Radio Astronomy Radiometers, Dipoles, Pulsars

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Astronomy 423 at UNM

Radio Astronomy

Announcements

- Schedules for VLA in preparation
- Homework assignments should be submitted to me by e-mail

$$(\cancel{k}\cancel{T_a} + \cancel{k}T_{rx})G_1G_2G_3 = (\cancel{k}\cancel{T_a} + \cancel{k}T_1)G_1G_2G_3 + \cancel{k}T_2 G_2G_3 + \cancel{k}T_3 G_3$$

$$T_{rx} G_1G_2G_3 = T_1 G_1G_2G_3 + T_2 G_2G_3 + T_3 G_3$$

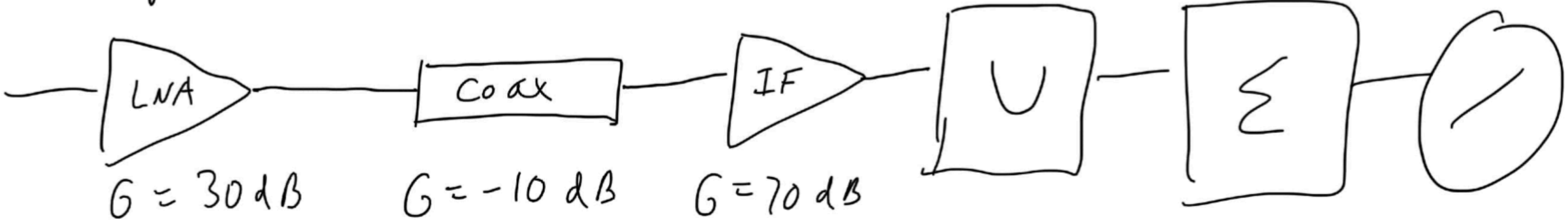
$$T_{rx} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1G_2}$$

which amplifier noise is most important?

why do we care?

Sensitivity $\Delta T = \frac{T_{sys}}{\sqrt{\Delta\nu\,\tau}}$

LWA example



G = 30 dB
NF = 3 dB

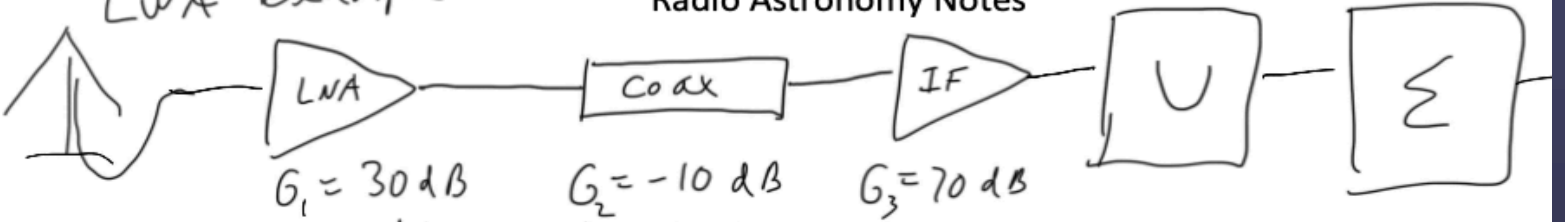
G = −10 dB
NF = 10 dB

G = 70 dB
NF = 10 dB

$NF = \frac{T_{noise}}{T_{ref}} + 1$ $T_{ref} = 290\,K$

Radio Astronomy Notes

LWA Example



$G_1 = 30\,dB$ $G_2 = -10\,dB$ $G_3 = 70\,dB$

$NF = 3\,dB$ $NF = 10\,dB$ $NF = 10\,dB$

$$NF = \frac{T_{noise}}{T_{ref}} + 1 \qquad T_{ref} = 290\,K \qquad T = T_{ref}\left(10^{NF/10} - 1\right)$$

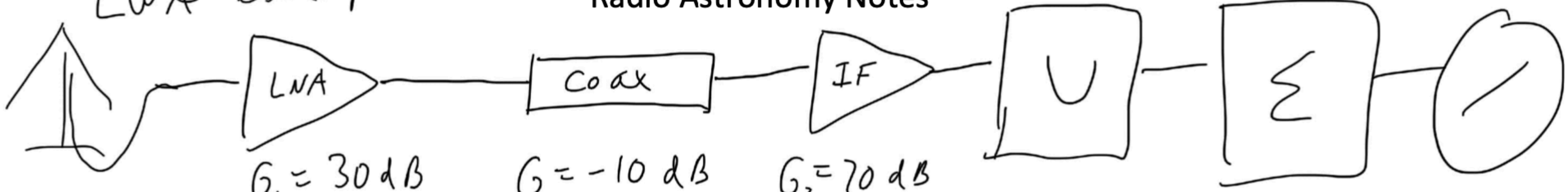
Worksheet #3

- Download the worksheet from:

http://www.phys.unm.edu/~gbtaylor/astr423/WS3.pdf

Solve it in class.
Ask questions if you are stuck
Tell me when you have the answer.

LWA Example



$G_1 = 30$ dB $G_2 = -10$ dB $G_3 = 70$ dB

NF = 3 dB NF = 10 dB NF = 10 dB

$NF = \frac{T_{noise}}{T_{ref}} + 1$ $T_{ref} = 290\,K$ $T = T_{ref}\left(10^{NF/10} - 1\right)$

$G_{Total} = 30 - 10 + 70 = 90$ dB $NF_{total} = 23$ dB

$$T_{rx} = T_{LNA} + \frac{T_{coax}}{G_1} + \frac{T_{IF}}{G_1 G_2}$$

$T_{LNA} = 290\,K$

$T_{coax} = 2610\,K$

$T_{IF} = 2610\,K$

$$T_{rx} = 290 + \frac{2610}{1000} + \frac{2610}{1000 \cdot 0.1}$$

$$= 290 + 2.6 + 26$$

$$= 319\,K$$

What if T_{LNA} doubled? $T_{rx} = 609\,K$ (ouch)

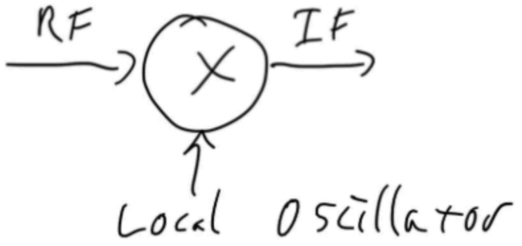
What if T_{IF} doubled? $T_{rx} = 345\,K$ (not so bad)

Radio Astronomy Notes 5-4

Heterodyne receiver

what if we want to transmit signals at a fixed frequency?

So called intermediate frequency
IF

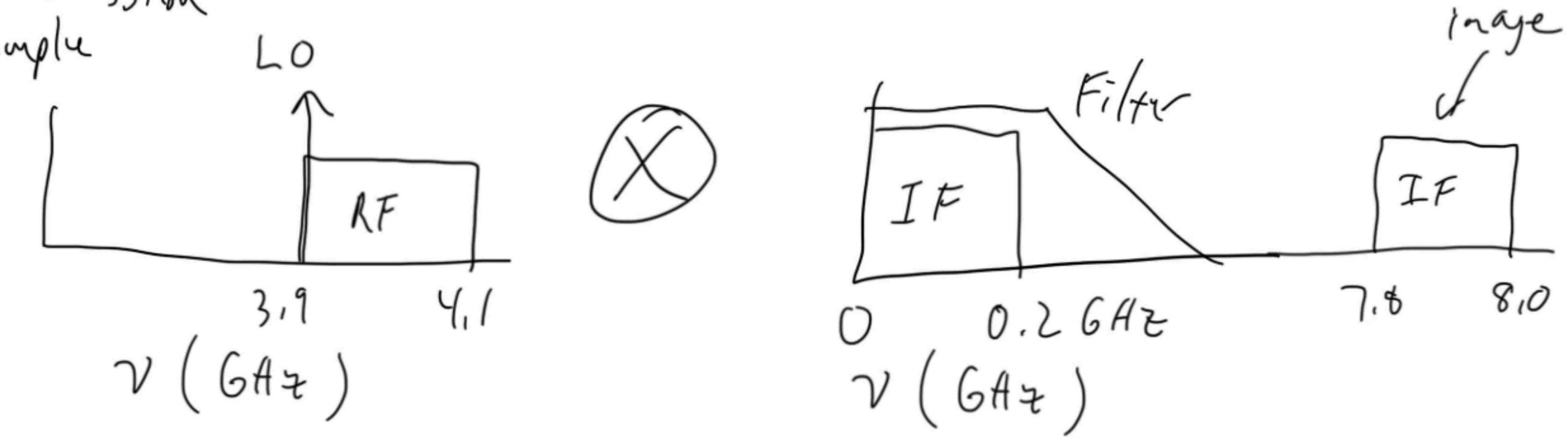


Mixers: multiply two signals in time domain

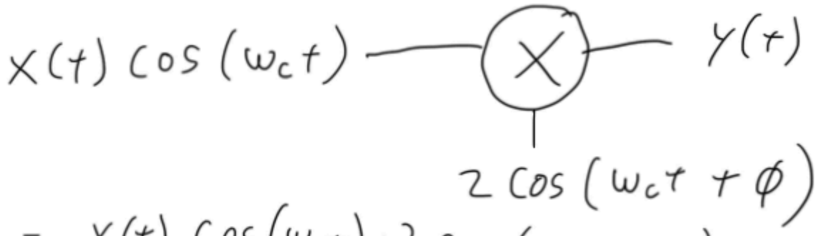
$$\text{IF:} \quad \sin(\omega_{RF} t)\cos(\omega_{LO} t)$$

$$= \frac{1}{2}\left[\sin((\omega_{RF} - \omega_{LO})t) + \sin((\omega_{RF} + \omega_{LO})t)\right]$$

Baseband Transmission
Example



What happens to phase of the RF signal?



$$y(t) = x(t)\cos(\omega_c t)\cdot 2\cos(\omega_c t + \phi)$$

$$= 2x(t)\cdot\frac{1}{2}\left[\cos(\omega_c t + \omega_c t + \phi) + \cos(\omega_c t + \phi - \omega_c t)\right]$$

filter this high frequency term OUT

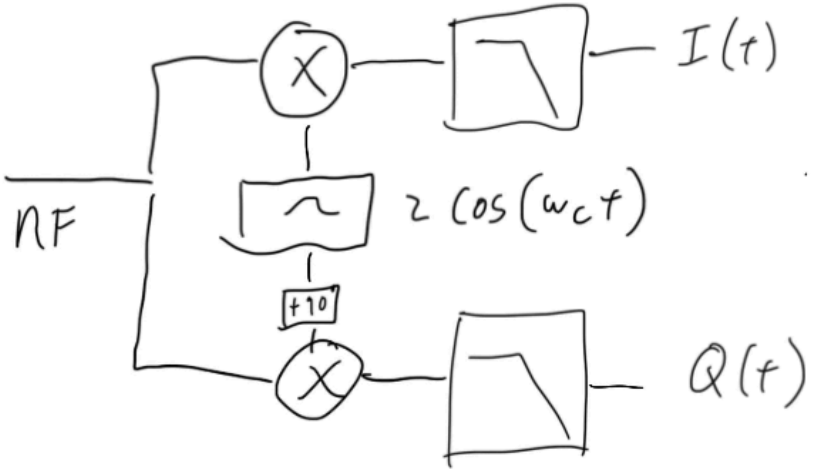
$$= x(t)\left[\cancel{\cos(2\omega_c t + \phi)} + \cos(\phi)\right]$$

$$= x(t)\cos(\phi)$$

downconverted signal depends on LO phase. what happens when $\phi = \frac{\pi}{2}$?

