include multiwavelength observations of ~ 1700 nearby stars and 100 nearby galaxies, a radio survey of one million additional nearby stars and radio and optical observations of the Galactic Plane and the Galactic Center (GP/GC). The one million star survey will be performed using dedicated digital beamformer hardware at MeerKAT, allowing dozens of stars within the primary MeerKAT field of view to be observed simultaneously. These commensal (contemporaneously using the same data stream) observations will occur with the BL instrument alongside all other uses of the facility.

In addition to the core program, BL occasionally observes other targets of interest. These have thus far included objects in our own Solar System, including the asteroid BZ 509 (Price et al. 2019) the interstellar object ‘Oumuamua (Enriquez et al. 2018), as well as other “exotica” such as Boyajian’s Star (Wright & Sigurdsson 2016), Ross 128 (Enriquez et al. 2019), candidate technosignatures from other research programs (Croft et al. 2016) and a number of fast radio bursts (FRBs). The BL backends at GBT and Parkes have also been made available in shared-risk mode for proposals from the astronomical community, which are considered for allocations of general observer time by the telescope time allocation committees.

The bulk of observations conducted during the first three years of the BL program have focused on nearby stars drawn from the sample described by Isaacson et al. (2017). An initial SETI search of GBT data on 692 stars from this sample was presented by Enriquez et al. (2017). Since 2016, additional stars from Isaacson et al. (2017) have been observed by the BL facilities, and our analysis techniques have been, and continue to be, refined. An updated analysis of radio observations of a larger sample of these stars is presented in Price et al. (submitted).

This paper describes our data acquisition, formats, reduction, and archiving. We also announce the release of ~ 1 PB of public data, which forms BL Data Release 1.0 (BLDR 1.0), and consists of:

- Radio spectrograms for the 1327 stars presented in the analysis of Price et al. (submitted) – 882 from *L*-band and 1005 from *S*-band receivers at GBT (Table 1) and 189 from the 10-cm receiver at Parkes, along with corresponding observations of pulsar, flux calibrator, and reference (“off”) sources
- Optical spectra, including both 2D and corresponding extracted 1D spectra, for 789 stars observed by APF
- Raw time domain voltage data and corresponding spectrograms from radio observations of FRB 121102 (GBT) and FRB 180301 (Parkes)

The remainder of this paper is structured as follows: Section 2 describes data acquisition and reduction procedures for BL observations with GBT and Parkes, Section 3 describes data acquisition and reduction procedures for BL observations with APF, and Section 4 details the design and interface for the BL public data archive. Appendix A describes the file naming conventions used for BL data products. Appendix B lists the header information for raw and filterbank files.

2. BREAKTHROUGH LISTEN ON GBT AND PARKES

The digital backends used by BL at radio observatories consist of clusters of compute nodes with large amounts of storage, each with one or more graphics processing units (GPUs) for reduction and processing; storage nodes, with additional capacity intended for longer-term data storage, and head nodes that provide boot images and a login gateway to the compute and storage nodes. The GBT BL instrument (MacMahon et al. 2018) saw first light in 2015 December, and currently consists of 9 storage nodes and 65 compute nodes (64 active plus one spare), with a total usable capacity of ~ 8 PB. The Parkes BL instrument (Price et al. 2018) saw first light in 2016 September, and currently consists of 6 storage nodes and 27 compute nodes (26 active plus one spare), with capacity 3.5 PB. The upcoming MeerKAT instrument will be described in a future paper.

The basic data pipeline is illustrated graphically in Figure 1, and is described in detail below. At Parkes and GBT, BL compute nodes receive digitized complex voltages from FPGA data acquisition systems (MacMahon et al. 2018), which are subsequently written to large disk arrays in GUPPI (Green Bank Ultimate Pulsar Processing Instrument; Ransom et al. 2009) raw format. The GUPPI format is derived from the FITS standard (Wells et al. 1981; Pence et al. 2010), and has been used in a number of other SETI experiments that employed the original GUPPI instrument, beginning with Siemion et al. (2013) and continuing more recently with Margot et al. (2018) and Pinchuk et al. (2019).

Each BL compute node (denoted blc00 through blcXY in Figure 1) captures a portion of the total bandwidth during observing with a maximum of 187.5 MHz of dual-polarization, 8-bit sampled voltage data at a rate of 6 Gb s^{-1} per node. While the raw data format allows for frequency overlap between nodes, BL does not implement this functionality.

BL observing sessions last between 2 and 12 hours. During the gaps between sessions, which are at least as long as the sessions themselves, raw data are processed using a GPU-accelerated Fast Fourier Transform (FFT) code, and the resultant spectrograms are archived. For certain targets of interest, we also choose to archive some of the raw voltages to permit additional post-processing. One example of such a target is FRB 121102; the 400 TB raw dataset that was used in the analysis of Gajjar et al. (2018) and Zhang et al. (2018) is being made publicly available as part of BLDR 1.0.

Searches for technosignatures are performed with custom pipelines. These include SPANDAK (Gajjar et al. 2018), used to search for broadband pulses, and TURBOSETI (Enriquez et al. 2017), used to search for narrowband drifting signals, in addition to algorithms under development including machine learning approaches.

2.1. Observing strategy

The standard BL observing procedure at GBT and Parkes is to observe in cadences of 30 minutes. Primary targets are selected from a MySQL target database (Figure 1), and observing scripts are generated for each session based on designated target priorities and the amount of data already obtained for each target. The database is updated after each run. The observing script controls the observations via an interface with the facility software (ASTRID and CLEO at GBT¹; TCS at Parkes²), and also manages the operation of the BL backend cluster which records the digitized raw voltages from the telescope.

For single-pixel instruments at GBT and Parkes, an observing strategy of alternating (or “nodding”) between intended sources and nearby reference points in the sky is adopted in order to discriminate against the main contaminant for any radio SETI search: human generated radio frequency interference (RFI). The intensity and morphology of detected RFI signals may vary with time and with telescope position, but almost never in such a way that only the intended sources are affected but not the reference sources. By looking for signals detected in only the primary location, we thereby apply a spatial filter that preferentially isolates signals that may be coming from the direction of the primary target being observed.

Each primary target is observed for three 5-minute integrations, interspersed with three 5-minute scans of nearby comparison targets. Primary targets are denoted as “A” or “ON” targets. Early in the BL program our “OFF” targets were a nearby blank sky pointing (reflected with an “_OFF” suffix in the target name), but several months after our GBT program began we modified the strategy. Instead of nodding to a nearby blank part of the sky we now alternate the primary “A” targets with three different nearby stars (denoted “B”, “C”, and “D”), such that our standard cadence is now “ABACAD”. This method maximizes the number of observed stars while still allowing for RFI detection and removal. An example set of recently recorded Green Bank data is shown in Figure 2. Information regarding the file naming conventions is given in Appendix A.

¹ GBT Observer’s Guide - <https://science.nrao.edu/facilities/gbt/observing/GBTog.pdf>

² Parkes Radio Telescope Users Guide - http://www.parkes.atnf.csiro.au/observing/documentation/user_guide/pks_ug.pdf



For Parkes we kept the original strategy of nodding between the target source and a nearby blank point in the sky. The naming of on/off targets is different than at GBT due to TCS conventions. The “ON” targets have an “_S” suffix (source) and the “OFF” targets have an “_R” suffix (reference).

At GBT we can record up to a 10 GHz-wide band from any of the GBT receivers; this is the full bandwidth that the analog downconversion systems can deliver from any given receiver. The first three years of our GBT program

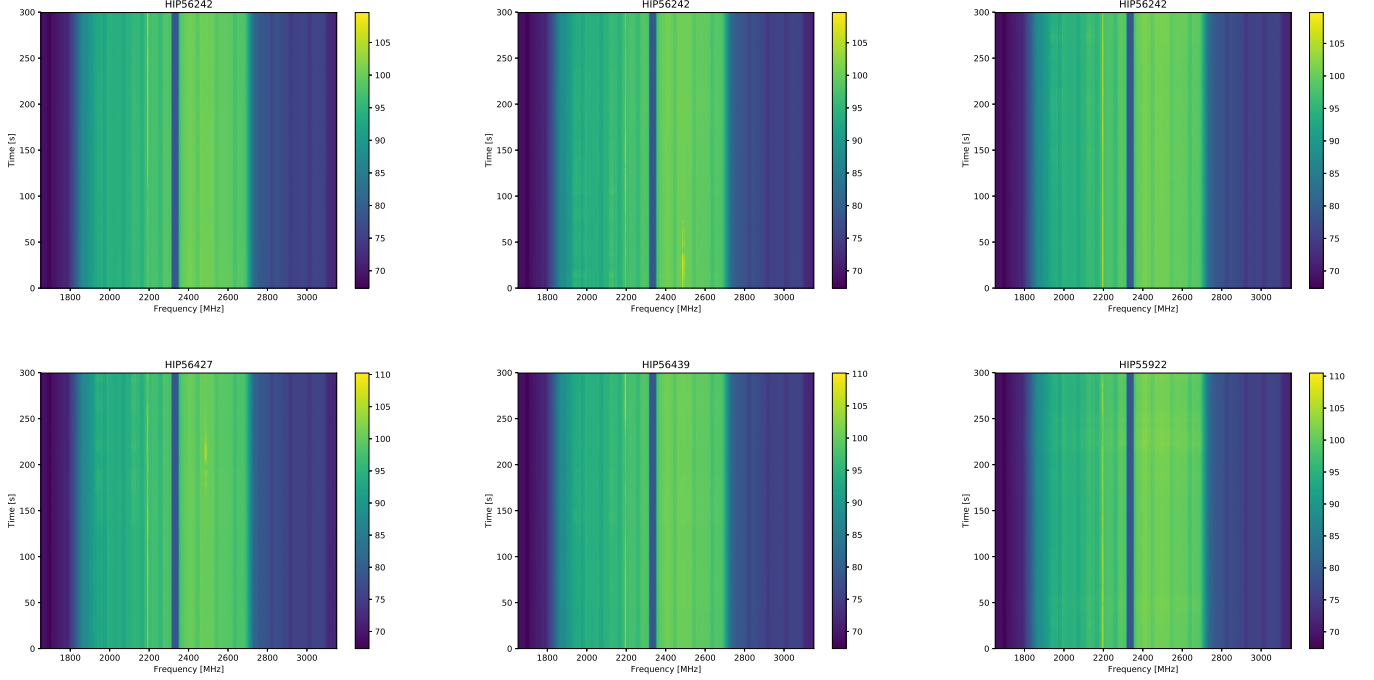


Figure 2. Spectrograms (time versus frequency) from an example “ABACAD” cadence showing S-band data spliced from 8 compute nodes, plotted from the corresponding filterbank (§ 2.3) files using BLIMPY. Observations of the primary (“A”) target (HIP 56242 in this case) are alternated with the “B”, “C”, and “D” targets (in this case, HIP 56427, HIP 56439, and HIP 55922, respectively). Good candidate technosignatures would be expected to appear only in observations of the “A” target (top row), and be absent from the comparison observations (bottom row).

