A Triggered Search for Fast Radio Bursts using LWA

LWA Users Meeting 2023

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Collaborators

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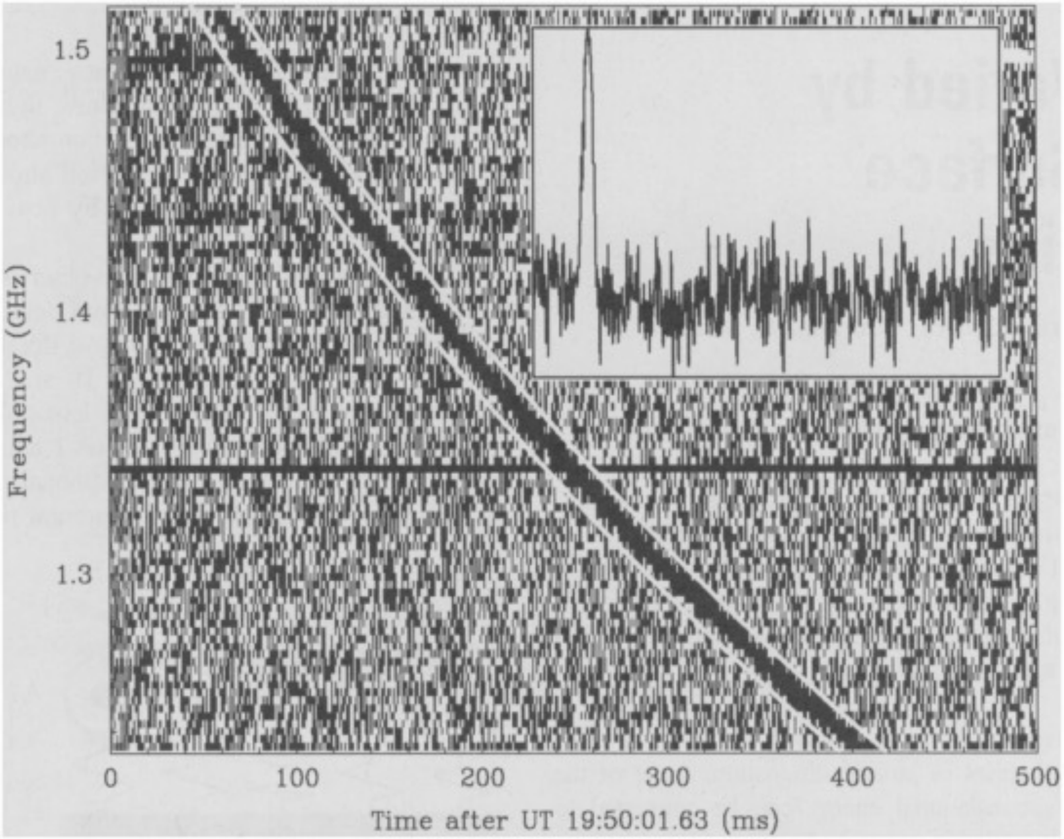
- Jim Furches

Fast Radio Bursts



30 Jy, 1.4 GHz

Single dispersed pulse

Pulse width $W = 5$ ms

$\Delta t(s) \propto \frac{\mathrm{DM}}{\nu^2}$

DM $= \int n_e \, dl =$ 375 pc cm^{-3}

$W \propto \nu^{-4.8 \pm 0.4}$ (Kolmogorov)

Lorimer Burst

FRB 010724 (24 July 2001)

Parkes Observatory, archival pulsar survey data

Lorimer et al., Science 318, 5851 (2007)

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FRBs To Date

Many hundreds have been discovered

Most appear to be extragalactic (DM > 100 cm^{-3} pc, isotropic sky distribution)

Unresolved point sources

Most detected at ~1 GHz, some at ~400 to 800 MHz

Most are non-repeating, “one-shot” sources

Some tens of FRBs appear to be non-periodic repeaters (are all FRBs, repeaters?)

Some exhibit periodicity

- FRB 180916 (~16 day periodicity)
- FRB 121102 (~157 day periodicity)

Explanations include:

- Compact-object mergers (but not for repeaters, two populations?)
- Hyperflares of magnetars from normal core collapse supernovae
- (One is identified with the magnetar SGR 1935+2154 in our Galaxy)
- Host of exotic ideas: cosmic strings, BH explosions, ETs,…

CHIME

Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst Collaboration (CHIME/FRB)
Nature 582, 351 (2020)

The major FRB "factory."

535 FRBs in its first year of operation, starting in 2018.

CHIME longitude ~ 120° W
LWA longitude ~ 107° W

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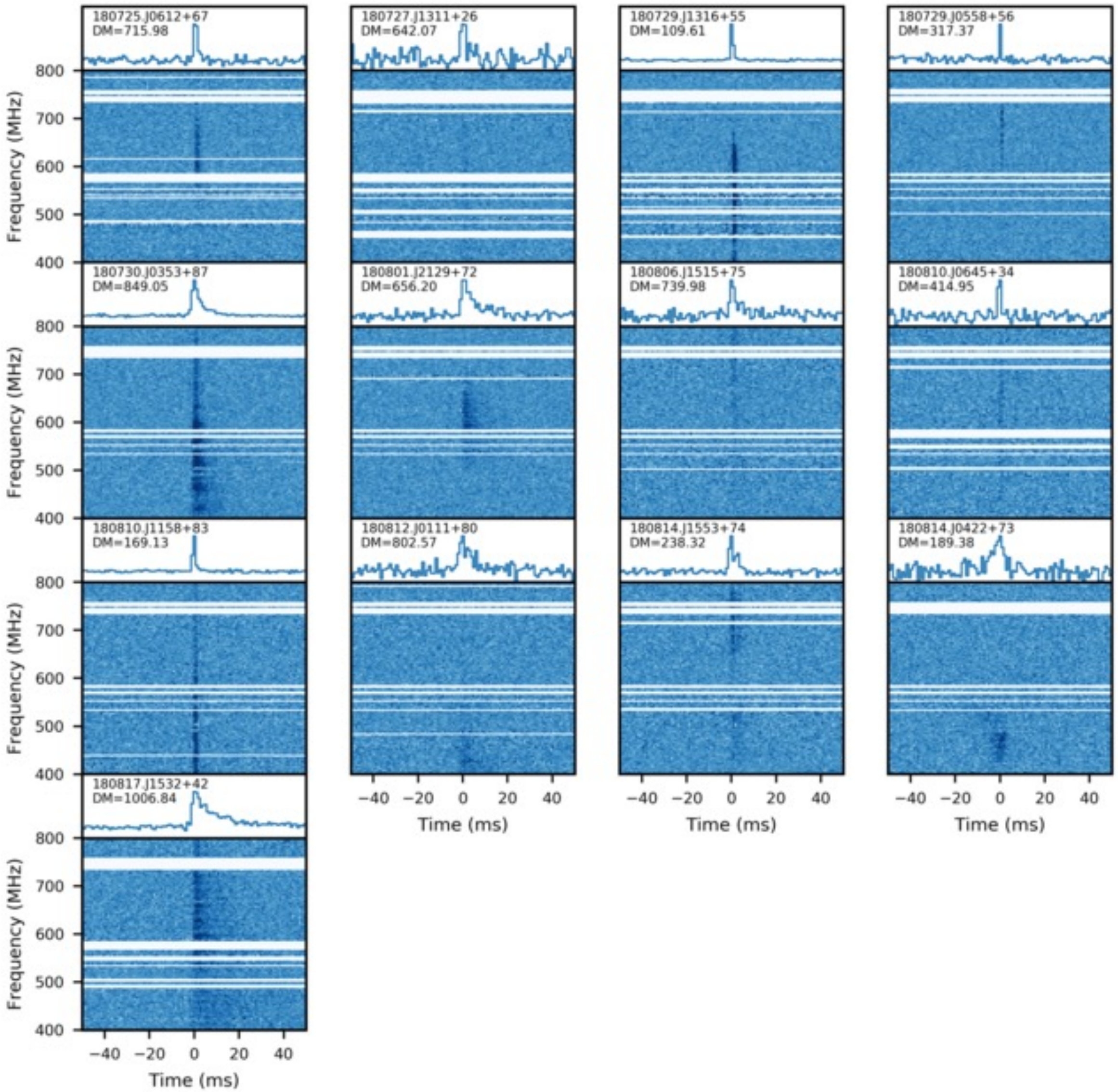
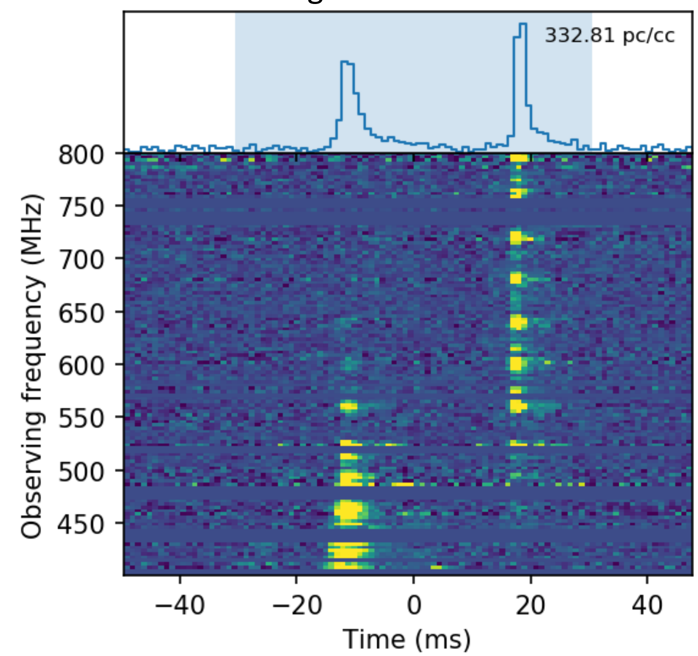
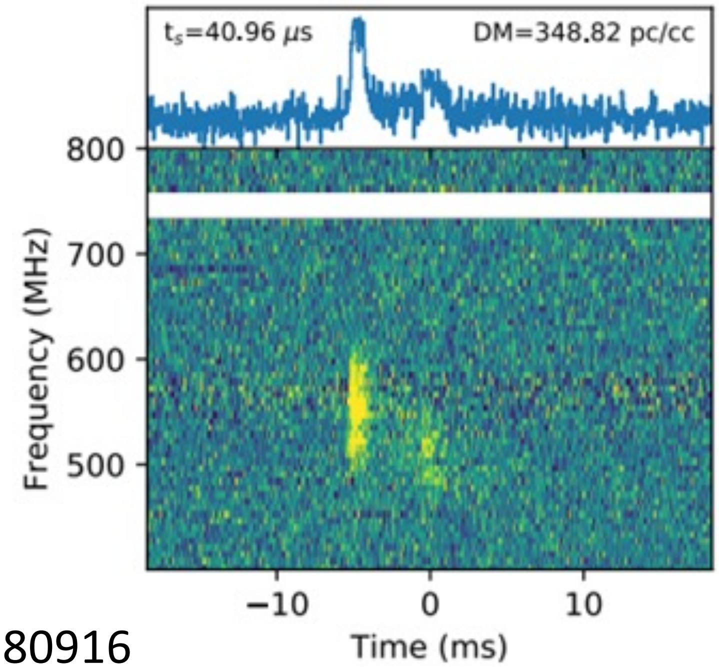


Galactic magnetar SGR 1935+2154





FRB 180916

FRB 180916.J0158+65 (16-day repeater)

In a nearby spiral galaxy ($z = 0.034$)

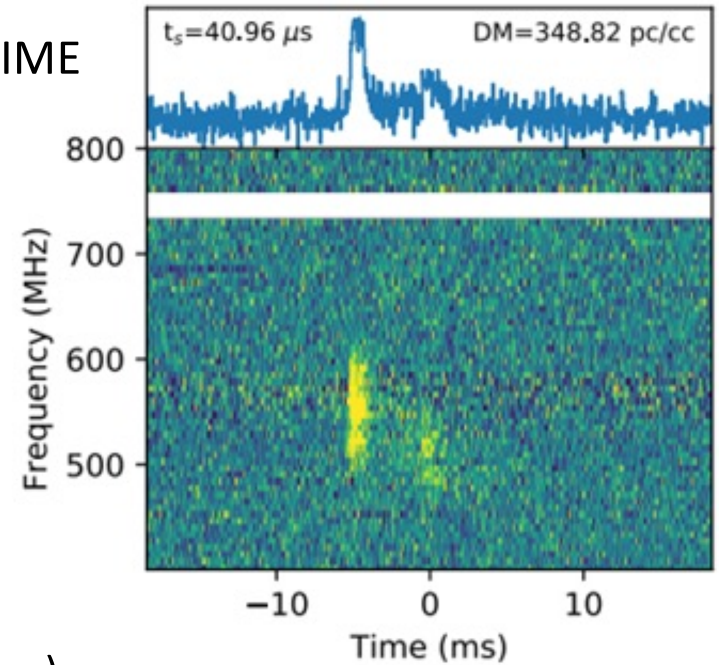
16.35 ± 0.18 day period (binary orbit?)

4-day phase window

DM ≈ 349 pc cm^{-3}

$S_\nu \sim$ a few Jy, pulse $W \sim$ a few ms

CHIME



Detected by others

- 100-m Effelsburg (1.4 GHz)
- Sardinia Radio Telescope (328 MHz)
  - $S_\nu \sim$ a few Jy, $W \sim$ 10 ms (consistent with scattering)
- LOFAR (110-188 MHz)
  - $W \sim$ 40-160 ms at 150 MHz (consistent with scattering)
  - Some delay in time from higher frequencies to 150 MHz (~ days)

For Kolmogorov interstellar scattering

$$W \sim \left(\frac{500\ \mathrm{MHz}}{80\ \mathrm{MHz}}\right)^{4.4} 2\ \mathrm{ms} \sim 6\ \mathrm{s}$$

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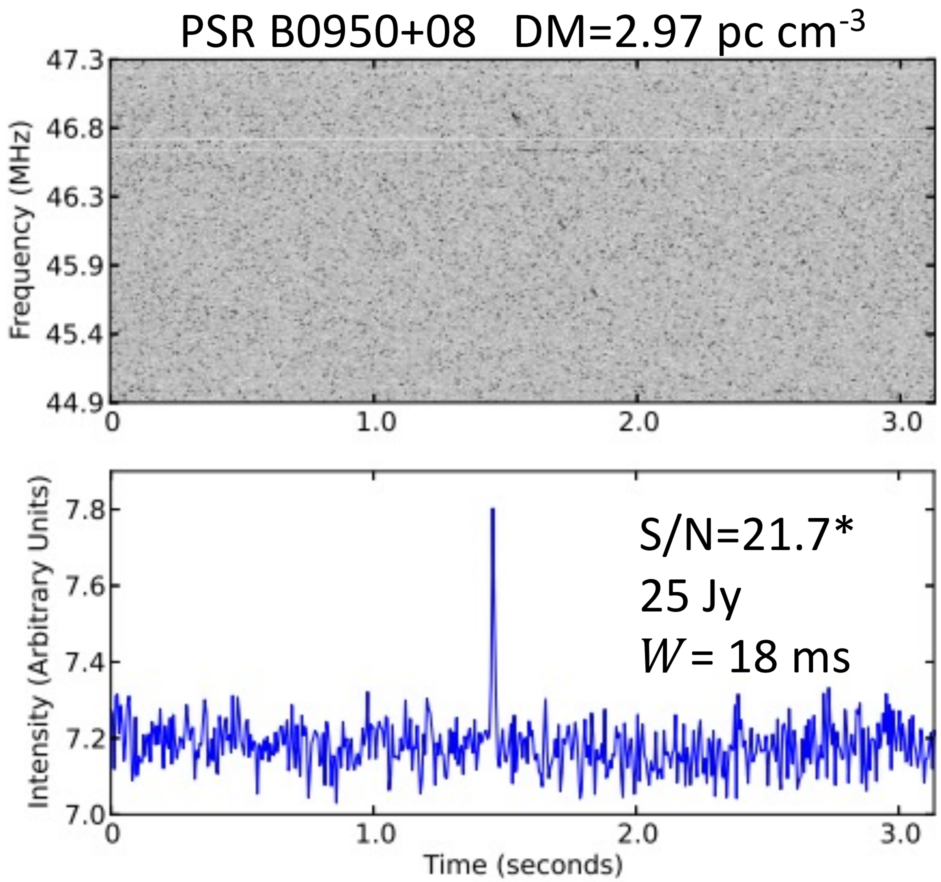
Transient Pulse Detection



*For the full bandwidth. For this 2.4 MHz chunk, S/N =8.8

The flux density of a pulse:

SEFD (System Equivalent Flux Density) = the flux density a source needs to produce a SNR = 1, for $B = 1$ Hz, $\Delta t = 1$ second.

Ellingson determined a SEFD for LWA-1 of ~15,000 Jy, taking account of galactic emission (dominate) and other noise sources, and comparing with drift scans of some sources. Uncertainty ~50%, and similar at lower and higher frequencies.

For an isolated pulse of a measured SNR in a time series:

$$S_\nu \sim 2\ \mathrm{Jy}\left(\frac{SNR}{10}\right) B_{20\mathrm{MHz}}^{-\frac{1}{2}}\ \Delta t_{\mathrm{seconds}}^{-\frac{1}{2}}$$

Triggered Observations: CHIME Real-Time Alerts

Virtual Observatory Event (VOEvent) – a standard for reporting astrophysical transients

CHIME began public VOEvent service in October 2021

- The real-time localization is reported as an on-sky circle in celestial coordinates. The precision and accuracy sensitive to whether the FRB was detected in one beam or multiple beams.
- Error radius varies $\sim$0.5° (single beam) to 2° (multibeam)
- VOEvent includes estimated dispersion measure (DM) and SNR
- Not every alert will represent a true FRB

LWA subscribed for potential follow-up, using BERT / HAL / SAL

- Triggers simultaneous observations (1 beam) at LWA-1 and LWA-SV
- Duration of observation proportional to reported DM
- DM = 300 pc cm^{-3} is equivalent to a 5.8 minute delay at 60 MHz

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Data Processing Pipeline

DRX and session metadata provided in LWA archive.

