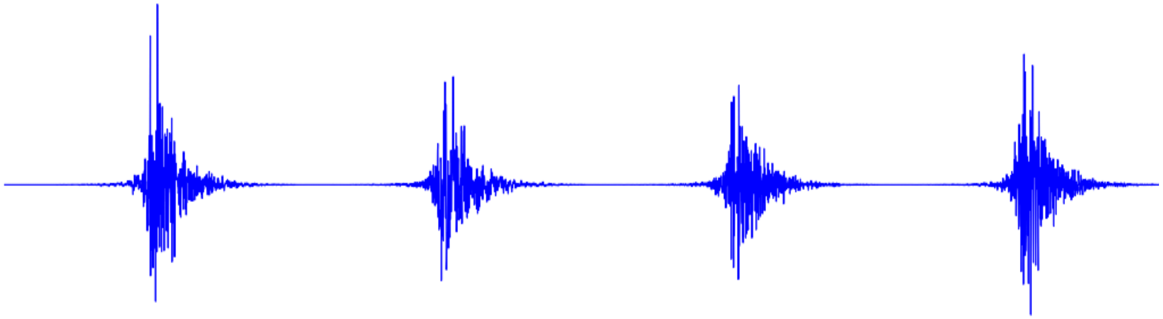

Practical application of cyclic spectroscopy to pulsar signals

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With help from

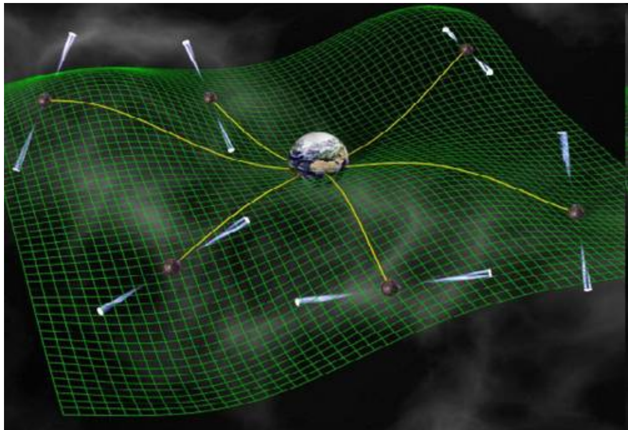
- The NANOGrav Interstellar Medium Mitigation (IMM) group
  - Jim Cordes
  - Paul Demorest
  - Tim Dolch
  - Maura McLaughlin
  - Lina Levin
  - Nipuni Palliyaguru
  - Dan Stinebring
- Arecibo Engineers
  - Luis Quintero
  - Phil Perillat
  - Dana Whitlow
- And
  - Willem van Straten
  - Ue-Li Pen

Outline

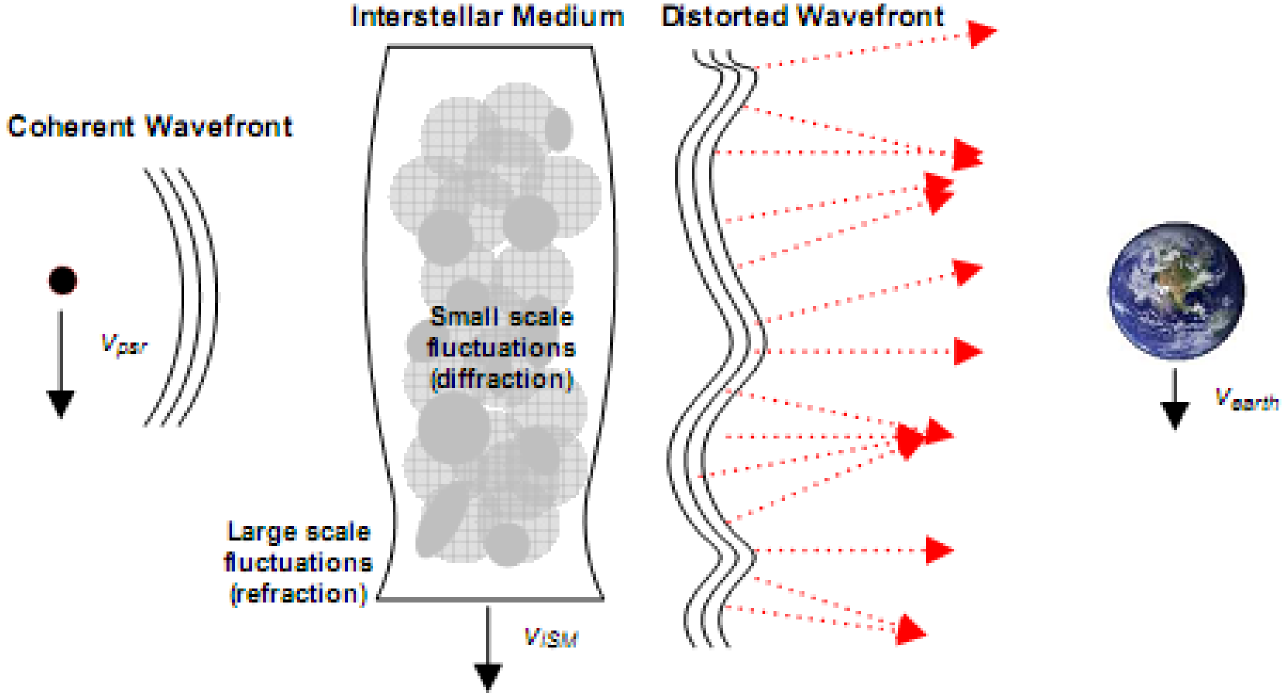
- Motivation
- Pulsar signals and the ISM
- Intro to cyclic spectroscopy – what is it?
- Deconvolution with CS
- Results from real observations
- How well can we expect CS deconvolution to perform?
- Towards routine use of CS

Motivation: Improving pulsar timing

- Careful measurement of time of arrival of pulsar signals provides a unique probe of exotic physics.
- Time of arrival accuracy scales as SNR / width
- Pulsars typically have steep spectra → would like to observe at lowest frequencies
- But… at frequencies below ~1 GHz, pulsar time of arrival estimation is strongly influenced by scattering in the interstellar medium (scales $\sim f^{-4.4}$)
- Projects like NANOgrav need more pulsars which can be accurately timed



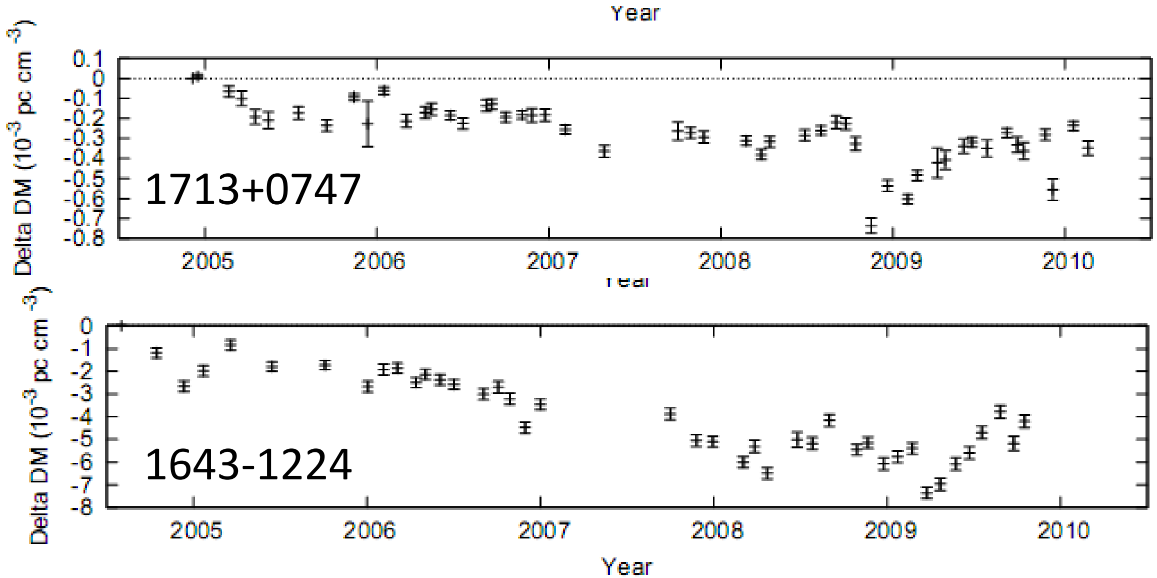
Effects of the ISM



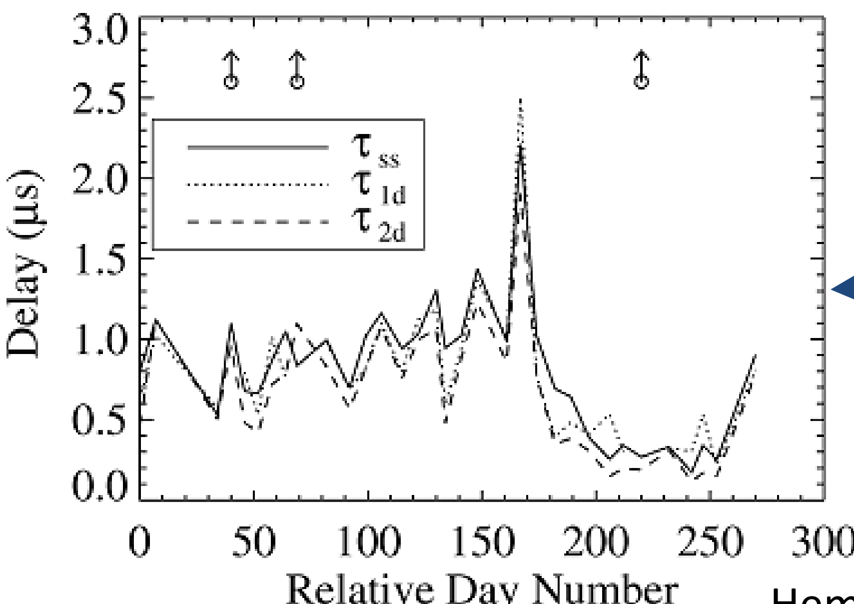
- Dispersion (total electron content)
- Diffraction
- Refraction

Need to monitor the ISM!

Dispersion Measure variations



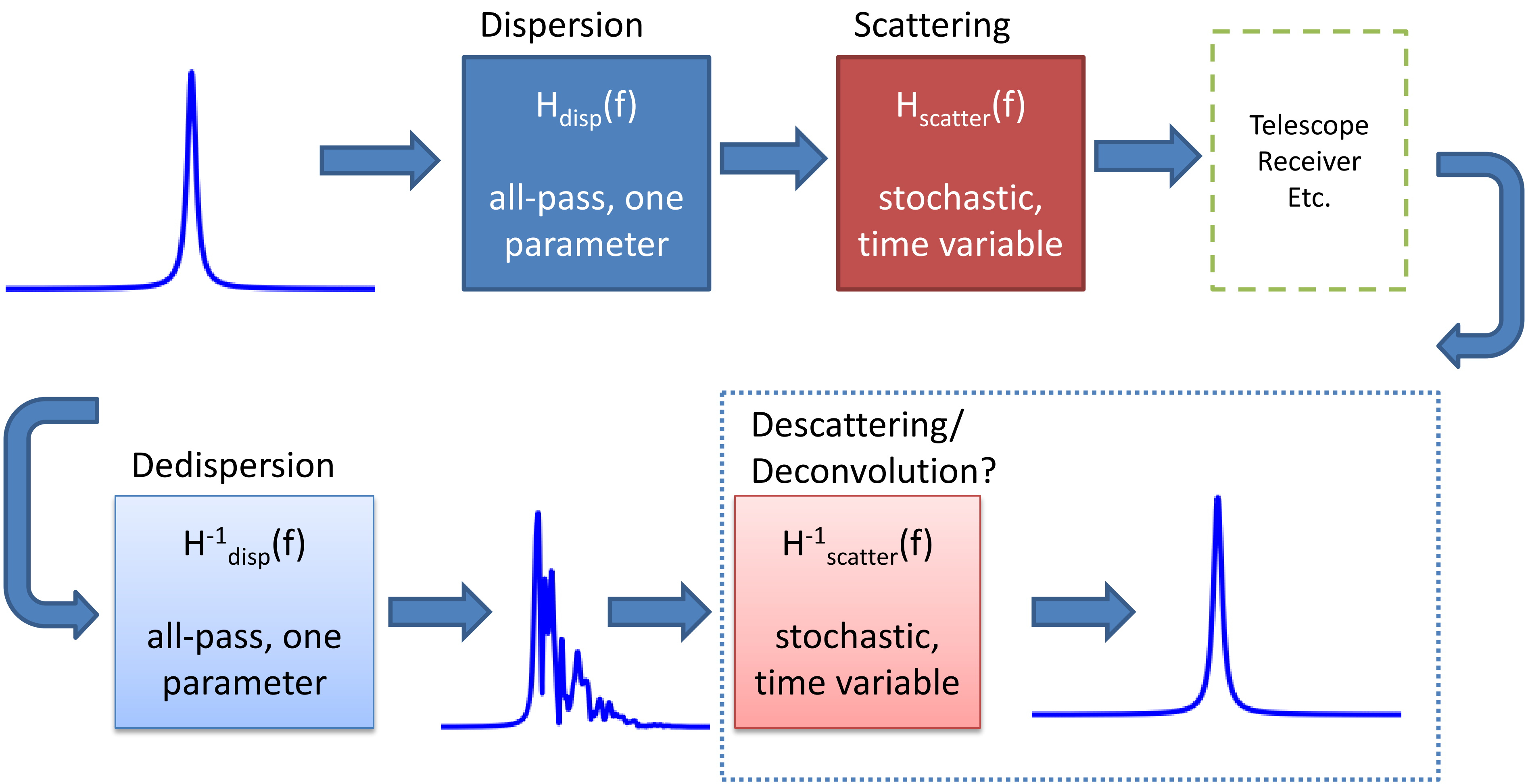
Demorest et al. 2013



Scattering Time variations

Hemberger & Stinebring 2008

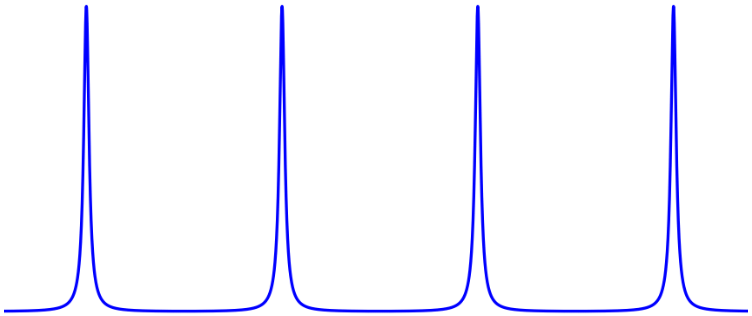
Motivation: Deconvolving the ISM

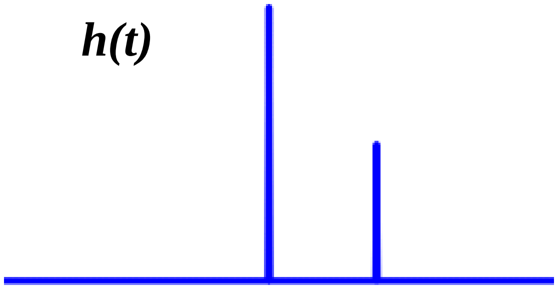


The dream...

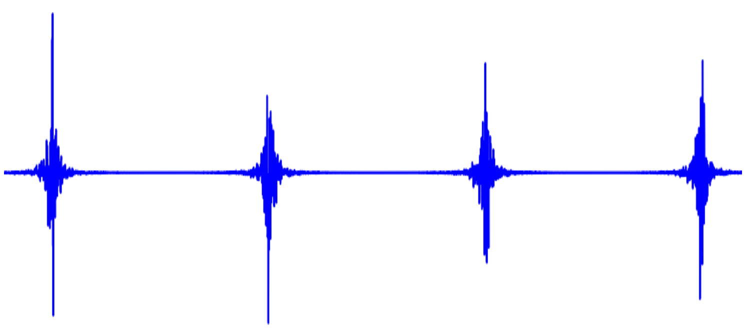
Intro to pulsar signals

Idealized pulsar signal

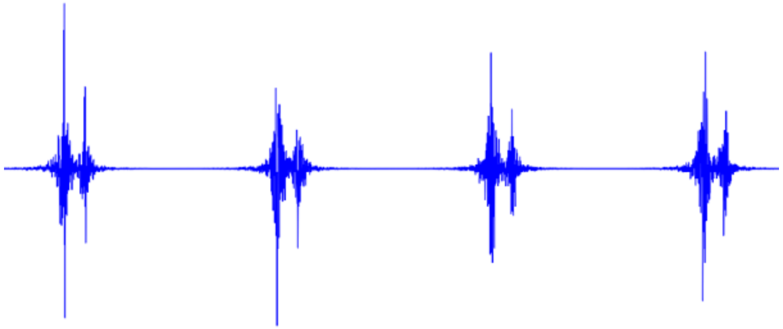




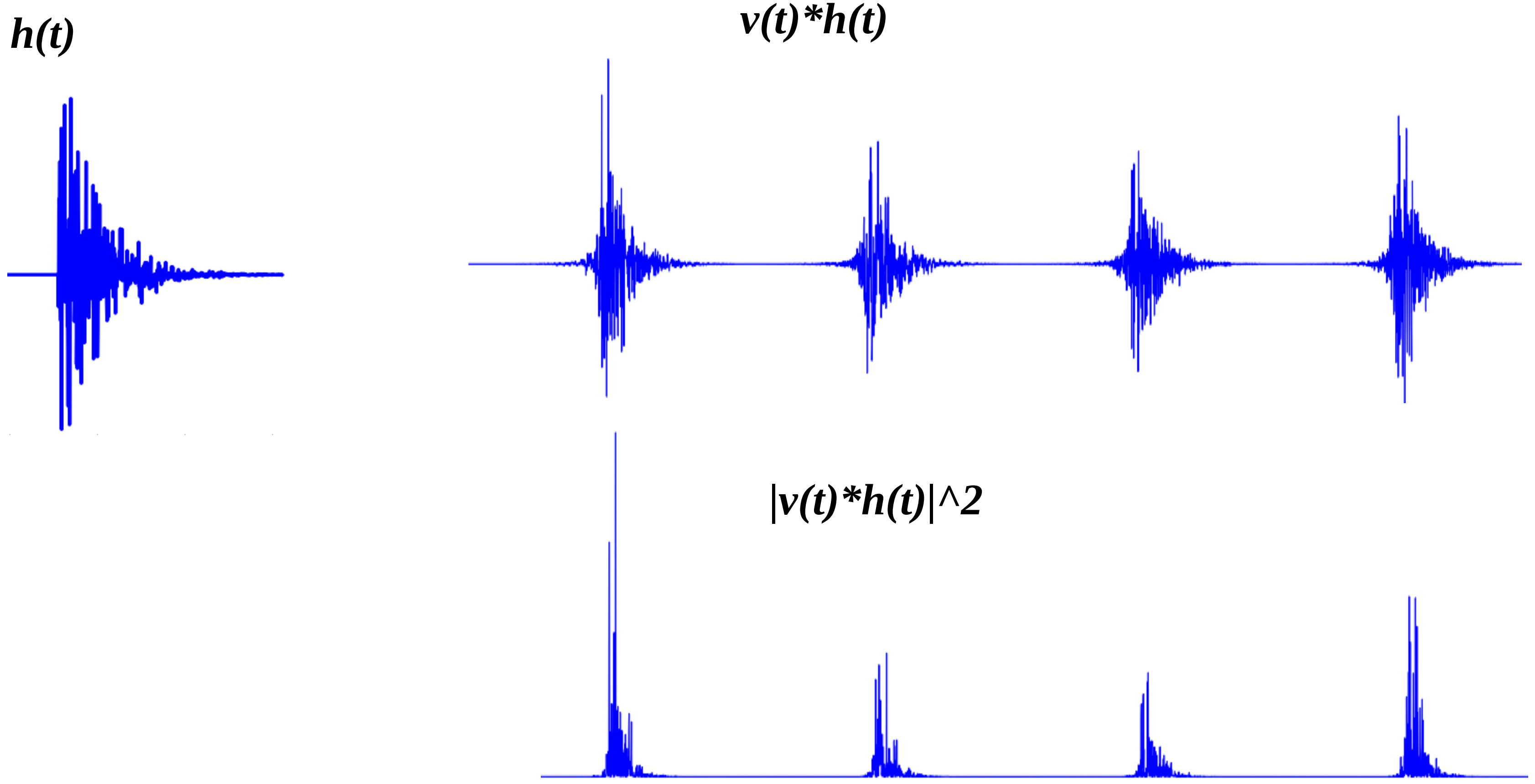
More realistic pulsar signal



After convolution

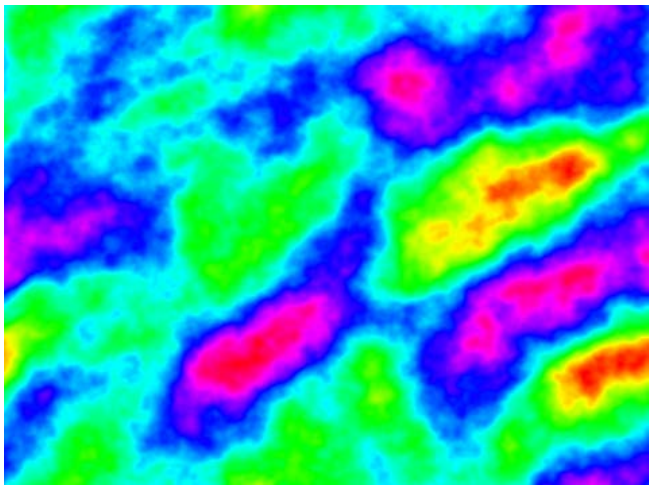


A more realistic transfer function

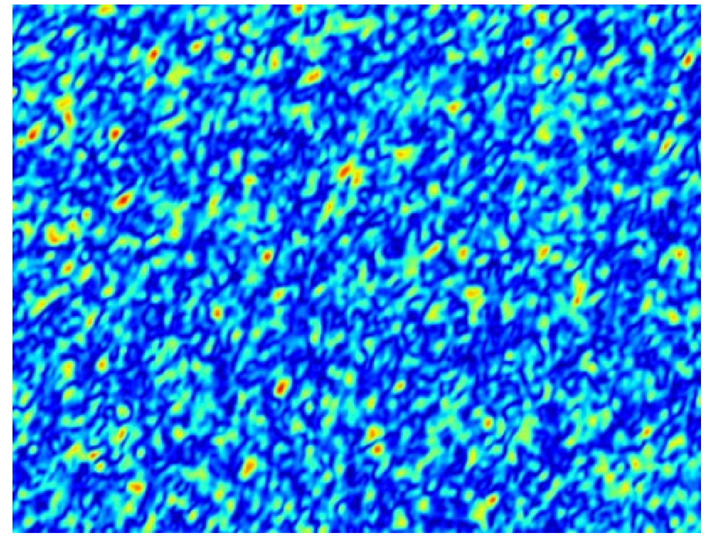


Aside: What does ISM scattering look like?