$y(t) = 0$???

Solution: use LO and 90° shifted LO to recover complete signal



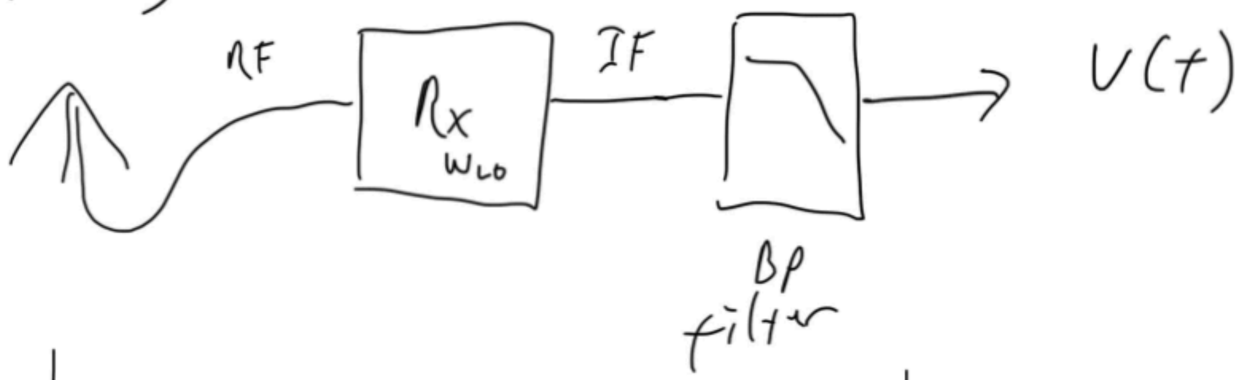
$$|RF| = \sqrt{I^2 + Q^2}$$

$$\phi_{RF} = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right)$$

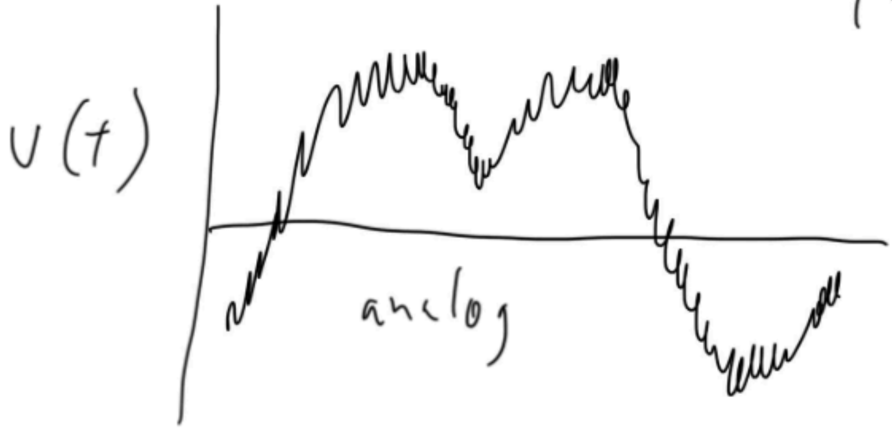
recovers amplitude & phase at baseband

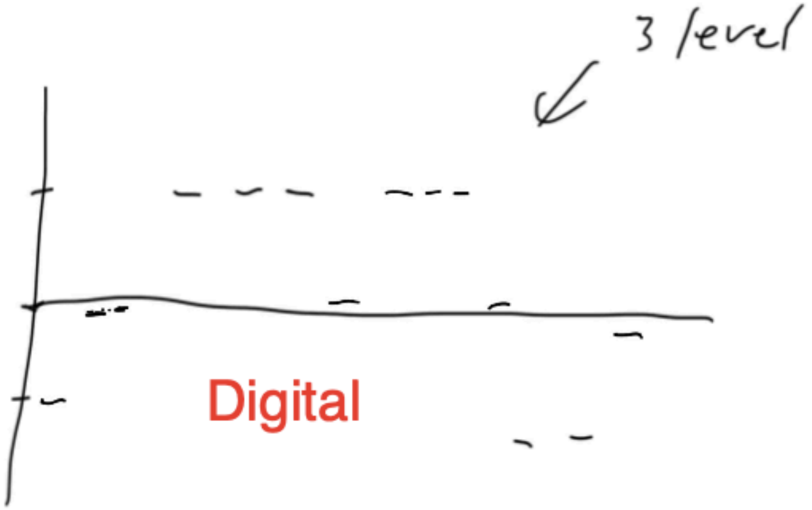
Radio Astronomy Notes S-6

Sampling



voltage time series





Some loss of information (η_s)
Sample interval Δt

$\Delta t = \frac{1}{\Delta\nu}$

Nyquist sampling is $\Delta t = \frac{1}{2\Delta\nu}$

Efficiency η_s

# bits	$1/(2\Delta\nu)$	$1/(4\Delta\nu)$
1	0.64	0.74
2	0.81	0.89
3	0.88	0.94
∞	1.00	1.00

Problems: RFI
: weak signals

Data rates

Suppose you want to record 64 MHz × 8 tunings (512 MHz) in two polarizations (RCP, LCP) from a VLBA antenna and store it for 4 hours

How much storage do you need?

$$\text{Data rate} = \underset{\uparrow\,\text{Nyquist}}{2\Delta\nu}\;\;\overset{\text{bits}}{\underset{\downarrow}{N}}\;\;\overset{\text{pol}}{\underset{\downarrow}{2}}\;\;\overset{\text{tunings}}{\underset{\downarrow}{8}}\quad \text{Samples/sec}$$

$$= 2 \cdot 64\times10^6 \cdot 2 \cdot 2 \cdot 8$$

$$= 4096 \times 10^6 \text{ samples/sec}$$

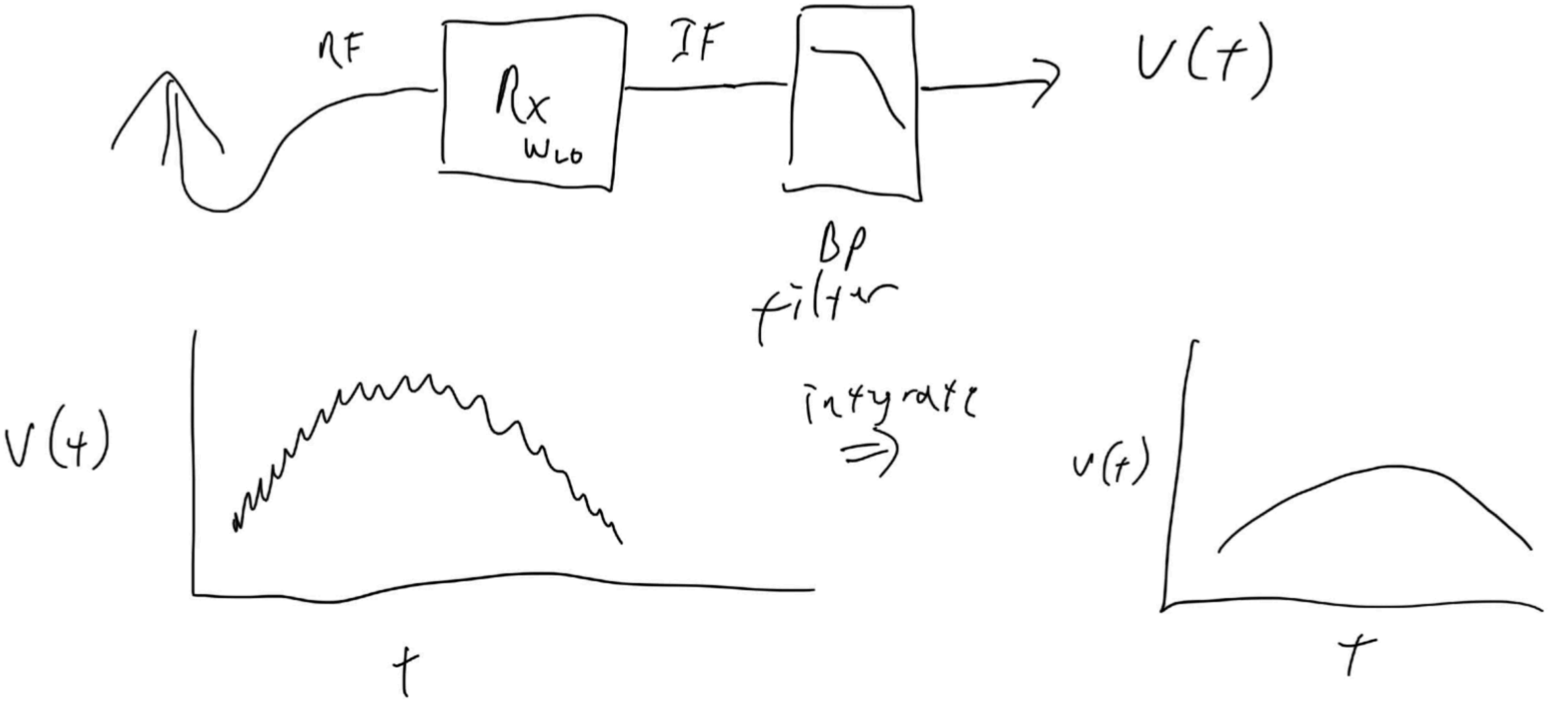
$$= 4096 \text{ Mbps} \simeq 4 \text{ Gbps}$$

In 4 hours: $4096 \text{ Mbps} \cdot 3600 \frac{\text{sec}}{\cancel{\text{hr}}} \cdot 4 \cancel{\text{hr}} = 74 \text{ TB}$ fill up 7× 12 TB drives

