Pulsar Observations Using LWA1

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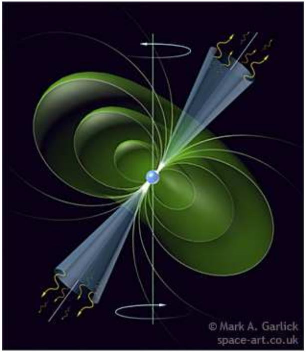
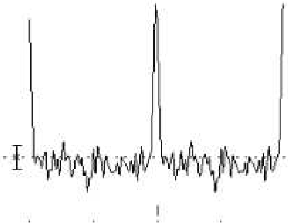
Background

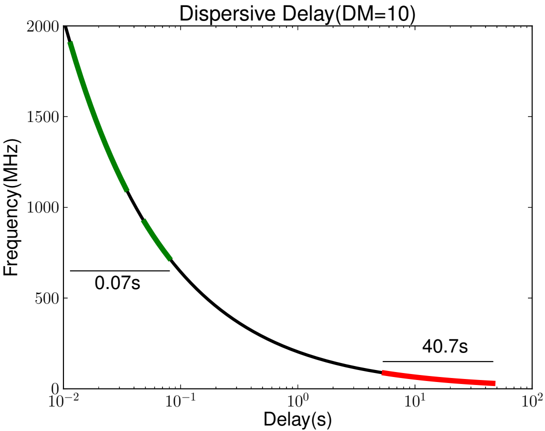
- The first pulsar (B1919+21) was discovered in 1967 at ∼80 MHz.
- Pulsar astronomy moved to primarily being performed at higher frequencies (300 MHz and above) for the next several decades.
- Interstellar medium (ISM) effects are significantly greater at low frequencies.
- Pulsar spectra are generally modelled as power law with spectral indices of about -1.8. However, many pulsars show a break in their spectra at around 100 to 200 MHz.





Effects of Interstellar Medium

- Dispersion
  $t_{DM} \propto \nu^{-2}$
- Interstellar Scattering
  $\tau_d \propto \nu^{-4}$
- Scintillation
- Faraday Rotation
  $\Delta\phi \propto \nu^{-2}$

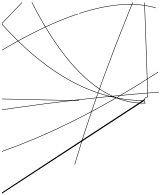


ΔDM of 0.0005
GBT $\sim 34\mu s$
LWA1 $\sim 2ms$

Pulsar Detections

J0030+0451
B0031-07
J0034-0534
B0138+59
B0320+39
B0329+54
B0355+54
B0450+55
B0525+21
B0531+21
B0628-28
B0655+64
B0809+74
B0818-13
B0823+26
B0834+06
B0919+06
B0943+10
B0950+08
B1112+50
B1133+13
B1237+25
B1508+55
B1540-06
B1541+09
B1604-00
B1612+07
B1642-03
B1706-16
B1749-28
B1822-09
B1839+56
B1842+14
B1919+21
B1929+10
B2020+28
B2110+27
J2145-0750
B2217+47

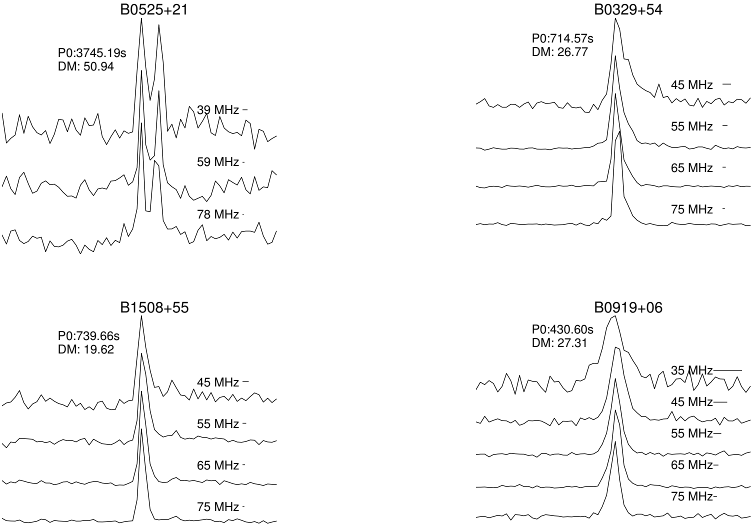
39 Pulsars detected (38 pulsations, 1 GPs*)
3 MSPs detected
Periods from 1.9 ms to 4.3 s