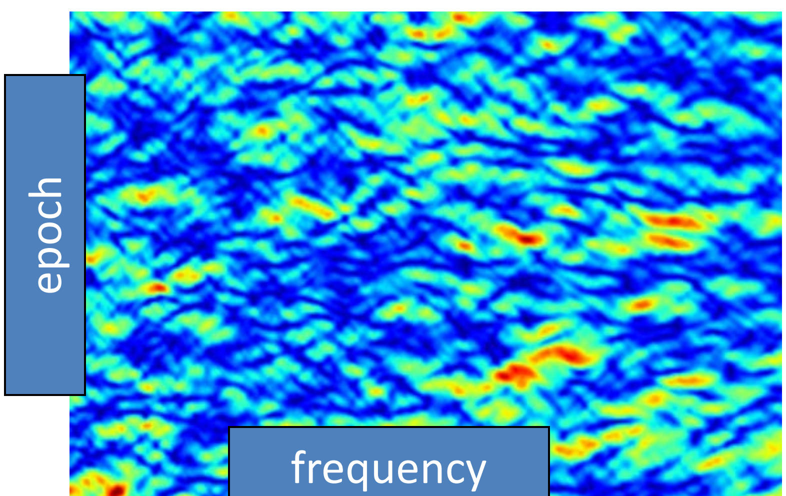
Phase perturbations from clumpy ISM



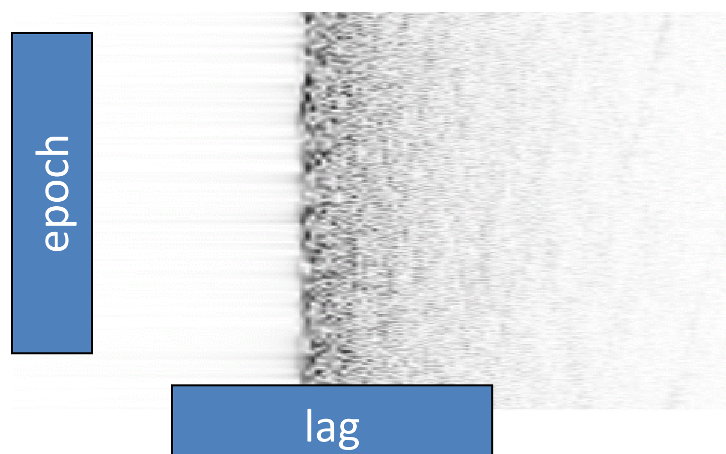
Electric field at earth



Dynamic spectrum

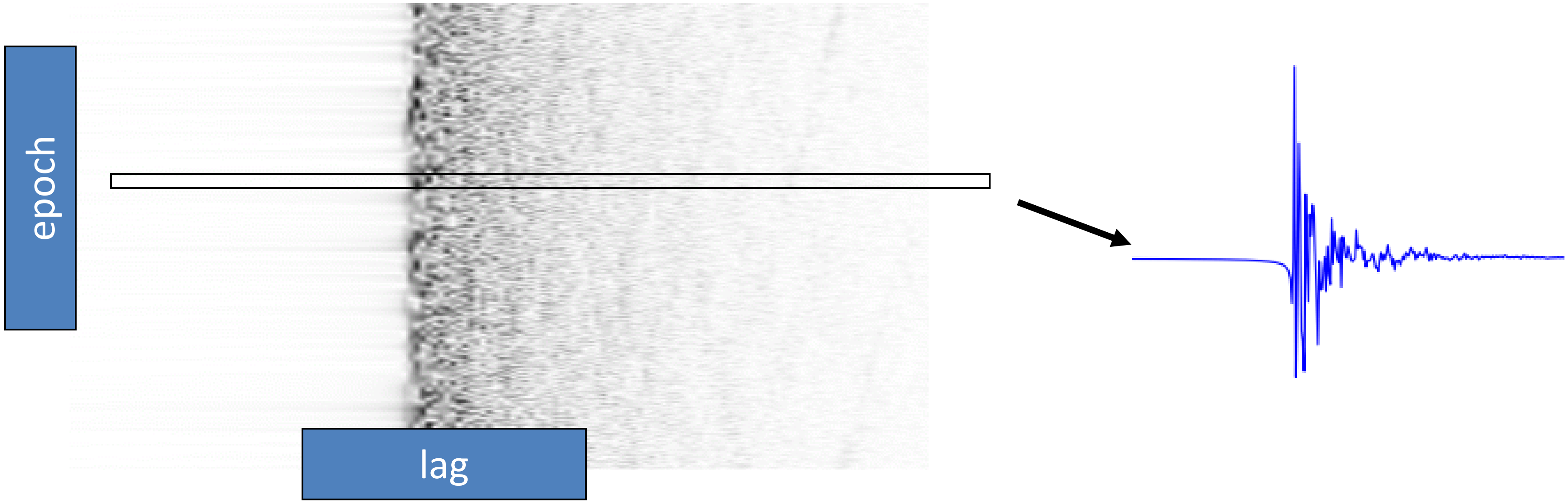


Impulse response functions

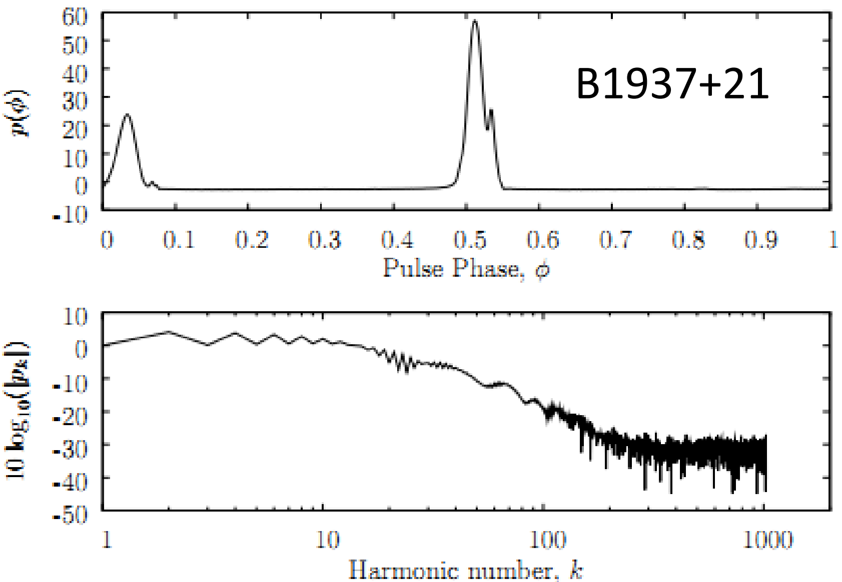


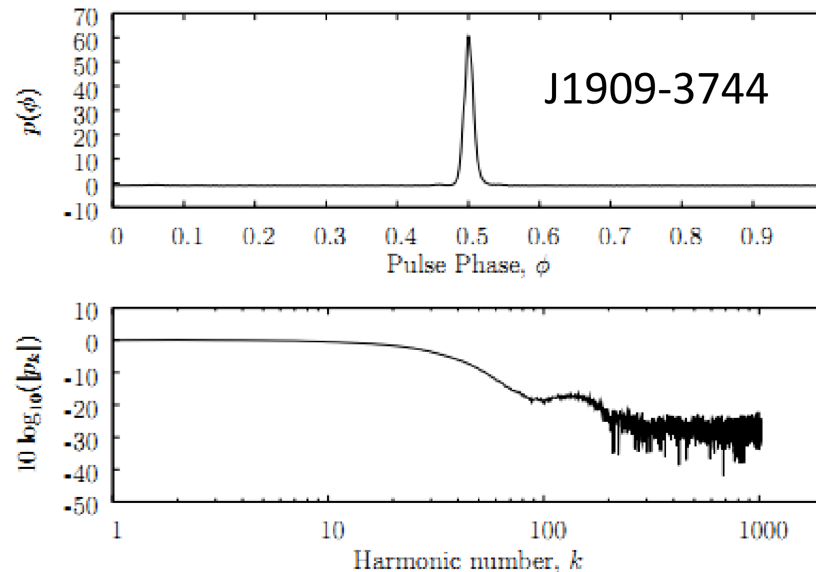
Simulations based on code from Coles et al. 2011

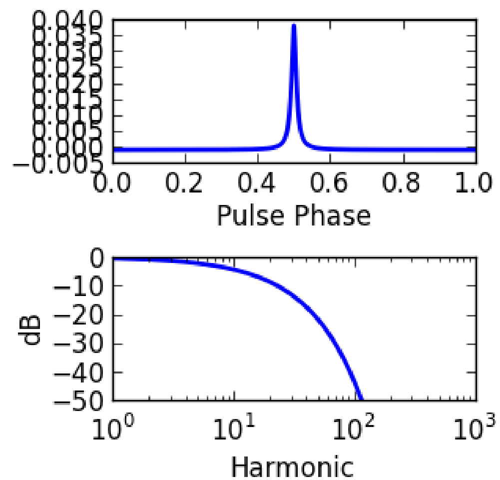
Evolving complex impulse response function



Pulse profiles and Harmonics

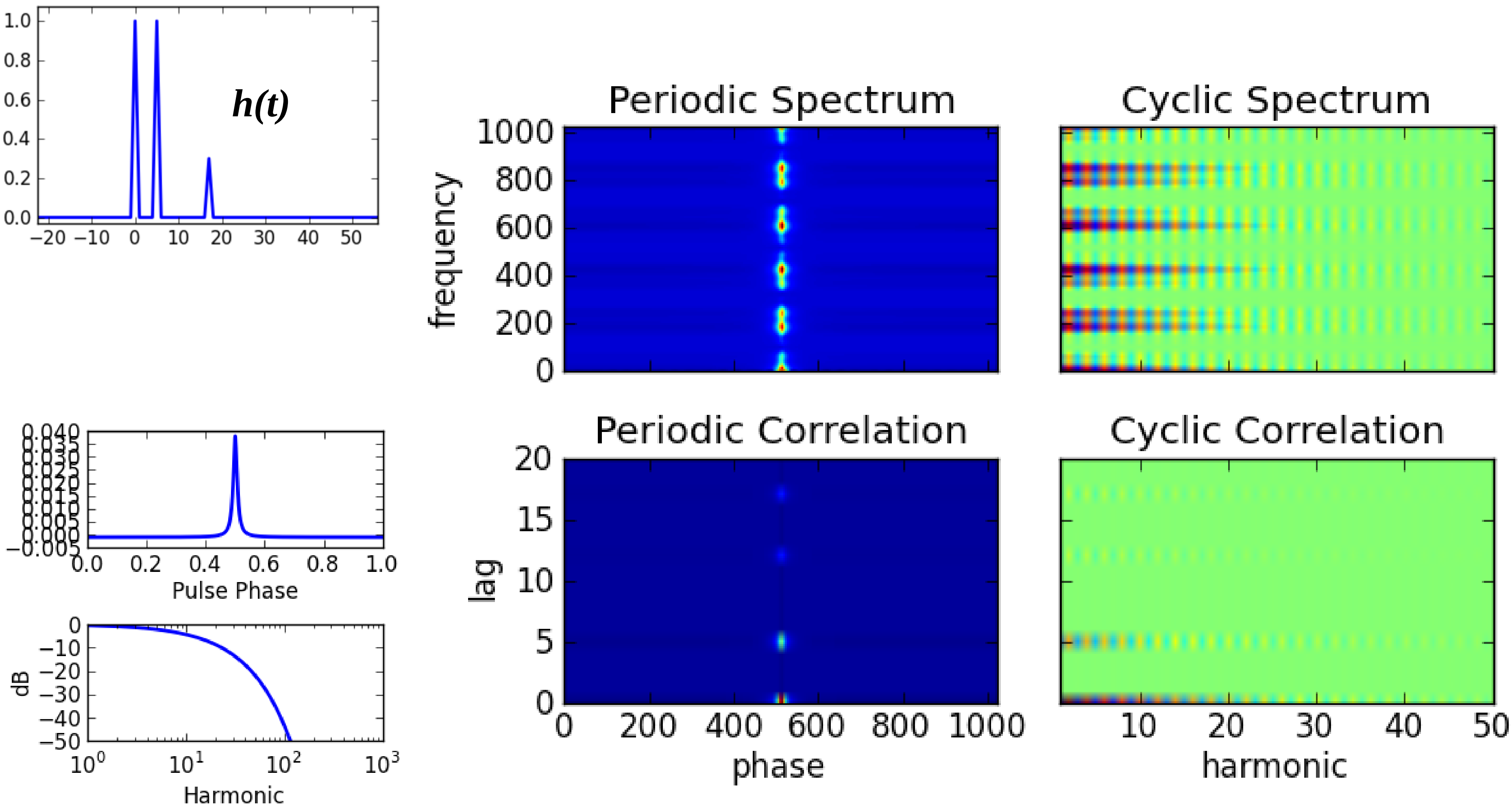






Plots from P. Demorest PhD thesis

Intro to cyclic spectrscopy:
A simple simulated example



Traditional spectrum of filtered noise: Only magnitude is retained

Observed signal

ISM scattering

Original pulsar signal

$$y(t) = h(t) \star x(t)$$

$$Y(\nu) = H(\nu)X(\nu)$$

$$S_y(\nu) = \left|H(\nu)\right|^2 S_x(\nu)$$

Cyclic spectrum of filtered cyclostationary noise: Phase information can be retrieved!

Observed signal

ISM scattering

Original pulsar signal

$$y(t) = h(t) \star x(t)$$

$$Y(\nu) = H(\nu)X(\nu)$$

Radio frequency

Pulsar harmonic frequency

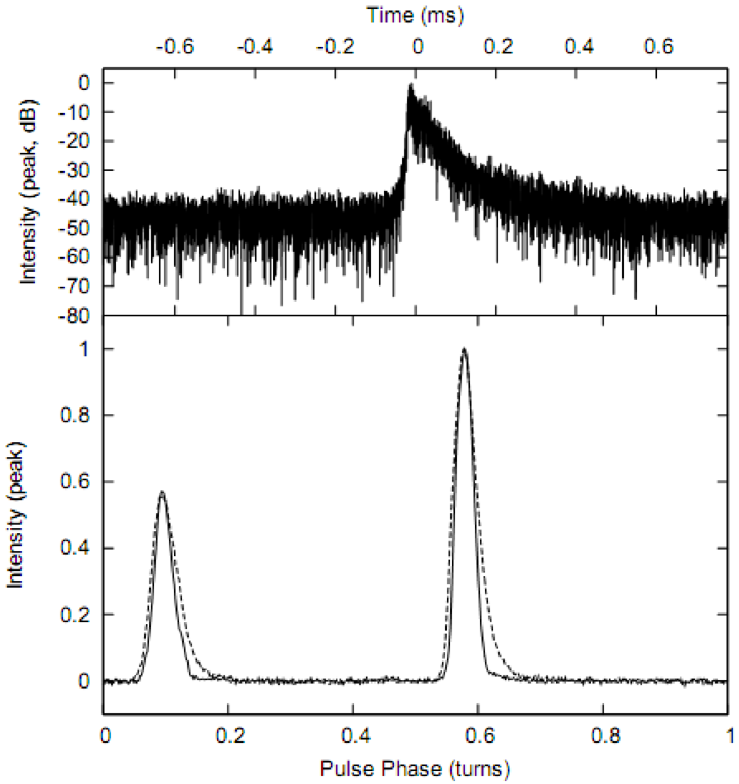
$$S_y(\nu) = \left|H(\nu)\right|^2 S_x(\nu)$$

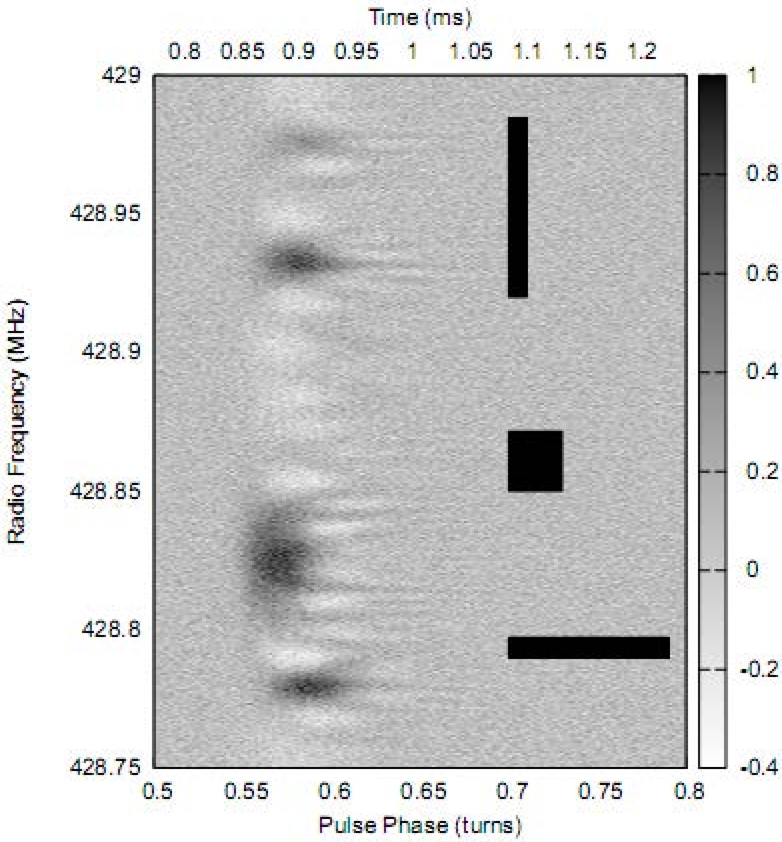
$$S_y(\nu;\alpha) = H(\nu + \alpha/2)H^*(\nu - \alpha/2)S_x(\nu;\alpha)$$

$$S_y(\nu;\alpha_n) = H_{ISM}(\nu + \frac{\alpha_n}{2})H^*_{ISM}(\nu - \frac{\alpha_n}{2})I(n)S_0$$