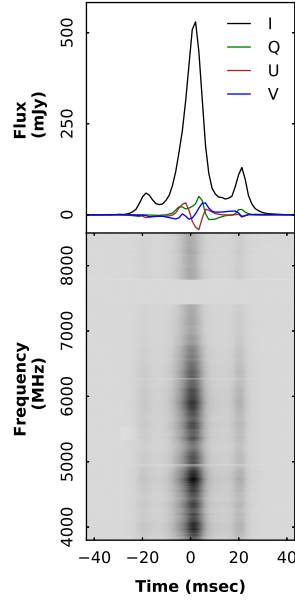


Figure 3. Detection of PSR B0329+54 across 4 to 8 GHz using the BL backend at GBT, plotted using the PSRCHIVE software package. The top panel shows integrated full-Stokes profiles obtained from 5-minute long observations. The bottom panel shows the intensity as a function of frequency and pulse phase. Frequencies between 7100 to 7500 MHz were flagged due to RFI.

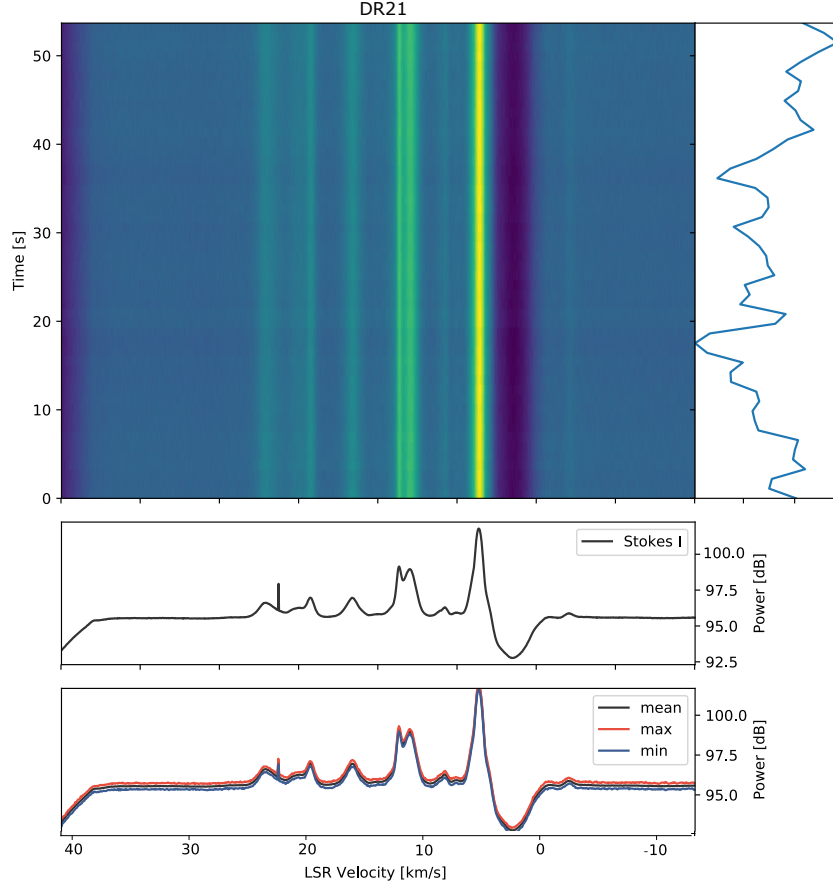


Figure 4. Detection of the 22 GHz H_2O maser feature in DR21 using the KFPA receiver at GBT and the medium resolution (MR) BL data product as described in Table 3. The polyphase channel shape and DC feature described in Section 2.5 are apparent.

Table 1. Receivers currently in regular use for BL observations.

Telescope	Receiver	Standard Center Frequency (MHz)	Frequency Range for Public HDF5 Products
GBT	L-band	1500	1025–1925
GBT	S-band	2400	1820–2720
GBT	C-band	6000	TBD
GBT	X-band	9375	TBD
Parkes	1050CM	2900	2574–3444
Parkes	Multibeam	1382	TBD

Note: There are no C-band, X-band, or Parkes Multibeam HDF5 products as part of this release - we haven't yet decided how much we want to trim down these products and will make such determinations when we have a more complete data set.

have primarily consisted of stars drawn from the [Isaacson et al. \(2017\)](#) sample, observed at L -, S -, C -, and X -bands (Table 1). The majority of the stars from that sample that are visible from GBT have now been observed at both L - and S -band (center frequencies of 1500 and 2400 MHz respectively), and the associated data files are being made available in BLDR 1.0. Raw data files are native linear polarization; filterbank files are Stokes I.

At Parkes, we can record up to an aggregate 4.875 GHz of bandwidth, dual polarization (native linear), either from single-pixel feeds such as the 10-cm receiver or the Ultra-Wide-Band feed (Hobbs et. al., in prep), or distributed as

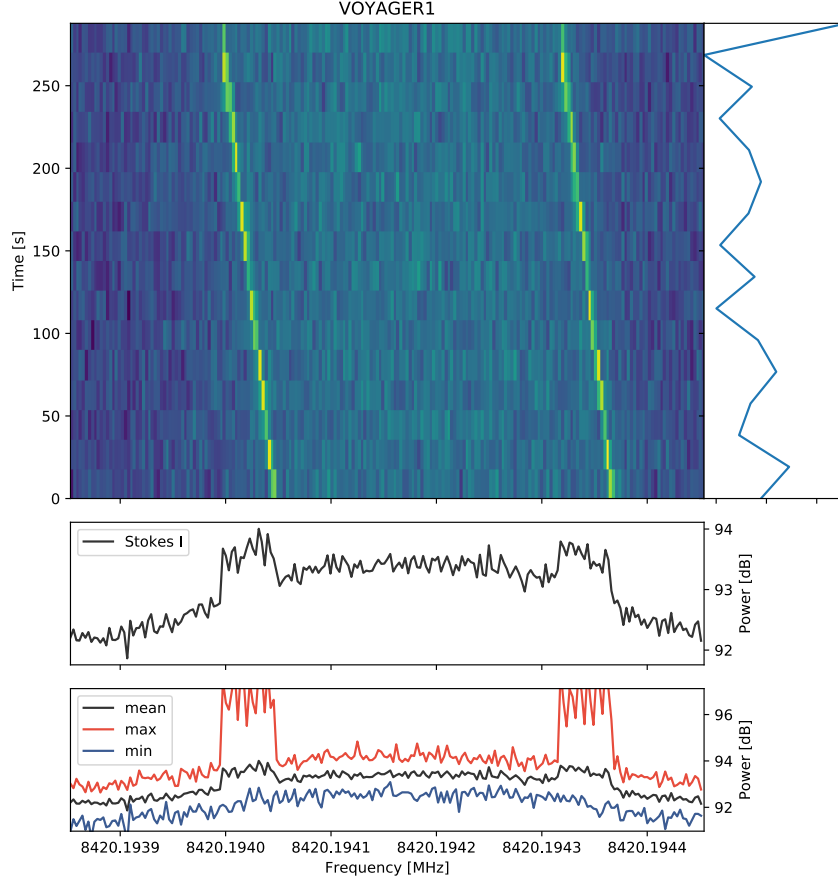


Figure 5. Detection of one sideband of the communication downlink from the spacecraft Voyager I using the X-band receiver at GBT and the high spectral resolution (HSR) BL data product as described in Table 3. These data are presented in the topocentric frame for MJD 57386.843889.

308 MHz bands from each of the 13 beams of the Multibeam receiver. We focused on nearby stars with declinations less than -20 degrees from the sample of Isaacson et al. (2017) with the 10-cm receiver, and the associated data files are being made available in BLDR 1.0.

We are in process of commissioning use of additional receivers at both telescopes – for example the K-band focal plane array (KFPA) at GBT, and the Ultra-wideband receiver (UWL) at Parkes. Data from these receivers will be made available in the future.

2.2. Raw data

Each raw file consists of a sequence of header units and corresponding chunks of data referred to as blocks, representing data collected over the course of an observation in time-contiguous order.

