Small Aperture, Low SNR Pulsar Detection

Peter East

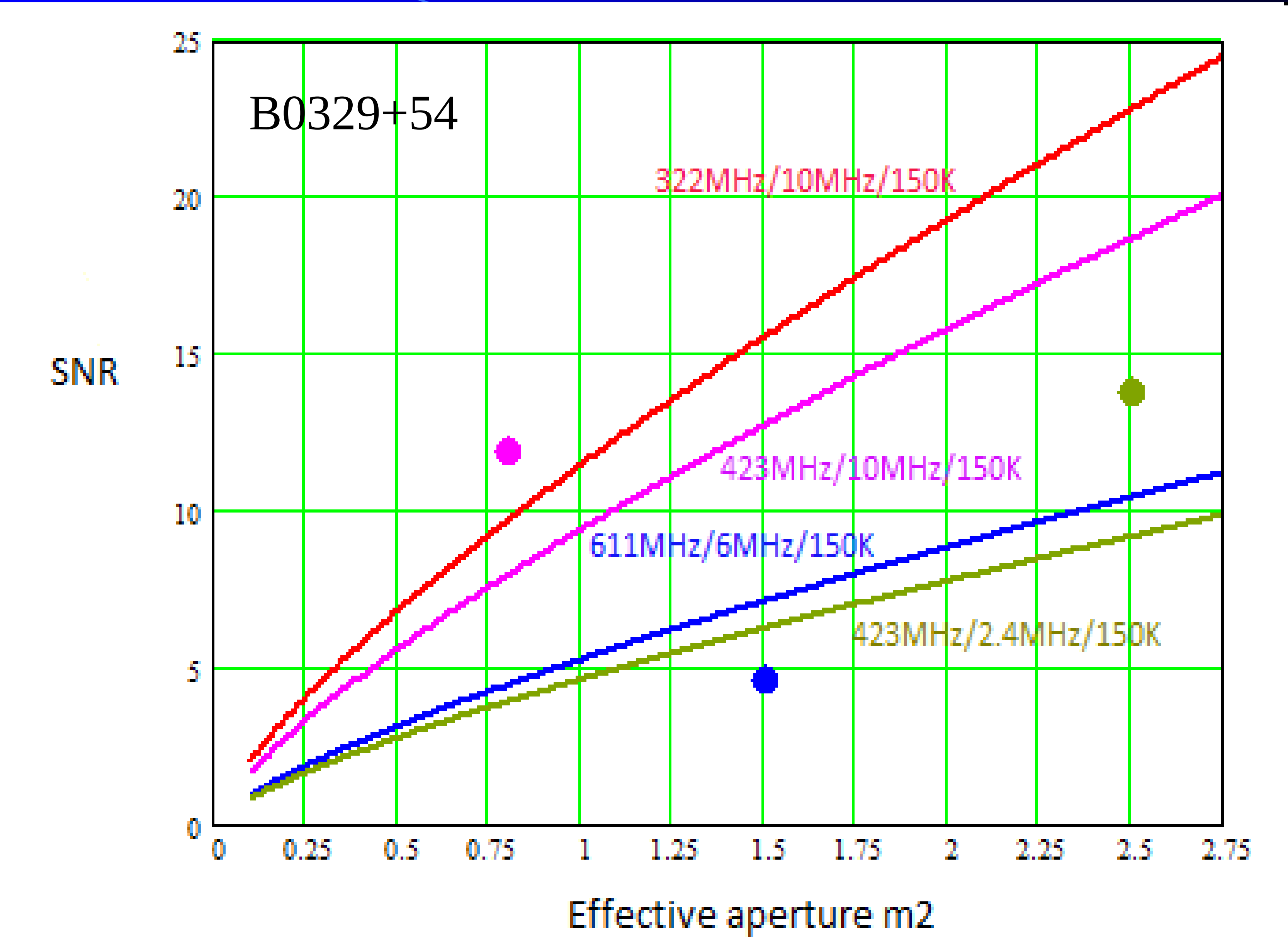
www.y1pwe.co.uk/RAProgs/Pulsars.html

Introduction

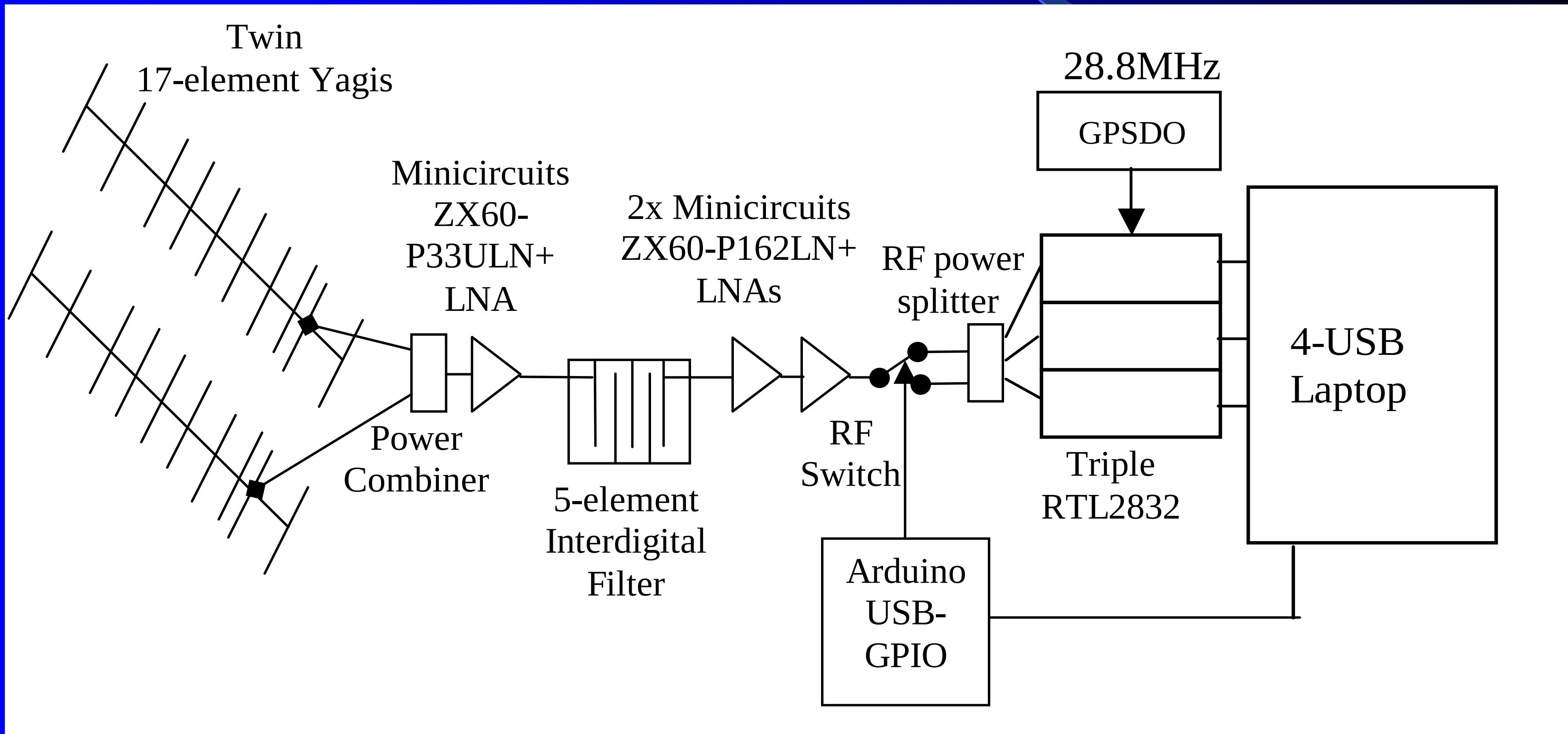
- Background
- Key System Drivers
- Low SNR Tests
- Conclusions

LK Radiometer Equation

$$SNR = \frac{S_p A_e \sqrt{n_p t_{\text{int}} \Delta f}}{2\beta k_b T_{sys}} \sqrt{\frac{P - W}{W}}$$


B0329+54
SNR
Effective aperture m2
322MHz/10MHz/150K
423MHz/10MHz/150K
611MHz/6MHz/150K
423MHz/2.4MHz/150K
0
5
10
15
20
25
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75

Mini Pulsar Radio Telescope



System Temperature - T_{SYS}

Receiver noise

power with Antenna..