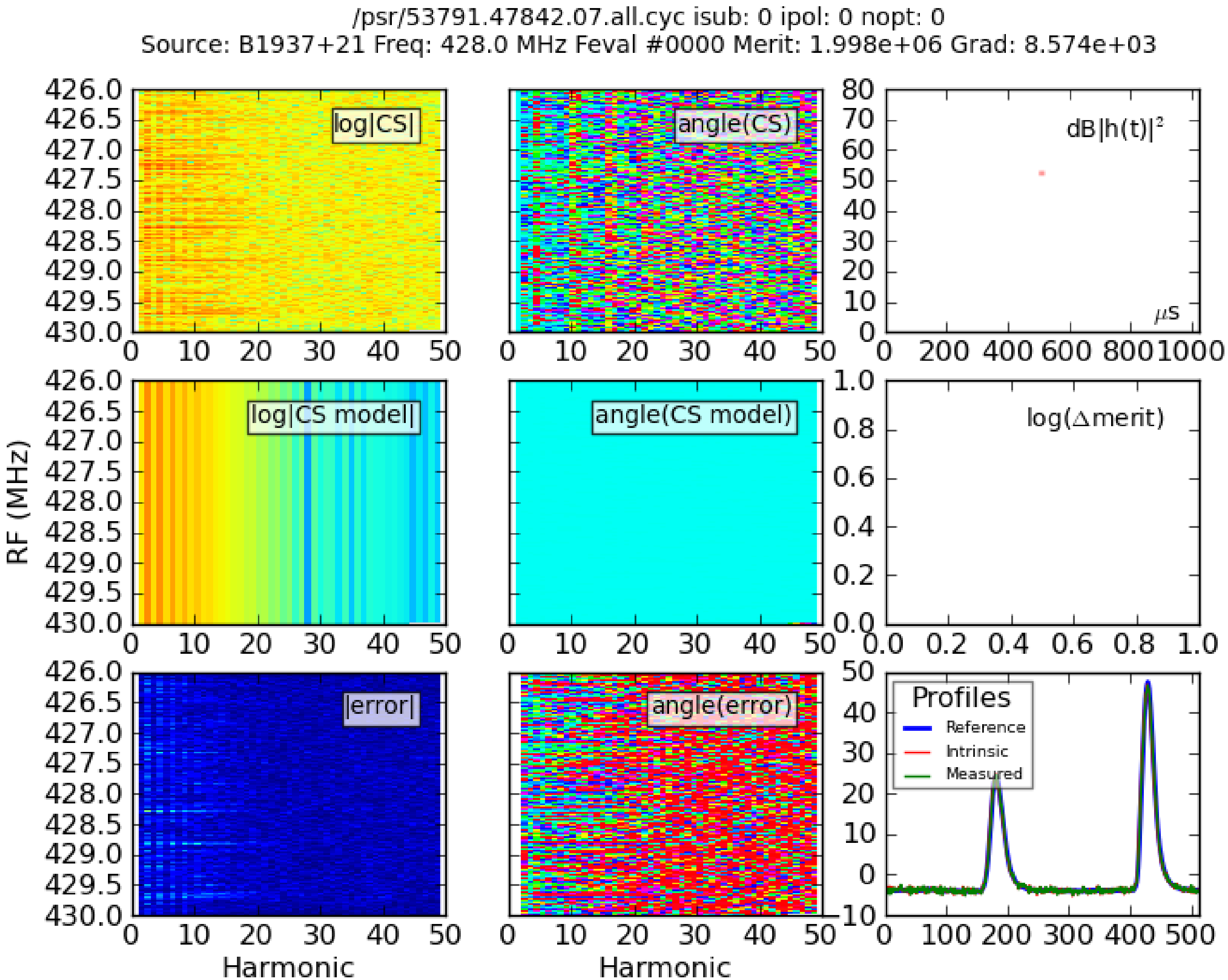
First application: B1937+21 at Arecibo

- Single 4 MHz subband using ASP @ 430 MHz
- Demorest 2011 arXiv:1106.3345

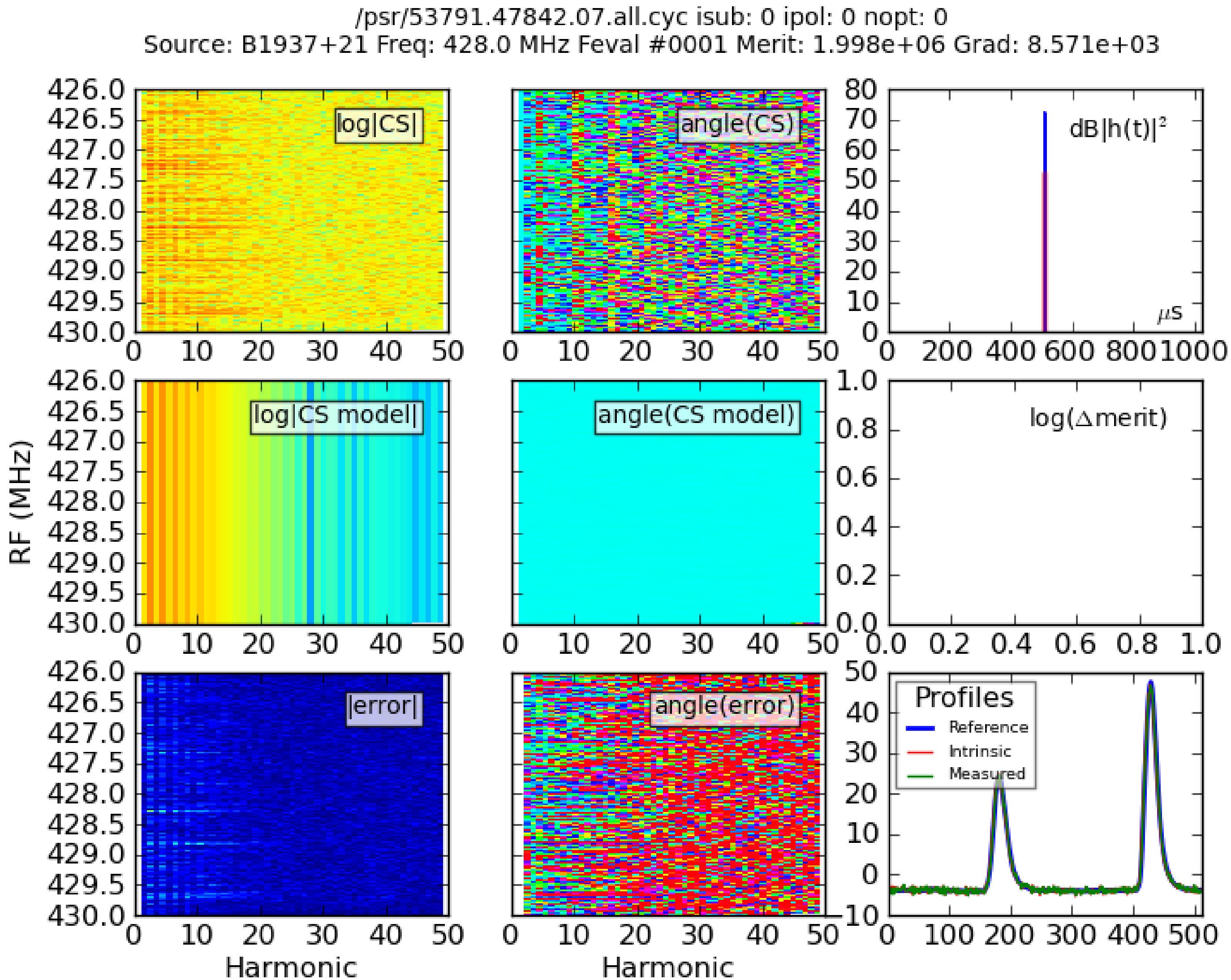




B1937+21 Deconvolution step-by-step

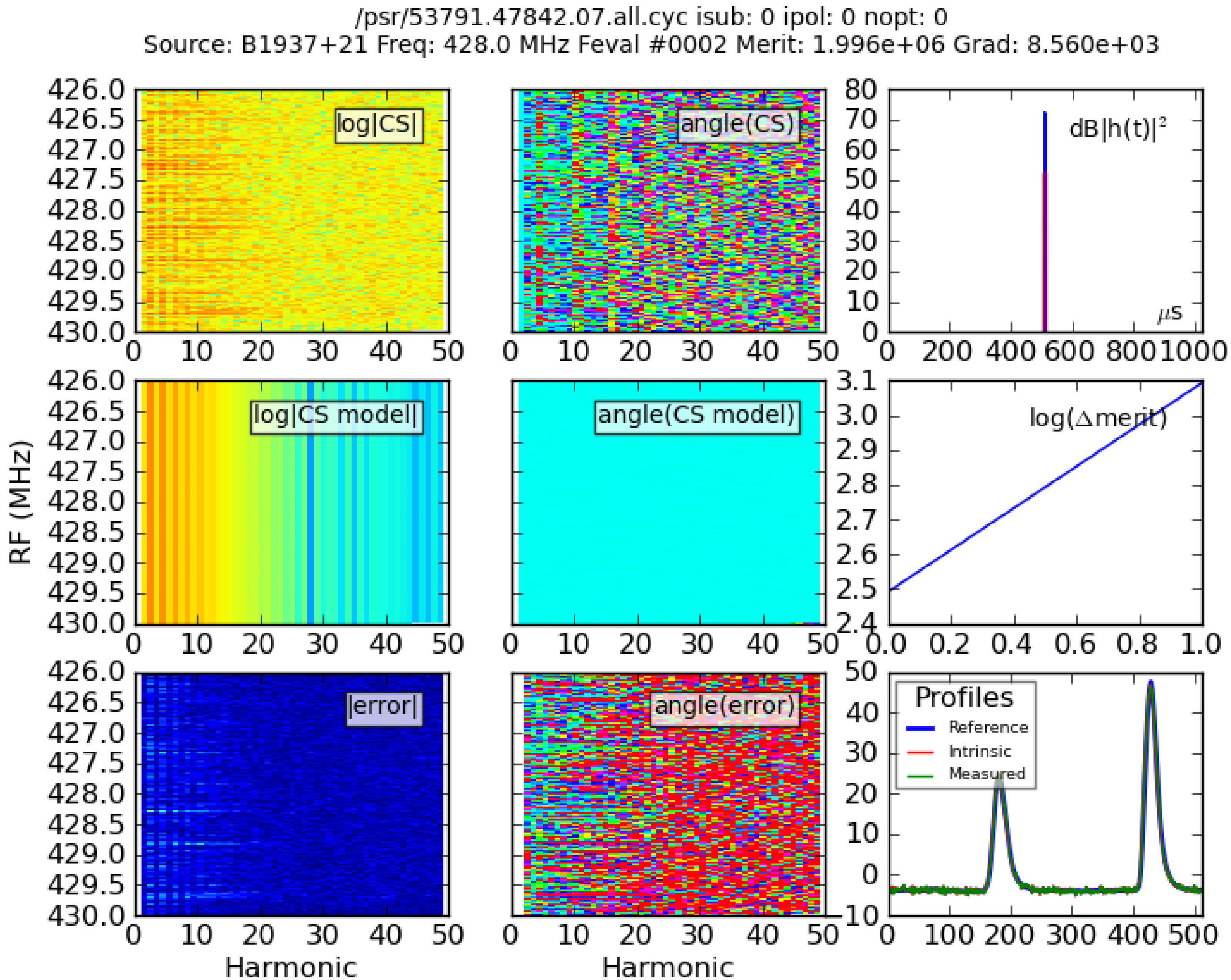


Iteration 2



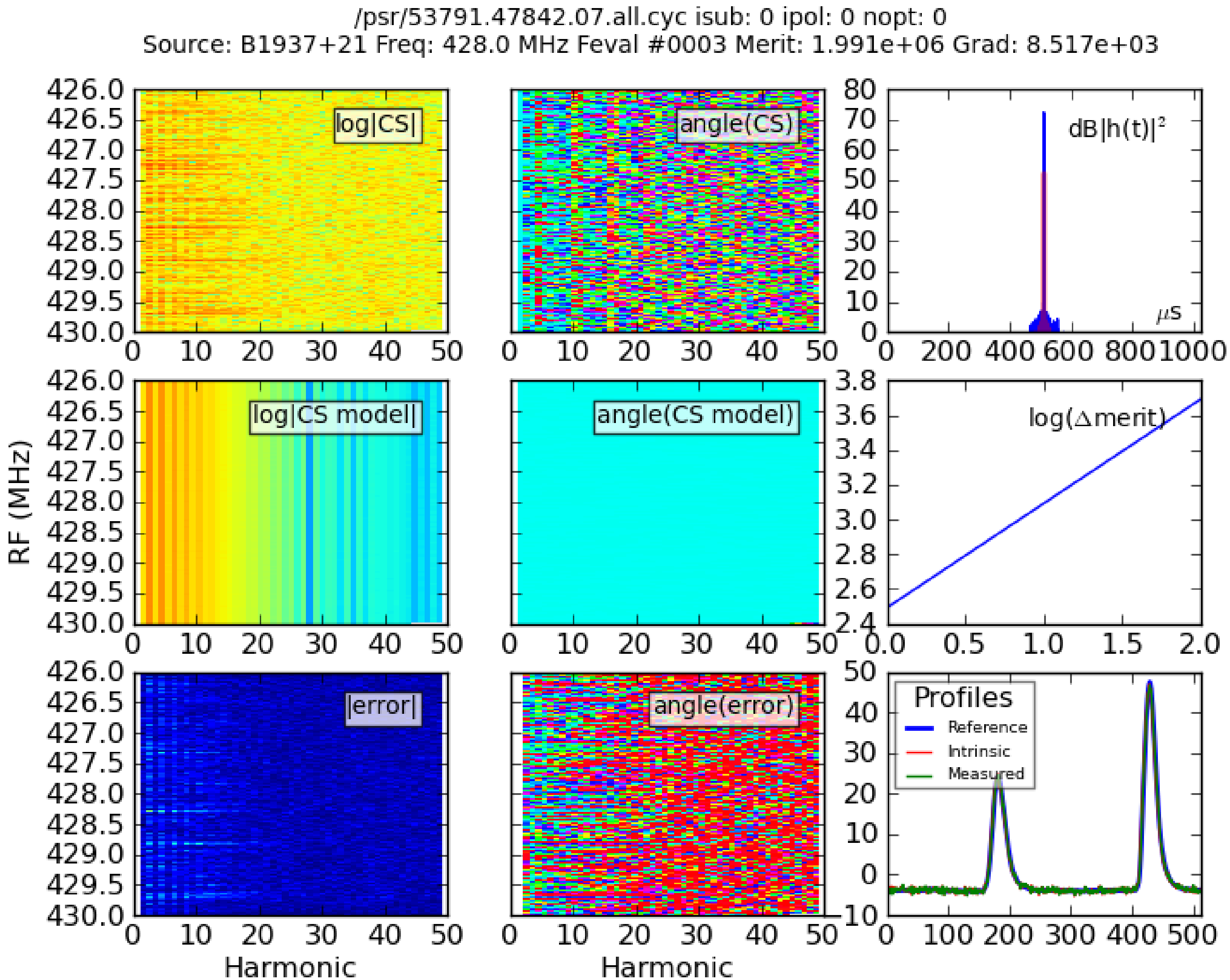
/psr/53791.47842.07.all.cyc isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 428.0 MHz Feval #0001 Merit: 1.998e+06 Grad: 8.571e+03
log|CS|
angle(CS)
dB|h(t)|²
μs
log|CS model|
angle(CS model)
log(Δmerit)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
RF (MHz)
Harmonic
Harmonic

Iteration 3

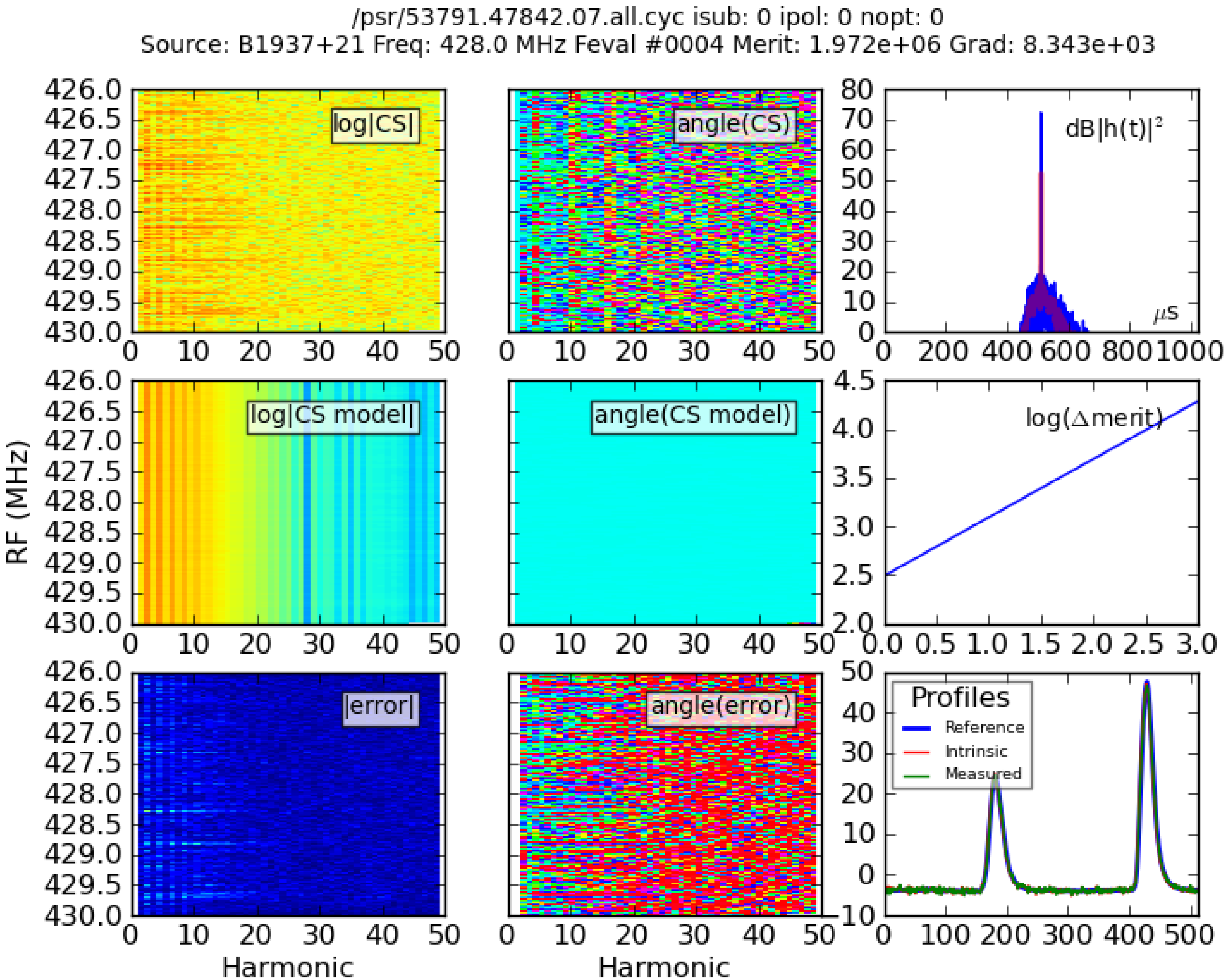


/psr/53791.47842.07.all.cyc isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 428.0 MHz Feval #0002 Merit: 1.996e+06 Grad: 8.560e+03
log|CS|
angle(CS)
dB|h(t)|²
μs
log|CS model|
angle(CS model)
log(Δmerit)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
RF (MHz)
Harmonic
Harmonic

Iteration 4


/psr/53791.47842.07.all.cyc isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 428.0 MHz Feval #0003 Merit: 1.991e+06 Grad: 8.517e+03
log|CS|
angle(CS)
dB|h(t)|²
μs
log|CS model|
angle(CS model)
log(Δmerit)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
RF (MHz)
Harmonic
Harmonic

Iteration 5



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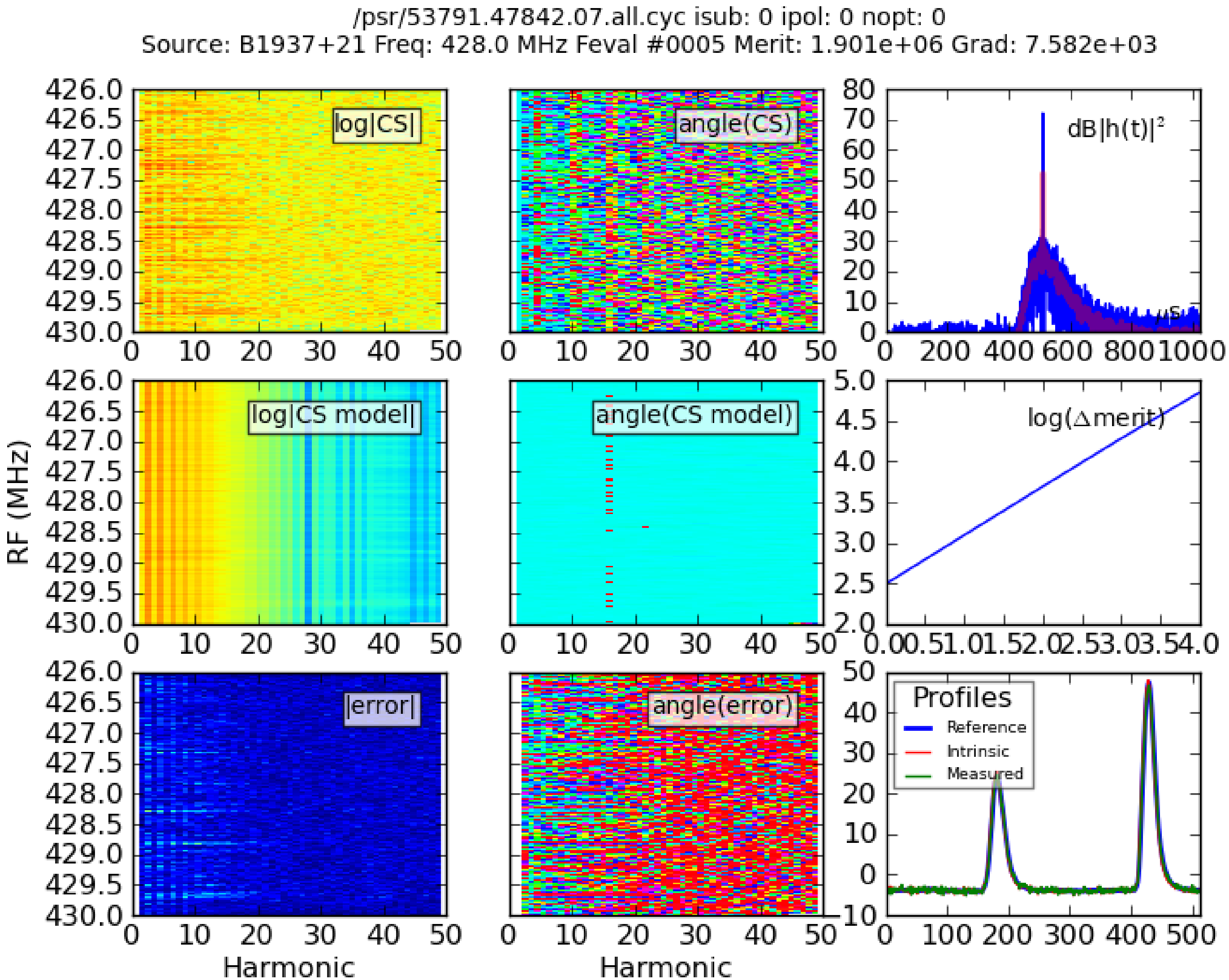
Source: B1937+21 Freq: 428.0 MHz Feval #0004 Merit: 1.972e+06 Grad: 8.343e+03
log|CS|
angle(CS)
dB|h(t)|²
μs
log|CS model|
angle(CS model)
log(Δmerit)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
RF (MHz)
Harmonic
Harmonic

Iteration 6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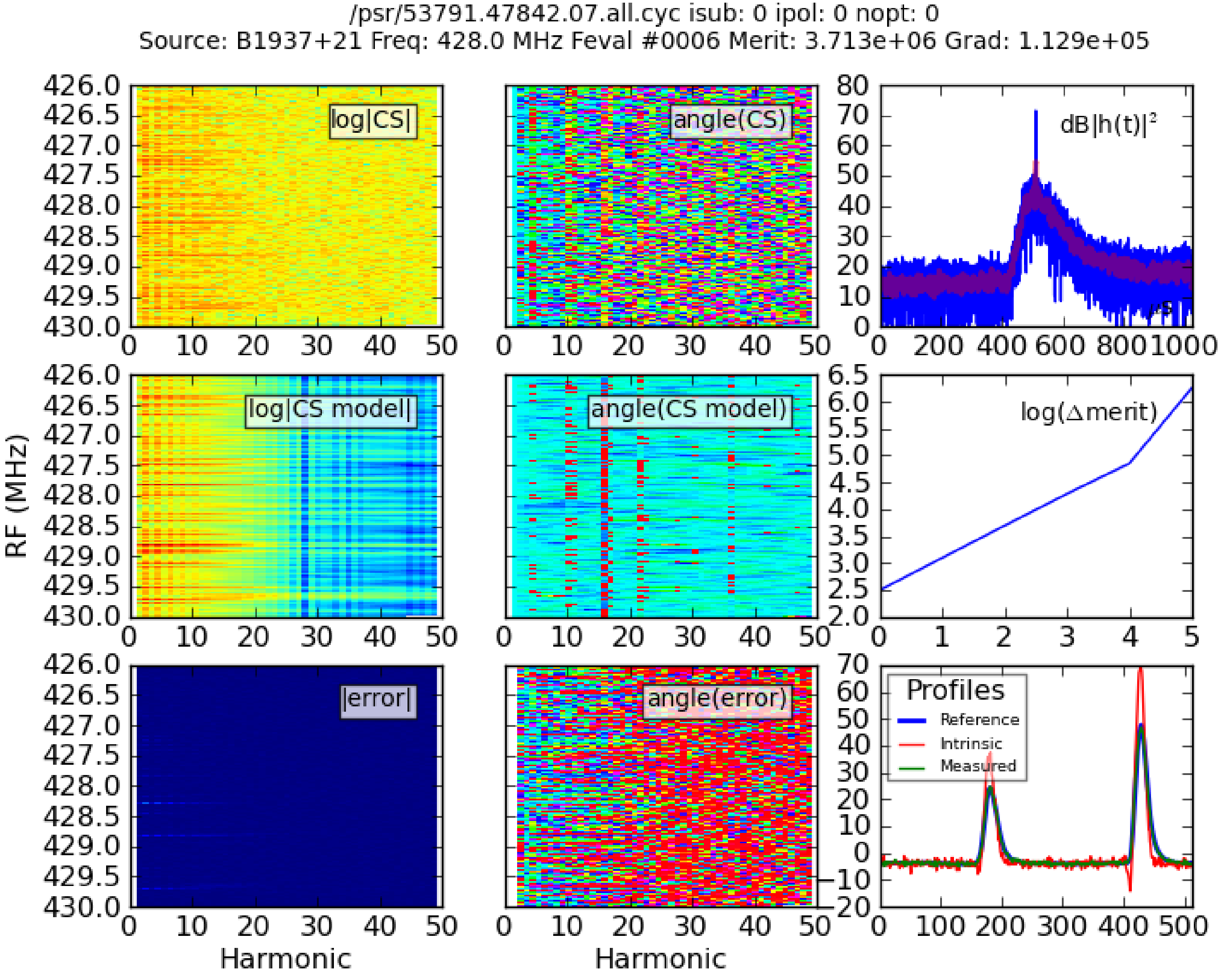
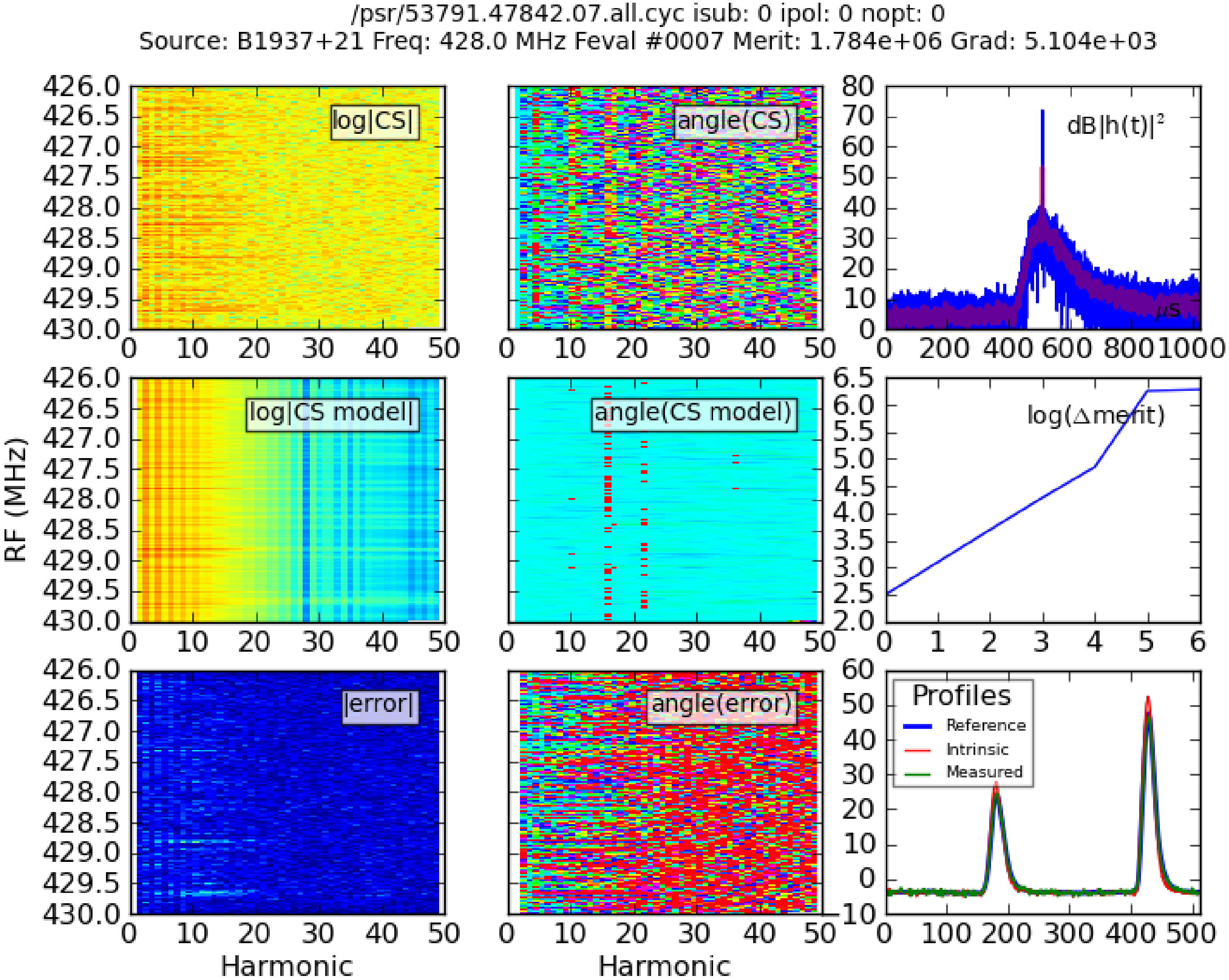
Source: B1937+21 Freq: 428.0 MHz Feval #0005 Merit: 1.901e+06 Grad: 7.582e+03
log|CS|
angle(CS)
dB|h(t)|²
μs
log|CS model|
angle(CS model)
log(Δmerit)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
RF (MHz)
Harmonic
Harmonic