We rely on LSL and DRX/HDF commissioning tools:

- **hdfWaterfall.py** – FFT to produce spectrogram from DRX data
- **calculateSK.py** – pseudo-Spectral Kurtosis for RFI masking
- **dedisperseHDF.py** – incoherent de-dispersion based on reported DM

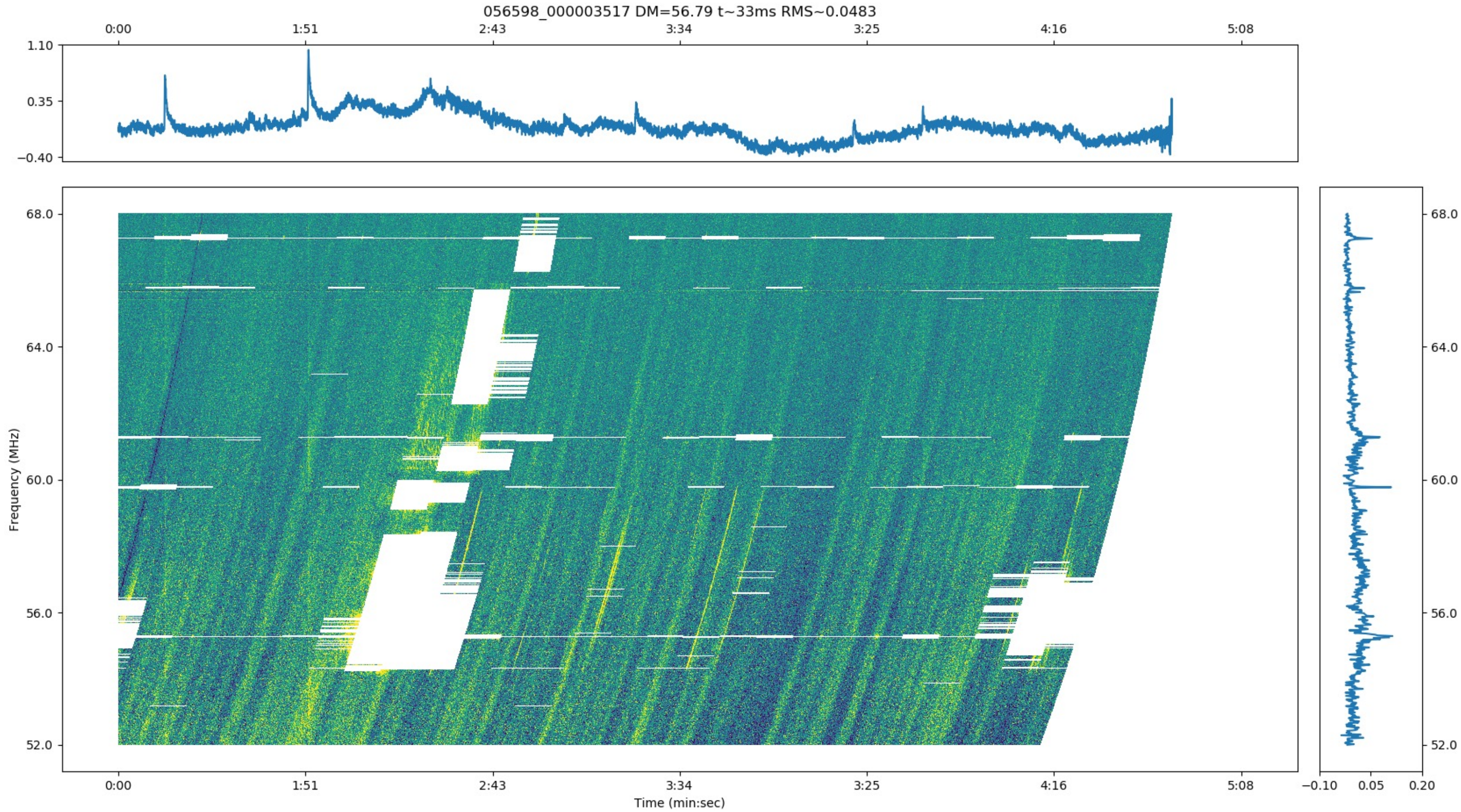
We composed scripts to:

- Orchestrate the above, including…
- Remove the spectral bandpass
- Normalize arbitrary intensities by the standard deviation across the spectrogram
- Average and decimate along the time axis for different time sampling
- Produce time series by averaging along the frequency axis
- Produce final display of spectrogram and time series
  - Note: The *displayed* spectrogram is clipped to $\pm 3\sigma$ to enhance color contrast

The following slides illustrate
the results of our analysis procedure
using Crab giant pulse data.

Crab Pulsar Giant Pulses*

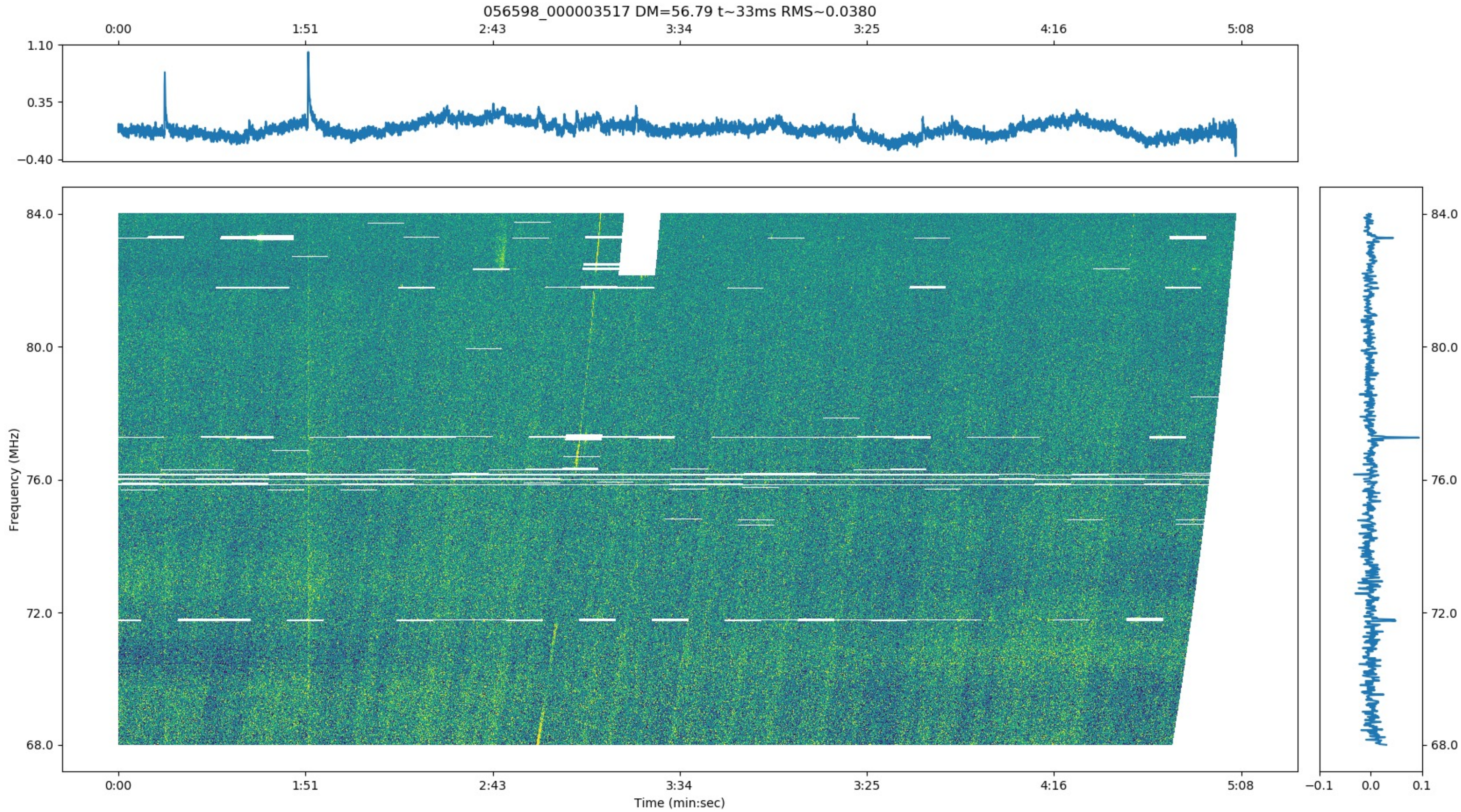
60 MHz, $B = 16$ MHz, $\Delta t = 33$ ms



*Raw data from LWA LSL tutorial (Dowell).
Same processing/display procedure we used for our data.

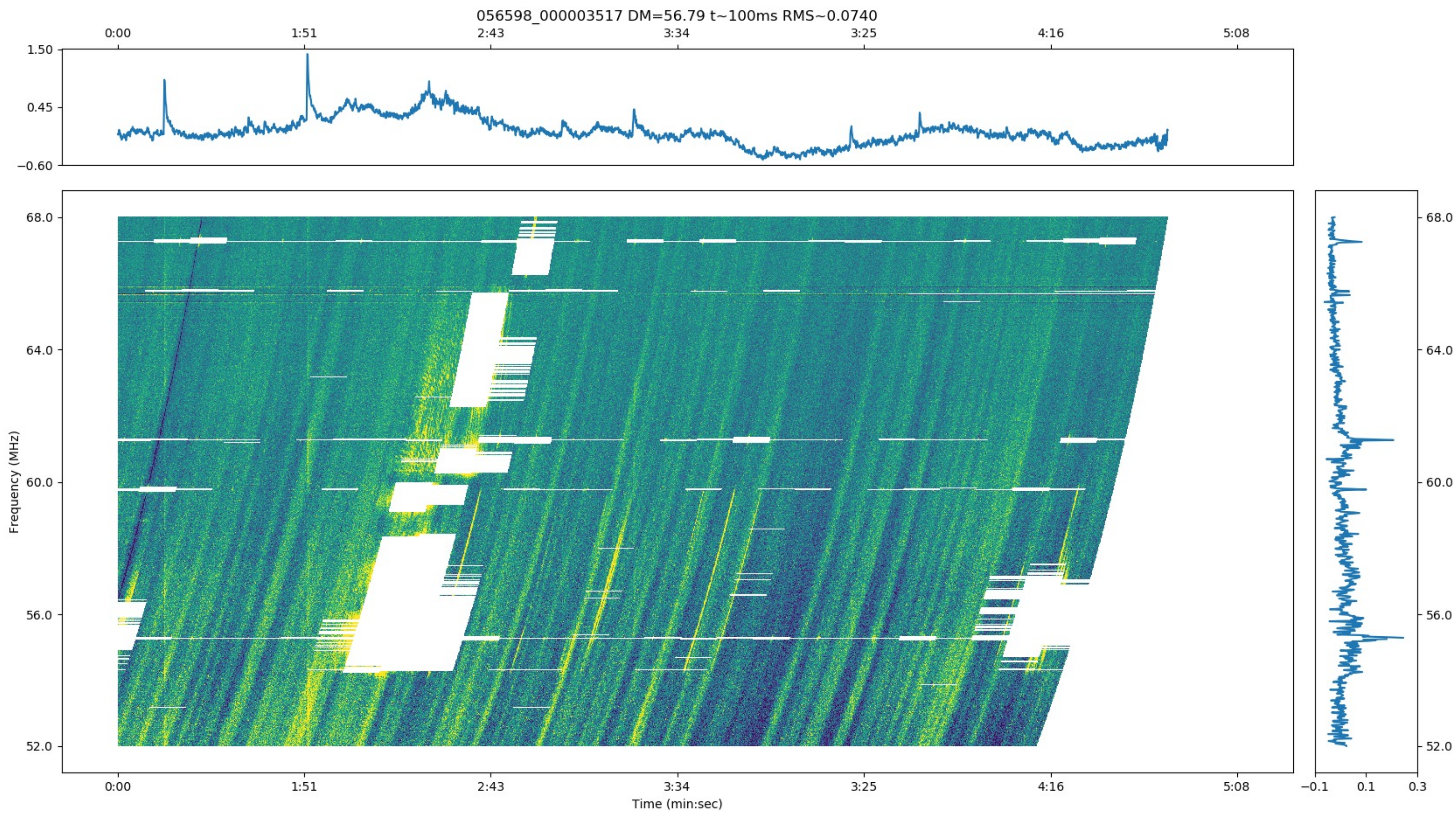
Crab Pulsar Giant Pulses

76 MHz, $B = 16$ MHz, $\Delta t = 33$ ms



Crab Pulsar Giant Pulses

60 MHz, $B = 16$ MHz, $\Delta t = 100$ ms



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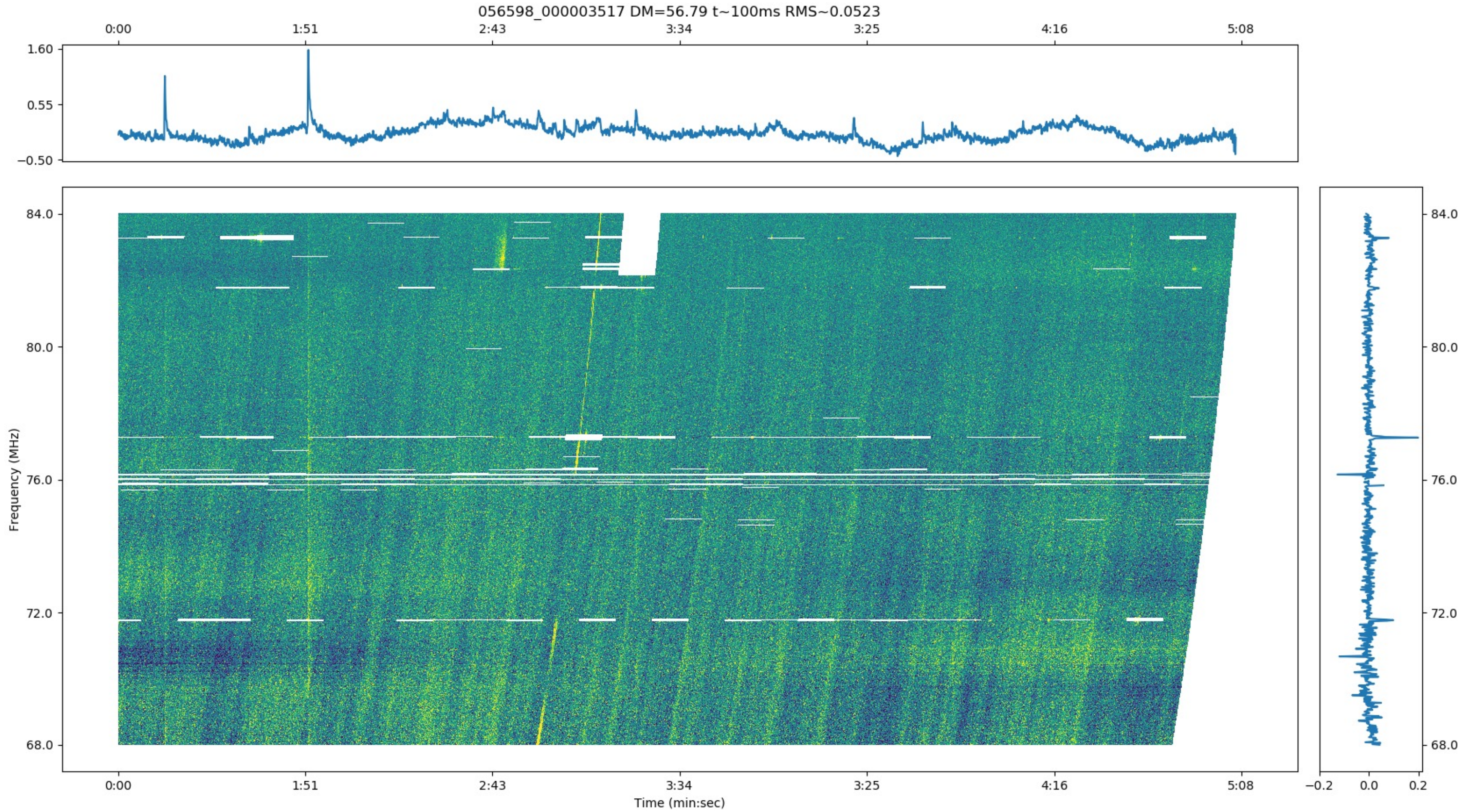
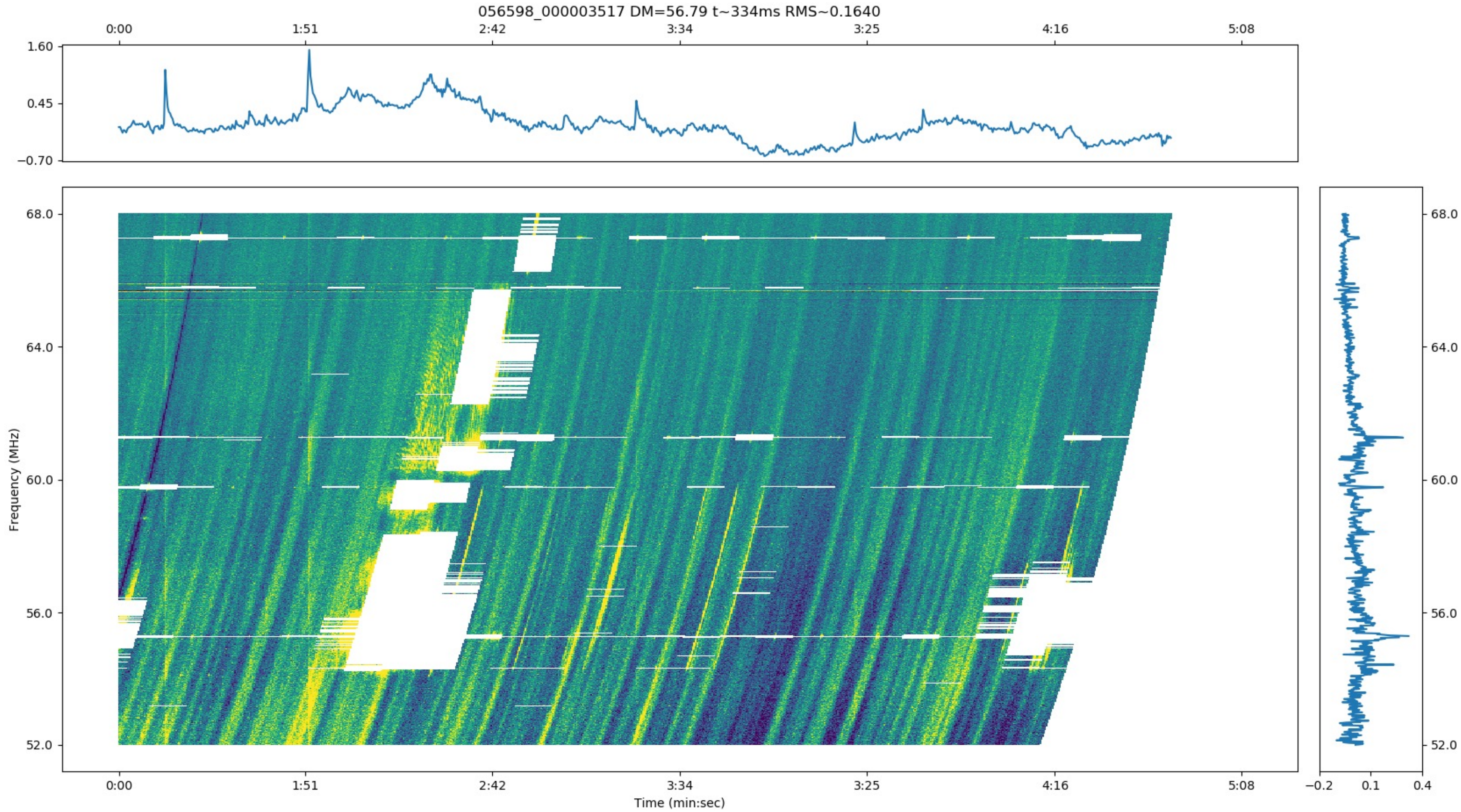


