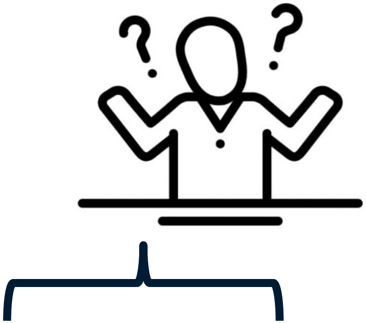
Single dish radio astronomy

George Hobbs

Radio school | Sept. 2023

Australia’s National Science Agency



Single dish radio astronomy

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Australia's National Science Agency

To do radio astronomy
… you don’t need an interferometer
… you don’t even need a dish!

You do need an antenna

Antenna

Amplification

Filtering

Digitisation

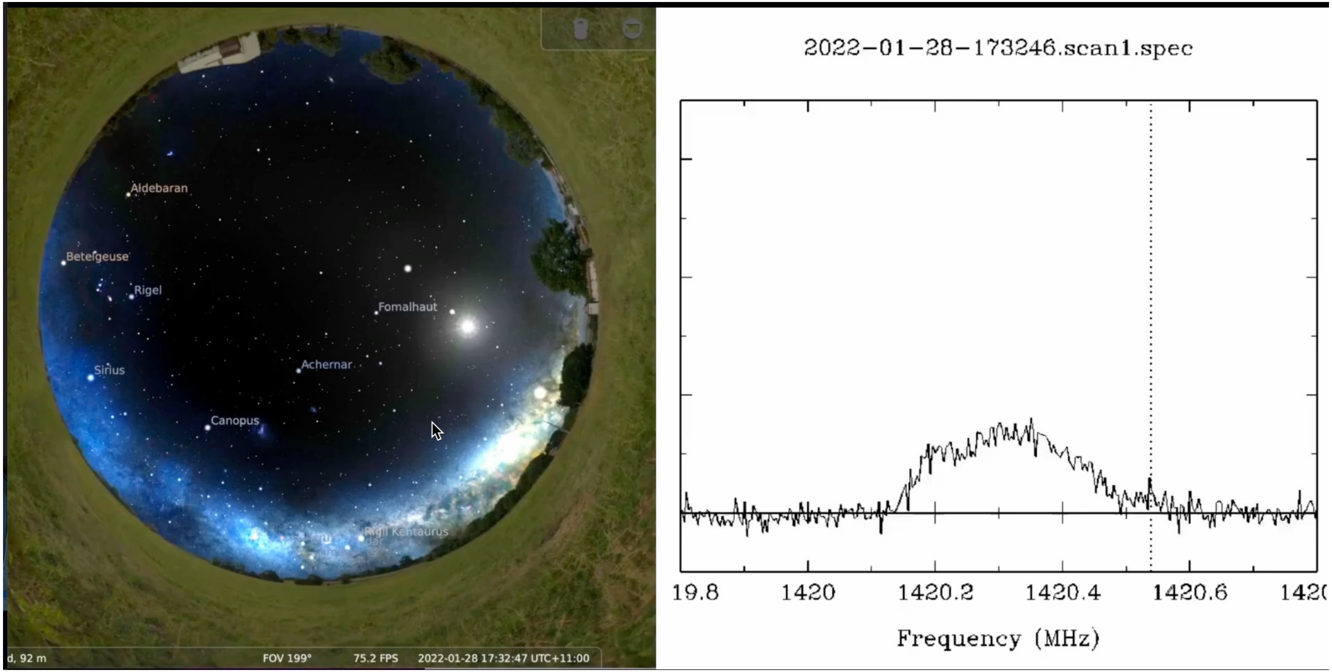
Data processing
storage

RTL-SDR Blog V3 R860 RTL2832U 1PPM TCXO SMA Software Defined Radio (Dongle Only) (Black)

★★★★☆ 2,468

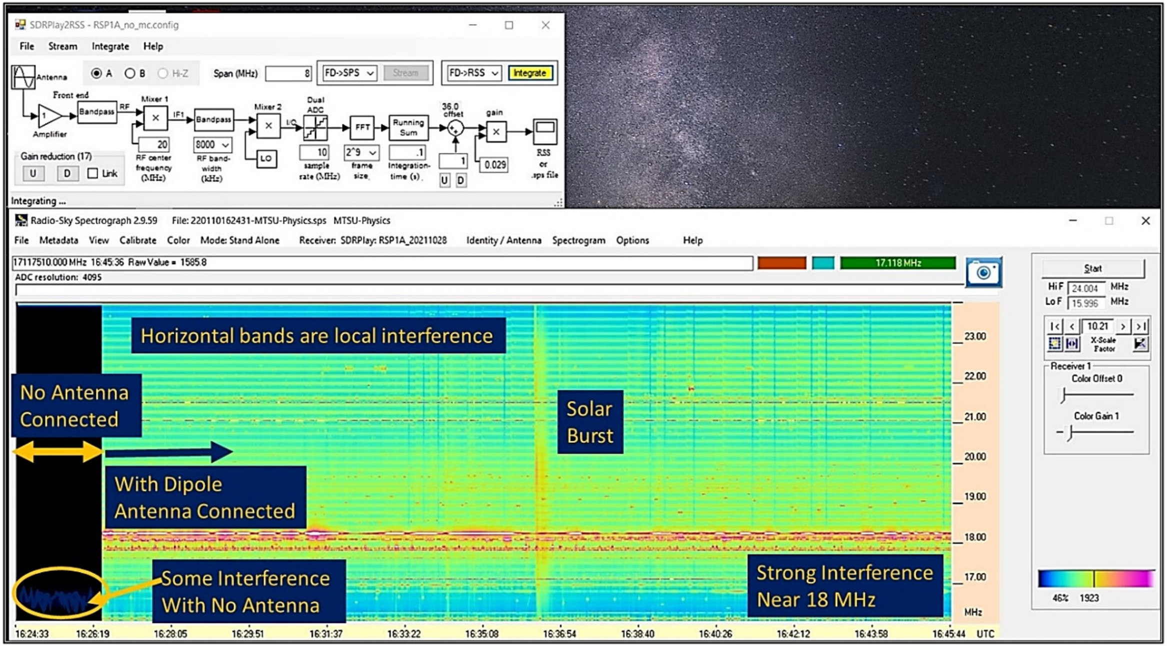
$91.65

See JR’s talk



Movie from Tash Moy, a metal can and a $50 software defined radio

Typical output



Horizontal bands are local interference

No Antenna Connected

With Dipole Antenna Connected

Solar Burst

Some Interference With No Antenna

Strong Interference Near 18 MHz

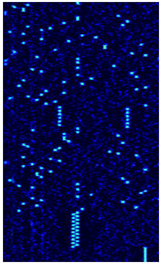
Example Radio JOVE spectrograph output using RSS display software. Note the large increase in signal denoted by the colored background after the antenna is connected.

https://radiojove.gsfc.nasa.gov/radio_telescope/building_testing.php

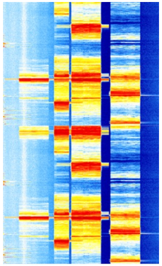
Waterfall plots/spectrograms

https://www.sigidwiki.com/wiki/Signal_Identification_Guide

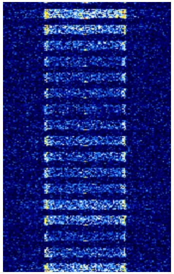
Time ->



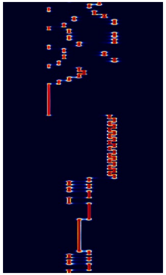
Inmarsat
1.5GHz



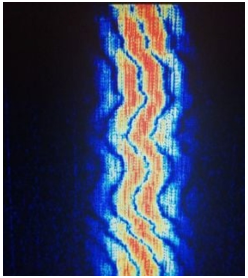
LTE
700-2600MHz



Weather balloon
400 MHz



Numbers station
3-30MHz

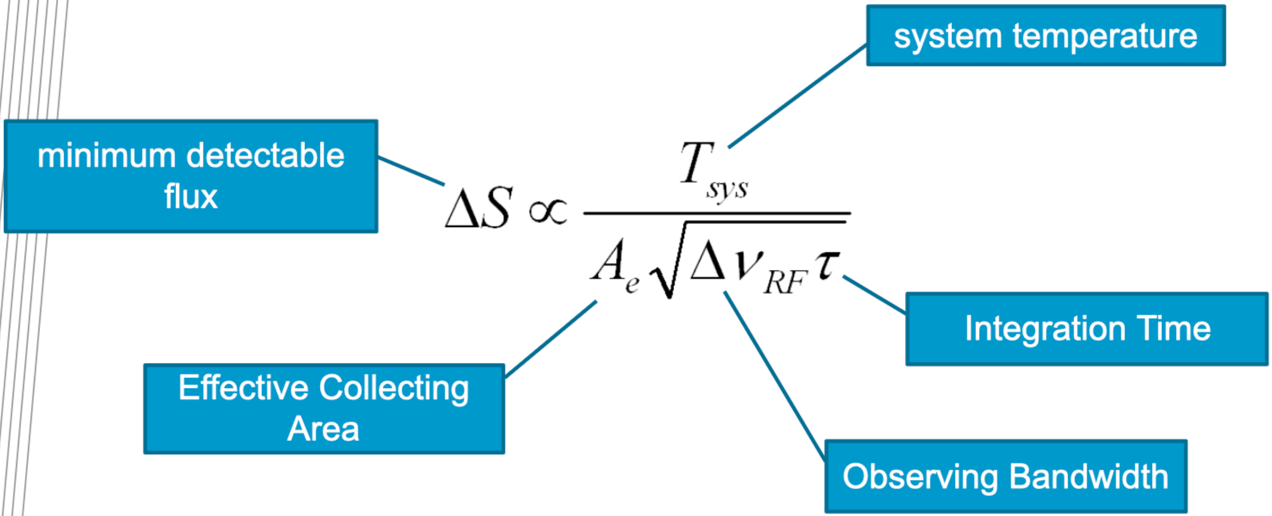


Unidentified
420 MHz

Frequency ->

Signal strength as a function of frequency and time

The key properties



system temperature

minimum detectable flux

$$\Delta S \propto \frac{T_{sys}}{A_e \sqrt{\Delta \nu_{RF} \tau}}$$

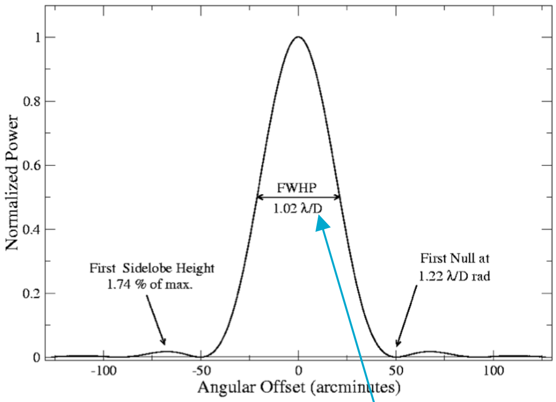
Integration Time

Effective Collecting Area

Observing Bandwidth

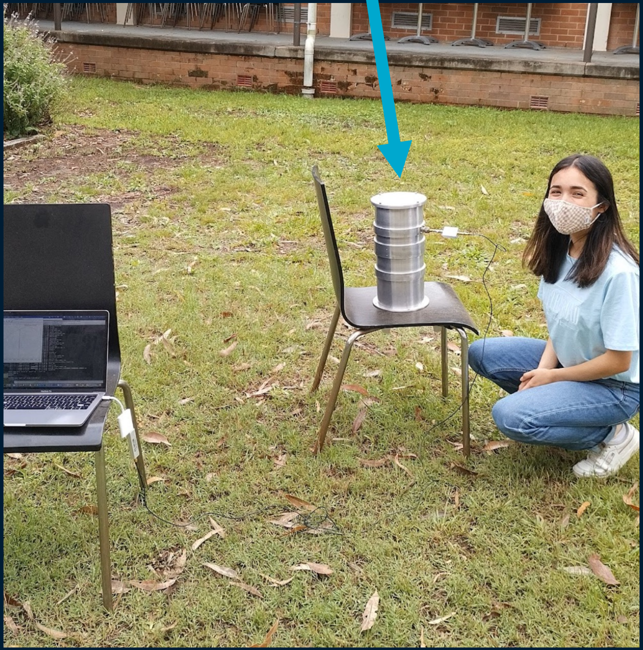
Why bother with a dish?

- Aeff … goes up
- But … field of view goes down



D = diameter

Aeff limited, or observing frequency will change



Let’s have a dish!

