

Verification Tests for FRB Detections

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ABSTRACT

The one-off nature of most Fast Radio Bursts (FRBs) requires extra scrutiny in reporting an astrophysical FRB and triggering automated follow-ups with a telescope network. The ALFABURST commensal FRB survey at Arecibo Observatory has been in operation since June 2015. In that time a number of false-positive events, which on initial inspect appear to be FRB-like, have been found to be of local origin. Here we report on one such event as an example of the difficult challenge of fully automating an FRB search. We discuss observational and post-processing techniques which are useful to further automate an FRB search survey.

Key words: radio continuum: transients – methods: observational

1 INTRODUCTION

In the two years of the initial ALFABURST survey (Chennamangalam et al. 2017) over 125k 8-second windows have been recorded in which our Fast Radio Burst (FRB) search pipeline detected an event above the minimum Signal-to-Noise Ratio (SNR) detection threshold. The vast majority of these events have been due to Radio-frequency Interference (RFI), some of the events are due to bright single pulses of known pulsars. Sorting through these false positive events is the main focus of our post-processing methods. Most of the events are clearly RFI which are classified with an automated classifier model. A small number of windows contain FRB-like events which only on further inspection of the data, the telescope operation status, and contextual information is it clear that these events are from local sources.

We expect a number of false-positives to pass our post-processing detection tests, as we would like to severely limit the potential for type-II errors in our classifier by accepting a number of type-I errors. So far, all false-positives we have detected are explainable as relating to the telescope or RFI by examining the observing situation after the fact. This creates a challenge of automating the triggering of follow-up signalling to other telescopes. Either there will be an excess of false-positive triggers but with a short delay between detection and triggering. Or, a non-automated, expert examination of the event is required to verify, creating a delay in any follow-up.

In this letter, we report on FRB-like signals detected with our ALFABURST system, and discuss how we have improved our post-processing pipeline and observing system to handle unexpected, but explainable signals. These improvements are valuable to incorporate into any FRB search survey.

2 AN EXAMPLE OF A FRB-LIKE SIGNAL DETECTED WITH ALFABURST

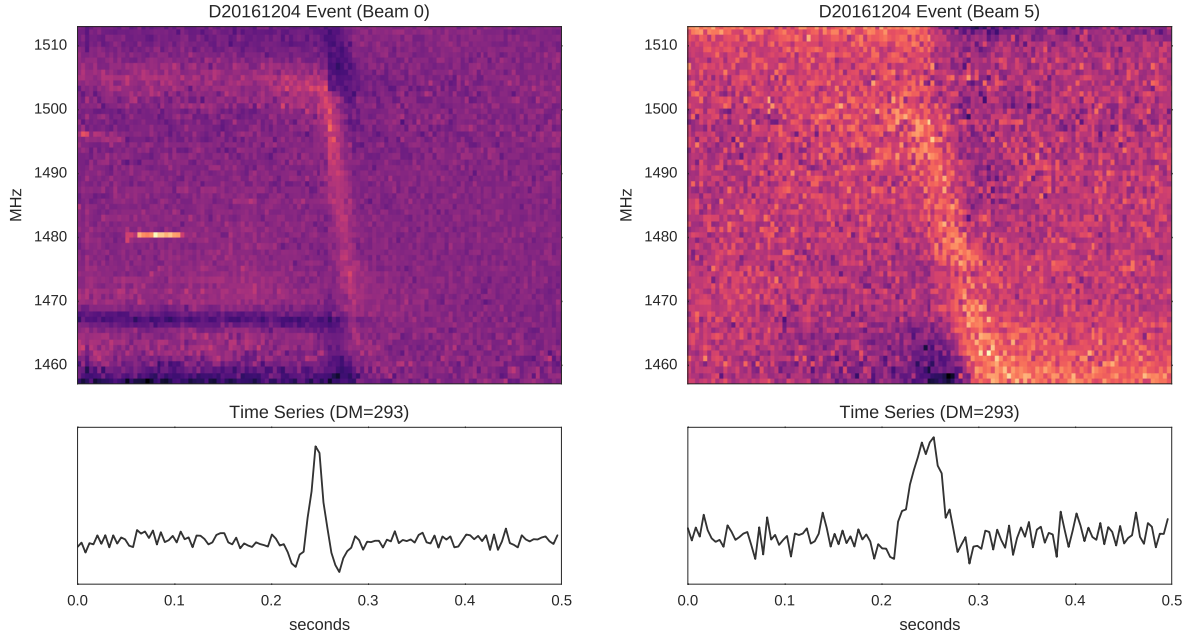
A narrow-in-time, broad-in-frequency, millisecond pulse was detected with the ALFABURST system at MJD 57726.563263913 / Unix time 1480858266 (09:31:06 Arecibo local time) in Beam 0 (the central beam) of the Arecibo L-Band Feed Array (ALFA) receiver¹ (Figure 1a). ALFABURST was processing 56 MHz of bandwidth between 1457 MHz and 1513 MHz. The SNR of this pulse is maximized (10.46) when the pulse is dedispersed with a Dispersion Measure (DM) of 293 and the 256 microsecond resolution is decimated by a factor of 16 to 4 ms time resolution. The dedispersed time series shows an approximately 20 ms Full-Width at Half-Maximum (FWHM) pulse. The dip before and after the pulse is due to the DM-zero removal (i.e. the moving average is subtracted) during pulse detection. This is a simple way to remove a drifting gain baseline at the cost of removing some of the overall pulse power, particularly at low DM. The bright, narrow-band signal at approximately $t = 0.1$ seconds is locally generated RFI which we will cover later in this section.