1. Connected: P_{AC}
2. Feed O/C: P_{OC}
3. Feed matched: P_{ML}

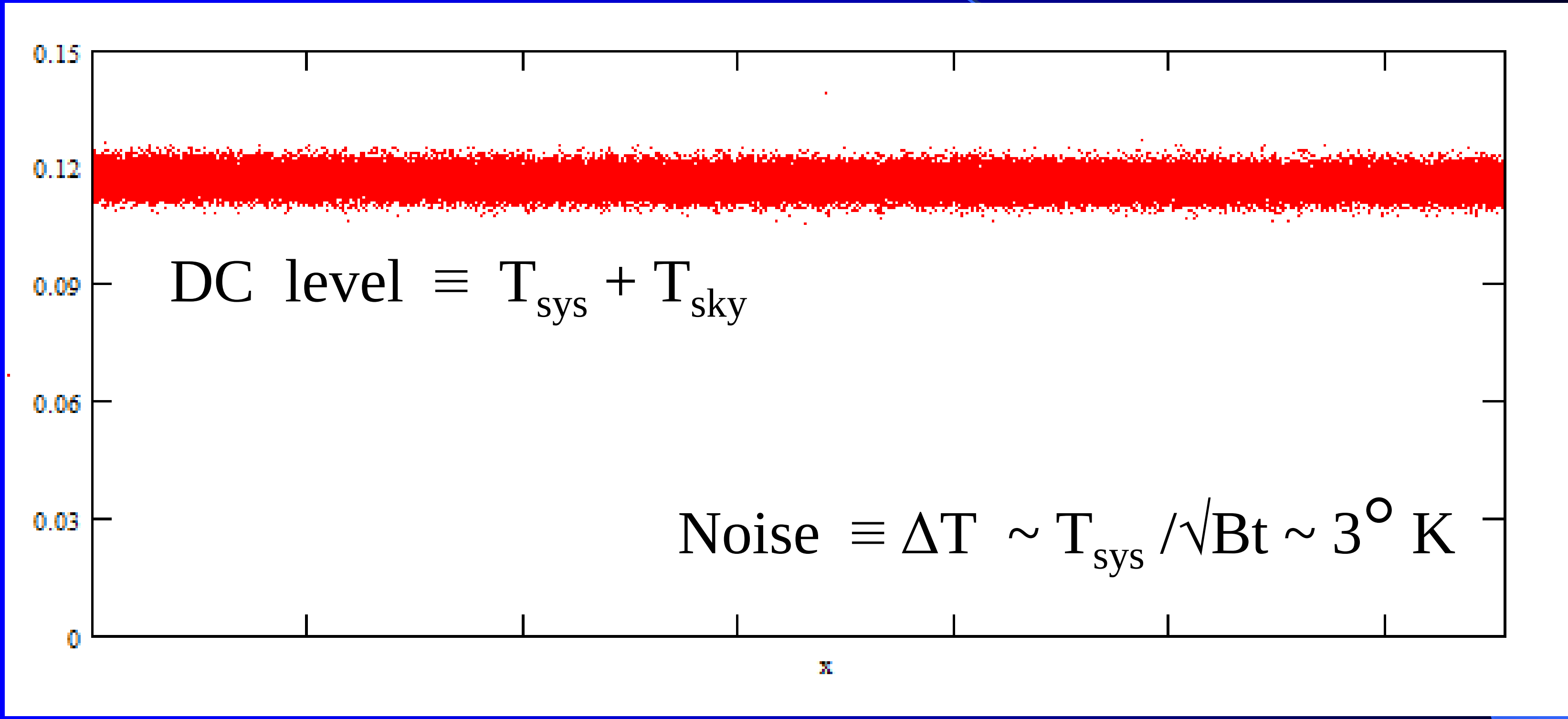
$$\frac{P_{OC}}{P_{ML}} = \frac{T_{RX}}{T_{RX} + 290}$$

$$T_{RX} = T_{LNA} + T_{Losses}$$

$$\frac{P_{AC}}{P_{OC}} = \frac{T_{SYS}}{T_{RX}}$$

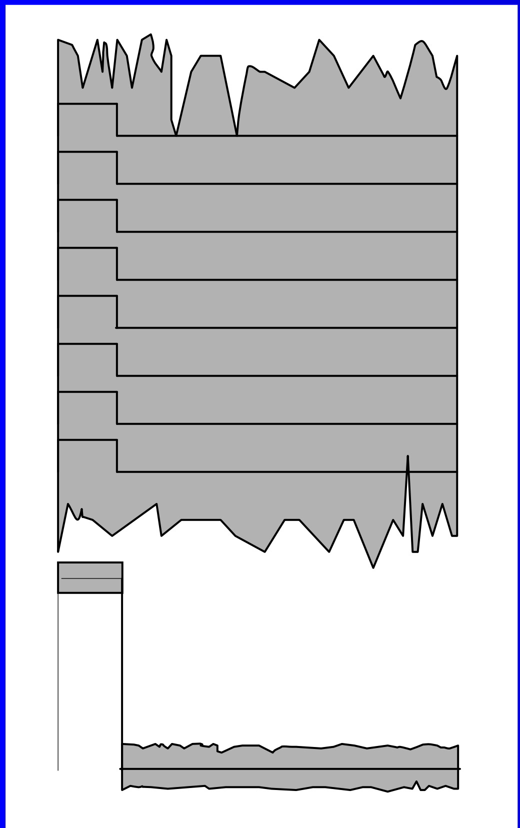
$$T_{SYS} = T_{RX} + T_{SKY} + T_{Antenna}$$

Detected Video



B = 2.4MHz, t = 1ms, and, $(T_{sys} + T_{sky})/\Delta T = 50$

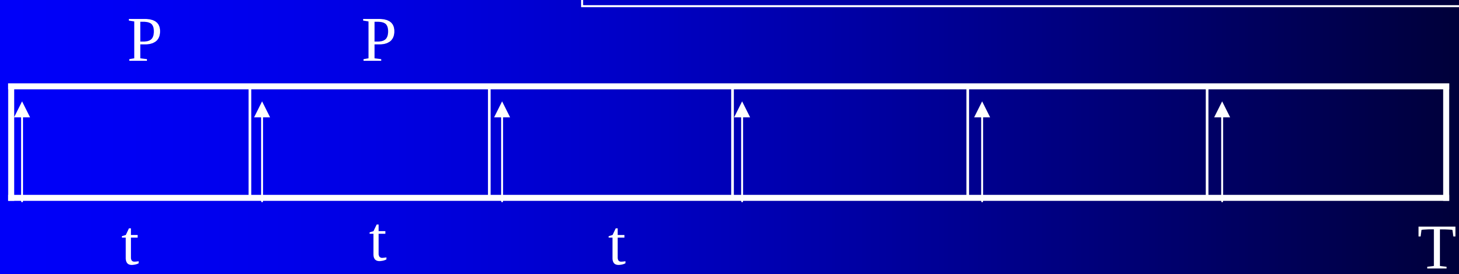
Folding Algorithm



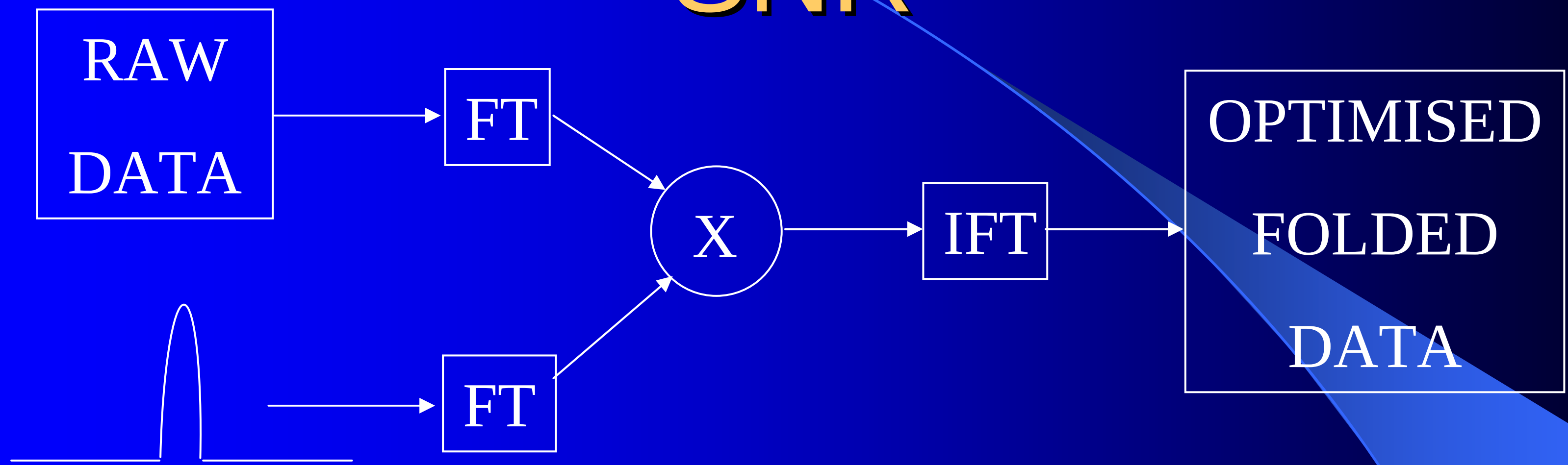
- * Pulse adds linearly
- * Noise adds as square root
- * SNR improves as $\sqrt{(\text{Folds} = F)}$