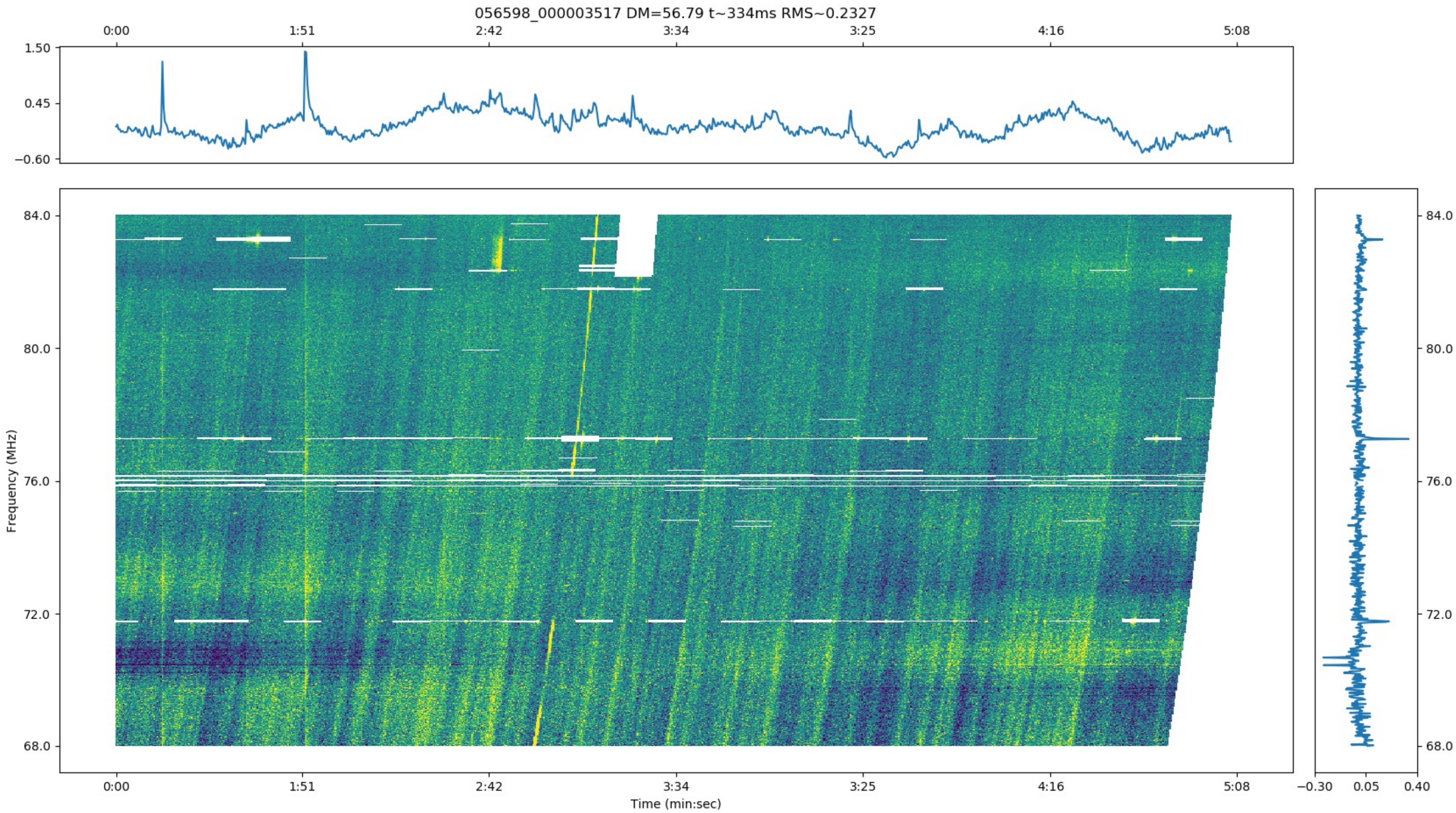
Crab Pulsar Giant Pulses

60 MHz, $B = 16$ MHz, $\Delta t = 334$ ms



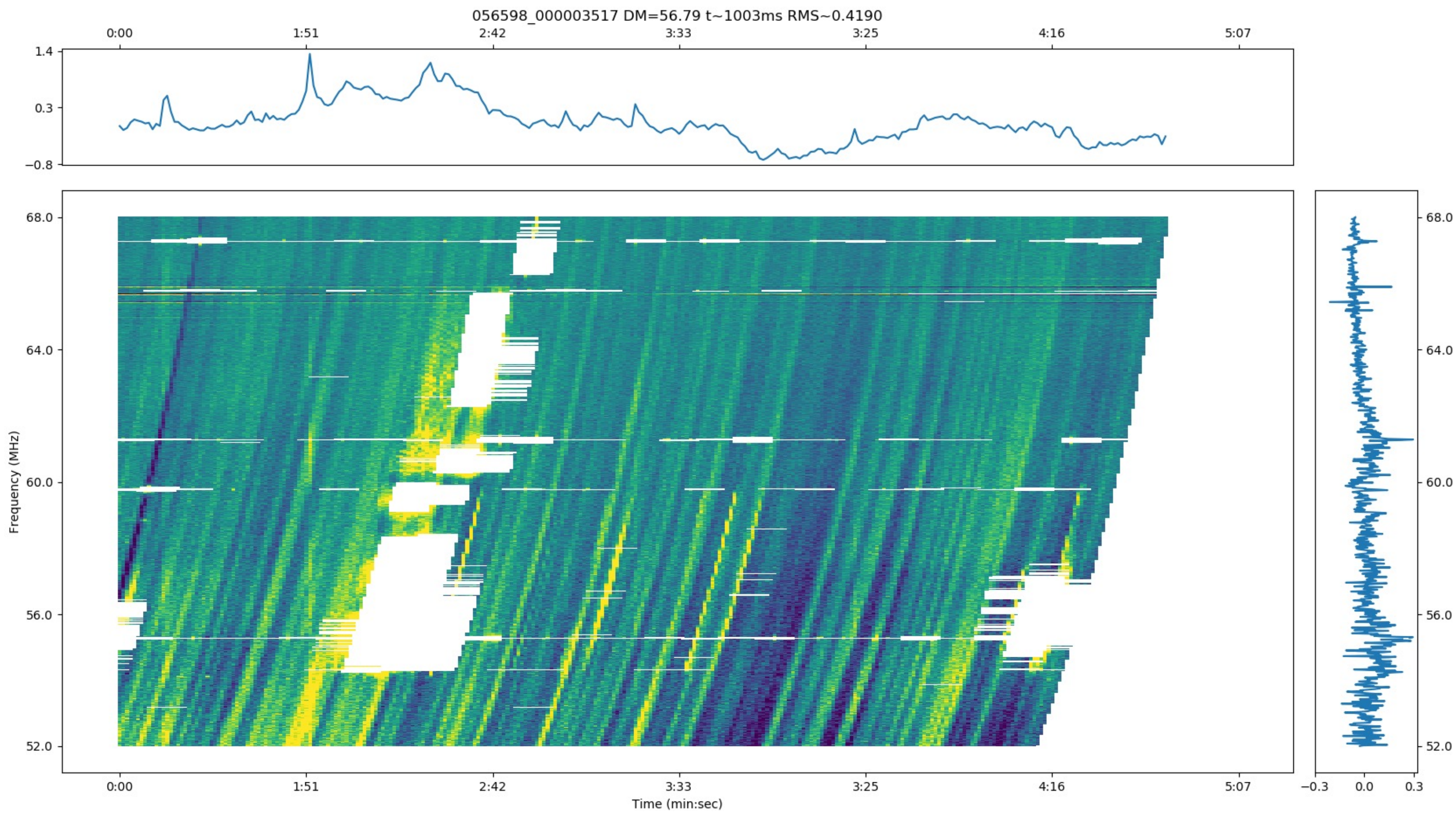
Crab Pulsar Giant Pulses

76 MHz, $B = 16$ MHz, $\Delta t = 334$ ms



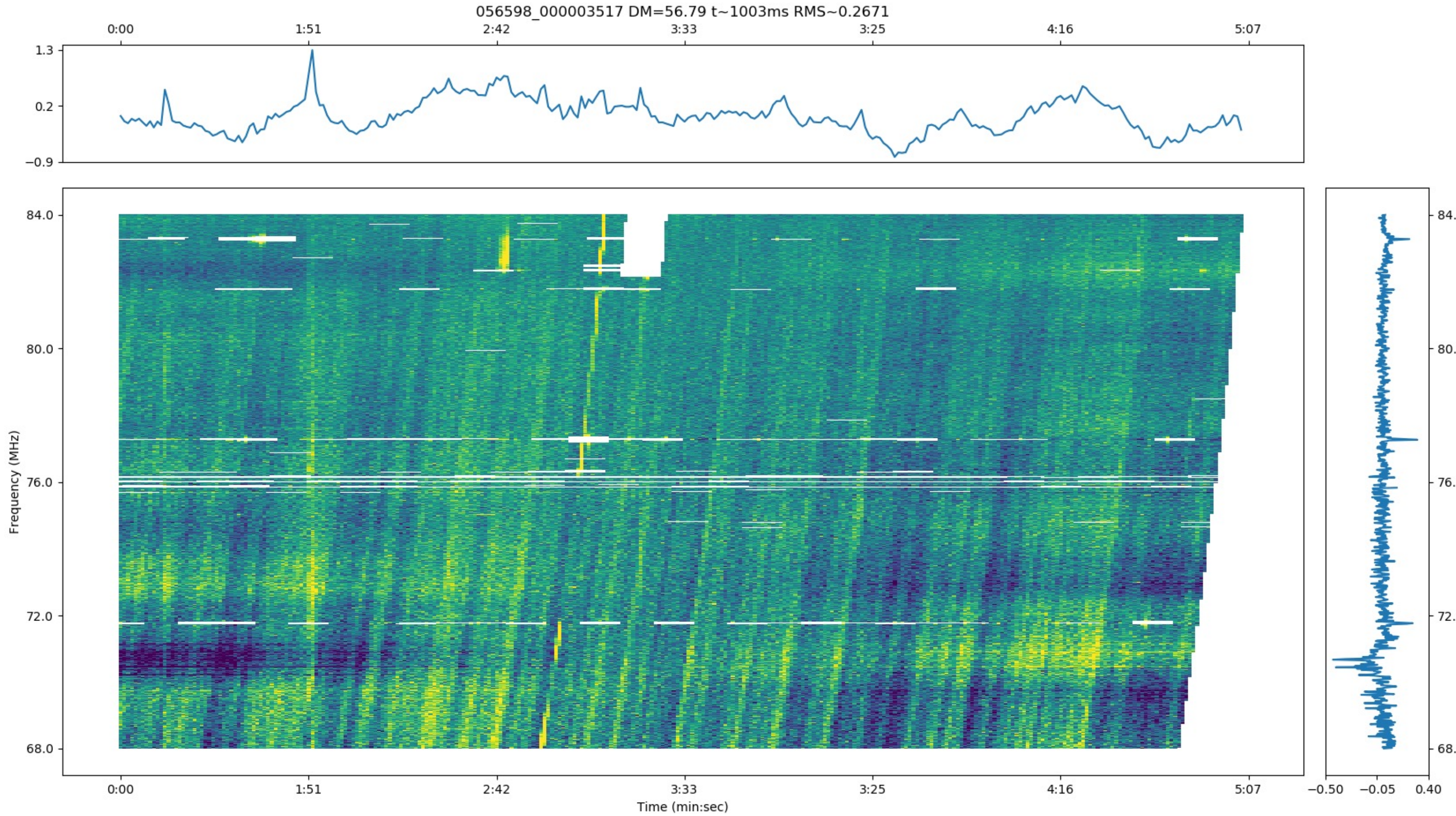
Crab Pulsar Giant Pulses

60 MHz, $B = 16$ MHz, $\Delta t = 1$ s



Crab Pulsar Giant Pulses

76 MHz, $B = 16$ MHz, $\Delta t = 1$ s



Our Observing Program Summary

We have CHIME FRB-triggered observations.*

- First processed observation: 2022 Nov 8
- Processed to date: 2023 May 14

- 78 triggers were successfully followed-up
- DM range 56—398 pc cm^{-3}

- Most observations used both LWA-1 and LWA-SV simultaneously
- Observation durations ~ 2—15 minutes
- Observing started at reception of alert

- About 9.5 hours of follow-up using LWA-1 (9:30:29)
- About 9 hours of follow-up with LWA-SV (8:59:24)

- One source may have produced a few triggers on a few different dates
  (RA ~ 11.8^h Dec ~ 66°, DM ~ 57. In our Galaxy?)

*These data are available under Project Code DD002 (DD = "Director Discretionary")

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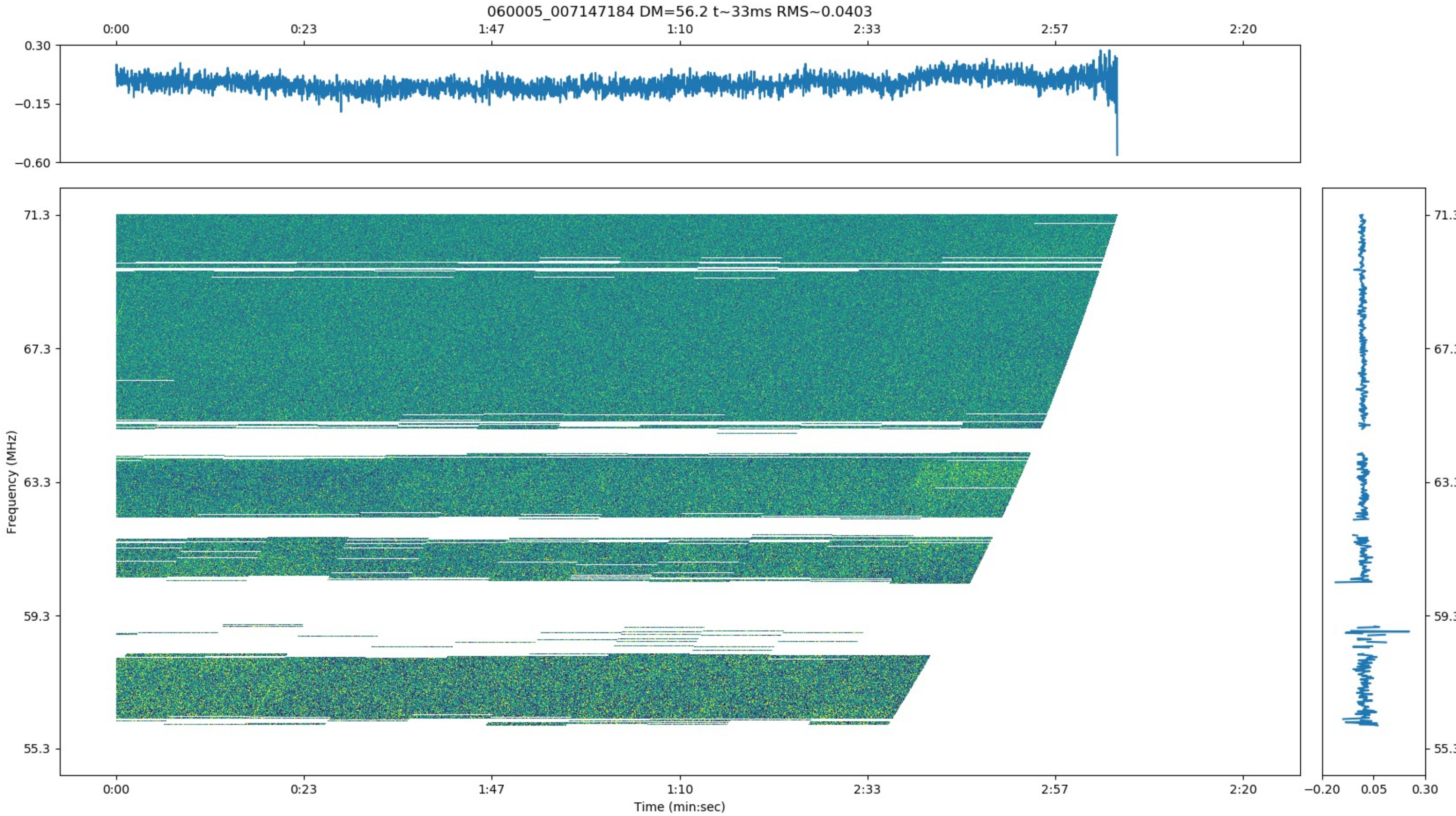
The following slides are illustrative of LWA-1 observations for a specific trigger event.