On initial inspection, this event looks like a promising new astrophysical FRB. The flux density of the event can be computed with the radiometer equation

$$S = \text{SEFD} \frac{\text{SNR}}{\sqrt{D \Delta\tau \Delta\nu}}$$

using a System Equivalent Flux Density (SEFD) of 3 Jy for the ALFA receiver. This results in a flux density of $S = 66$ mJy from Beam 0, which would be lower flux than any previously detected FRB (Petroff et al. 2016). This flux estimate is a lower limit, as we are assuming the source was at the

¹ <http://www.naic.edu/alfa/>



(a) Detected FRB-like event in beam 0 of ALFA. The characteristic dip before and after the event is due to zero-DM removal which is part of the ALFABURST RFI exciser. The strong, narrowband source at 1480 MHz around 0.1 s is due to a local RFI source.

(b) Detected FRB-like event in beam 5 of ALFA. The event width appears wider than the beam 0 event as the zero-DM dips are not as prominent.

Figure 1. Dynamic spectrum (top) and dedispersed time series (bottom) of an FRB-like event that was detected simultaneously in beam 0 and 5 of the ALFA receiver on December 4, 2016. The dynamic spectrum has been bandpass normalized.

centre of the beam. The width is on the high end for FRBs but still within the range of those previously reported.

We inspected all other events in the same time window as the Beam 0 event. An event was found in Beam 5 only (Figure 1b). This pulse lines up exactly in time with the Beam 0 event but the FRB was maximized (15.99) with a DM=829 dedispersion. Upon further inspection and testing different DMs for dedispersion we found that this event appeared to narrow in width at lower DM trials. We see that there was RFI clipping in this event which is known to introduce a bias, resulting in a maximized SNR at a different DM trial. The beam 0 and beam 5 event are the same event.

The beam 5 detection has a lower SNR than the beam 0 detection at DM trial 293. This is still reasonable as the beam 0 side-lobes overlap with all the other beams, as does the beam 5 side-lobe overlap with the beam 0 primary beam. This would indicate that the sky source is somewhere between the beam 0 and beam 5 pointing centres. And, the detection was from the edge of the primary lobe or in the side-lobe of each beam.

The width of the dedispersed pulse in beam 5 appears wider, but this is likely due to the lower SNR of the event having a smaller effect on the spectrum normalization.

One can look at the immediate period before and after the pulse to see that there are no similar events (Figure 2). The event appears to be isolated in time, with a fairly compact representation in DM-space. The event would be detected with significant SNR at higher DM trials due to the wide width of the pulse, but peaks at a DM trial of 293.