$$\text{SNR} = \sqrt{(F P \Delta f / N)} \times Tp/Tsys$$

- Optimum bins N = Period/Pwidth
- B0329: $Tp \sim 0.03°\text{K/m}^2\text{/pol}$

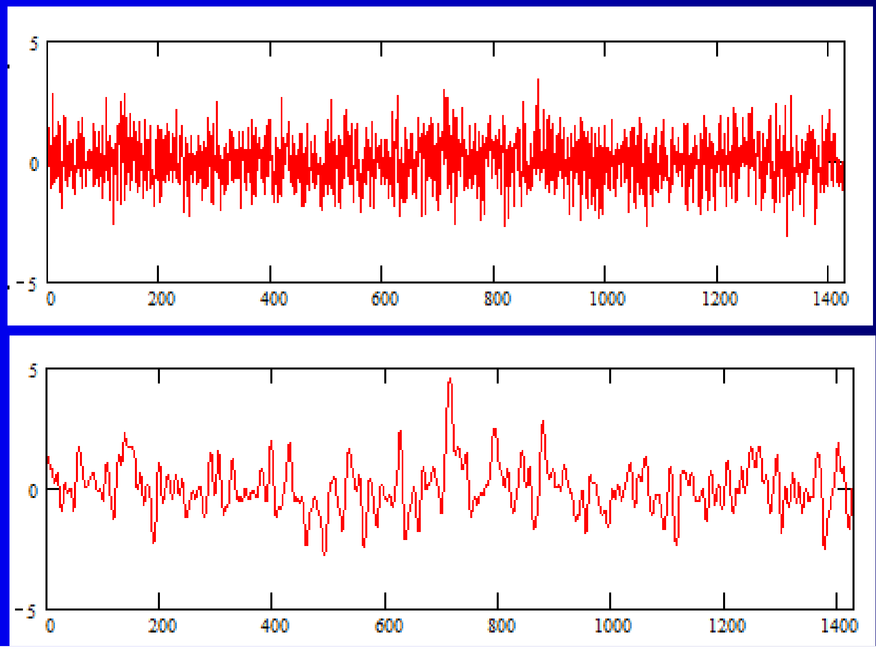


Matched Filter - optimises SNR



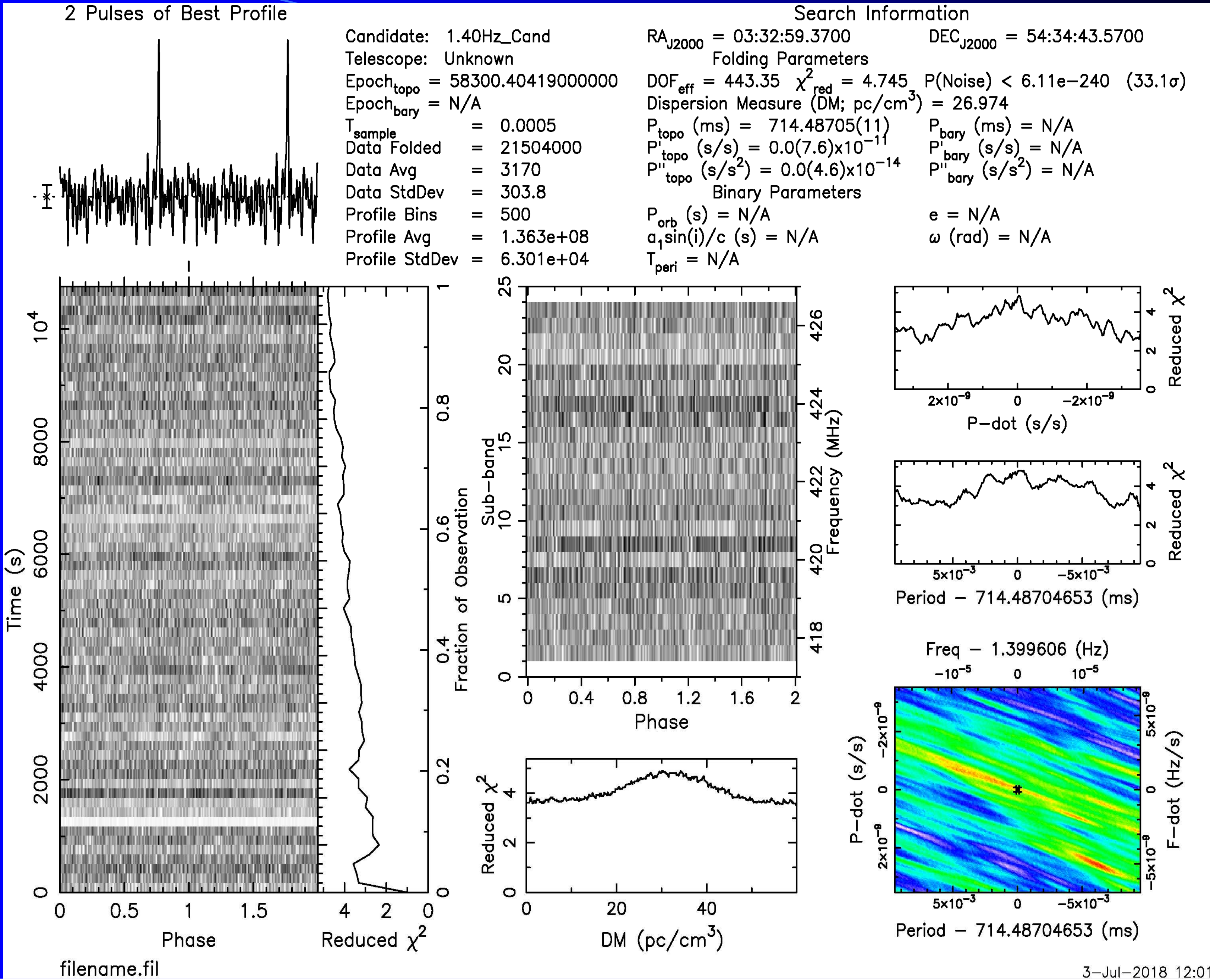
For B0329

$$\frac{P-W}{W} \approx 109$$



Finding and Validating

- Strong signal - Presto Plot
- Weak signal - exploit pulsar characteristics
  1. Correct period –TEMPO + GPS/Rubidium DO
  2. Check pulse width – Matched filter peak
  3. Two-period fold correlation.
  4. Two-section fold correlation
  5. Multi-band correlation.
  6. Period search peak – profile, offset and pulse width
  7. P-dot search peak – profile, offset and pulse width
  8. Dispersion search peak – amplitude and pulse width


2 Pulses of Best Profile
Search Information
Candidate: 1.40Hz_Cand
Telescope: Unknown
Epoch_topo = 58300.40419000000
Epoch_bary = N/A
T_sample = 0.0005
Data Folded = 21504000
Data Avg = 3170
Data StdDev = 303.8
Profile Bins = 500
Profile Avg = 1.363e+08
Profile StdDev = 6.301e+04
RA_J2000 = 03:32:59.3700
DEC_J2000 = 54:34:43.5700
Folding Parameters
DOF_eff = 443.35 χ²_red = 4.745 P(Noise) < 6.11e−240 (33.1σ)
Dispersion Measure (DM; pc/cm³) = 26.974
P_topo (ms) = 714.48705(11)
P'_topo (s/s) = 0.0(7.6)x10⁻¹¹
P''_topo (s/s²) = 0.0(4.6)x10⁻¹⁴
P_bary (ms) = N/A
P'_bary (s/s) = N/A
P''_bary (s/s²) = N/A
Binary Parameters
P_orb (s) = N/A
a₁sin(i)/c (s) = N/A
T_peri = N/A
e = N/A
ω (rad) = N/A
Time (s)
Phase
Reduced χ²
Fraction of Observation
Sub−band
Frequency (MHz)
DM (pc/cm³)
P−dot (s/s)
Period − 714.48704653 (ms)
Freq − 1.399606 (Hz)
F−dot (Hz/s)
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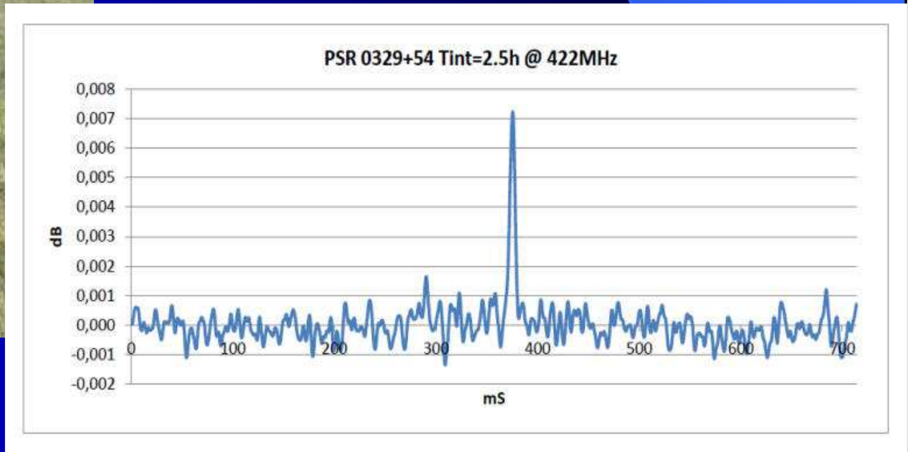
3−Jul−2018 12:01