Each line in the headers conforms to the FITS standard of 80 bytes (an 8 byte keyword and associated values). To reduce overhead and maximize the rate at which data are written to disk, files are written using Direct I/O, a method by which applications can bypass the operating system caches and write more directly to storage devices. This mode is faster and preferred when doing long sequential writes of random data (and thus caching is ineffective). However Direct I/O requires 512 byte writes. Headers must therefore be padded with zeros after the last 80 byte FITS header to round them up multiples of 512 bytes. This padding is incompatible with many existing data reduction tools which expect the data payload to begin immediately after the header’s last key/value pair. At first our pipeline contained a “fix up” script, rewriting the files without the header padding. We later updated the reduction tools to handle raw data files with or without this padding. The two methods are differentiated by an extra field in the header (keyword DIRECTIO) which is either 0 to reflect that the current header is not padded or 1 to reflect the header is padded. The last line contains END, after which the binary data, or the padding up to the next 512 byte boundary, begins.

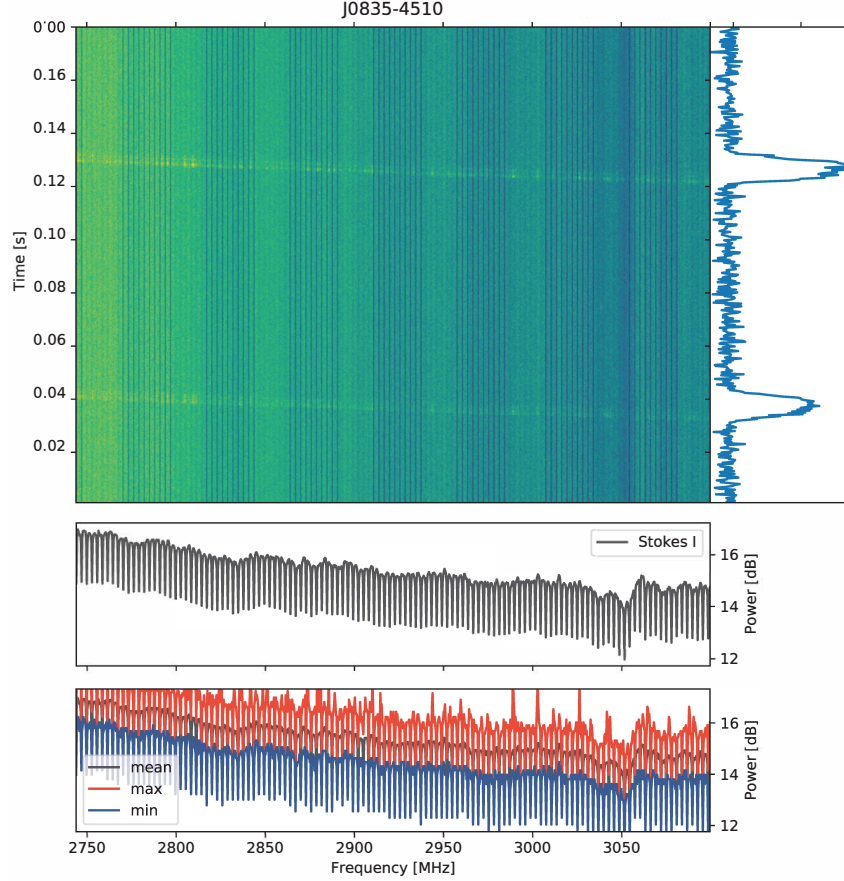


Figure 6. Detection of two pulses from the Vela Pulsar (J0835-4510) using the 1050 receiver at Parkes and the high time resolution (HTR) BL data product as described in Table 3. These data are presented in the topocentric frame for MJD 58008.024838.

Table 2. Data block sizes

Revision	Date ranges (or receiver)	Integrations	Channels	Bytes per sample	Total file size (bytes)
GBT Rev. 1A	2016/1/1 - 2016/6/16; 2016/11/21 - 2016/11/22	512×1009	64	4	134,251,648
GBT Rev. 1B	2017/2/10; 2017/3/29	512×988	64	4	129,499,136
GBT Rev. 2A	2016/6/17 - present	512×1024	64	4	134,217,728
Parkes	1050CM	512×1024	64	4	134,217,728
Parkes	Multibeam	512×1024	44	4	92,274,688

The data portion of each block consists of voltages split into a number (typically 44 or 64 – see Table 2) of coarse frequency channels (Figure 7), specified by the header keyword OBSNCHAN. Each coarse channel is ~ 3 MHz wide, and made up of $\sim 512,000$ 8-bit real / 8-bit imaginary samples in two polarizations (32 bits, or 4 bytes, total per sample). There are slight differences in block sizes in BLDR 1.0 (keyword BLOCSIZE in the file headers), due to moving from older standards which accounted for overlapping blocks (Figure 8) to more optimal sizes, and in the case of Parkes data, due to network bandwidth limitations (Table 2). The differences in block size result in slightly different resolutions in the resulting filterbank data products, as detailed in § 2.3 and Table 4. The raw file format is illustrated graphically in Figure 7.

The binary data is natively recorded in 8 bits. Every four bytes of the binary data contains two sets of two 8-bit values that each correspond to four mean-subtracted samples. The first set of two 8 bit values in the byte contain

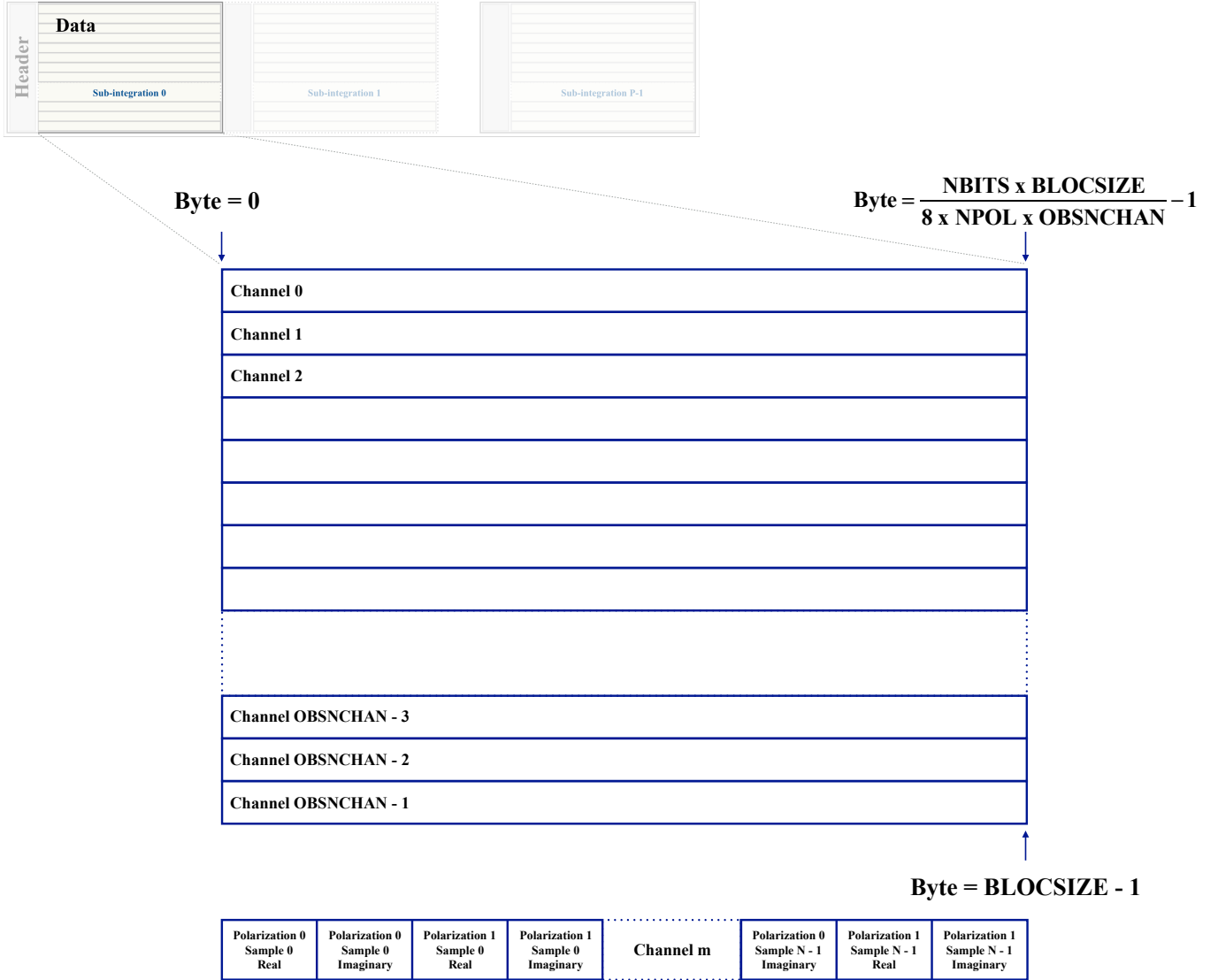


Figure 7. GUPPI raw format showing frequency channelization of each sub-integration. The values used in byte calculations are raw data header keywords described in Appendix B.

the real and imaginary values for channel 1, polarization 1, and time block 1. The second set contains the real and imaginary values for channel 1, polarization 2, and time block 1. The subsequent bytes contain the same information for increasing time blocks. This pattern follows for the remaining channels (Figure 7).

2.3. Spectrograms

As noted above (§ 2), during the time between observing sessions, the raw data passes through the reduction and analysis pipeline, and in most cases the raw data are deleted to make space on the drives for the subsequent observing session.

A selection of raw files, or a small subset of coarse channels extracted from these raw files, are copied offsite for distribution (Figure 1) to the SETI@home volunteer distributed computing project (Anderson et al. 2002). The selected raw voltages are requantized from 8-bit down to 2-bit (1 bit real / 1 bit imaginary) and copied to the SETI@home network, and are then converted into smaller workunits, each roughly 350 KB, and distributed to participants' home computers or mobile devices.