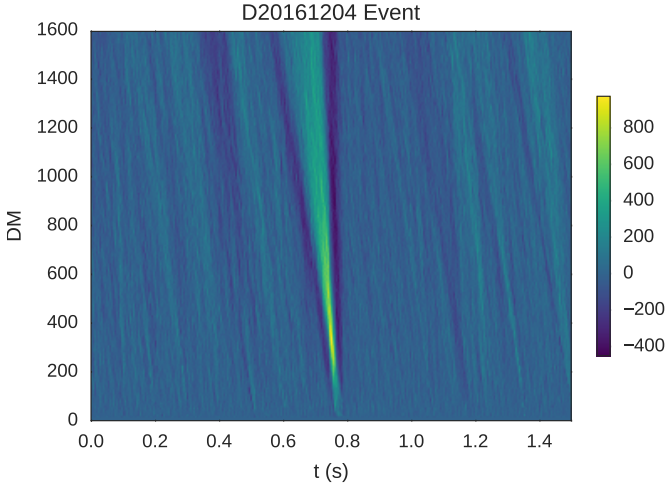
The Arecibo telescope logging data is reported locally

in SCRAM packets which provide pointing, frequency tuning, and receiver information at approximately one second resolution. From these logs, the telescope was pointed at a fixed Dec (+15:11:28.34) and drifting in RA (event detected at RA=14:42:26.18), i.e. a fixed (alt,az) pointing during the event. No known pulsar or RRAT is within the beam at this pointing.

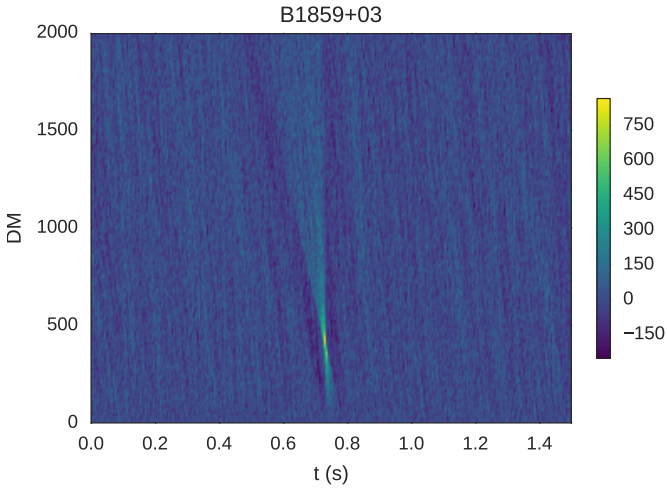
We considered that the observing band could have been changed in that time. We have setup the automated system to restart observations when the Intermediate Frequency (IF) frequency is changed. During the time of the event, there was no change in the IF during that time.

The SCRAM logs do provide the first indication that this event is due to a local source. Beyond the pointing and IF, the SCRAM logs report the position of the receiver turret and if ALFA is active. ALFA is at a position angle of approximately 26.64° in the turret, the system reported the turret was at 206° . ALFA is not in, or even near the focus. Our commensal observation script checks if ALFA is active before we run ALFABURST. This is a check on whether the analogue receiver chain is properly setup for ALFA, which almost always means that ALFA is in the focus. But, as we have found out, there are times when this is not true.

The SCRAM logs do not report the active project or observing schedule. During the time of the event it appears that no receiver was in use, otherwise, ALFA would not have been active, and we see that ALFA was deactivated approximately 20 minutes after the event when a new observation began. Looking at the observation schedule for the morning



(a) DM vs. time plot of for a 1.5 second window centred on the December 4th event in beam 0. The SNR peaks at a DM of 293. There is a significant detection at larger DM trials due to the width of the pulse.



(b) DM vs. time plot of a bright single pulse from B1859+03 which has a DM of 402 and pulse width of 11 ms (W50).

Figure 2. DM-space plot shows the characteristic butterfly pattern of the narrow-in-time, dispersed pulse detected by ALFABURST. A single pulse detection of B1859+03 is shown for reference.

of December 4, project P3080² was using ALFA to perform an FRB survey of the Virgo cluster until 09:00 local time. After 09:00 local time Project R3037³ was scheduled, this is an S-Band RADAR observation.