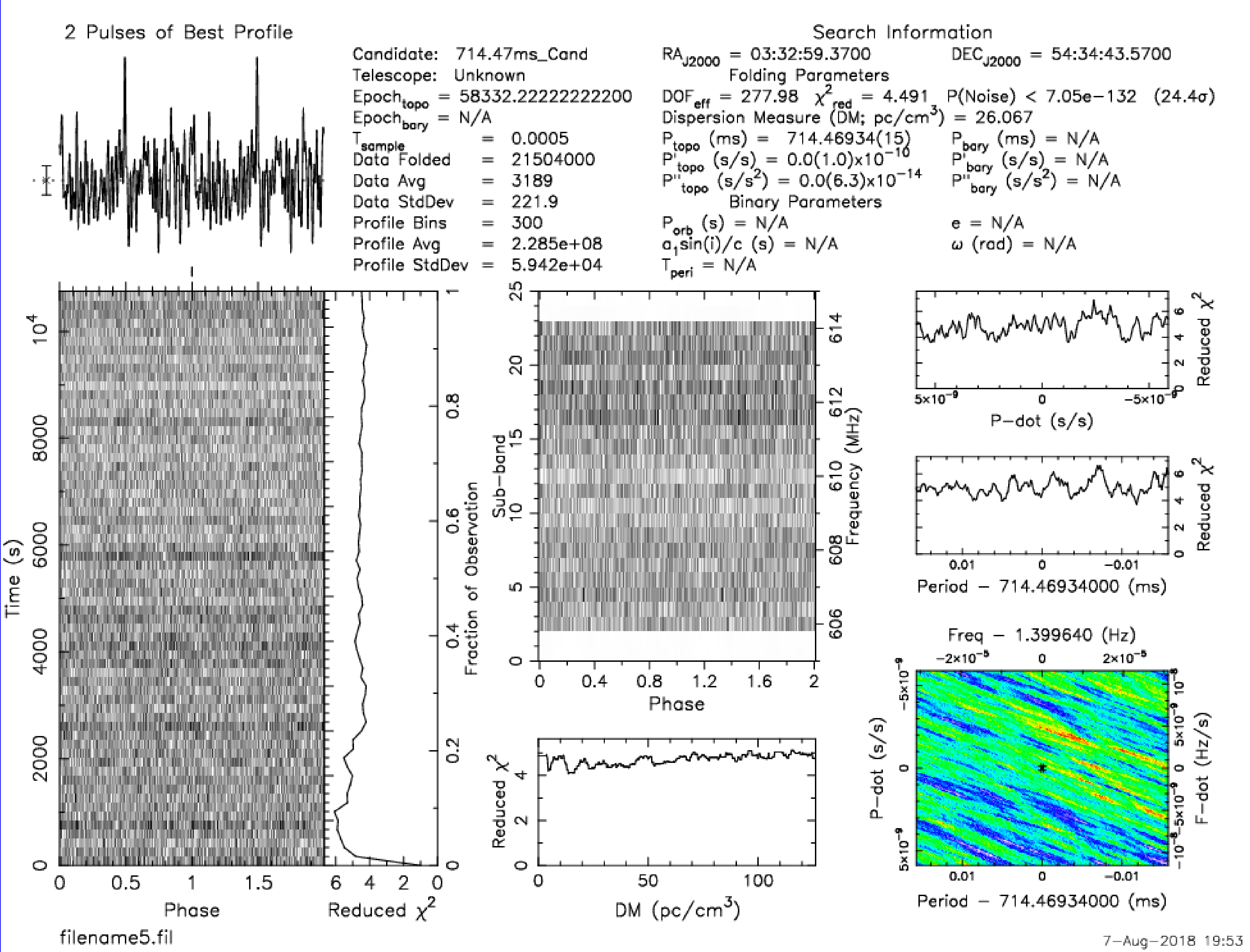
Andrea Dell'Immagine - Italy
422MHz + 2.4MHz RTL+ 3Hrs
2x2x2m 3D corner reflector antenna

Automatic Daily Observatory
$2.5m^2$ Aperture

SNR = 11.5



http://iw5bhy.altervista.org/


2 Pulses of Best Profile
Candidate: 714.47ms_Cand
Telescope: Unknown
Epoch_topo = 58332.22222222200
Epoch_bary = N/A
T_sample = 0.0005
Data Folded = 21504000
Data Avg = 3189
Data StdDev = 221.9
Profile Bins = 300
Profile Avg = 2.285e+08
Profile StdDev = 5.942e+04
Search Information
RA_J2000 = 03:32:59.3700
DEC_J2000 = 54:34:43.5700
Folding Parameters
DOF_eff = 277.98 χ²_red = 4.491 P(Noise) < 7.05e−132 (24.4σ)
Dispersion Measure (DM; pc/cm³) = 26.067
P_topo (ms) = 714.46934(15)
P_bary (ms) = N/A
P'_topo (s/s) = 0.0(1.0)x10^−10
P'_bary (s/s) = N/A
P''_topo (s/s²) = 0.0(6.3)x10^−14
P''_bary (s/s²) = N/A
Binary Parameters
P_orb (s) = N/A
e = N/A
a_1sin(i)/c (s) = N/A
ω (rad) = N/A
T_peri = N/A
Time (s)
Phase
Reduced χ²
Fraction of Observation
Sub−band
Frequency (MHz)
DM (pc/cm³)
P−dot (s/s)
Period − 714.46934000 (ms)
Freq − 1.399640 (Hz)
F−dot (Hz/s)
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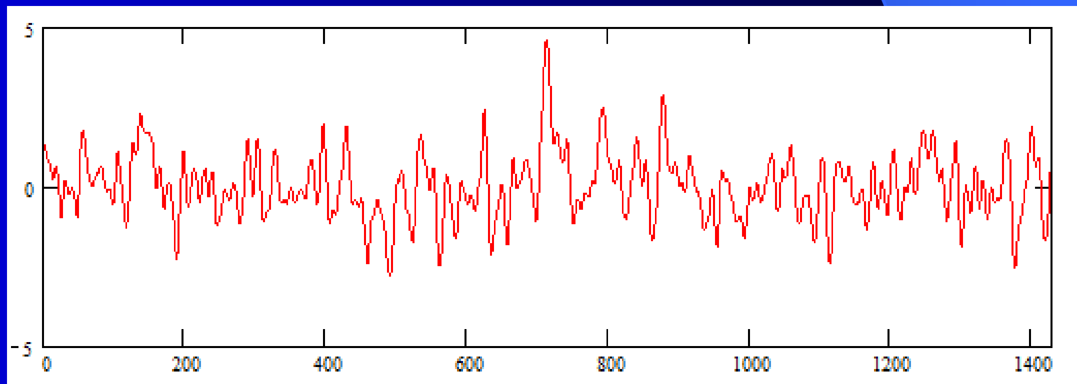
611MHz + 6MHz (3x2.4MHz) + 2Hrs
Twin 2.5m Yagis

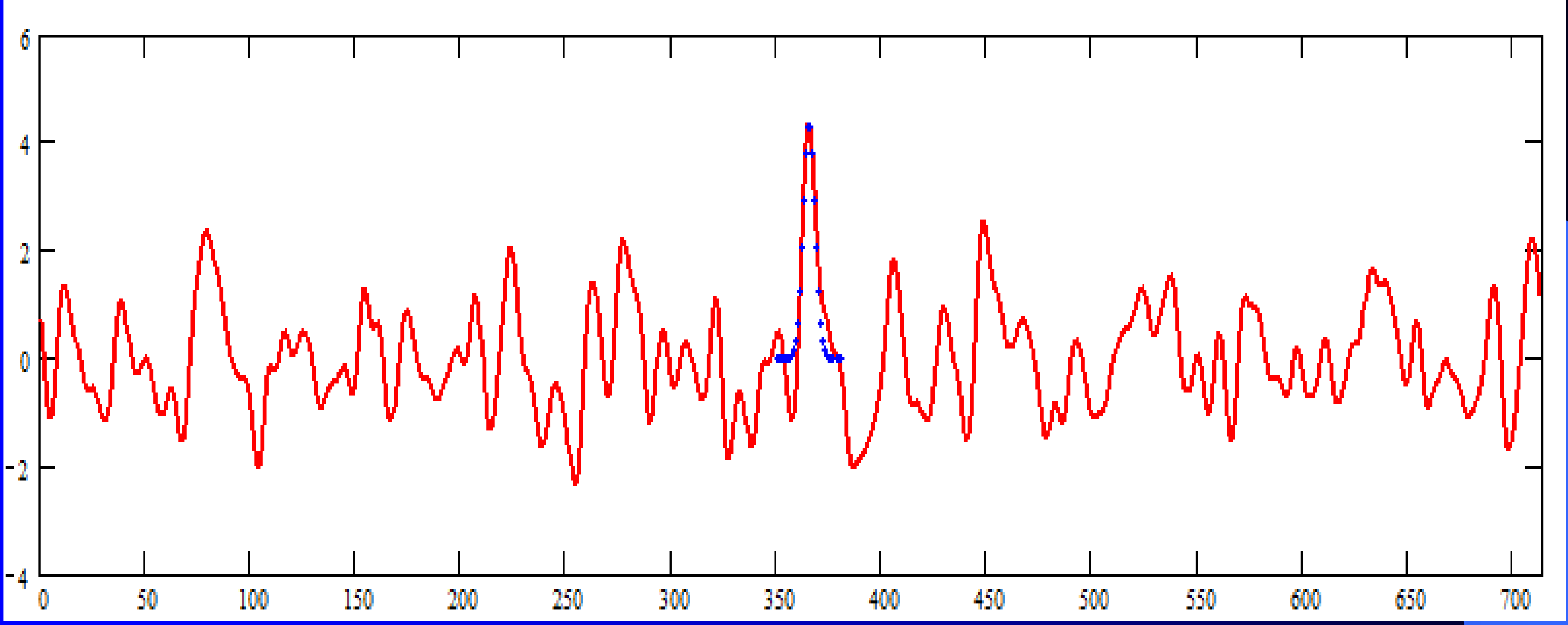
Minimal Affordable System
1.5m^2 aperture