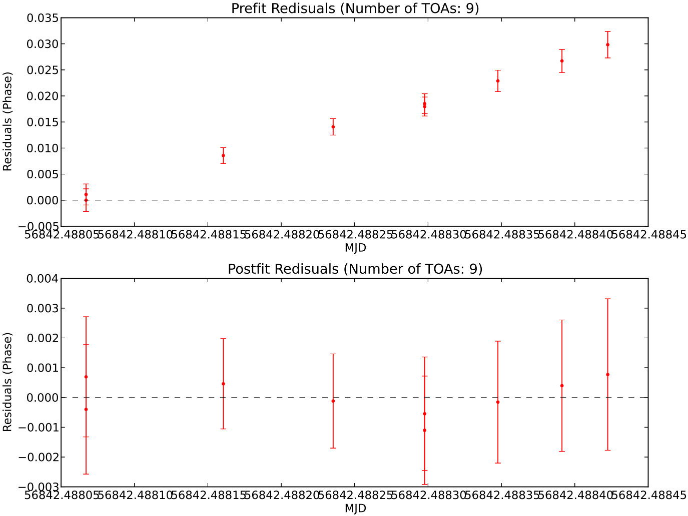
Ongoing LWA1 Pulsar/Transient Projects

- Low frequency study of known pulsars (flux density, DM, scattering, mode changing, etc.)
- MSP monitoring
- All-sky pulsar and fast transient survey (FRBs, RRATs)
- Study of giant pulses from B0535+21 (Crab) and other pulsars
- Follow-up of known RRATs at low frequency
- Follow-up of FERMI discovered pulsars and unassociated point sources
- Radio follow-up of LIGO triggers
- Radio follow-up of Gamma-Ray Burst (GRB) triggers

Profiles


B0525+21
P0:3745.19s
DM: 50.94
39 MHz
59 MHz
78 MHz
B0329+54
P0:714.57s
DM: 26.77
45 MHz
55 MHz
65 MHz
75 MHz
B1508+55
P0:739.66s
DM: 19.62
45 MHz
55 MHz
65 MHz
75 MHz
B0919+06
P0:430.60s
DM: 27.31
35 MHz
45 MHz
55 MHz
65 MHz
75 MHz

DM Measurement



TOA file: B2217+47.tim, Parameter file: B2217+47.par

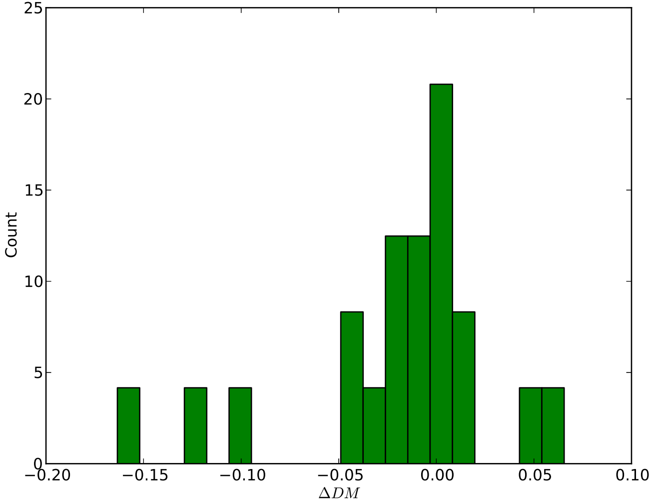
DM

Pulsar	P ms	DM_{ATNF} pc cm^{-3}	DM_{LWA1} pc cm^{-3}
J0030+0451	0.0048654532073692(3)	4.333(1)	4.33268(6)
B0031-07	0.9429509945598(17)	11.38(8)	10.922(6)
J0034-0534	0.0018771818845850(2)	13.76517(4)	13.76502(6)
B0138+59	1.2229485205457(18)	34.797(11)	34.926(4)
B0320+39	3.032071956385(10)	26.01(3)	26.173(2)
B0329+54	0.714519699726(4)	26.7641(1)	26.779(1)
B0355+54	0.1563824177774(15)	57.1420(3)	57.1453(8)
B0450+55	0.340729436235(10)	14.495(7)	14.5943(9)
B0525+21	3.74553925030(3)	50.937(17)	50.93(1)
B0628-28	1.24441859615(8)	34.468(17)	34.425(1)
B0655+64	0.19567094516627(16)	8.771(5)	8.777(1)
B0809+74	1.292241446862(3)	5.733(1)	5.771(2)
B0818-13	1.2381295438682(8)	40.938(3)	40.981(2)
B0823+26	0.53066051169(3)	19.454(4)	19.4789(2)
B0834+06	1.2737682915785(7)	12.889(6)	
B0919+06	0.430627098928(17)	27.271(6)	27.2986(5)
B0943+10	1.09770570486(7)	15.4(5)	15.334(1)
B0950+08	0.2530651649482(9)	2.958(3)	2.96927(8)
B1112+50	1.656439759937(3)	9.195(8)	9.1830(4)