Looking at the average bandpass of beam 0 and 5 during the time of the event, we see that the shape and system noise appear different to what is expected during typical observations (Figure 3). The detection band of ALFA was chosen because it is the most sensitive region of the band, and relatively flat. But during the event, there is a noticeable shape and slant to the bandpass which is different than the typical bandpass. Beam 0 and 5 bandpasses look related

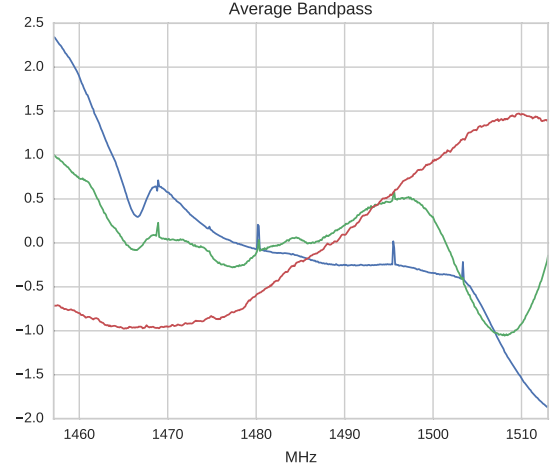


Figure 3. Average bandpass response during the December 4, 2016 event for beam 0 (green) and beam 5 (blue). A typical bandpass (red) is plotted for reference. These bandpasses have been normalized in the detection pipeline.

in elements of their bandpass shape, and the narrow-band features due to the short, bright RFI events that occur during the recorded time window. The system noise appears to be higher during the event, which leads to the bandpasses appearing smoother than the typical bandpass. In the detection pipeline the data is normalized, so all absolute scaling is removed in the process. This indicates that the SEFD is too low in our flux calibration. This increase is system noise is due to the change in turret position, and the ALFA feed picking up reflections from other equipment in the dome, and the dome as a warm source.

We then looked at previously recorded events close in time to the event. Approximately 80 seconds earlier another window was recorded which has large structures across the band (Figure 4a). Though not as narrow in time as the event, they appear related to the same phenomenon.

The DM - time plot (Figure 4b) shows that much of the structure would be detected as dispersed pulses. In particular, the structure around 4 seconds would be detected as a wide-in-time, highly dispersed pulse. And the structure immediately preceding it would be detected as a negative dispersed pulse. We do not detect these as pulses because we have limited our search space to narrow-in-time width pulses and positive DMs. Our choice of search space is reasonable for the type of events we wish to detect given limited computing resources. But, there are practical advantages to searching negative DMs and wider-in-time pulse widths. We expect astrophysical pulses to have positive DMs. But, system variation and RFI can produce signals which result in positive and negative DM detections. A statistical measure can be made in any time window to differentiate times of significant, but low-level RFI or system variation from actual astrophysical pulses. Testing out to larger pulse widths is computationally cheap as the time window is decimated, reducing the memory usage. A full sampling of larger pulse

² <http://www.naic.edu/vscience/schedule/tpfiles/MichillitagP3080tp.pdf>

³ <http://www.naic.edu/vscience/schedule/tpfiles/TaylorTagR3037tp.pdf> not necessary. Only a subset can be computed to provide a

useful information on the stability of the system and RFI environment.

The narrow-in-frequency, periodic RFI at 1468, 1480, 1496, 1504 MHz is not usually seen in this band. In the high time and frequency resolution view these short pulses in 12.5 MHz steps have a characteristic dampened harmonic oscillation due to frequency locking with a Phased-locked Loop (PLL) (Figure 5). With help from the Arecibo Observatory staff, this has been identified as an instrumental RFI from an instrument that is routinely used to monitor the local RFI environment. The exact physical process which generated these apparently dispersed pulses is not perfectly well known. But, the picture is that the ALFA receiver was out of the main focus, likely picking up reflections from the dome, leading to an increase in the system temperature. An RFI monitoring program was being run on an instrument not included in the telescope SCRAM data. This instrument introduced the narrowband RFI due to changing of a Local Oscillator (LO), and possibly the broadband RFI. With high certainty, we can classify this as a local event which created the appearance of an FRB. In isolation, and the one-off, transient nature of FRBs make the initial Beam 0 detection look very reasonable. It is only with an extended study of the meta-data, earlier-in-time evolution of the band, and use of multiple beams to confirm that this is indeed not an FRB of astronomical origin.