B0329+54 Pulsar
period: 714.4816893ms

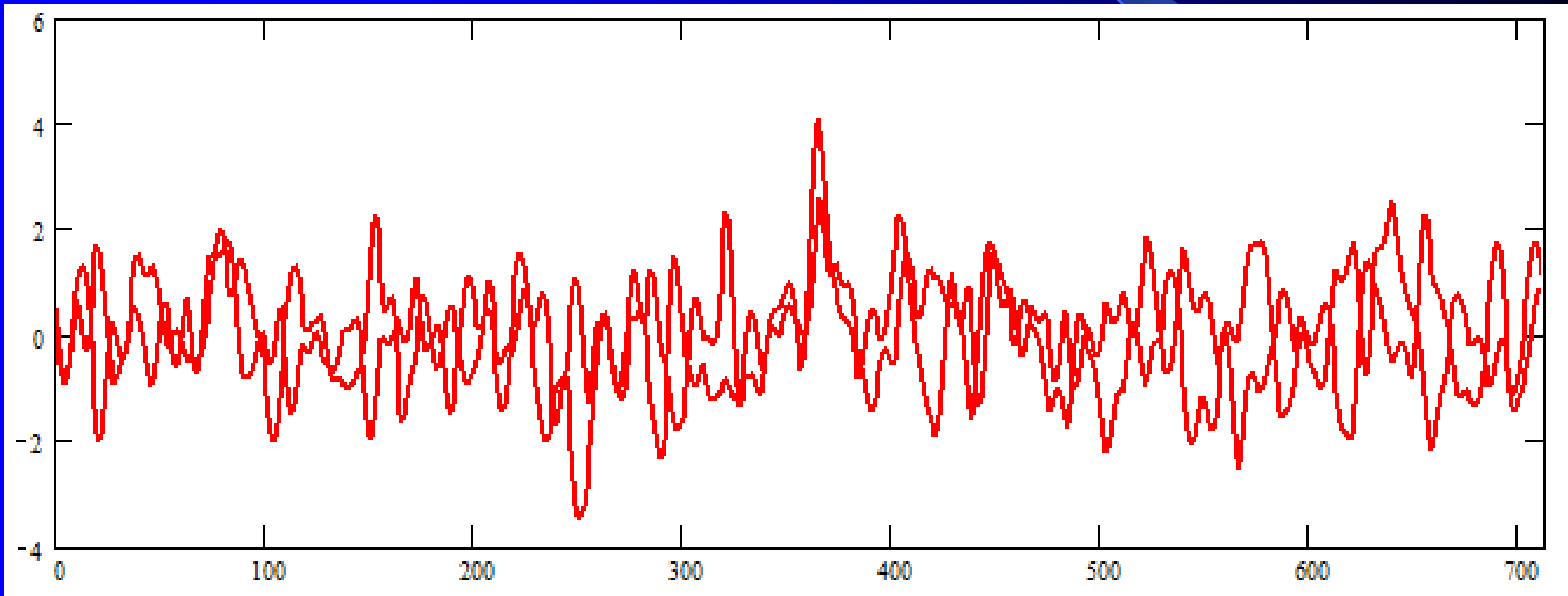
SNR = 4.5



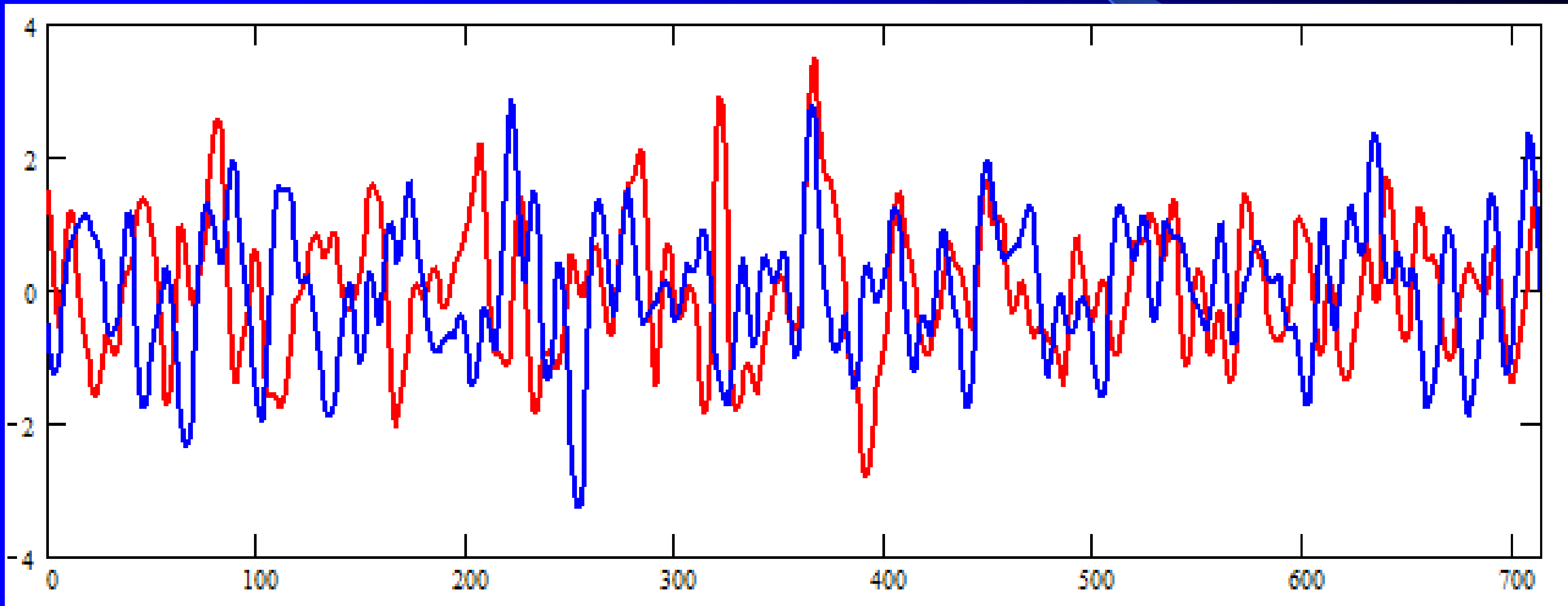
B0329 Tests 1,2. Period/Pulse Width Check



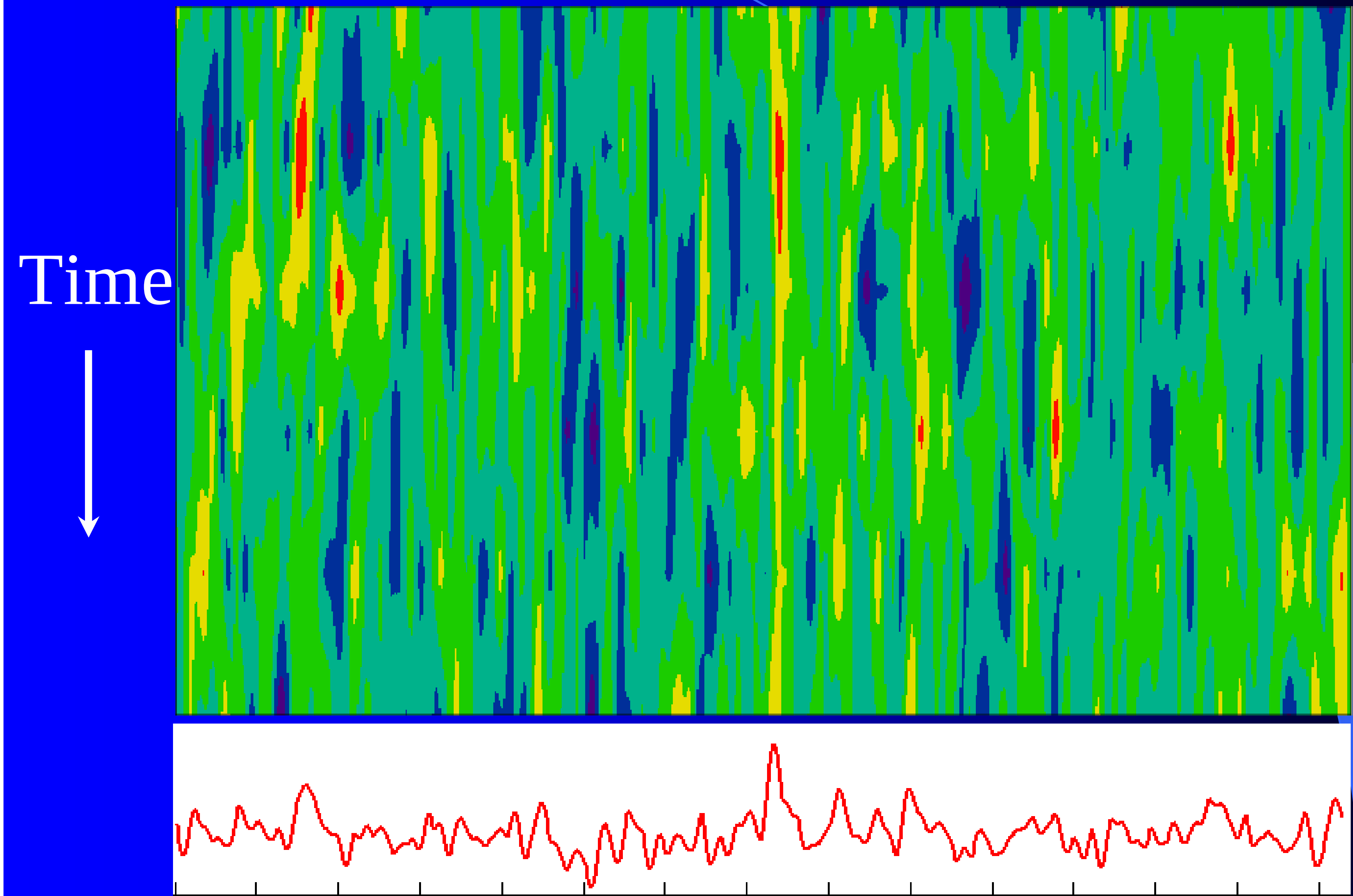
Test 3. 2-Period Fold - 2 sections overlaid