For the majority of targets, the raw data are passed to a GPU-accelerated code, GPUSPEC, to produce arrays of integrated power as a function of frequency and time. In order of operation, this code:

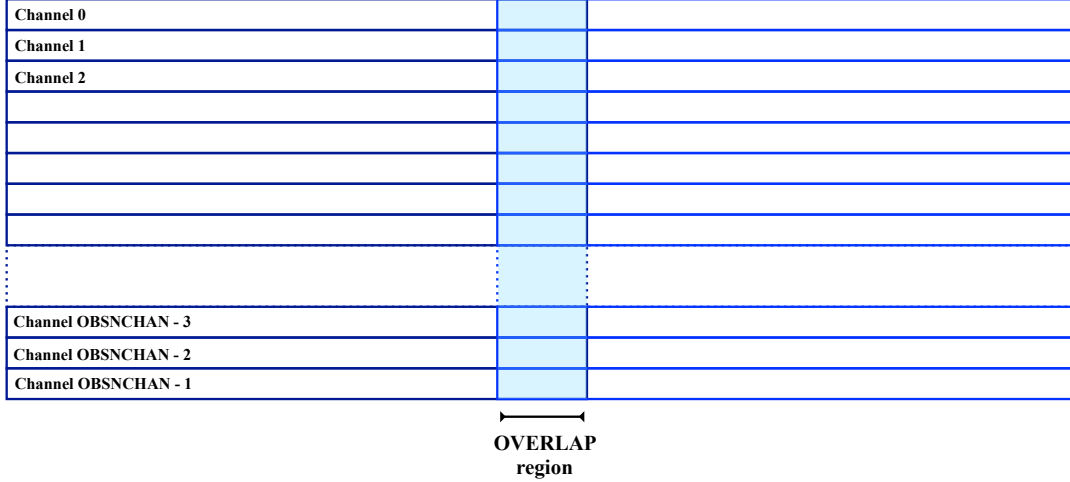


Figure 8. The OVERLAP header field has units of samples. Each sub-integration overlaps with the subsequent sub-integration by OVERLAP samples per channel. In general, this is 0 for all BL raw data.

Table 3. Standard BL data products

Product	Purpose	Filename Suffix	Frequency Resolution	Time Resolution
High Spectral Resolution (HSR)	SETI	.gpupsec.0000.fil	~ 3 Hz	~ 18 s
High Time Resolution (HTR)	Pulsar	.gpuspec.8.0001.fil	~ 366 kHz	$\sim 349 \mu\text{s}$
Medium Resolution (MR)	Spectral line	.gpuspec.0002.fil	~ 3 kHz	~ 1 s

Note: See Appendix A for more information about the filename suffixes.

- Reads data from file in GUPPI raw format.
- Performs three different fast Fourier Transforms (FFTs) with different numbers of channels. This operation is performed on the GPU device, using the NVIDIA CUFFT library.
- Squares the channelized output, add the two polarizations together, and integrates in time to form Stokes I data in GPU device memory.
- Writes output data to files in Sigproc filterbank format (Figure 2).

GPUSPEC is run on each raw file to produce three filterbank files of varying time/frequency resolutions (Table 3). The input raw data are the same, but the output resolutions of the three files are optimized to support narrow-band SETI searches, pulsar observations, and astrophysical spectral line studies (although in practice they are not limited to these applications). The resultant files are written in “filterbank” format, a relatively simple type of spectral data file with an origin in pulsar astronomy (Lorimer 2006).

The filterbank files are simply a header followed by a two dimensional array of integrated power (as 32-bit floats) as a function of radio frequency and time (as shown in Figure 9). The filterbank format was chosen as it is well understood by already existing pulsar analysis tools.

The set of three filterbank products take up roughly 2% the disk space of the original GUPPI raw data products. A small number of targets (e.g. “special” observations such as FRB 121102, diagnostic targets, and pulsar observations) are denoted by adding the string ‘DIAG’ to the target name in order to preserve the raw data products as discussed in Appendix A.

Once reduced, the filterbank files are spliced (i.e. data from each of the 187.5-MHz-wide frequency bands from each compute node are combined) and collated onto local storage nodes at each respective observatory.

Figure 9. Graphical representation of filterbank file, consisting of a series of spectra as a function of time.

Data Product	FFT Length	Integration Blocks	Frequency Resolution	Time Resolution
Revision 1A (BLOCKSIZE = 132251648)				
HSR	1033216	51	~ 2.84 Hz	~ 17.98 s
HTR	8	128	~ 366.21 kHz	$\sim 349.53 \mu\text{s}$
MR	1024	3027	~ 2.86 kHz	~ 1.06 s
Revision 1B (BLOCKSIZE = 129499136)				
HSR	999424	51	~ 2.93 Hz	~ 17.40 s
HTR	8	128	~ 366.21 kHz	$\sim 349.53 \mu\text{s}$
MR	1024	2928	~ 2.86 kHz	~ 1.02 s
Revision 2A (BLOCKSIZE = 134217728)				
HSR	1048576	51	~ 2.79 Hz	~ 18.25 s
HTR	8	128	~ 366.21 kHz	$\sim 349.53 \mu\text{s}$
MR	1024	3072	~ 2.86 kHz	~ 1.07 s

For a given number of coarse channels, N_c , and number of fine channels, N_f , the frequency of the first coarse channel (F_{cchan0}) from any given node is:

where the GUPPI raw header values `OBSFREQ` and `OBSBW` are the center frequency of the raw file, and the width of the passband in the node, respectively.

The frequency of the first fine channel, F_{fchan0} , is given by:

$$F_{\text{chan0}} = F_{\text{cchan0}} - \text{floor}\left(\frac{N_f}{2}\right) \times \frac{\text{OBSBW}}{N_c N_f}$$

The resulting frequencies are shown in Table 5. For C-band and X-band, multiple banks of compute nodes are used for recording (e.g. for X-band, three banks numbered blc00 – blc07, blc10 – blc17, and blc20 – blc27, although in practice any three of the eight available banks may be used). In order to preserve sensitive parts of the bandpass, frequencies overlap between adjacent banks.

2.4. Hierarchical Data Format - HDF5

The Hierarchical Data Format version 5 (HDF5)³ is in wider use than filterbank (particularly outside of the scientific community). To improve the accessibility of BL data, as well as to take advantage of additional functionality provided by HDF5 (including improved data compressibility) we convert our filterbank files into HDF5 before making them publicly available.

We have developed a software suite⁴, BLIMPY (Breakthrough Listen I/O Methods for PYthon), to import and display filterbank, HDF5, and GUPPI RAW data in Python (BL Collaboration 2019). BLIMPY also contains tools for conversion of filterbank to HDF5. BLIMPY will be described in more detail in an upcoming paper.

As part of the conversion from filterbank to HDF5 we check pointings against historic telescope records and adjust fine channel offsets. Originally reduced data products were created with first channels incorrectly labeled at their center frequencies instead of at the edge; these half-channel errors only affect the headers and not the data. We also trim away the edges of the frequency range where the bandpass sensitivity falls off, thus significantly reducing the size of the data using the BLIMPY `bldice` command.

In general, we trim the GBT L-band data down to the 1025–1925 MHz range, GBT S-band data to 1820–2720 MHz, and Parkes 10CM to 2574 – 3444 MHz. Some files contain smaller ranges of frequencies; reasons for this may include:

- Early on in the project files were trimmed by including only data from the central four compute nodes recording the most sensitive parts of the bandpass
- Due to intermittent system/disks failures while building out each backend system, data from some nodes were unusable, and thus certain ranges are missing.
- Occasional tuning errors caused the center frequency to be off by enough to bring the bandpass outside of the recorded range.

2.5. Instrumental Effects and Data Artifacts

At both GBT and Parkes, the complete BL signal chain includes numerous components, from radio receivers, through analog signal downconversion, digital sampling, channelization, retransmission, recording and finally software post processing. Virtually all of these components impose instrumental effects on the resultant data products, and many of them suffer sporadic faults. These issues are compounded by instrument commissioning, testing and continuous software development. Here we detail several of the most prominent instrumental features found in BLDR 1.0 and highlight known data artifacts affecting a small percentage of the collection. We note that this list is not exhaustive, and caution should be taken in ruling out previously undiscovered instrumental problems when encountering anomalies in the data set.

2.5.1. Radio Frequency Interference

Radio telescopes are highly susceptible to RFI, from local transmitters as well as both airborne and spaceborne sources. Such interference can dominate the data, given its power, perseverance, and multitude of forms. Often the strength of these transmitters is sufficient to cause their apparent power to spread well beyond the time and frequency extent of the specific transmission due to analog saturation and digital overflow. It is difficult to overstate the pervasiveness, diversity and challenge of RFI in searches for radio technosignatures.