DM

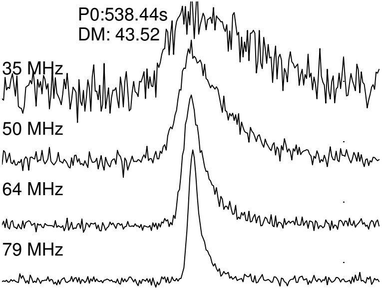
Pulsar	P ms	$\mathrm{DM_{ATNF}}$ $\mathrm{pc\ cm^{-3}}$	$\mathrm{DM_{LWA1}}$ $\mathrm{pc\ cm^{-3}}$
B1133+16	1.187913065936(3)	4.8451(1)	4.8480(2)
B1237+25	1.3824491030388(10)	9.242(6)	
B1508+55	0.739681922904(4)	19.613(20)	19.6191(3)
B1540-06	0.709064069786(4)	18.403(4)	18.3774(9)
B1541+09	0.748448416229(6)	35.24(3)	35.012(5)
B1604-00	0.42181623358258(13)	10.682(5)	10.6823(1)
B1612+07	1.206801436397(5)	21.39(3)	21.3949(3)
B1642-03	0.387689698034(7)	35.727(3)	35.7555(8)
B1706-16	0.65305397126(4)	24.873(5)	24.891(1)
B1749-28	0.56255763553(3)	50.372(8)	50.39(1)
B1822-09	0.769005855083(12)	19.38(4)	19.3833(9)
B1839+56	1.6528618528869(20)	26.698(11)	26.774(1)
B1842+14	0.37546337852(3)	41.510(4)	
B1919+21	1.3373021601895(9)	12.4370(1)	12.437(2)
B1929+10	0.226517635038(5)	3.180(4)	3.1828(5)
B2020+28	0.3434021577860(13)	24.640(3)	24.632(1)
B2110+27	1.2028517540847(12)	25.113(4)	25.1171(2)
J2145-0750	0.0160524239143660(16)	8.9977(14)	9.00451(4)
B2217+47	0.5384688219194(12)	43.519(12)	43.4975(5)

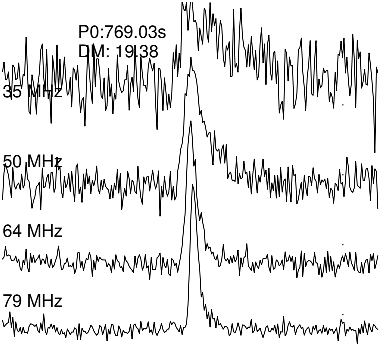
DM difference



Interstellar Scattering

Pulsar	P	DM
	ms	pc cm^{-3}
B0329+54	715	26.8
B1749-28	563	50.4
B1822-09	769	19.4
B2217+47	538	43.5