500m diameter

2m diameter

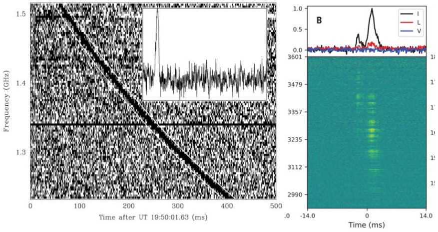
38x25m

CSIRO’s Parkes Murriyang Radio telescope

This is Parkes

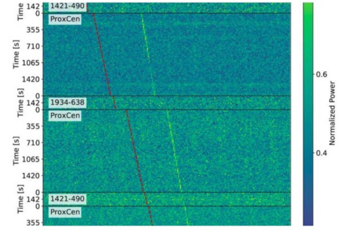
This is not Parkes

A quick look at some recent science with The Dish



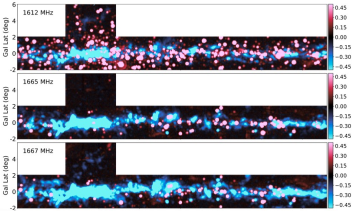
Fast radio bursts

Gravitational waves

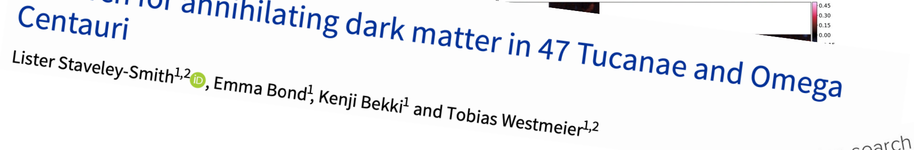


The BLC1 signal. Each panel in the plot is an observation toward Proxima Cen...

Breakthrough Listen Candidate #1

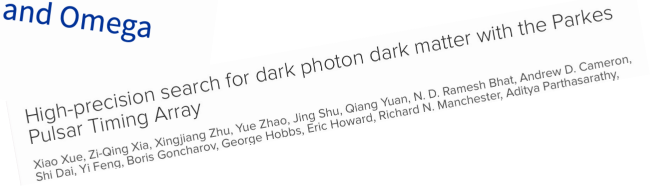


OH spectral lines



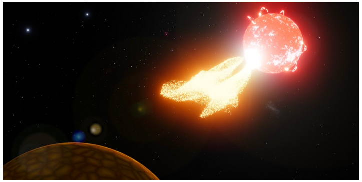
A search for annihilating dark matter in 47 Tucanae and Omega Centauri

Lister Staveley-Smith[1,2], Emma Bond[1], Kenji Bekki[1] and Tobias Westmeier[1,2]



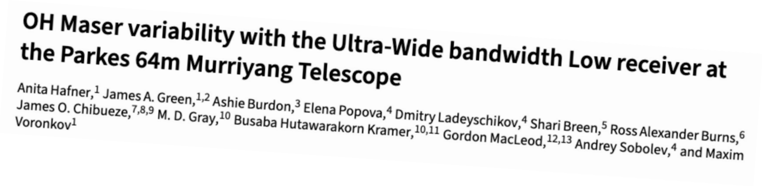
High-precision search for dark photon dark matter with the Parkes Pulsar Timing Array

Xiao Xue, Zi-Qing Xia, Xingjiang Zhu, Yue Zhao, Jing Shu, Qiang Yuan, N. D. Ramesh Bhat, Andrew D. Cameron, Shi Dai, Yi Feng, Boris Goncharov, George Hobbs, Eric Howard, Richard N. Manchester, Aditya Parthasarathy,



Flare stars

Mark Myers/OzGrav



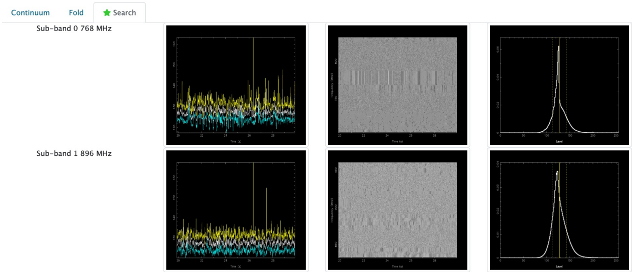
OH Maser variability with the Ultra-Wide bandwidth Low receiver at the Parkes 64m Murriyang Telescope

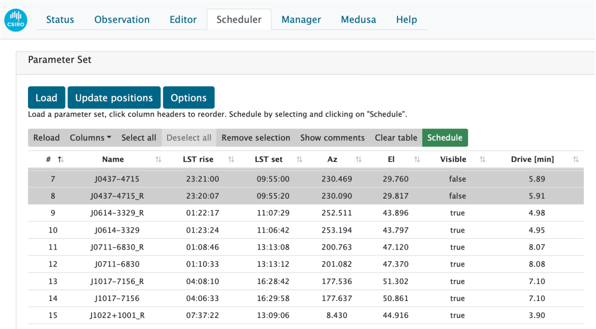
Anita Hafner,[1] James A. Green,[1,2] Ashie Burdon,[3] Elena Popova,[4] Dmitry Ladeyschikov,[4] Shari Breen,[5] Ross Alexander Burns,[6] James O. Chibueze,[7,8,9] M. D. Gray,[10] Busaba Hutawarakorn Kramer,[10,11] Gordon MacLeod,[12,13] Andrey Sobolev,[4] and Maxim Voronkov[1]

Thanks to Stacy Mader

Observing with Parkes is easy

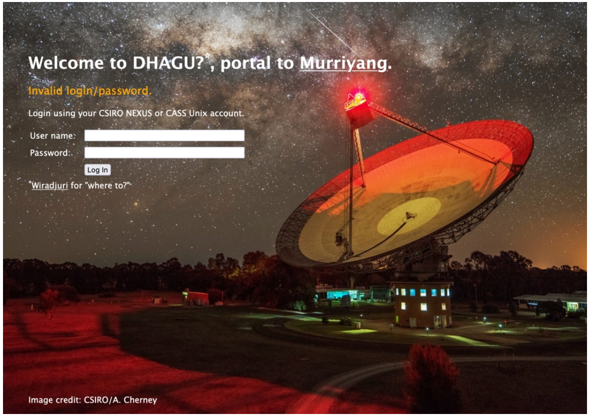
- Just need a web browser





Load a parameter set, click column headers to reorder. Schedule by selecting and clicking on "Schedule".

#	Name	LST rise	LST set	Az	El	Visible	Drive [min]
7	J0437−4715	23:21:00	09:55:00	230.469	29.760	false	5.89
8	J0437−4715_R	23:20:07	09:55:20	230.090	29.817	false	5.91
9	J0614−3329_R	01:22:17	11:07:29	252.511	43.896	true	4.98
10	J0614−3329	01:23:24	11:06:42	253.194	43.797	true	4.95
11	J0711−6830_R	01:08:46	13:13:08	200.763	47.120	true	8.07
12	J0711−6830	01:10:33	13:13:12	201.082	47.370	true	8.08
13	J1017−7156_R	04:08:10	16:28:42	177.536	51.302	true	7.10
14	J1017−7156	04:06:33	16:29:58	177.637	50.861	true	7.10
15	J1022+1001_R	07:37:22	13:09:06	8.430	44.916	true	3.90



Welcome to DHAGU?*, portal to Murriyang.

Invalid login/password.

Login using your CSIRO NEXUS or CASS Unix account.

User name:

Password:

*Wiradjuri for "where to?"

Image credit: CSIRO/A. Cherney

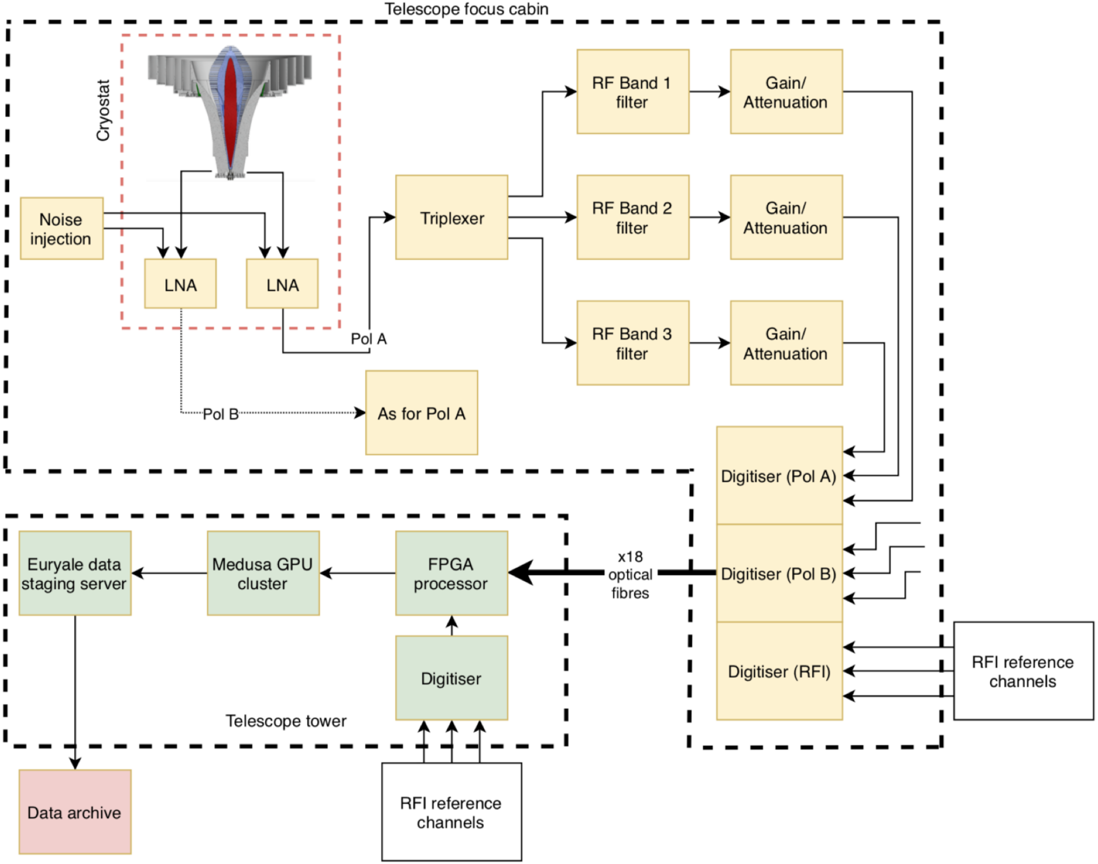
Observer in Charge: Tim Ruckley

DOY/UTC: 265/00:02:59

AEST: 10:02:59

LMST: 09:58:27

MJD: 60209



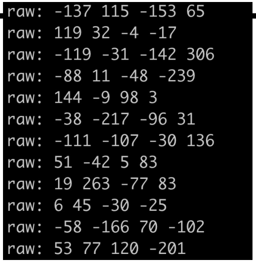
Hobbs et al. (2020)

Voltage data streams to frequency/time/power

Digitised voltage data stream

1GB/second

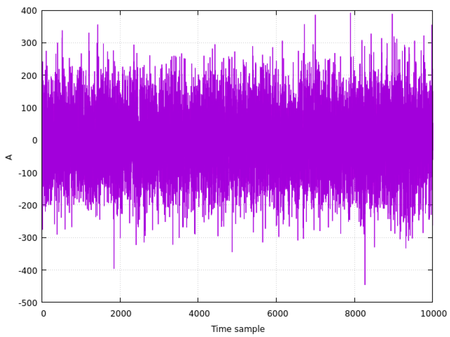
FPGAs -> GPUs

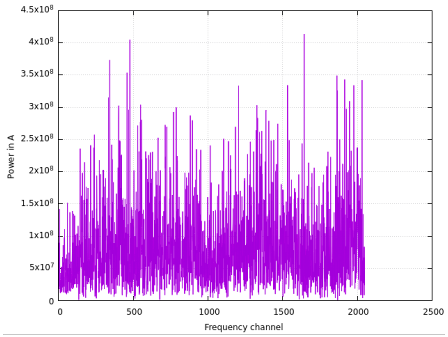


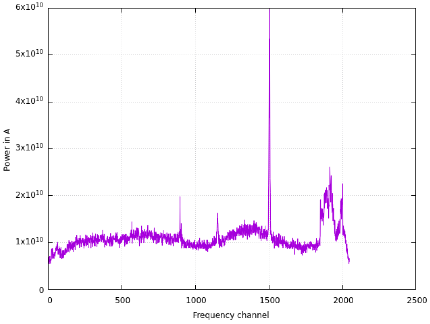
```
raw: -137 115 -153 65
raw: 119 32 -4 -17
raw: -119 -31 -142 306
raw: -88 11 -48 -239
raw: 144 -9 98 3
raw: -38 -217 -96 31
raw: -111 -107 -30 136
raw: 51 -42 5 83
raw: 19 263 -77 83
raw: 6 45 -30 -25
raw: -58 -166 70 -102
raw: 53 77 120 -201
```

