Pulsar Detection

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Deep Space Exploration Society Open House, Sept. 16, 2023

Pulsar Detection with 60 ft Dish: Live Demos and Training

Saturday, October 21, 10 am – 3 pm

Alternate date (weather or construction) - Saturday, November 4, 10 am – 3 pm

Plan on minimum of 2 hours Radio quiet day (no Wi-Fi, no cells, no xmitters)

Please confirm if attending:

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Outline

- Amateur radio astronomy
- Properties of pulsars
- Pulsar detection
- Detecting pulsars with the Plishner 60' dish
- Pulsars in the news gravitational waves

Atmospheric Window for Radio Astronomy



The atmosphere is transparent to frequencies from 5 MHz to 30+ GHz

Radio waves are much longer than optical waves. So radio telescopes must be much larger than optical telescopes

Several frequency segments are protected for radio astronomy

<u>Goal</u>: minimize RFI; maximize SNR

Radio Signals from Space are Weak



5

Radio Astronomy With the 60' Dish

- Detect <u>pulsars</u> = broadband emitters
 - 408, 1296, & 1420 MHz
- Detect 21 cm (1420.4 MHz) neutral <u>hydrogen</u>
 - Map the Milky Way; detect supernova remnants & radio galaxies
 - Bright sources (e.g., Cass A) used to calibrate dish tracking
- Detect OH (Hydroxyl) masers (1612, 1665 MHz)
 - 1420 MHz feed being modified to cover 1400 1800 MHz (new antenna probe, new LNA)

Pulsar Properties & Detection

Pulsars

- Pulsars are highly magnetized, rapidly rotating neutron stars
 - Formed from collapsed core of a supernova explosion
 - Appear to emit periodic short pulses of radio radiation
- <u>Observables</u> are spin period and period derivative
 - Pulse timing is very consistent. Periods range from msecs to secs
- Propagation effects
 - ISM dispersion: higher freq arrive earlier
 - Scintillation: multipath interference
 - Doppler shift: motion of observer



Pulsar Properties



The PP diagram shows properties derived from period (P) and period derivative (P), including

- Characteristic age
- Minimum magnetic field strength
- Spin-down luminosity

Old, stable millisecond pulsars (MSPs) in lower left are mostly binaries that were "recycled" via accretion from their companion stars

Dispersion

- Higher frequencies detected slightly before lower frequencies due to pulse dispersion through interstellar medium
 - Gray scale shows uncorrected delay
 - Dedispersed, integrated profile at top
- Dispersion Measure (DM) is proportional to density of electrons along line of sight
 - DM can indicate distance, depending on look direction
 - Dedispersion corrects the delay

 $\Delta t = 8.3 \times DM \times BW / v^3 [units: \Delta t \mu s, DM \ pc \ cm^{-3}, BW \ MHz, vGHz]$



Credit: Essential Radio Astronomy, Condon & Ransom

Pulsar Data Folding

- <u>Top</u>: Weak pulsar signal buried in noise
- <u>Middle</u>: Fold at desired period (known or search trial)
- <u>Bottom</u>: Add (integrate) small contributions until pulse appears
 - Shape of individual pulse varies, while the average pulse profile is stable at given freq
- Performed in frequency domain or time domain
- Use published values for P, DM, etc.

https://www.atnf.csiro.au/research/pulsar/psrcat/



Credit: "Searching for and Identifying Pulsars," R. Lynch

Pulsar Detection



Credit: "Handbook of Pulsar Astronomy", Lorimer & Kramer (2005)

Parkes Example: B0833-45 (Vela)



Period = 0.089328 sec, S1400 = 1050.0 mJy Brightest pulsar (time series plot via Presto exploredat)

Parkes 64 m 1Bit_FB data from CSIRO https://data.csiro.au/domain/atnf

Typical Plishner Sample: B0835-41



Plishner 60' data collected June 4, 2022, Haswell, CO

Amateur Pulsar Detection

- Amateurs have detected pulsars using EME equipment
 - 3 meter dish with Airspy SDR
 - Twin 23 element Yagi with RTL-SDR
 - Need to track pulsar several hours and integrate data
- Best fishing frequencies (requires different antennas)
 - 408 MHz (70 cm); 1296 MHz (23 cm); 1420 MHz (21 cm)
- DSES has detected 24 (known) pulsars
 - 60' dish means we don't need to track as long as smaller dishes
 - Safety requirements: no remote ops, 2-person rule
 - Scripts run GnuRadio (data collection) and Presto (pulsar processing)