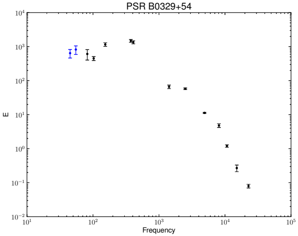


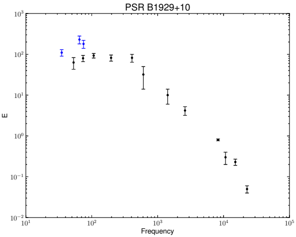


Mean Flux Densities

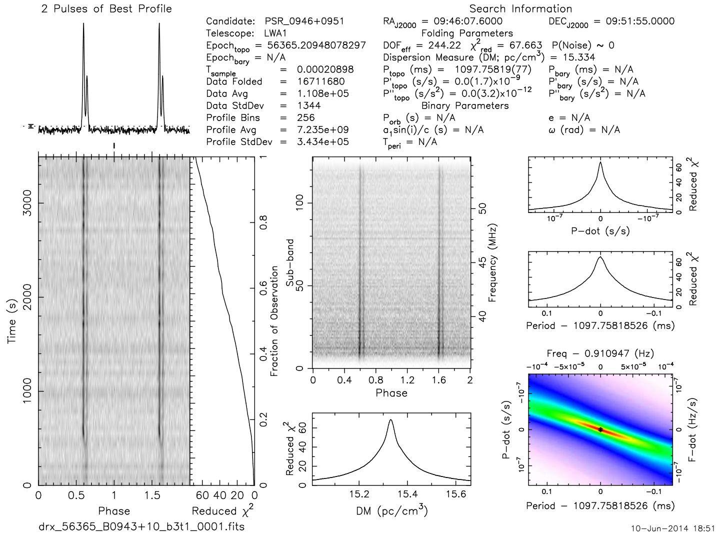
Pulsar	Izvekova 1980 f_{cen} MHz	Izvekova 1980 Flux mJy	LWA1 f_{cen} MHz	LWA1 Flux mJy
B0031−07	39	490 ± 210	48	440 ± 90
	61	460 ± 100	64	440 ± 90
B0138+59	61	90 ± 30	58.6	150 ± 30
	85	260 ± 50	78.2	220 ± 30
B0329+54	39	360 ± 280	45	900 ± 180
	61	430 ± 170	55	1150 ± 230
B0525+21	61	150 ± 40	39	220 ± 50
	85	350 ± 90	58.6	190 ± 40
			78.2	210
B0950+08	61	1070 ± 400	62	810 ± 160
	88	1820 ± 400	74	1370 ± 270
B1508+55	61	840 ± 200	68.4	490 ± 100

Pulsar	Izvekova 1980 f_{cen} MHz	Izvekova 1980 Flux mJy	LWA1 f_{cen} MHz	LWA1 Flux mJy
B1642−03	40	<260	48	<30
	61	410 ± 130	64	150 ± 30
B1706−16	61	180 ± 60	48	90 ± 20
			64	170 ± 30
B1919+21	40	250 ± 80	42	1480 ± 300
	61	2100 ± 430	56	1730 ± 350
			67	1430 ± 290
			75	1610 ± 320
B1929+10	102.5	220	35	110 ± 20
			65	230 ± 50
			75	180 ± 40
B2020+28	39	<60	39	40 ± 10
	61	30 ± 20	58.6	100 ± 20
	85	40 ± 20	78.2	80 ± 20



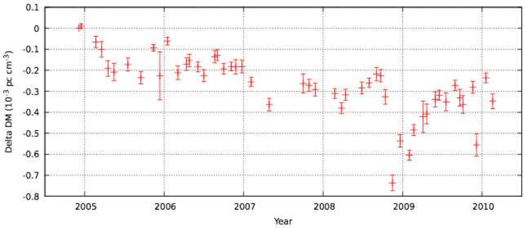


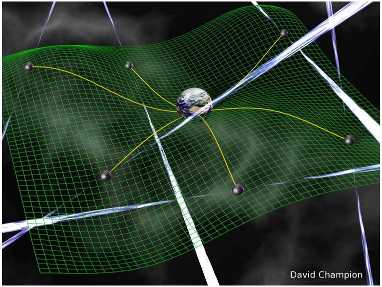
Mode Change?


2 Pulses of Best Profile
Search Information
Candidate: PSR_0946+0951
Telescope: LWA1
Epoch_topo = 56365.20948078297
Epoch_bary = N/A
T_sample = 0.00020898
Data Folded = 16711680
Data Avg = 1.108e+05
Data StdDev = 1344
Profile Bins = 256
Profile Avg = 7.235e+09
Profile StdDev = 3.434e+05
RA_J2000 = 09:46:07.6000
DEC_J2000 = 09:51:55.0000
Folding Parameters
DOF_eff = 244.22 χ²_red = 67.663 P(Noise) ~ 0
Dispersion Measure (DM; pc/cm³) = 15.334
P_topo (ms) = 1097.75819(77)
P_bary (ms) = N/A
P'_topo (s/s) = 0.0(1.7)x10⁻⁹
P'_bary (s/s) = N/A
P''_topo (s/s²) = 0.0(3.2)x10⁻¹²
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 − 1097.75818526 (ms)
Freq − 0.910947 (Hz)
F−dot (Hz/s)
drx_56365_B0943+10_b3t1_0001.fits
10−Jun−2014 18:51