³ <https://support.hdfgroup.org/HDF5/>

⁴ <https://github.com/UCBerkeleySETI/blimp>

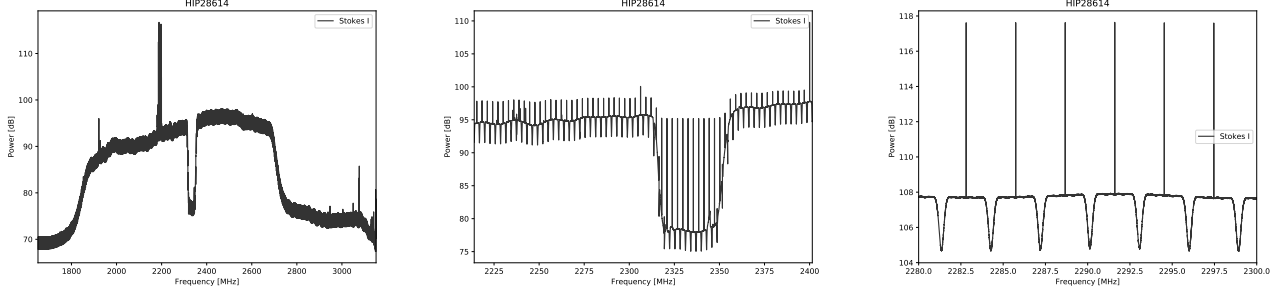


Figure 10. One-dimensional S-band spectra (collapsing the time dimension from the spectrogram) plotted using the same data for HIP 28614 from the top left panel of Figure 2. The left panel shows the spliced data for all 8 compute nodes. The dip around ~ 2330 MHz is due to the observatory’s S-band notch filter (which is used to reduce interference from Sirius and XM satellite transmissions). Bright RFI is also visible at ~ 2200 MHz. The middle panel zooms in to show 1/8 of the data (the 187.5 MHz from compute node blc04), showing the lower-gain region corresponding to the notch filter in more detail. The 64 individual 3-MHz-wide coarse channels are visible, each with a fall-off at each edge of the coarse channel, and each with a spike in the DC bin at the center of the coarse channel. Each of the coarse channels is more finely channelized by the GPUSPEC FFT: 8 fine channels per coarse channel for the HTR data product, 1024 fine channels per coarse channel for the MR (the data product plotted here), and 1,048,576 fine channels per coarse channel for the HSR data product (Table 3). The right panel is zoomed into the 2280–3000 MHz range to better depict the polyphase shape of roughly 7 coarse channels.

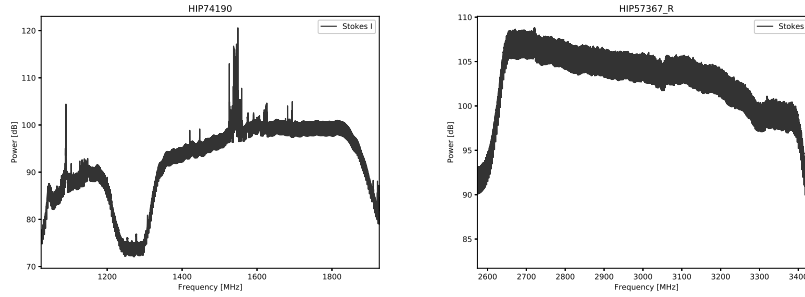


Figure 11. Examples of spectra similar to Figure 10 for both the L-band receiver at Green Bank (left) and the Parkes 10CM receiver (right). The L-band receiver has a notch filter between 1.2–1.34 GHz to reduce interference from nearby air surveillance radar. These examples are also trimmed to a smaller range of frequencies, as described in Section 2.4.

2.5.2. Analog and Digital Filtering

The incoming analog bandpass is not flat, and passes through filters before reaching the BL backend. The BL instrument also imposes its own polyphase filter shape on the data. Each coarse channel (~ 3 MHz) has a reduction in sensitivity toward the channel edges, and a DC channel in the center. A typical coarse channel shape (along with some RFI) is shown in Figure 10.

2.5.3. Dropped Blocks and Lost Data

Occasionally other issues affecting data quality arise. During observations each compute node receives about 1 GBs^{-1} of data from the telescope. Hardware issues (failing hard drives, degraded RAID arrays, faulty switches, bad cables, xfs partition fragmentation which reduces write speeds even when using Direct I/O) can impede the ability of the compute nodes to record data at this rate, resulting in dropped blocks (short spots of missing data). This causes an occasional reduction in sensitivity, the effects of which are shown in Figure 12.

More rarely, problems with the communication between the BL backend and the telescope may result in gaps of 187.5 MHz where data are completely lost for a particular compute node.

In addition to these occasional hardware or software issues, bad weather may reduce sensitivity, or cause observations to stop mid-scan to park the telescope for safety. Additionally, observations at the end of each BL session may consist of less than five minutes of data.

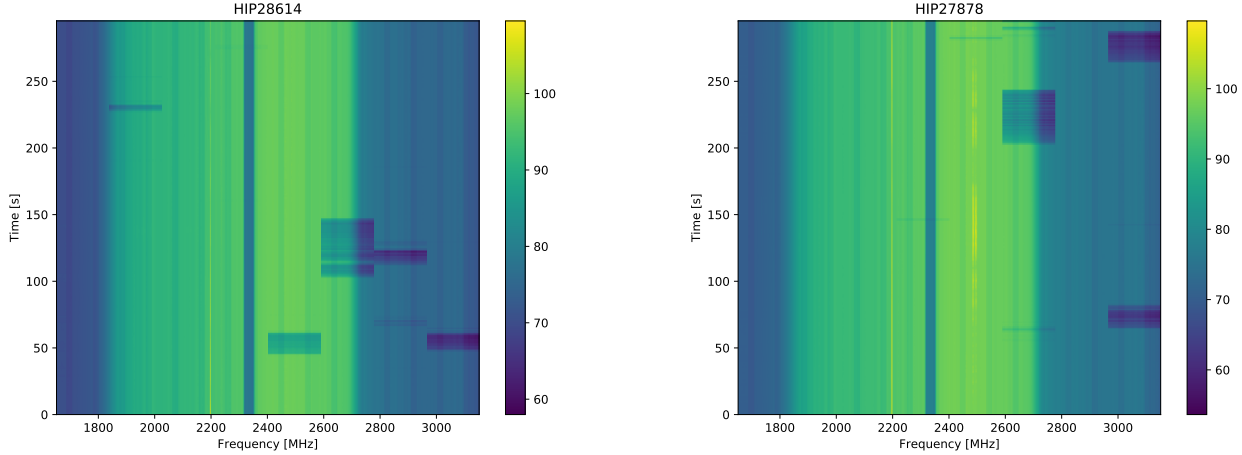


Figure 12. These are targets from one of a small number of observational cadences affected by patches of reduced sensitivity due to dropped ethernet packets during the course of an observation. The affected data are visible as blue rectangles spanning 1/8 of the total band of a given 1500 MHz band of eight compute nodes, i.e. the 187.5 MHz associated with individual nodes. The length in time (or “height”) of these rectangles is arbitrary, as it only happens when a particular node is missing data due to several factors that are hard to predict or control. Most datasets in BLDR 1.0 are not affected in this manner, but these dropped packets are not to be confused with expected reduced sensitivity due to notch filters (such as the one shown here from 2300–2360 MHz) and the areas outside of the bandpass (i.e. below 1800 MHz and above 2700 MHz in this case).

2.5.4. Two-bit requantization of raw data

During early commissioning at GBT (approximately MJD 57402–57502) we requantized the raw data from 8-bit to 2-bit using the `RAW_QUANT` program⁵ but this step is no longer performed (except when creating data for the SETI@home pipeline). Data requantized to 2-bits shows a significantly diminished analog bandpass response, has reduced sensitivity and issues with saturation in the presence of strong sources.

3. OPTICAL: BL ON APF

The Automated Planet Finder Telescope (APF; Radovan et al. 2014) is a 2.4-meter optical telescope at Lick Observatory in California. Its primary aim is to search for earth-like extrasolar planets. The single instrument is a $R \sim 95,000$ optical echelle spectrometer with wavelength coverage from 374 to 950 nm. BL uses the APF for 36 nights per year and targets nearby stars with a maximum exposure time of 20 minutes (aiming for an optimal signal-to-noise ratio of 100:1). Three spectra are obtained for each star in order to more easily distinguish cosmic ray hits from interesting signals. The nominal decker projects to a sky angle of $1.0'' \times 3.0''$, which at 10 pc corresponds to 10×30 AU, allowing the detection of laser emission from planets that are offset from their stars, as well as emitters that may lie in the foreground or background within the line of sight (Tellis & Marcy 2015).

The two standard data products available from the APF are the raw 2D image (each 18.3 MB), an example of which is shown in Figure 13, and the extracted 1D spectrum (each 1.4 MB), as shown in Figure 14. BL utilizes both the raw and reduced images to search for monochromatic laser lines that are narrow in wavelength space and match the point-spread-function (in the raw images) and line-spread-function (in the reduced images) of the instrument. Typical searches by BL are described by Tellis & Marcy (2017) and Lipman et al. (2019), including details of cosmic ray removal, telluric absorption and emission lines, and blaze function correction. Each BL night is run in collaboration with the California Planet Search and utilizes scheduling software described by Holden et al. (2016).

As with the radio searches of nearby stars, targets are selected from the sample of Isaacson et al. (2017). Files for a total of 789 targets are available as part of BLDR 1.0. A tutorial and example files are also available online⁶.

4. THE BREAKTHROUGH LISTEN PUBLIC DATA ARCHIVE

⁵ https://github.com/UCBerkeleySETI/gbt_seti

⁶ <https://github.com/UCBerkeleySETI/breakthrough/tree/master/APF>

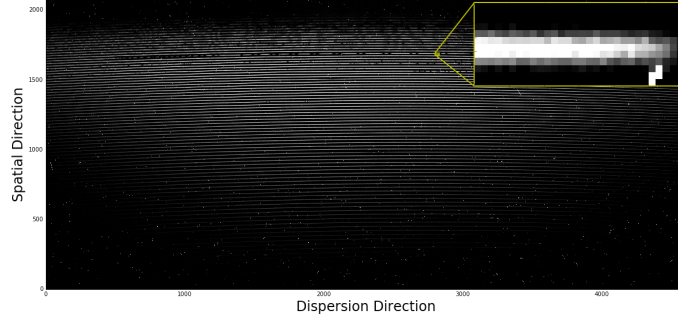


Figure 13. A raw 2D echelle spectrum (figure from [Lipman et al. 2019](#)) of Boyajian’s Star, 4,608 pixels in the dispersion direction and 2,080 pixels in the spatial direction, containing 79 spectral orders. The zoomed image in the upper-right corner is a segment of one of these spectral orders, which shows a cosmic ray in the bottom right corner. The wavelength coverage of the Levy is 373.0 – 1020.6 nm; however CCD fringing limits the usability of the reddest orders.