\$2800

Radio Astronomy Notes 6-1

Radiometers



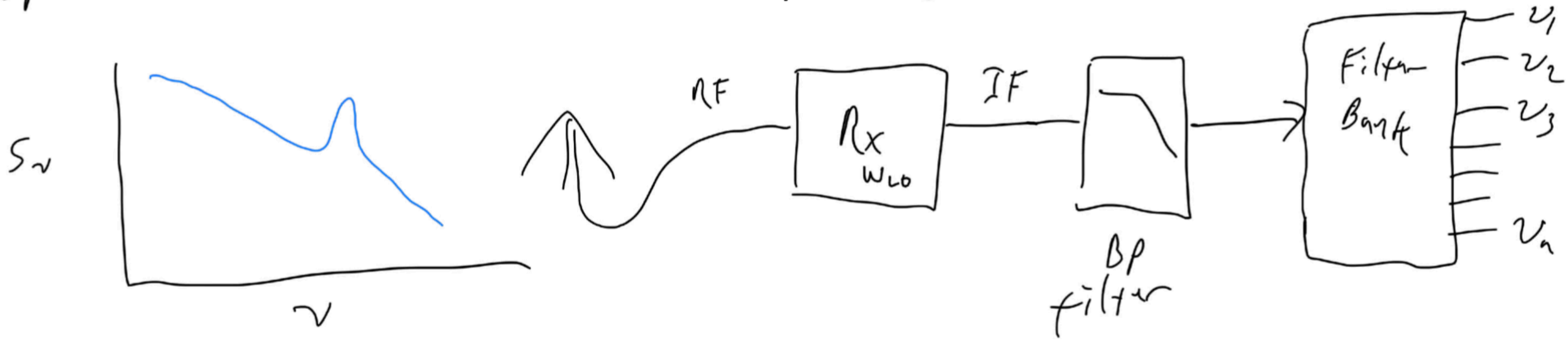
Incoherent radiometer: Like a square law detector

also - bolometer, basically broad-band calorimeters

Focal Plane Arrays of bolometers useful at high ν

Coherent radiometer: Preserve phase information $\phi(t)$

Spectra



Pro: simple to understand and use

Con: not very flexible

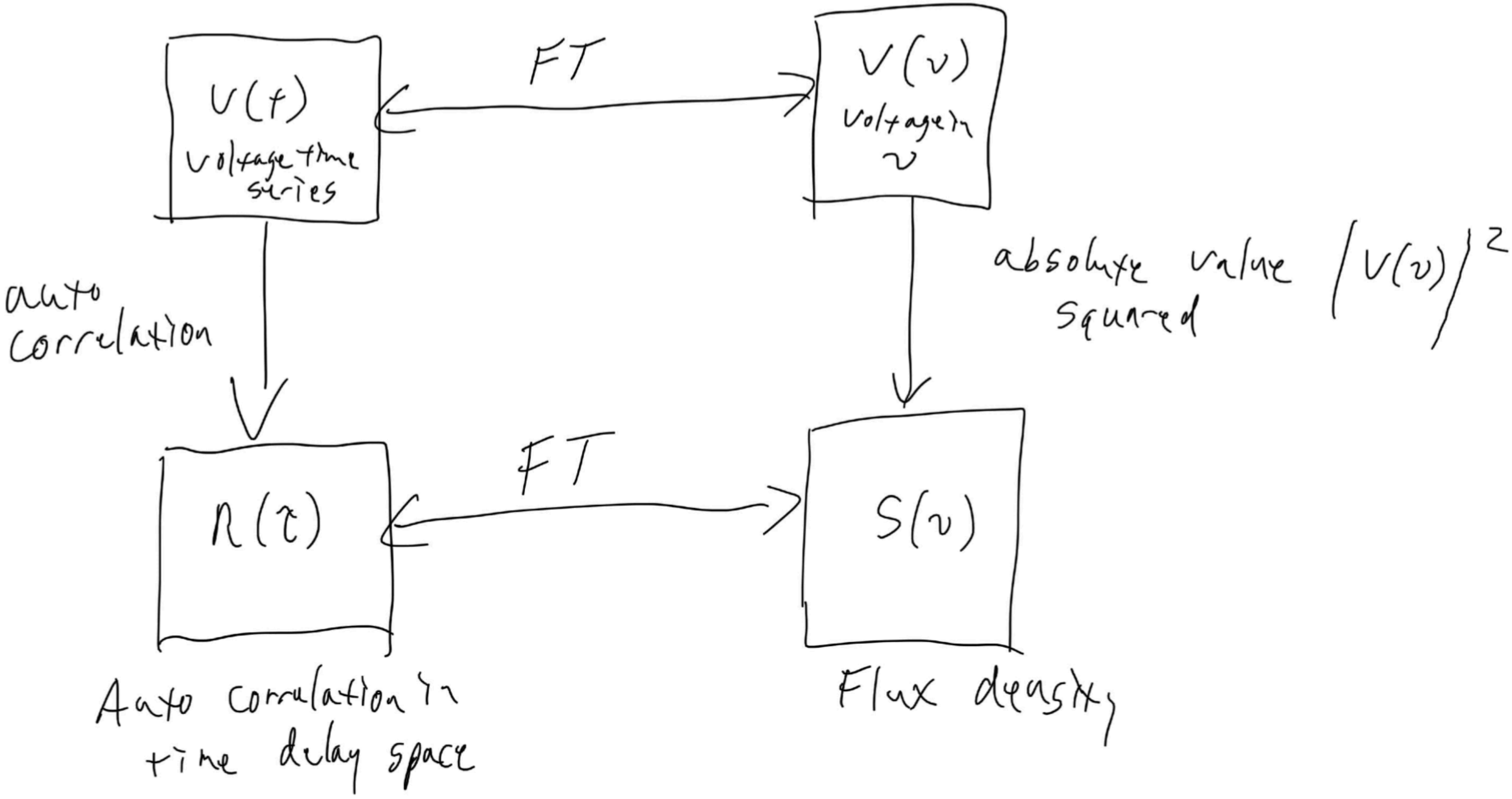
alternate strategy: Consider $V(t)$ as stationary random process

$$V(t) = A(t)\, e^{-2\pi i \nu t}$$

power spectral density $$S(\nu) = \lim_{T\to\infty} \frac{1}{T} E\left\{ V(\nu)^2 \right\}$$

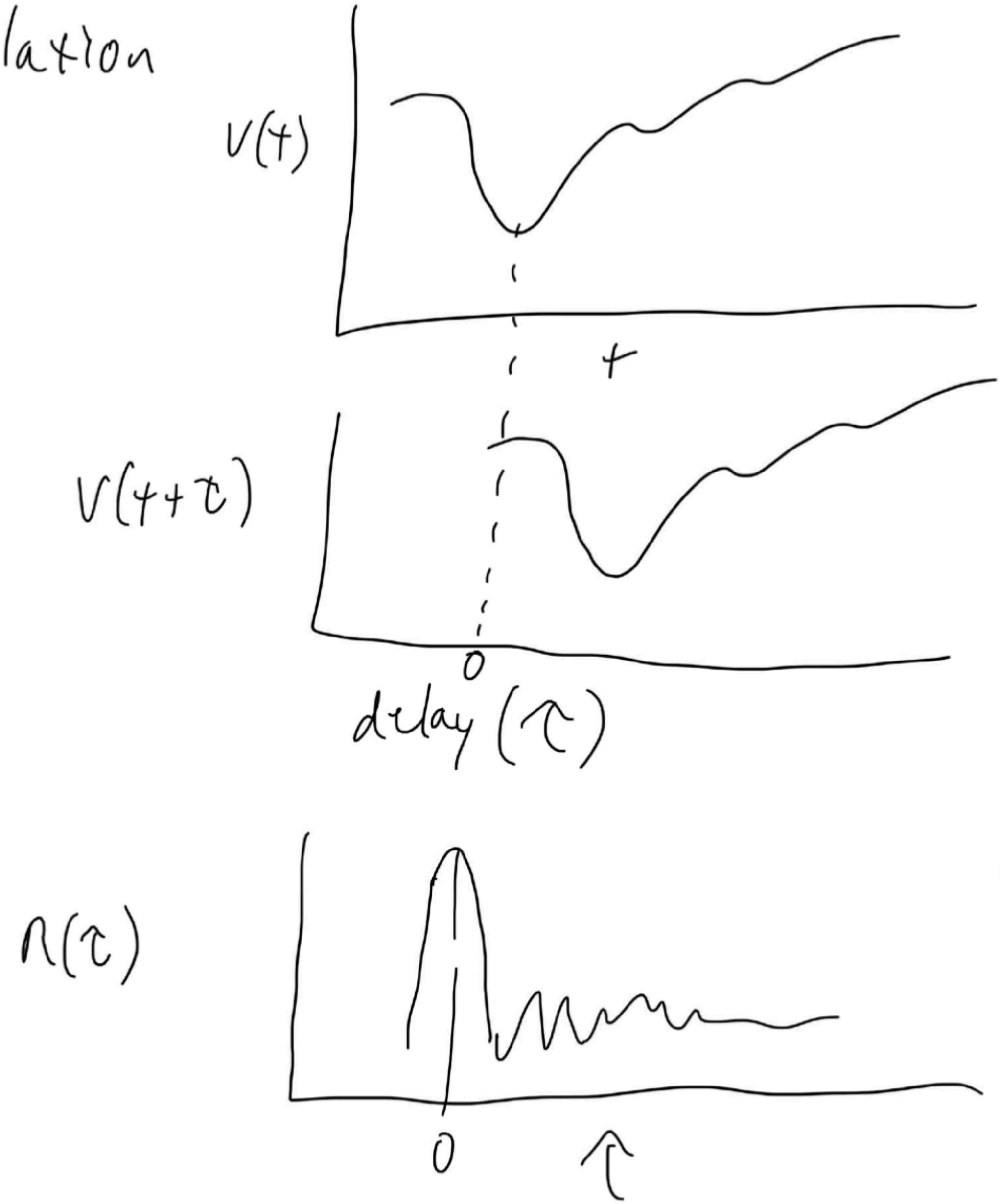
$$V(\nu) = \boxed{\int_{-\infty}^{\infty} A(t)\, e^{-2\pi i \nu t}\, dt} \Rightarrow \text{A Fourier Transform}$$