Plishner 60' dish, Haswell, CO- GPS clock sync- 32-core, Ubuntu 22.04 Host- USRP B2D0 (56 MHz) SDRFeedhornPol.LNAFilter408 MHzLin.30 db90 MHz1296 MHzCirc.30 db30 MHz1420 MHzCirc.35 db60 MHz

DSES System Configuration

Software Tool	Purpose
0NAA Murmur, Stellarium	Plan observations
ATNF database	Ephemeris data (.par)
DSES System 1 Dish Control	Dish pointing and tracking
Spectrum analyzer	Calibrate gain, check RFI
GnuRadio 3.10 filterbank	Data recording (SDR)
PRESTO 4.0 with TEMPO	Pulsar detection
RIPTIDE 0.2.4	Pulsar detection
SIGPROC, watutil, Pint	Misc utilities

DSES Pulsar Catalog

	#	PSR Name	First Detection	Period (sec)	Pulse Width (ms)	DM	S400 (mJy)	S1400 (mJy)	Feed horn MHz	Int. Time (min)
	1.	B0329+54	09-2020	0.714	6.6	26.7	1500		408	15
	2.	B0355+54	07-2022	0.156	3.9	57.4		46	1296	240
	3.	J0437-4715	08-2021	0.005	0.1	2.6		150	1420	30
	4.	B0531+21	07-2020	0.033	3.0	56.7	550		408	60
	5.	B0628-28	07-2022	1.244	63.3	34.4		32	1296	60
	6.	B0736-40	06-2022	0.375	22.7	160.9		112	1296	90
	7.	B0740-28	09-2020	0.167	4.2	73.7	296		408	30
ľ	8.	B0833-45	09-2020	0.089	1.4	67.7	5000		408	15
	9.	B0835-41	06-2022	0.752	4.4	147.2		35	1296	90
	10.	B0950+08	09-2020	0.253	8.9	2.9	400		408	60
	11.	B1133+16	09-2020	1.118	5.9	4.8	257		408	240
	12.	B1508+55	09-2020	0.739	10.9	19.6	114		408	60
	13.	B1556-44	11-2022	0.257	6.5	55.9		37	1296	180
	14.	B1641-45	08-2021	0.455	8.0	478.6		300	1420	30
	15.	B1642-03	09-2020	0.388	3.4	35.8	393		408	90
	16.	B1749-28	09-2020	0.563	6.1	50.4	1100		408	20
	17.	B1859+03	11-2022	0.655	9.0	402.0	165		437	180
	18.	B1929+10	09-2020	0.227	5.7	3.2	303		408	90
	19.	B1933+16	09-2020	0.359	6.0	158.5	242		408	60
	20.	B1946+35	09-2020	0.717	19.3	129.4	145		408	240
	21.	B2016+28	09-2020	0.558	14.9	14.2	314		408	90
	22.	B2020+28	03-2022	0.343	12.0	24.6		38	1296	180
	23.	B2021+51	09-2021	0.529	7.4	22.5		27	1420	30
	24.	B2111+46	02-2022	1.014	32.1	141.3		19	1296	90

Murmur (using ATNF database)