Select Nsamples => FFT => Power

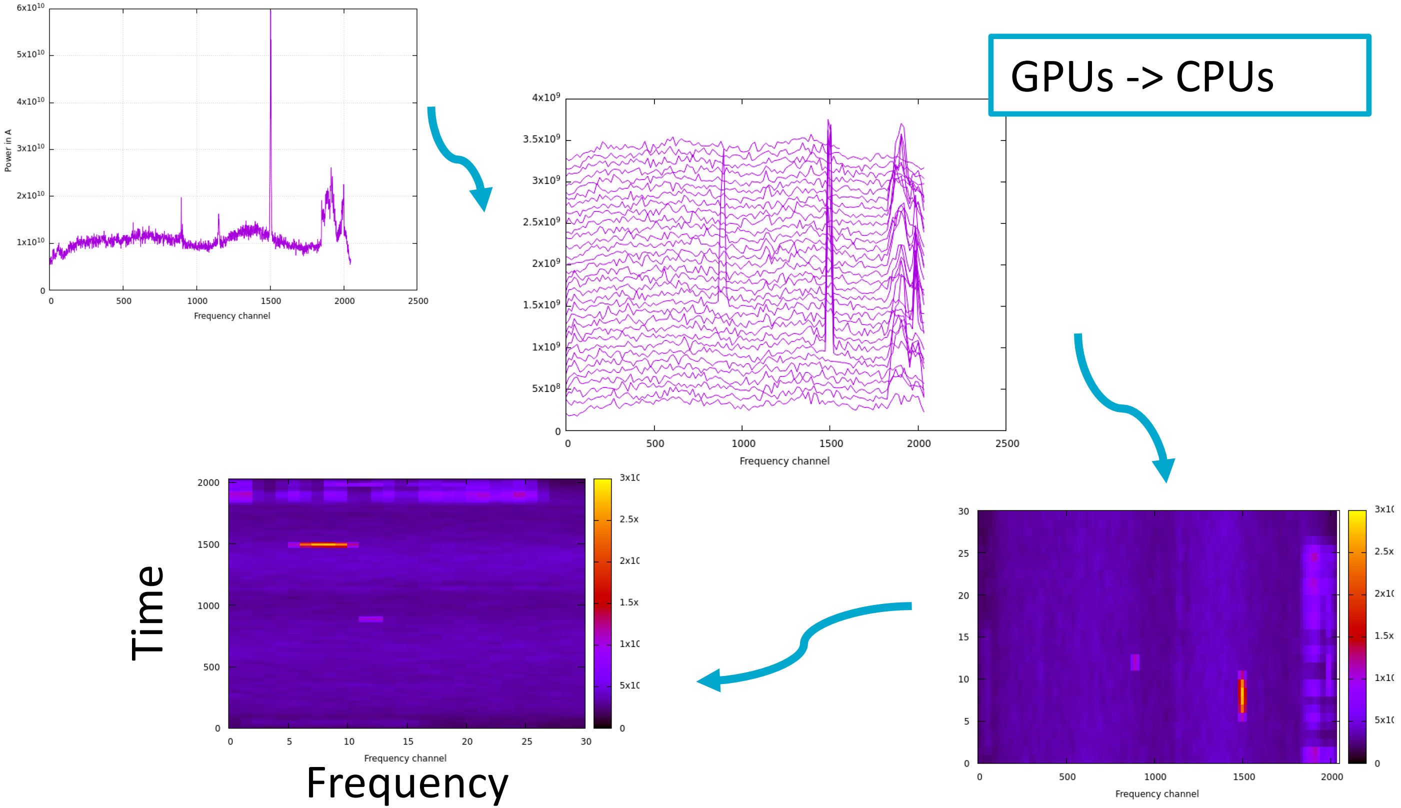
Integrate in time





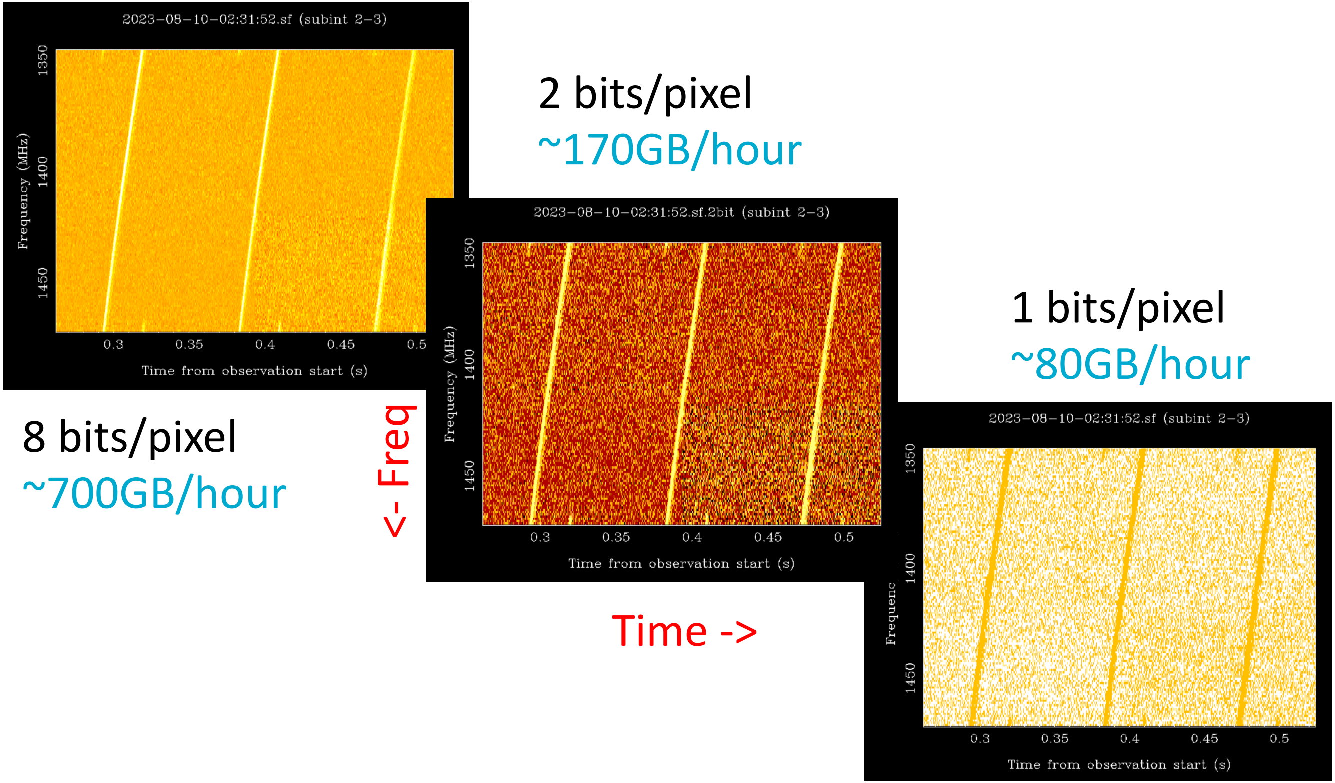


To high-time-resolution data sets


GPUs -> CPUs

1024 channels, 64us sampling,
1 pol, 13 beams

Reduce the number of bits in the spectrograms!



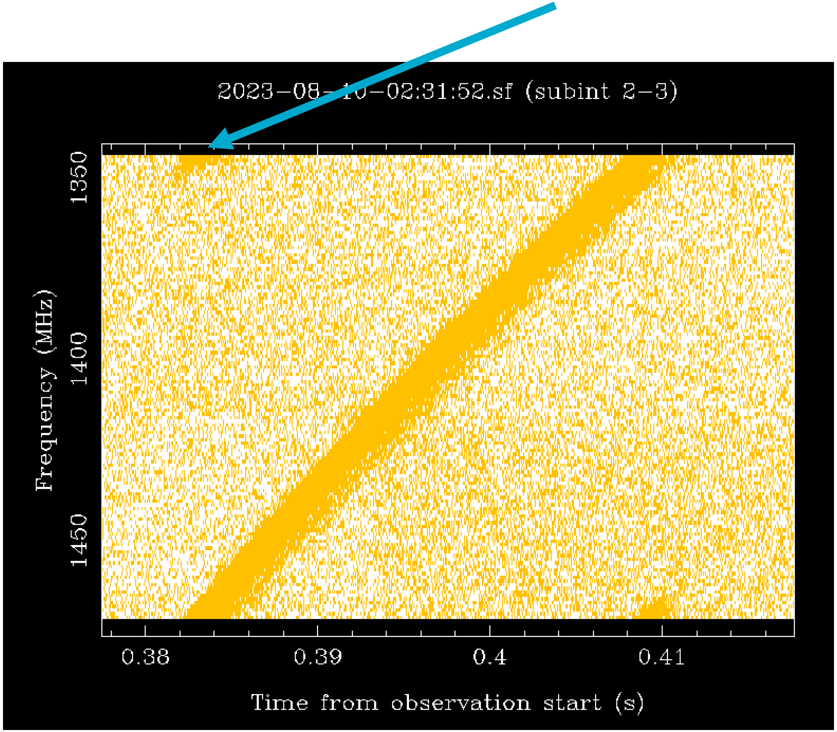
8 bits/pixel
~700GB/hour

2 bits/pixel
~170GB/hour

1 bits/pixel
~80GB/hour

A dispersed pulse

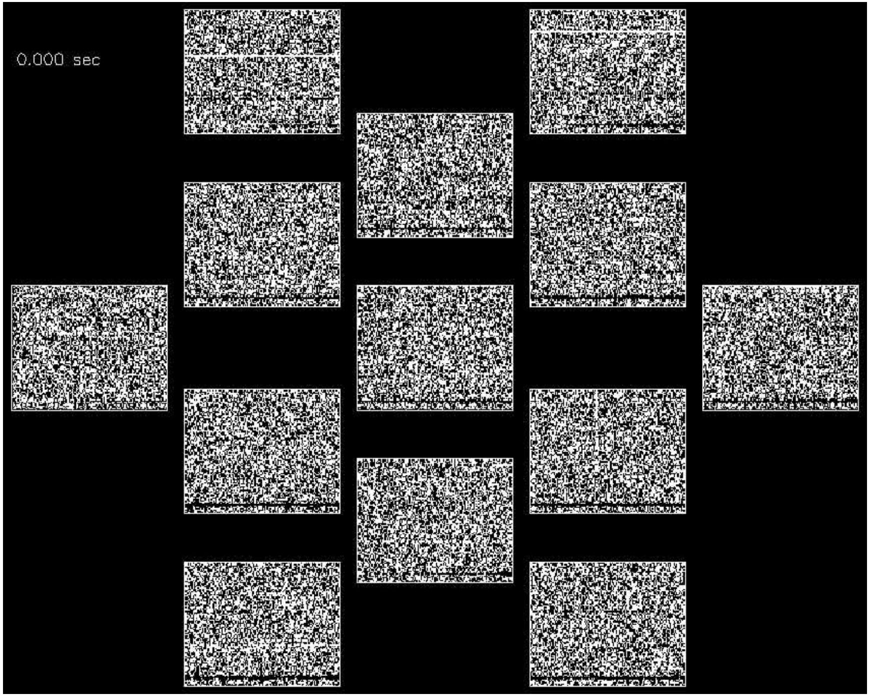
Pulsar?
FRB?
RRAT?
Flare star?
RFI?
Alien?
…



Ask Chris

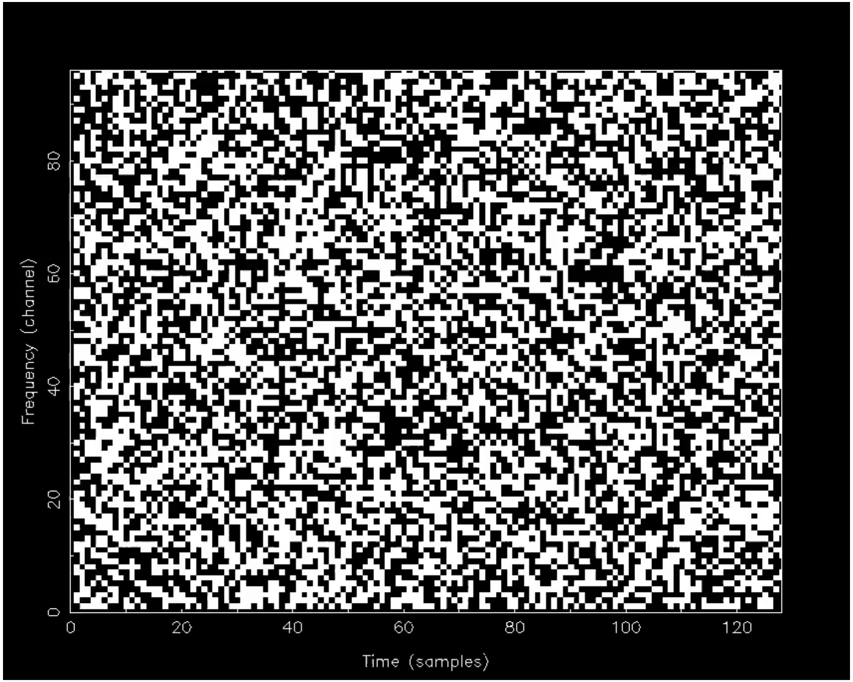
This is a single pulse from the Vela pulsar

Multibeams and what is in the data?