Millisecond Pulsars

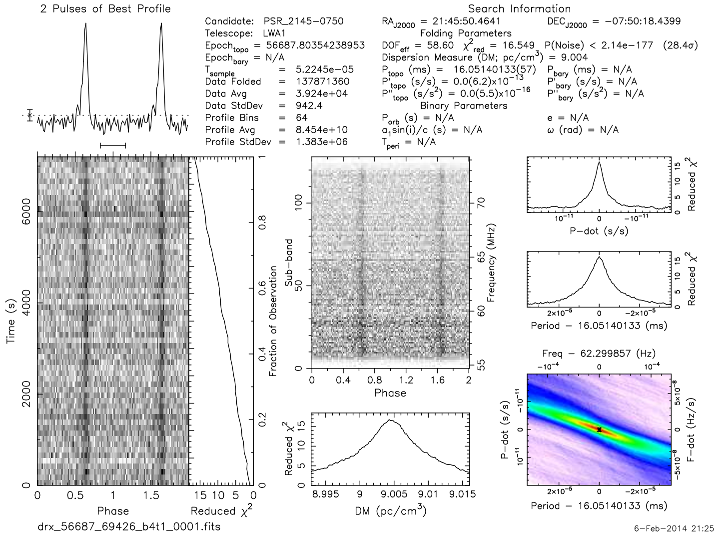
- Pulsars with spin periods of a few tens of milliseconds.
- Very stable clocks, arrival times of pulses can be predicted to within tens to hundreds of nanoseconds.
- An array of very precise MSPs can be used to detect nanohertz gravitational waves.



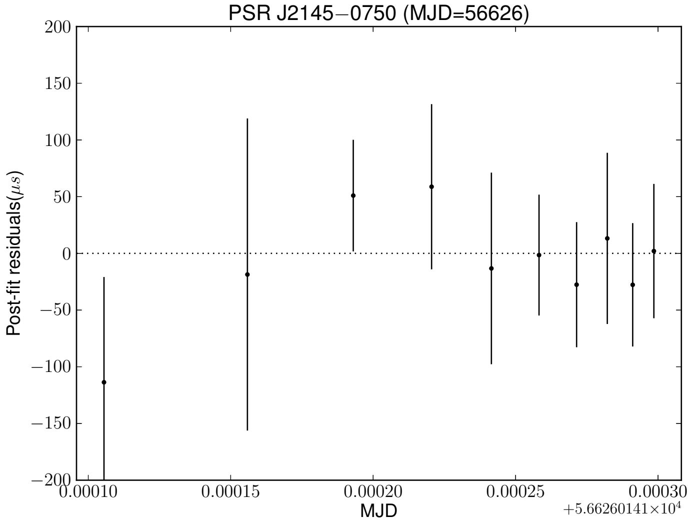


- One of the issues is how to handle DM variations with time.
- Current method is to fit for DM for each observation epoch. This could end up removing part of the signature of a GW signal.

J2145-0750


2 Pulses of Best Profile
Search Information
Candidate: PSR_2145−0750
Telescope: LWA1
Epoch_topo = 56687.80354238953
Epoch_bary = N/A
T_sample = 5.2245e−05
Data Folded = 137871360
Data Avg = 3.924e+04
Data StdDev = 942.4
Profile Bins = 64
Profile Avg = 8.454e+10
Profile StdDev = 1.383e+06
RA_J2000 = 21:45:50.4641
DEC_J2000 = −07:50:18.4399
Folding Parameters
DOF_eff = 58.60 χ²_red = 16.549 P(Noise) < 2.14e−177 (28.4σ)
Dispersion Measure (DM; pc/cm³) = 9.004
P_topo (ms) = 16.05140133(57)
P'_topo (s/s) = 0.0(6.2)x10^−13
P''_topo (s/s²) = 0.0(5.5)x10^−16
P_bary (ms) = N/A
P'_bary (s/s) = N/A
P''_bary (s/s²) = N/A
Binary Parameters
P_orb (s) = N/A
a_1sin(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 − 16.05140133 (ms)
Freq − 62.299857 (Hz)
F−dot (Hz/s)
drx_56687_69426_b4t1_0001.fits
6−Feb−2014 21:25

