Thrifty PDV analysis

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PDV workshop

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Overview

- PDV analysis overview (short-time Fourier transform)
  - Some quick reminders
  - Spectrograms, histories, and the problems of each
- Thrifty analysis is frugal on many levels
  - Only read signal data as needed (large data sets)
  - Fit **complex** spectra with window transforms
  - Retain (t,f) locations that are **not noise**
- We will only scratch the surface today
  - **Generating a spectrogram from a signal**
  - History extraction is a topic for another day…

PDV in a nutshell

- Velocity encoded as beat frequency, possibly with an offset
  - 1 km/s → 1.29 GHz at 1550 nm
- Beat uncertainty limited by:
  - Time duration*
  - Sample rate**
  - Signal amplitude
  - Noise floor**

$$B = \left| \underbrace{c\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)}_{B_0} + D \right|$$

$$D \equiv \frac{2v'}{\lambda_1}$$

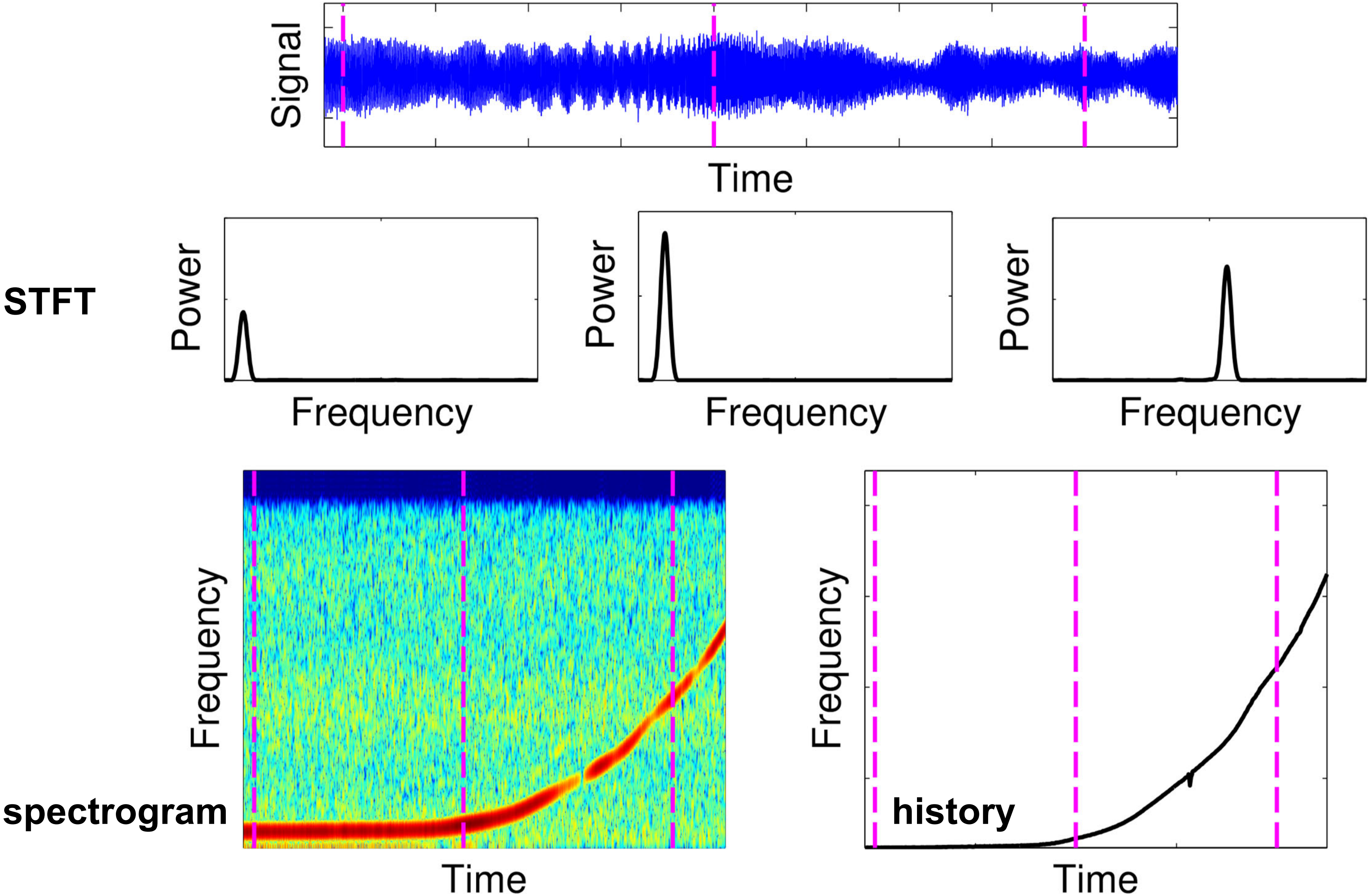
Optical Doppler shift

$$\sigma_B \geq \sqrt{\frac{6}{f_s \tau^3}} \frac{\sigma_s}{A_s} \frac{1}{\pi}$$

D.H. Dolan, "Extreme measurements with Photonic Doppler Velocimetry (PDV)", Review of Scientific Instruments **91**, 051501 (2020).

* Adjustable ** Fixed

Short-time Fourier transform analysis



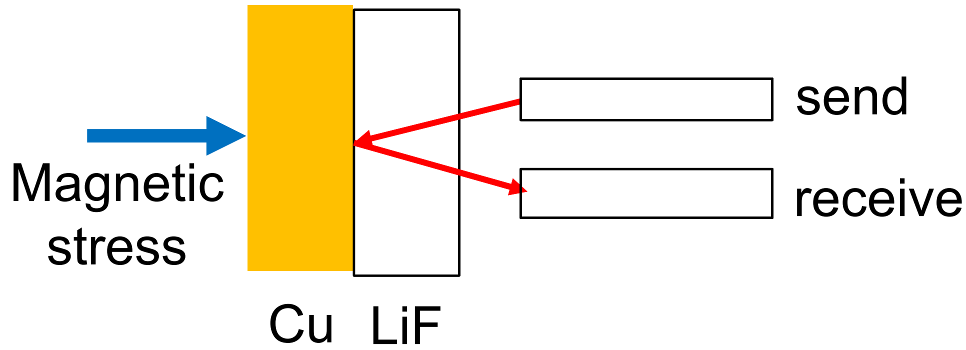
So what is the problem?

- Spectrograms are unbiased representations of time-frequency content and **easy to look at**
  - Become HUGE (gigapixels to terapixels) for high resolution
- Histories have quantitative information of interest, i.e. wave profiles, that **people really want**
  - Can be systematically wrong
- Neither does well with overlapping spectral content
  - Truly single frequency PDV measurements are rare

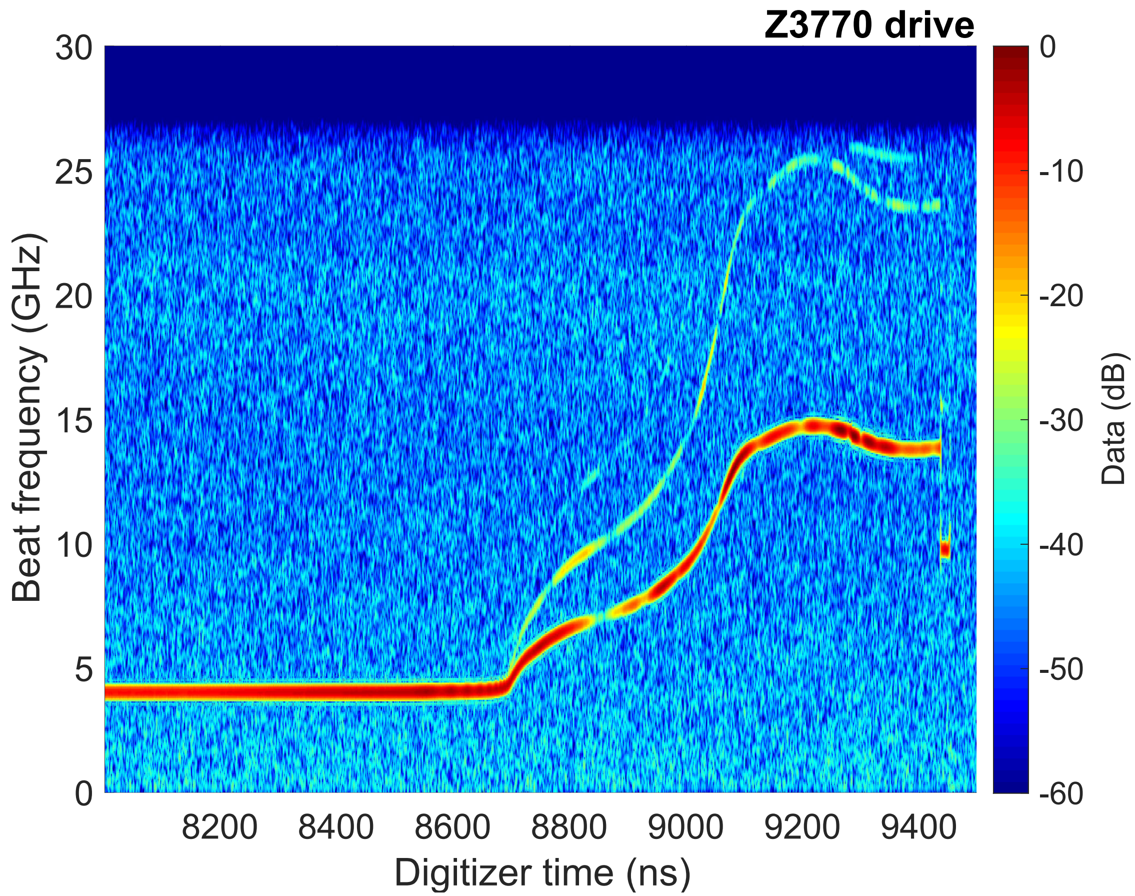
"Spectrograms never lie, but histories sometimes do", David Holtkamp (LANL)