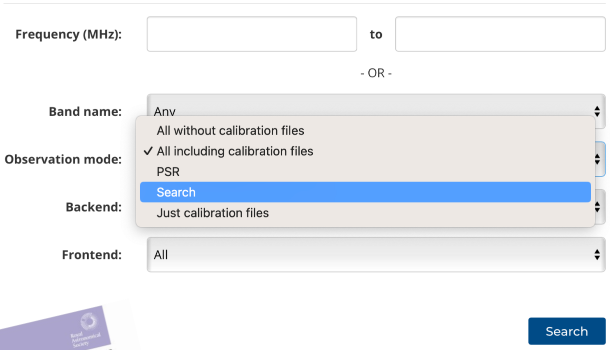
What is in the data?

- Unexpected transients?
- How do we find the rare, unexpected events in TBs (or PBs) or data?



Have a play

- https://data.csiro.au/domain/atnf


Frequency (MHz): to

- OR -

Band name: Any

Observation mode:

Backend:

Frontend: All

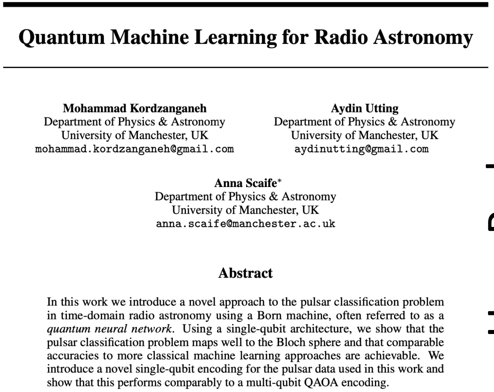

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **516**, 5832–5848 (2022)
Advance Access publication 2022 September 9

https://doi.org/10.1093/mnras/stac2558

SPARKESX: Single-dish PARKES data sets for finding the uneXpected – a data challenge

Suk Yee Yong [1★], George Hobbs [1], Minh T. Huynh [2,3] Vivien Rolland [4], Lars Petersson,[5] Ray P. Norris [1,6] Shi Dai [6], Rui Luo [1] and Andrew Zic [1,7]


Quantum Machine Learning for Radio Astronomy

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Abstract

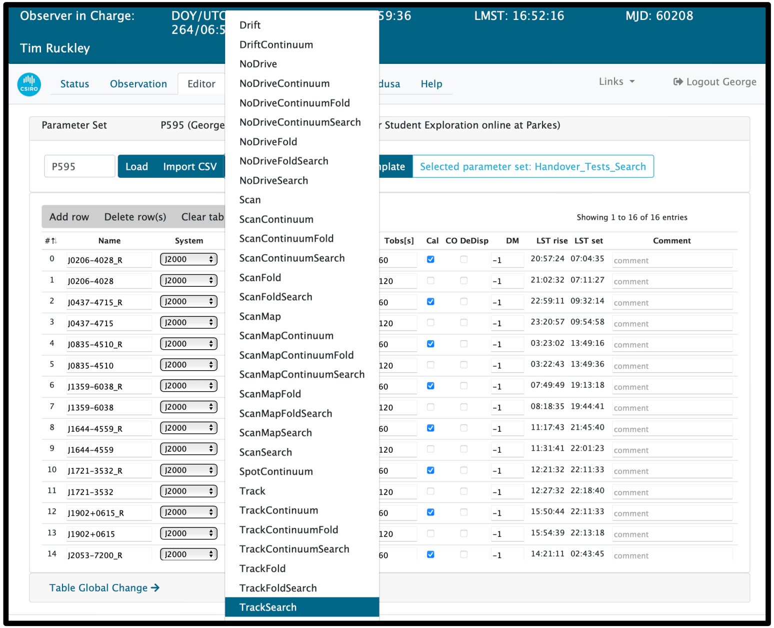
In this work we introduce a novel approach to the pulsar classification problem in time-domain radio astronomy using a Born machine, often referred to as a *quantum neural network*. Using a single-qubit architecture, we show that the pulsar classification problem maps well to the Bloch sphere and that comparable accuracies to more classical machine learning approaches are achievable. We introduce a novel single-qubit encoding for the pulsar data used in this work and show that this performs comparably to a multi-qubit QAOA encoding.

Uses Parkes pulsar data

Software:

Presto, sigproc, pfits, heimdall …

Have a go observing!



Observer in Charge: Tim Ruckley

DOY/UTC 264/06:5

59:36

LMST: 16:52:16

MJD: 60208

Parameter Set P595 (George

r Student Exploration online at Parkes)

P595

Selected parameter set: Handover_Tests_Search

Showing 1 to 16 of 16 entries

#	Name	System	Tobs[s]	Cal	CO DeDisp	DM	LST rise	LST set	Comment
0	J0206-4028_R	J2000	60	☑	☐	-1	20:57:24	07:04:35	comment
1	J0206-4028	J2000	120	☐	☐	-1	21:02:32	07:11:27	comment
2	J0437-4715_R	J2000	60	☑	☐	-1	22:59:11	09:32:14	comment
3	J0437-4715	J2000	120	☐	☐	-1	23:20:57	09:54:58	comment
4	J0835-4510_R	J2000	60	☑	☐	-1	03:23:02	13:49:16	comment
5	J0835-4510	J2000	120	☐	☐	-1	03:22:43	13:49:36	comment
6	J1359-6038_R	J2000	60	☑	☐	-1	07:49:49	19:13:18	comment
7	J1359-6038	J2000	120	☐	☐	-1	08:18:35	19:44:41	comment
8	J1644-4559_R	J2000	60	☑	☐	-1	11:17:43	21:45:40	comment
9	J1644-4559	J2000	120	☐	☐	-1	11:31:41	22:01:23	comment
10	J1721-3532_R	J2000	60	☑	☐	-1	12:21:32	22:11:33	comment
11	J1721-3532	J2000	120	☐	☐	-1	12:27:32	22:18:40	comment
12	J1902+0615_R	J2000	60	☑	☐	-1	15:50:44	22:11:33	comment
13	J1902+0615	J2000	120	☐	☐	-1	15:54:39	22:13:18	comment
14	J2053-7200_R	J2000	60	☑	☐	-1	14:21:11	02:43:45	comment

Table Global Change →

16 2816MHz
17 2944MHz
18 3072MHz
19 3200MHz
20 3328MHz
21 3456MHz
22 3584MHz
23 3712MHz
24 3840MHz
25 3968MHz

Search

ACTIVE: true
Process subband in Search mode

OUTPUT NBIT: 8
Number of bits per output sample [1,2,4,8]

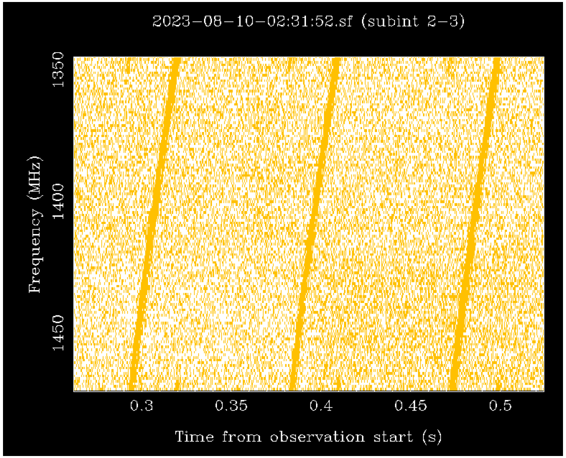
OUTPUT NCHAN: 1024
Number of output channels for Pulsar Search mode per sub-band [8-4096, power of two]

OUTPUT STOKES: 3
Stokes parameters to form [1=AA+BB, 2=AA,BB, 3=AA,BB,Real(AB),Imag(AB)]

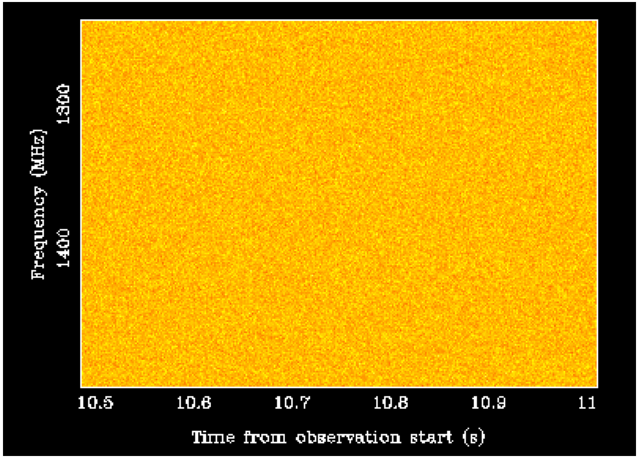
OUTPUT TSAMP: 128
Output sampling interval in microseconds [1-1048576, power of two] unit = microseconds

OUTPUT TSUBINT: 30
Length of output sub-integration in seconds [15-3600] unit = seconds

Folding the data

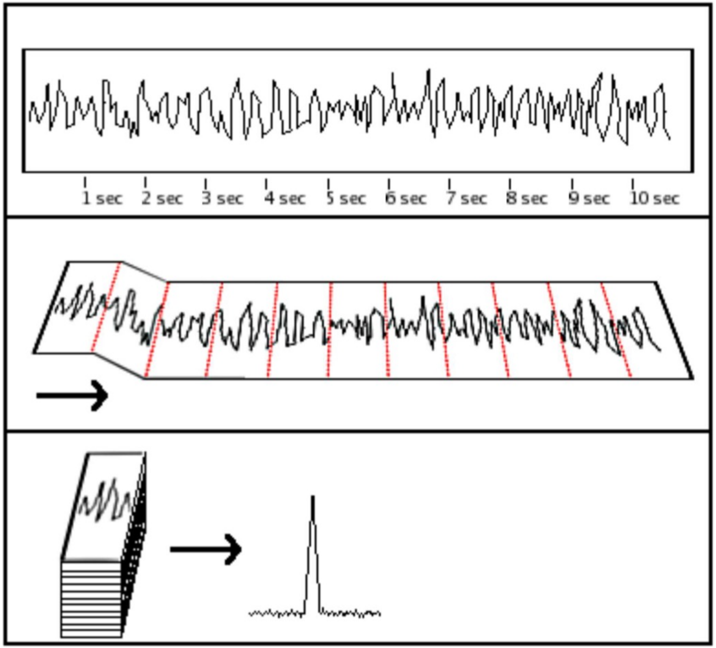


Easy to find the Vela pulsar!