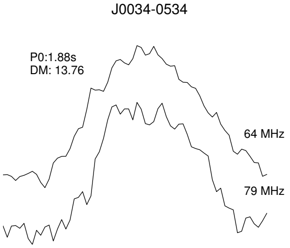
Residuals

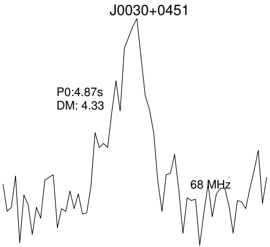

PSR J2145−0750 (MJD=56626)
200
150
100
50
0
−50
−100
−150
−200
Post-fit residuals(μs)
0.00010
0.00015
0.00020
0.00025
0.00030
MJD
$+5.66260141\times10^4$

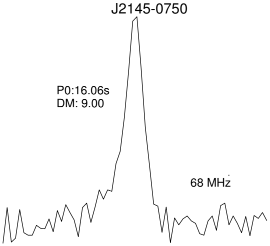
Millisecond Pulsars

Pulsar	MJD	DM	DM_{err}
		pc cm^{-3}	pc cm^{-3}
J0034−0534	56631	13.765017	0.000063
J0030+0451	56606	4.332741	0.000077
J2145−0750*	56588	9.004393	0.000059

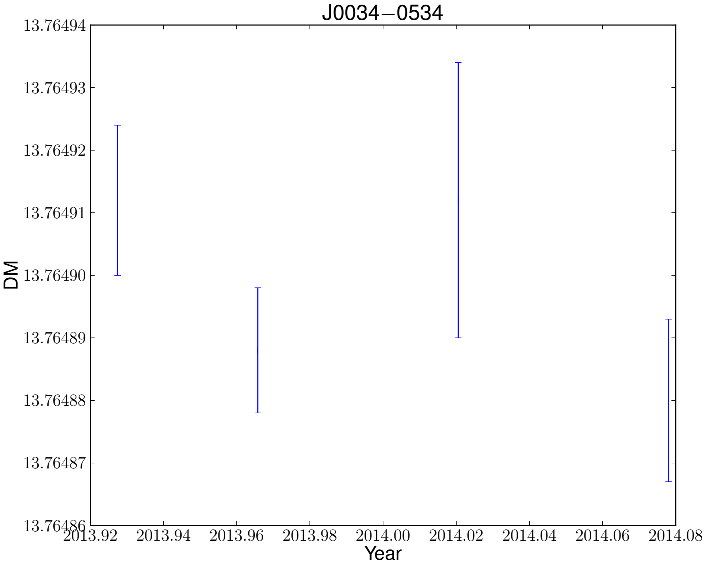
*Dowell et al. 2013, ApJL 775, L28





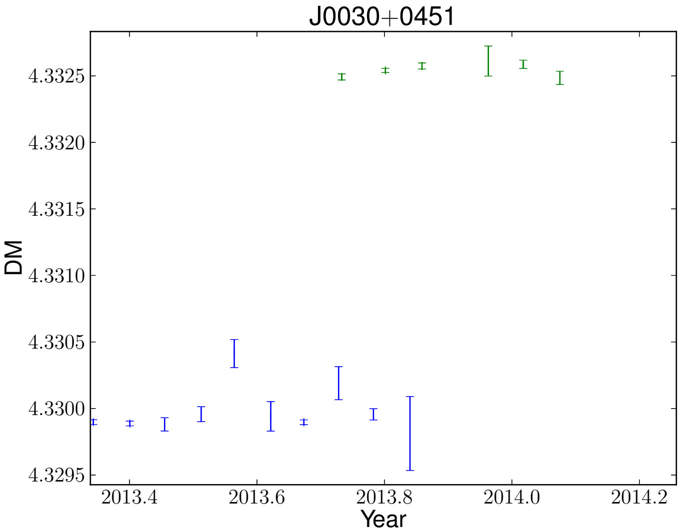


J0034-0534



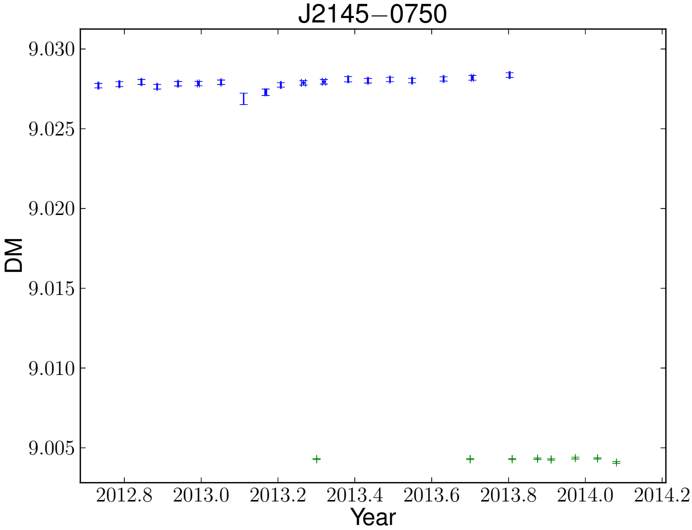
J0034−0534
13.76494
13.76493
13.76492
13.76491
13.76490
13.76489
13.76488
13.76487
13.76486
DM
2013.92
2013.94
2013.96
2013.98
2014.00
2014.02
2014.04
2014.06
2014.08
Year

J0030+0451



J0030+0451
DM
4.3325
4.3320
4.3315
4.3310
4.3305