	Murmur 17.0.0 31 March 2022 mario.natal	i@gmail.com http://i0naa.altervista.org ×	
Pulsar mode Location Latitude Plishner 18m 38.3814 Current Time Zone Name : Mountain Daylight Time	Longitude UTC Time -103.1540 Thu Mar 23 19	Local Time 12:58 2023 Thu Mar 23 13:12:58 2023 Rev. History Help RESET Settings and EXIT Check for updates EXIT	
System evaluation mode SAVE of Pulsar mode SET 0	rrent set as default CALCULATE Servation location	TRACK noise sources Culminations Next 24h PSR visibility Next 24h PSR tracking CALCULATE Noise Y-Factor 1 Month PSR visibility 1 Month PSR tracking	
© Dish antenna C Other antenna Dish diameter 18.3 m	Wave length 0.75 m Effective ant. aperture 181.4 m^2 i Dish area 262.89 m^2	'.ist of detectable PULSARS Minimum S/N > 10 ▼ PULSARS extracted with S1400 flow >0: 720 720 PULSARS extracted with S1400 flow >0: 1979 S/N > 10 suggested for reliable results ATNF Pulsar catalogue Version : 1.67	
Dish efficiency 69 % Frequency 400 Mhz Line loss before LNA 0.1 dB	Far field 893 m i Antenna gain 36.07 dBi i HPBW 2.87 deg i	Sorted by S/N Right Ascension J2000 (RAJD) 53.25 deg Above horizon Declination (DECJD) 54.58 deg B0329+54 J0341+5711 Pulse with @ 50% of peak (W50) 6.6 msec. i B2016+28 Dergraphic period (R0) 6.7155 core i	W50
LNA Noise figure 0.5 dB LNA gain 42 dB Line loss after LNA 4 dB	System noise temp. 57.06 K i System noise figure 0.78 dB i	B 1929+10 Barycentric period (P0) 0.71452 sec. B 1933+16 Dispersion Measure (DM) 26.76 cm^-3 pc B 1937+21 Flux @ 400 Mhz (S400) 1500.0 mJy i B 2045-16 Flux @1400 Mhz (S1400) 203.0 mJy i	DM
Receiver noise figure 4 dB T sky 4 K T spillover 10 K	Noise floor -100.19 dBm i MDS 4.58 mJy i	B2111+46 J2238+6021 Distance (Dist) 1.70 kpc 5528.4 Iy i B1911-04 B2217+47 Age (age) 5.53e+06 years i Max Int. BW (no de-dispersion) 960 Khz i	Flux
Integration time 1800 sec. Integration bandwidth 20000 kHz	The analysis does not take into account the polarization of the signal as this parameter is strongly depending on the specific Pulsar. Please evaluate carefully case by case as this may deteriorate performance up to 3dB.	Show all PSR List Expected S/N 3394.8 i PLAN Observation Azimuth 47.16 deg Select object to track Elevation 54.59 deg	BVV

System 1 Dish Control



GnuRadio Filterbank Data Collection



Resulting Presto Plot: PSR B0329+54



437 MHz dual helical antenna BO329+54 Analysis

10 minutes at 30 MHz, Aug. 13, 2022 Automatic Presto plot via ATNF pulsar ephemeris



Clean spectrum, some ripple is okay



PSR B2154+40 Failure No response. 3 hours, S400 = 105 mJy

RFI and red-noise decreases S/N, causing problems folding slow pulsars





B0835-41



Time series shown earlier



1.5 Periods of Signal Input: B0835-41 20220604 214521.tim.inf seconds) 2000 ime 4000 50 100 150 200 250 abu 30 amplit 20 10 ահերհերհեր 100 200 250 150 Phase bin Period (Topo) 751.664452 ms Source Telescope DSES B0835-41 DM 147.20 pc cm⁻³ RA 08:37:21.10 Low frequency 1285.0 MHz Width 3 bins Dec 41:35:14.50 High frequency 1315.0 MHz Duty cycle 1.40 % MID 59734.906498 Channels 512 SNR 37.7 UTC 2022-06-04 21:45:21 Sample time 0.2730 ms

RIPTIDE Period = 751.66445 ms, $SNR_{ffa} = 37.7$

PRESTO Period = 751.66446 ms, SNR_# = 12.7

B2020+28



Double-peak pulse (mode-changing) Pulse at end of collection: Scintillation



RIPTIDE Period = 343.393918 ms, SNR_{ffa} = 16.3

PRESTO Period = 343.394280 ms, SNR_{ff} = 4.8

Pulsars in the News: Gravitational Wave Detection

- NANOGrav* found (Bayesian) evidence for gravitational waves that oscillate with periods of years to decades
- The 15-year data set uses highprecision radio timing of millisecond pulsars (MSPs)

*NANOGrav = North American Nanohertz Observatory for Gravitational Waves



Pulsar Timing Array (PTA) Illustration

nanograv.org

Gravitational Wave Spectrum



Credit: NASA/GSC

NANOGrav 15-Year PTA

79 MSPs at two frequencies (from 800 MHz to 3 GHz) every one to four weeks for roughly 20-30 min using Arecibo (41 MSPs), the GBT (39 MSPs), and the VLA (7 MSPs)



GBT & CHIME replaced Arecibo

CHIME

Pulsar Timing Residuals



Credit: D. Champion, K. Liu 2017

- Disturbances to pulse arrival times
- Timing residuals show scatter in excess of that predicted by formal timing uncertainties

- TOA = pulse Time Of Arrival
- Residual = observed TOA modeled TOA
- Every pulse accounted for via phase alignment



rotation period rotation period derivative timing noise	dispersion measure dispersion meas. variations	position proper motion parallax
Keplerian orbital elements relativistic orbital elements		solar electron density
kinematic perturbations of orbital elements (secular and annual phenomena)		

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Questions?