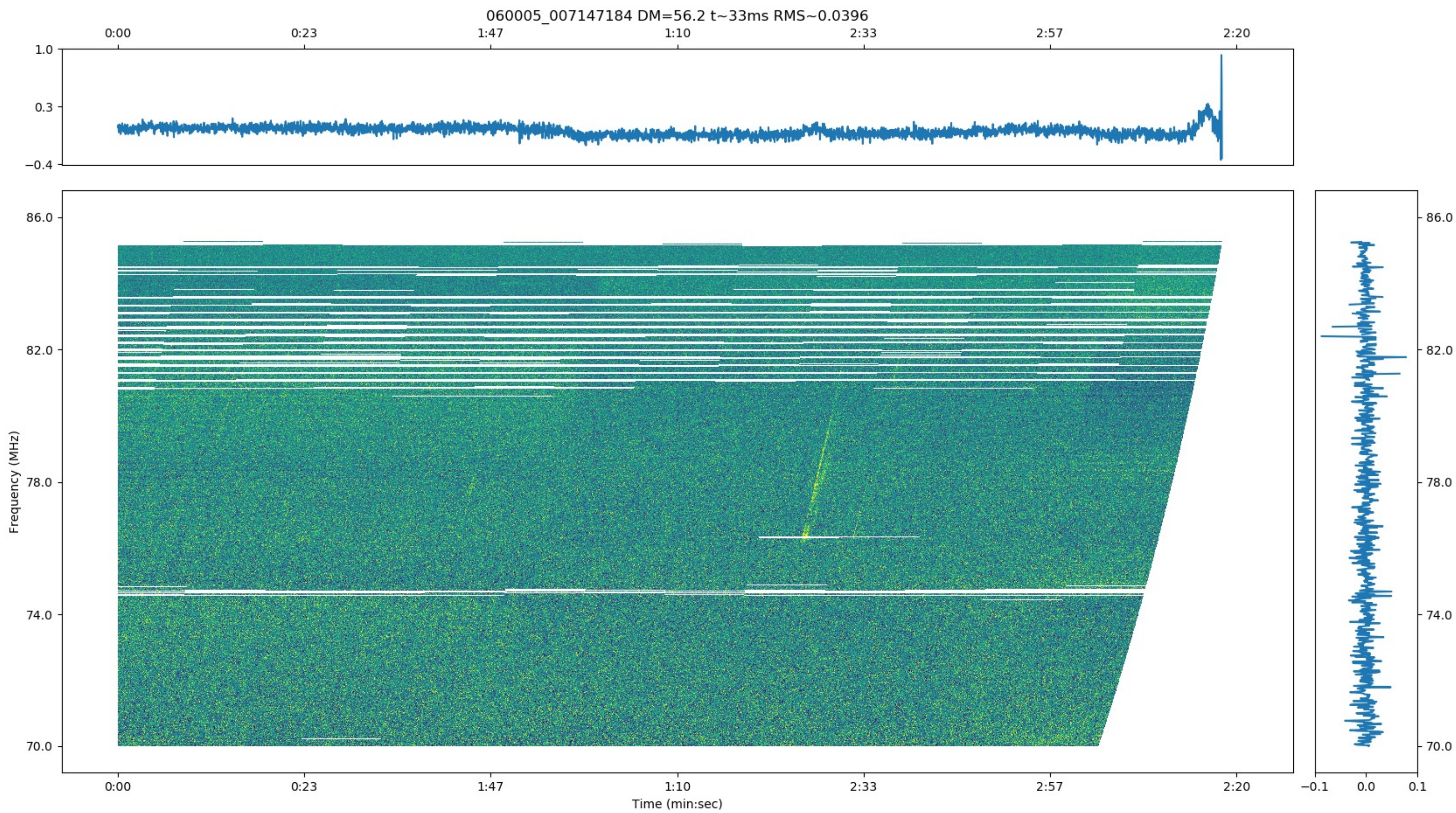
2023-03-02-06:38:05.991101 UTC DM=56.2 63.3 MHz, $B = 16$ MHz, $\Delta t = 33$ ms

LWA-1 9.29^h 40.85°



2023-03-02-06:38:05.991101 UTC DM=56.2 78.0 MHz, $B = 16$ MHz, $\Delta t = 33$ ms

LWA-1 9.29^{h} 40.85°



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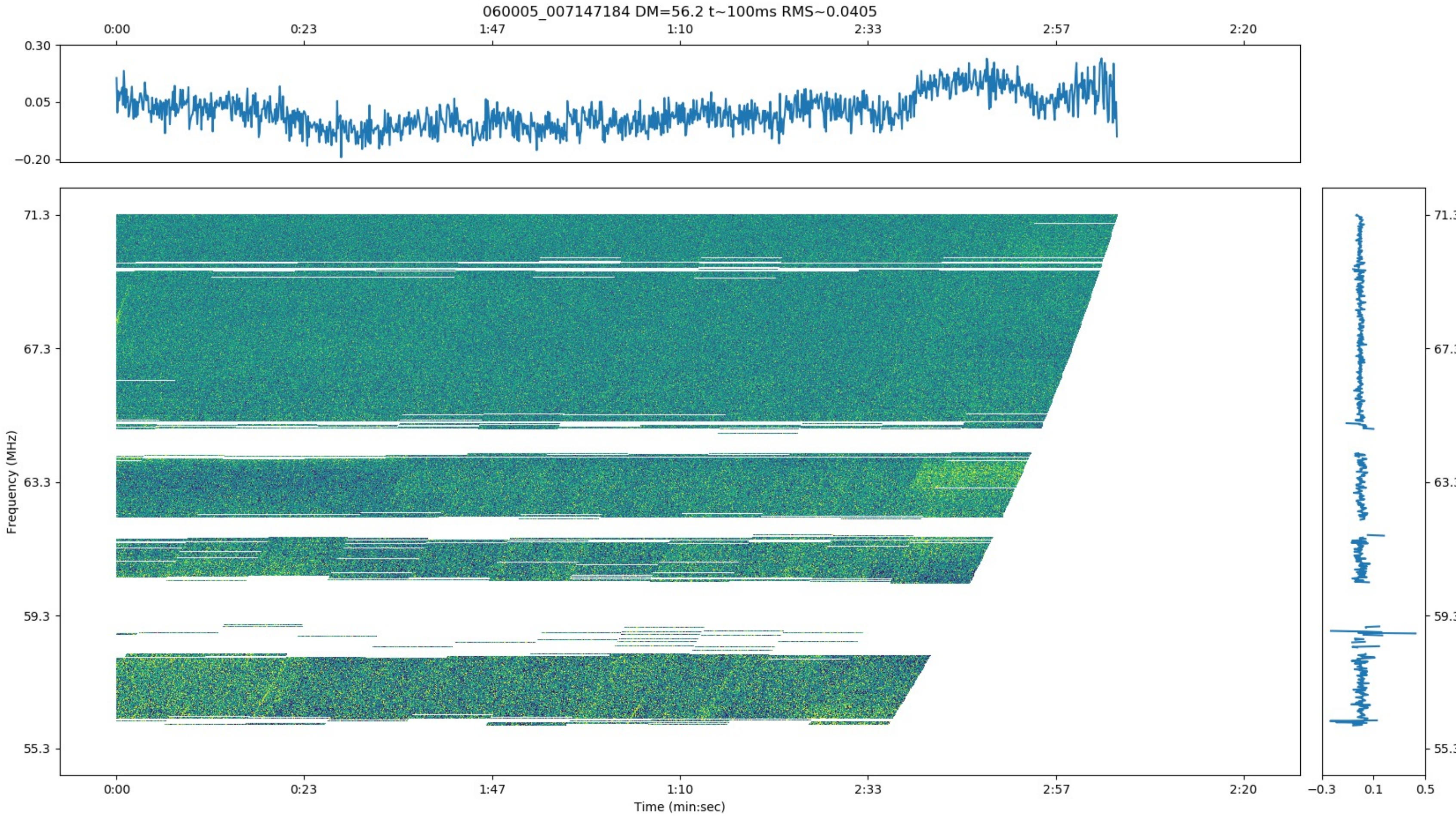

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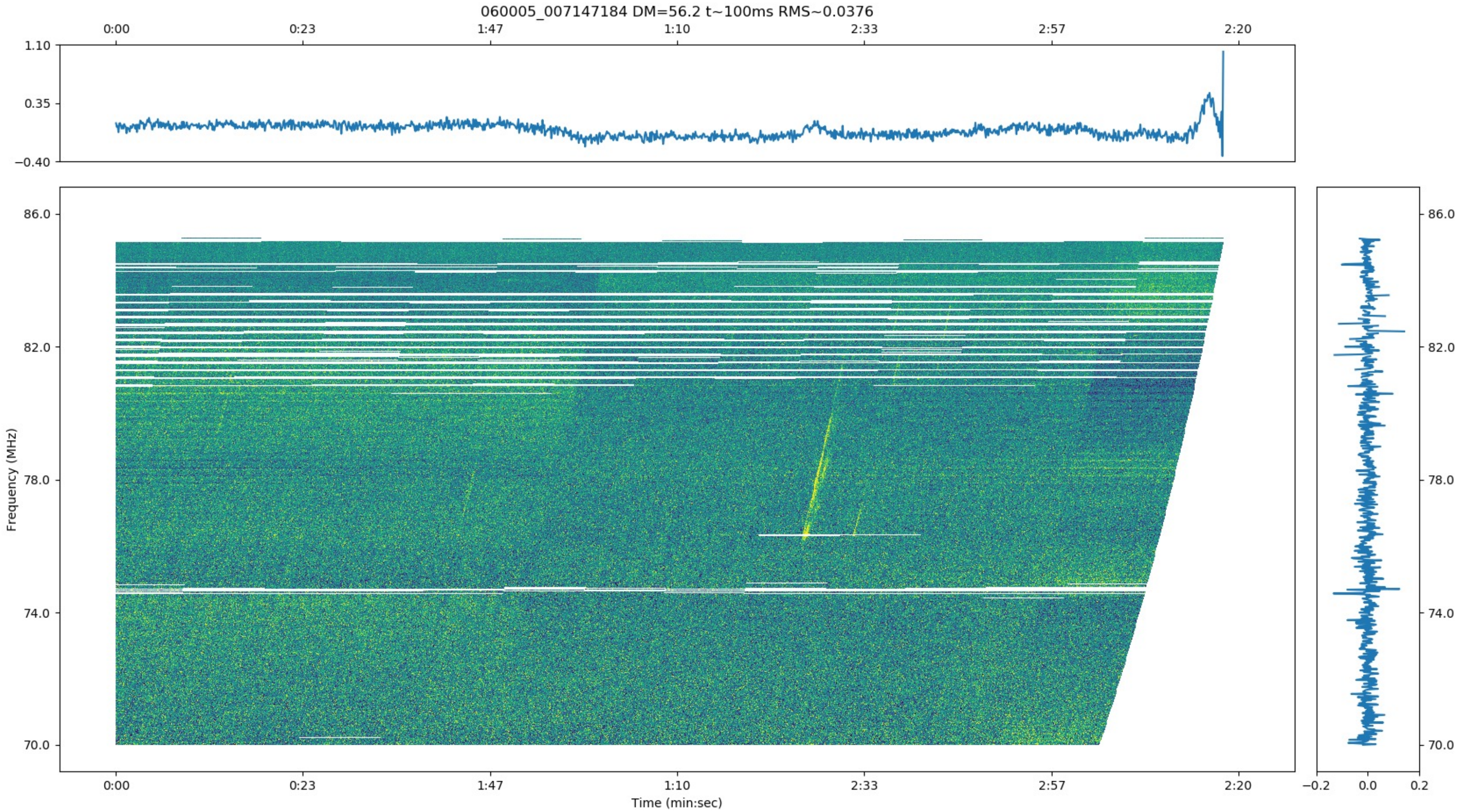
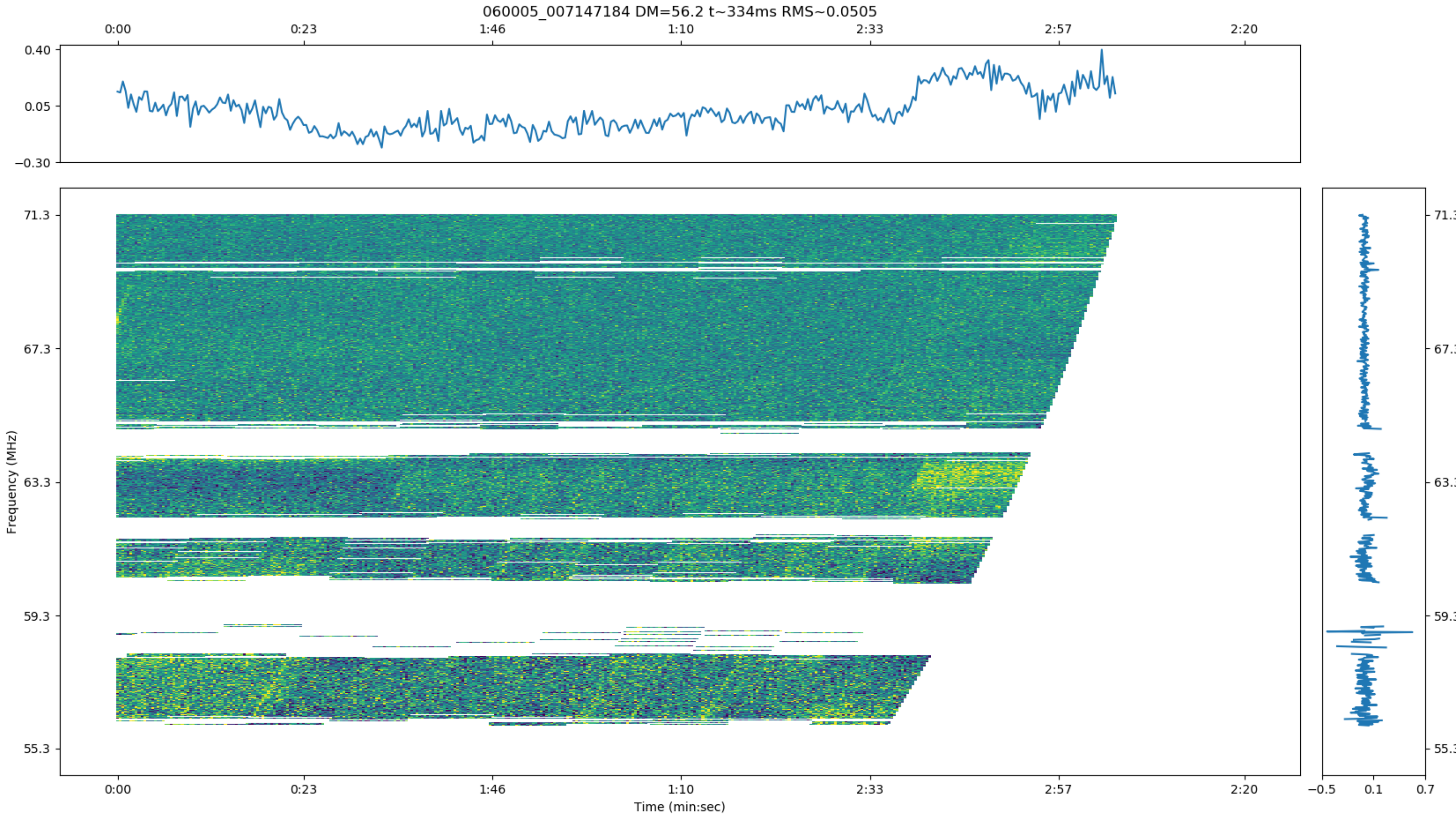


2023-03-02-06:38:05.991101 UTC   DM=56.2   63.3 MHz, $B = 16$ MHz, $\Delta t = 334$ ms

LWA-1 9.29^h 40.85°



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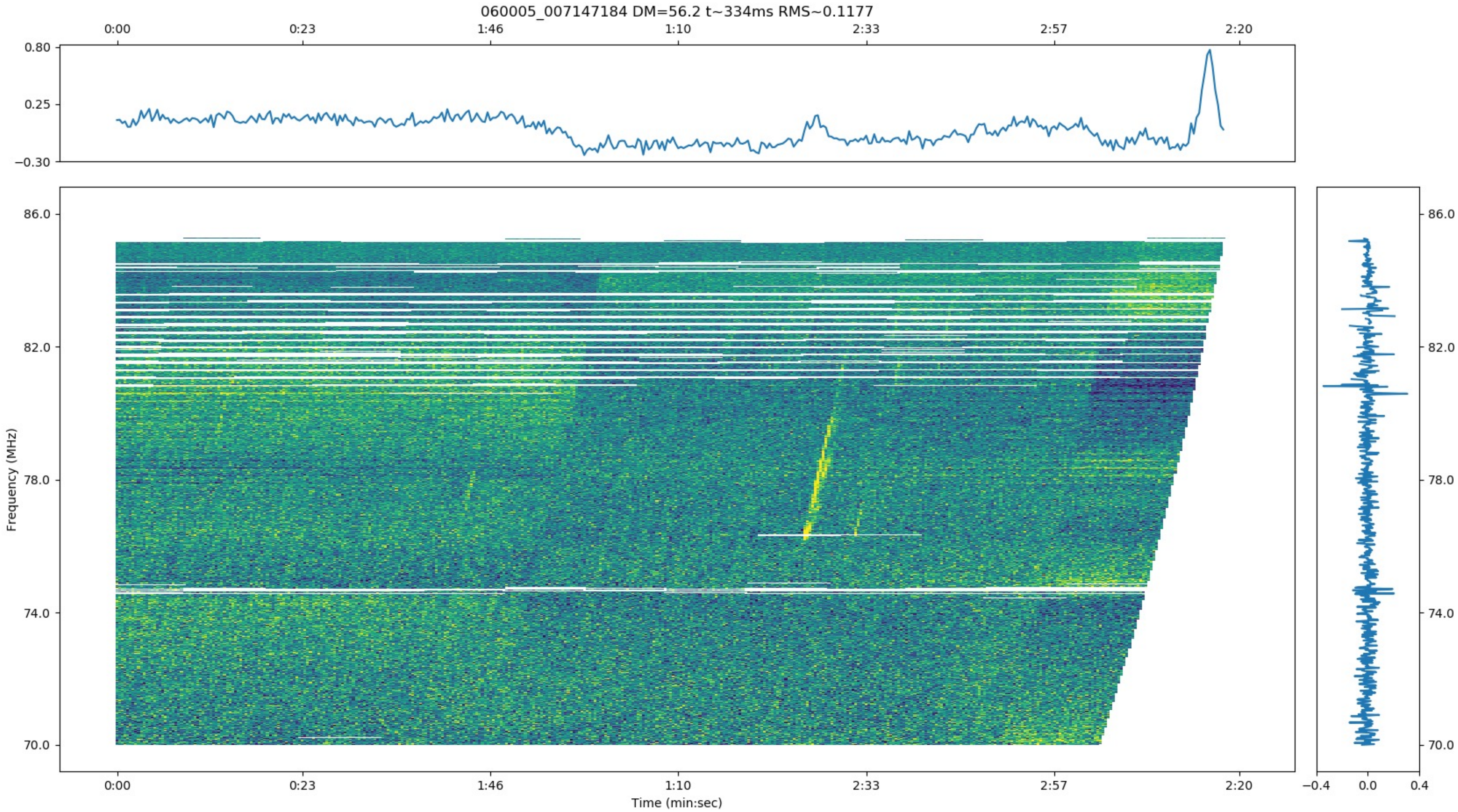
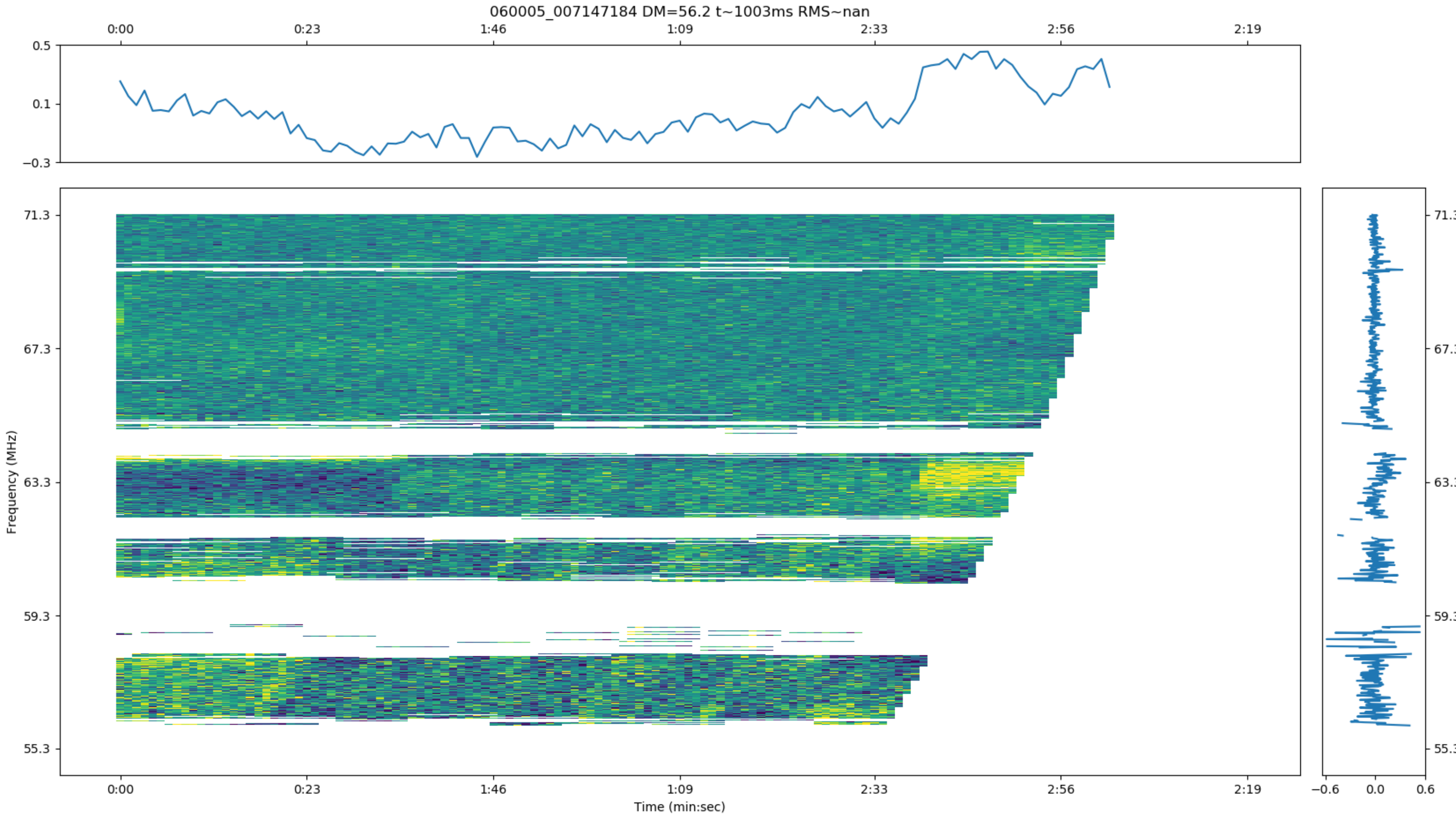