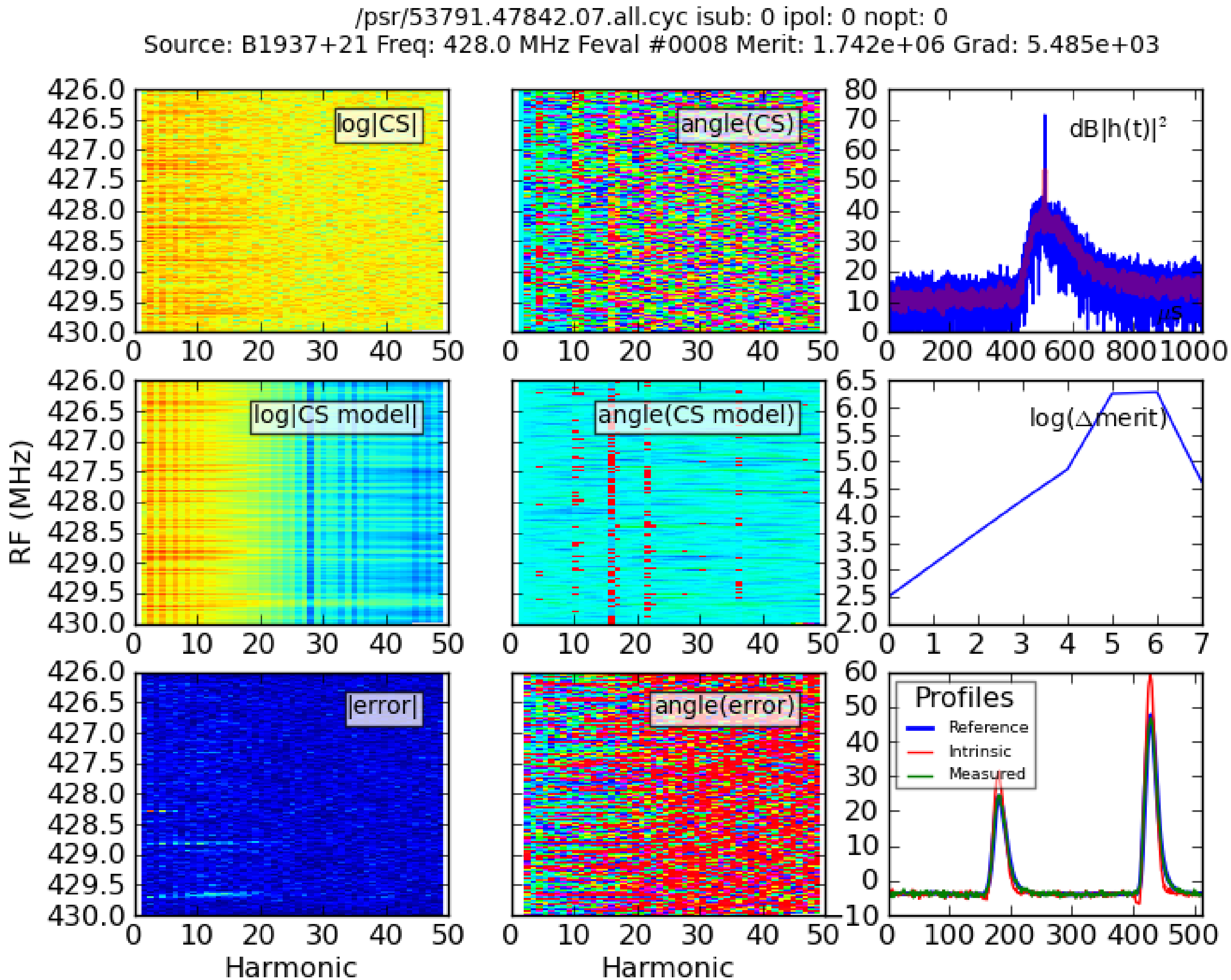
Iteration 7


/psr/53791.47842.07.all.cyc isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 428.0 MHz Feval #0006 Merit: 3.713e+06 Grad: 1.129e+05
log|CS|
angle(CS)
dB|h(t)|²
log|CS model|
angle(CS model)
log(Δmerit)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
RF (MHz)
Harmonic
Harmonic

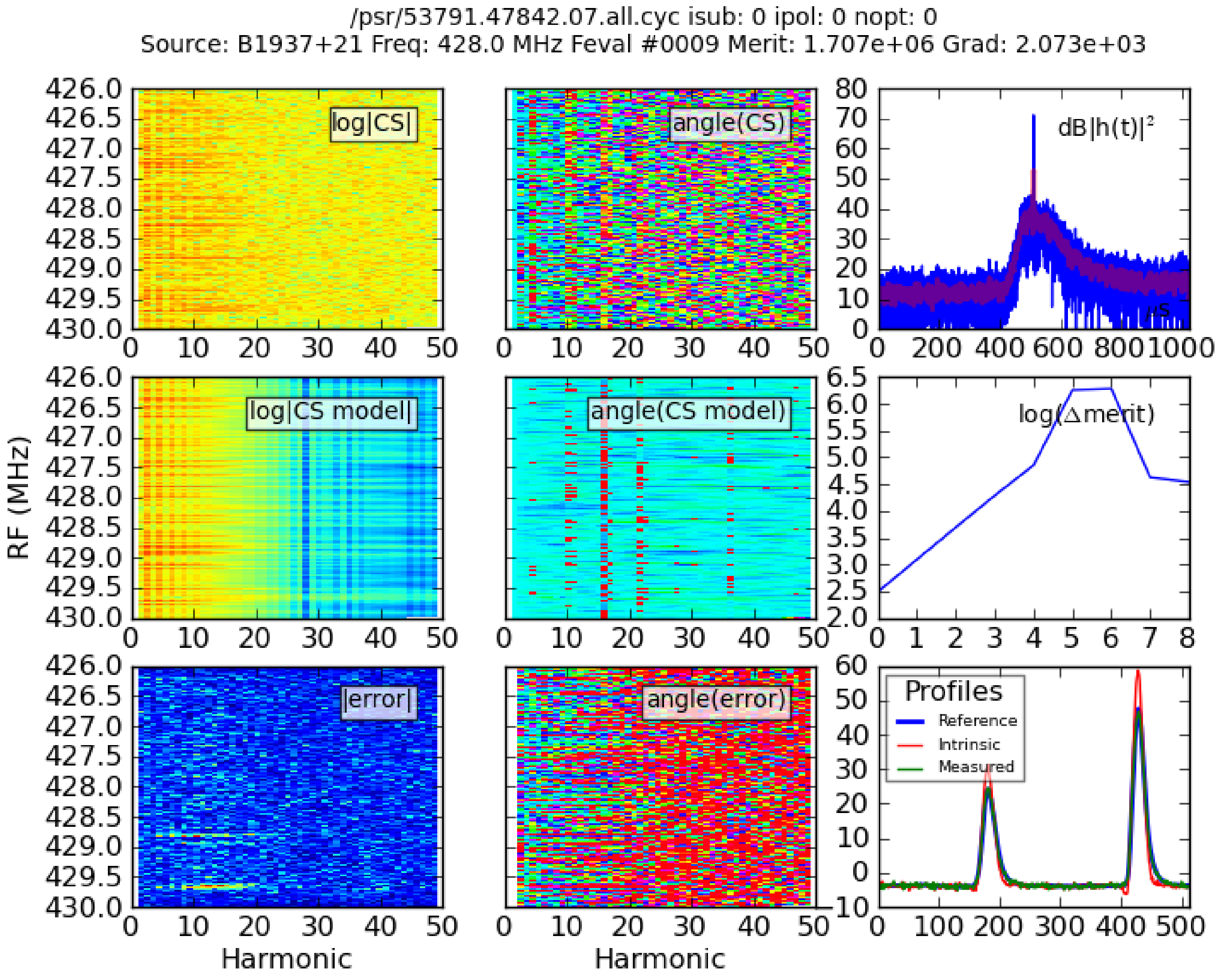
Iteration 8


/psr/53791.47842.07.all.cyc isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 428.0 MHz Feval #0007 Merit: 1.784e+06 Grad: 5.104e+03
log|CS|
angle(CS)
dB|h(t)|²
μs
log|CS model|
angle(CS model)
log(Δmerit)
RF (MHz)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
Harmonic
Harmonic

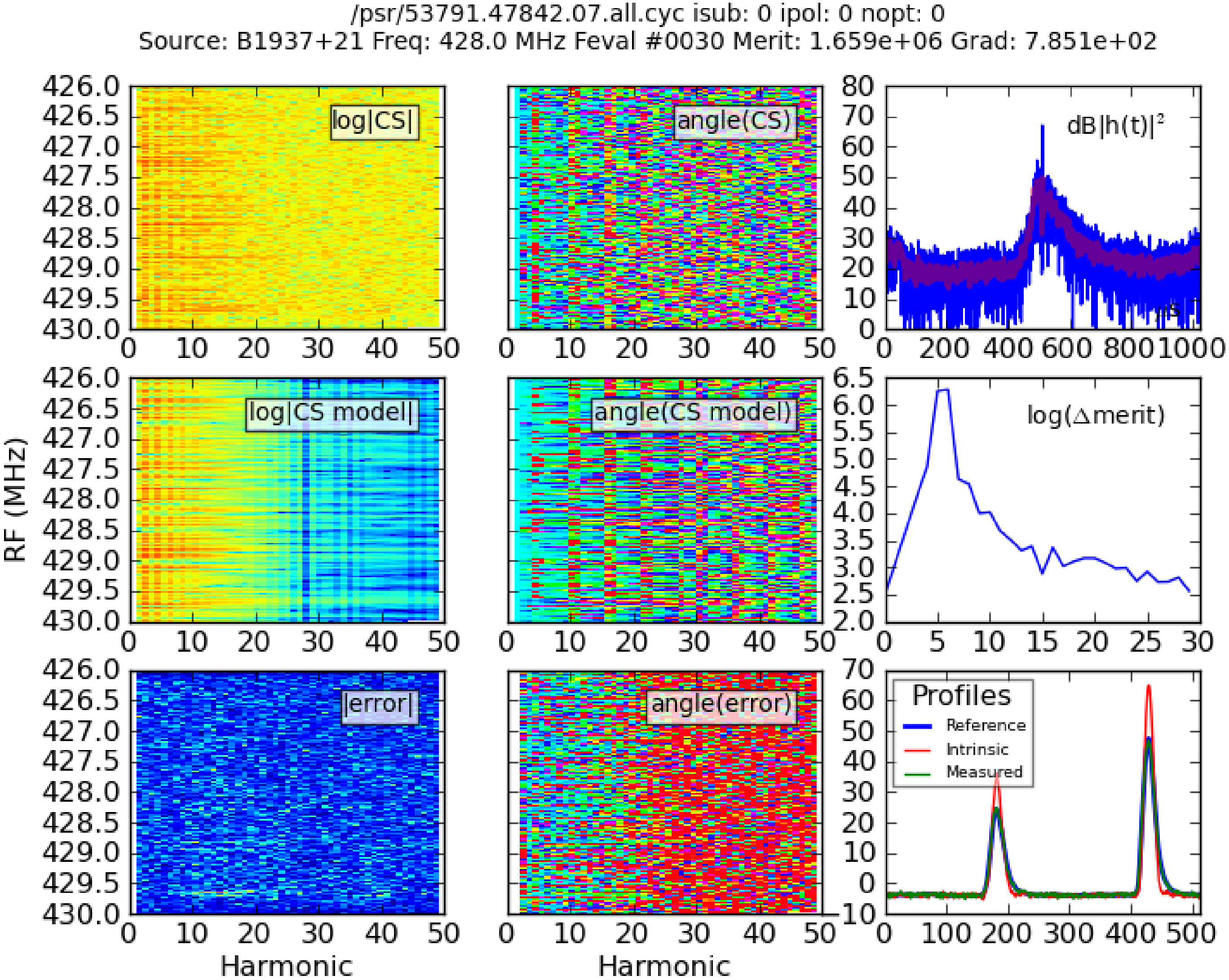
Iteration 9


/psr/53791.47842.07.all.cyc isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 428.0 MHz Feval #0008 Merit: 1.742e+06 Grad: 5.485e+03
log|CS|
angle(CS)
dB|h(t)|²
μs
log|CS model|
angle(CS model)
log(Δmerit)
|error|
angle(error)
Profiles
Reference
Intrinsic
Measured
RF (MHz)
Harmonic
Harmonic

Iteration 10

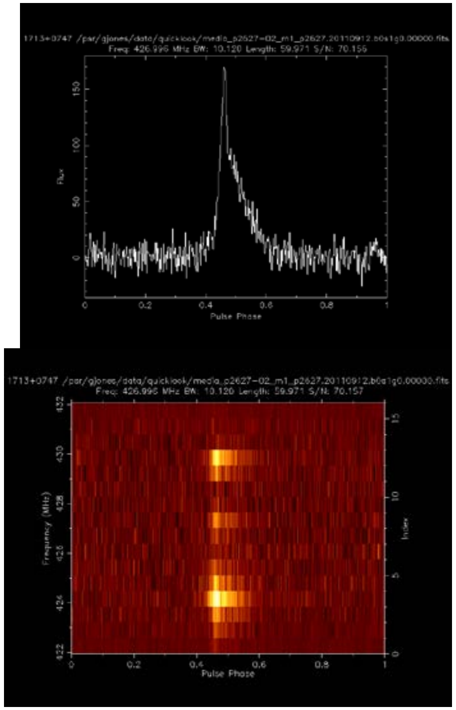


Iteration 31

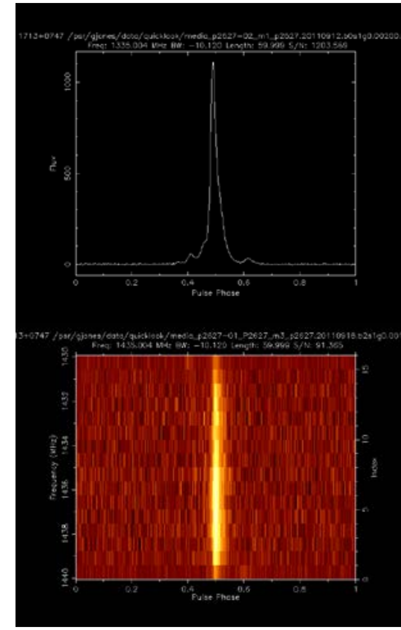


Second dataset: J1713+0747 at Arecibo

430 MHz

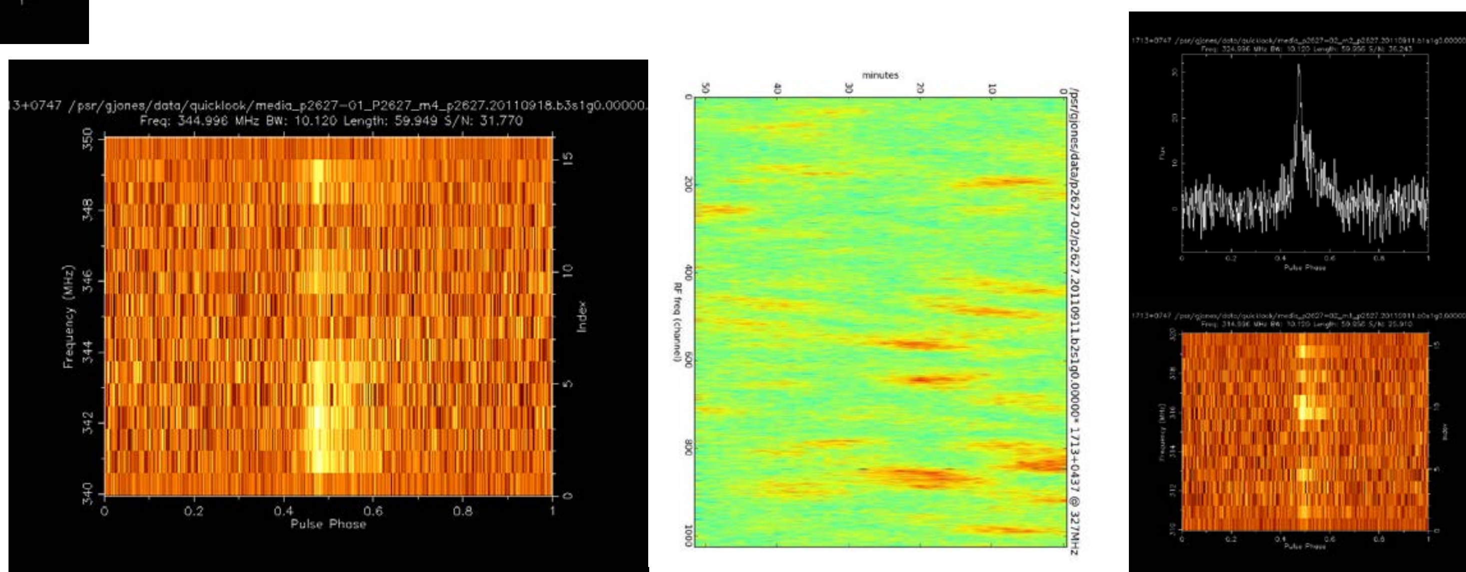


1400 MHz

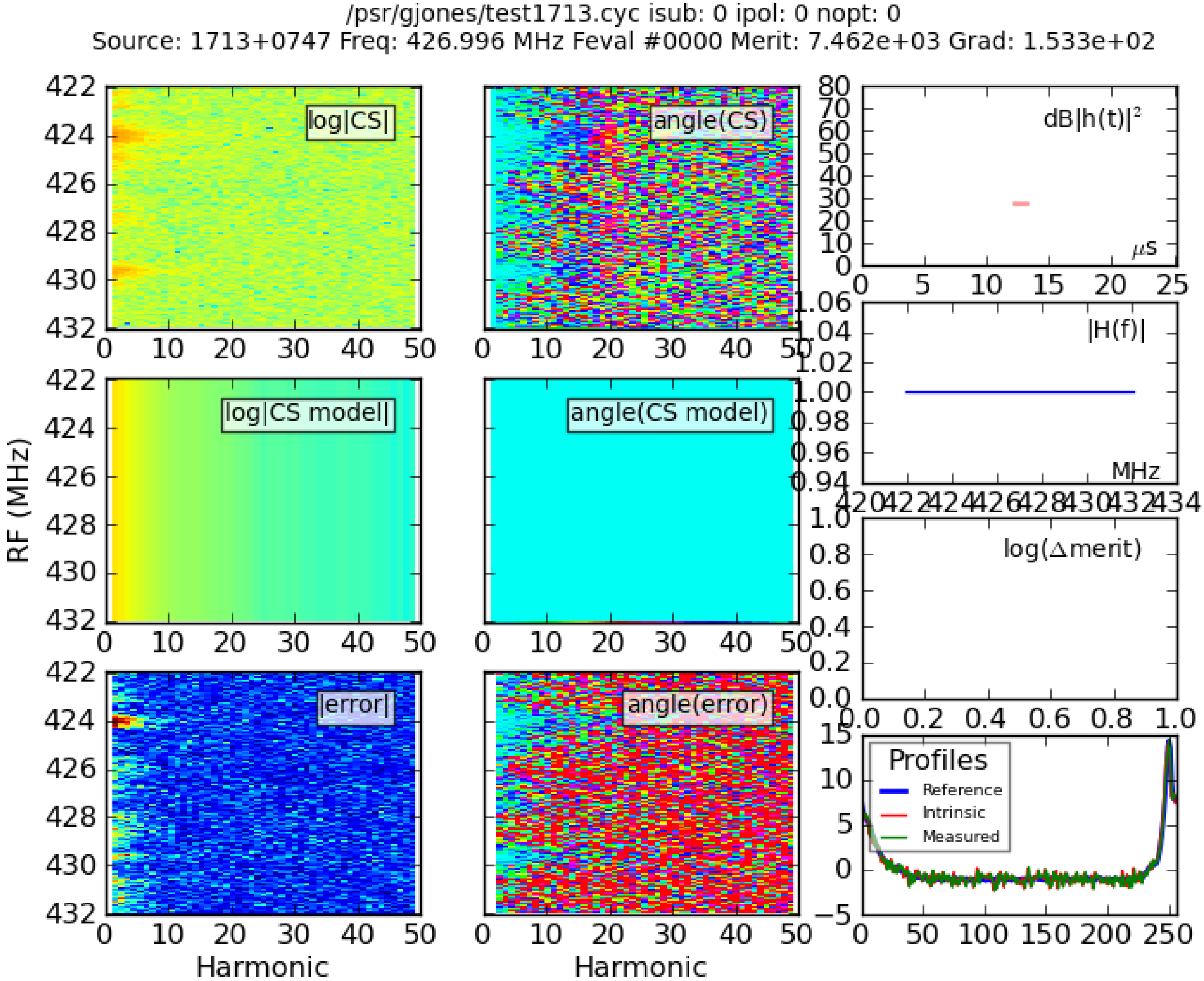


- 327 MHz, 430 MHz, and 1400 MHz
- 10 MHz subbands
- Best timing NANOGrav pulsar (~40 ns RMS)
- Nipuni Palliyaguru leading this effort