Radio Astronomy Notes 6-3

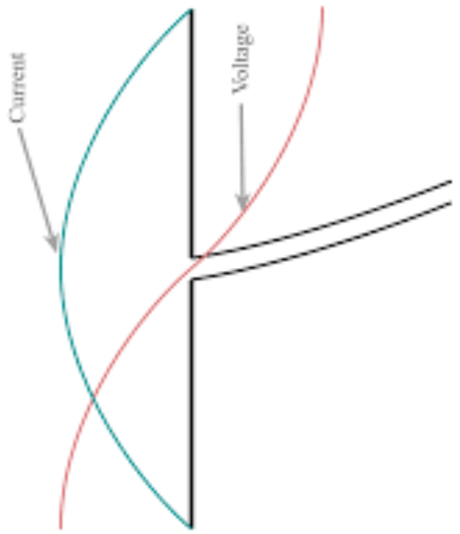


Radio Astronomy Notes 6-4

Auto Correlation



max at $\tau = 0$
varies with τ



Current and voltage waveforms on a half wave dipole

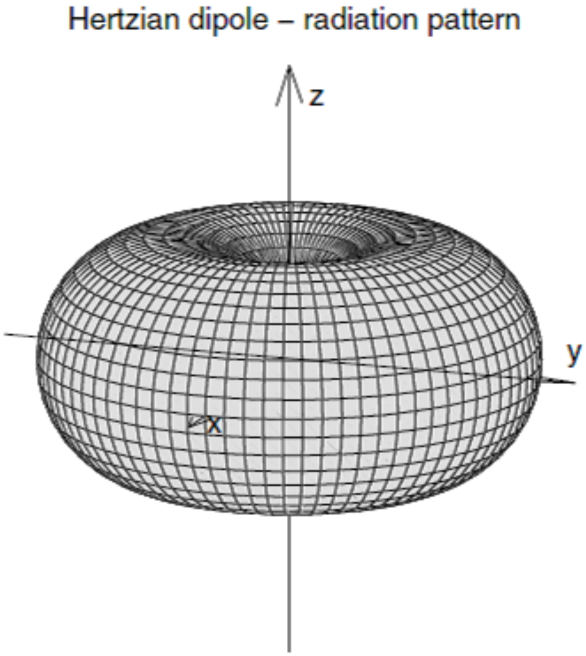


Figure 12.6 MATLAB plot of the 3-D normalized field polar radiation pattern of a Hertzian dipole (Fig.12.1); for MATLAB Exercise 12.17. *(color figure on CW)*

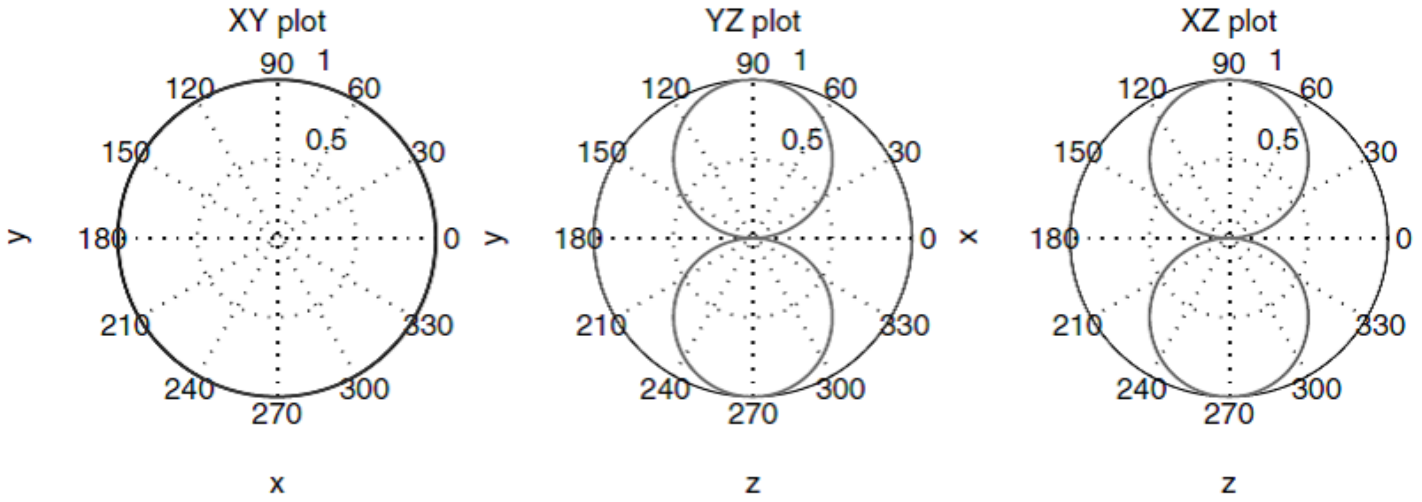


Figure 12.7 Cuts in three characteristic planes of the radiation pattern in Fig.12.6; for MATLAB Exercise 12.17. *(color figure on CW)*

Gain for a Dipole Ant

gain $g = \frac{dP/d\Omega}{P/4\pi} = \frac{4\pi}{\Omega_a}$ and $\frac{A_e \Omega_a}{\lambda^2} = 1$

$$= \frac{4\pi A_e}{\lambda^2}$$

Hertz Dipole $A_e = \frac{3}{8\pi}\lambda^2 = \frac{\lambda^2 g}{4\pi}$ $g = \frac{3}{2}$

$A_e = \frac{g\lambda^2}{4\pi}$ $g = 3{,}5$ for LWA antenna

$A_e = 10\ m^2$ at 6 m wavelength

Station $A_e = 10 m^2 \cdot 256 = 2560\ m^2$ at 50 MHz

$$G = \frac{A_e}{2k} = \frac{2560\ m^2\ (100)^2 \frac{cm^2}{m^2}}{2 \cdot 1.381 \times 10^{-16} \frac{ergs}{K}} \cdot 10^{-23}\ ergs\ s^{-1}\ cm^{-2}\ Hz^{-1}$$

$G = 0{,}93$ K/Jy SEFD $= \frac{T_{sys}}{G} = \frac{6000\ K}{0{,}93\ K/Jy} = 6.5$ kJy

10-88 MHz usable Galactic noise-dominated (>4:1) 24-87 MHz

4 independent beams x 2 pol. X 2 tunings each ~16 MHz bandwidth

SEFD ~ 9 kJy (zenith)

All sky (all dipoles) modes: TBN (70 kHz-bandwidth; continuous)

TBW (78 MHz-bandwidth, 61 ms burst)

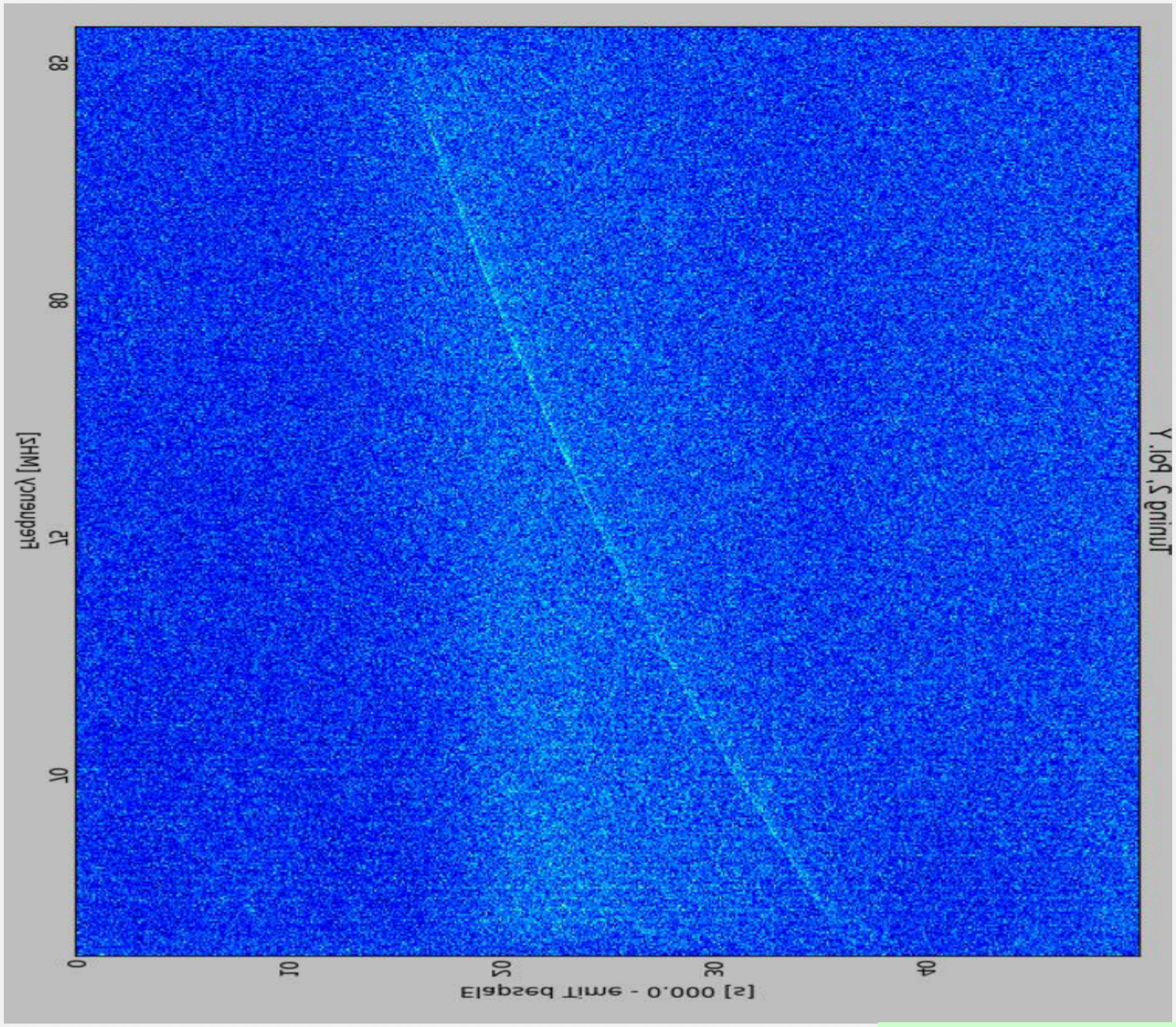
Data are GPS Time Tagged (better than one part in 10^{11})