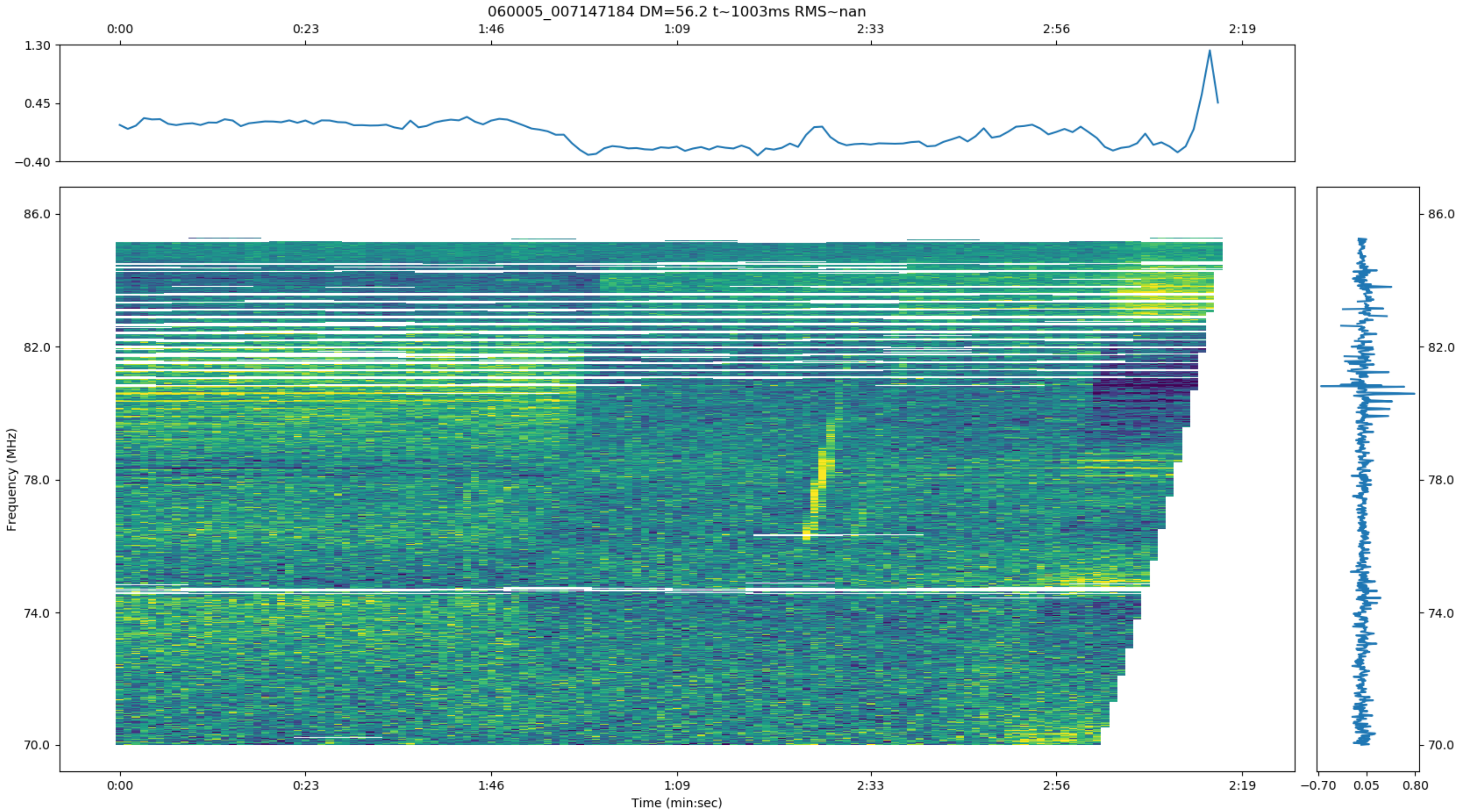
2023-03-02-06:38:05.991101 UTC DM=56.2 63.3 MHz, $B = 16$ MHz, $\Delta t = 1$ s

LWA-1 9.29^h 40.85°



2023-03-02-06:38:05.991101 UTC DM=56.2 78.0 MHz, $B = 16$ MHz, $\Delta t = 1$ s

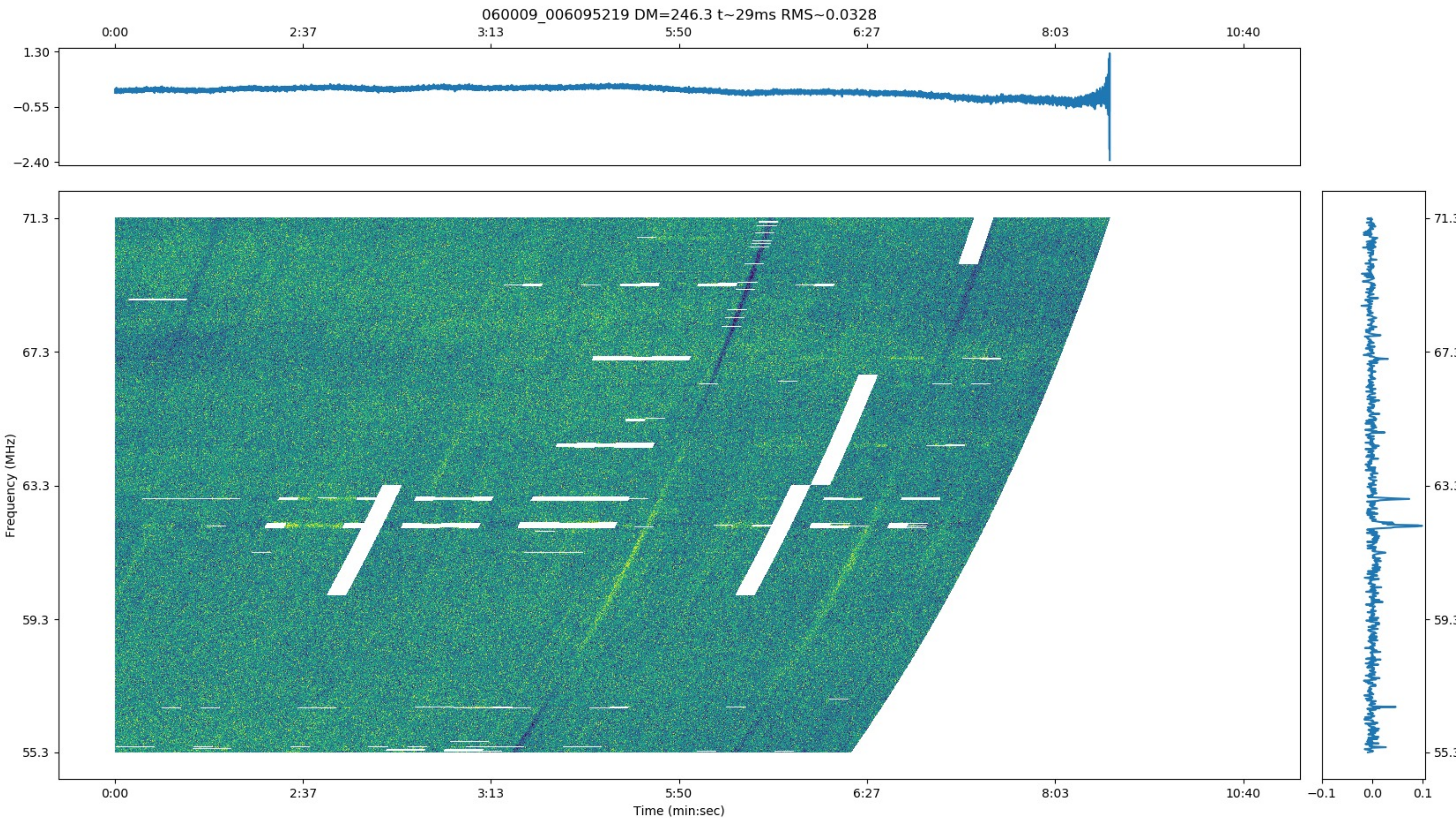
LWA-1 9.29^h 40.85°



The following slides are of illustrative LWA-SV observations for a specific trigger event.

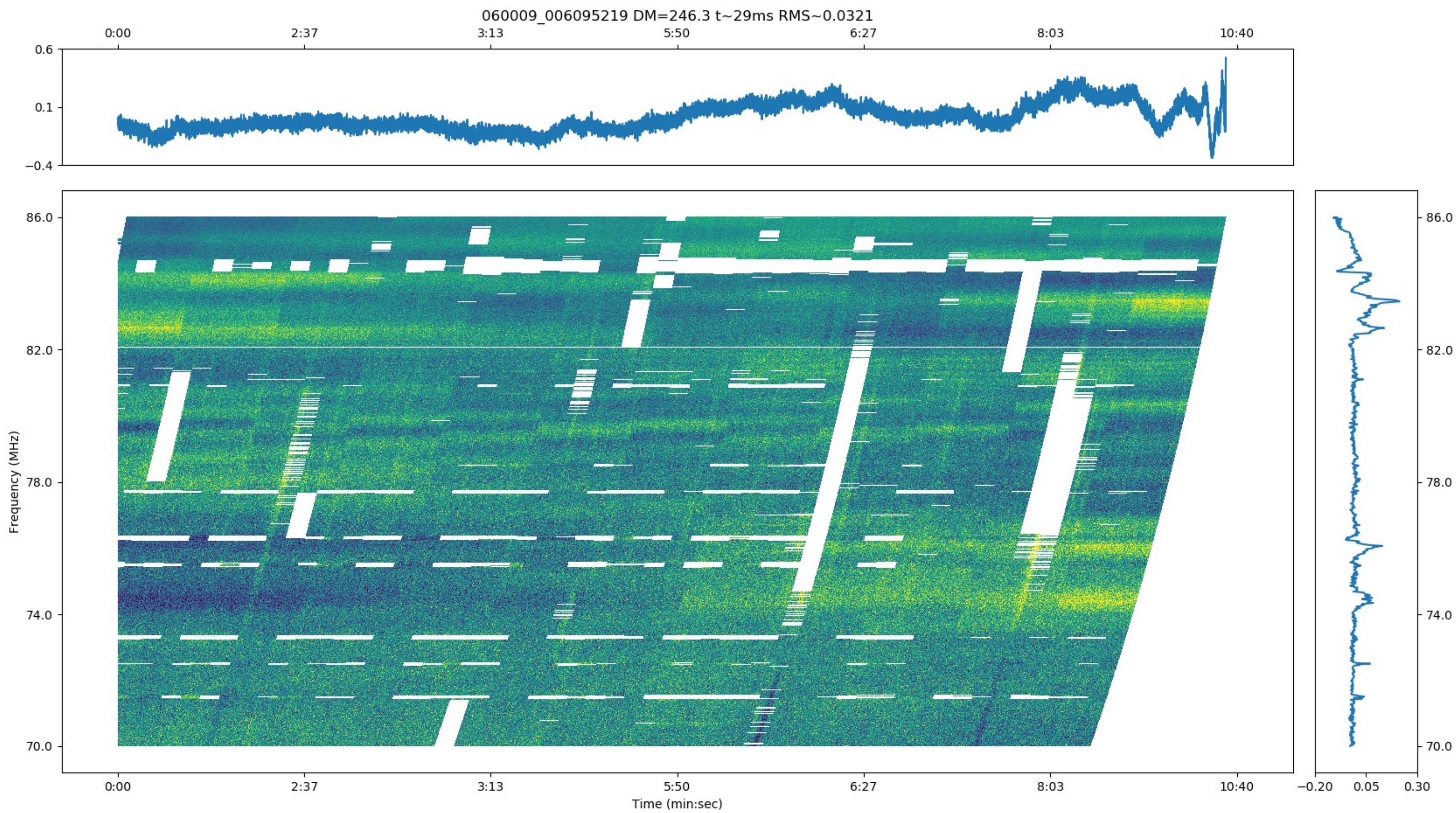
2023-03-06-20:26:23.314846 UTC DM=246.3 63.3 MHz, $B = 16$ MHz, $\Delta t = 29$ ms

LWA-SV 23.4^h 7.66°



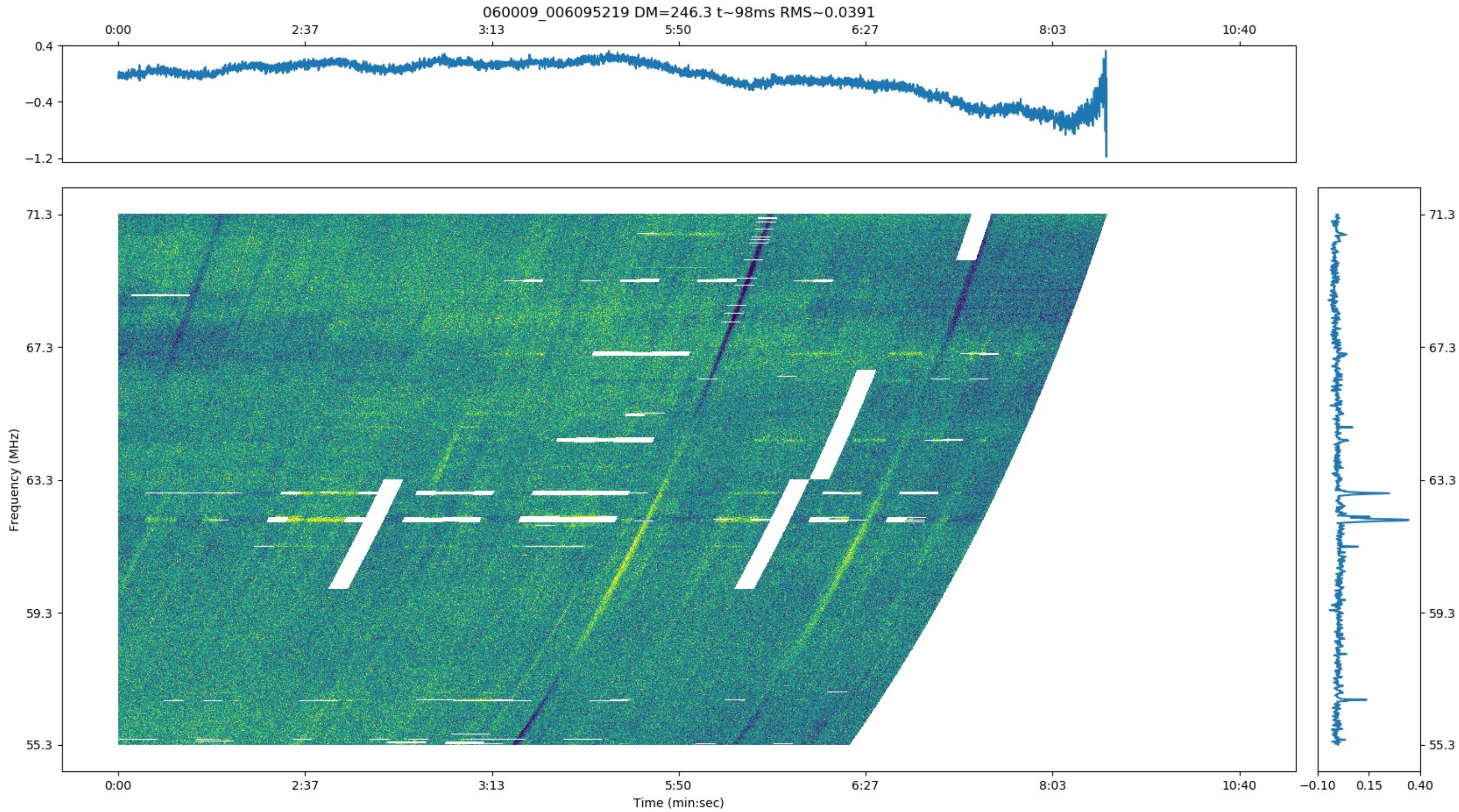
2023-03-06-20:26:23.314846 UTC DM=246.3 78.0 MHz, $B = 16$ MHz, $\Delta t = 29$ ms