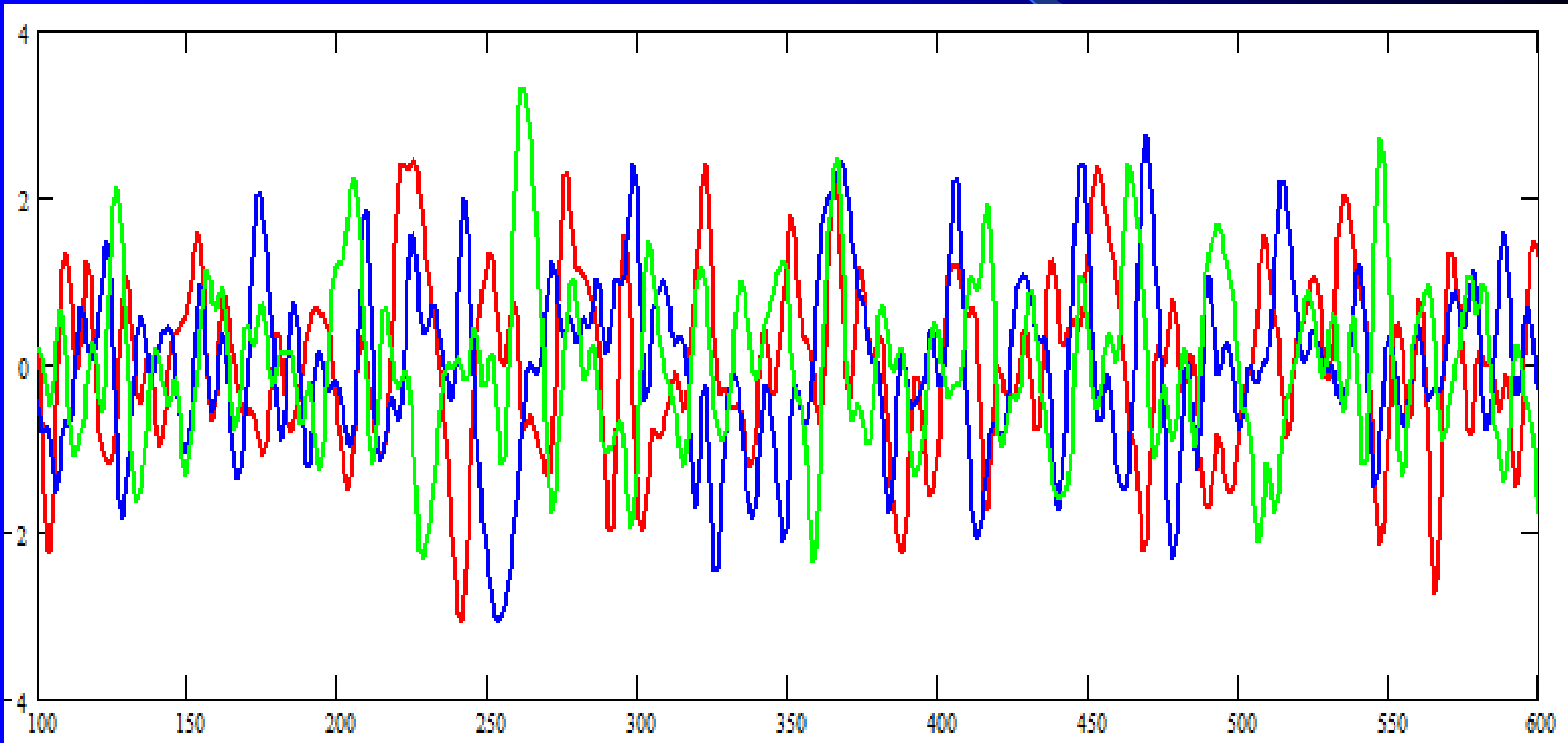
Test 4. Half File Correlation



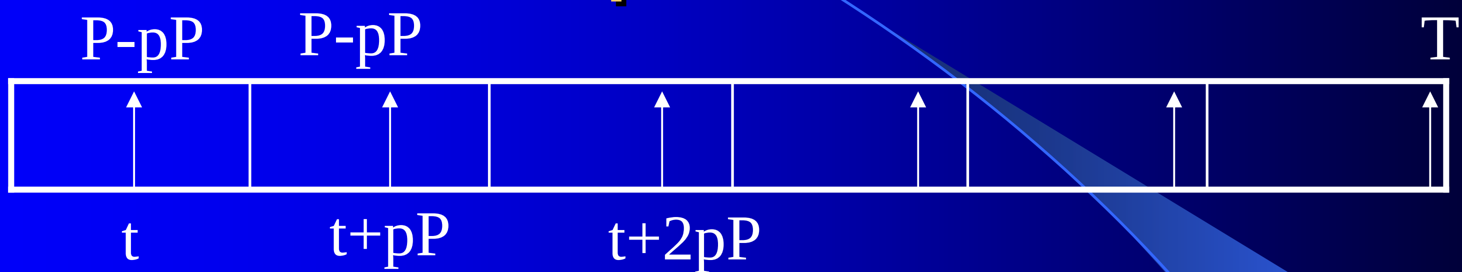
Test 4. cont'd. Falling Raster

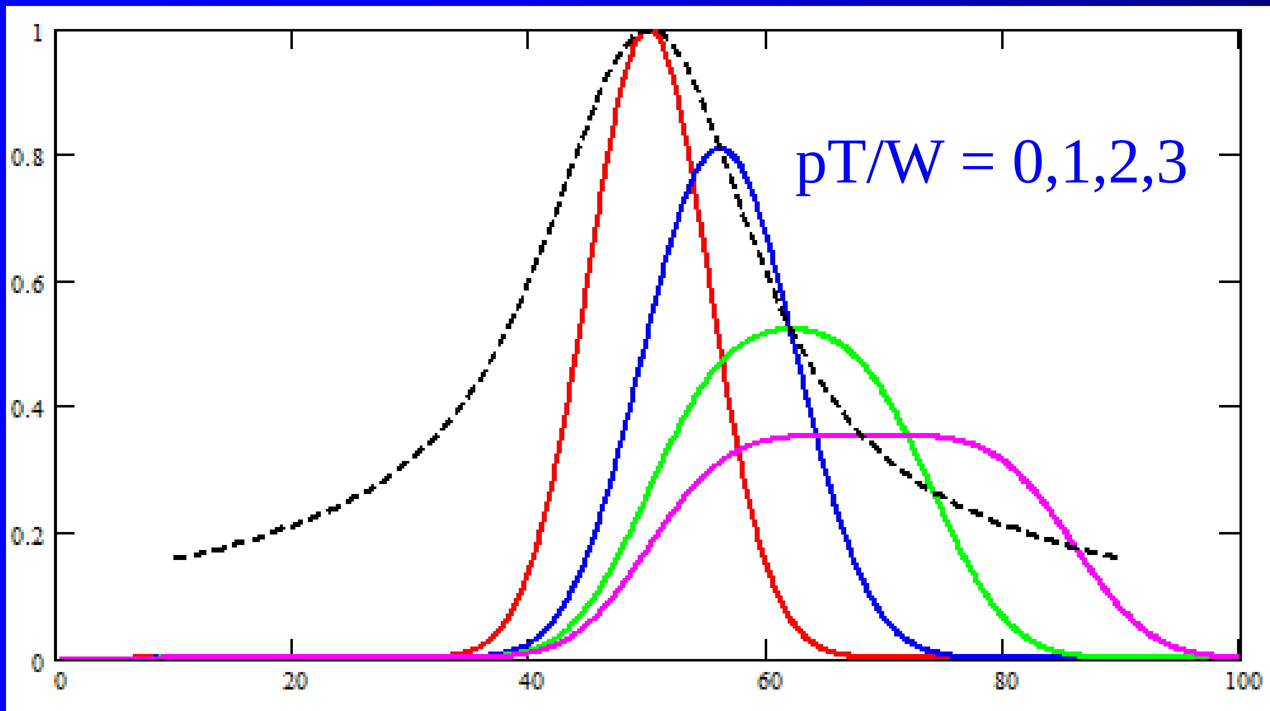


Test 5. Sub-Band Correlation



Test 6. Period Search Properties



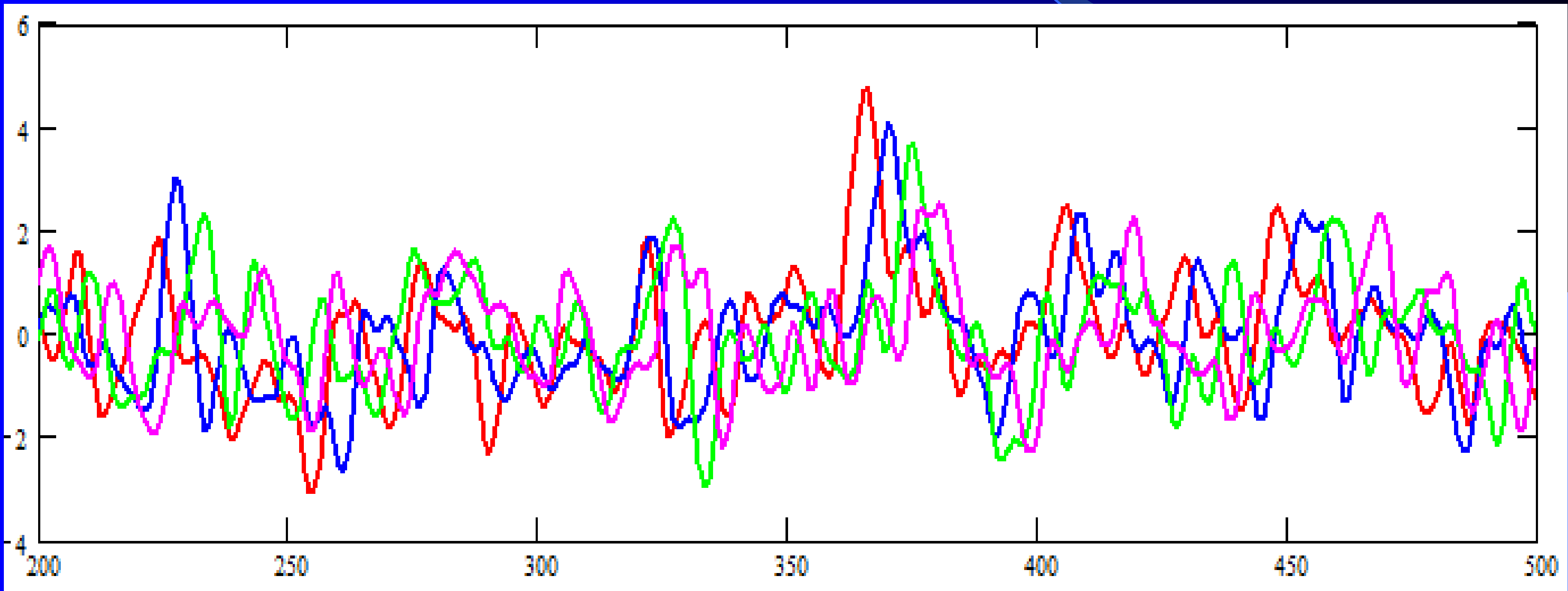


New Width: pT
New Peak: –pT/2

Example; T=7000s
p = -1ppm, P=700ms
Peak shift = +3.5ms

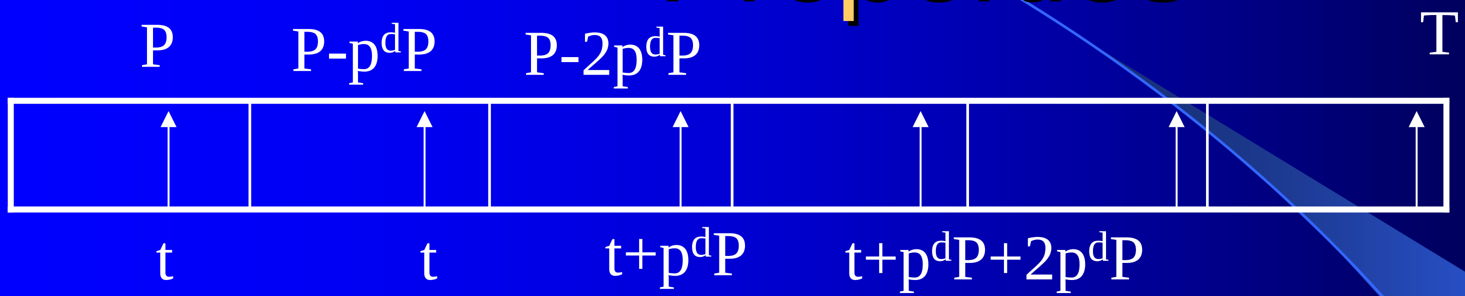
Half height, p=2W/T

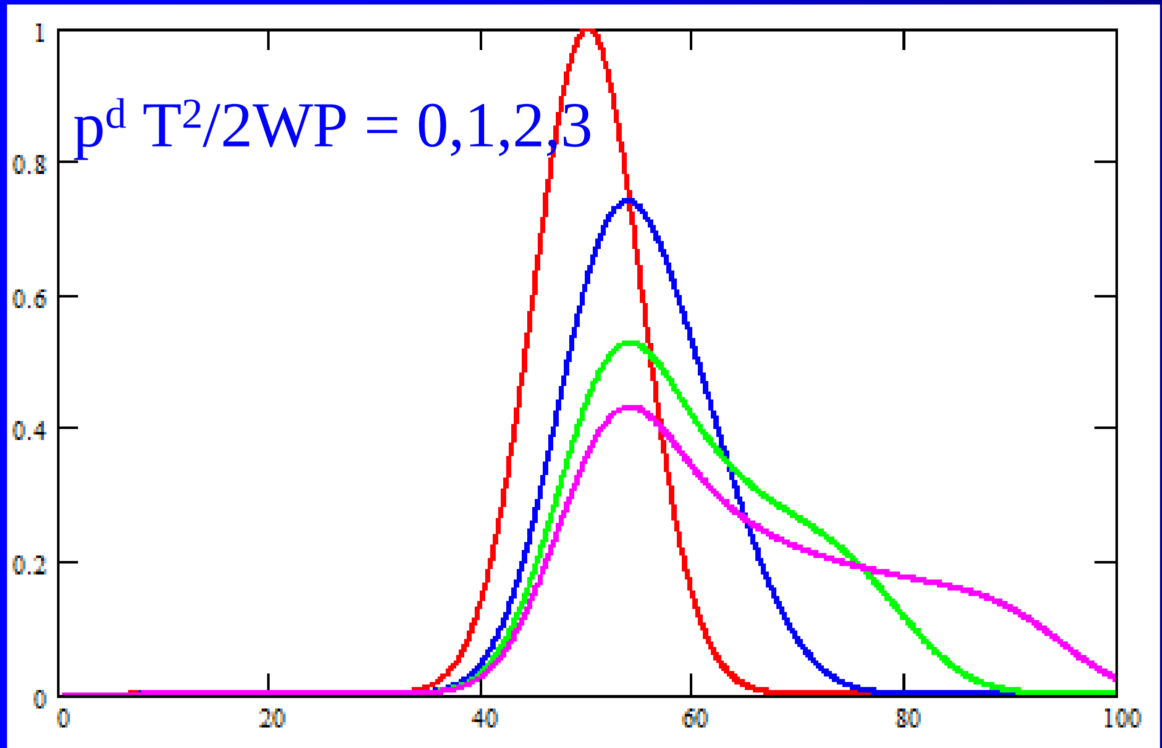
Test 6 cont'd. Period Search Data



p = 0, -1,-2,-3ppm

Test 7. p-dot ($\delta P/P$) Search Properties





For small p^d

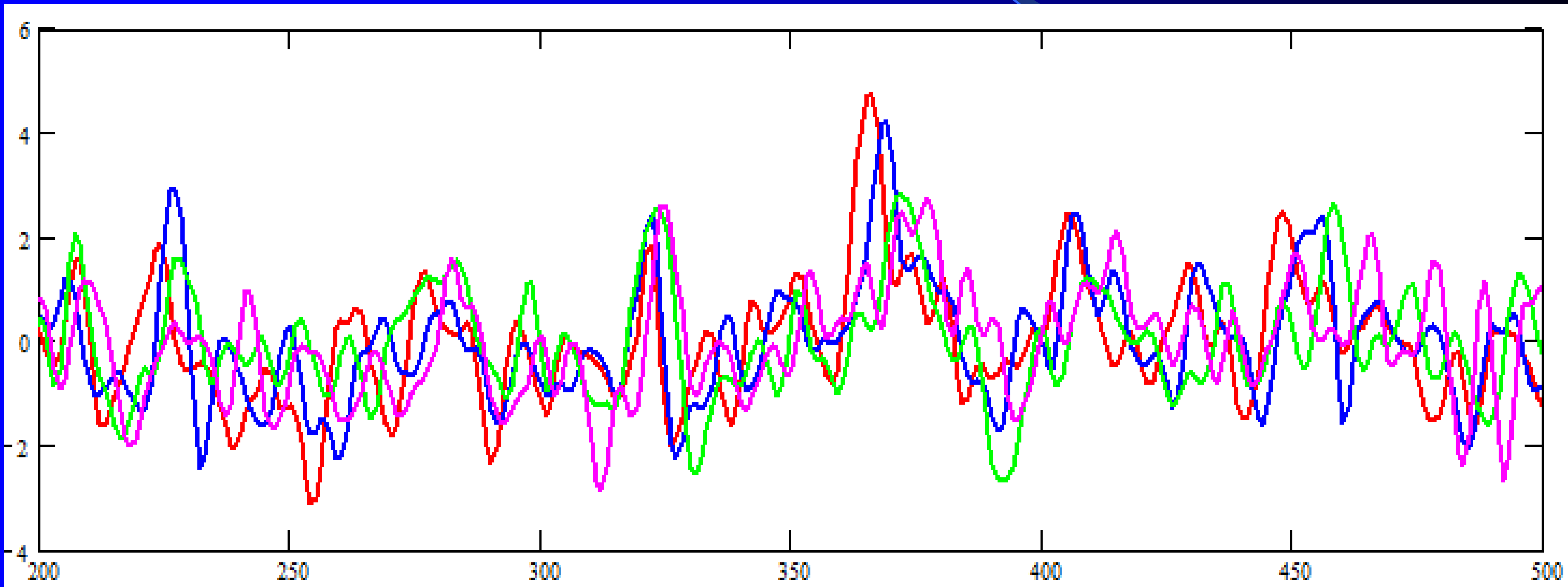