LWA1 science emphasis: transients, pulsars, Sun, Jupiter & Ionosphere

Open skies – LWA is funded by NSF as a University Radio Observatory

Crab Giant Pulses

Freq

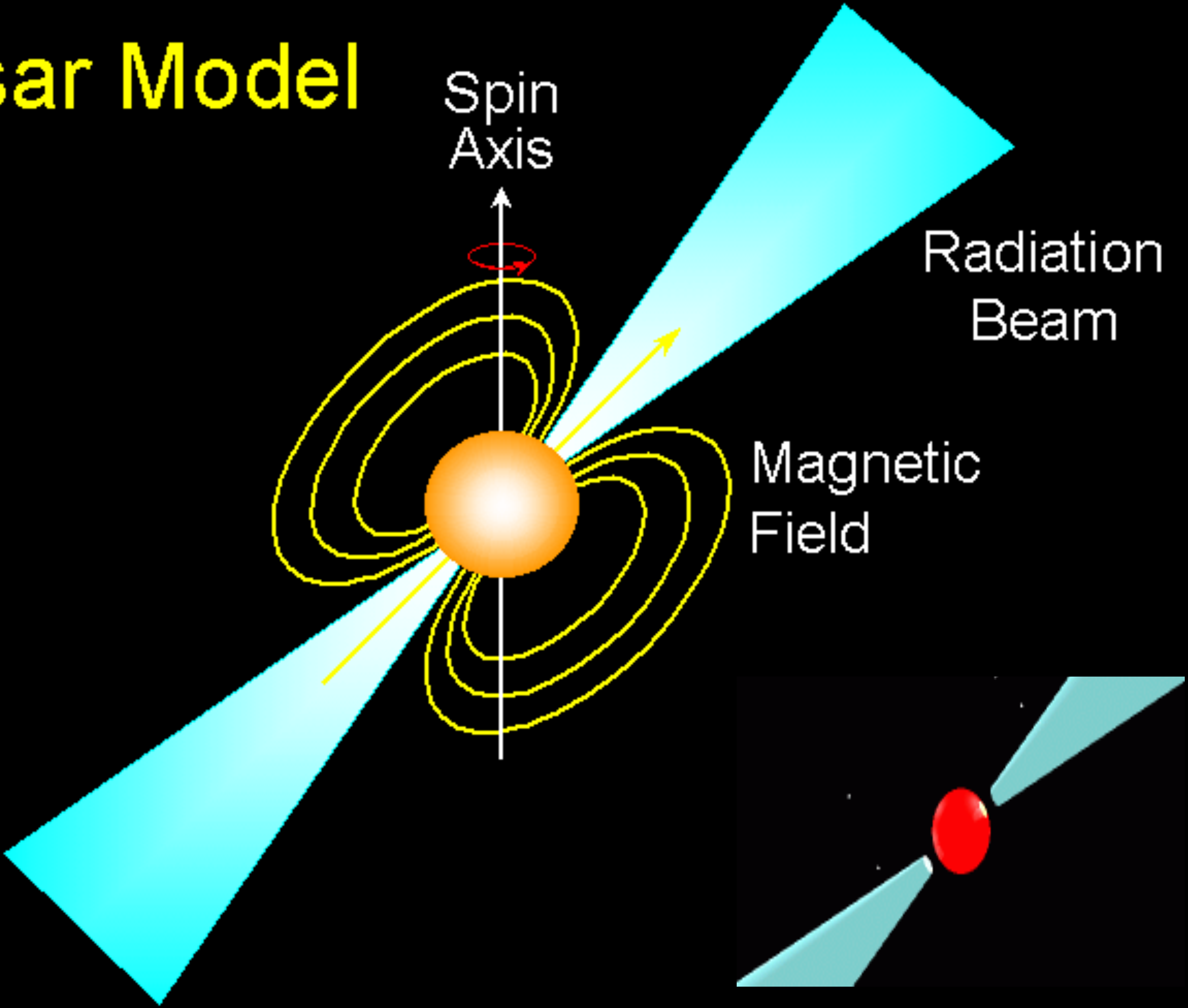


DM = 56.75 pc cm^-3

time

Eftekhari et al. 2015

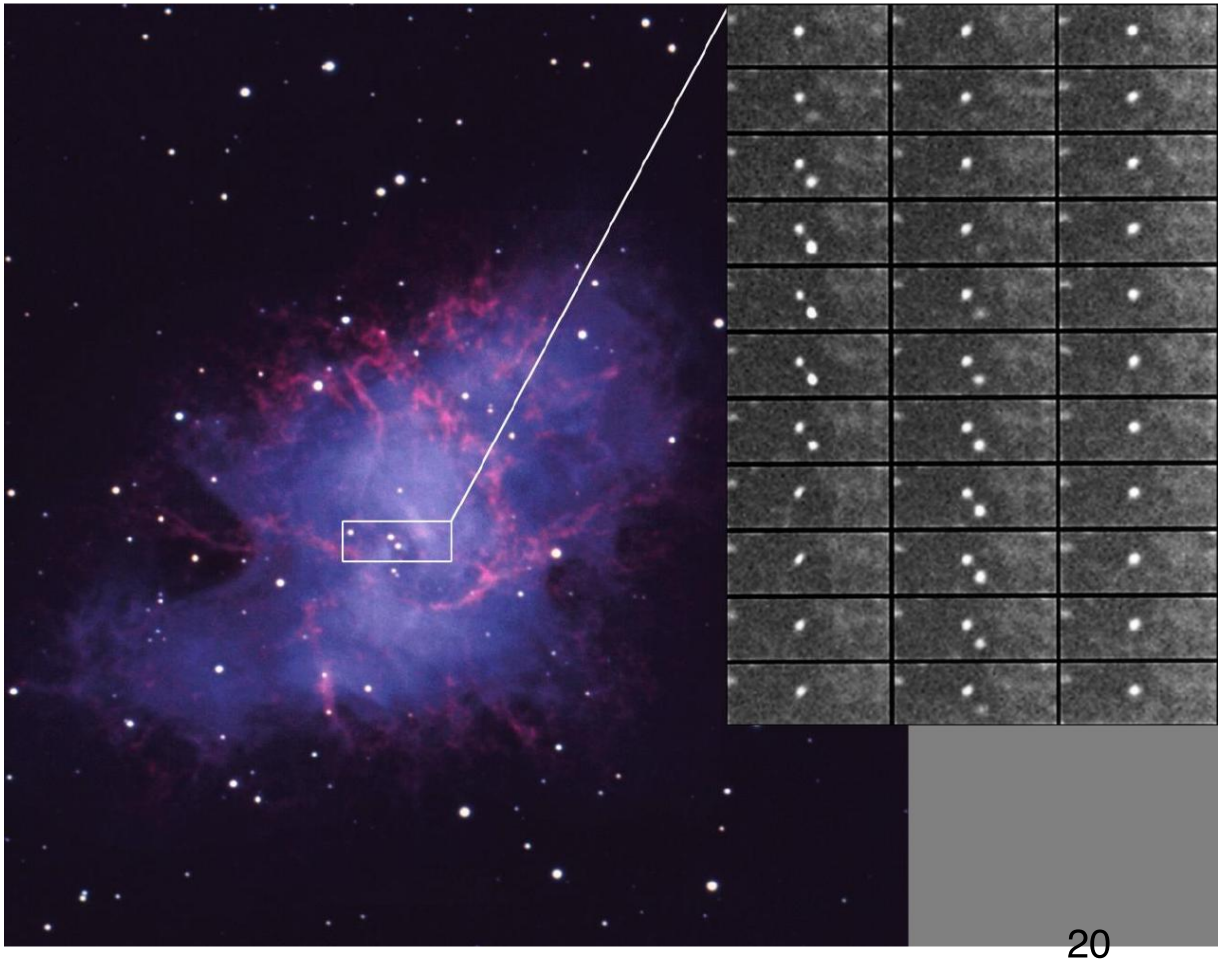
Pulsar Model



Pulsars

Periodic sources, discovered at radio wavelengths by Bell in 1967. Now over 2000 known.

Extremely regular, most have $P \sim$ 0.25-2 sec. Some are measured to ~15 significant figures and rival the best atomic clocks on earth.



They slow down, but very slowly:

for most.

Characteristic lifetime would correspond to ~10^7 years.

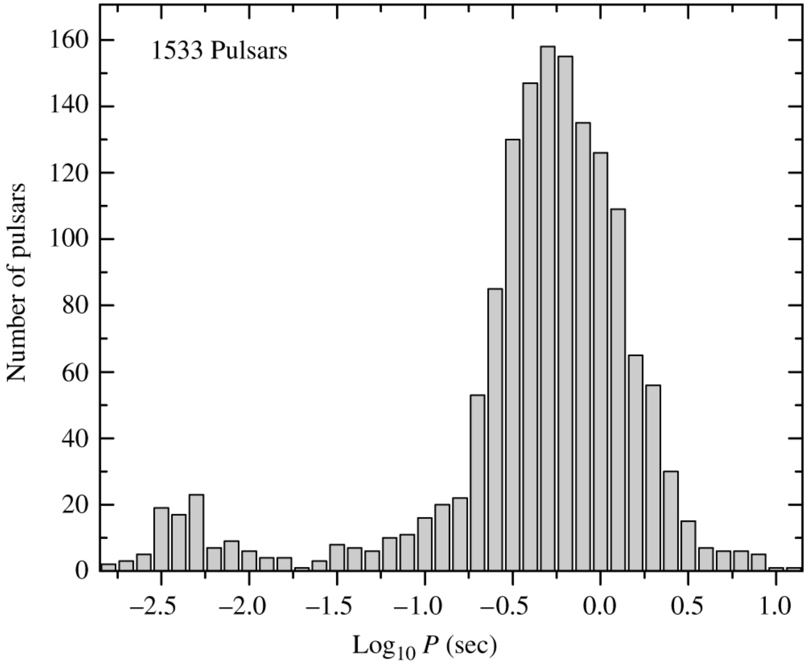
First explanation as NS by

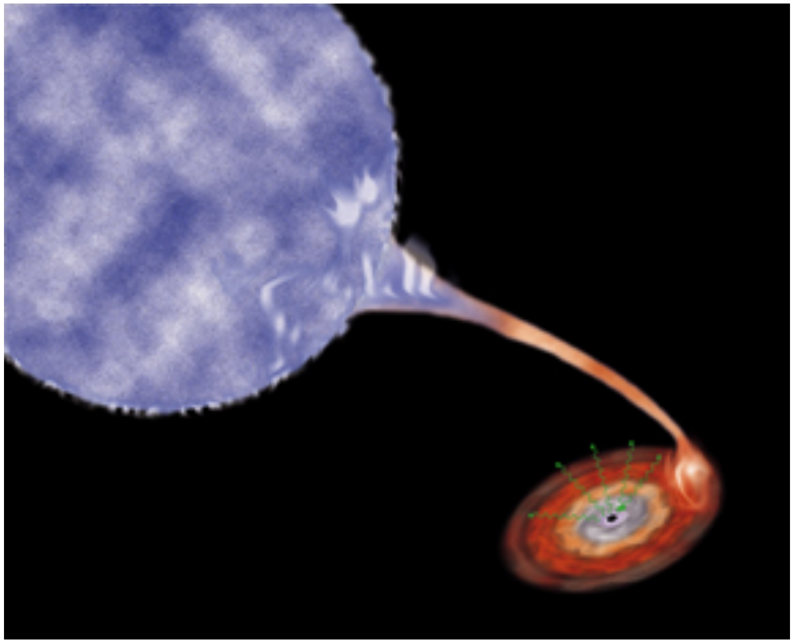
Pacini ’67, Gold ’68

(Gold predicted $\dot{P} > 0$)

Pulsar evolution

Since they slow down with age, they should lose energy to power the emission. Probably born with $P \sim$ several msec, die at ~ a few sec. Not clear how the emission mechanism turns off, but somehow associated with loss of rotational energy. Magnetic and electric fields may weaken, but highly uncertain.