LWA-SV 23.4^{h} 7.66°



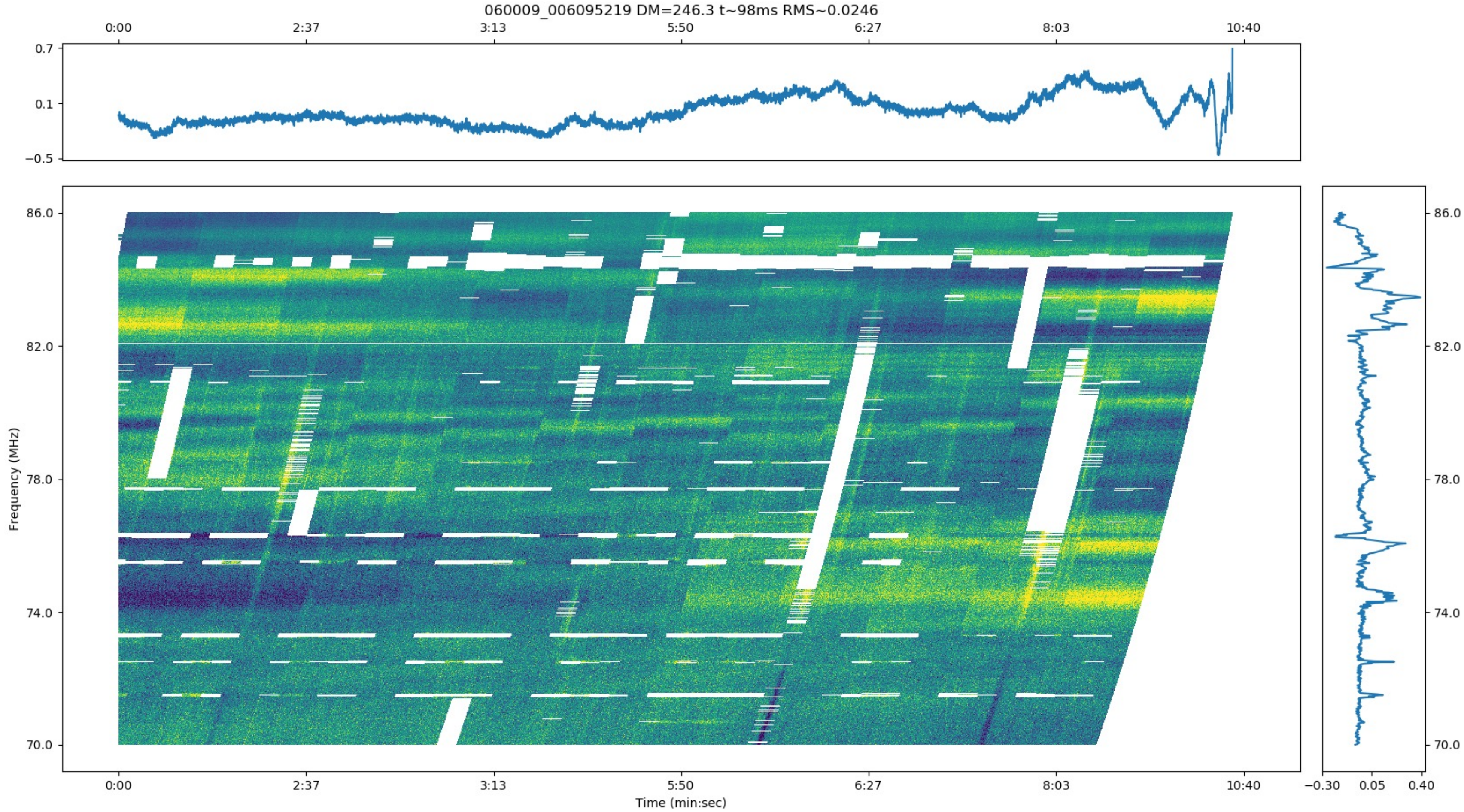
2023-03-06-20:26:23.314846 UTC DM=246.3 63.3 MHz, $B = 16$ MHz, $\Delta t = 98$ ms

LWA-SV 23.4^{h} 7.66°



2023-03-06-20:26:23.314846 UTC DM=246.3 78.8 MHz, $B = 16$ MHz, $\Delta t = 98$ ms

LWA-SV 23.4^{h} 7.66°



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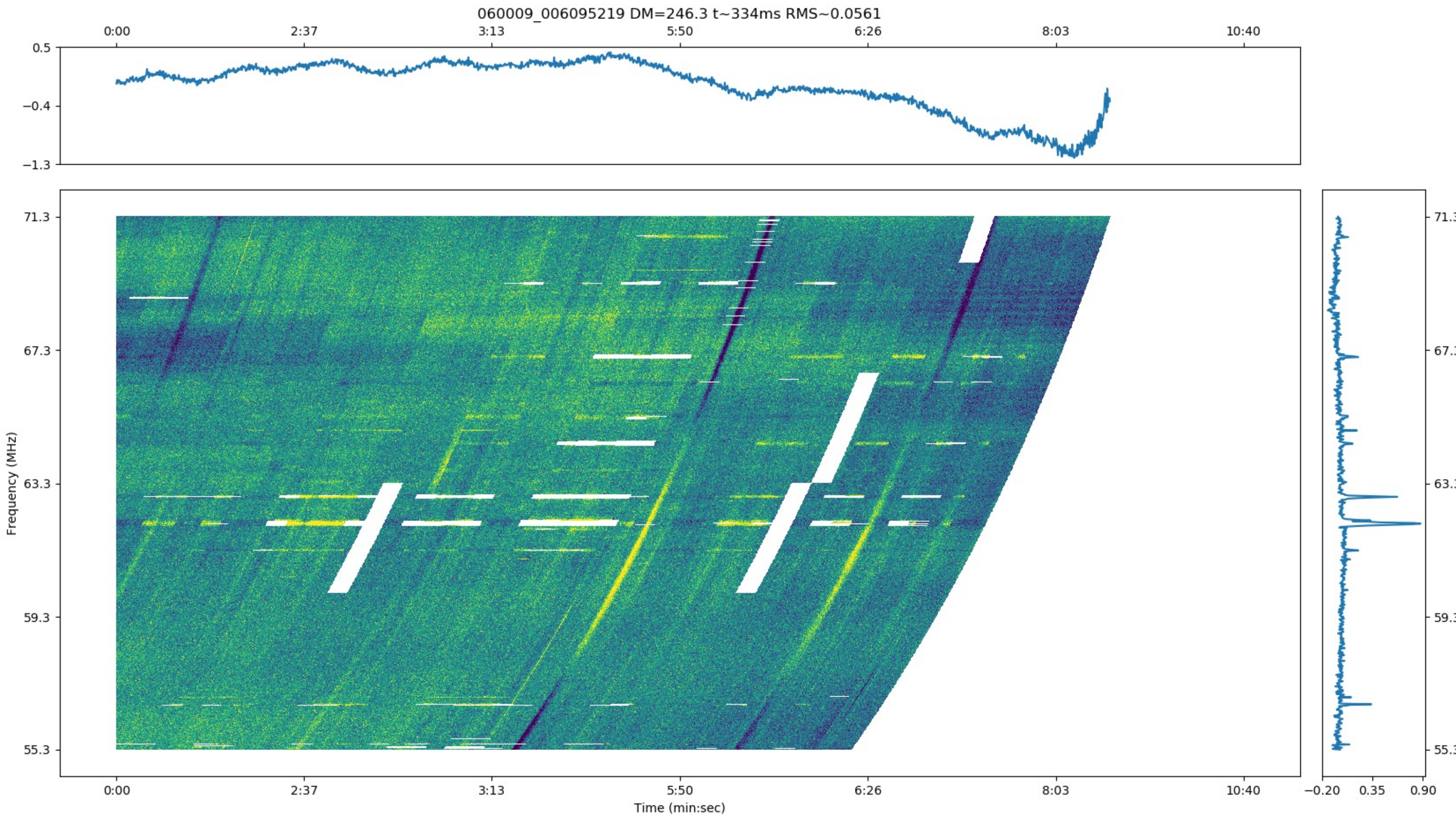
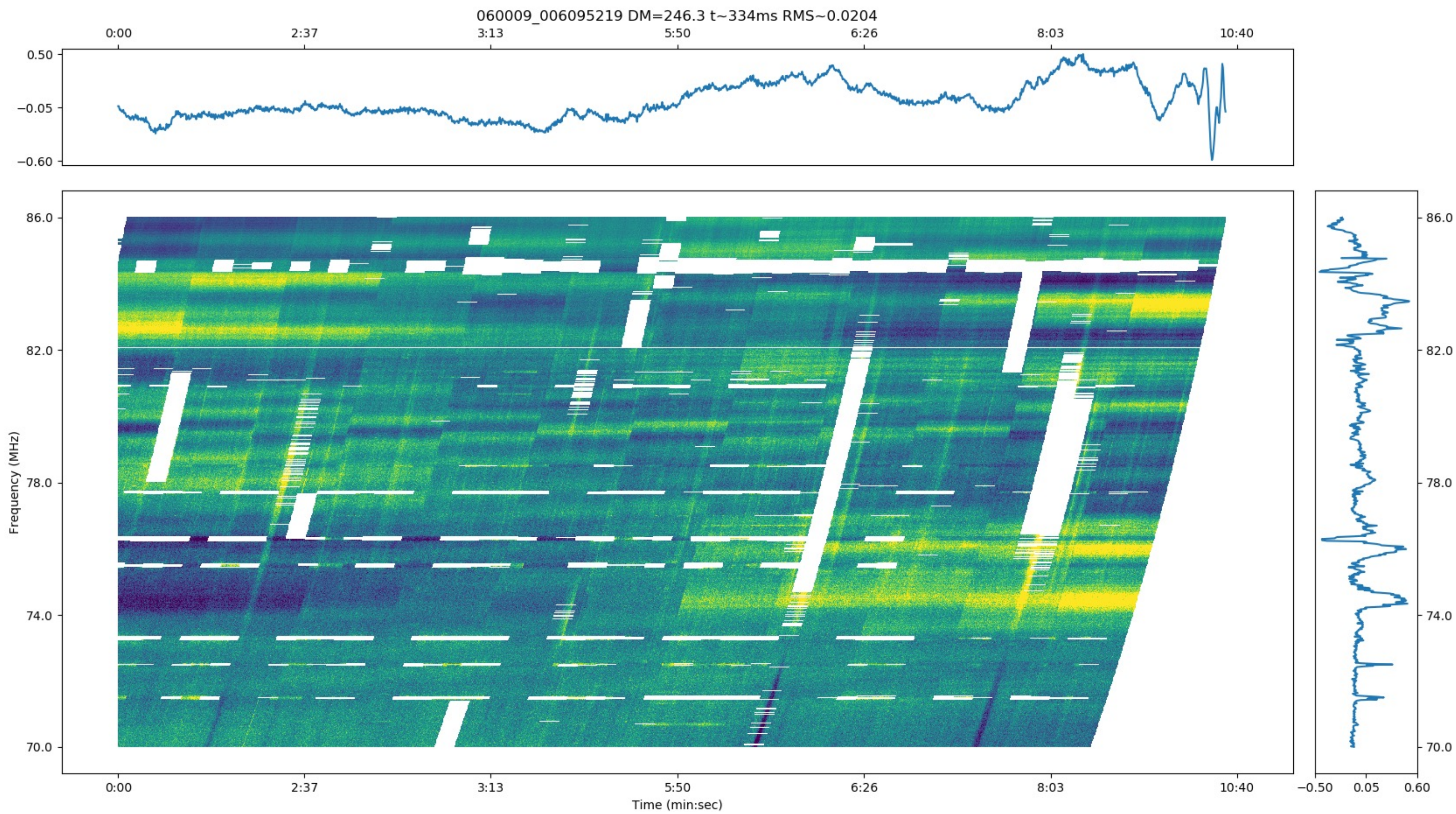


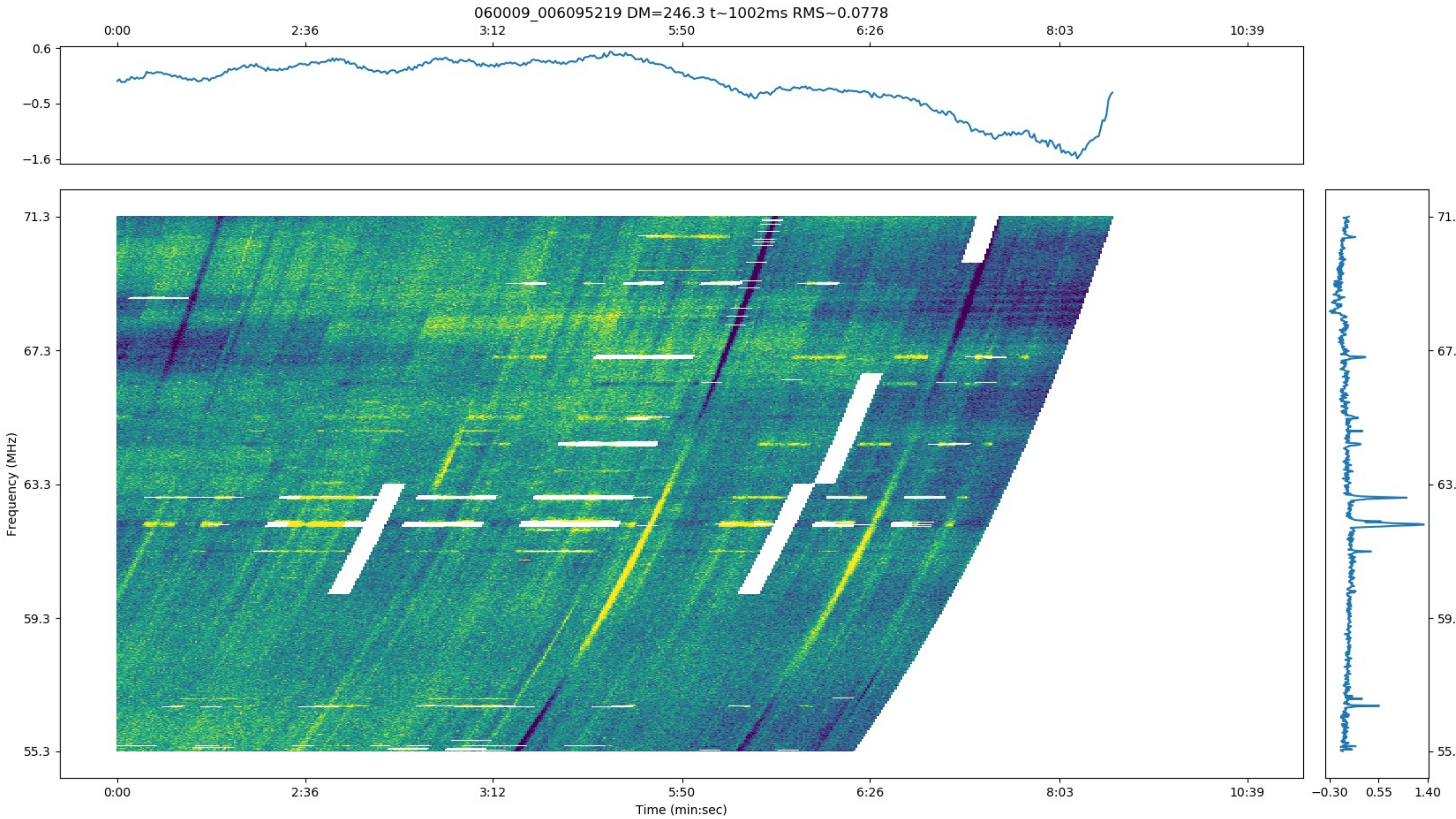
2023-03-06-20:26:23.314846 UTC   DM=246.3   78.0 MHz, $B = 16$ MHz, $\Delta t = 334$ ms

LWA-SV 23.4^h 7.66°



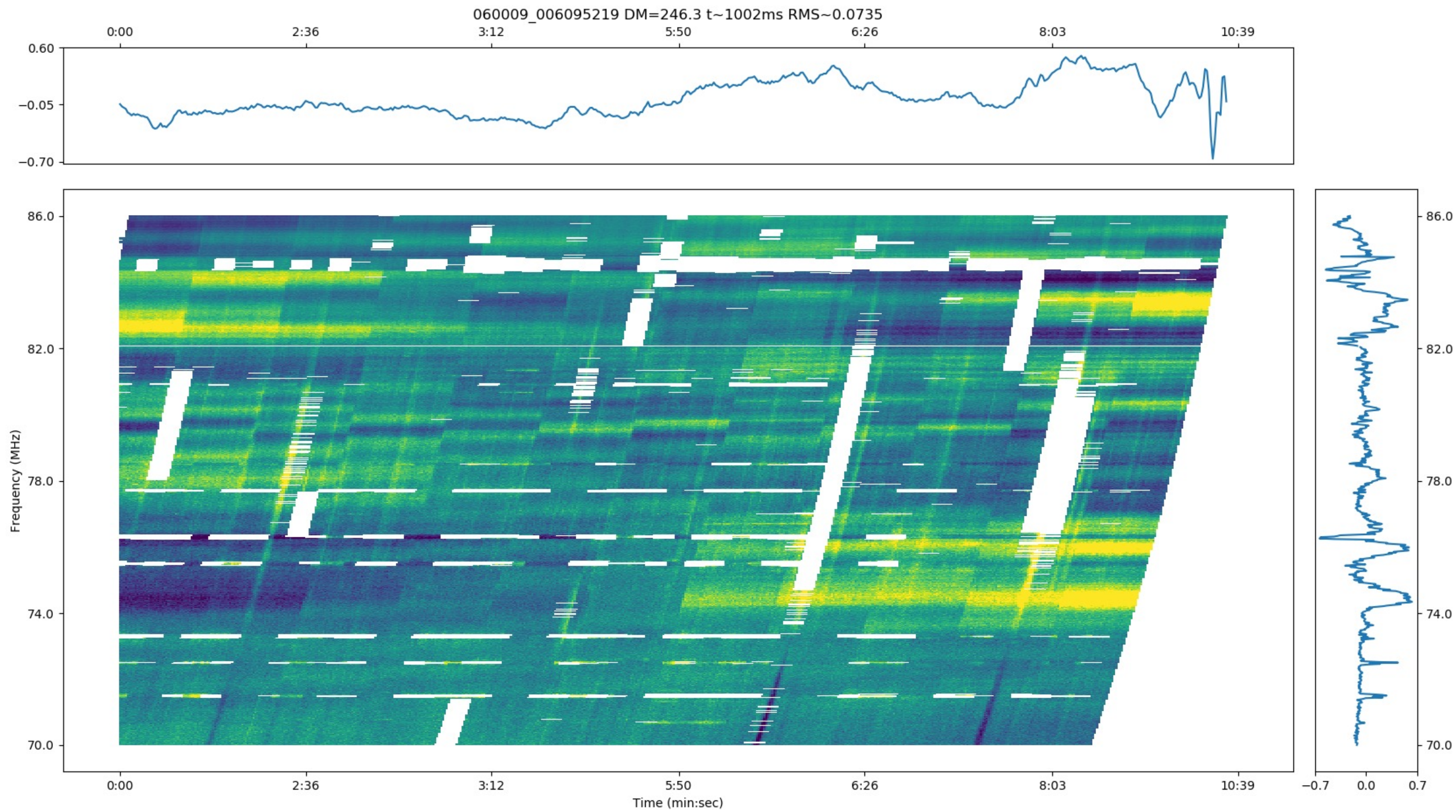
2023-03-06-20:26:23.314846 UTC DM=246.3 63.3 MHz, $B = 16$ MHz, $\Delta t = 1$ s

LWA-SV 23.4^{h} 7.66°



2023-03-06-20:26:23.314846 UTC DM=246.3 78.0 MHz, $B = 16$ MHz, $\Delta t = 1$ s

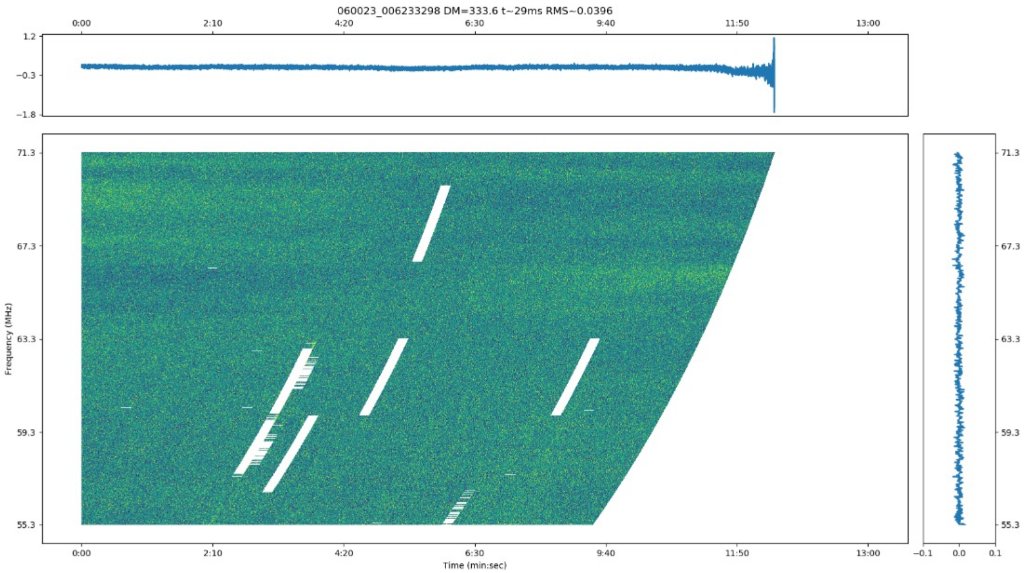
LWA-SV 23.4^{h} 7.66°



The following slides are illustrative of LWA-1 and LWA-SV observations for a specific trigger event.