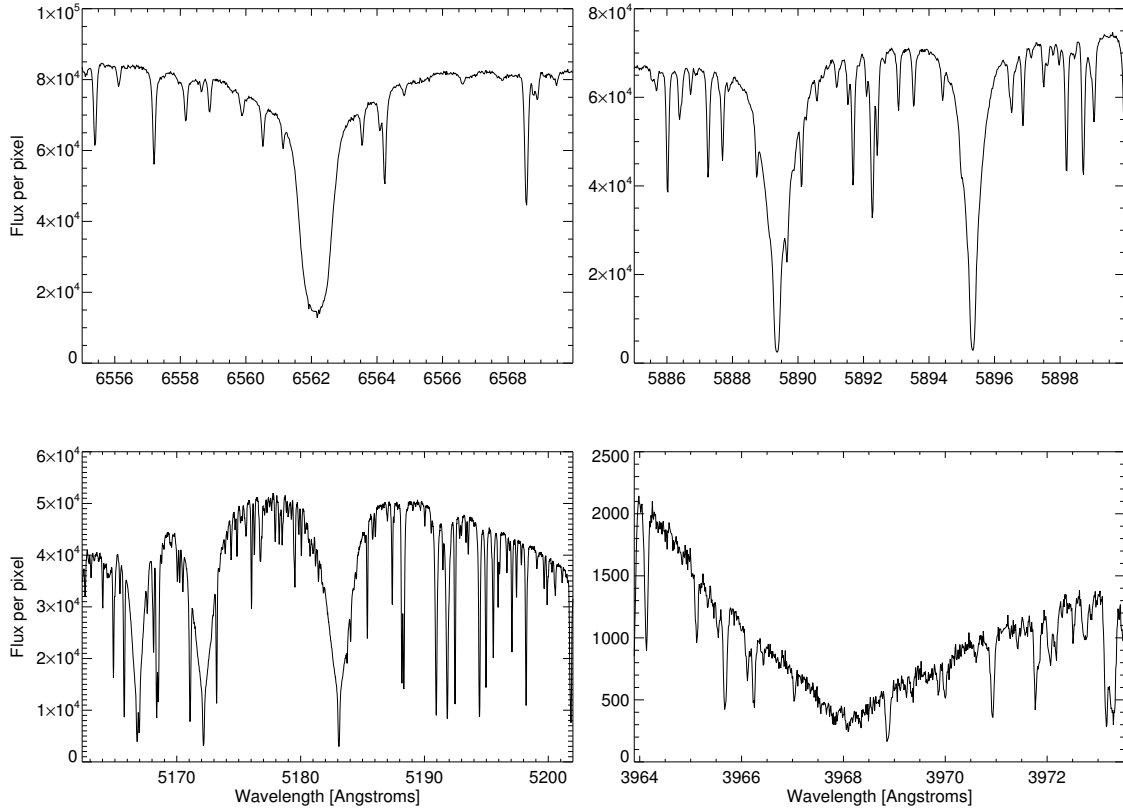


Figure 14. Four prominent absorption features extracted from a reduced, 1D, high-resolution spectrum of HD 10700 from the APF. The resolution of 95,000 allows for identification of potential laser lines emitted along the line of sight towards the target star. Clockwise from top left: H-alpha, the Sodium-D doublet, the Magnesium B triplet and the Calcium II H-line showing broad absorption. Fluxes are in photons per pixel.

The BL data archive strategy is designed to facilitate analysis by the internal science team as well as engagement by external parties. Key information about the public data products is kept in a MySQL database containing basic metadata and URLs for all available files. Frontends to this database are provided via a portal on the Breakthrough Initiatives website, and also by a beta interface with additional functionality hosted by Berkeley SETI Research Center (Figure 15). Data can be searched by target name, times, frequencies, or location.

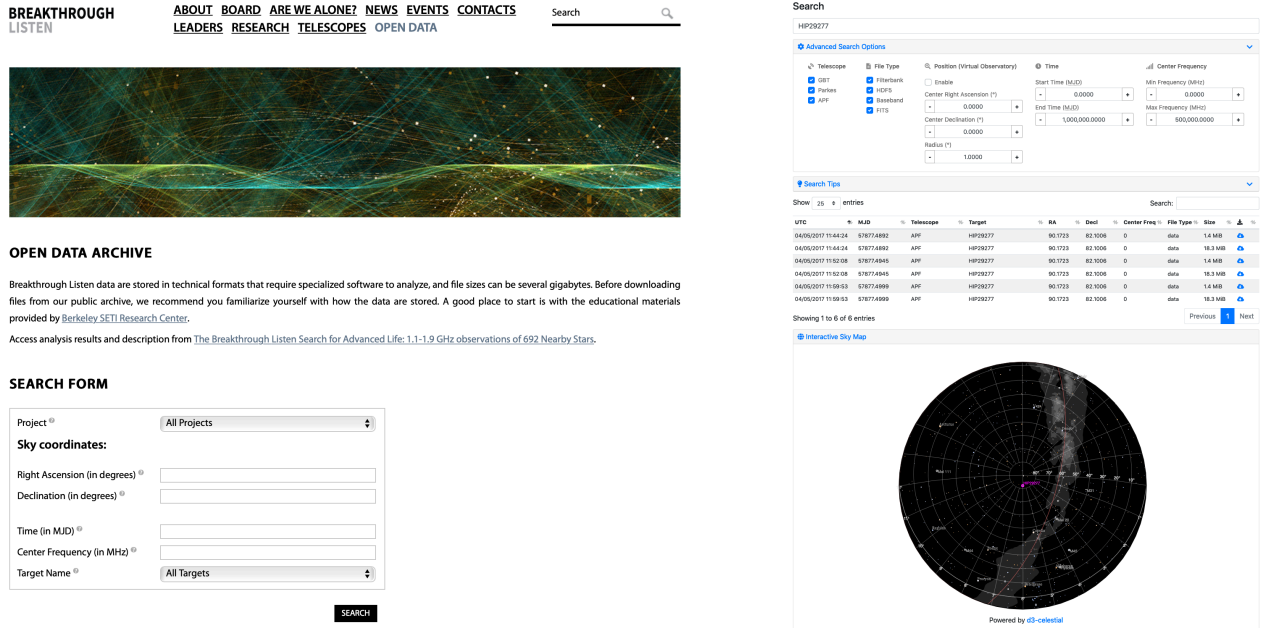


Figure 15. Left: Open Data Archive hosted on the Breakthrough Initiatives web site ^c. Right: Beta interface to the same dataset, with additional search and visualization options, as hosted by Berkeley SETI Research Center. ^d.

^a <https://breakthroughinitiatives.org/opendatasearch>

^b <http://seti.berkeley.edu/opendata>

^c <https://breakthroughinitiatives.org/opendatasearch>

^d <http://seti.berkeley.edu/opendata>

The majority of data in BLDR 1.0 are stored on 11 commodity public data servers at UC Berkeley, each with roughly 200 TB of usable storage and its own 10 Gb s⁻¹ link to the internet. Having a fleet of separate servers increases parallelization as well as uptime. Since the database can link to files hosted at any publicly-accessible URL, we can also seamlessly link to data at national computing centers and commercial cloud providers. We anticipate our use of cloud storage for BL data may increase in future.

Additional data, not yet available in BLDR 1.0, are still located on storage hardware at the telescope sites. Network bandwidth limitations (a few Gb s⁻¹) at the telescope sites prevent us from incorporating files stored there into the archive directly, but as they are transferred to public servers on fast connections at UC Berkeley (or in the cloud), the BL public data archive will continue to grow.

In future we also anticipate making increasing amounts of data available in other popular community-supported formats such as SigMF (West & Hilburn 2019), or as images appropriate for machine learning algorithms.

The total volume of the archive is expected to grow to approximately 25 PB over the next several years, and will ultimately include data from many facilities.

We are also exploring technologies such as Ceph⁷ and Globus⁸, which in combination with more flexible downloads enabled by HDF5 will allow users to download portions of files rather than necessitating an entire file (which can be up to ~ 100 GB in size) to be retrieved from the archive.

5. SUMMARY

The large data volumes, complex instrumentation and the intricacies of varied file formats make acquisition, processing, and storage of BL data a challenging undertaking. With the release of BLDR 1.0, the BL open data archive currently contains almost 1 PB of data. These data include the complete set of 1.10–3.45 GHz observations used in

⁷ <https://ceph.com>

⁸ <https://globus.org>

the technosignature search presented by Price et al. (submitted) as well as raw data from a number of particularly interesting targets for both SETI and general astrophysics. Data continue to be acquired at APF, GBT and Parkes, including new observing modes and radio receivers. Future BL Data Releases will include these data, as well as data collected from new BL facilities such as MeerKAT. With BLDR 1.0 and future releases, it is our hope that experts from outside the SETI community, and even from outside radio astronomy, will be empowered to help us improve our technosignature searches and increase the general scientific return from BL observations.