No sign of any pulses for this pulsar

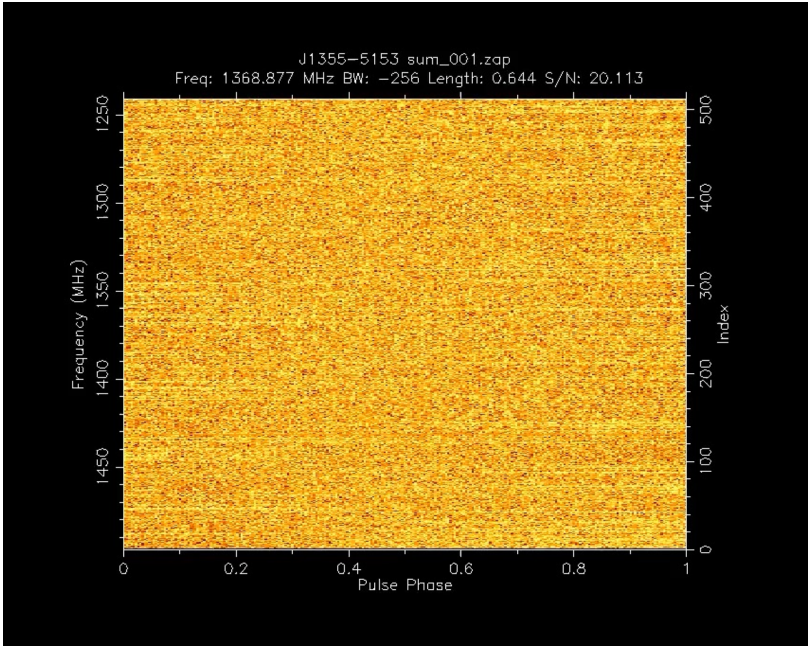
But … we know the period of the pulsar



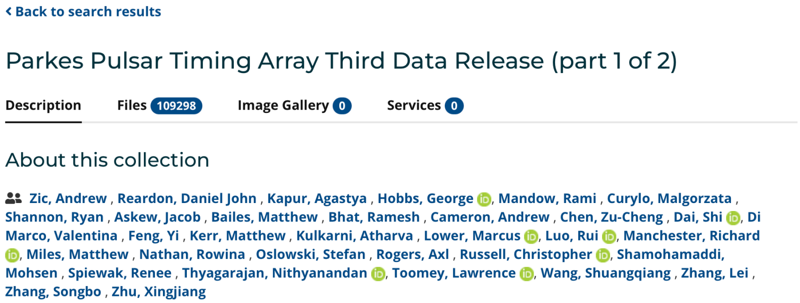
https://www.physics.mcgill.ca/~rlynch/Outreach/PSC_search_guide.pdf

Let’s find that pulsar

- Folding the frequency-time data at the period of the pulsar



Have a play



‹ Back to search results

Parkes Pulsar Timing Array Third Data Release (part 1 of 2)

About this collection

Zic, Andrew , Reardon, Daniel John , Kapur, Agastya , Hobbs, George , Mandow, Rami , Curylo, Malgorzata , Shannon, Ryan , Askew, Jacob , Bailes, Matthew , Bhat, Ramesh , Cameron, Andrew , Chen, Zu-Cheng , Dai, Shi , Di Marco, Valentina , Feng, Yi , Kerr, Matthew , Kulkarni, Atharva , Lower, Marcus , Luo, Rui , Manchester, Richard , Miles, Matthew , Nathan, Rowina , Oslowski, Stefan , Rogers, Axl , Russell, Christopher , Shamohamaddi, Mohsen , Spiewak, Renee , Thyagarajan, Nithyanandan , Toomey, Lawrence , Wang, Shuangqiang , Zhang, Lei , Zhang, Songbo , Zhu, Xingjiang

https://doi.org/10.25919/j4xr-wp05

Australian astronomers find possible 'fingerprints' of gravitational waves

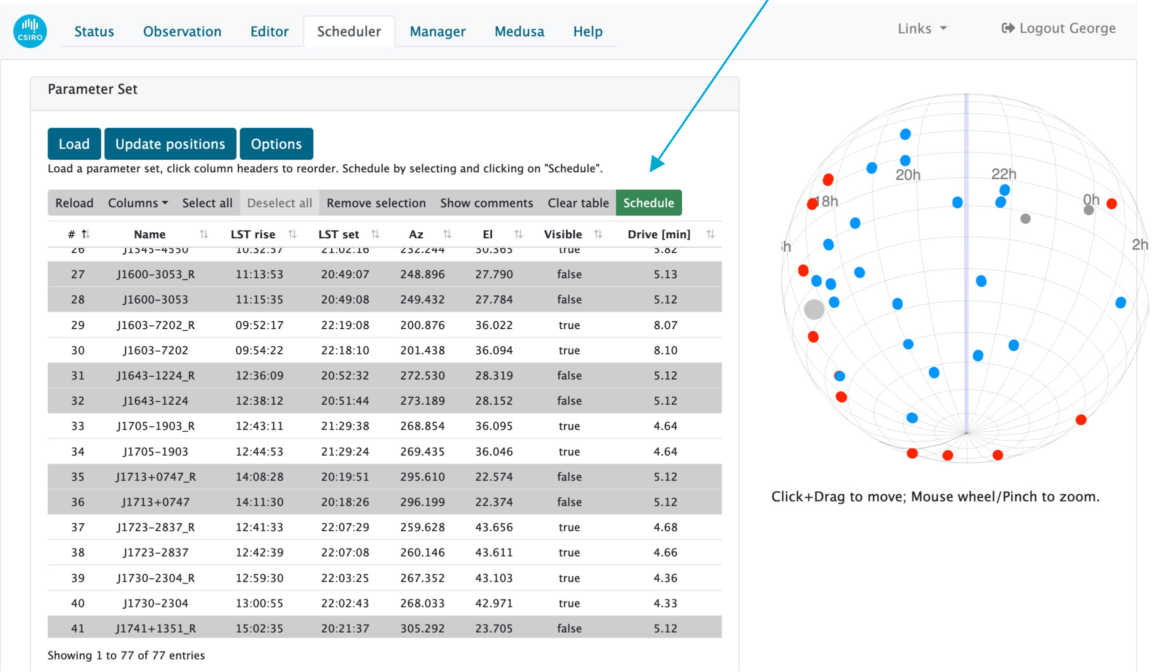
This is the strongest evidence yet for low-frequency gravitational waves, building on our understanding of the universe.

Software:

Psrchive, pfits, tempo2 …

Have a go observing!

Click here!



Parameter Set

Load | Update positions | Options

Load a parameter set, click column headers to reorder. Schedule by selecting and clicking on "Schedule".

Reload | Columns | Select all | Deselect all | Remove selection | Show comments | Clear table | Schedule

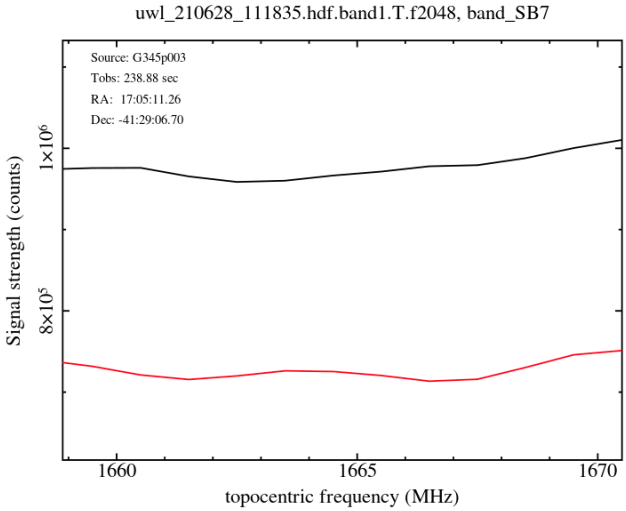
#	Name	LST rise	LST set	Az	El	Visible	Drive [min]
26	J1545−4550	10:32:57	21:02:16	232.244	30.365	true	5.82
27	J1600−3053_R	11:13:53	20:49:07	248.896	27.790	false	5.13
28	J1600−3053	11:15:35	20:49:08	249.432	27.784	false	5.12
29	J1603−7202_R	09:52:17	22:19:08	200.876	36.022	true	8.07
30	J1603−7202	09:54:22	22:18:10	201.438	36.094	true	8.10
31	J1643−1224_R	12:36:09	20:52:32	272.530	28.319	false	5.12
32	J1643−1224	12:38:12	20:51:44	273.189	28.152	false	5.12
33	J1705−1903_R	12:43:11	21:29:38	268.854	36.095	true	4.64
34	J1705−1903	12:44:53	21:29:24	269.435	36.046	true	4.64
35	J1713+0747_R	14:08:28	20:19:51	295.610	22.574	false	5.12
36	J1713+0747	14:11:30	20:18:26	296.199	22.374	false	5.12
37	J1723−2837_R	12:41:33	22:07:29	259.628	43.656	true	4.68
38	J1723−2837	12:42:39	22:07:08	260.146	43.611	true	4.66
39	J1730−2304_R	12:59:30	22:03:25	267.352	43.103	true	4.36
40	J1730−2304	13:00:55	22:02:43	268.033	42.971	true	4.33
41	J1741+1351_R	15:02:35	20:21:37	305.292	23.705	false	5.12

Showing 1 to 77 of 77 entries

Click+Drag to move; Mouse wheel/Pinch to zoom.

High spectral resolution data

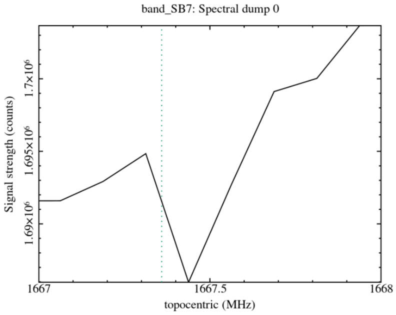
- Spectral line astronomers do not (usually) require microsecond sampling!
- But they want a lot better than ~1MHz-wide frequency channels



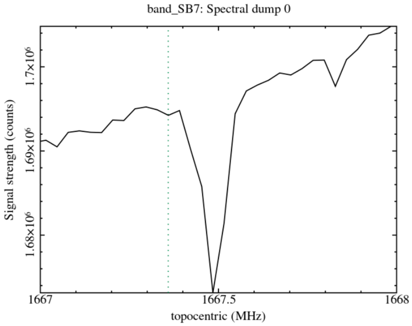
1 MHz channels

High spectral resolution data

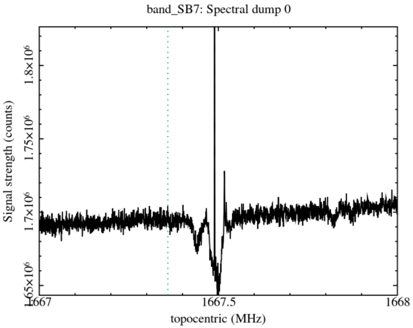
- Spectral line astronomers do not (usually) require microsecond sampling!
- But they want a lot better than ~1MHz-wide frequency channels



125 kHz



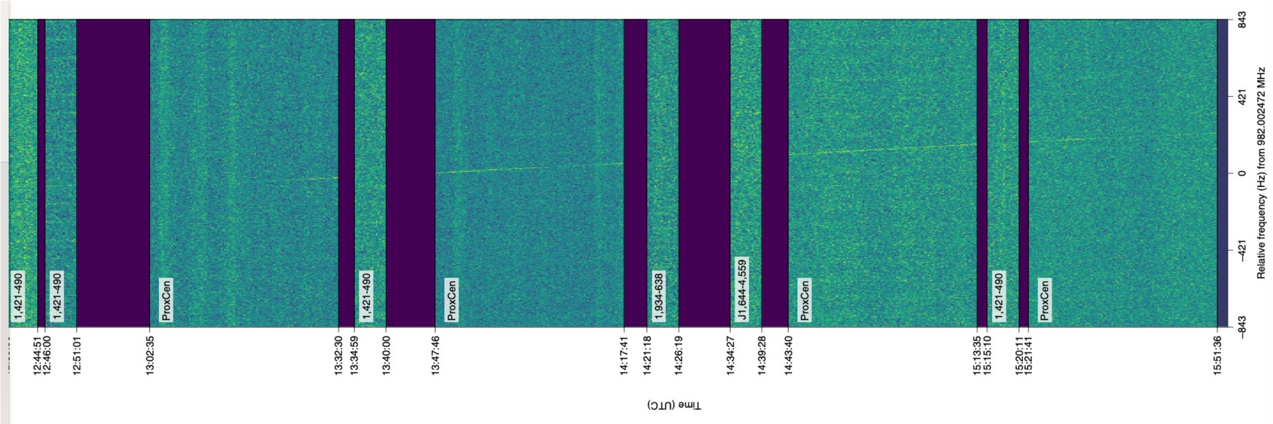
32 kHz



1 kHz

Alien hunting (BLC1)

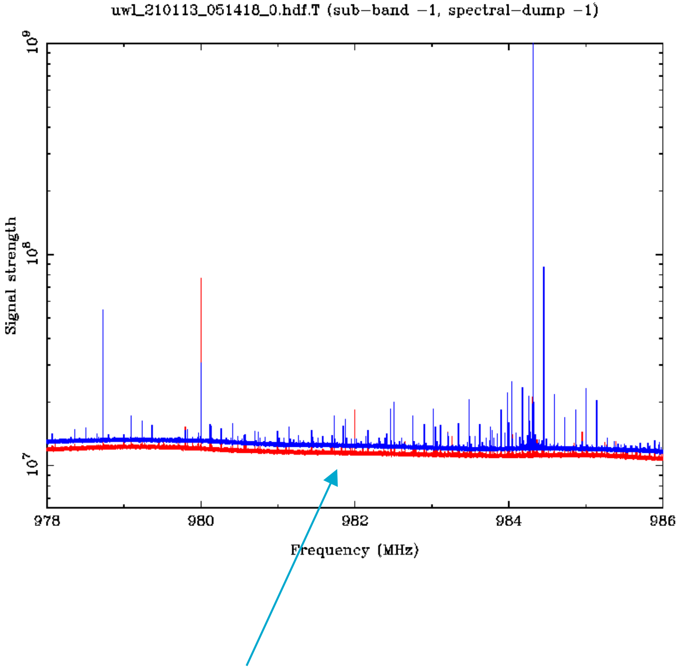
- High frequency and (relatively) high time resolution