3 LOW-SNR FALSE-POSITIVE DETECTIONS

4 DETECTED RADAR EVENT WITH ARTEMIS

ARTEMIS (Karastergiou et al. 2015) is a similar to ALFABURST FRB search survey run at the LOFAR-UK station at Chilbolton Observatory. The ARTEMIS survey uses a similar fractional bandwidth (~ 0.04) to the ALFABURST survey, but centred around 145 MHz. This survey is setup to have known pulsars regularly transit the fixed in local coordinate beams. Single pulses are routinely detected. Occasionally, RFI events are detected by the automated pipeline. A particularly interesting event was detected which had a maximized SNR with a DM of 85 is shown in Figure 6. The narrow-in-time pulse can be seen in the dynamic spectrum at frequencies above 146 MHz, but is not apparent at lower frequencies. As there is significant narrow band RFI below 146 MHz it could be that the pulse is buried. The dedispersed time series shows a strong detection of a pulse of approximately 20 ms in width. The celestial pointing of the beam during the time of the event is not associated with any known pulsar or RRAT at a DM around 85. This is DM is low compared to reported FRB detections.

Plotting the event in a DM-space across the ARTEMIS DM range (0-320) (Figure 7) shows a strong, compact detection which we would expect to see of a dispersed pulse during a time of minimal RFI. Since the pulse is only apparent in part of the band we became suspicious of its origin. It could be that the pulse is broadband but the brightest component is only seen in the 146-147 MHz region. Or, it could be a band-limited pulse. The search pipeline, like ALFABURST and many other search pipelines, decimates the dynamic spectrum in time to search for over a range of pulse

widths. In the case of the event shown in Figure 6 the maximized SNR occurred with a time decimation factor of 20, the native resolution is $327.68\mu\text{s}$, resulting in a decimated time resolution of 20 ms. By plotting the event at a higher time resolutions (Figure 8) we can see there is a distinct repeating pattern in time not previously apparent. This is a linearly frequency modulated signal used for pulse compression in RADAR. In RADAR observations the bandwidth of the transmitter provides information on the range and direction of a target. A narrow band RADAR transmitter can be used to approximate a larger bandwidth by modulating the frequency of the transmitted pulse. There are a number of allocated usages in this band which could be the source of this RADAR pulse (Ofcom 2017). As the RADAR signal is a dispersed pulse we would expect to detect such signals with ARTEMIS. Verification of this event was straight forward by examining the high-time and frequency resolution data to see the pulsed nature of the event. The frequency allocation and the use of standard RADAR techniques across the radio band is a clear indicator of the origin of this event. The challenge comes in the verification and automated signalling if the desire is to run the system in real-time with immediate follow-up with additional telescopes. The RADAR event occurs rarely and there is no obvious detection filter automate. Expert knowledge in radio signals and visual acuity are necessary to make a decision about the event. If we are willing to allow an automated VOevent trigger where we expect a number of false-positives then we can except the rare RFI trigger.

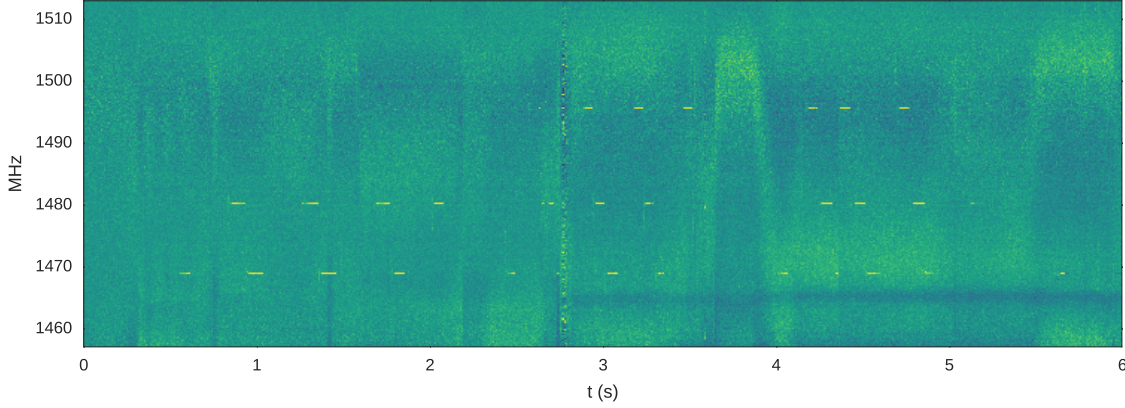
5 VERIFICATION CHECKS

The one-off nature of FRBs makes it essential that when reporting on a detection or triggering a follow-up observation that significant due-diligence is done in order to verify a positive detection as much as possible. Over the past decade of FRB surveys a number of techniques have been developed to efficiently filter for dispersed pulses. The vast majority of events are flagged by RFI excisers and setting a sufficiently high minimum SNR threshold.