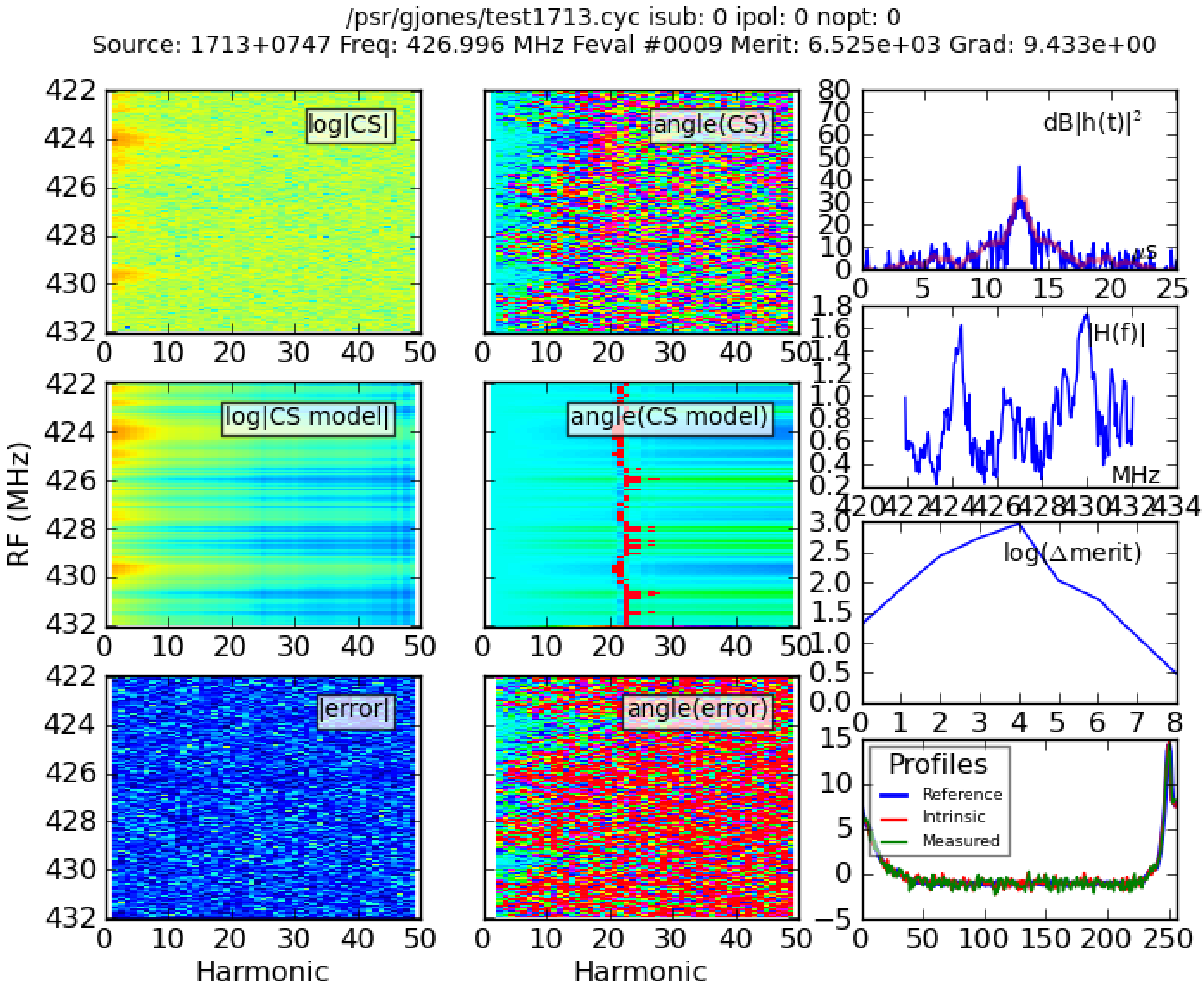
327 MHz



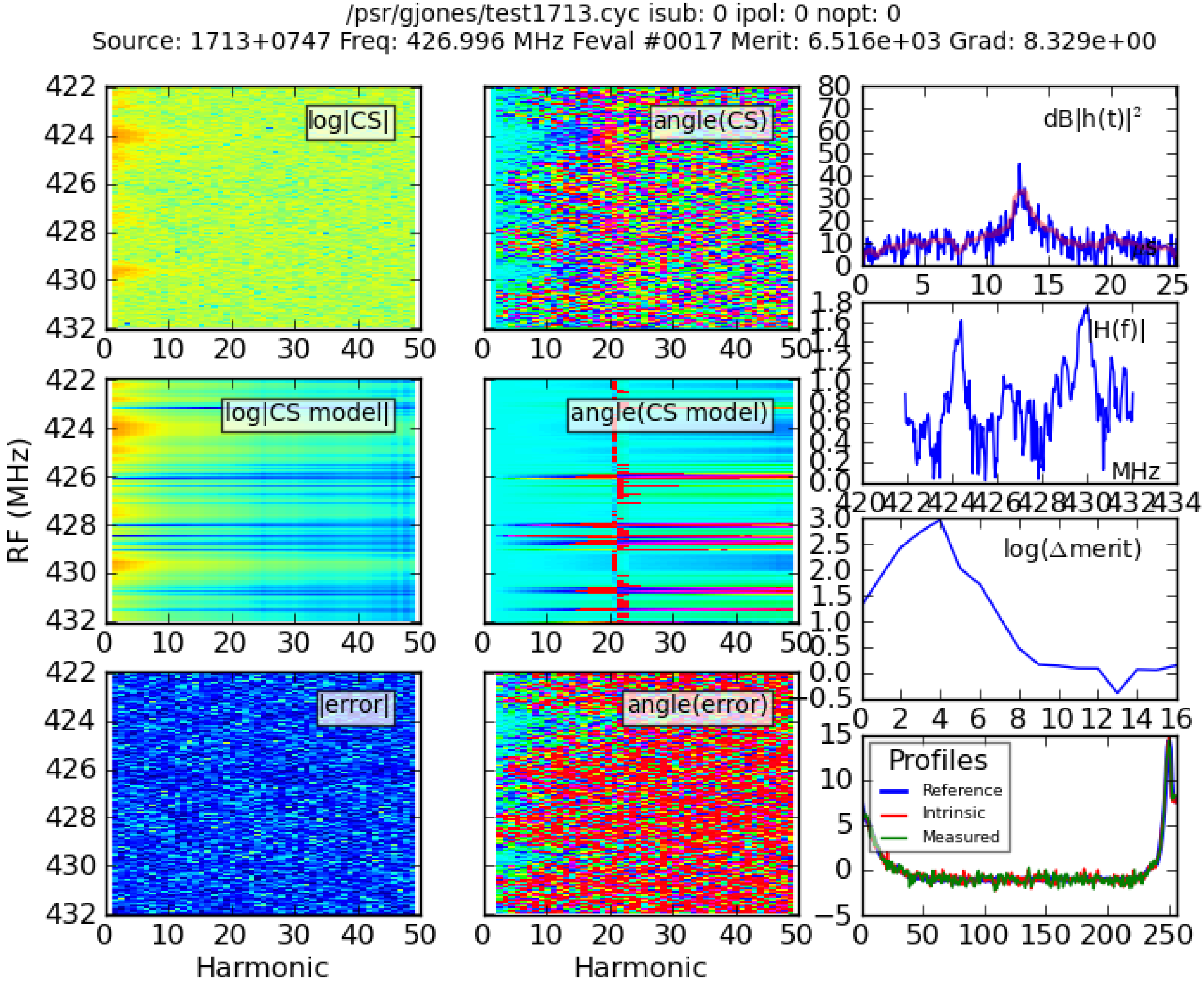
J1713+0747 Iteration 1



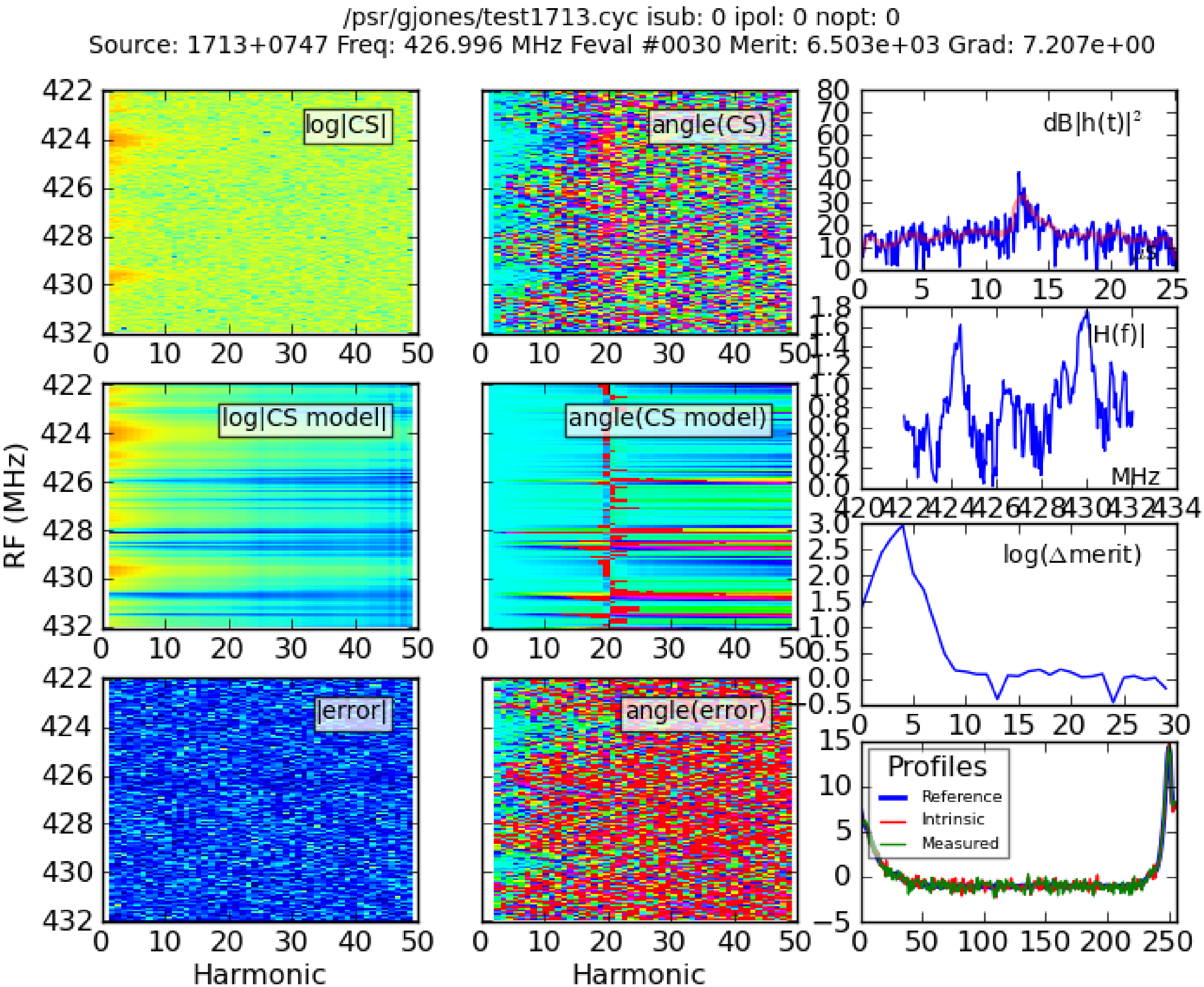
J1713+0747 Iteration 10



J1713+0747 Iteration 18



J1713+0747 Iteration 30



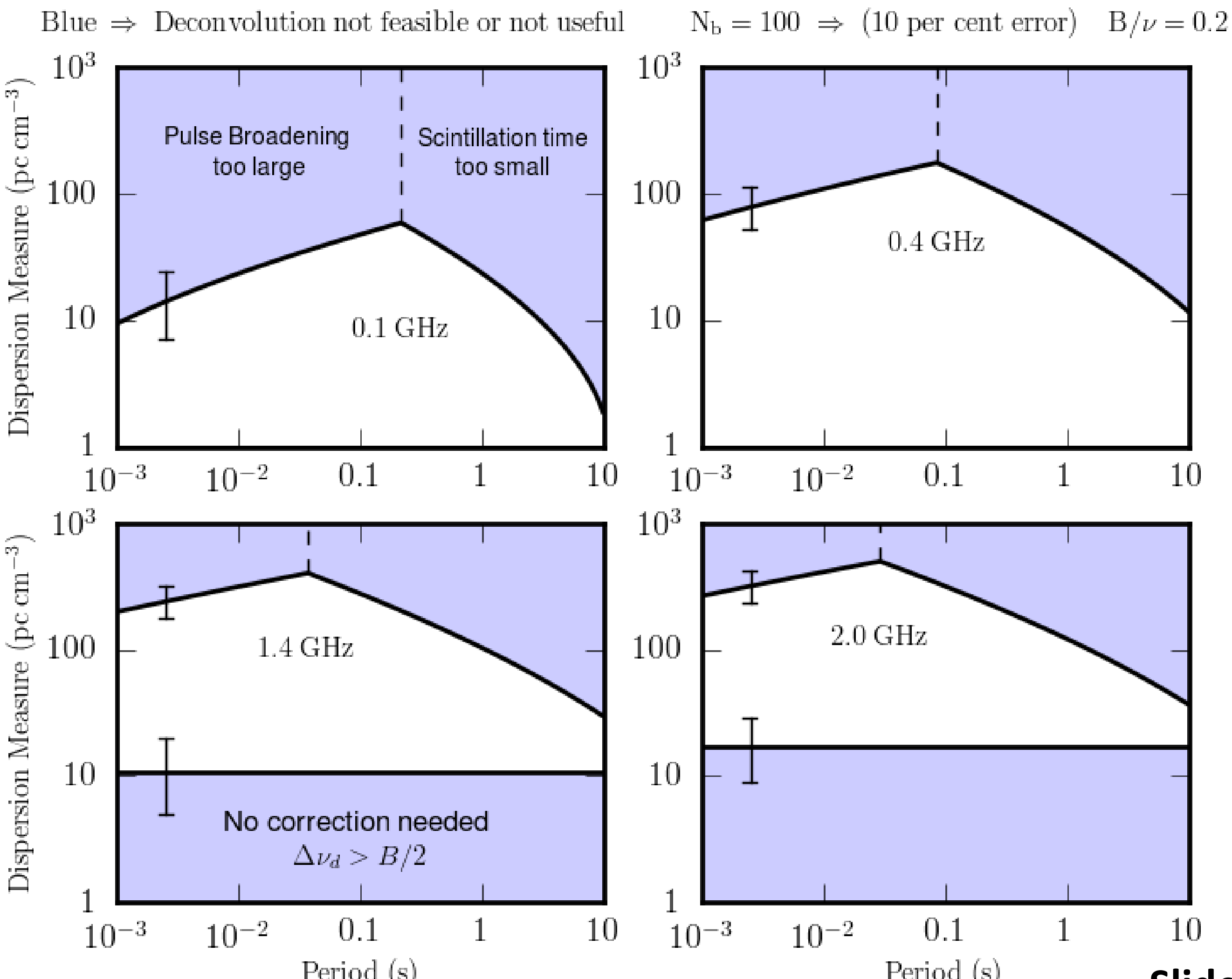
How well can we realistically expect CS deconvolution to "work"?

- Need to define success criteria
  - Improving timing precision
  - Determine amplitude AND phase of transfer function
  - Determine amplitude of transfer function
- Limitations are determined by nature more than by instrumentation
  - **Bandwidth set by scintillation bandwidth**
  - **Integration time set by scintillation timescale**
  - Harmonic content determined by pulse profile
  - Flux determined by pulsar
  - **Pulse period determines number of realizations of self-noise per scintillation timescale**