New Width: $p^d T^2/2P$

Example; T=7000s

$p^d = -2.10^{-10}$, P=700ms

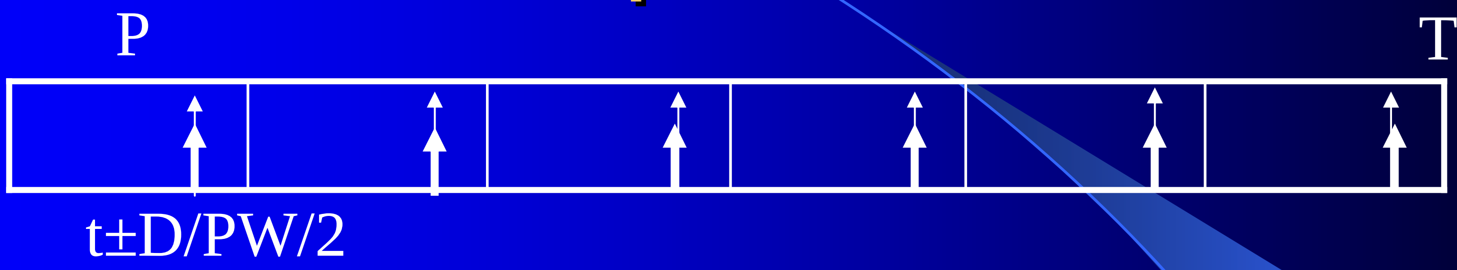
Median shift = +3.5ms

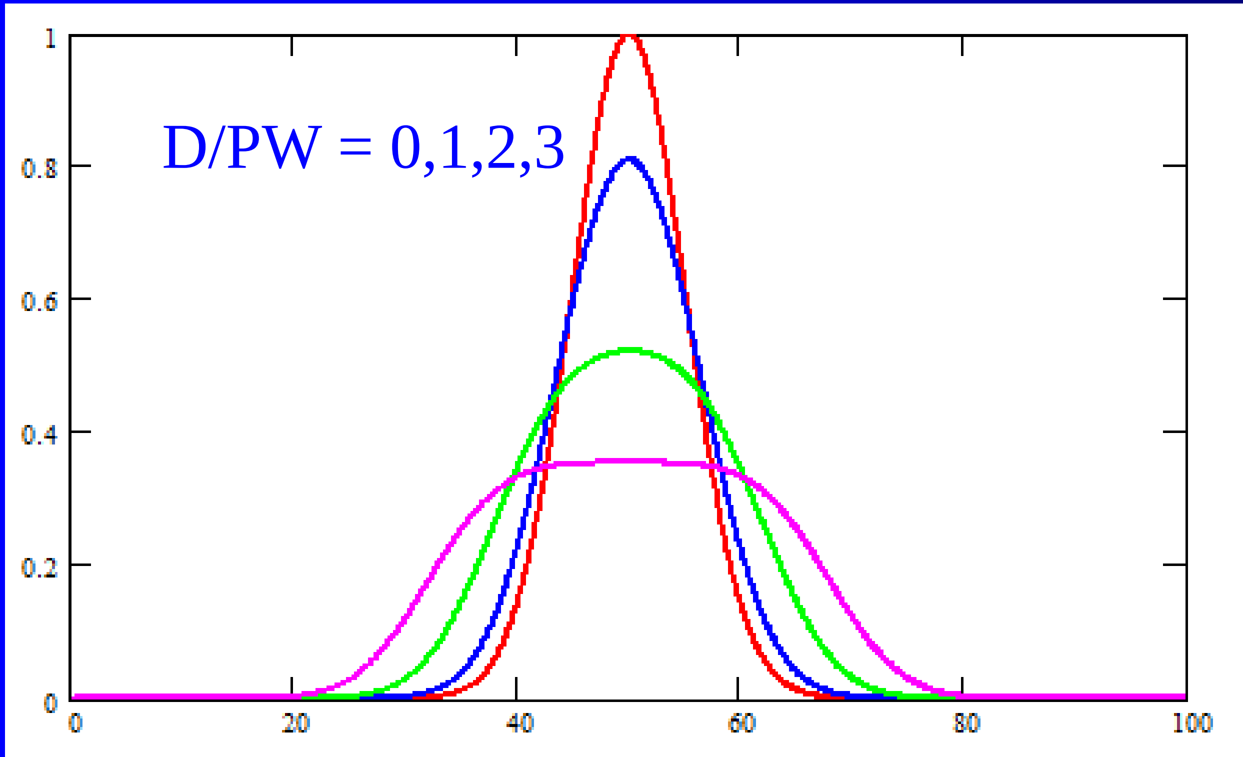
Test 7 cont'd. p-dot Search Data



$p^d = 0,-1,-2,-3x10^{-10}$

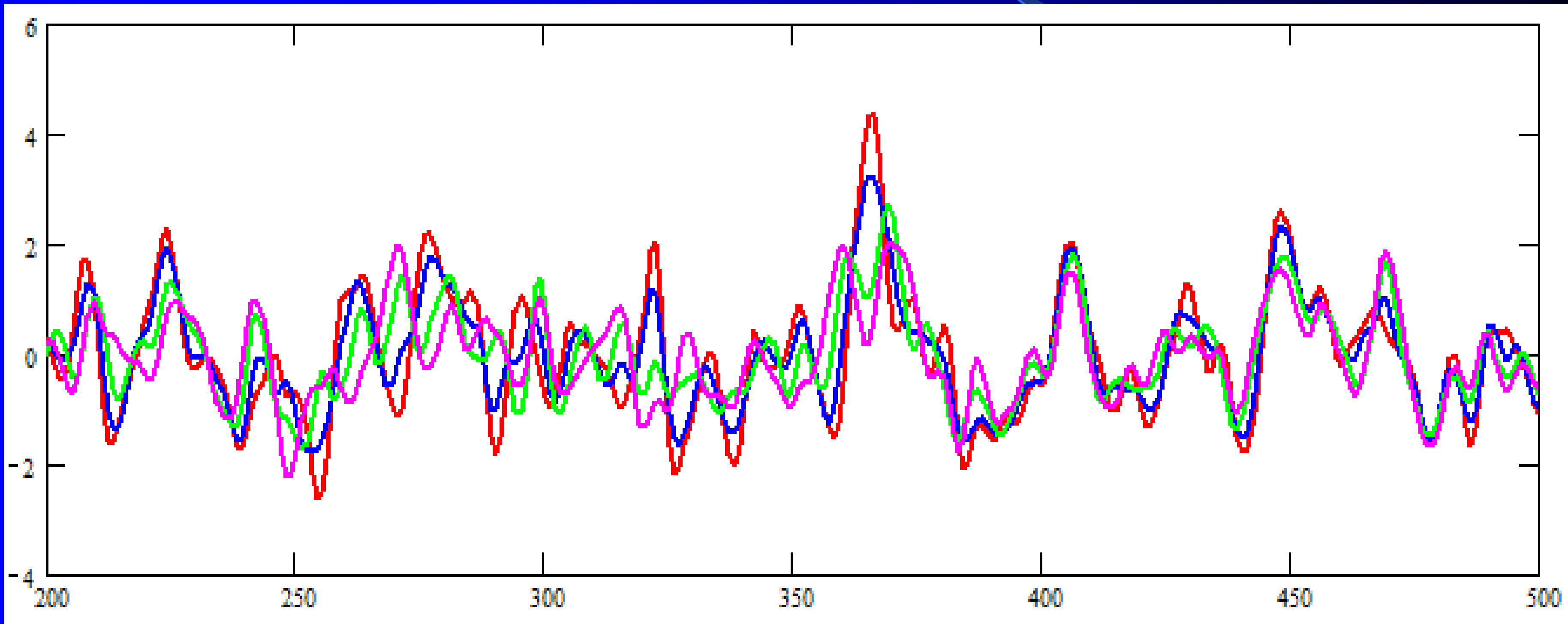
Test 8. Dispersion Search Properties





Dispersion
Zero at Band Centre

Test 8 cont'd. Dispersion Search Data



D/W = 0,±1,2,3 - dispersion zero at band centre

Low SNR Validation Summary

1. Pulsar SNR's below 10:1 require careful validation
2. Interference and peaks of natural noise cause confusion
3. The key to identifying these is to exploit the pulsar properties
4. The 8-point test plan discussed works well down to 4:1 SNRs
5. In areas of low RFI some candidates are recognised down to 3:1

Conclusions

1. Pulsar B0329 can be detected in the 300/400/600Mhz RA RF bands using home-made, small aperture (<2m^2) antennas.
2. The main antenna design requirement is for low sidelobes.
3. Exploiting pulsar pulse properties* is key to identifying low SNR pulsars in RFI and noise.
4. for more detail…..

   www.y1pwe.co.uk/RAProgs/MiniPulsarRx.pdf

*Keith MJ et al, 'Discovery of 28 pulsars using new techniques for sorting pulsar candidates' Mon.Not. R. Astron.Soc. 395, pp837-846(2009)