4.3300
4.3295
2013.4
2013.6
2013.8
2014.0
2014.2
Year

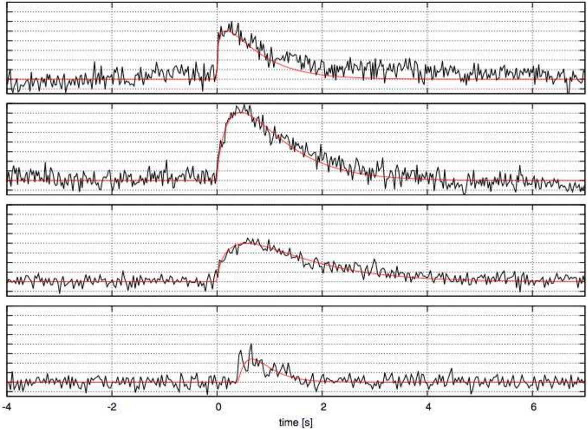
J2145-0750



J2145−0750
9.030
9.025
9.020
9.015
9.010
9.005
DM
2012.8
2013.0
2013.2
2013.4
2013.6
2013.8
2014.0
2014.2
Year

Crab Giant Pulses

- In initial analysis, CGPs seen at a rate of about 10 per hour.
- Have taken >100 hours of data on the Crab pulsar, analysis ongoing.



Ellingson et al. 2013, ApJ 768, p. 136

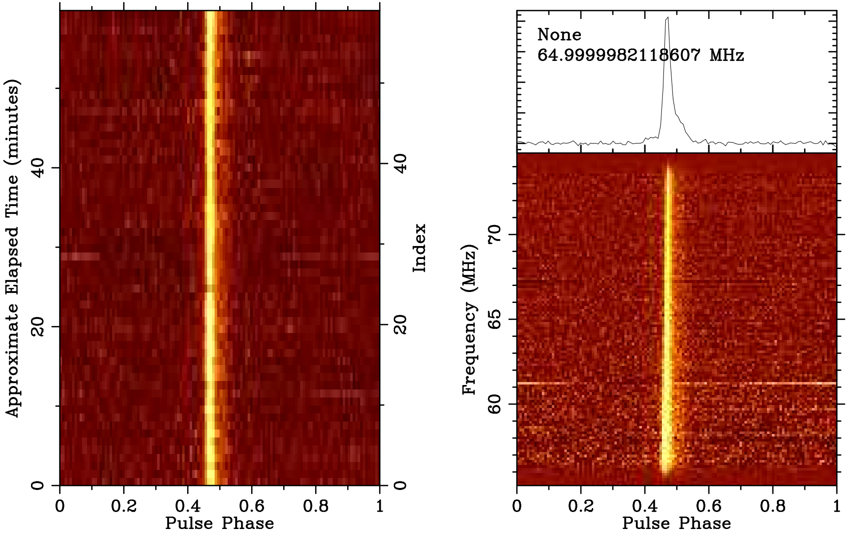
Pulsar and Fast Transient Survey

- All LWA1-visible sky survey ($\delta > 30^\circ$), 2 tunings at 40.2 and 59.8 MHz, 16384 freq. channels, 836 μs sample time
- Data on disk for about 8% of survey (5556 pointings)
- Data processing recently begun on Center for Advanced Research Computing (CARC) clusters
- Searching each tuning independently and combined using FFT search, linear acceleration search, and single pulses