P-DM Regimes for Deconvolution

Based on empirical DM-Scattering relation

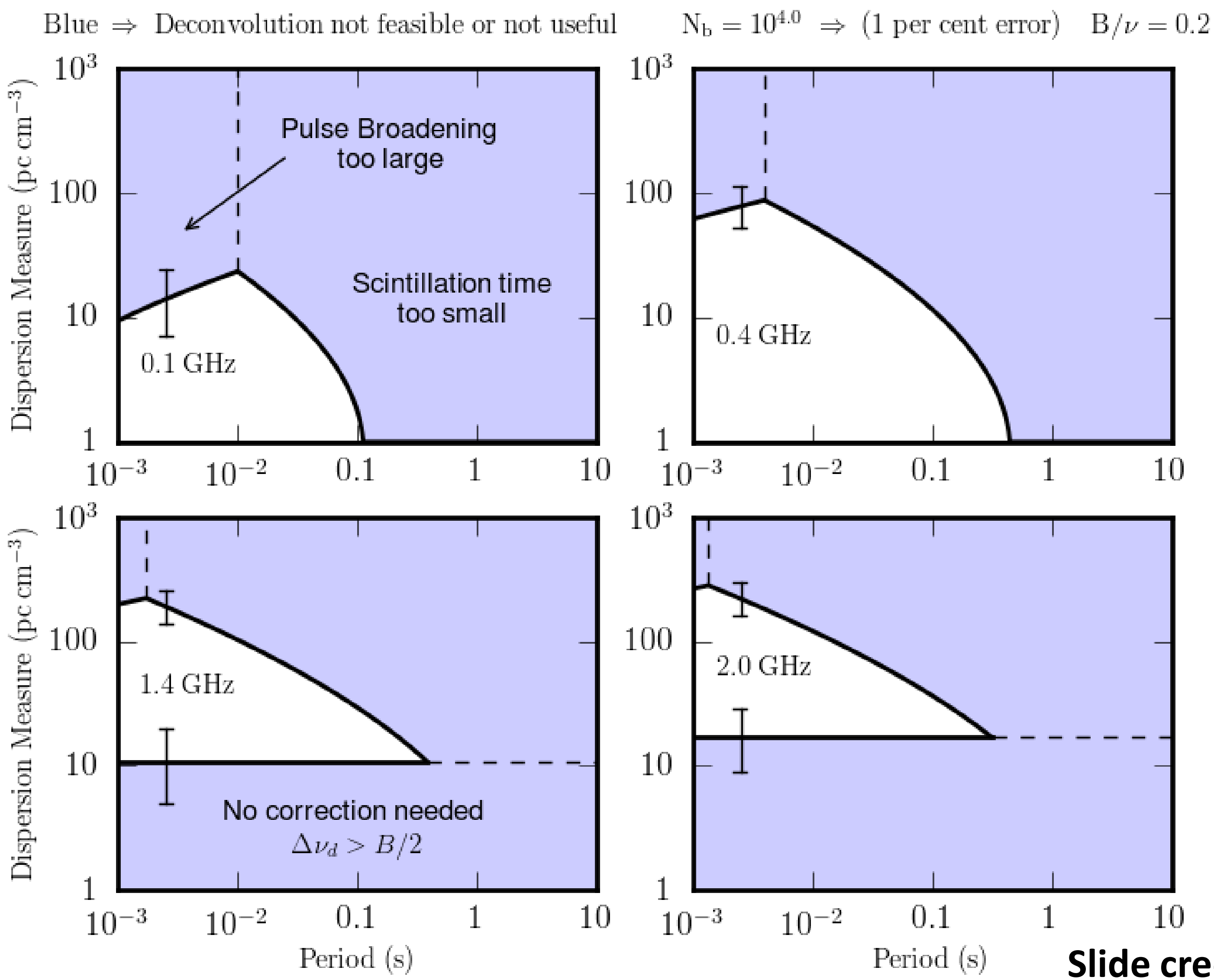
N_b = 100



Slide credit: Jim Cordes

P-DM Regimes for Deconvolution

$N_b = 10^4$



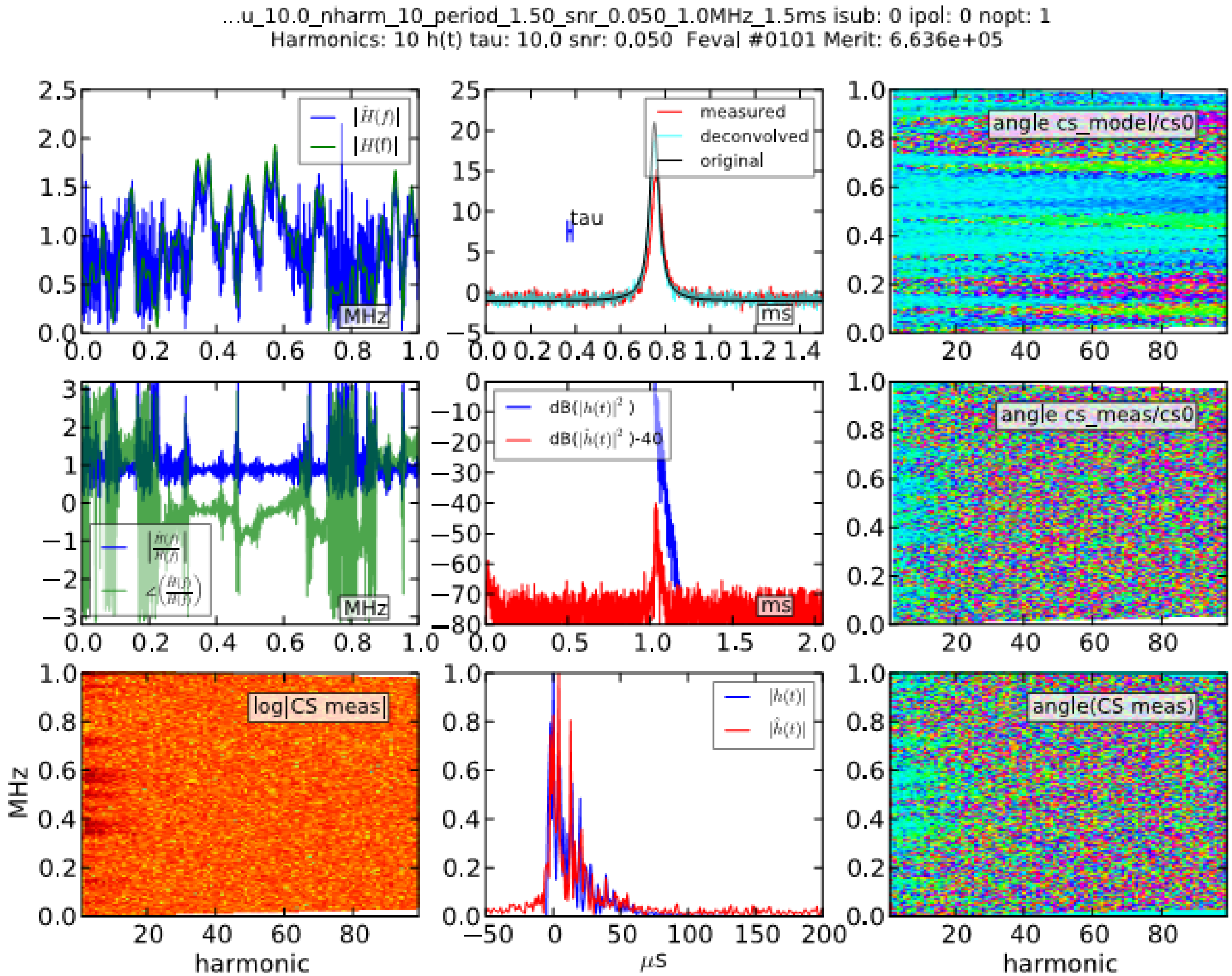
Slide credit: Jim Cordes

Simulations

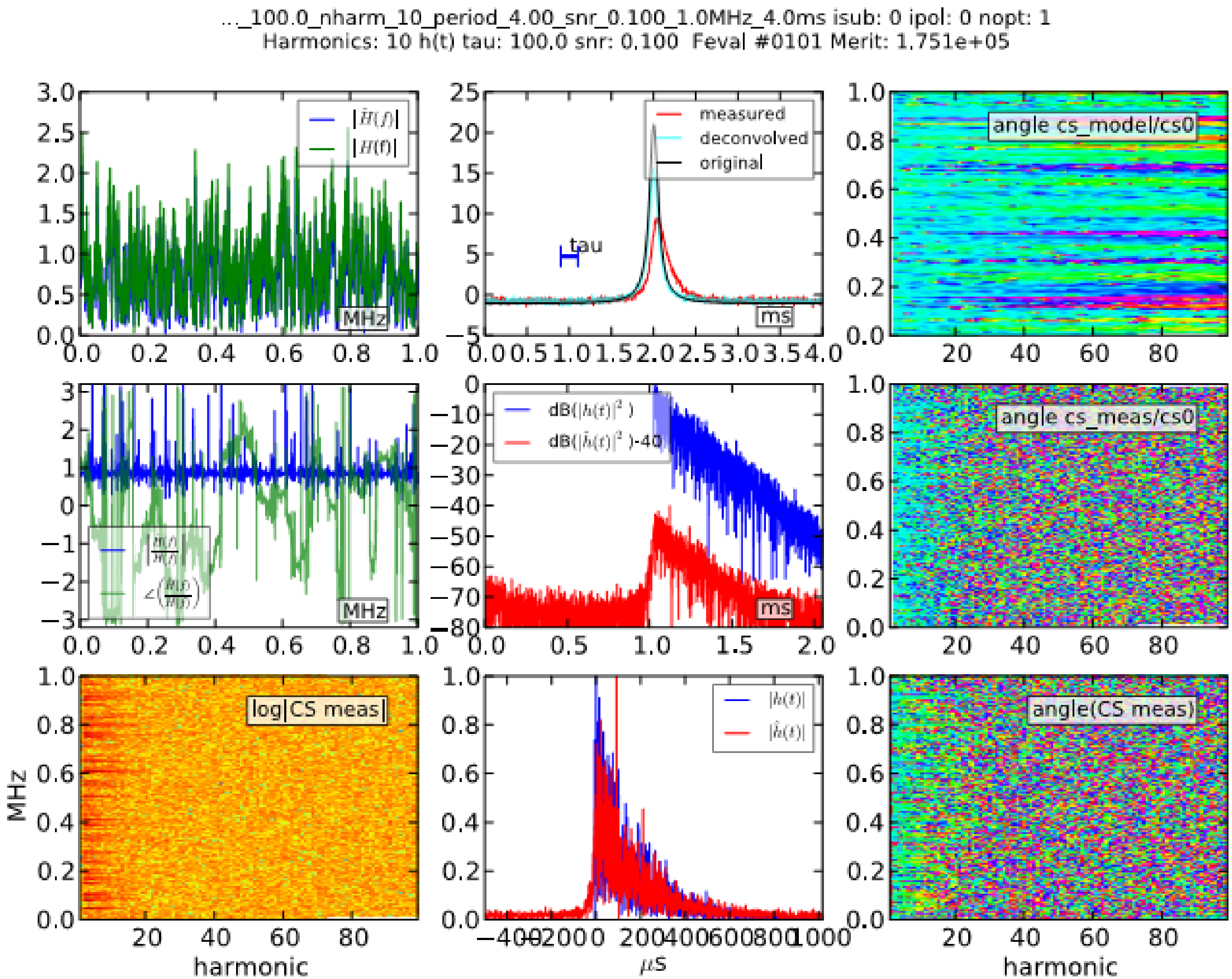
- Use simcyc code to simulate pulse profiles and transfer functions. Then compute CS
- Add noise to CS and attempt deconvolution
- Compare resulting transfer function to initial transfer function
- Experimented with a range of parameters

Tau (microseconds)	2.0, 10.0, 100.0
Profile harmonic decay constant (~1/width)	3.0, 10.0
Pulsar period (milliseconds)	1.5, 4.0, 10.0
Signal to Noise Ratio (arbitrary units)	0.05, 0.10

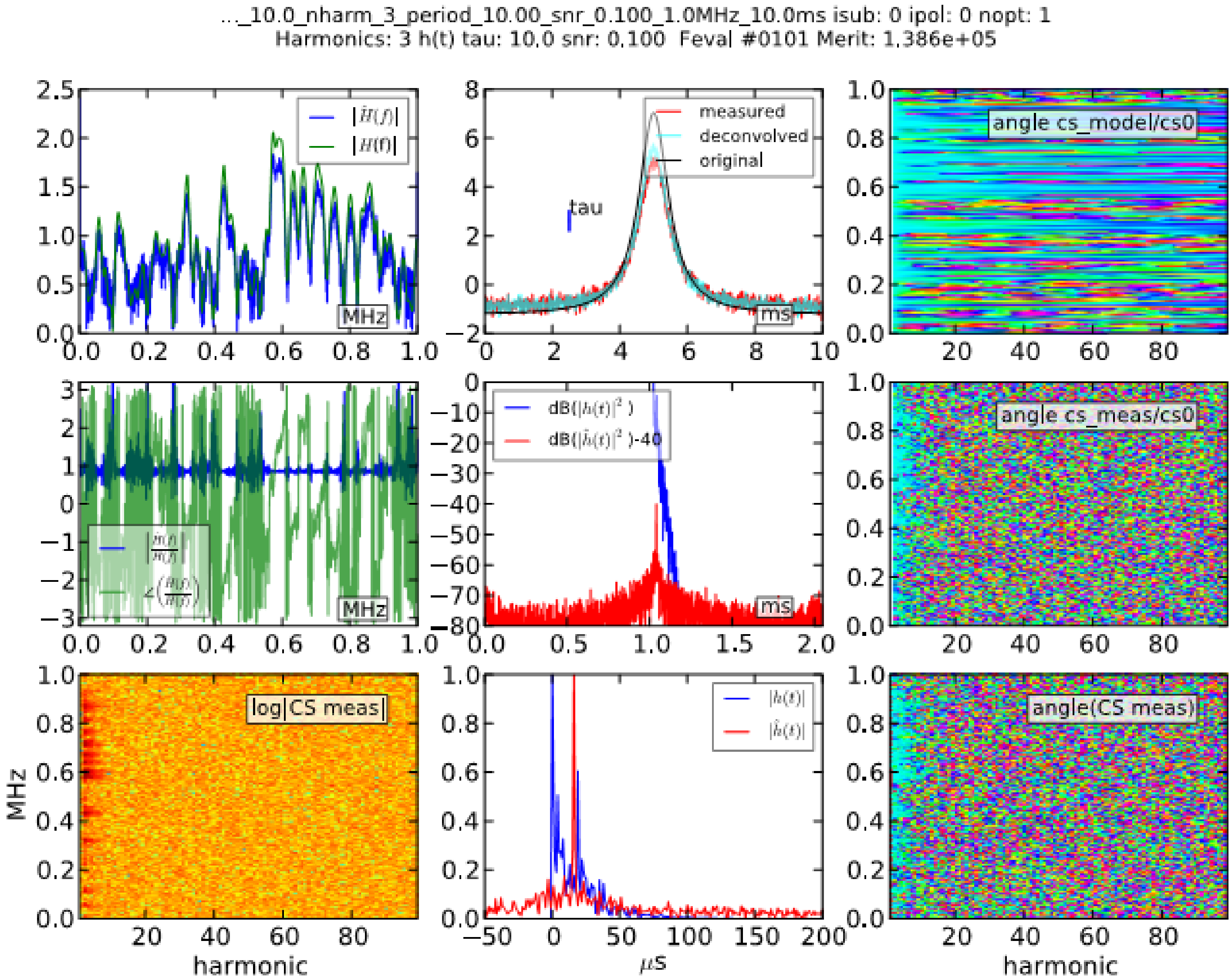
Sharp profile, short period, moderate scattering → decent recovery



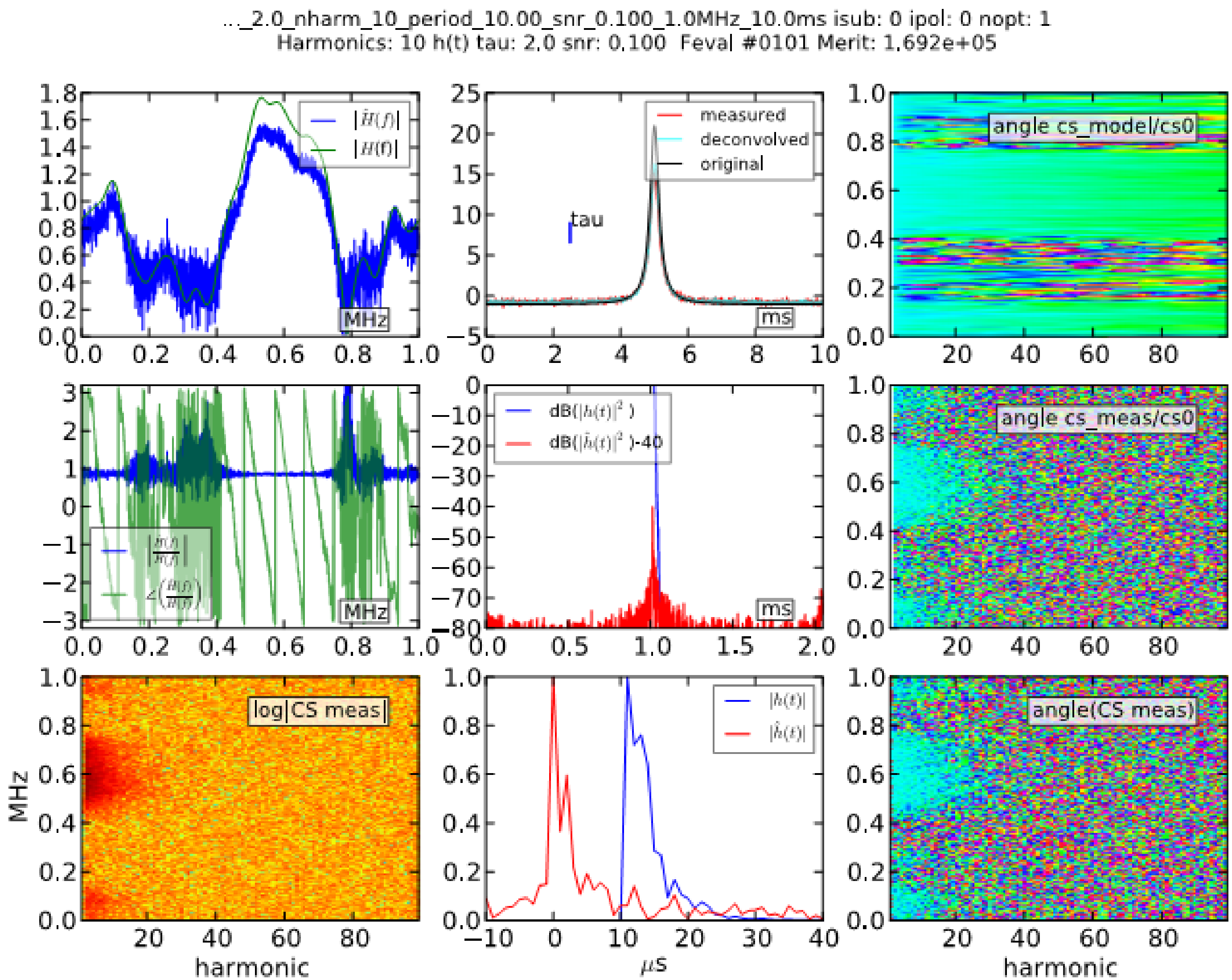
Sharp profile, longer period, significant scattering → partial recovery



Wide profile, long period, moderate scattering → poor recovery

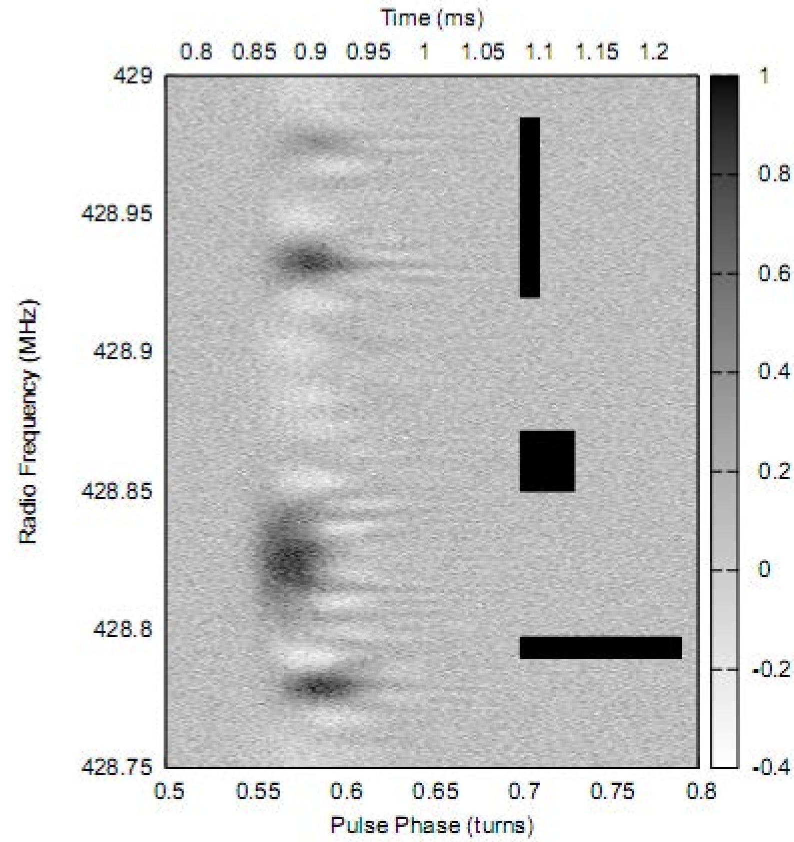


Sharp profile, long period, slight scattering → recovery possible



Other applications: Improved estimation of ISM scattering

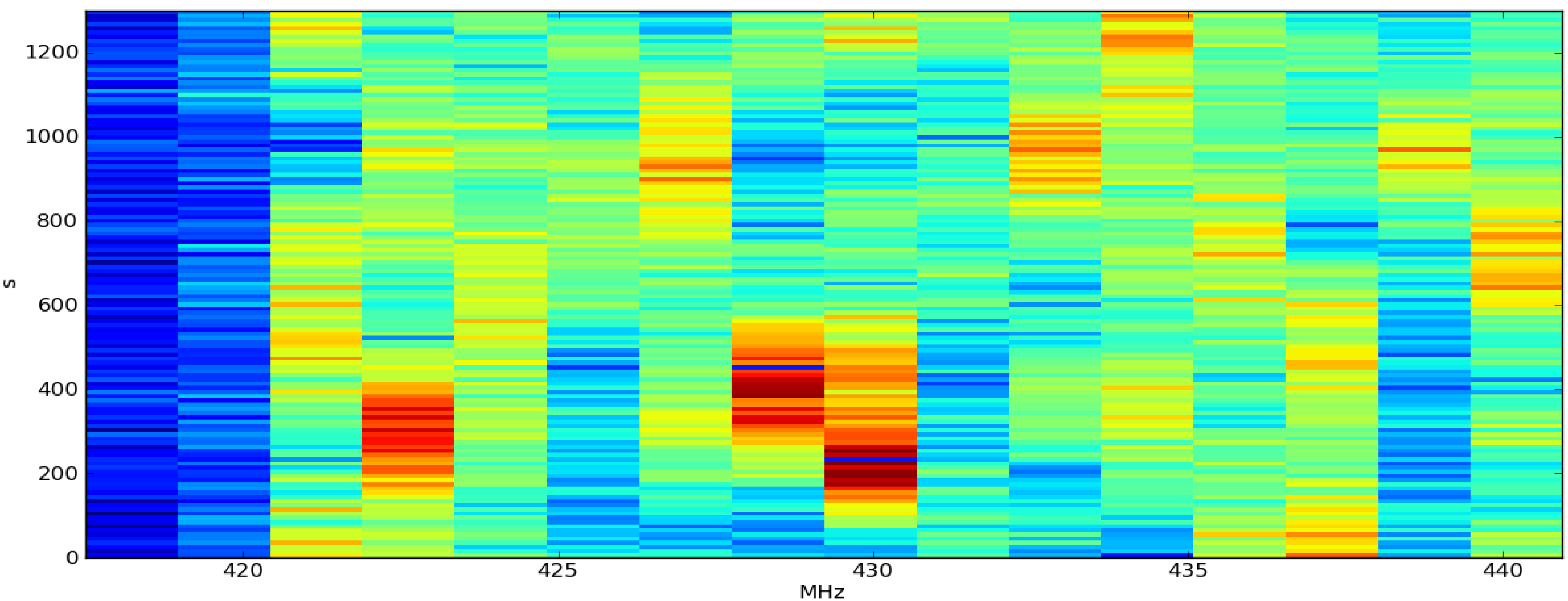
- Cyclic spectroscopy gives us high time AND frequency resolution
- Improved resolution of ISM features



Importance of time/frequency resolution:

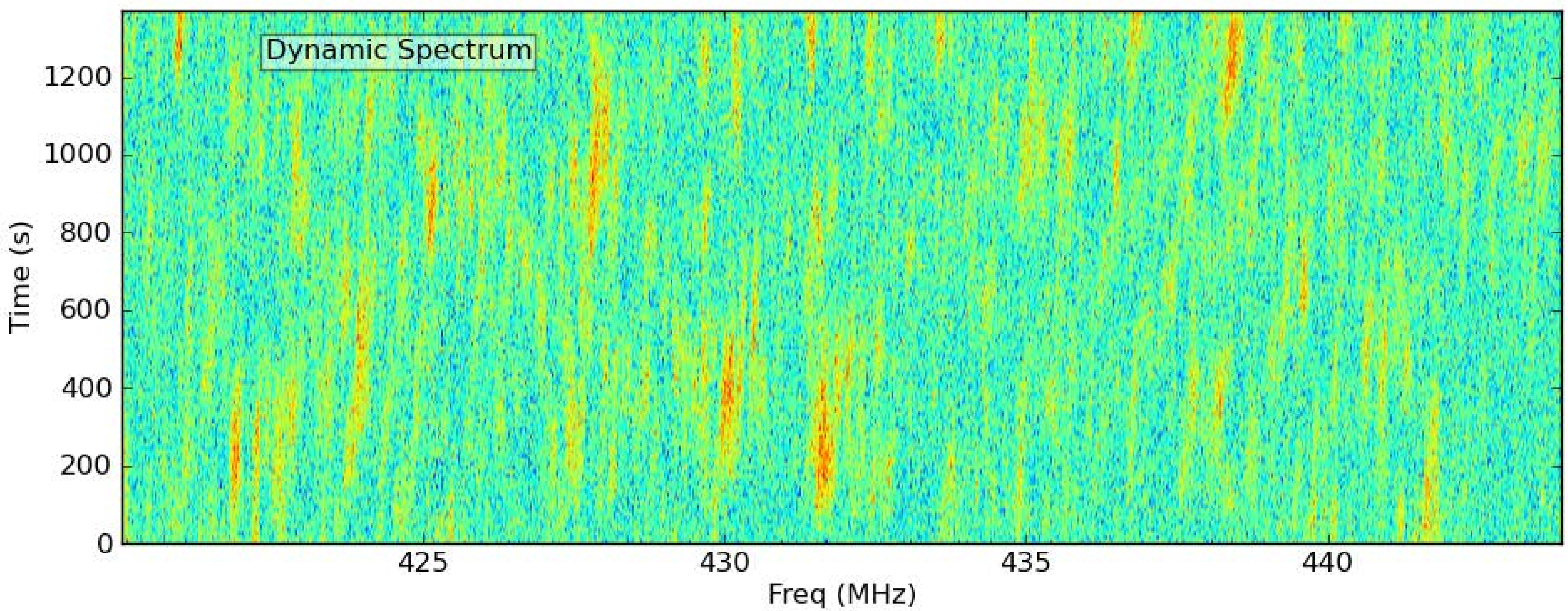
Dynamic spectrum from routine PUPPI observation of J1944+0907

- 1.5625 MHz
- → 640 ns → ~2048 bins for 1.5 ms pulsar
- (5 ms pulsar, 2048 bins, could do ~ 0.5 MHz channels)