Millisecond pulsars thought to be old neutron stars in binary systems. Many found in globular clusters.

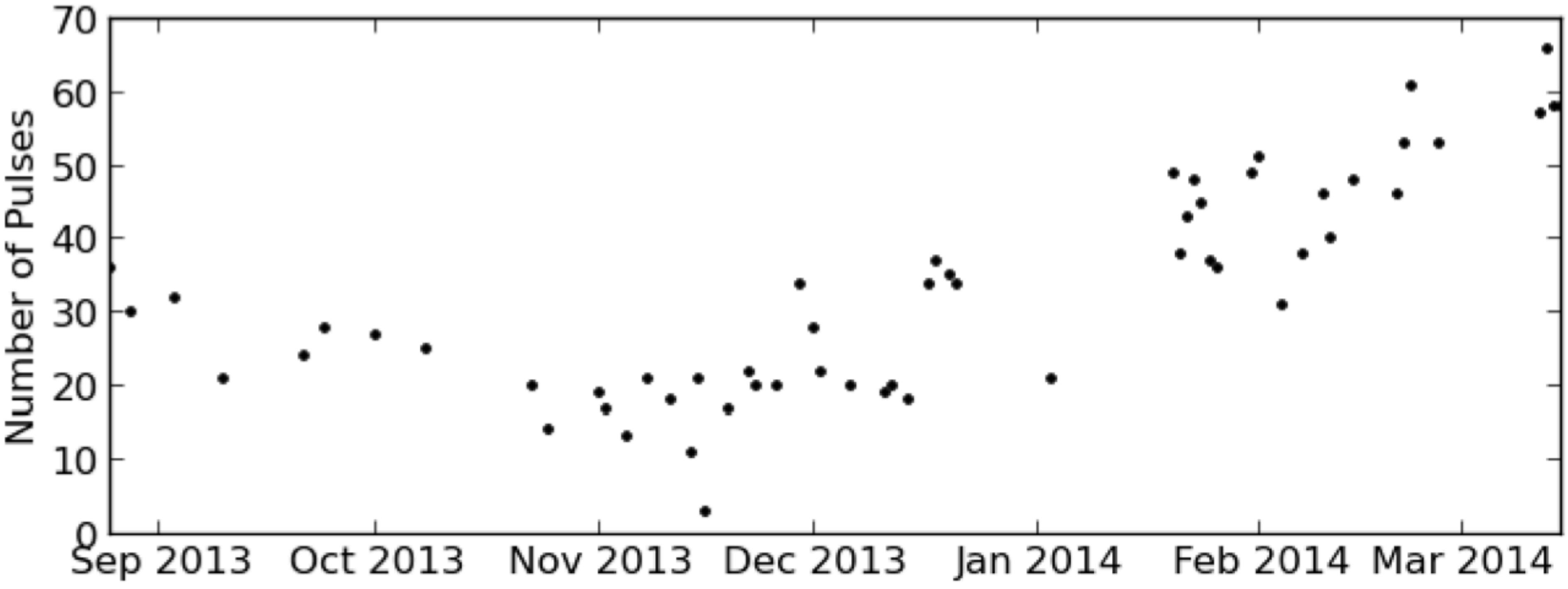
Companion expanded, spills material onto slow neutron star.

When material reaches NS surface, it is orbiting very rapidly. As it accretes, it adds to angular momentum of NS, spinning it up again.

Crab Giant Pulses

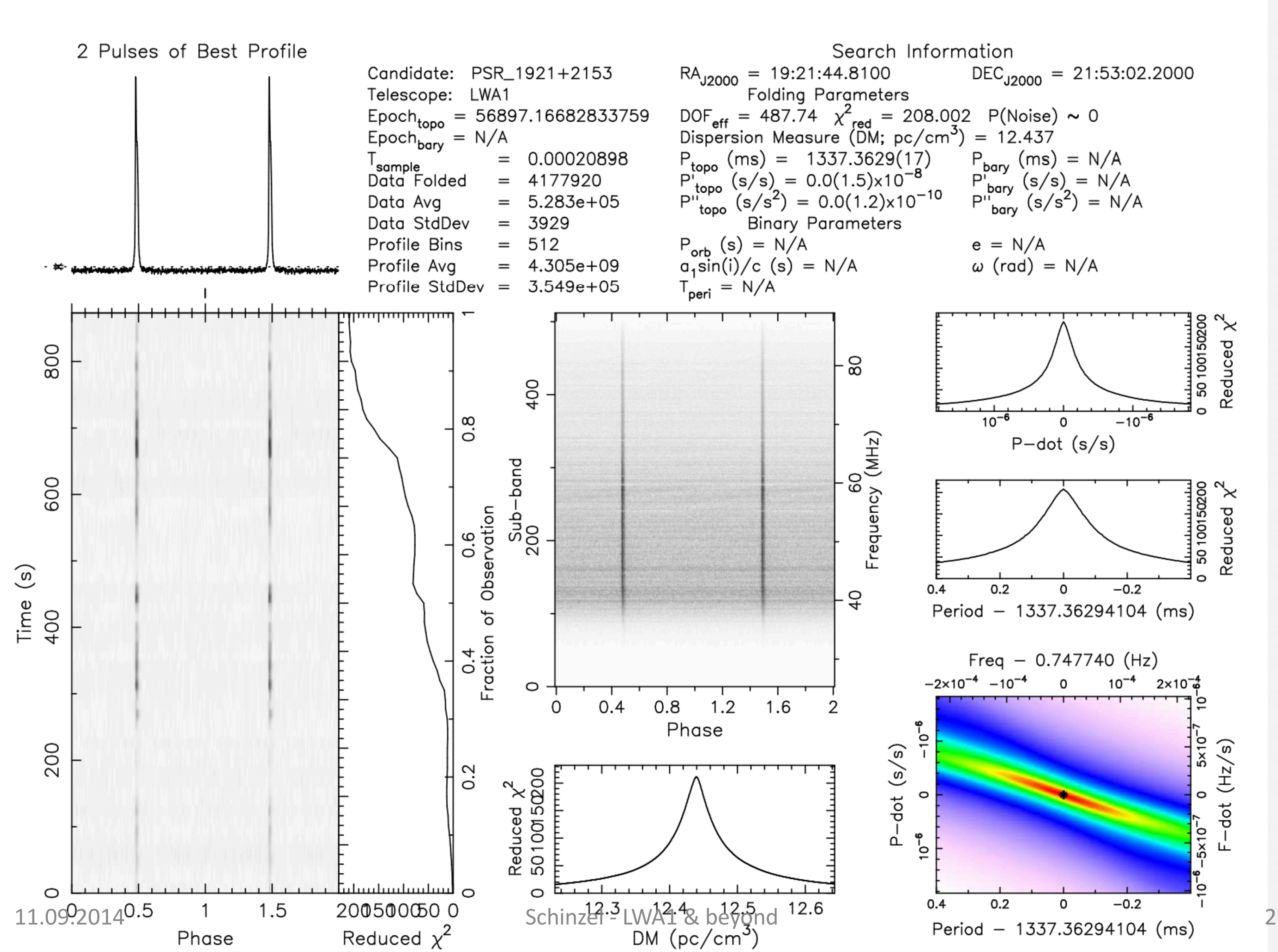
Flux densities 20-120 kJy

Number of pulses/hour went up by factor 3 over 6 month period



Eftekhari et al. 2015

Typical Pulsar Observation with LWA1



Candidate: PSR_1921+2153
Telescope: LWA1
$\mathrm{Epoch_{topo}}$ = 56897.16682833759
$\mathrm{Epoch_{bary}}$ = N/A
T_{sample} = 0.00020898
Data Folded = 4177920
Data Avg = 5.283e+05
Data StdDev = 3929
Profile Bins = 512
Profile Avg = 4.305e+09
Profile StdDev = 3.549e+05

Search Information
$\mathrm{RA_{J2000}}$ = 19:21:44.8100 $\mathrm{DEC_{J2000}}$ = 21:53:02.2000

Folding Parameters
$\mathrm{DOF_{eff}}$ = 487.74 χ^2_{red} = 208.002 P(Noise) ~ 0
Dispersion Measure (DM; pc/cm^3) = 12.437
P_{topo} (ms) = 1337.3629(17) P_{bary} (ms) = N/A
P'_{topo} (s/s) = $0.0(1.5)\times10^{-8}$ P'_{bary} (s/s) = N/A
P''_{topo} (s/s^2) = $0.0(1.2)\times10^{-10}$ P''_{bary} (s/s^2) = N/A

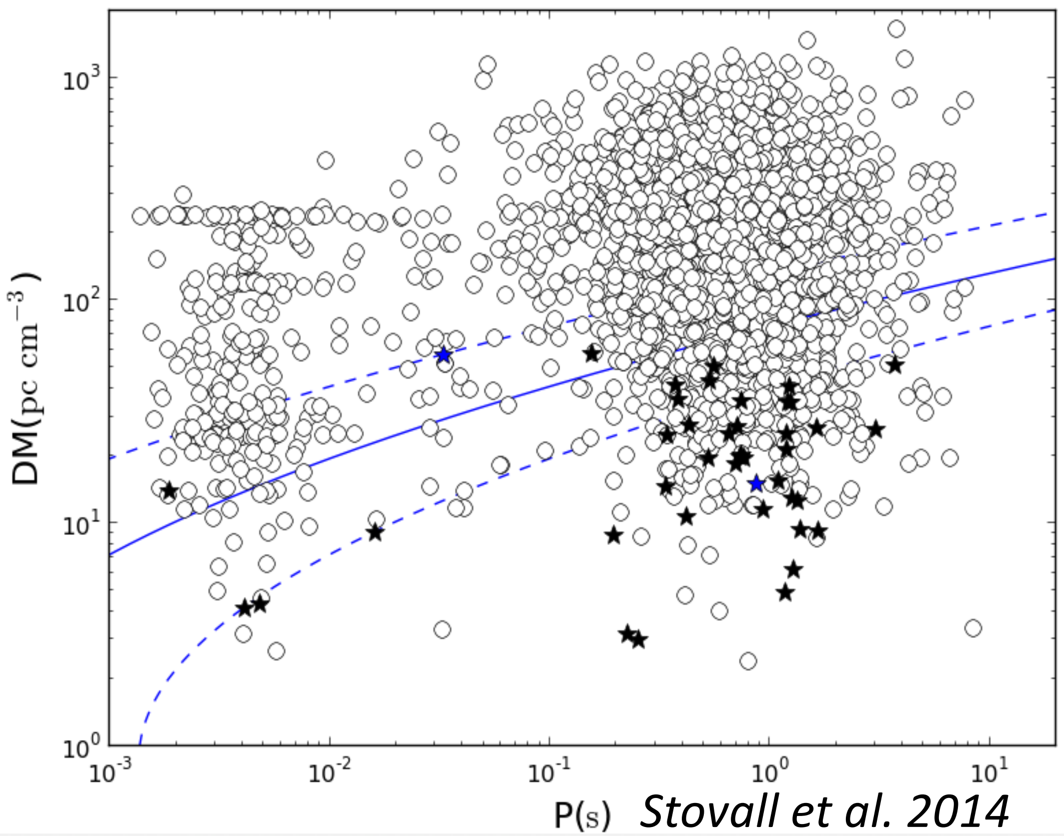
Binary Parameters
P_{orb} (s) = N/A e = N/A
$a_1\sin(i)/c$ (s) = N/A ω (rad) = N/A
T_{peri} = N/A