2023-03-20-03:29:05.089193 UTC DM=333.6

7.26^h $21.95°$

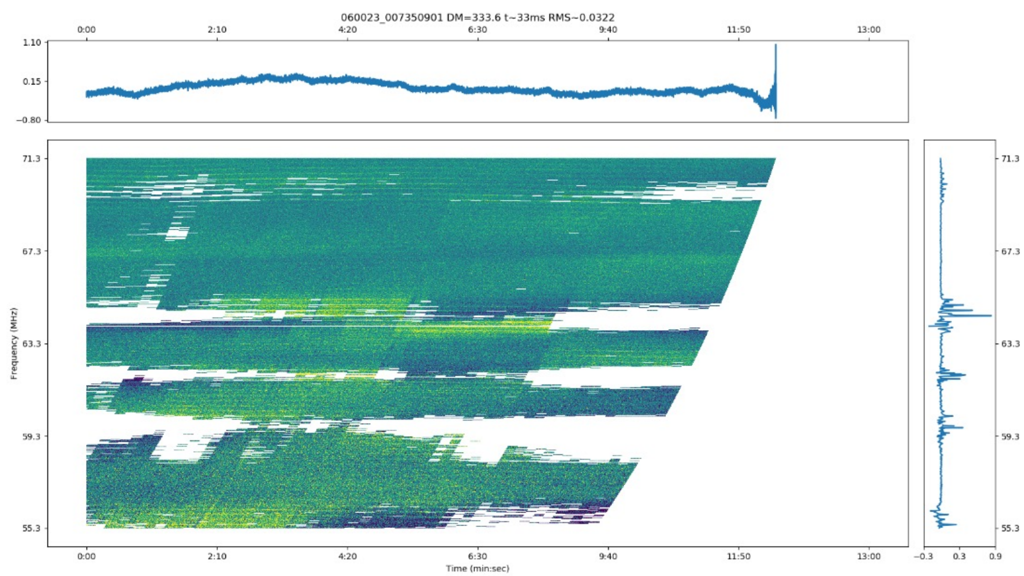


63.3 MHz

$B = 16$ MHz

$\Delta t = 29$ ms

LWA-SV



63.3 MHz

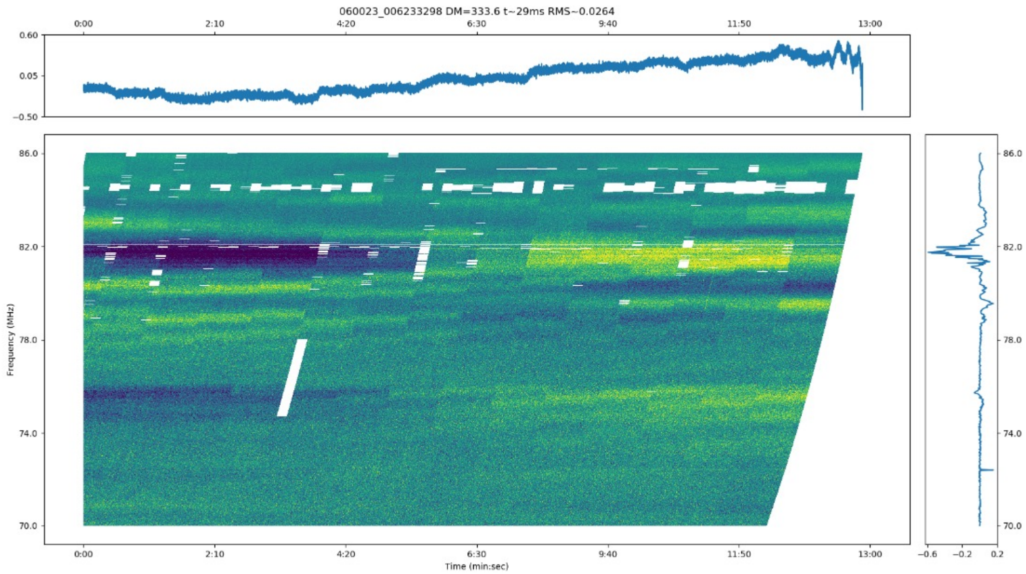
$B = 16$ MHz

$\Delta t = 33$ ms

LWA-1

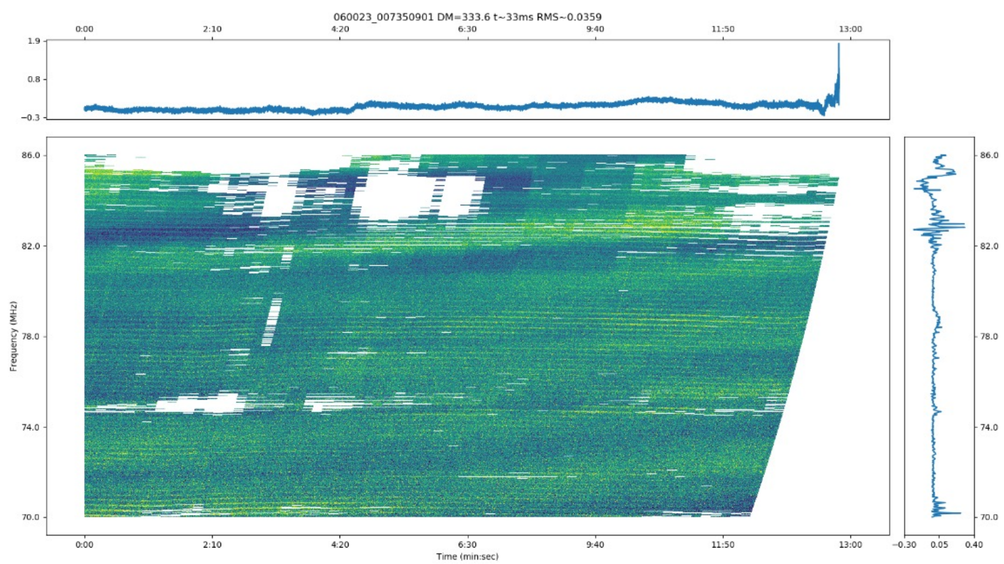
2023-03-20-03:29:05.089193 UTC DM=333.6

7.26^h 21.95°



78.0 MHz
$B = 16$ MHz
$\Delta t = 29$ ms

LWA-SV

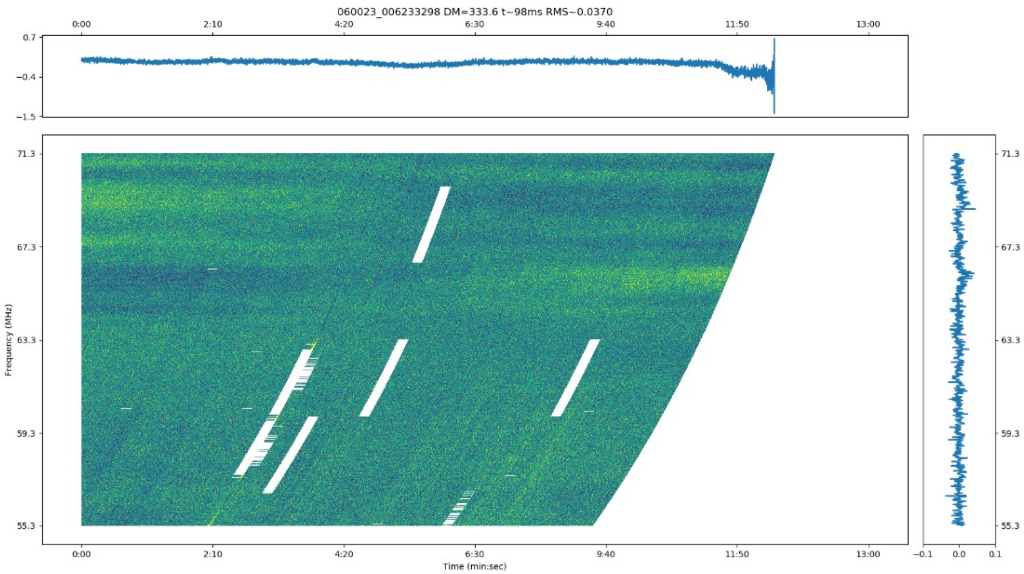


78.0 MHz
$B = 16$ MHz
$\Delta t = 33$ ms

LWA-1

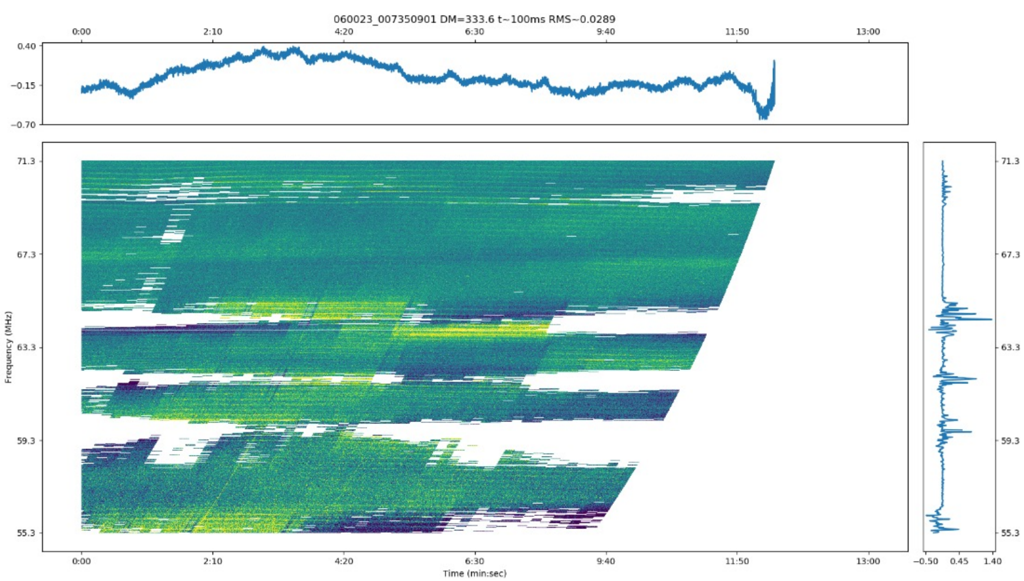
2023-03-20-03:29:05.089193 UTC DM=333.6

7.26^{h} 21.95°



63.3 MHz
$B = 16$ MHz
$\Delta t = 98$ ms

LWA-SV

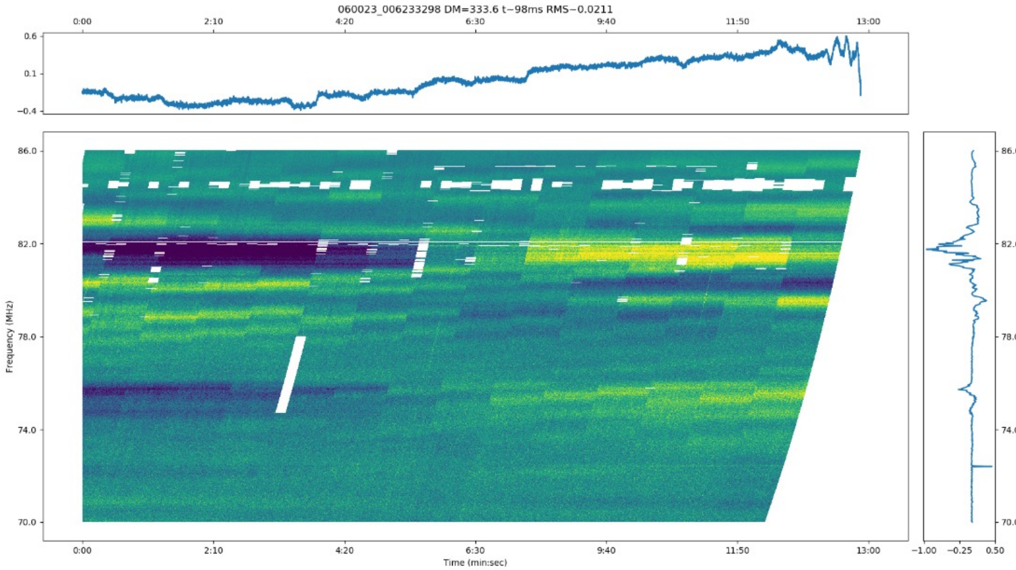


63.3 MHz
$B = 16$ MHz
$\Delta t = 100$ ms

LWA-1

2023-03-20-03:29:05.089193 UTC DM=333.6

7.26^h $21.95°$

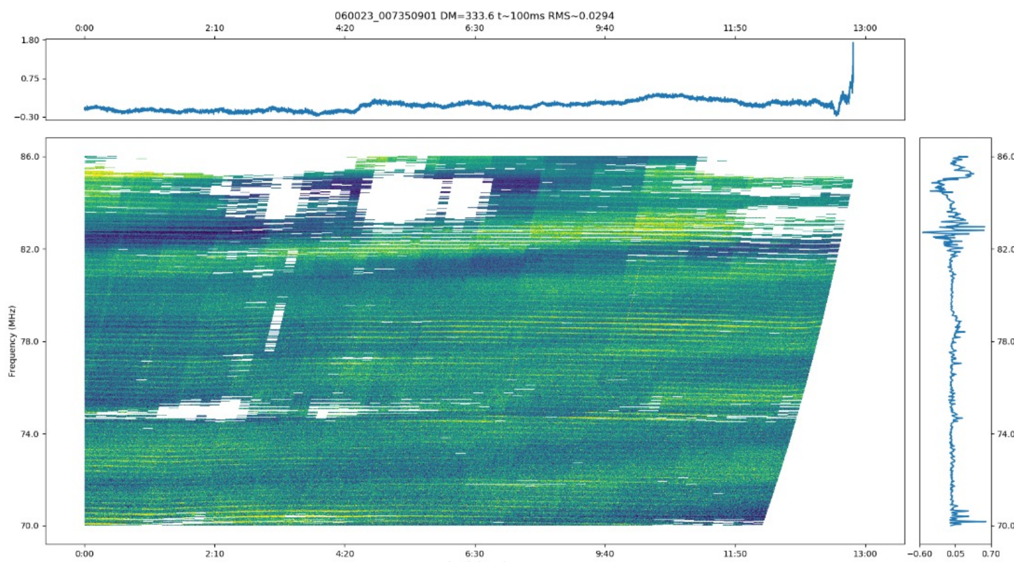


78.0 MHz

$B = 16$ MHz

$\Delta t = 98$ ms

LWA-SV



78.0 MHz

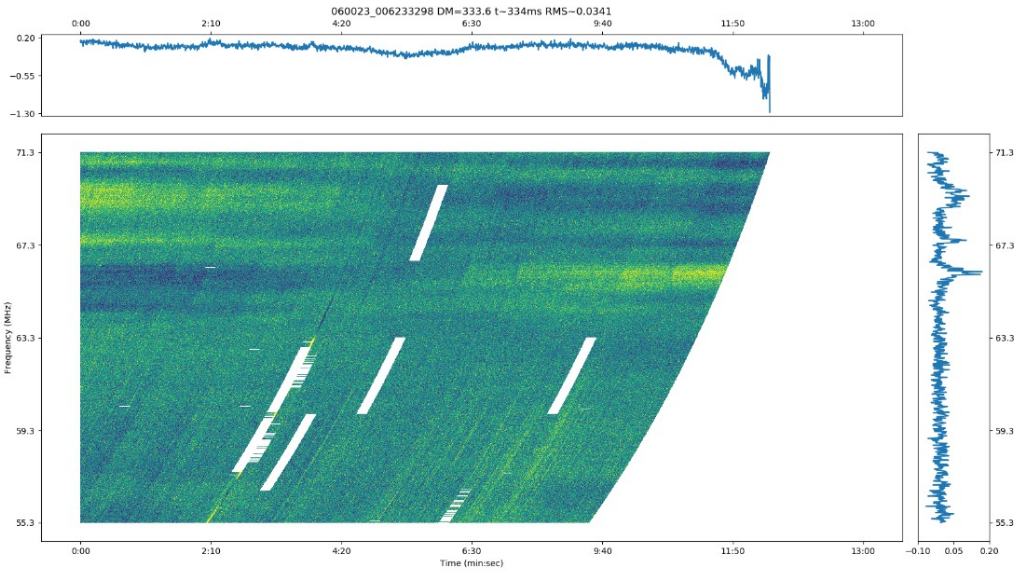
$B = 16$ MHz

$\Delta t = 100$ ms

LWA-1

2023-03-20-03:29:05.089193 UTC DM=333.6

7.26^h 21.95°

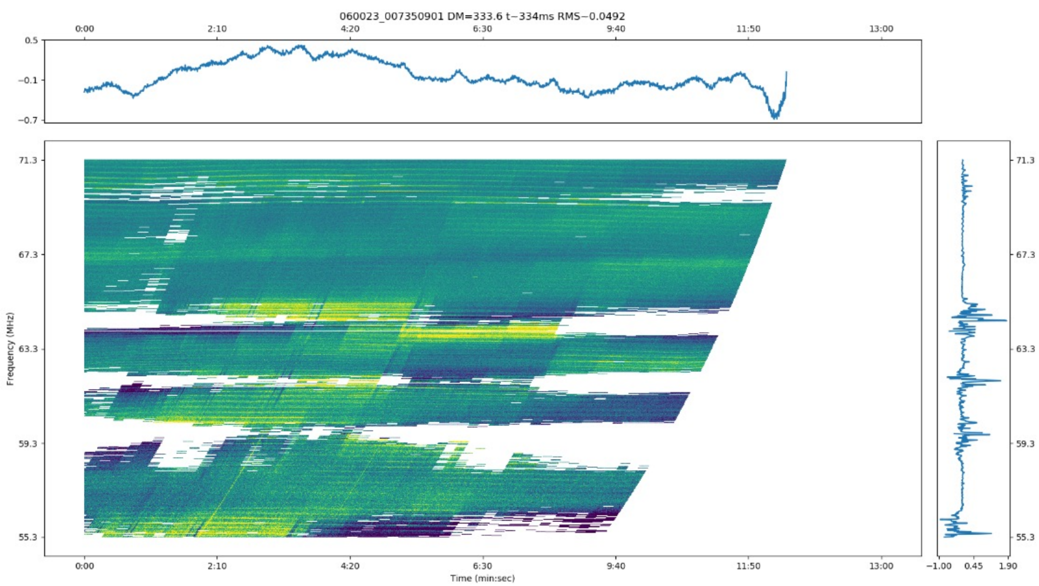


63.3 MHz

$B = 16$ MHz

$\Delta t = 334$ ms

LWA-SV



63.3 MHz

$B = 16$ MHz

$\Delta t = 334$ ms

LWA-1

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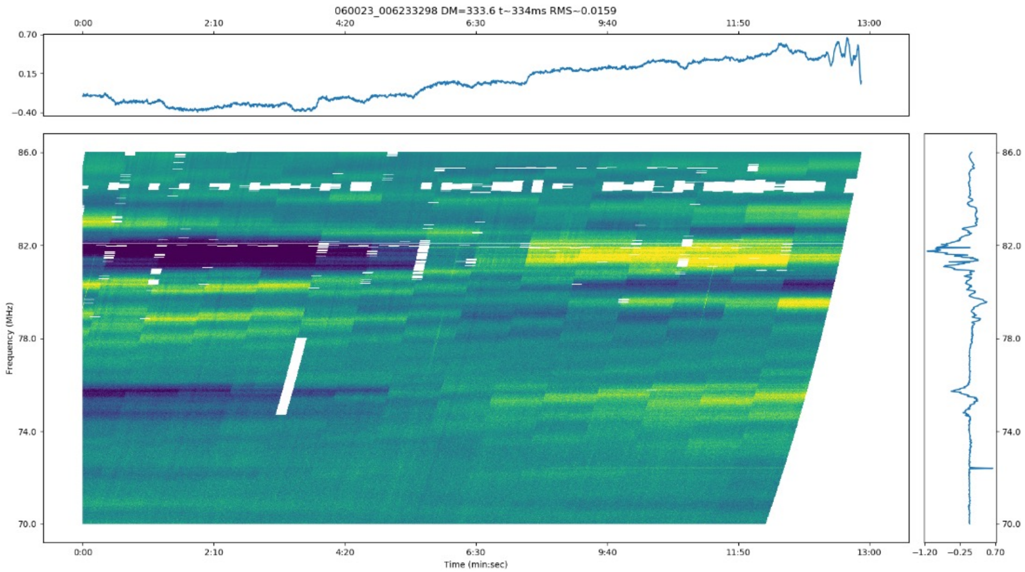
7.26^h 21.95°