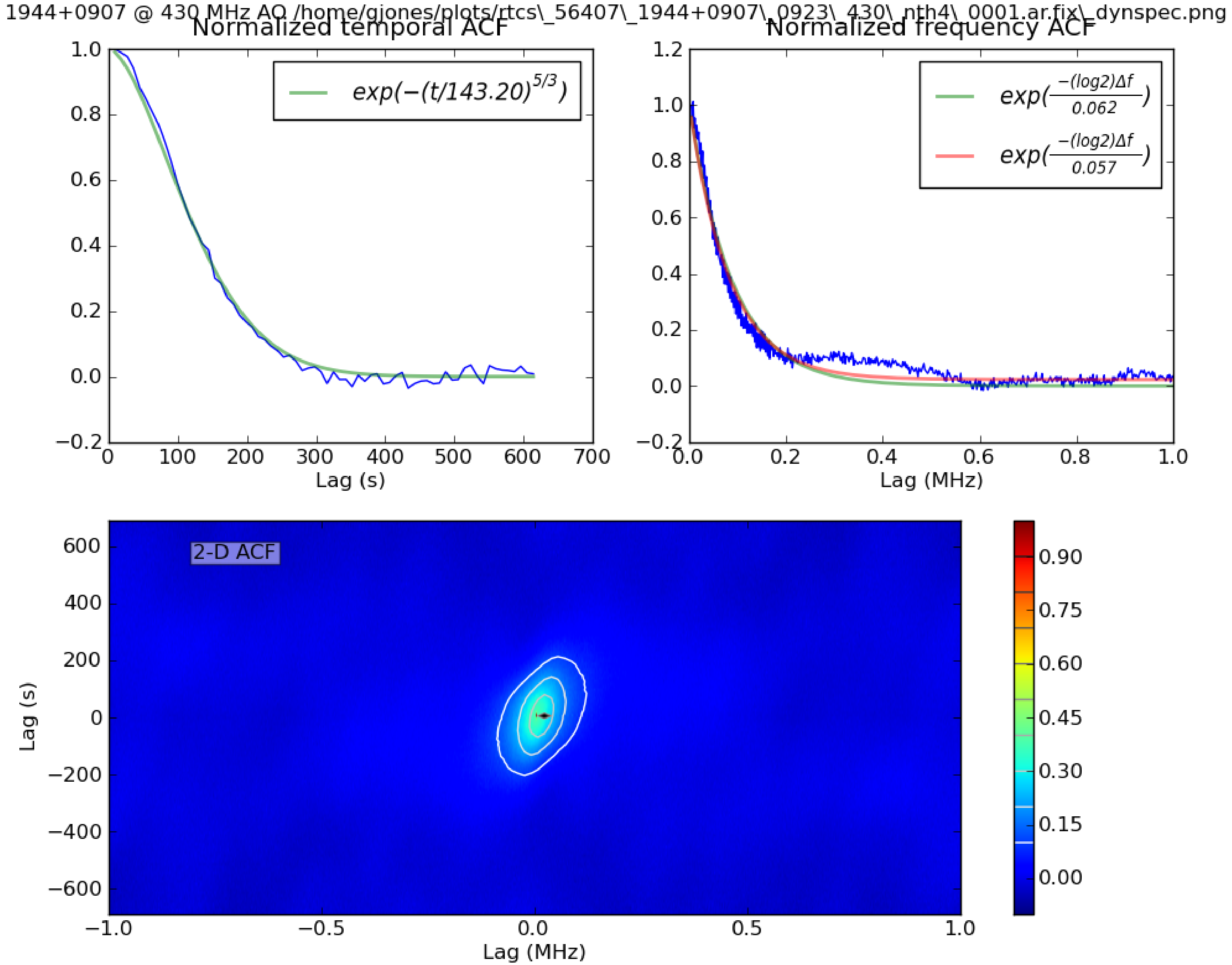


Dynamic spectrum from real-time cyclic spectrometer observation of J1944+0907

- 1953 Hz resolution
- Currently 2us time resolution, could easily be 640 ns



Analyzing dynamic spectra

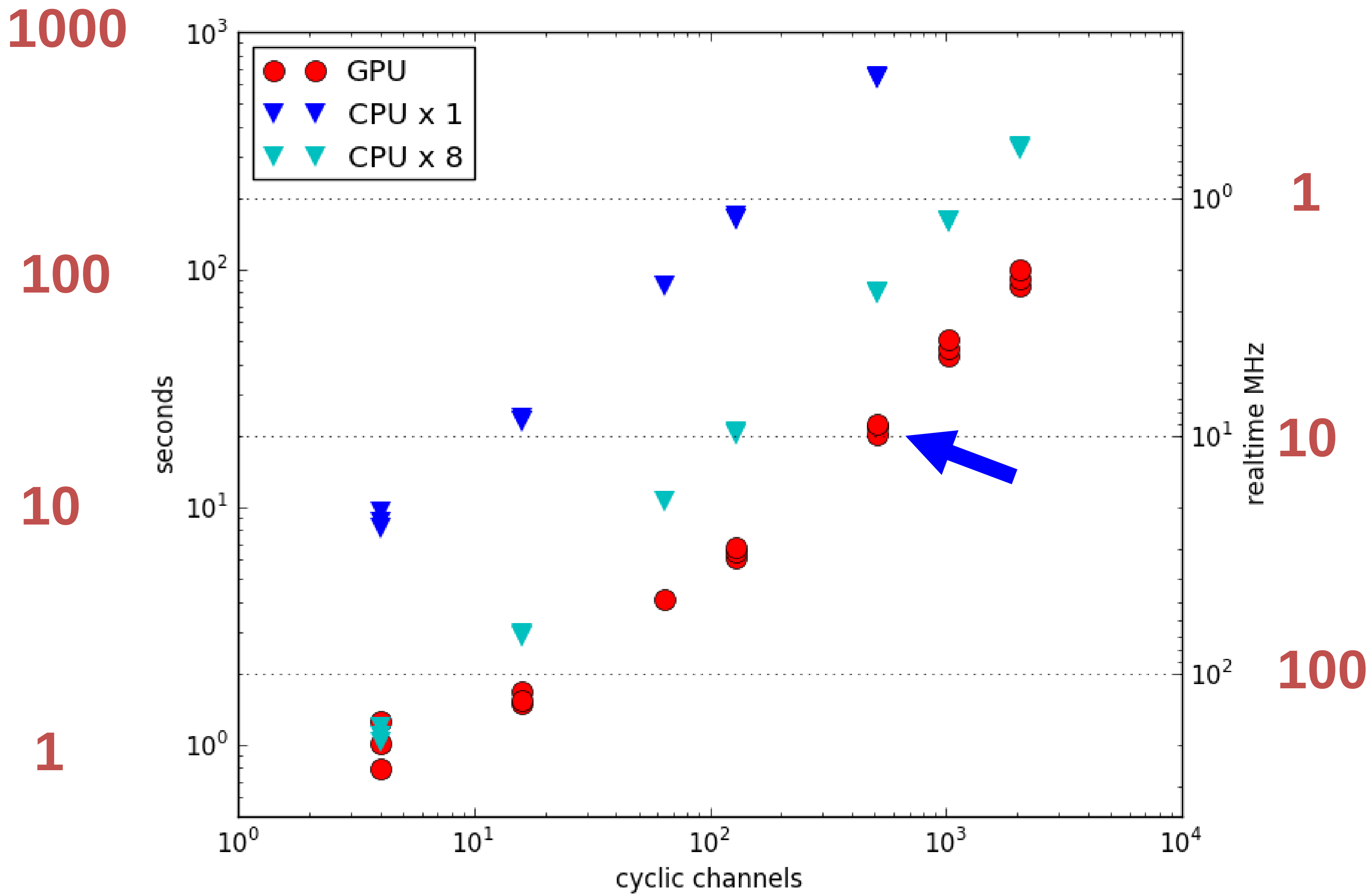


What's next?
We need real-time cyclic spectroscopy

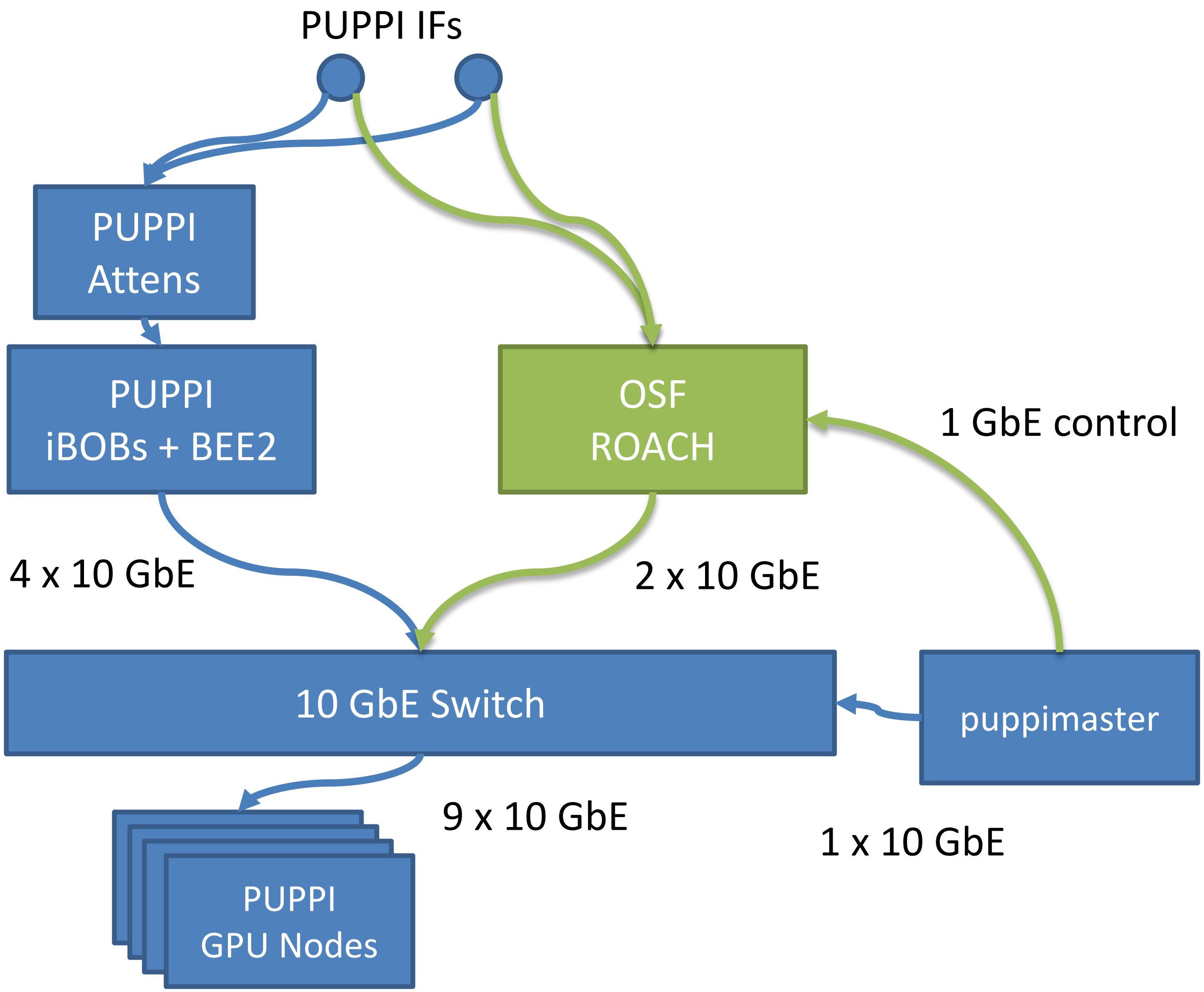
- Current observations involve recording TBs of raw voltage data → not sustainable
- Once the data is recorded, processing takes for-ever (→ real time processing be limited to very small bandwidths)
- Correlation has high arithmetic intensity: well suited to GPUs
- Have implemented an overlapping filterbank front-end to avoid losses at subband edges

GPU CS performance summary: 10-20 MHz per GPU node

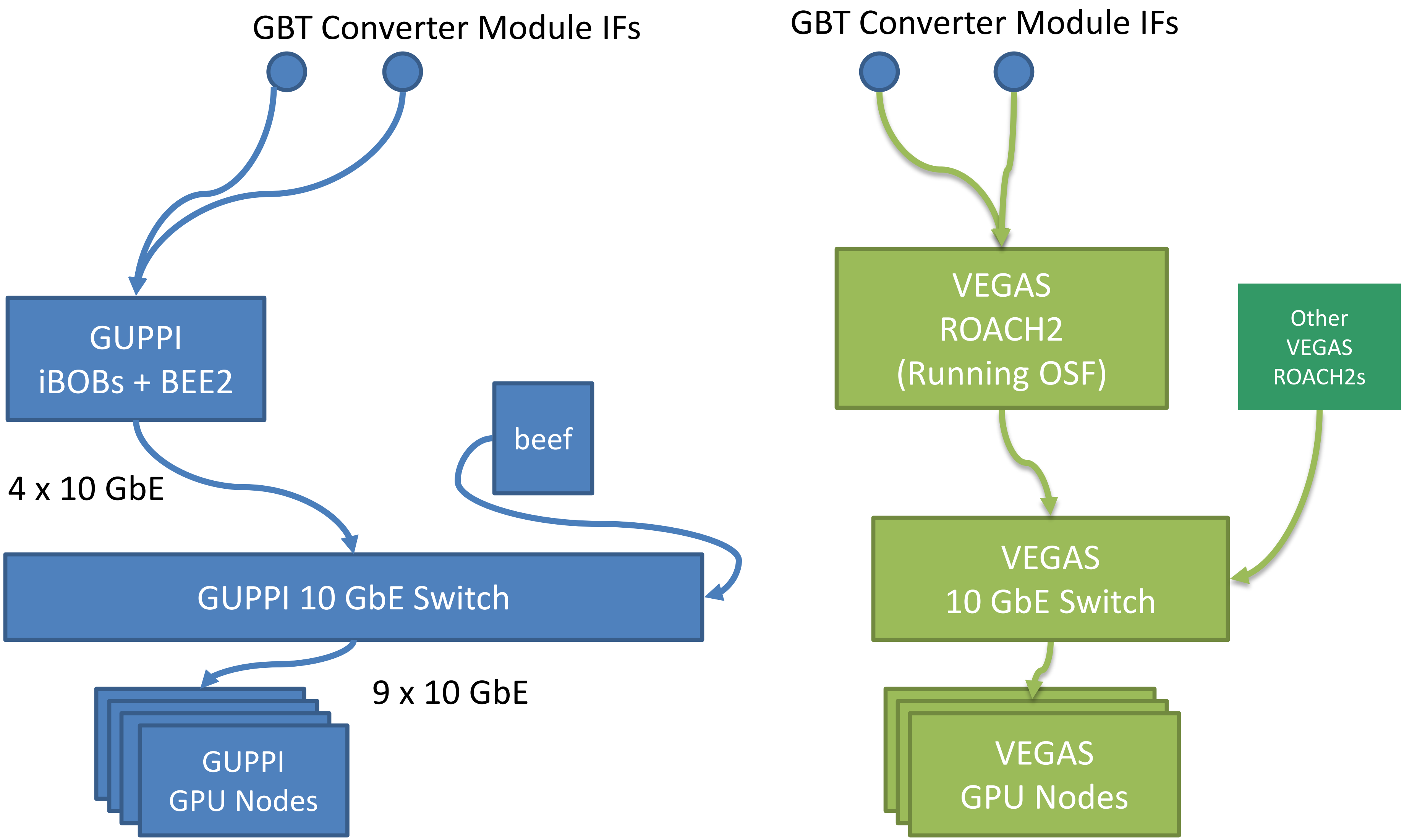
GTX485



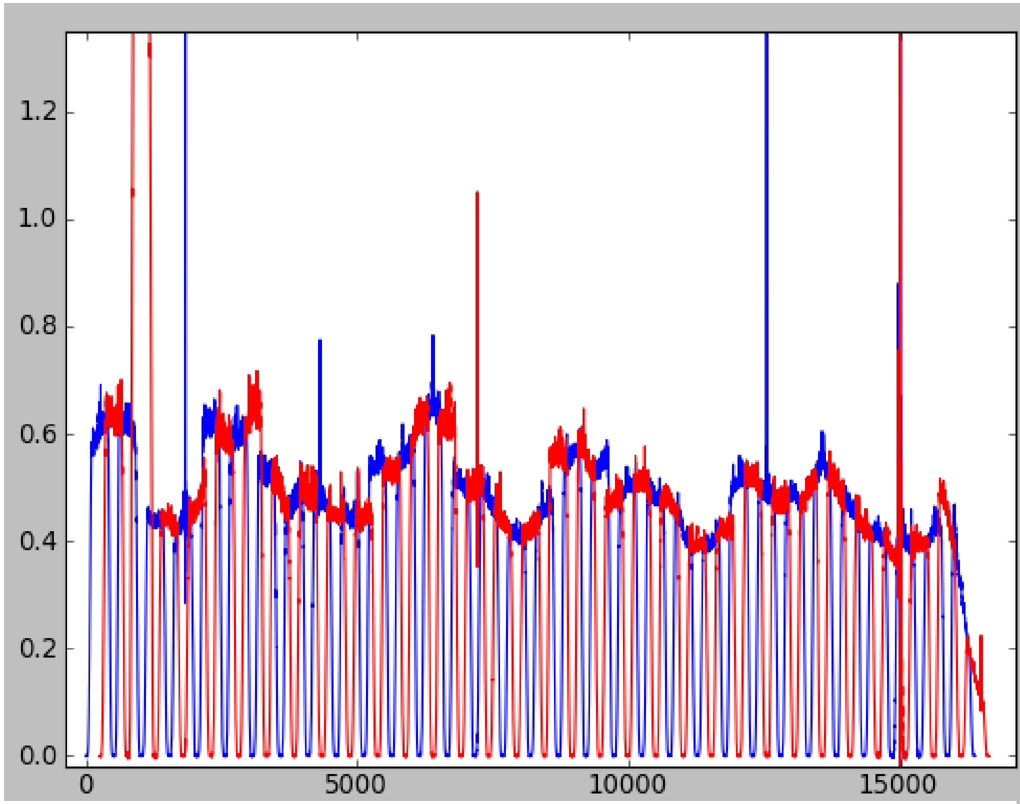
Over-sampled Filterbank: (OSF) Hardware setup at Arecibo



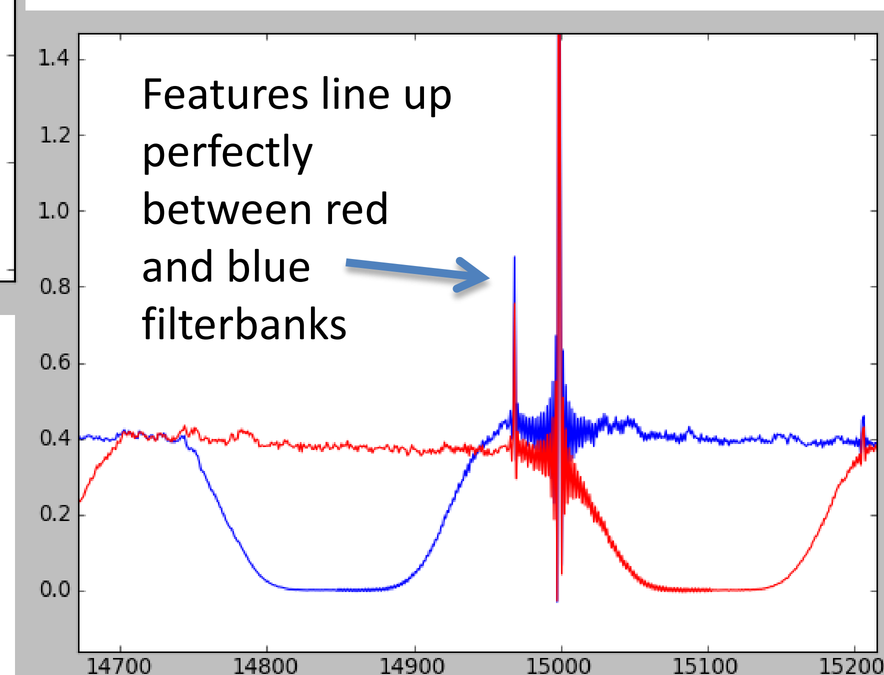
Over-sampled Filterbank: (OSF) (Coming soon to GBT)



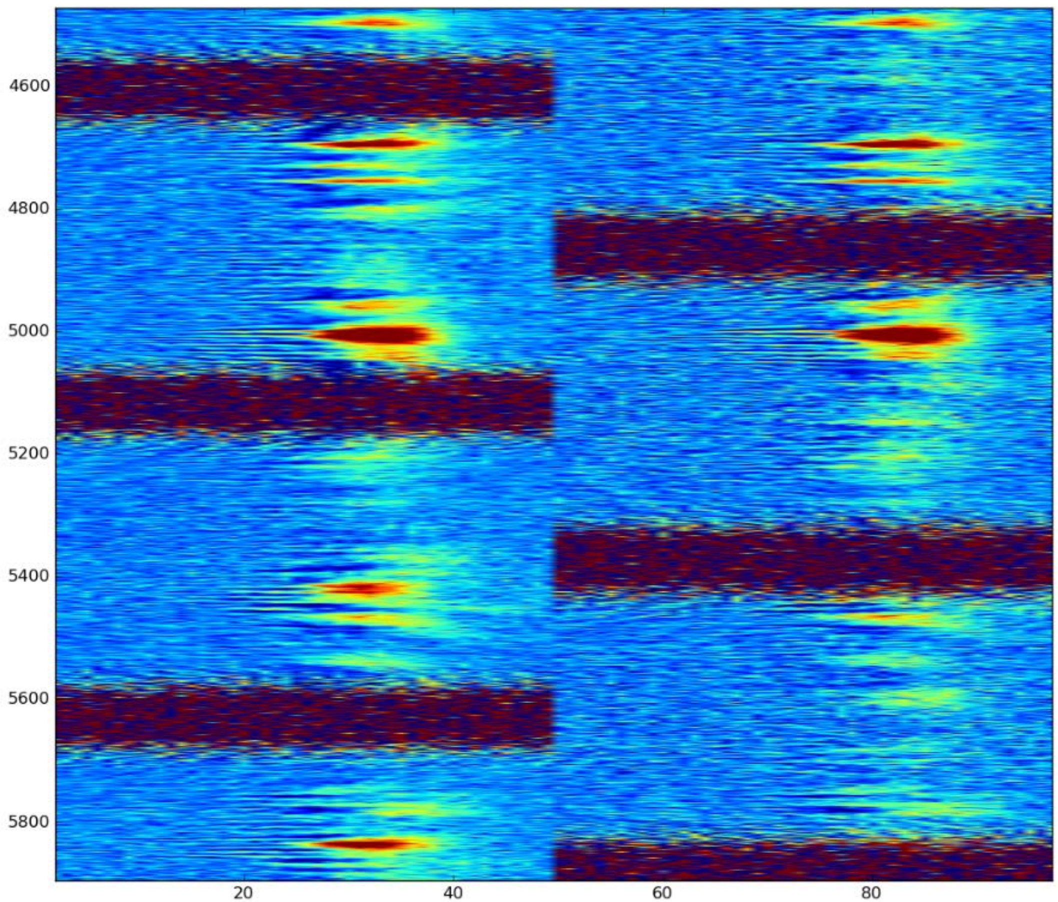
Overlapping, over-sampled filterbank

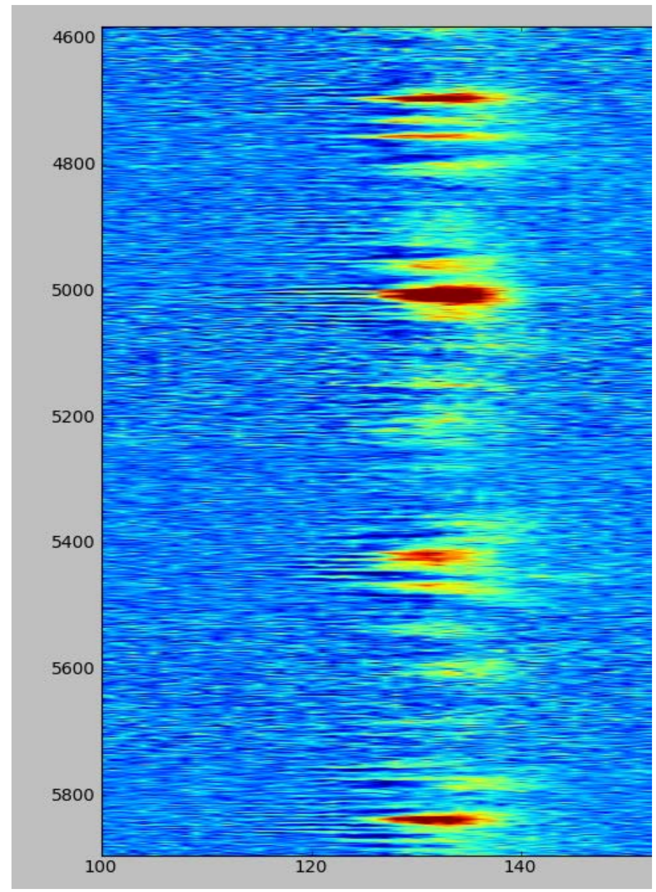


Red channels processed by one GPU,
Blue channels processed by the next.
Each GPU gets 32 channels = 16 MHz