Example data from Z3770

- Drive panel for monitoring magnetic stress



- Bare fiber probe
  - Three fiber pigtail
- Hann FFT (5/1 ns)
  - ~1.5 million pixels



What is thrifty analysis?

- Realizing that most of a conventional spectrogram is noise
- Using all FFT spectrum data, not just the power
- Removing computational inefficiencies where possible

Procedure:

Step 1: convert signal to Thrifty Array Format (*.taf)

Step 2: estimate signal noise floor

Step 3: select analysis parameters

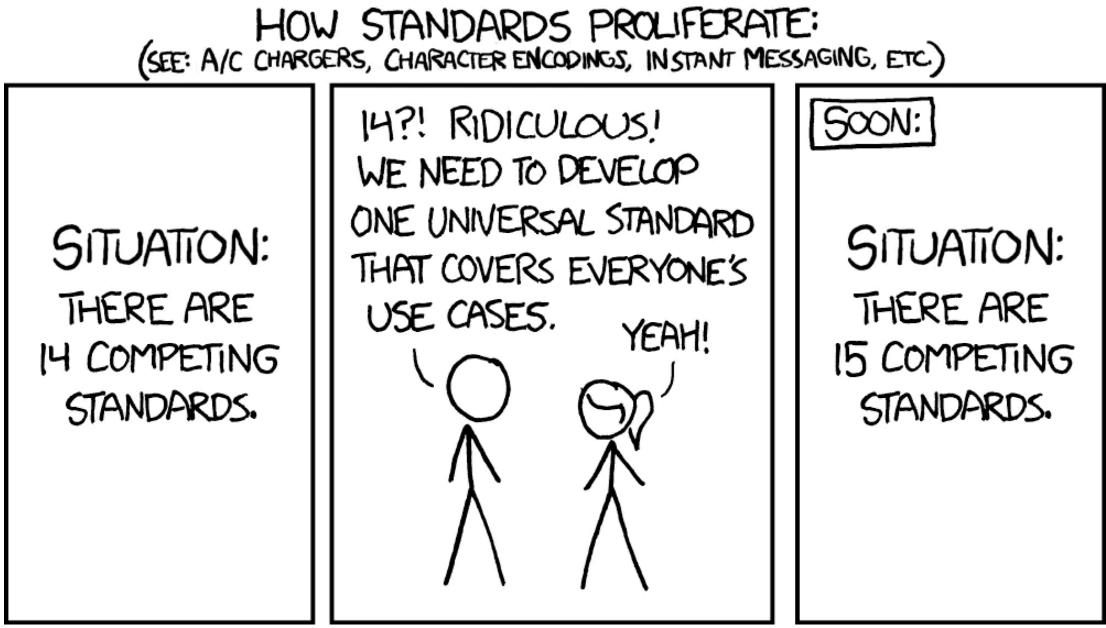
Step 4: create a sparse spectrogram

Step 5: visualization

Step 6: post processing and curve extraction(s)