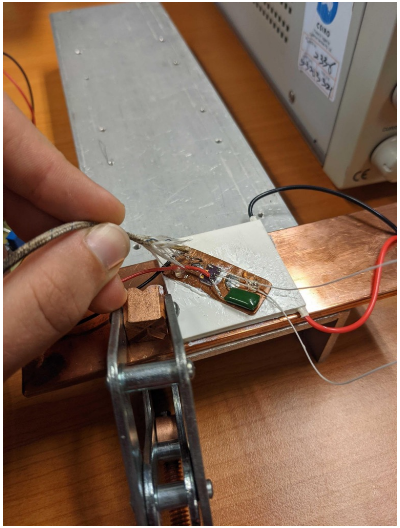
https://www.nature.com/articles/s41550-021-01508-8

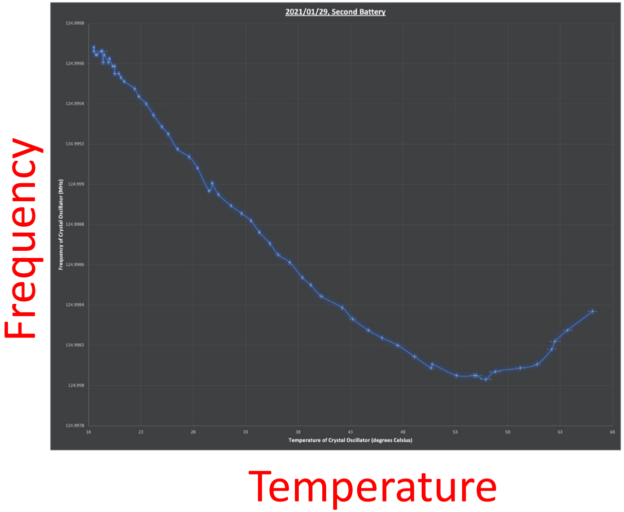
Challenge #1 with a single, single dish telescopes – how do tell an alien from local RFI?

An alien?



Slide from Elise Hardy and Sam Gordon

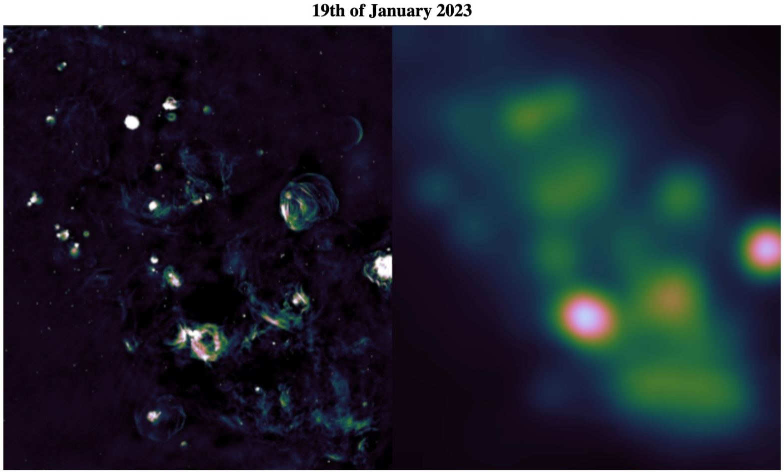




Challenge #2 with a single, single dish telescopes – resolution

Don’t forget continuum observations

- Pulsars switch on and off, FRBs are mostly not there, spectral lines are restricted in frequency … continuum sources are hard!



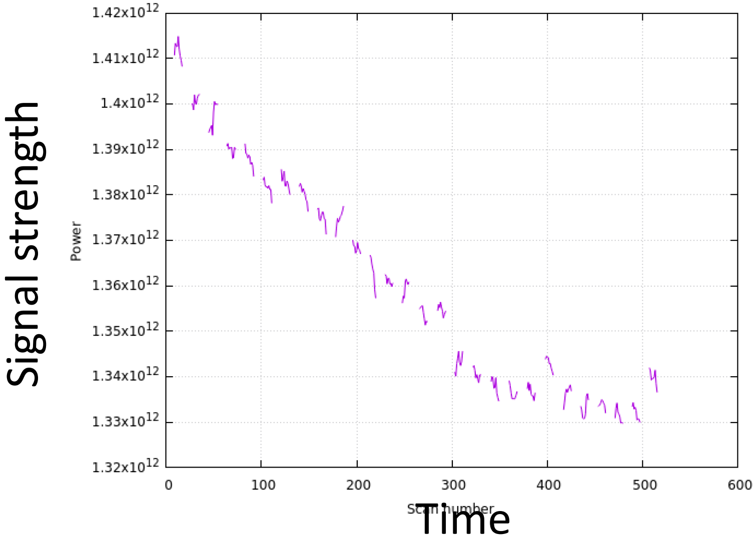
A. Hopkins ASKAP and Parkes

The resolution of radio-astronomy images depends on the size of the telescope. The Parkes Dish, Murriyang, is 64m in diameter, but the 36 ASKAP dishes are spread over 6km, proving almost 100 times better angular resolution. However, ASKAP's fine resolution but comes at the expense of missing radio emission on the largest scales, which are captured by the Parkes Dish. By combining the information from both Parkes and ASKAP, each fills in the gaps of the other to give us the best fidelity image of this region of our Milky Way galaxy.

Don’t forget continuum observations

Challenge #3 with a single, single dish telescopes – stability

- Single dish telescopes measure everything: the sky, the Sun, the RFI, the ground, the Galactic plane, all the sources in the beam …



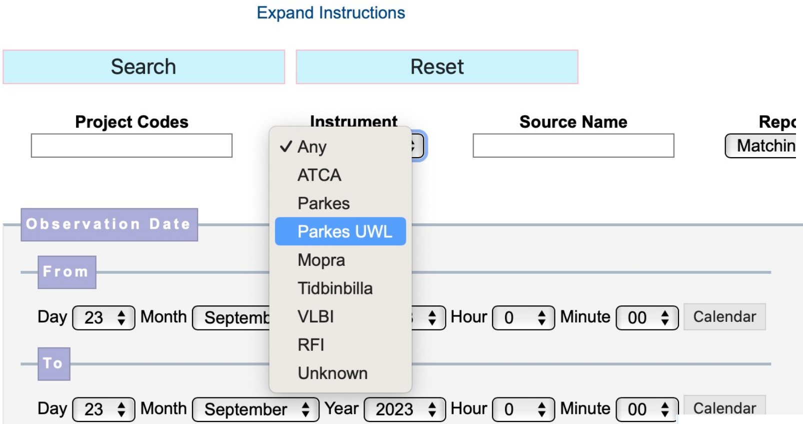
This source does not vary in brightness.

How to deal with the apparent variability?

- On-off pointings
- Stokes V
- LST-aligned tracks
- Multibeams
- Multiple scans
- …

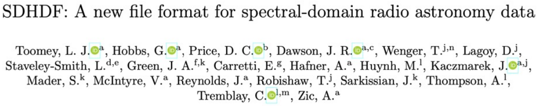
Having a play

- Data available on the ATOA: https://atoa.atnf.csiro.au



From: Day 23 Month Septemb Hour 0 Minute 00

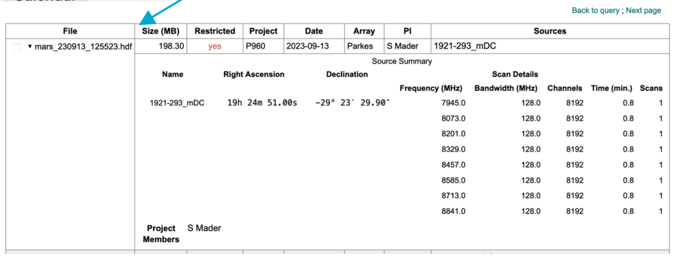
To: Day 23 Month September Year 2023 Hour 0 Minute 00



SDHDF: A new file format for spectral-domain radio astronomy data

Toomey, L. J.[a], Hobbs, G.[a], Price, D. C.[b], Dawson, J. R.[a,c], Wenger, T.[j,n], Lagoy, D.[j], Staveley-Smith, L.[d,e], Green, J. A.[f,k], Carretti, E.[g], Hafner, A.[a], Huynh, M.[l], Kaczmarek, J.[a,j], Mader, S.[k], McIntyre, V.[a], Reynolds, J.[a], Robishaw, T.[j], Sarkissian, J.[k], Thompson, A.[l], Tremblay, C.[l,m], Zic, A.[a]

sd**hdf** format



File	Size (MB)	Restricted	Project	Date	Array	PI	Sources
☐ ▾ mars_230913_125523.hdf	198.30	yes	P960	2023-09-13	Parkes	S Mader	1921-293_mDC

Source Summary

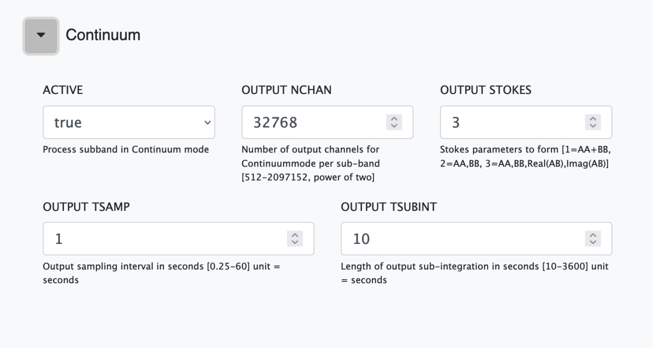
Name	Right Ascension	Declination	Scan Details				
			Frequency (MHz)	Bandwidth (MHz)	Channels	Time (min.)	Scans
1921-293_mDC	19h 24m 51.00s	−29° 23′ 29.90″	7945.0	128.0	8192	0.8	1
			8073.0	128.0	8192	0.8	1
			8201.0	128.0	8192	0.8	1
			8329.0	128.0	8192	0.8	1
			8457.0	128.0	8192	0.8	1
			8585.0	128.0	8192	0.8	1
			8713.0	128.0	8192	0.8	1
			8841.0	128.0	8192	0.8	1

Project Members S Mader

Software:

Inspecta, various python scripts

Have a go observing!



Continuum

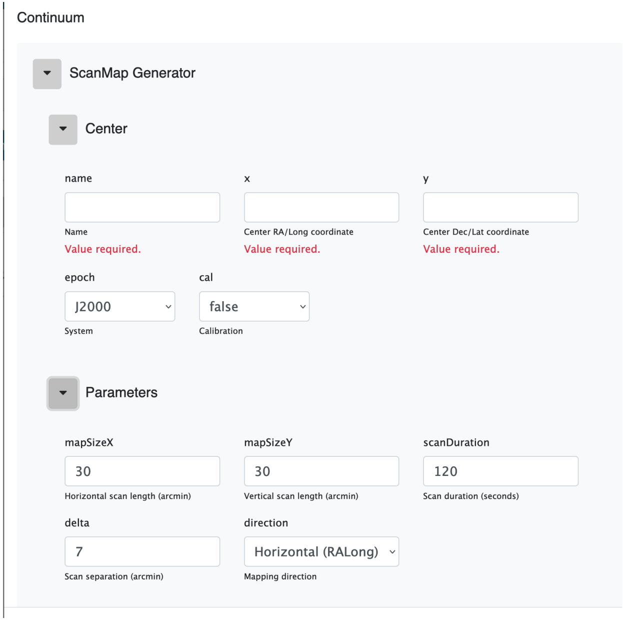
ACTIVE: true
Process subband in Continuum mode

OUTPUT NCHAN: 32768
Number of output channels for Continuummode per sub-band [512-2097152, power of two]

OUTPUT STOKES: 3
Stokes parameters to form [1=AA+BB, 2=AA,BB, 3=AA,BB,Real(AB),Imag(AB)]

OUTPUT TSAMP: 1
Output sampling interval in seconds [0.25-60] unit = seconds

OUTPUT TSUBINT: 10
Length of output sub-integration in seconds [10-3600] unit = seconds



Continuum

ScanMap Generator

Center

name:
Name
Value required.