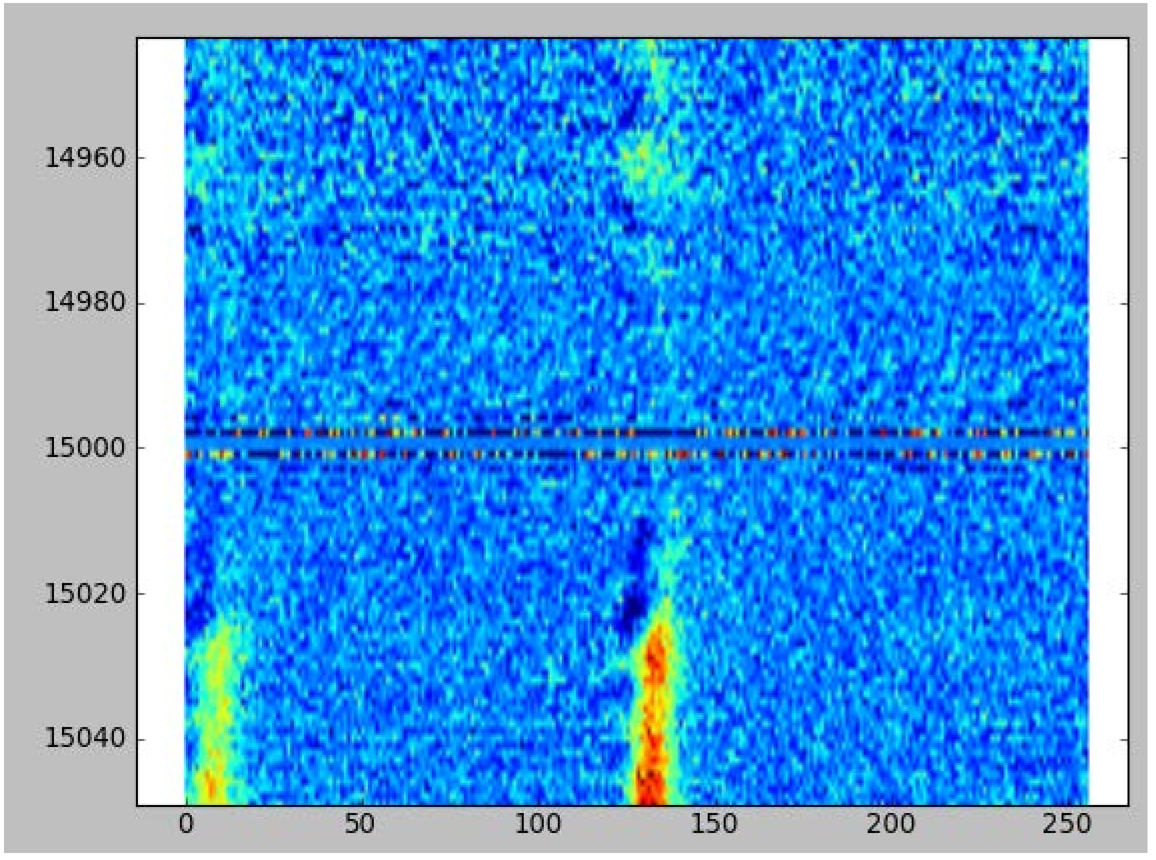
Overlapping filterbank: Merge to get complete cyclic spectrum



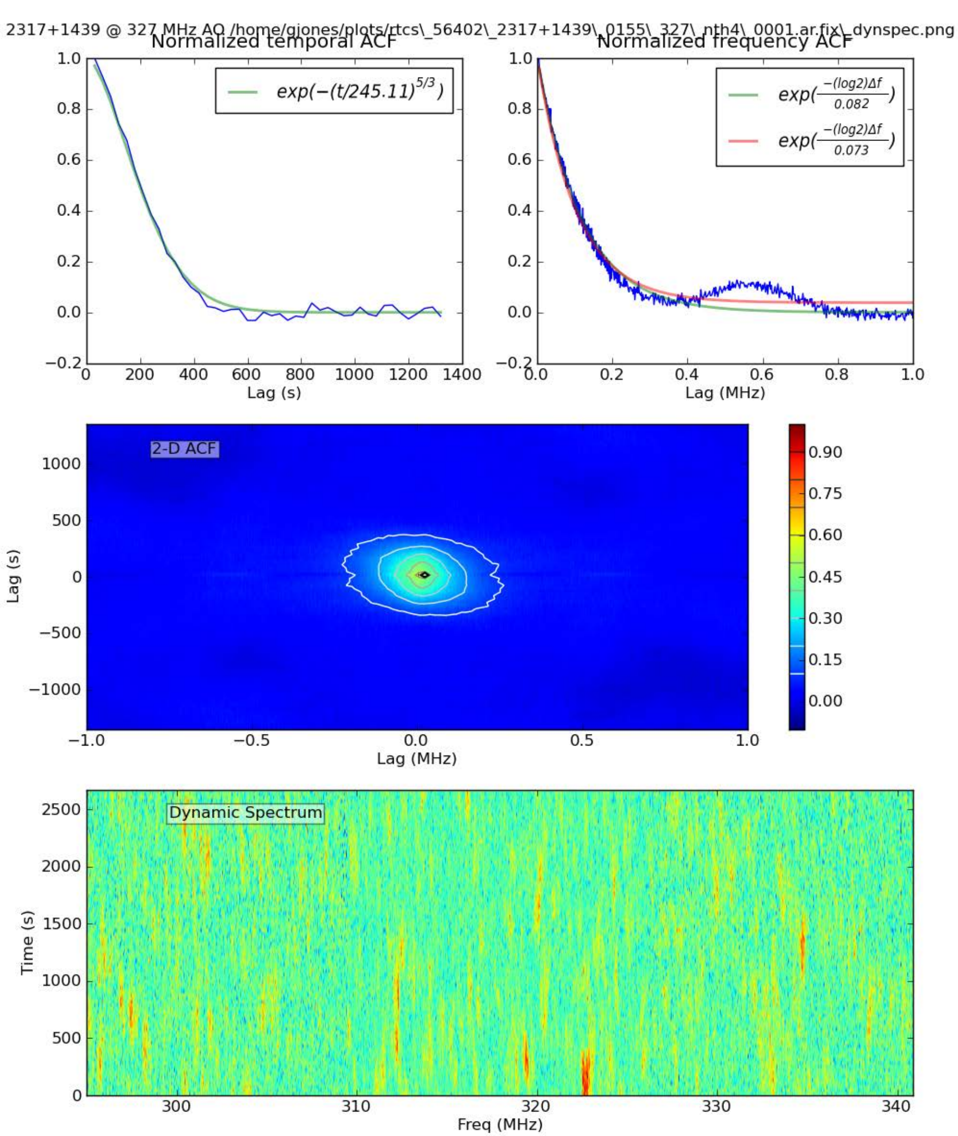


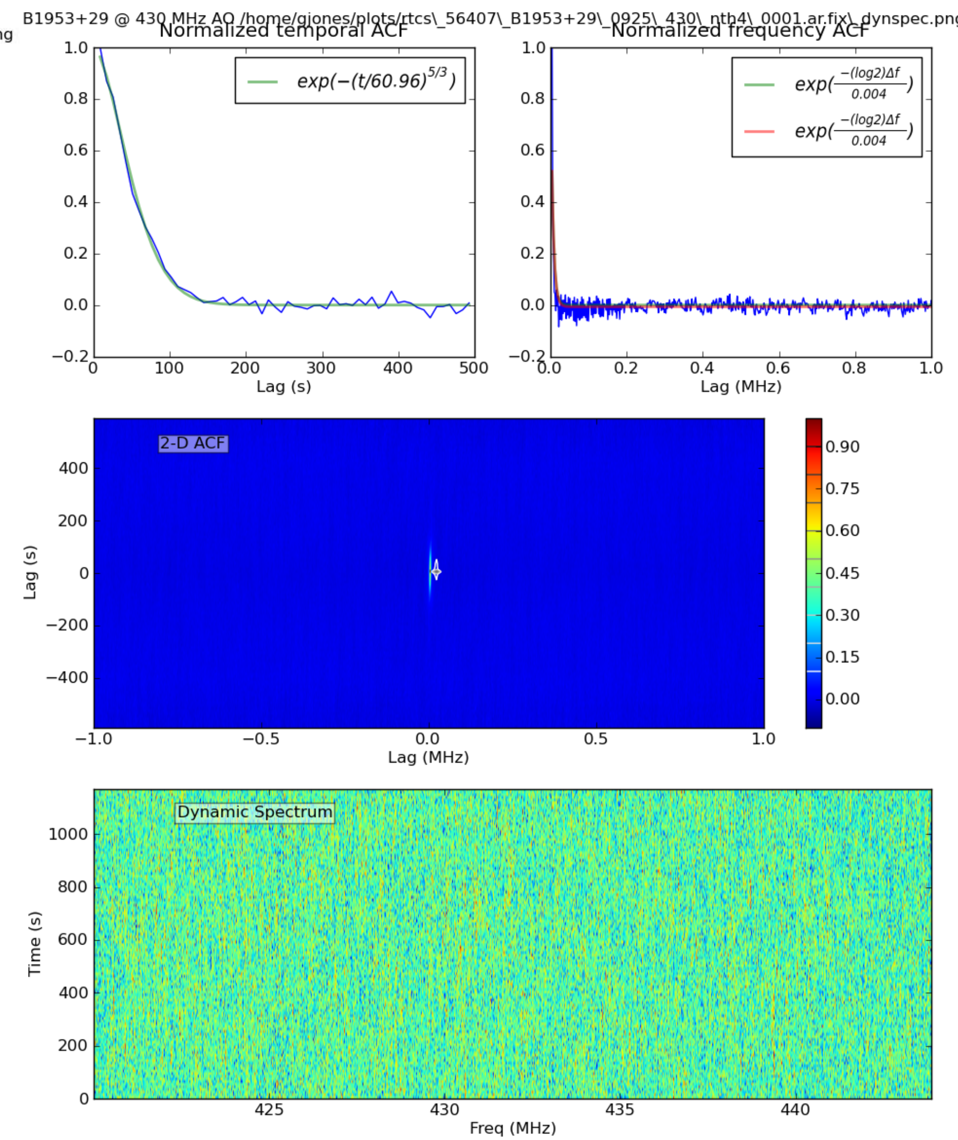
B1937+21, 430 MHz

CS provides precision RFI excision



We will be getting this kind of cyclic spectroscopy data on ~40+ pulsars every ~20-30 days!





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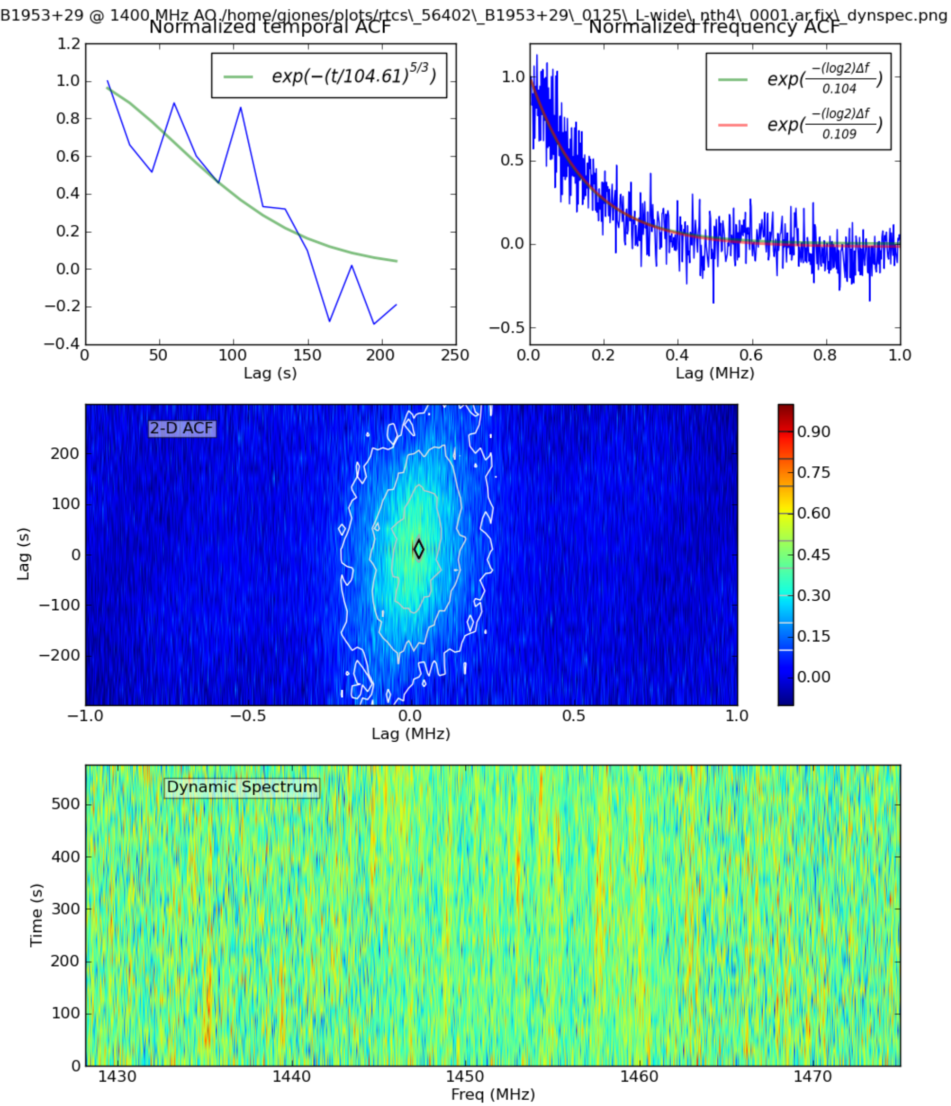
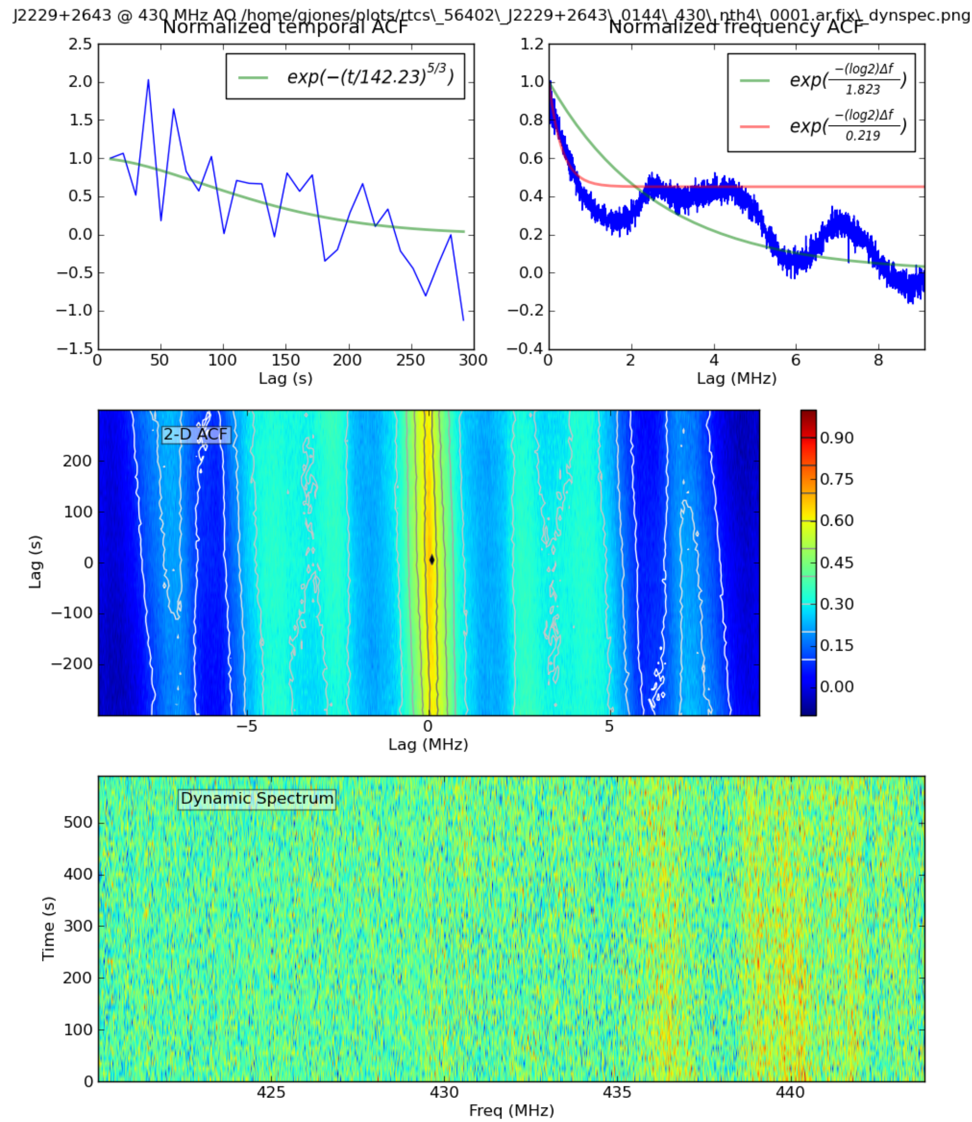




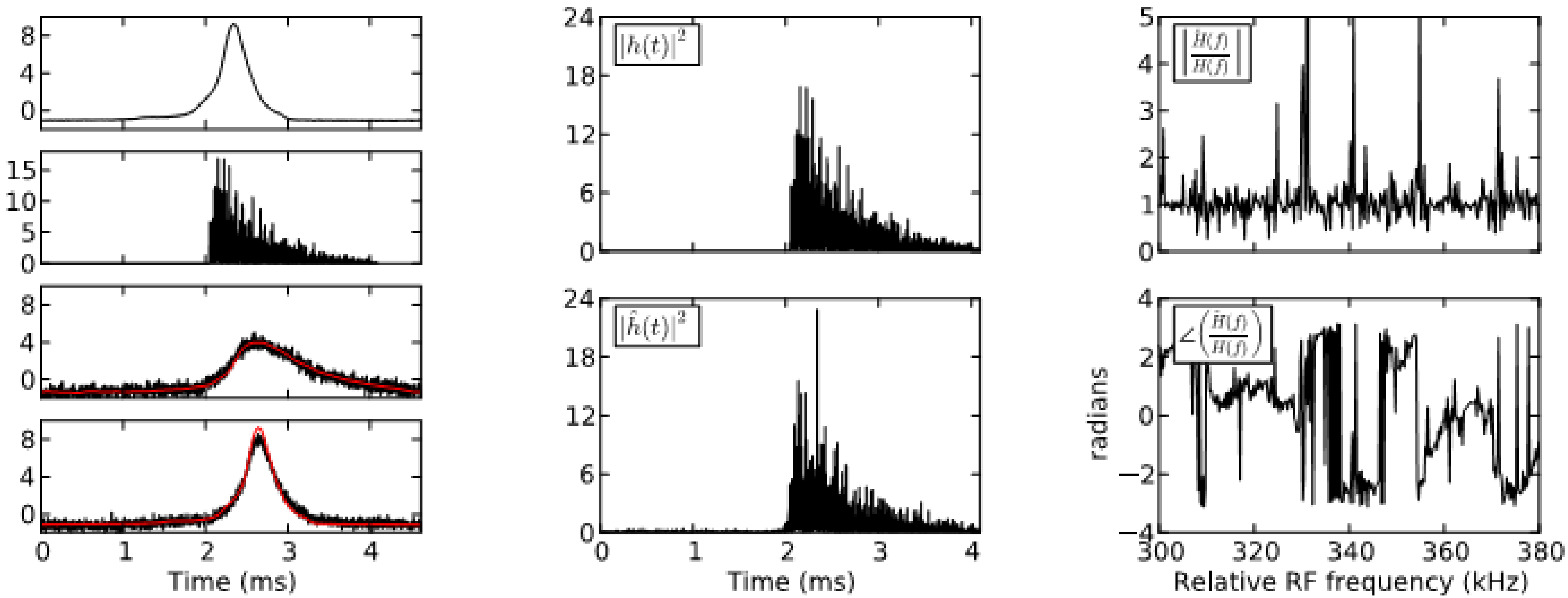
Other upcoming observations – J1643-1224 @ GBT

- Bright pulsar with unusually high RMS timing residual – one of the worst in the NANOGrav sample
- Significant scattering
- → Hopefully a good candidate for correction!
- 12 hours awarded to observe at 350, 820, and 1400 MHz at multiple epochs

Table 1: Properties of PSR J1643−1224

	350 MHz	**450 MHz**	**820 MHz**	**1000 MHz**	**1400 MHz**
Flux (mJy)	67	40.6	12.3	–	4.2
τ_d (μs)	600	200	17	7	1.7
ν_d (Hz)	270	770	9600	22000	90000
t_{DISS} (s)	183	242	468	582	843
SEFD (Jy)	45	28	13	–	10
SNR per scintle	3	6	18	–	33

Simulation of J1643-1224 deconvolution



Conclusions

- Cyclic spectroscopy is a fascinating technique for studying pulsars and the interstellar medium.
- Coherent deconvolution is promising but there is no free lunch.
- Still very much under development; many avenues to pursue in intelligently constraining the optimization.
- Not guaranteed to "work" for any pulsar at any frequency: More observations underway!
- Exact deconvolution is difficult, but CS has other uses: RFI removal, excellent estimates of magnitude of transfer function
- Hardware advances will allow it to be used routinely

Software for CS computation, deconvolution, and simulation

- CS computation:
  - **dspsr** http://dspsr.sourceforge.net/ (van Straten et al.)
  - Cudacyclo branch at https://github.com/gitj/dspsr : my effort to add GPU computation of CS
- Deconvolution:
  - **CyclicModelling** – Demorest and Walker: https://github.com/demorest/Cyclic-Modelling
  - pycyc & simcyc : my port of CyclicModelling to python with simulation capabilities: https://github.com/gitj/pycyc
  - Direct phase integration: Palliyaguru & Stinebring. Not yet released