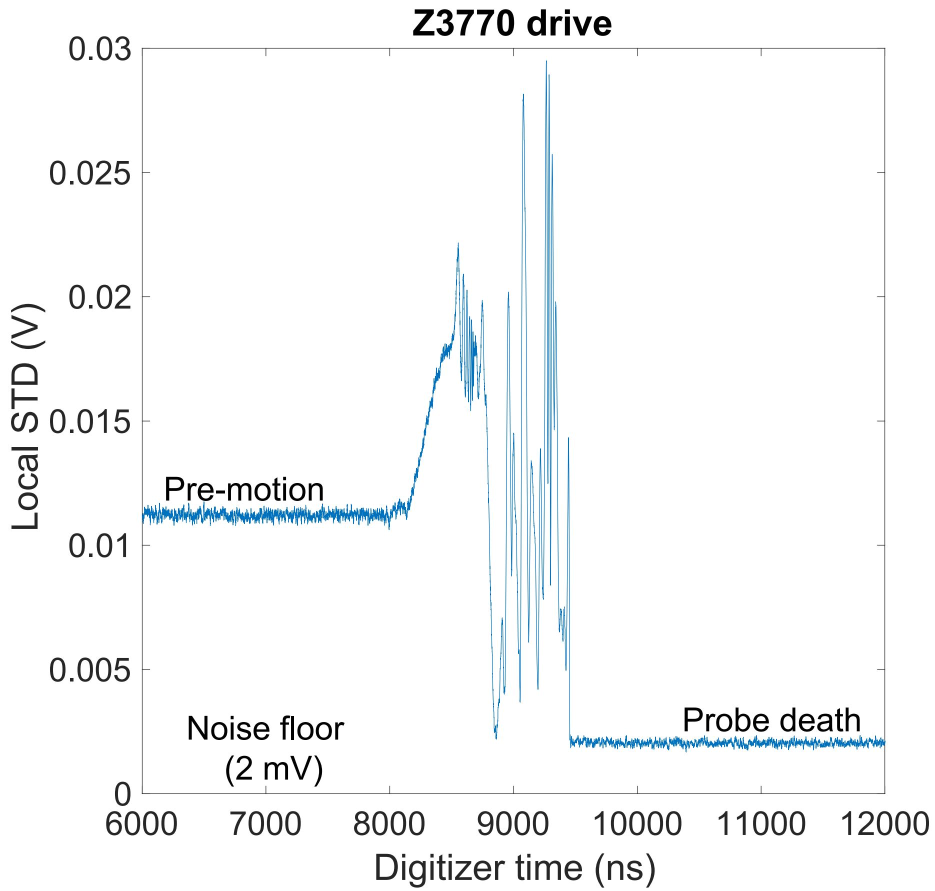
Step 1: convert signals to Thrifty Array Format

- Supported file types
  - Keysight **(*.h5**, *.bin)
    - One signal per file
  - Lecroy (*.trc)
  - Tektronix (*.isf, *.wfm)
  - NTS (*.dig)
  - ASCII (*.csv, …)
- Why add yet another format?
  - Binary *.taf files are readily mapped to memory
  - Standard modifications (time scale/shift) are easy
  - Analysis comments can be stored with array