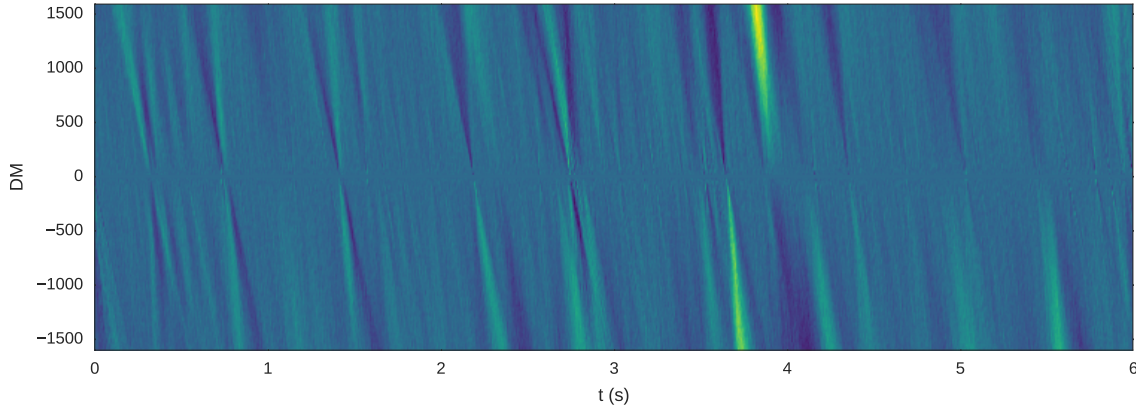
Current surveys typically search out to extreme DMs, in the case of ALFABURST we search out to a DM of 10000 as the additional computational cost is minimum. If the DM-redshift relation is approximately correct, searching to such high DMs is sufficient to sample out to the very early universe. We expect an astrophysical source to be dispersed by a positive DM value. As such we do not search for negatively dispersed pulses. But, RFI does show up as both positive and negative desipersion detections (Figure 4). As the dedispersion search is no longer computationally limited it would be possible to search the negative DM space. This would be useful as a statistical statement about the number of positive versus negative detections to quantify the amount of RFI during a detection. The full negative DM space would not need to be searched, a regular sampling of the space would be sufficient.

Jupyter notebooks and the filterbanks files are hosted on our public git repository⁴.

⁴ <https://github.com/griffinfoster/ab-survey-2017>



(a) Dynamic spectrum shows frequency evolution of the bandpass as a function of time with structures similar to the D20161204 event.



(b) DM trials from -1600 to 1600 show that there would be both positive and negative pulse detections during this time window.

Figure 4. Dynamic spectrum (top) and DM-time plot (bottom) of 6 seconds from beam 0 approximately 80 seconds before the D20161204 event.

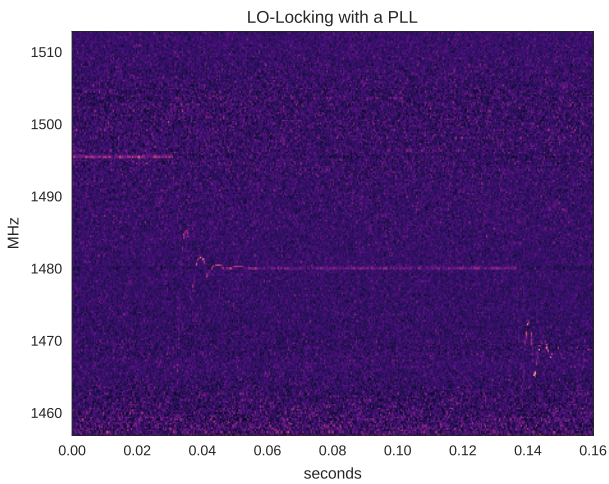


Figure 5. Dynamic spectrum when a local oscillator in the receiver dome is being locked with a phase-locked loop circuit. This LO is not related to the receiver analogue mixing chain, but rather it is associated with RFI monitoring equipment.