ACKNOWLEDGEMENTS

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Facilities: APF, GBT, Parkes

APPENDIX

A. FILE NAMING CONVENTIONS

A.0.1. *Raw*

For GBT:

`blc<Node #>_guppi_<MJD Day>_<MJD Seconds>_<Target>_<Scan #>.<File #>.raw`

For Parkes:

`blc<Node #>_guppi_<MJD Day>_<MJD Seconds>_<Packet Index>_<Target>_<Scan #>.<File #>.raw`

Node #: As data are being recording, the filenames begin with the ‘guppi_’ prefix. Once reduced into filterbank files, we add this ‘blc’ prefix (along with the number of the pertinent compute node) in order to denote successful completion of the reduction, as well as remove file name collision with similarly named files on other compute nodes.

MJD Day, MJD Seconds, and Packet Index: Next is ‘MJD Day’ which is the integer portion of the Modified Julian Date at the beginning of this scan, followed by ‘MJD Seconds’ which is the number of seconds of midnight UTC. Filenames of early BL GBT data products do not contain ‘MJD seconds’. Due to naming collisions of multiple observations of the same star in the same day, this was added at the end of 2016 January. At Parkes there is an additional integer field inserted in the filename between ‘MJD seconds’ and ‘Target’ relating to current packet index, that is used for debugging the BL backend.

Target: The target name may contain underscores (making parsing difficult). Diagnostic sources (e.g. pulsars) also contain the string ‘DIAG’; the processing pipeline recognizes this tag and preserves raw data which would otherwise be deleted after filterbank files have been generated. These raw data are kept for continued analysis, since they contain the full resolution, as well as amplitude and phase information, that are lost on conversion to spectrograms. In all other cases the raw data are immediately deleted after the filterbank files have been generated.

Scan number: These are provided by the observatory, start at 0001 at the beginning of each session, and increment for each scan; due to diagnostics and interruptions numbers are not always sequential in the BL public datasets.

File number: Each raw file corresponds to ~ 22.9 s of observation (128 blocks per file at 0.179s per block), so a typical 5-minute observation is split into 14 raw files, numbered sequentially. The file number starts at 0000 and increments by 1 for each 128-block file. A 128-block file is about 16 GB. A partial raw file at the end of the series will contain enough full blocks to complete the exact 5-minute scan and so is typically smaller than 16 GB.

A.0.2. *Filterbank*

Same as raw above, except `.raw` is replaced by: `.gpuspec.<Resolution Type>.fil` where `<Resolution Type>` (noted in Table 3) is one of the following:

- 0000 : high spectral resolution (HSR)

- 0001 : high time resolution (HTR)
- 8.0001 : high time resolution, but 8-bit integers (a data type required, or preferred, by some analysis tools) instead of the default 32-bit floats
- 0002 : medium spectral/time resolution (MR)

Some data products in BLDR 1.0 were processed with an updated version of GPUSPEC called RAWSPEC which has been optimized for speed and better use of GPU memory. In such cases “gpuspec” in the filenames is replaced by “rawspec”.

The filterbank products from the separate compute nodes are typically spliced together. The names of these single files contain the word “spliced”, along with an ordered list of the processing nodes which went into making up these collated files. In a small fraction of cases where nodes experienced problems during recording for a particular target, lost data from the missing nodes are padded with zeros, and the node numbers in the filename replaced with ‘zz’. Unused overlapping nodes are also removed, and denoted ‘oo’ in the output filenames.

A.0.3. HDF5

<Telescope>_<MJD Day>_<MJD Seconds>_<Target>_<Resolution>.h5

Since the HDF5 version is the “final” version, we remove some diagnostic information from the filenames, renaming them for simplicity.

‘Telescope’ identifies the telescope where the data were taken (GBT, Parkes, or future telescopes, e.g. MKat for MeerKat). ‘MJD,’ ‘MJDsec,’ and ‘Target’ are the same as before, and as such the target name may include underscores. ‘Resolution’ is either “fine” for fine spectral resolution, “time” for fine time resolution, and “mid” for mid spectral/time resolution. Names are globally unique, human readable, and computer parsable.

A.0.4. FITS (APF)

2D echelle spectrogram:

ucb-<Session Index><Scan #>.fits

1D extracted spectrum:

r<Session Index>.<Scan #>.fits

B. RAW AND FILTERBANK HEADERS

ACC_LEN: Accumulation length (# of spectra averaged together in time) - set to 1 for coherent modes only.

AZ: Azimuth of the telescope

BACKEND: A name for the backend (or backend compatibility) of the recorded data. Breakthrough Listen canonically uses GUPPI for maximizing backwards compatibility with legacy code.

BANDNUM: For telescopes with multiple IF downconverters (aka “bands”), this field identifies which IF band provided the data for the given RAW file.

BANKNAM: Name of the Breakthrough Listen bank where this file was recorded, labeled by the “Player” name (see [MacMahon et al. 2018](#))

BANKNUM: Once channelized, different parts of the IF band are received and processed by different backend hosts. This field identifies which portion of the IF band is present in a given RAW file.

BASE_BW: Occupied portion of the Nyquist bandwidth (no longer used).

BINDHOST: Ethernet device for receiving data

BLOCKSIZE: The size of the following raw data segment, in bytes. Does not include padding bytes from Direct I/O. Can be expressed as $2 \times \text{NPOL} \times \text{NTIME} \times \text{NCHAN} \times \text{NBITS}/8$

BMAJ: Full width half maximum of the major axis of the beam

BMIN: Full width half maximum of the minor axis of the beam

CAL_DCYC: Duty cycle for pulsed calibrator

CAL_FREQ: Pulse frequency of the calibrator signal. May be unspecified.

CAL_MODE: Setting of calibration noise diode

CHAN_BW: Bandwidth (in MHz) of a single channel. Will be negative if the frequency axis is reversed (e.g. due to a lower sideband mix).

CHAN_DM: Dispersion measure for COHERENT_SEARCH mode. Set to 0 for all other modes.

DAQCTRL: This field is used by the telescope interface code to control the data acquisition (e.g. to initiate recording).

DAQPULSE: Heartbeat from GUPPI DAQ (data acquisition) server

DAQSTATE: State of GUPPI DAQ server

DATADIR: Path prefix for data directory of output files

DATAHOST: Hostname or IP address of the FPGA 10Gbe port to receive from

DATAPORT: Port number for receiving data

DEC_STR: Declination of the telescope (string form)

DEC: Declination of the telescope (degrees) (Parkes: same as DEC_STR)

DIRECTIO: Indicates whether Direct I/O was used to optimize file writing. If used, indicated by a non-zero value, the header is padded to be a multiple of 512 bytes.

DISKSTAT: Status of disk write thread

DROPAVG: Average fraction of recently dropped data

DROPBLK: Fraction of data dropped in the current block

DROPTOT: Fraction of total data dropped during this scan

DS_FREQ: Enables software reduction of frequency resolution (SEARCH and COHERENT_SEARCH only). Only powers of 2 are allowed. Set to 1 for all other modes.

DS_TIME: Enables additional software accumulation of spectra in time (SEARCH and COHERENT_SEARCH only). Only powers of 2 are allowed. Set to 1 for all other modes.

FD_POLN: Polarization type of the feed (LIN or CIR)

FFTLLEN: Total number of frequency channels in the digitized band from which these data are drawn. Not used by Breakthrough Listen code.

FREQ: Parkes: center frequency tuning according to TCS (MHz)

FRONTEND: Name of the receiver that was used.

LST: Local sidereal time at the start of the block (seconds)

NBIN: Number of bins in profile for folding and calibration modes. Ignored in all other modes.

NBITS: Number of bits in each complex component per sample – one complex-valued sample has $2 \times \text{NBITS}$ bits

NDROP: Number of packets dropped during this block

NETBUFST: Recording diagnostic regarding how many network buffers were used during recording – usually only 1 out of 24 are required, but if there are disk or filesystem bottlenecks this goes up.

NETSTAT: Status of network thread

NPKT: Number of packets received for this block

NPOL: Number of samples per time step – 4 corresponds to dual-polarization complex data

NRCVR: Number of receiver channels (polarizations)

OBSBW: Width of passband in this node; negative sign indicates reversed frequency axis

OBSERVER: The observer on duty when these data were recorded

OBSFREQ: Center frequency of the frequencies spanned by the data in the RAW file

OBSNCHAN: The number of frequency channels contained within the file.

OBS_MODE: Current observing mode (SEARCH, FOLD, CAL, COHERENT_SEARCH, COHERENT_FOLD, COHERENT_CAL, or RAW)

OFFSET0: Not used

OFFSET1: Not used

OFFSET2: Not used

OFFSET3: Not used

ONLY_I: Setting this to 1 enables total intensity data to be recorded in SEARCH and COHERENT_SEARCH only. Otherwise, this will be set to 0 for full-Stokes data.

OVERLAP: Number of time samples per channel overlapping between blocks. Always 0 for Breakthrough Listen data.

PARFILE: For pulsar folding modes, full path the parameter file. Ignored in other modes.

PFB_OVER: PFB number of overlapping channels. Not used by Breakthrough Listen code.

PKTFMT: UDP packet format. FAST4K or 1SFA.

PKTIDX: Recording diagnostic – current first packet ID # of this block

PKTSIZE: Packet size (bytes)

PKTSTART: This is the expected PKTIDX value at the start of the scan (i.e. when recording should start).

PKTSTOP: This is the PKTIDX value at the end of the scan (i.e. when recording should stop).

POL_TYPE: Not used

PROJID: Observing project ID / session code

RA_STR: Right Ascension of the telescope (string form)

RA: Right ascension of the telescope (degrees) (Parkes: same as RA_STR)

SCALE0: Not used

SCALE1: Not used

SCALE2: Not used

SCALE3: Not used

SCANLEN: Overall duration of the scan (i.e. recording) in seconds.

SCANREM: Seconds of scan time remaining. Intended primarily as feedback for the observer while a scan is occurring.