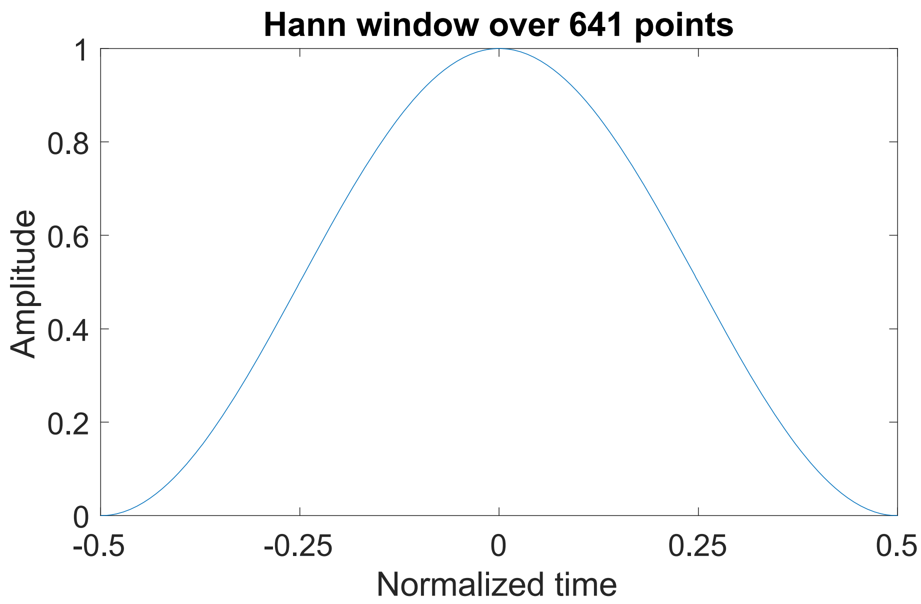
Step 2: estimate noise floor

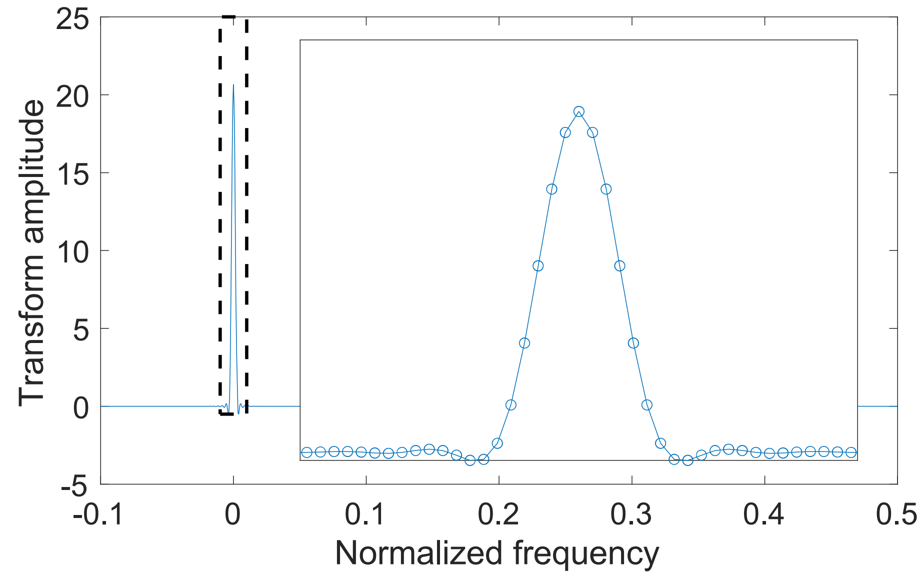
- PDV is dominated by photon and/or digitizer noise
  - Reference signal 15-20+ dB larger than signal
  - **Noise spectrum does not change with time**
- Estimate noise from signals with no coherent content
  - Target lasers off, reference lasers on
  - Late time data
- Time range 8-9.5 us most important in this example



Step 3: select analysis parameters

- Analysis duration and advance time
  - How **large** are the FFTs, and how much **time** is between them?
- Frequency-domain meshing
  - Automatic zero padding
- Digital window shape
  - (Feature may be removed)
- Example:
  - 5 ns @ 128 GS/s
  - >11 points for FFT peak