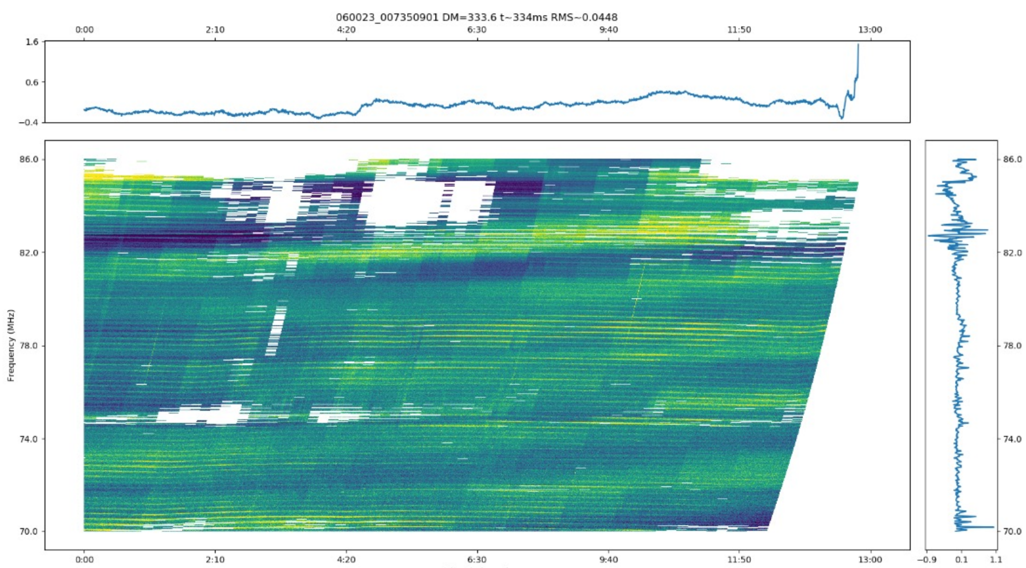


78.0 MHz

$B = 16$ MHz

$\Delta t = 334$ ms

LWA-SV



78.0 MHz

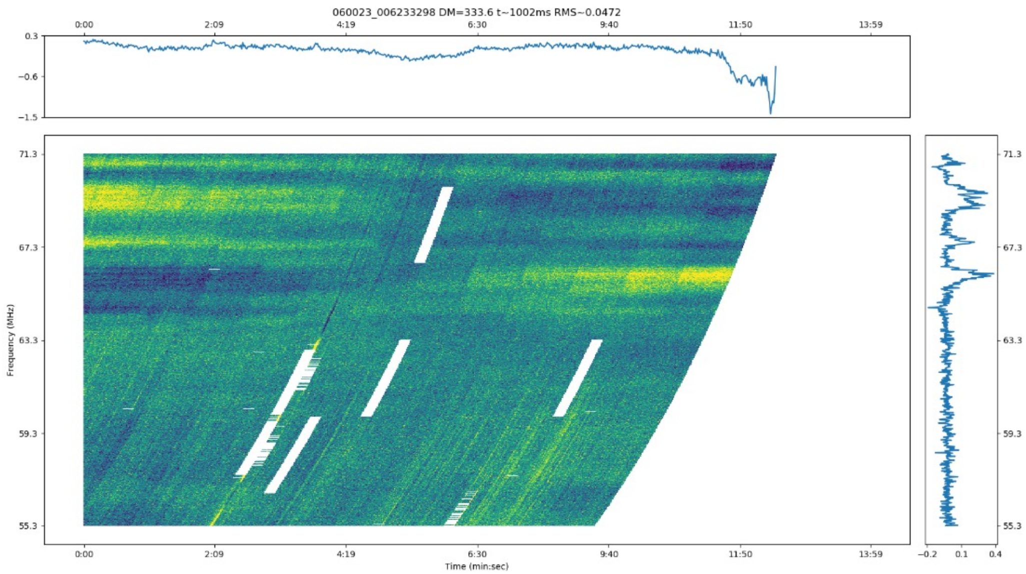
$B = 16$ MHz

$\Delta t = 334$ ms

LWA-1

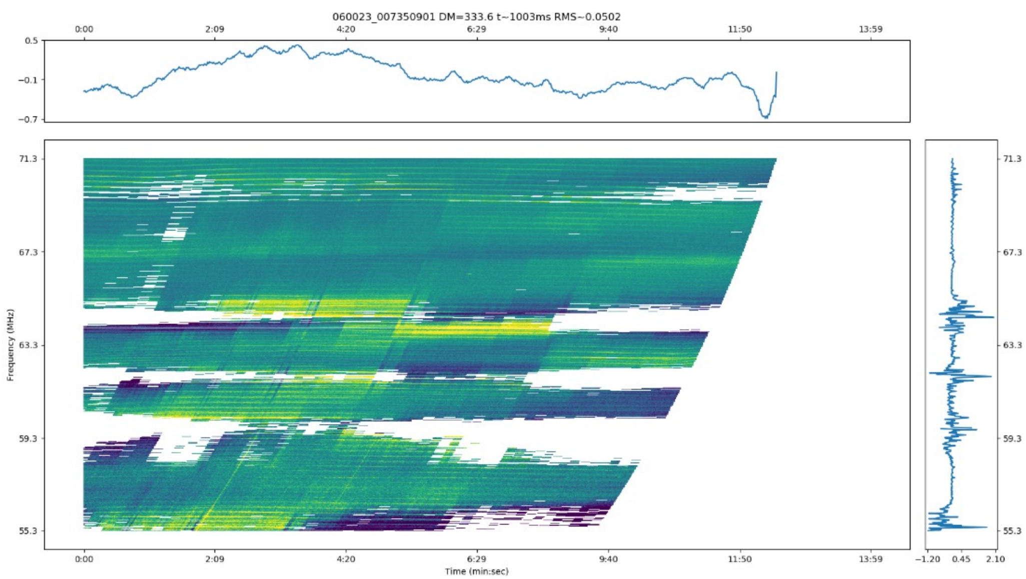
2023-03-20-03:29:05.089193 UTC DM=333.6

7.26^h 21.95°



63.3 MHz
$B = 16$ MHz
$\Delta t = 1$ s

LWA-SV

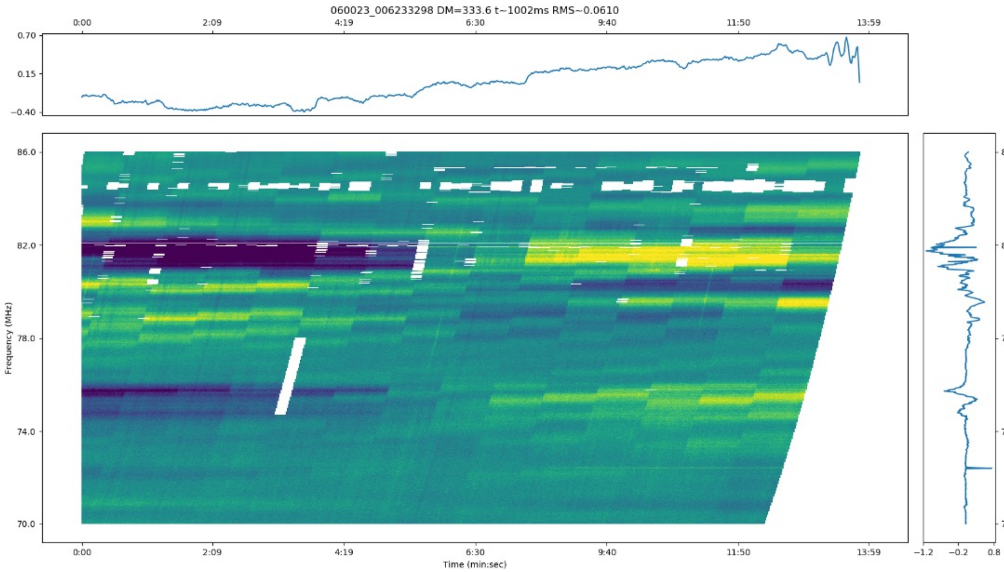


63.3 MHz
$B = 16$ MHz
$\Delta t = 1$ s

LWA-1

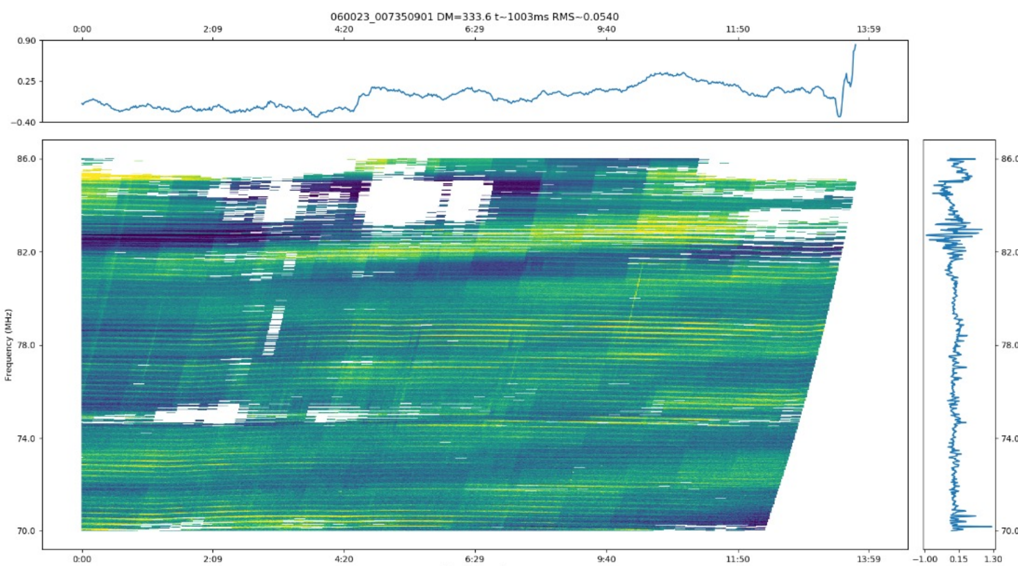
2023-03-20-03:29:05.089193 UTC DM=333.6

7.26^h $21.95°$



78.0 MHz
$B = 16$ MHz
$\Delta t = 1$ s

LWA-SV



78.0 MHz
$B = 16$ MHz
$\Delta t = 1$ s

LWA-1

Results

We have not detected any isolated pulses within a 2—15 minute window of a CHIME-triggered detection of an FRB.

That encompasses the delay expected from a pulse emitted at 60 MHz simultaneously with the pulse detected by CHIME, plus additional minutes for a delay of emission at lower frequencies.

With that specific window in mind, we can set a 5-sigma flux density upper limit for a pulse corresponding to these non-detections of

$$S_\nu \sim 10 \text{ Jy } \Delta t_{\text{seconds}}^{-\frac{1}{2}}$$

where Δt is the pulse width for which a limit is specified. The latter caveat takes account of our search in pulse-width space, with values of 30ms to 1s, at intervals of a factor of about 3 (30ms, 100ms, 300ms, 1s).

Scratch slides follow! Ignore!

I’m keeping them in this file in case I need some something from them.

LWA: FRB 180916.J0158+65

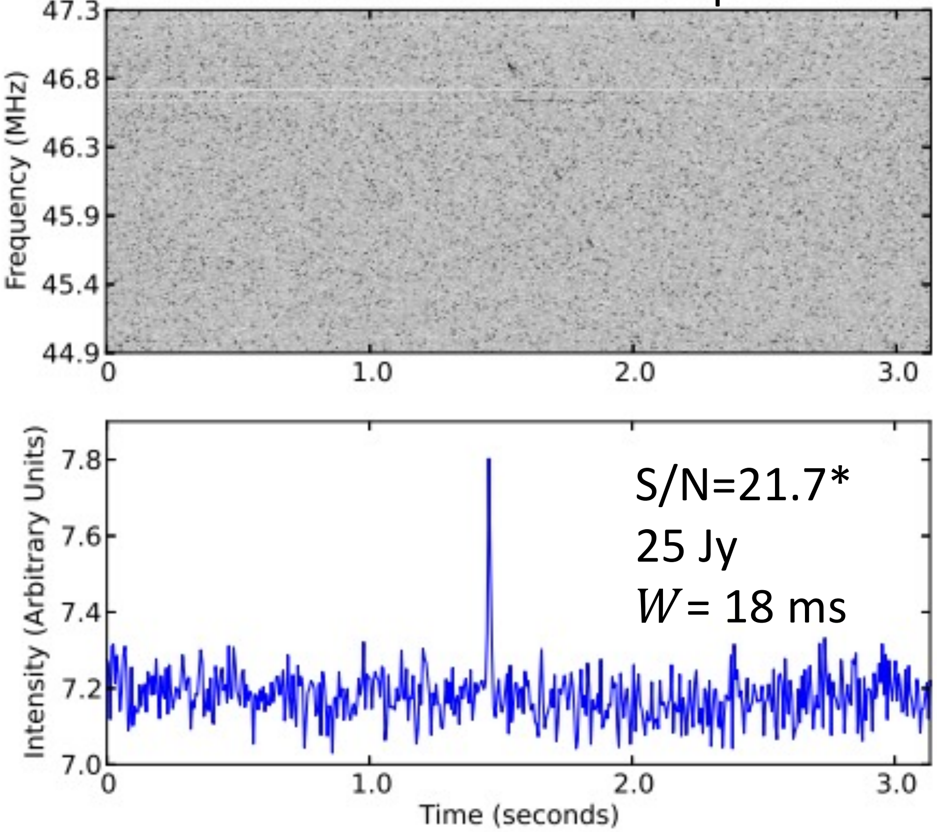
Our Observing Program

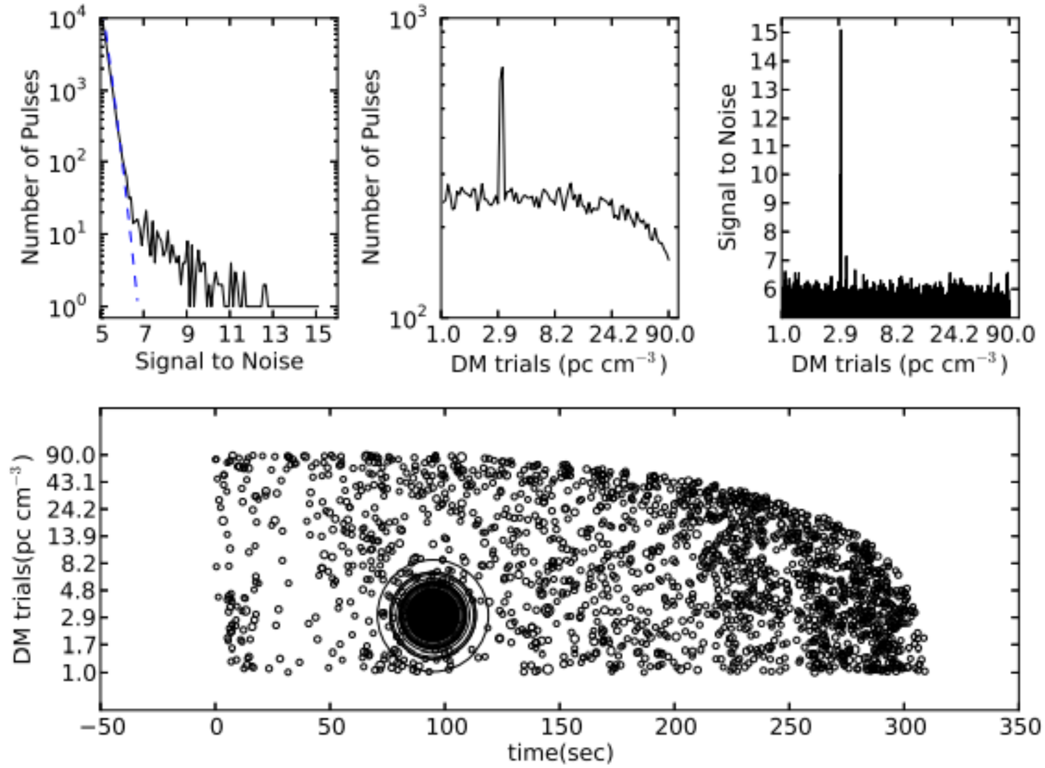
- Observed 180916 multiple times over the past few months
- Nighttime sessions
- CHIME detected a pulse (or more than one) during a few sessions

AND OUR RESULTS ARE…

Transient Pulse Detection

PSR B0950+08 DM=2.97 pc cm^{-3}





$$S_\nu \sim 2\ \mathrm{Jy}\ \left(\frac{SNR}{10}\right)\ B_{20\mathrm{MHz}}^{-\frac{1}{2}}\ \Delta t_{\mathrm{seconds}}^{-\frac{1}{2}}$$

*For the full bandwidth. S/N = 8.8 in this 2.4 MHz chunk.

1) 0.209ms sampled raw data, 4 hours, 19.6 MHz BW → (LSL, FFT) → spectrogram
2) Bandpass removal
3) Removal of diurnal variation
4) RFI removal (impulsive, narrowband)
5) DM and pulse-width search

VIRGINIA TECH.