SCAN: GBT scan index #

SRC_NAME: Name of current target, taken from the input catalog.

STTVVALID: 1 if valid start time has been set

STT_IMJD: Start time, integer MJD

STT_OFFS: Start time, fractional second

STT_SMJD: Start time, integer seconds within day (UTC)

SYNCTIME: (Parkes) Current UNIX epoch seconds.

TBIN: Time resolution of incoming data, $(1 / \text{abs}(\text{CHAN_BW}))$

TELESCOP: Telescope name

TFOLD: Not used

TRK_MODE: Tracking mode in use

ZA: Zenith Angle of the telescope

```

BACKEND = 'GUPPI'
DAQCTRL = 'start'
DAQPULSE= 'Thu Nov 15 00:22:14 2018'
DAQSTATE= 'record'
NBITS = 8
OFFSET0 = 0.0
OFFSET1 = 0.0
OFFSET2 = 0.0
OFFSET3 = 0.0
BANKNAM = 'BLP00'
TFOLD = 0
DS_FREQ = 1
DS_TIME = 1
FFTLEN = 512
CHAN_BW = -2.9296875
BANDNUM = 0
NBIN = 256
OBSNCHAN= 64
SCALE0 = 1.0
SCALE1 = 1.0
DATAHOST= 'blr2-1-10-0.gb.nrao.edu'
SCALE3 = 1.0
NPOL = 4
POL_TYPE= 'AABBCRCI'
BANKNUM = 0
DATAPORT= 60000
ONLY_I = 0
CAL_DCYC= 0.5
DIRECTIO= 1
BLOCSIZE= 134217728
ACC_LEN = 1
OBSERVER= 'Steve Croft'
CAL_MODE= 'OFF'
PROJID = 'AGBT18B_999_63'
OVERLAP = 0
OBS_MODE= 'RAW'
CAL_FREQ= 'unspecified'
DATADIR = '/datax/dibas'
OBSFREQ = 11157.71484375
PFB_OVER= 12
SCANLEN = 300.0

PARFILE = '/opt/dibas/etc/config/example.par'
OBSBW = -187.5
FD_POLN = 'CIRC'
SCALE2 = 1.0
BINDHOST= 'eth4'
TELESCOP= 'GBT'
NRCVR = 2
PKTFMT = '1SFA'
TBIN = 3.413333333333333E-07
BASE_BW = 1450.0
SRC_NAME= 'HIP3979'
CHAN_DM = 0.0
FRONTEND= 'Rcvr8_10'
BMAJ = 0.02198635849376383
BMIN = 0.02198635849376383
TRK_MODE= 'TRACK'
RA_STR = '00:51:11.1600'
RA = 12.7965
DEC_STR = '-05:02:24.0000'
DEC = -5.04
LST = 13193
AZ = 231.5728
ZA = 58.1904
STT_SMJD= 19335
STT_IMJD= 58437
STTVALID= 1
NETSTAT = 'receiving'
DISKSTAT= 'waiting'
PKTIDX = 0
DROPAVG = 0.000171566
DROPTOT = 0.519159
DROPBLK = 0
PKTSTOP = 27459584
NETBUFST= '1/24'
SCAN = 40
STT_OFFS= 0
SCANREM = 0.0
PKTSIZE = 8192
NPKT = 16384
NDROP = 0
END

```

Figure 16. Typical raw header for BL data

C. FREQUENCY TUNINGS AND DATA PRODUCTS

Table 5. GBT band frequency table.

L-band (1.1–1.9 GHz)			S-band (1.7–2.7 GHz)			C-band (4.0–8.0 GHz)			X-band (8.0–11.6 GHz)			
Node	.raw	OBSFREQ	.fl	fch1	.raw	OBSFREQ	.fl	fch1	.raw	OBSFREQ	.fl	fch1
b1c00	2157.71484375	2251.46484375	3057.71484375	3151.46484375	8345.21484375	8345.21484375	8438.96484375	8438.96484375	11157.71484375	11157.71484375	11251.4648437	11251.4648437
b1c01	1970.21484375	2063.96484375	2870.21484375	2963.96484375	8157.71484375	8157.71484375	8251.46484375	8251.46484375	10970.21484375	10970.21484375	11063.9648437	11063.9648437
b1c02	1782.71484375	1876.46484375	2682.71484375	2776.46484375	7970.21484375	7970.21484375	8063.96484375	8063.96484375	10782.71484375	10782.71484375	10876.4648437	10876.4648437
b1c03	1595.21484375	1688.96484375	2495.21484375	2588.96484375	7782.71484375	7782.71484375	7876.46484375	7876.46484375	10595.21484375	10595.21484375	10688.9648437	10688.9648437
b1c04	1407.71484375	1501.46484375	2307.71484375	2401.46484375	7595.21484375	7595.21484375	7688.96484375	7688.96484375	10407.71484375	10407.71484375	10501.4648437	10501.4648437
b1c05	1220.21484375	1313.96484375	2120.21484375	2213.96484375	7407.71484375	7407.71484375	7501.46484375	7501.46484375	10220.21484375	10220.21484375	10313.9648437	10313.9648437
b1c06	1032.71484375	1126.46484375	1932.71484375	2026.46484375	7220.21484375	7220.21484375	7313.96484375	7313.96484375	10032.71484375	10032.71484375	10126.4648437	10126.4648437
b1c07	845.21484375	938.96484375	1745.21484375	1838.96484375	7032.71484375	7032.71484375	7126.46484375	7126.46484375	9845.21484375	9845.21484375	9938.96484375	9938.96484375
b1c10					7220.21484375	7220.21484375	7313.96484375	7313.96484375	10032.71484375	10032.71484375	10126.4648437	10126.4648437
b1c11					7032.71484375	7032.71484375	7126.46484375	7126.46484375	9845.21484375	9845.21484375	9938.96484375	9938.96484375
b1c12					6845.21484375	6845.21484375	6938.96484375	6938.96484375	9657.71484375	9657.71484375	9751.46484375	9751.46484375
b1c13					6657.71484375	6657.71484375	6751.46484375	6751.46484375	9470.21484375	9470.21484375	9563.96484375	9563.96484375
b1c14					6470.21484375	6470.21484375	6563.96484375	6563.96484375	9282.71484375	9282.71484375	9376.46484375	9376.46484375
b1c15					6282.71484375	6282.71484375	6376.46484375	6376.46484375	9095.21484375	9095.21484375	9188.96484375	9188.96484375
b1c16					6095.21484375	6095.21484375	6188.96484375	6188.96484375	8907.71484375	8907.71484375	9001.46484375	9001.46484375
b1c17					5907.71484375	5907.71484375	6001.46484375	6001.46484375	8720.21484375	8720.21484375	8813.96484375	8813.96484375
b1c20					6095.21484375	6095.21484375	6188.96484375	6188.96484375	8907.71484375	8907.71484375	9001.46484375	9001.46484375
b1c21					5907.71484375	5907.71484375	6001.46484375	6001.46484375	8720.21484375	8720.21484375	8813.96484375	8813.96484375
b1c22					5720.21484375	5720.21484375	5813.96484375	5813.96484375	8532.71484375	8532.71484375	8626.46484375	8626.46484375
b1c23					5532.71484375	5532.71484375	5626.46484375	5626.46484375	8345.21484375	8345.21484375	8438.96484375	8438.96484375
b1c24					5345.21484375	5345.21484375	5438.96484375	5438.96484375	8157.71484375	8157.71484375	8251.46484375	8251.46484375
b1c25					5157.71484375	5157.71484375	5251.46484375	5251.46484375	7970.21484375	7970.21484375	8063.96484375	8063.96484375
b1c26					4970.21484375	4970.21484375	5063.96484375	5063.96484375	7782.71484375	7782.71484375	7876.46484375	7876.46484375
b1c27					4782.71484375	4782.71484375	4876.46484375	4876.46484375	7595.21484375	7595.21484375	7688.96484375	7688.96484375
b1c30					4970.21484375	4970.21484375	5063.96484375	5063.96484375				
b1c31					4782.71484375	4782.71484375	4876.46484375	4876.46484375				
b1c32					4595.21484375	4595.21484375	4688.96484375	4688.96484375				
b1c33					4407.71484375	4407.71484375	4501.46484375	4501.46484375				
b1c34					4220.21484375	4220.21484375	4313.96484375	4313.96484375				
b1c35					4032.71484375	4032.71484375	4126.46484375	4126.46484375				
b1c36					3845.21484375	3845.21484375	3938.96484375	3938.96484375				
b1c37					3657.71484375	3657.71484375	3751.46484375	3751.46484375				

Table 6. Parkes Telescope 10CM band frequency table. The “X” in the 10CM node name should be replaced by 0, 1, or 2 depending on which bank of nodes recorded that session. “AB” in the Multibeam node name refers to any given beam pair, where $\text{beam} = \text{int}(((A \times 8) + B - 1)/2)$; “AC” is the next highest node. For example, blc01 and blc02 are beam 0, blc03 and blc04 are beam 1, blc05 and blc06 are beam 2, blc07 and blc10 are beam 3, etc.

10CM			Multibeam		
(2.7–3.5 GHz)			(1.2–1.5 GHz)		
Node	.raw	OBSFREQ .fil fch1	Node	.raw	OBSFREQ .fil fch1
blcX0	2667.78515625	2574.03515625	blcAB	1438.5	1513.75
blcX1	2855.28515625	2761.53515625	blcAC	1284.5	1359.75
blcX2	3042.78515625	2949.03515625			
blcX3	3230.28515625	3136.53515625			
blcX4	3417.78515625	3324.03515625			
blcX5	3605.28515625	3511.53515625			

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