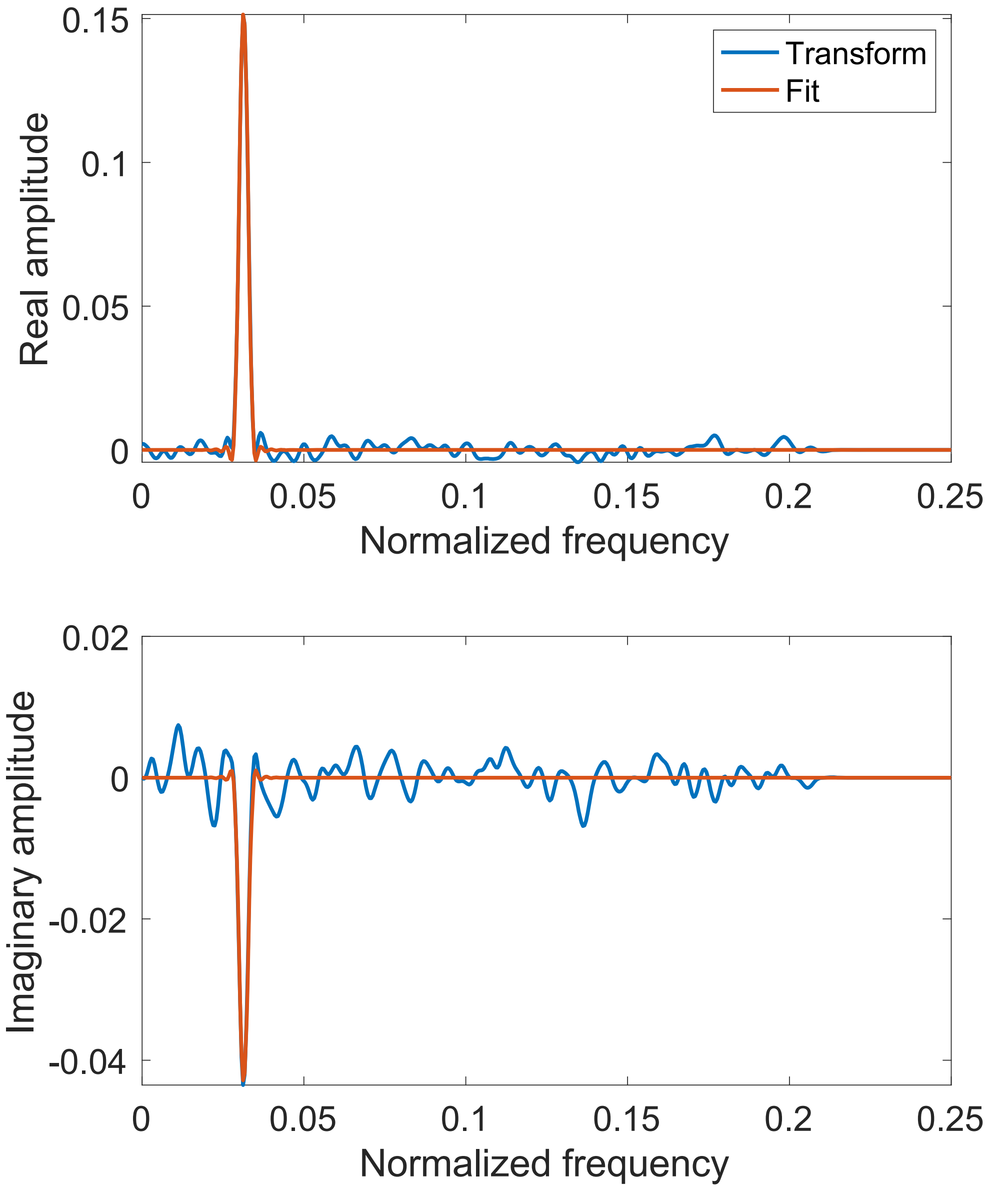


Step 4: create a sparse spectrogram

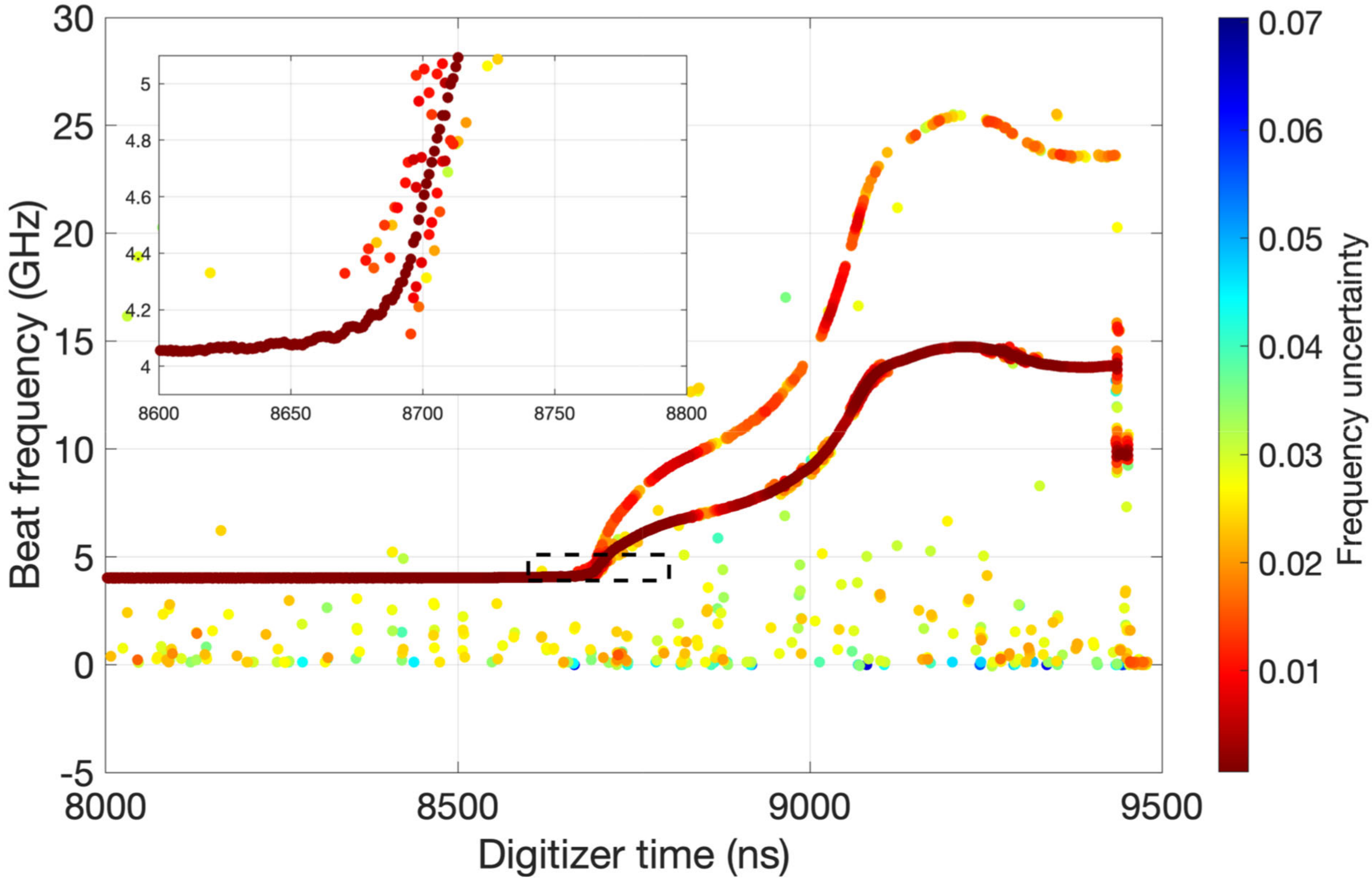
For every analysis duration:

1. Read local signal
2. Set fit to zero
3. Generate complex FFT
4. Calculate residual (FFT – fit)
5. Calculate Residual Square Area
6. If RSA < STD, go to next duration