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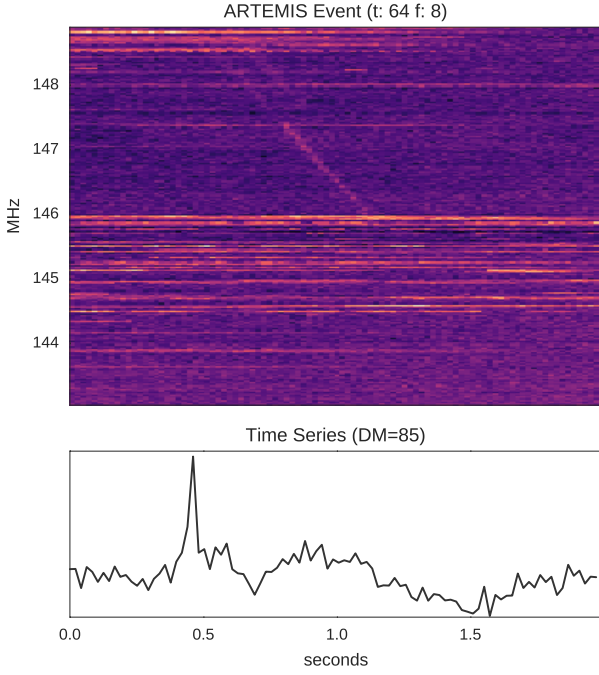


Figure 6. A dispersed pulse detected by the automated ARTEMIS search pipeline. The dispersed pulse only appears over a narrow band of just over 1 MHz.

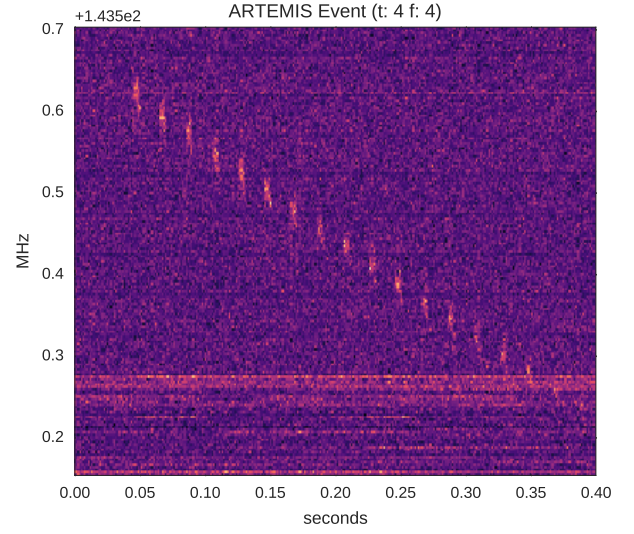


Figure 8. A zoomed in view of the event in Figure 6 at high time and frequency resolution shows the distinct pattern of a linearly frequency modulated RADAR pulse.

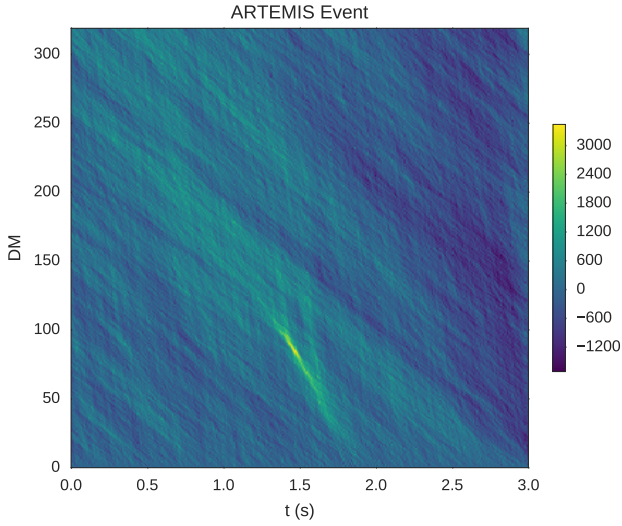


Figure 7. DM-space plot of the event shows a strong, compact detection around DM=85 with no other apparent events during at the time.