LWA1 Pulsar Detections

J0030+0451
B0031-07
J0034-0534
B0138+59
J0203+70
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

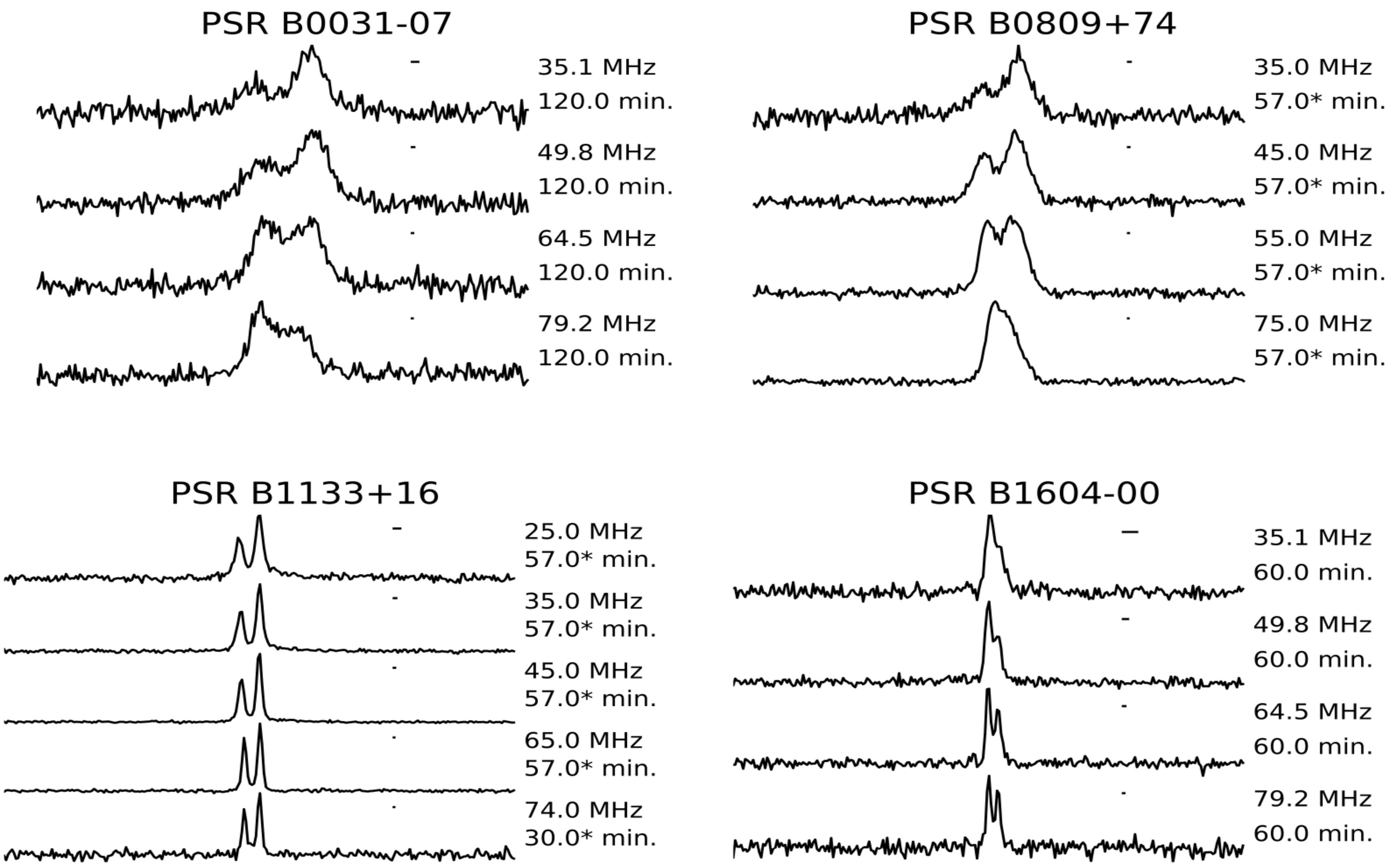
B1133+16
B1237+25
J1327+34
B1508+55
B1540-06
B1541+09
B1604-00
B1612+07
B1642-03
B1706-16
B1749-28
B1822-09
B1839+56
B1842+14
B1919+21
B1929+10
B2020+28
B2110+27
J2145-0750
B2217+47
J2324-05

- >100 Pulsars detected (>94 through pulsations, 6 through single pulses)
- 6 MSPs detected
- Periods from 1.9ms to 4s



Stovall et al. 2014

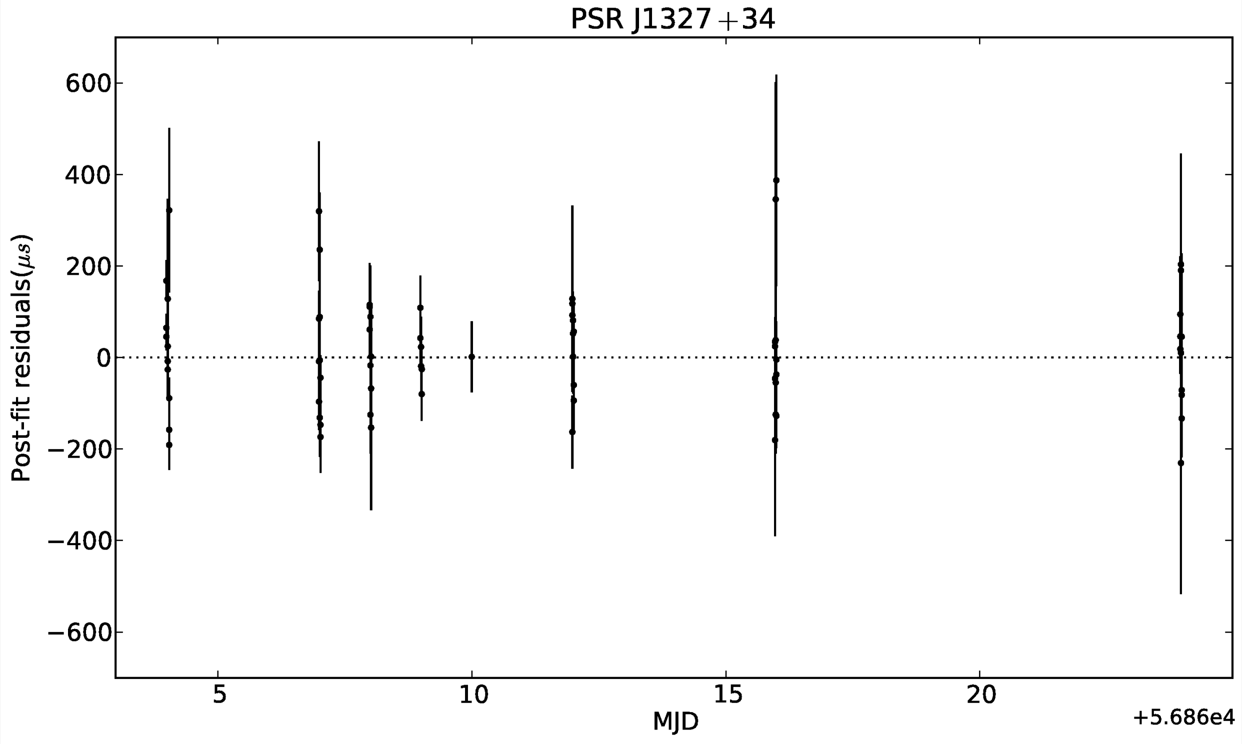
Frequency Evolution



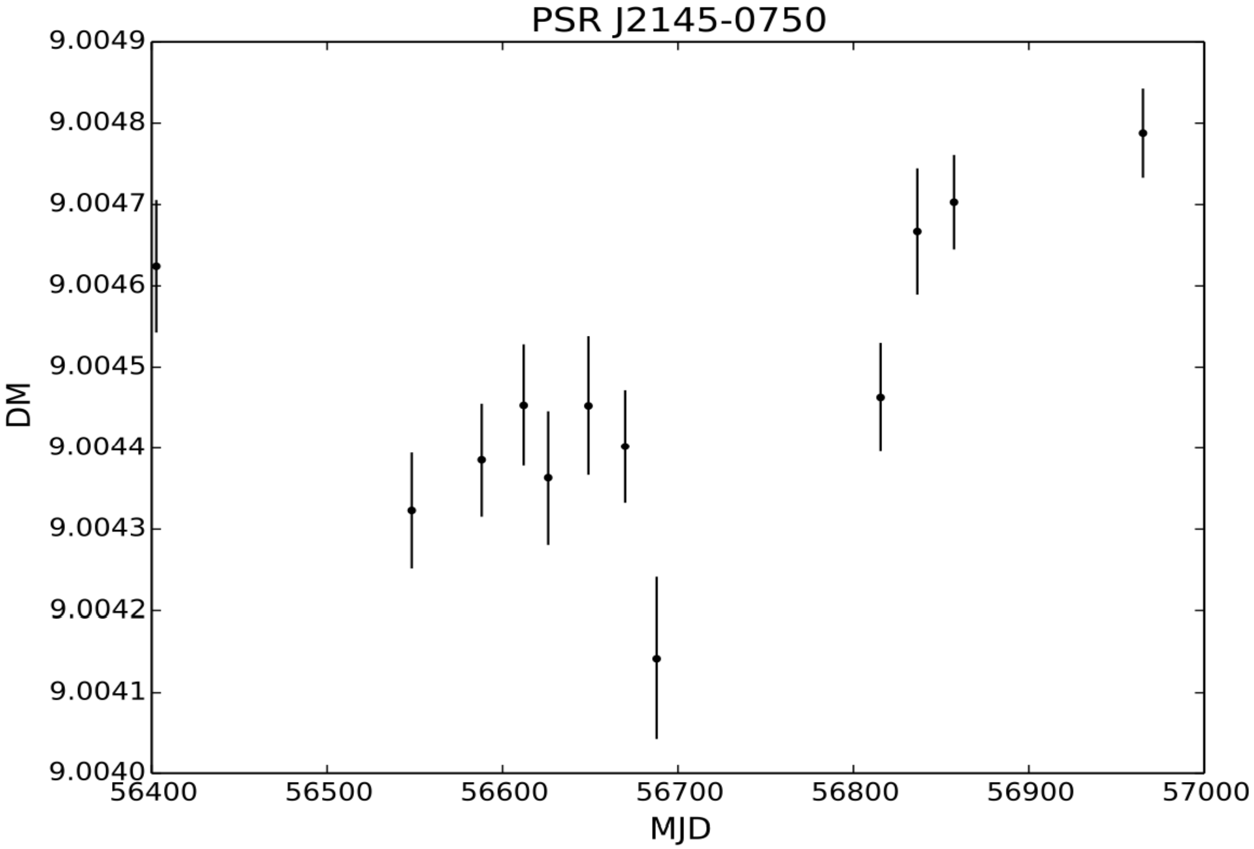
Pulsar Timing

Recently detected J0203+70 and J1327+34 are unpublished GBNCC (*Stovall et al. 2014*) discoveries, J2324-05 is an unpublished GBT350 (*Boyles et al. 2013*) discovery.