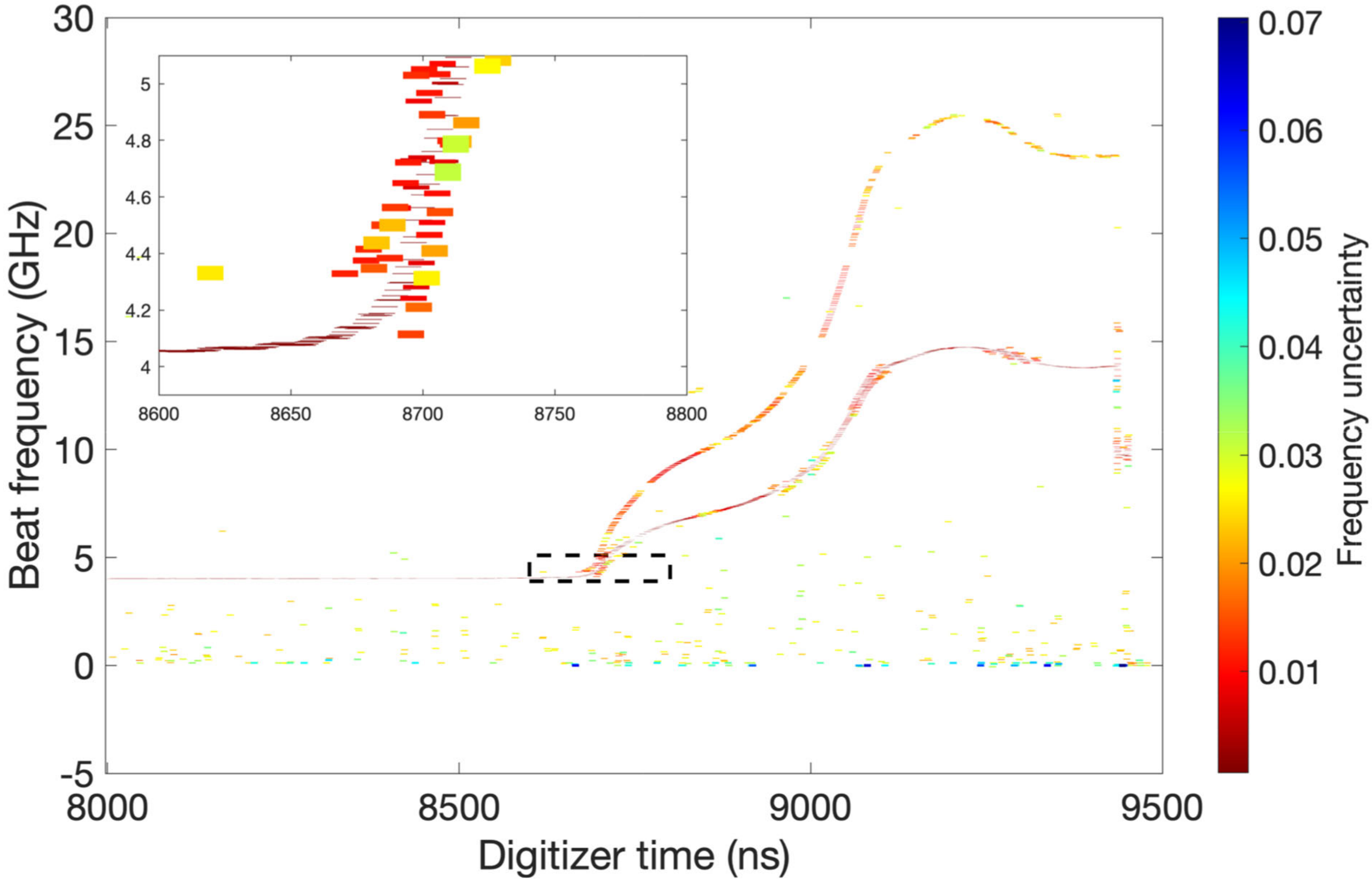
   Output peak locations and uncertainty
7. Add a new peak to the fit
8. Optimize all existing peaks
9. Go back to step 4



Step 5: visualization by points



Step 5: visualization by patches



Comparison

- Thrifty spectrogram stores high-resolution information in a few thousand points
- Conventional spectrogram would require billions/trillions of points for the same fidelity
- Unlike a history, no assumptions have been made about the number of beat frequencies or their time variation
  - Points/patches are not intrinsically connected at this stage

Thrifty analysis summary

- Signal analysis yields sparse spectrograms
  - Complex FFT analysis at every time step
  - Four numbers (time, duration, frequency, uncertainty) stored for each spectral peak
  - High resolution without massive files/memory use
- Curve selection happens later on
  - End user can focus on what is really there
    - How many distinct frequencies are there?
  - Noise artifacts **should** be minimal
  - Lots of development remains to be done

Some important details (time permitting)

- Complex fit uses window transform as basis function
  - Real signals have positive and negative frequency peaks
  - Positions determined by nonlinear least squares
  - Amplitudes determined by linear least squares
    - Amplitudes can be positive or negative
  - Energy must be conserved!

- Noise floor has two roles
  - Directly proportional to frequency uncertainty
  - Controls when to stop adding peaks
  - Statistical fluctuations in the noise floor are observed over short time durations
  - Setting analysis cutoff somewhat higher than steady RMS value avoids many (but not all) junk points