Pulsar Software Support

- TEMPO supports TOAs from LWA1
- PRESTO supports LWA1, including new prepsubband argument -dmprec
- psr_utils' fold_psrfits support added (UCF only)
- psr_utils' combine_lwa can combine data sets with appropriate frequency spacing
- PSRCHIVE requires minor modification (works on taurus)
- PSRFITs standard changed to double from floats for Frequency Labels

fold_psrfits and PSRCHIVE

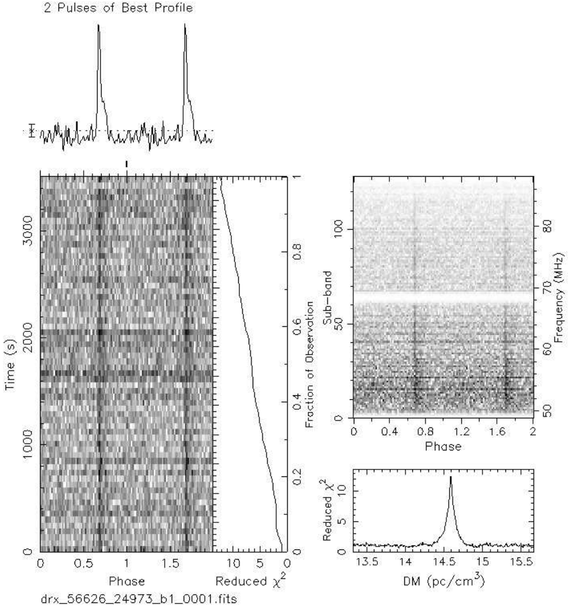


LSL Pulsar capabilities

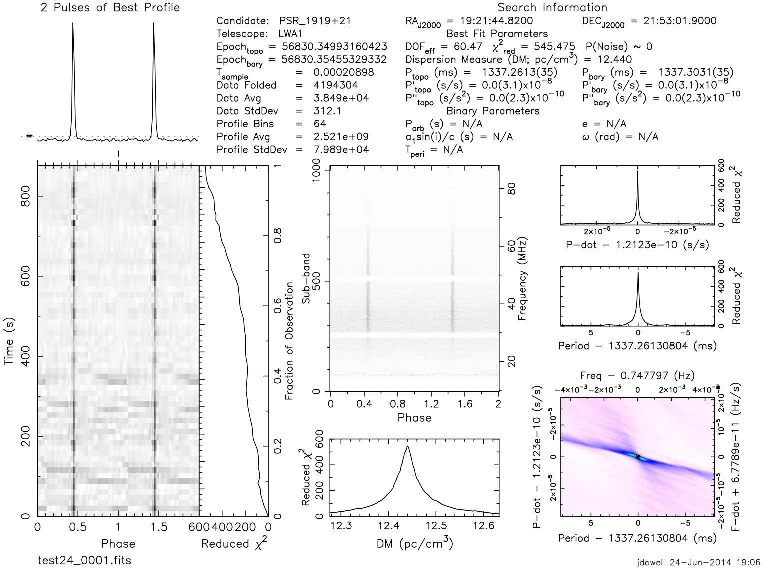
- LWA raw beamformed data to PSRFITs
  writePsrfits2.py, writePsrfits2D.py, writePsrfits2Multi.py
- LWA spectrometer to PSRFITs
  writePsrfitsFromDRSpec.py
- Conversion between PSRFITs and HDF5
  writeHDF5FromPsrfits.py, writePsrfits2FromHDF5.py

Combined tunings

Individual tunings are 19.6 MHz (16 MHz usable) wide.
Two tunings from the same beam can be combined if spaced appropriately to get ∼32 MHz of bandwidth.



Combined beams



LWA1 Pulsar Data Archive

- Will store reduced results for all pulsars detected at LWA1 (after proprietary period).
  - PRESTO folded product, image, profile (with rfi masking)
  - RFI Mask
  - PSRFITs folded product (no masking, suitable for PSRCHIVE)
  - Sub-banded PSRFITs file (de-dispersed, file size reduced by 8-32 times)
  - De-dispersed time series
  - DM=0 time series (to examine RFI environment)
- Allows TOA generation, study of singlepulses, analysis of profiles, etc.
- Plans - generate TOAs, update timing solution and DM monitoring, provide summed pulse profile for variety of frequencies