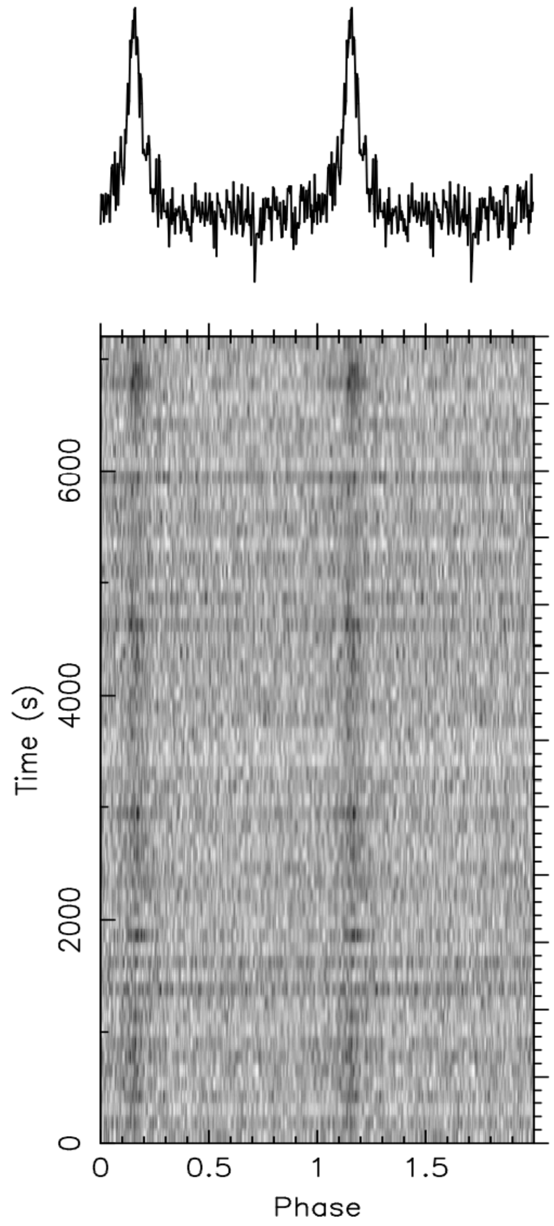
Timing Residuals: J1327+24 (DM 4.2 pc cm^-3; P=41.5 ms)



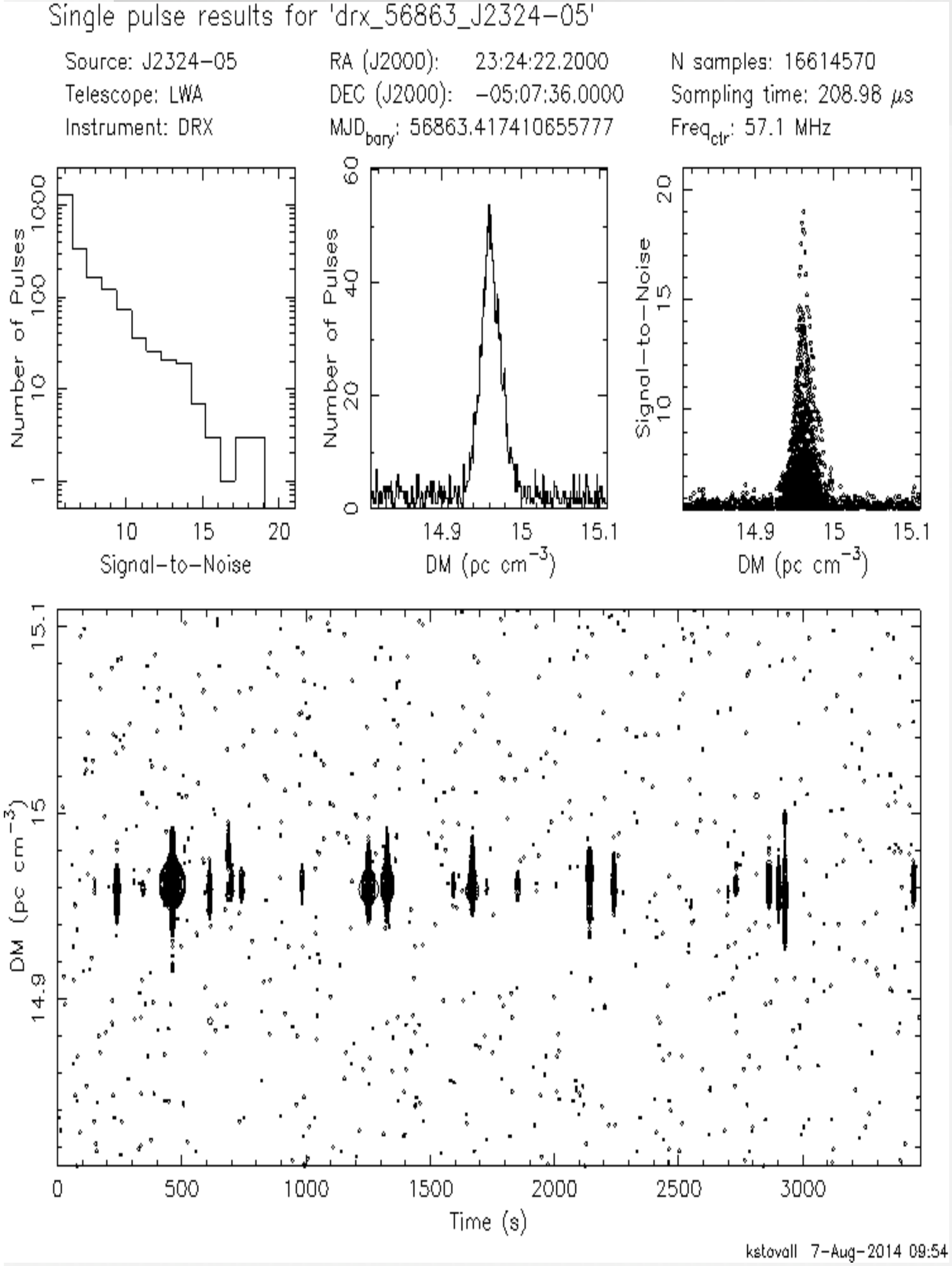
DM Monitoring



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



RRATs



Single pulse results for 'drx_56863_J2324-05'

Source: J2324-05
Telescope: LWA
Instrument: DRX

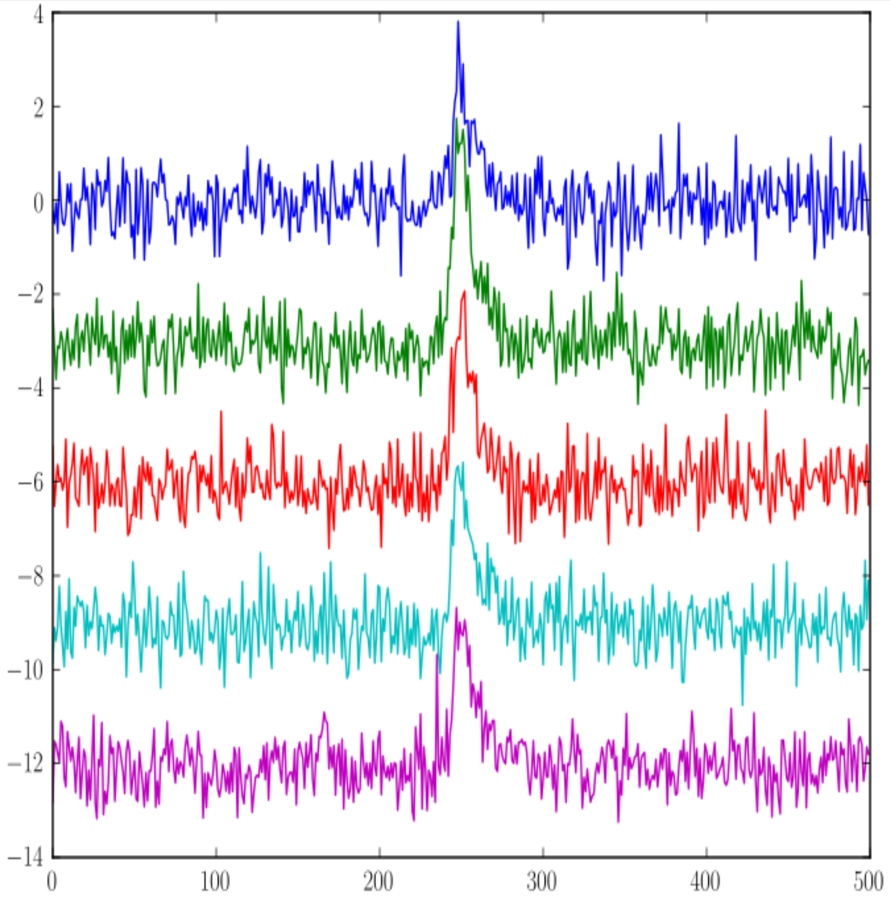
RA (J2000): 23:24:22.2000
DEC (J2000): −05:07:36.0000
MJD_{bary}: 56863.417410655777

N samples: 16614570
Sampling time: 208.98 μs
$Freq_{ctr}$: 57.1 MHz

kstovall 7-Aug-2014 09:54

Detection plot of J2324-05 with LWA

Profiles of pulses for LWA detection



LWA Dispersion Measure: 14.96 pc cm^{-3}

LWA Period: 870 ms

FUTURE DEVELOPMENTS