x:
Center RA/Long coordinate
Value required.

y:
Center Dec/Lat coordinate
Value required.

epoch: J2000
System

cal: false
Calibration

Parameters

mapSizeX: 30
Horizontal scan length (arcmin)

mapSizeY: 30
Vertical scan length (arcmin)

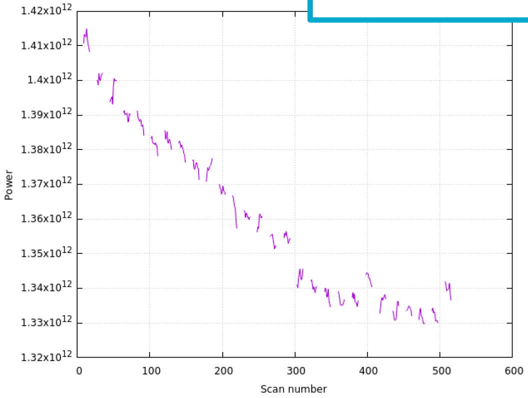
scanDuration: 120
Scan duration (seconds)

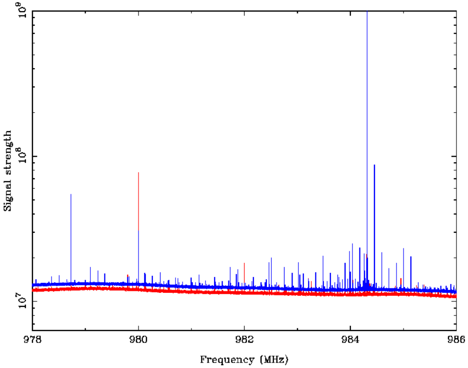
delta: 7
Scan separation (arcmin)

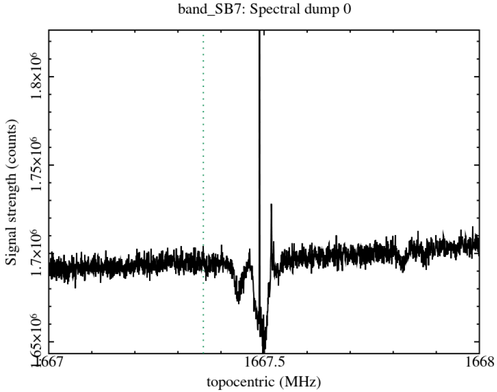
direction: Horizontal (RALong)
Mapping direction

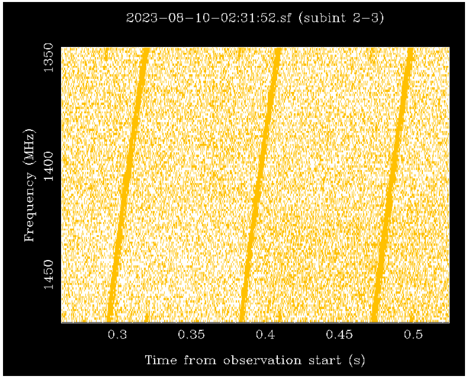
Calibration!

All the signal strength axes are “arbitrary”
What about polarization?
– how do we calibrate the data?

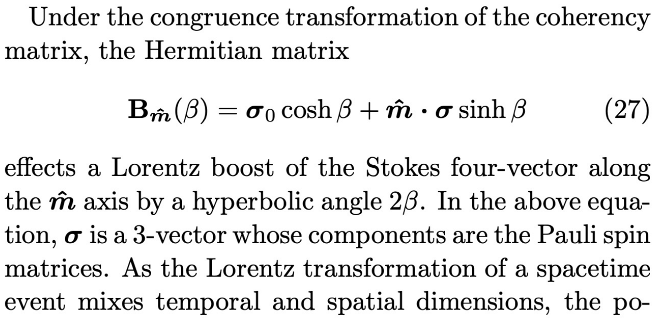








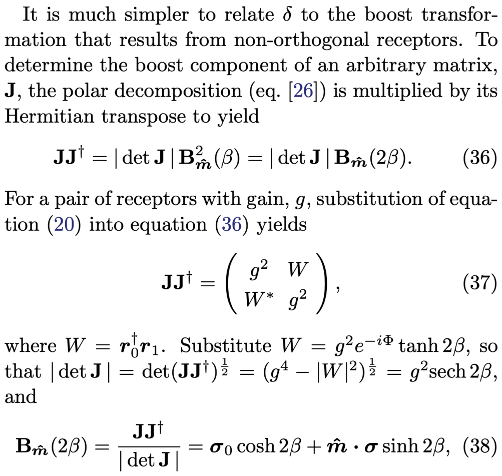
The pulsar papers on calibration …



Under the congruence transformation of the coherency matrix, the Hermitian matrix

$$\mathbf{B}_{\hat{\boldsymbol{m}}}(\beta) = \boldsymbol{\sigma}_0 \cosh\beta + \hat{\boldsymbol{m}}\cdot\boldsymbol{\sigma}\sinh\beta \tag{27}$$

effects a Lorentz boost of the Stokes four-vector along the $\hat{\boldsymbol{m}}$ axis by a hyperbolic angle 2β. In the above equation, $\boldsymbol{\sigma}$ is a 3-vector whose components are the Pauli spin matrices. As the Lorentz transformation of a spacetime event mixes temporal and spatial dimensions, the po-



It is much simpler to relate δ to the boost transformation that results from non-orthogonal receptors. To determine the boost component of an arbitrary matrix, $\mathbf{J}$, the polar decomposition (eq. [26]) is multiplied by its Hermitian transpose to yield

$$\mathbf{J}\mathbf{J}^\dagger = |\det\mathbf{J}\,|\,\mathbf{B}^2_{\hat{\boldsymbol{m}}}(\beta) = |\det\mathbf{J}\,|\,\mathbf{B}_{\hat{\boldsymbol{m}}}(2\beta). \tag{36}$$

For a pair of receptors with gain, g, substitution of equation (20) into equation (36) yields

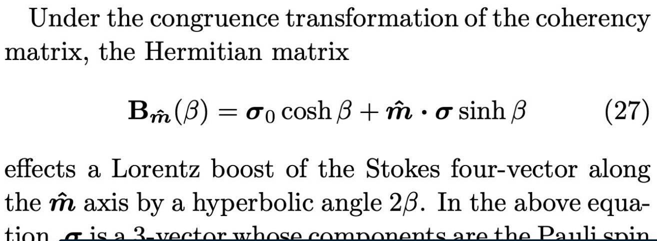
$$\mathbf{J}\mathbf{J}^\dagger = \begin{pmatrix} g^2 & W \\ W^* & g^2 \end{pmatrix}, \tag{37}$$

where $W = \boldsymbol{r}_0^\dagger \boldsymbol{r}_1$. Substitute $W = g^2 e^{-i\Phi}\tanh 2\beta$, so that $|\det\mathbf{J}\,| = \det(\mathbf{J}\mathbf{J}^\dagger)^{\frac{1}{2}} = (g^4 - |W|^2)^{\frac{1}{2}} = g^2 \mathrm{sech}\, 2\beta$, and

$$\mathbf{B}_{\hat{\boldsymbol{m}}}(2\beta) = \frac{\mathbf{J}\mathbf{J}^\dagger}{|\det\mathbf{J}\,|} = \boldsymbol{\sigma}_0 \cosh 2\beta + \hat{\boldsymbol{m}}\cdot\boldsymbol{\sigma}\sinh 2\beta, \tag{38}$$

https://arxiv.org/pdf/2202.07818.pdf

The spectral line papers on calibration …



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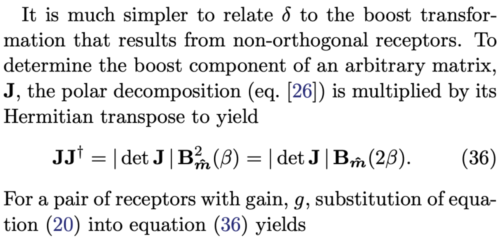
matr

even



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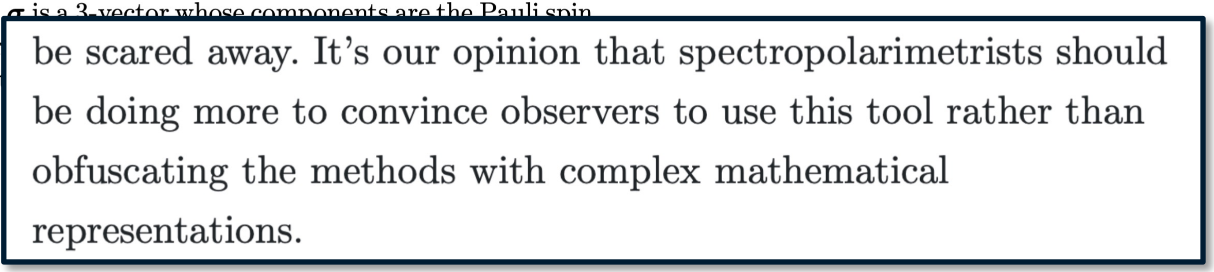
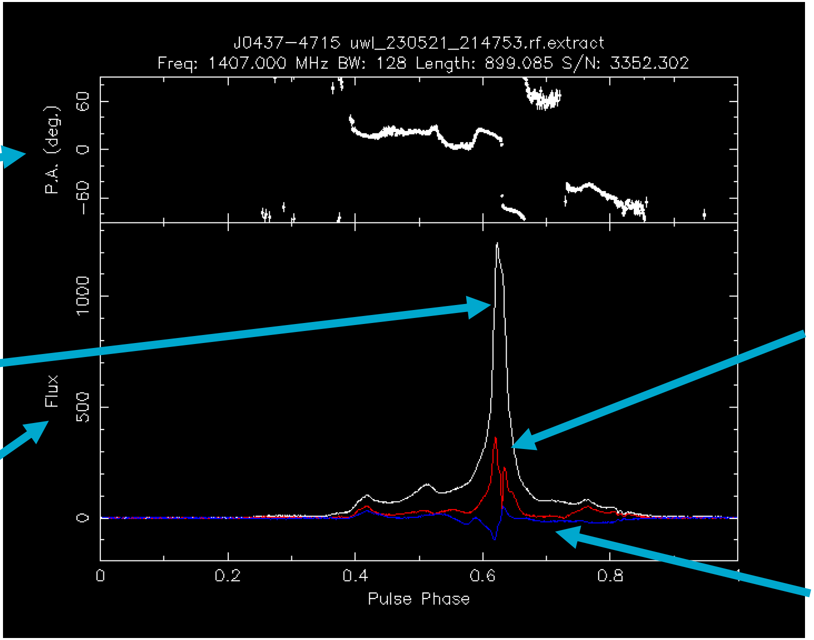


be scared away. It's our opinion that spectropolarimetrists should be doing more to convince observers to use this tool rather than obfuscating the methods with complex mathematical representations.

https://arxiv.org/abs/1806.07391

Somewhere in the middle?

- An observation of PSR J0437-4715



Position angle of the linear polarisation

Stokes I

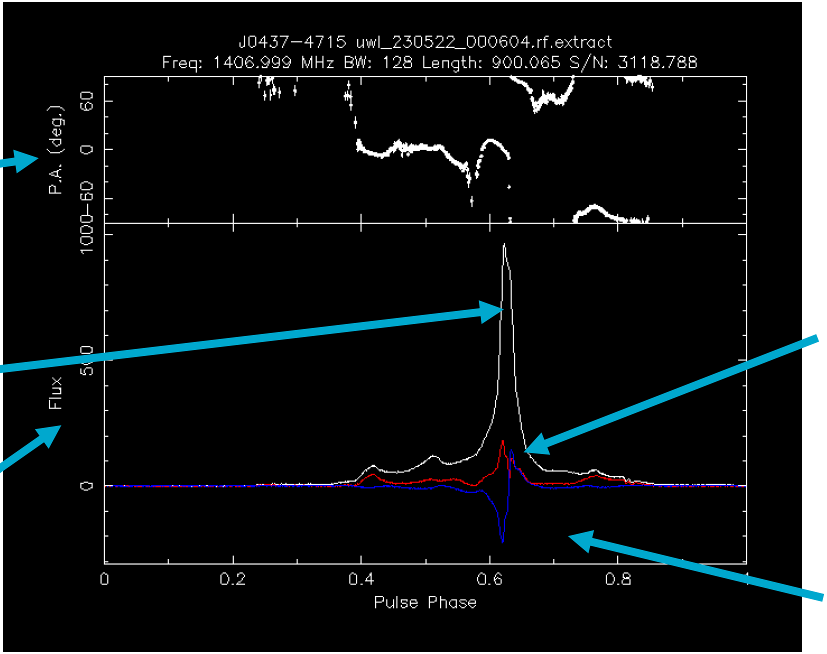
No units

Linear polarisation

Stokes V

Somewhere in the middle?

- An observation of PSR J0437-4715 a few hours later
- It looks different



Position angle of the linear polarisation

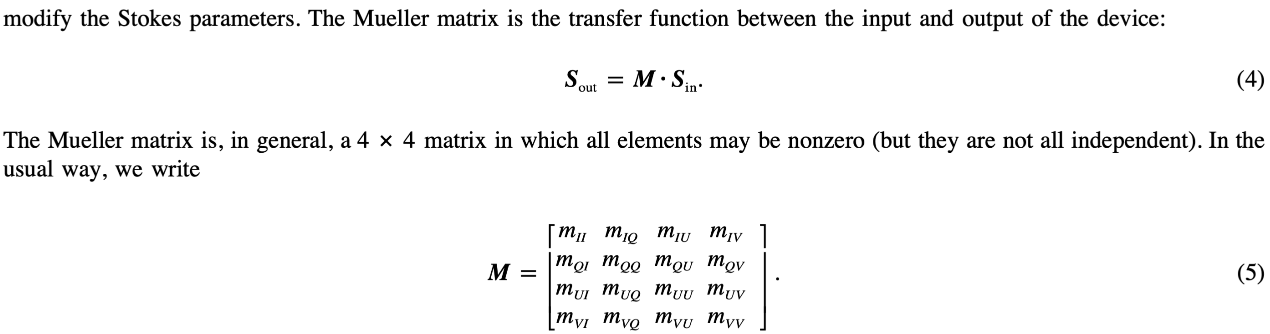
Stokes I

No units

Linear polarisation

Stokes V

Why?



modify the Stokes parameters. The Mueller matrix is the transfer function between the input and output of the device:

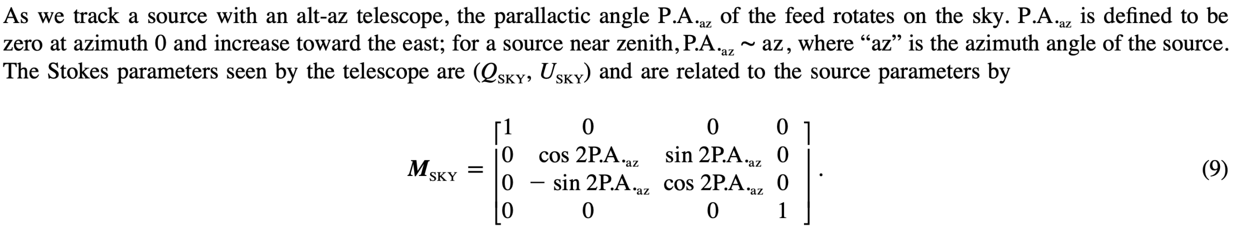
$$\boldsymbol{S}_{\text{out}} = \boldsymbol{M} \cdot \boldsymbol{S}_{\text{in}}. \tag{4}$$

The Mueller matrix is, in general, a 4 × 4 matrix in which all elements may be nonzero (but they are not all independent). In the usual way, we write

$$\boldsymbol{M} = \begin{bmatrix} m_{II} & m_{IQ} & m_{IU} & m_{IV} \\ m_{QI} & m_{QQ} & m_{QU} & m_{QV} \\ m_{UI} & m_{UQ} & m_{UU} & m_{UV} \\ m_{VI} & m_{VQ} & m_{VU} & m_{VV} \end{bmatrix}. \tag{5}$$

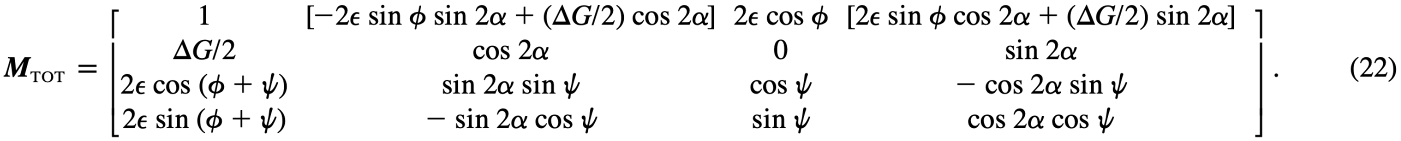
https://iopscience.iop.org/article/10.1086/323289/pdf

Why?



As we track a source with an alt-az telescope, the parallactic angle $\mathrm{P.A.}_{\mathrm{az}}$ of the feed rotates on the sky. $\mathrm{P.A.}_{\mathrm{az}}$ is defined to be zero at azimuth 0 and increase toward the east; for a source near zenith, $\mathrm{P.A.}_{\mathrm{az}} \sim \mathrm{az}$, where “az” is the azimuth angle of the source. The Stokes parameters seen by the telescope are $(Q_{\mathrm{SKY}}, U_{\mathrm{SKY}})$ and are related to the source parameters by

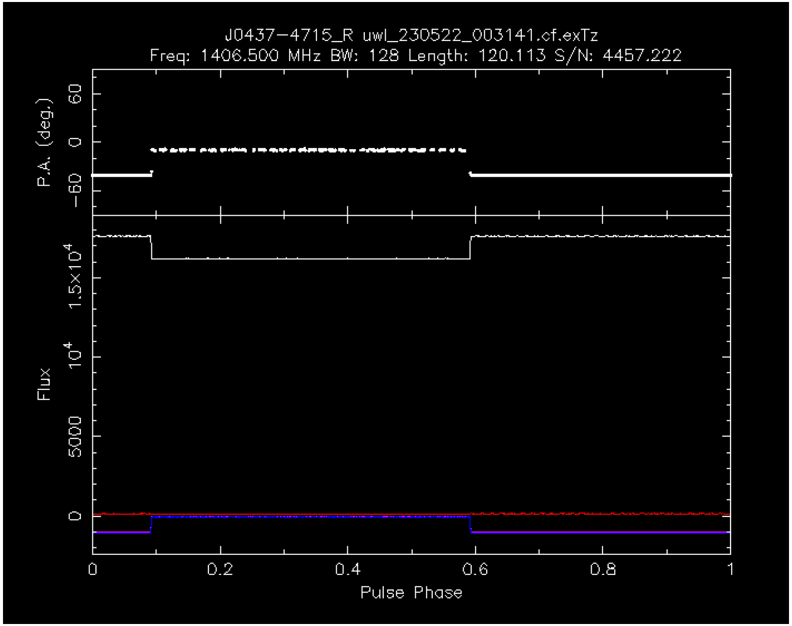
$$\boldsymbol{M}_{\mathrm{SKY}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\mathrm{P.A.}_{\mathrm{az}} & \sin 2\mathrm{P.A.}_{\mathrm{az}} & 0 \\ 0 & -\sin 2\mathrm{P.A.}_{\mathrm{az}} & \cos 2\mathrm{P.A.}_{\mathrm{az}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \qquad (9)$$



$$\boldsymbol{M}_{\mathrm{TOT}} = \begin{bmatrix} 1 & [-2\epsilon \sin\phi \sin 2\alpha + (\Delta G/2) \cos 2\alpha] & 2\epsilon \cos\phi & [2\epsilon \sin\phi \cos 2\alpha + (\Delta G/2) \sin 2\alpha] \\ \Delta G/2 & \cos 2\alpha & 0 & \sin 2\alpha \\ 2\epsilon \cos(\phi + \psi) & \sin 2\alpha \sin\psi & \cos\psi & -\cos 2\alpha \sin\psi \\ 2\epsilon \sin(\phi + \psi) & -\sin 2\alpha \cos\psi & \sin\psi & \cos 2\alpha \cos\psi \end{bmatrix} . \qquad (22)$$

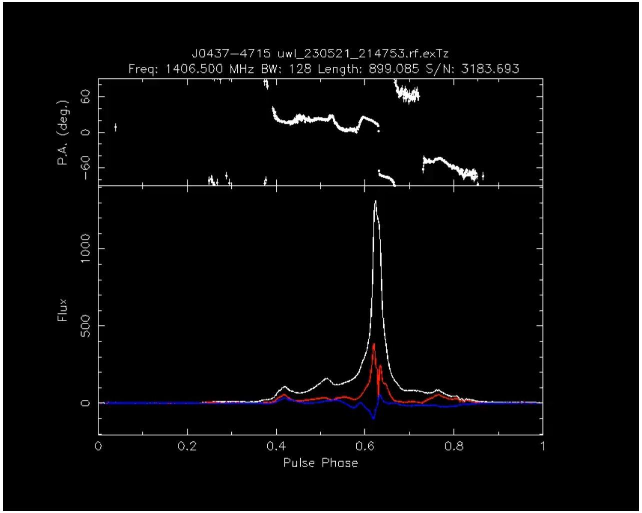
https://iopscience.iop.org/article/10.1086/323289/pdf

Where do all the numbers come from?

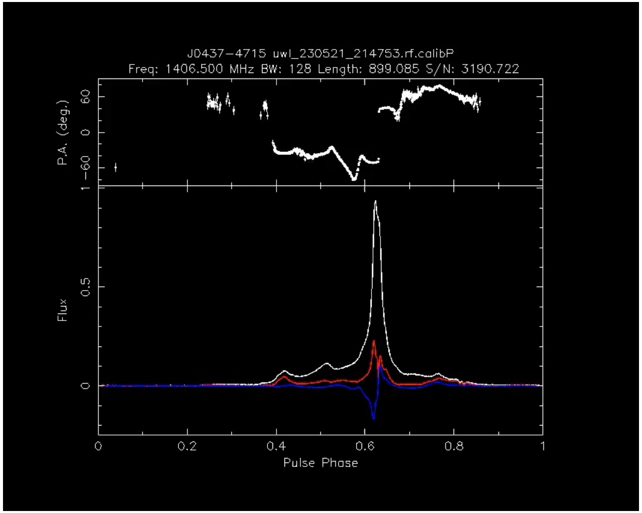


Use a stable, switching noise source injected into the signal path.

From rise to set

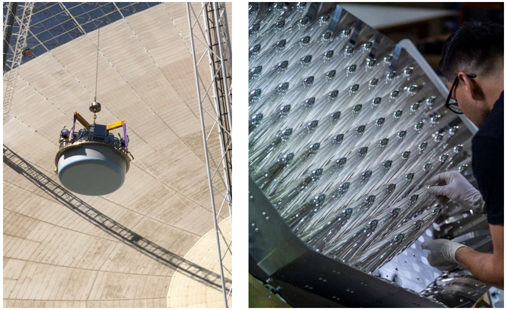


Raw data



After applying Mueller matrix

The future



Thursday last week

72 beams! 700-1950MHz,

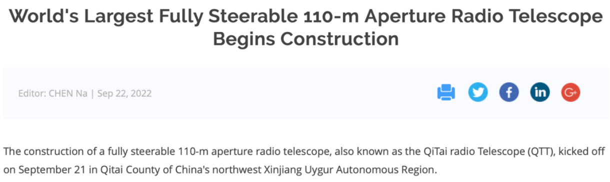
Tsys < 20K

Digital data rate out: 7.8Tb/s

https://www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/lunar_crater_radio_telescope/

The world's largest fully movable low-frequency radio telescope project launched in Jingdong, Yunnan

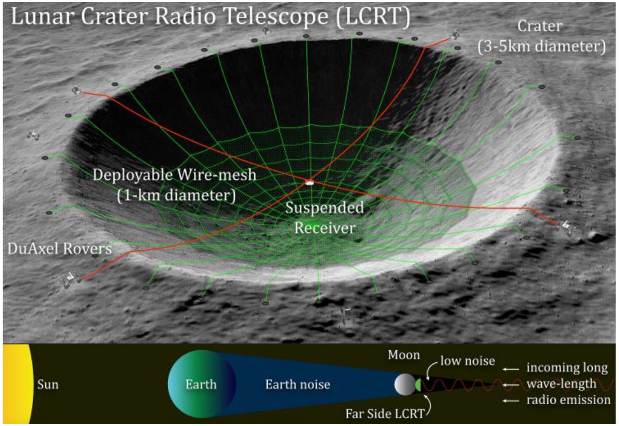
2020/09/29 22:52:04 technology 2424



World's Largest Fully Steerable 110-m Aperture Radio Telescope Begins Construction

Editor: CHEN Na | Sep 22, 2022

The construction of a fully steerable 110-m aperture radio telescope, also known as the QiTai radio Telescope (QTT), kicked off on September 21 in Qitai County of China's northwest Xinjiang Uygur Autonomous Region.



Thank you

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Presenter Name
Presenter Title

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firstname.surname@csiro.au
csiro.au/lorem

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csiro.au/lorem